NOTES AND ANALYTICAL DATA ON

CORDIERITE-BEARING PELITIC ROCKS

SERRA DE JACOBINA

BAHIA, BRAZIL

By

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Introduction

This report describes the preliminary phases of research on cordierite-bearing metapelitic rocks at the southern end of the Serra de Jacobina (Jacobina Range) in the state of Bahia, Brazil. The geology of the area has been described in detail (Leo, Cox and de Carvalho, 1964)and summarized in English (Cox, 1967); the cordierite relationships are briefly described elsewhere (Leo, 1962). Work on this project was suspended in 1967 due to the pressure of other commitments. The present report is open-filed in the hope that the accumulated data including chemical analyses of a number of rocks and minerals, and a map otherwise available only in a Portuguese-language publication (Leo and others, 1964) may be useful to geologists interested in the region and/or in the unusual cordierite-bearing assemblages. No attempt has been made to update any of the contents since 1967.

Geologic Setting

The area of this study is situated between the town of Jacobina and Miguel Calmon, a distance of about 30 km (Fig. 1). In this area, the Jacobina range is about 10 km. wide, and consists of north trending ridges of quartzite, conglomerate and metapelitic rocks (Jacobina Series), with intervening longitudinal valleys eroded into ultramafic rocks. The metasedimentary rocks are in fault contact on both sides of the range with granitic rocks of the Brazilian shield. All of the rocks in the area are of Precambrian age.

Metapelitic rocks constitute the bottom (Bananeira Formation) and the top (Cruz das Almas Formation) of the Jacobina Series. The Bananeira Formation is exposed predominantly near the village of Bananeira in the southernmost part of the range; the Cruz das Almas Formation is intermittently exposed along the eastern side of the range. The rocks considered in the present study are from 1) the Cruz das Almas Formation at several points along the range southward from the latitude of Jacobina, notably exposures on Rio Itaitu where cordierite-bearing assemblages are developed, and 2) the Bananeira Formation in its exposures north of Bananeira village along Rio da Horta and its tributaries.

The metamorphic grade of the Jacobina Series in the area near Jacobina generally corresponds to the amphibolite facies, with local exposures of upper greenschist facies. Near the latitude of Itaitu, there is a rather abrupt increase in metamorphic grade to upper amphibolite and/or hornblende hornfels facies, which appears to reflect an episode of thermal metamorphism superimposed on regionally metamorphosed rocks. This change could be related to demonstrated deeper burial of the southern part of the metasedimentary sequence prior to transverse faulting (Leo and others, 1964, p. 75). Local subjacent intrusions may also have been involved, although there is little direct evidence for such intrusions.

Field Work

Field work, done in December 1962 and January 1963, involved mapping by pace and compass traverse of several sections along streams where dense, cordierite-bearing rocks had previously been found. The principal traverse was along Rio Itaitu on the eastern side of the Jacobina Range, where there are intermittent exposures of pelitic rocks, including thin beds of iron-rich metasediments, for a distance of about 1,700 feet across strike. It was found that cordierite-bearing granofelses comprise only 400 stratigraphic feet at the bottom of the section; above this horizon the rocks are quartz-biotite schists with or without andalusite. Similar rocks occur in the nearest available exposures northward along strike, about 2 miles from Rio Itaitu. These facts strengthen the impression that the granofelses represent the contact aureole of a small intrusion.

Rocks of the Bananeira Formation along Rio da Horta are generally similar to the Cruz das Almas metapelites near Itaitu, except that distinctly iron-rich rocks are not represented. The metapelitic rocks near Bananeira are mostly coarse and granoblastic, characterized by large andalusite porphyroblasts. Rocks of the highest grade contain sillimanite in addition to andalusite.

Samples were collected at sufficient localities to provide an adequate picture of distribution and compositional variations in the metapelitic rocks.

Petrography

Rocks north of Rio Itaitu. The most striking feature of the pelitic rocks, which initially prompted this study, is the difference in petrographic aspect between metapelitic rocks of Jacobina, and those near Itaitu and southward. East of Jacobina and as far south as 2 miles north of Rio Itaitu, rocks of the Cruz das Almas Formation are typically fine-grained schists with abundant biotite, muscovite, spongy and skeletal andalusite porphyroblasts, and local garnet-rich layers. Some rocks contain muscovite and prograde chlorite; hence they belong to the greenschist facies. Variations in metamorphic grade are not progressive from north to south as was the impression gained during original mapping; rather, such changes appear to be random.

Staurolite is present in isolated layers, always accompanied by garnet and biotite. It forms small euhedral prisms which show no sign of reaction to cordierite, as staurolite invariably does in rocks from Rio Itaitu and Rio da Horta.

In summary, the pelitic rocks north of Rio Itaitu are schists of amphibolite facies and upper greenschist facies, with mineral assemblages and textures indicative of simple isochemical recrystallization during a single metamorphic episode. Analyses of selected rocks from this area are listed in Table 1.

Rocks from Rio Itaitu. In the 400-foot stratigraphic section referred to above, metapelitic rocks are granofelses instead of schists, i.e., they have granoblastic textures which have largely obliterated original schistosity. A pronounced compositional layering is nevertheless retained (e.g., analyses 8 and 9, Table 1). The most common mineral assemblage is quartz-biotite-garnet-cordierite; anthophyllite is locally abundant. Andalusite is comparatively rare, and staurolite very rare. Isolated thin beds consist of garnet, anthopyllite, and cummingtonite (Table 1, analysis 10). Such rocks correspond to the silicate facies of iron formation. No other iron formation (e.g., itabirite) was found in the area.

Consistent mineral reactions (based on visual inspection) in the Rio Itaitu granofelses include replacement of biotite and staurolite by cordierite, and replacement of biotite (and cordierite?) by anthophyllite. The relative abundance and evident stability of garnet in most of the rocks suggest late growth of garnet, although this is not evident from textural relations as are the other reactions. Trains of tiny subhedral biotite flakes in cordierite may represent a second generation of biotite distinct from the biotite which has reacted to form cordierite.

An empirical and approximately balanced equation expressing the apparent reactions can be written as follows:

$$\text{Staurolite} + 2\ \text{biotite}_{I} \rightarrow \text{cordierite} + \text{anthophyllite} + \text{biotite}_{II} + K_2O$$

Rocks in the Bananeira area. Metapelitic rocks of the Bananeira Formation are generally higher in Si and Al, and lower in Fe and Mg, than Cruz das Almas rocks (Table 1). Mineral assemblages and textures, however, as well as key mineral transformations, are generally comparable to those in the rocks along Rio Itaitu, and reflect a similar metamorphic history.

Rocks of the Bananeira Formation are typically coarse, massive, dark gray granofelses with conspicuous andalusite porphyroblasts up to 1 inch long, sheaves of sillimanite needles, and coarse biotite. Schistosity is virtually absent, but an indistinct alignment of andalusite crystals is apparent. Relict bedding is preserved in some places.

Microscopic features give clear evidence of a second episode of metamorphism superimposed on an originally schistose fabric. Andalusite porphyroblasts have obviously increased in size, crowding aside formerly aligned trains of mica flakes and engulfing mineral grains along their margins. Biotite flakes show similar enlargement to shapeless patches, but muscovite shows no evidence of such growth. As K-feldspar is absent, some muscovite must nevertheless have formed late to accommodate K^+ released by breakdown of biotite. A finely granoblastic mesostasis of quartz, with or without plagioclase, characterizes all the rocks. Graphite is an almost universal accessory.

New Minerals are sillimanite and cordierite. Sillimanite forms fibrolitic aggregates that have developed from both biotite and andalusite, and also individual prisms intergrown with andalusite. The two minerals are apparently in stable equilibrium. Cordierite forms spongy, inclusion-filled patches in about half of the rocks. Its replacement relationship to both staurolite and biotite has already been noted. The textural evidence for this is most striking in the case of staurolite, which appears as intricately embayed grains and highly irregular relics completely surrounded by cordierite. The relationship between cordierite and biotite is similar in some instances, but cordierite may also form lobate patches in biotite, with inclusion-filled cores and clear margins, indicating two stages of cordierite growth.

Local relics of staurolite are surrounded by andalusite with fringes of pale chlorite, without any trace of cordierite.

An empirical, approximately balanced equation based on the various mineral reactions observed in rocks from the Bananeira area may be expressed as follows:

3 staurolite + biotite + 4 quartz + 2 water → cordierite + almandine + 7 andalusite + muscovite + chlorite

Refinements of these preliminary equations should be possible after calculations of rocks and mineral analyses and determinations of modes.

Rock Analyses

Analyses of 14 metapelitic rocks from the area of investigation are listed in Table 1. (Nine additional analyses of related rocks were obtained, but do not bear directly on the central problem). The analyzed rocks were chosen to reflect as completely as possible the compositional range or originally argillaceous rocks of the Cruz das Almas and Bananeira Formations.

The purpose of the analyses is two-fold: (1) to show differences or similarities between cordierite-free and cordierite-bearing rocks, especially within the Cruz das Almas Formation; and (2) to relate bulk rock composition to compositional variations of constituent minerals, especially where various replacement (e.g., staurolite → cordierite) are evident.

Regarding (1), overall similarities in bulk composition between some cordierite-free and cordierite-bearing rocks are evident (analses 1 and 4, 6; 3 and 12; possibly 2 and 5), and suggest that development of cordierite could have taken place in initially cordierite-free rocks by a change in metamorphic environment, and did not require a significantly different bulk composition. Other cordierite-bearing rocks obviously are not closely comparable to the analyzed cordierite-free samples. More critical evaluation of the rock analyses, and possibly additional analyses of cordierite-free rocks, will be required to establish this point.

Compositions of rocks in different parts of the Cruz das Almas Formation as revealed by the analyses are not notably similar. A range of composition is obviously represented, and exposures are inadequate to allow detailed stratigraphic correlation between different areas. Some general differences that do emerge are higher average MgO and lower K_2O in rocks near Itaitu as compared to those near Jacobina, as well as the appearance of highly ferruginous (garnet-amphibole) rocks in the Itaitu section. These are regarded on the basis of field evidence as facies changes in the sedimentary section; there is no reason to suspect metasomatic introduction and removal of the substances in question.

Analyses of Bananeira rocks show generally higher Al_2O_3 and Na_2O, and lower FeO and MgO, than Cruz das Almas rocks. The difference in iron and mangnesium are reflected at least partially by the common presence of anthophyllite in Cruz das Almas rocks near Itaitu and its absence in Bananeira rocks.

Quantitative and graphic evaluation of the chemical data, especially in relation to mineral analyses, remains to be done.

Separations and Analyses of Minerals

Six garnets, 6 biotites, 3 staurolites, 3 cordierites, and 1 anthophyllite were separated from 6 metapelitic rocks, as shown below:

LJ-4-1: garnet, anthophyllite, cordierite, biotite

LJ-7-12: garnet, cordierite, biotite

LJ-65-1-2: garnet, staurolite, cordierite, biotite

LJ-65B: staurolite, biotite

LJ-79-3: garnet, staurolite, biotite

LJ-88-1: garnet, biotite

Separation and purification of minerals was accomplished by standard methods and required about 3 months. Purification was tedious partly because of the fine grinding and prolonged centrifuging required to remove microscopic inclusions, and partly (notably in the case of cordierite) because of the difficulty in getting rid of minerals of similar density. Disappointingly, cordierite proved so difficult to purify that only three concentrates (from rocks without plagioclase) were obtained. Even these are contaminated by quartz, which however can be calculated out. The cordierite analyses are not listed for this reason.

Analyses of garnets, biotites, staurolites and anthophyllite are listed in Tables 2 to 4.

Preliminary inspection of the mineral analyses shows that, in general, they are relatively high in FeO and low in MgO and Fe_2O_3. The anthophyllite especially shows an unusually high FeO/MgO ratio[1/]. The relationships are in agreement with the generally high FeO/MgO ratios in the host rocks, and also indicate that reducing conditions prevailed during metamorphism; the latter observation is supported by the presence of accessory graphite in nearly all of the rocks examined.

1/ The total absence of Fe_2O_3 in at least 3 of the biotites may reflect possible contamination (by organic matter?) although the FeO values as such are not unduly high.

References

Cox, Dennis P., 1967, Regional environment of the Jacobina auriferous conglomerate, Brazil: Econ. Geol., v. 62, p. 773-780.

Leo, G. W., 1962, Cordierite paragenesis in some pelitic rocks of the Serra de Jacobina, Brazil (abs): Geol. Soc. America Spec Paper 73, p. 196.

Leo, G. W., D. P. Cox, and J. P. de Carvalho, 1964, Geologia da parte sul da Serra de Jacobina, Bahia, Brasil: Departamento Nacional da Produção Mineral, Bol. 209, Rio de Janeiro.

Table 1. Analyses of metapelitic rocks from the southern part of the Serra de Jacobina, Bahia, Brazil

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
SiO_2	59.9	63.7	62.0	61.6	67.7	59.8	55.7	72.1	45.3	53.0	64.5	61.3	56.8	66.7
TiO_2	0.56	0.44	0.79	0.58	0.40	0.66	0.70	0.38	0.58	0.24	0.65	0.77	1.6	0.75
Al_2O_3	16.7	13.2	21.9	16.1	9.7	19.2	20.5	8.7	18.5	7.5	21.9	23.0	24.8	18.8
Fe_2O_3	1.4	1.5	1.0	0.62	0.57	0.90	1.0	0.48	0.90	1.7	0.51	2.6	2.3	2.3
FeO	10.7	11.3	5.6	11.8	11.8	9.0	10.6	8.2	23.0	25.4	2.9	4.6	5.0	5.5
MgO	3.6	3.4	3.4	4.2	4.5	4.0	4.9	5.7	6.5	8.7	2.1	1.8	2.1	1.7
MnO	0.14	0.09	0.04	0.06	0.14	0.03	0.07	0.02	0.36	0.81	0.04	0.12	0.13	0.21
CaO	0.32	0.30	0.22	0.55	0.32	0.40	0.32	0.48	1.1	0.48	0.48	0.80	1.6	0.72
Na_2O	0.10	0.10	0.09	0.17	0.03	0.19	0.19	1.6	0.32	0.03	2.9	1.0	2.4	0.38
K_2O	4.1	3.7	3.2	2.2	1.7	2.8	3.1	0.26	0.62	0.00	2.3	1.1	0.59	0.41
H_2O	1.8	1.9	1.5	1.8	2.2	2.1	2.1	1.5	2.3	1.3	1.5	1.9	1.6	1.5
H_2O	0.10	0.08	0.12	0.10	0.13	0.14	0.16	0.08	0.10	0.14	0.17	0.08	0.28	0.32
P_2O_5	0.06	0.06	0.07	0.09	0.10	0.10	0.13	0.07	0.14	0.17	0.06	0.11	0.07	0.15
CO_2	0.05	0.05	0.05	0.05	0.10	0.08	0.05	0.06	0.16	0.11	0.05	0.05	0.05	0.05
Sums	99	100	100	100	100	99	99	100	100	100	100	99	99	100

Rapid rock analyses by chemists of the U. S. Geological Survey, Washington, D. C.; Leonard Shapiro, Project Leader.

Data on Samples in Table 1

A. Cruz das Almas Formation

1. LJ-88-1, quartz-biotite-andalusite-garnet-staurolite schist, 3.3 km. E of Jacobina

2. LJ-79-3, quartz-biotite-garnet-staurolite schist, app. 6km. SSE of Jacobina

3. LJ-78-1, quartz-biotite-andalusite schist, app. 8 km. SSE of Jacobina

4. LJ-6-5, quartz-garnet-biotite-cordierite granofels, Rio Itaitu ~~Creek~~ 1.9 km. WNW of Itaitu village

5. LJ-6-3, quartz-garnet-biotite-cordierite-anthophyllite granofels, same location as (4)

6. LJ-7-3, quartz-biotite-cordierite-garnet-andalusite-staurolite granofels, same general location as (4)

7. LJ-7-12, quartz-biotite-garnet-cordierite-staurolite granofels, same general location as (4)

8. LJ-4-1b, quartz-anthophyllite-cordierite-biotite granofels, garnet-free portion of layered granofels LJ-4-1; same general location as (4)

9. LJ-4-1a, garnet-cordierite-anthophyllite-quartz-biotite granofels, garnetiferous portion of layered granofels LJ-4-1

10. LJ-7-5, garnet-anthophyllite-cummingtonite granofels, same general location as (4)

B. Bananeira Formation

11. LJ-56-2, quartz-andalusite-sillimanite-biotite-muscovite-cordierite-plagioclase granofels, Rio da Horta 1.9 km. NNE of Bananeira village

12. LJ-65-63, quartz-staurolite-biotite-cordierite-plagioclase granofels, Rio da Horta 3 km. NNE of Bananeira village

13. LJ-65-3, quartz-staurolite-cordierite-plagioclase-biotite-sillimanite-granofels, same location as (12)

14. LJ-65-1-2, quartz-garnet-andalusite-staurolite-cordierite-biotite-sillimanite granofels, same location as (12)

Table 2. Garnets from metapelitic rocks.

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	37.06	36.86	37.35	37.09	37.15	36.99
TiO_2	0.02	0.01	0.08	0.09	0.07	0.10
Al_2O_3	21.18	21.15	21.14	21.13	21.30	21.01
Fe_2O_3	0.51	1.23	0.35	0.45	0.44	0.55
Cr_2O_3	0.04	0.03	0.04	0.04	0.07	0.07
FeO	36.14	37.19	34.88	37.76	34.75	34.61
MgO	2.48	2.30	3.42	2.58	2.57	2.58
MnO	1.02	0.68	0.59	0.67	2.45	2.40
CaO	1.61	0.81	2.04	0.41	1.48	1.51
Na_2O	0.03	0.01	0.02	0.01	0.03	0.01
K_2O	0.01	0.01	0.02	0.02	0.02	0.01
H_2O^+	0.02	0.00 (nil)	nil	nil	nil	nil
H_2O^-	0.02	0.01	0.06	0.01	0.03	0.01
Total	100.14	100.29	99.99	100.26	100.36	99.85

1) LJ#88-1, quartz-biotite-andalusite-garnet-staurolite schist, Cruz das Almas Formation, 3.3 Km. E of Jacobina.

2) LJ 79-3, quartz-biotite-garnet-staurolite schist, Cruz das Almas Formation, app. 6 km. SSE of Jacobina.

3) L4-1, quartz-garnet-cordierite-biotite-anthophyllite granofels, Cruz das Almas Formation, Itaitú Creek, 1.9 Km. WNW of Itaitú village.

4) LJ 7-12, quartz-garnet-cordierite-biotite-staurolite granofels, same general location as (3). (C. das A. Fm.)

5) LJ65-1-2, quartz-andalusite-garnet-staurolite-cordierite-biotite-sillimanite granofels, Bananeira Formation, Rio da Horta 3 km. NNE of Bananeira village

6) LJ65-1-3, same specimen as LJ65-1-2, but garnet less finely ground and subjected to less intensive acid treatment; to serve as control for (5).

Analyses by Vertie C. Smith, U.S. Geological Survey, Denver, Colorado.

Table 3. Staurolites and anthophyllite from metapelitic rocks.

	(1)	(2)	(3)	(4)
SiO_2	27.89	27.10	27.23	52.78
TiO_2	0.25	0.51	0.53	0.16
Al_2O_3	53.80	54.56	54.34	2.82
Fe_2O_3	1.61	1.18	1.74	0.34
Cr_2O_3	0.08	0.18	0.13	n.d.
FeO	13.2	13.2	12.9	25.09
MgO	1.34	1.39	1.37	16.08
MnO	nil	0.02	0.03	0.05
CaO	nil	nil	nil	0.06
Na_2O	nil	0.13	nil	0.11
K_2O	nil	0.01	nil	0.02
H_2O^+	1.62	1.50	1.48	2.16
H_2O^-	0.06	0.02	0.02	0.08
Total	99.85	99.82	99.77	99.75

1) Staurolite, LJ 79-3, quartz-biotite-garnet-staurolite schist, Cruz das Almas Formation, app. 6 km. SSE of Jacobina. Also 0.03% Li, 0.02% Ni, 0.007% V, 0.07% Zn (semiquant. spec.)

2) Staurolite, LJ 65-1-2, quartz-garnet-andalusite-staurolite-cordierite-biotite-sillimanite granofels, Bananeira Formation, Rio da Horta 3 Km. NNE of Bananeira village. Also 0.03% Li, 0.01% Ni, 0.05% V, 0.1% Zn (semiq. spec.)

3) Staurolite, LJ 65-6B, quartz-staurolite-biotite-cordierite-plagioclase granofels, same general location as (2). Also 0.03% Li, 0.03% Ni, 0.02% V, 0.07% Zn (semiquant. spec.)

4) Anthophyllite, LJ 4-1, quartz-garnet-cordierite-biotite-anthophyllite granofels, Cruz das Almas Formation, Itaitée Creek, 1.9 km. WNW of Itaité village. Also 0.07% Cr, 0.05% Ni, 0.007% V, 0.007% Zr (semiq. spec.)

Analyses by Vertie C. Smith, U.S. Geological Survey, Denver, Colorado.

Table 4. Biotites from metapelitic rocks.

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	35.07	34.62	38.40	34.83	35.60	34.81
TiO_2	1.40	1.08	2.64	1.83	1.36	2.22
Al_2O_3	22.85	22.92	18.10	20.83**	23.41	22.15**
Fe_2O_3	nil	nil	18.54*	0.89	21.81*	nil
FeO	18.57	19.79	(16.7)*	19.98	(19.6)*	20.78
MgO	9.01	8.09	—	8.25	—	7.13
MnO	0.02	0.02	—	0.03	0.57	0.10
CaO	nil	nil	nil	nil	nil	nil
Na_2O	0.20	0.25	—	0.22	—	0.34
K_2O	8.93	8.78	7.19	7.98	7.17	7.79
H_2O^+	3.92	3.97	—	4.04	—	3.46
H_2O^-	0.12	0.11	—	0.08	—	0.06
P_2O_5	0.01	0.02	—	—	—	—
Cl	0.04	0.01	—	0.01	—	nil
F	0.12	0.11	—	0.09	—	0.20
Sub-total	100.26	99.77		99.06		99.04
Less O	0.06	0.05		0.04		.08
Total	100.20	99.72		99.02		98.96

1) LJ 88-1, quartz-biotite-andalusite-garnet-staurolite schist, Cruz das Almas Formation in Vale do Côxo, 3.3 Km. east of Jacobina. Also 0.1% Ba, 0.1% Cr, 0.05% Ni, 0.02% V (semiquant. spec.)

2) LJ 79-3, quartz-biotite-garnet-staurolite schist, Cruz das Almas Formation, app. 6 Km. SSE of Jacobina. Also 0.1% Ba, 0.1% Cr, 0.05% Ni, 0.02% V (semiquant. spec.)

3) Partial analysis by X-ray fluorescence. LJ-4-1, quartz-garnet-cordierite-biotite-anthophyllite granofels, Itaitu Creek, 1.9 Km WNW of Itaitu village (C. das A. Fm.)

4) LJ 7-12, quartz-garnet-cordierite-biotite-staurolite granofels, same general location as (3). Also 0.03% B, 0.1% Ba, 0.1% Cr, 0.07% Ni, 0.02% V (semiquant. spec.) (C das A Fm)

5) LJ 65-1-2, quartz-andalusite-garnet-staurolite-cordierite-biotite-sillimanite granofels, Rio da Horta 3 Km NNE of Bananeira village (Bananeira Formation). Partial analysis by X-ray fluorescence

6) LJ-65-6B, quartz-staurolite-biotite-cordierite-plagioclase granofels, same general location as (5); Bananeira Formation. Also 0.3% Ba, 0.3% Cr, 0.15% Ni, 0.02% Sc, 0.05% V (semiquant. spec.)

* Total iron as Fe_2O_3; figure for FeO based on 0% Fe_2O_3. ** includes P_2O_5.
Gravimetric analyses by Vertie C. Smith, USGS, Denver; X-ray fluorescence by Roberta J. Brown.