SAPPHIRINE FROM SALVADOR, BAHIA, BRAZIL: EVIDENCE FOR FORMATION BY EX-SOLUTION

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ABSTRACT Sapphirine was found for the first time (1966) in a lenticular pyroxenite body in granulites of Rio Vermelho, Salvador, Bahia, Brazil. Recently another occurrence of sapphirine was found in Vitória within the Salvador city. Both occurrences are similar. The Vitória sapphirine bearing body has tabular shape with 1.5 m long, 1.0 m wide and 0.1 m - 0.15 m thick, concordant to the country granulitic rock foliation. This sapphirine bearing rock consists of biotite, orthopyroxene, cordierite, sapphirine, spinel and small amount of plagioclase, apatite, zircon. Biotite is an abundant mineral and it is a replacement product of orthopyroxene.

The sapphirine is in irregular, lenticular or wormlike grains, and is associated with orthopyroxene as an unmixing product. Very often reaction rims of cordierite appear between sapphirine and orthopyroxene. The formation of sapphirine explains some aspects on the origin of the country rocks.

RESUMO Em 1966 foi encontrada uma ocorrência de safirina num corpo de piroxenito lenticular encaixado nos granulitos de Rio Vermelho, Salvador, Bahia, Brasil. Recentemente uma outra ocorrência desse mesmo mineral foi encontrada no Bairro da Vitória, em Salvador. As duas ocorrências são semelhantes. O corpo de rocha com safirina de Vitória tem a forma tabular com 1,5 m de comprimento, por 1,0 m de largura e 0,1 m a 0,15 m de espessura e é concordante com a foliação da rocha encaixante granulítica. A rocha que contém a safirina é constituída de biotita, ortopiroxênio, cordierita, safirina, espinélio e pequenas quantidades de plagioclásio, apatita e zirconita. A biotita é um mineral muito abundante e é um produto de substituição do ortopiroxênio.

A safirina se apresenta em grãos irregulares, lenticulares ou vermiformes e está associada com ortopiroxênio como um produto de iniciabilidade. Frequentemente, corôas de reação de cordierita aparecem entre safirina e ortopiroxênio. A formação de safirina explica também alguns aspectos da origem das rochas encaixantes.

INTRODUCTION Fujimori & Allard (1966) described the first occurrence of sapphirine in Brazil, in the place called Rio Vermelho, in Salvador, Bahia. Sapphirine is not a rare mineral, but it is an interesting mineral due to its origin still not well known and also to petrological informations about country rocks that it may furnish.

The Rio Vermelho sapphirine occurrence was recently chemically studied by Stormer (1973). In another place called Vitória in Salvador, (Fig. 1) the author localised another occurrence of this mineral. The characteristics of this occurrence will be presented here.

GENERAL GEOLOGY Salvador city, the capital of the State of Bahia, Brazil, presents two distinct topographical parts: the higher part and the lower part. The higher part of the city is on high grade metamorphic rocks of the granulite facies (Turner & Verhoogen 1960), of Precambrian age. The lower part of the city is in part, on deeply eroded to near sea-level Precambrian rocks, and mostly on the Cretaceous sedimentary rocks of the Recôncavo Sedimentary Basin. These two different types of rocks are separated by Salvador fault, trending N10°E approximately. The Recôncavo Sedimentary Basin is in the west side of this fault and the high grade metamorphic Precambrian rocks are in the east side of this same fault.

The Precambrian metamorphic rocks are mineralogically very complex. Even in thin section scale it is possible to find different mineral bandings. These variable mineralogical assemblages were classified in two main groups: acid or felsic granulites and basic or mafic granulites (Fujimori 1968).

The following mineral assemblages were included in felsic granulites: quartz-K feldspar - garnet ($\pm$ plagioclase $\pm$ biotite), quartz-K feldspar - plagioclase - garnet - sillimanite - spinel ($\pm$ biotite - rutile), quartz-K feldspar - plagioclase - garnet - cordierite - sillimanite - spinel - corundum ($\pm$ biotite) and quartz-K feldspar - plagioclase.

In the mafic granulites the following mineral assemblages were considered: plagioclase - clinopyroxene - orthopyroxene ($\pm$ hornblende $\pm$ biotite), quartz - plagioclase - clinopyroxene - orthopyroxene ($\pm$ hornblende $\pm$ biotite) and quartz - plagioclase - orthopyroxene ($\pm$ K feldspar $\pm$ hornblende $\pm$ biotite).

Felsic and mafic granulites are the predominant rocks of the Precambrian terrain but, small, very often tabular to lenticular bodies of ultramafic assemblages are concordantly intercalated in the granulites. These ultramafic mineral assemblages are: clinopyroxene ($\pm$ plagioclase $\pm$ biotite) (diopsidites), clinopyroxene - epidote, clinopyroxene - scapolite - plagioclase ($\pm$ hornblende $\pm$ biotite), orthopyroxene ($\pm$ biotite $\pm$ cordierite) (hypersthénite).

Aplite and homogeneous pegmatite dikes cut the granulites and ultramafic metamorphic assemblages. Diabases constitute younger pre-Mesozoic dikes cutting all the previous rocks.

The sedimentary rocks of the Mesozoic Recôncavo Basin are mostly shales and sandstones and conglomerates (fanglomerates) that occur near the Salvador fault scarp line. These sedimentary rocks are grouped in the following formations (from bottom to top): Aliança formation (red shale, conglomerates, evaporites), Sergi formation (sandstone, conglomeratic sandstones), Itaparica formation (mar-

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Figure 1 – Sapphirine bearing rock of Vitória, Salvador, Bahia, Brazil

roon shale), Candeias formation (greenish shale, sandstones), Ilhas formation (greenish shale, siltstones, sandstones), São Sebastião formation (sandstones, shales), Marisal formation (conglomerates, sandstones, shales), Salvador formation (conglomerates, siltstones, shales). Tertiary sediments (Barreiras sediments) cover both Precambrian and Mesozoic sedimentary rocks. The base of Barreiras sediments is around 60 m above the sea-level, around Salvador city.

GEOLOGICAL CONDITIONS AROUND THE SAPPHIRINE CONTAINING ROCK

The new sapphirine containing body was found on the Salvador fault scarp line, about 0.5 m above the high tide level, in the place called Vitória, within the limits of Salvador city, Bahia (Fig. 1).

It is a tabular body with 0.10–0.15 m thick, and elliptical in map with 1.0 m by 1.5 m approximately. The shape of the body shown in the geological sketch map is due to the erosion and resultant relief. This body is enclosed by granulitic rocks and it is concordant to their general foliation.

The rocks around the sapphirine bearing body are mostly granulites, amphibolites and pegmatites.

The *granulites* are predominant rocks and show bluish gray colour when fresh and yellowish gray on surface due

to the weathering. They are fine grained, saccharoidal, with mineral and quartz lenticular aggregate orientations that originate the foliation of the rock. The foliation is produced also by mineralogical banding, and it trends N10°W 20°NE on average in this part of the region. The granulites are locally strongly sheared, giving cataclastic microbreccias.

The mineralogical composition of the granulites are: plagioclase (~50%), orthopyroxene (~40%), clinopyroxene, perthite, quartz, and small amounts of opaques, apatite, biotite, hornblende. The mineralogical banding of the granulites are due to the quartz and feldspar enrichment in some layers.

The plagioclase (An 25) is granular, 0.4–0.5 mm in average size and it presents poorly developed polysynthetic twinning. When polysynthetic twinning is present, the lamellae are often bent and they have fine wedge shape. Many sections of the plagioclases do not show clear twinning but wavy extinction. The contact between plagioclase grains and between plagioclase and pyroxene grains are straight giving very often triple points. Myrmekite type of texture develops commonly between plagioclase and quartz grains. Bubbles or fluids as aligned small inclusions in plagioclase are common.

The orthopyroxene (En 82–58) are also granular and with average grain size similar to that of the plagioclases. It is pleochroic from light pinkish colour (X) to very pale

green (Z) and they have 2V (–) around 65 – 70° and distinct dispersion ($r > v$). The contact between orthopyroxenes and clinopyroxenes are straight and smooth, and replacement relations are not clear. But, both ortho and clinopyroxene are partially replaced by biotite, particularly through the sheared zones. The orthopyroxenes alone or with clinopyroxenes appear concentrated in narrow layers even in thin sections.

The clinopyroxenes are also granular, with average grain-size (0.2–0.3 mm) smaller than the orthopyroxenes. They are associated with orthopyroxene and they have very pale greenish colour and no pleochroism. Very small size opaque inclusions concentrate in certain parts of some of the clinopyroxene grains, and aligned fluid inclusions are also present. The amount of this pyroxene is in general small, but in some parts of the rock it forms an aggregate only made by clinopyroxenes.

Some grains of perthite appear as prismatic porphyroblasts sizing up to 2.0 mm and oriented parallel to the foliation. The small (0.05 mm) plagioclase (An 10–15) inclusions are prismatic and oriented parallel to the length of the host grains. These inclusions amount up to 10–15% of the grain.

The biotite flakes range in size from 0.1 mm to 1.0 mm. They are strongly pleochroic from reddish brown to very pale yellow. Greater flakes of biotite are oriented parallel to the rock foliation, and they are bent and kink banded. The biotite has 2V ~ 0° and it replaces orthopyroxene mostly through the fractures and sheared zones. This replacement relation is best shown by smaller grains of biotite. Hornblende is also replaced by biotite. Normally biotite amounts up to 5% in the rock.

The hornblende appears in small amount, and it concentrates in some layers. The hornblende grains are very irregular and the size ranging from 0.1 mm to 0.5 mm. It is pleochroic from olive green to pale yellowish green. The prismatic grains are oriented parallel to the general rock foliation. Small prismatic opaque inclusions are oriented within the hornblende, but granular opaque minerals appear around the hornblende grains. There is some replacement relation between hornblende and clinopyroxene (Fig. 2).

Figure 2 — Granulite: cp-clinopyroxene; b-biotite; hb-hornblende, pl-plagioclase

The opaque minerals show irregular shape, and they are interstitial or they occur contouring the ferromagnesian minerals. The size is variable but predominantly in the range 0.3–0.4 mm. Most of these opaque minerals are magnetite. In fractures and sheared zones it appears string of fine granular magnetite and small amount of pyrite. But outside these zones, there are also some pyrite together with magnetite.

The quartz forms lenticular aggregates sizing up to 2.0 mm. Within these aggregates the contact between quartz grains are sutured and they show strong wavy extinction, with a difference of up to 8° between extreme extinction positions.

The apatite grains are euhedral prismatic crystals around 0.1 mm long. Some greater crystals have acicular inclusions of apatite and opaques and also aligned globular blue inclusions.

Zircon and monazite are also present in small amount.

The amphibolites appear as narrow bands within the granulites. They are dark coloured, fine equigranular rock with saccharoidal texture but showing some hornblende grain orientation. Hornblende and plagioclase are the predominant minerals with small amount of biotite and opaque minerals.

The plagioclase of the amphibolites are granular with convex boundary and they have an average size around 0.4–0.5 mm. The composition is approximately An 40, and locally calcite substitution is observed. The contacts between plagioclase grains and plagioclase and hornblende grains give a mosaic type of texture. Polysynthetic twinning is not clear, and in many sections of grains it is absent. If present, the lamellae are bent and very often broken. The amount of plagioclase in the rock is around 40%.

The hornblende grains are prismatic and granular with irregular contourline. It is olive green (Z) to pale yellow (X). Small bubble and opaque mineral inclusions are present in hornblende grains, which are also bounded by string of small granular opaque minerals. The contact between hornblende grains is generally straight, giving very often triple points, but between hornblende and plagioclase, its contact becomes concave towards the hornblende due to the convex shape of plagioclase grains. In some places hornblende becomes interstitial to the plagioclase, and it is replaced by biotite. The grain size of the hornblende is around 0.8–0.9 mm, so, greater than the plagioclases. The hornblende constitutes about 60% of the rock.

Biotite appears in small amount, as minute crystals with 0.1–0.2 mm in average size. It is reddish brown to pale yellow in colour, and it is bent. Biotite is frequently associated with hornblende and it is a replacement product.

The opaque minerals occur generally in minute crystals (0.05 mm) between grains of hornblende, and sometimes between hornblende and plagioclase crystals. Interstitial grains of opaque minerals are greater in size (Fig. 3). These opaque minerals are mostly ilmenite, but some pyrite is also present.

Apatite as minute prismatic and euhedral crystals (< 0.05 mm) is present in very small amount.

THE SAPPHIRINE CONTAINING ROCK The rock body with sapphirine of Vitória, Salvador, occurs within the granulites. It is a dark gray coloured rock, relatively weathered due to the surface exposure. It shows strong

Figure 3 – Amphibolite: hb-hornblende; pl-plagioclase; op-opaques

schistosity in some parts of the body. Some transformation produced biotite enrichment in some parts of the rocks than in another ones. The main minerals are biotite, orthopyroxene, cordierite, sapphirine, spinel, and few amounts of plagioclase, apatite, zircon and chlorite as alteration product.

Biotite is the most abundant mineral, reaching in certain parts of the body more than 90%. It is pleochroic from yellowish brown to very pale yellow, and the grain size ranges from 0.5 mm to 1.0 mm. The biotite flakes are oriented, giving schistosity where they are abundant. The optical angle is about $2V \approx 0^\circ$, and pleochroic haloes result around zircon and also apatite inclusions. Biotite alters to chlorite, and it is an alteration of orthopyroxene. The relation between biotite and cordierite is not clear, but the texture in some places indicates that biotite is probably, in part, an alteration product of cordierite.

Figure 4 – Rock with sapphirine (sa), orthopyroxene (op), cordierite (c), spinel (s), biotite (b)

The orthopyroxenes are granular to prismatic, with variable grain-size ranging up to 2 mm. They are pleochroic from pale greenish colour (Z) to very pale rose (Y) and rose (X). The optical angle is large $2V(-) = \sim 80-85^\circ$, and distinct $r > v$, giving a composition around En80 (bronzite). The orthopyroxenes are associated with sapphirine and cordierite, or only with sapphirine. Cordierite is between sapphirine and bronzite (Fig. 4) as a reaction rim between these minerals, so there is a gradual transformation from bronzite-sapphirine assemblage to bronzite-sapphirine-cordierite association (Fig. 4). Biotite envelopes all these assemblages. The amount of bronzite depends on the degree of replacement by cordierite. It is abundant where cordierite is not present and diminishes as cordierite and biotite increase. Spinel is another mineral associated to bronzite.

The sapphirine appears in irregular, lenticular or wormlike grains (Fig. 5 and 6), with grain-size ranging from less than

Figure 5 – Relation between sapphirine (sa), orthopyroxene (op), cordierite (c), spinel (s), biotite (b)

Figure 6 – Rock with sapphirine (sa), orthopyroxene (op), cordierite (c), spinel (s), biotite (b)

0.1 mm up to 1.0 mm. It is strongly pleochroic from dark sky blue (Z) to blue (Y) and pale rose (X). The optical angle is around $2V(-) \sim 60^\circ$, and strong dispersion $r < v$. Due to the strong colour, in some position it shows an anomalous interference colour. It is associated to cordierite and very often the small lenses of sapphirine occur as optically oriented inclusions in cordierite (ex-solution) and when the cordierite rim is not present between them, there are some positions in which sapphirine is almost indistinct from cordierite due to their similar colours. When cordierite is completely replaced, present together with sapphirine is the green spinel (Fig. 7). No reaction rim between spinel and sapphirine is present (Fig. 8), as it is between cordierite and sapphirine. Sapphirine decreases in amount as cordierite increases. No clear relations exist between biotite and sapphirine.

The sapphirine of Rio Vermelho appears as optically oriented lenses in orthopyroxene (Fig. 9) and also as granular or irregular shaped grains.

The cordierite occurs in very irregular or granular grains with variable grain size. Very often, a single crystal of cordierite replaces bronzite, giving "sand crystal" aspect and poikiloblastic texture. Polysynthetic twinning is present and other irregular twinings give a wavy extinction to some grains of cordierite. Pleochroic haloes are formed around zircon and apatite inclusions. In some places the cordierite is replaced by biotite.

The spinel has dark grass green colour to almost opaque sometimes due to the inclusions. The spinel grain size is very small (0.05–0.1 mm) and it is associated with sapphirine. It also appears as inclusions in cordierite and very often it is rimmed by cordierite. But no cordierite rim is observed between spinel and sapphirine (Fig. 8).

Figure 7 – Relation between sapphirine (sa), orthopyroxene (op), cordierite (c), spinel (s), biotite (b)

Figure 8 – Relation between sapphirine (sa), spinel (s), cordierite (c), orthopyroxene (op), biotite (b)

Figure 9 – Sapphirine (sa) lamellae in orthopyroxene (op); c-cordierite; b-biotite; (Fujimori & Allard 1966)

Plagioclase is present in some parts of the body. It is granular, with grain size around 0.4–0.5 mm, and with poorly developed polysynthetic twinning. Small prismatic inclusions are concentrated in the central part of some plagioclase grains.

Apatite appears as very irregular grains, with grain size varying from less than 0.05 mm up to 1.0 mm. Larger apatite grains concentrate in some parts of the rock. The apatite grains form pleochroic haloes in biotite and cordierite in contact with them. Small aligned bubble inclusions occur in some apatite grains.

Opaque minerals are almost absent in this rock body containing sapphirine.

Cordani & Tyer (1979) determined for granulites of Salvador an age around 2.270 ± 40 Ma by Rb-Sr isotope analyses, with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.703 ± 0.001 .

Table 1 – Some occurrences of Sapphirine

OCCURRENCE	COUNTRY ROCK	SAPPHIRINE ASSOCIATED WITH	ORIGIN
Sukkertoppen, West Greenland (Ramberg, 1948).	Granodiorite gneisses	Al-rich hornblenda, bitownite, spinel and phlogopite.	Transfer of Si towards the spinel rich parts of the ultrabasic rocks.
West Greenland (Sorensen 1955)	Hornblenda gneisses	Corundum-anorthite-biotite Corundum bearing hornblendites	Sapphirine rims corundum and replaces spinel.
Dangin, Western Australia (Prider 1945)		Biotite-feldspar schists	Derived from spinel during feldspathization of hyperstenites by addition of K.
Madura, India (Muthuswami 1949)	Hypersthene granulite	Cordierite, spinel, garnet Biotite and anthophyllite.	
Sakena, Madagascar (Lacroix 1929)	Sillimanite-cordierite almandine paragneisses	Anorthite-augite (Sakenites) Spinel pyroxenites Spinel sakenites, Amphibolites	
Cortland, New York (Friedman 1952)	Emery deposits cut by quartz veins	Sillimanite, cordierite, and Garnet	Addition of Si to Spinel
Blinkwater, Transvaal (Mountain 1939)	Coarse – grained granite	Mica and corundum	
McRobertson Land, Antarctica (Segnit 1957)	Charnockites		
Rio Vermelho, Salvador, Bahia, Brazil (Fujiori & Allard 1966)	Granulites	Hypersthene Hypersthene-cordierite Spinel-cordierite Cordierite-garnet	Addition of silica to spinel (Stormer 1973)
Near Wilson Lake, Central Labrador, Canada (Morse & Talley 1971)	Granulites	Quartz-Magnetite Sillimanite-hypersthene Kyanite-hypersthene Corundum	
Vitória, Salvador, Bahia, Brazil (Fujimori, this paper)	Granulites	Hypersthene Hypersthene-cordierite Spinel-cordierite Cordierite	Ex-solution in orthopyroxene and latter reaction between sapphirine and orthopyroxene plus Si, to form cordierite.

ORIGIN OF SAPPHIRINE A reasonable number of sapphirine occurrences is known around the world as it is indicated in Table 1.

In general, sapphirine occurs in similar mineral assemblages which indicate a possible same origin for its occurrence.

The most common origin admitted for sapphirine is the alteration of spinel by addition of Si through a metasomatic process. Stormer (1973) in his chemical studies of sapphirine from Rio Vermelho, Salvador, adopted the same origin.

The sapphirine from Vitória, Salvador, has almost the same mineral association of the Rio Vermelho (Fujimori & Allard 1966): sapphirine-bronzite, sapphirine-spinel, sapphirine-bronzite-cordierite, sapphirine-bronzite-spinel-cordierite and sapphirine-cordierite. The primary association are sapphirine-bronzite and sapphirine-bronzite-spinel with sapphirine and spinel as ex-solution lamellae in orthopyroxene. The other associations including cordierite are due to reactions between bronzite and sapphirine or bronzite and spinel as showed by their textural relations.

Table 2 reproduces chemical analyses of sapphirine, cordierite, hypersthene and spinel of Rio Vermelho, Salvador, made by Stormer (1973).

Table 2 – Mineral analyses of the Rio Vermelho sapphirine occurrence (Stormer 1973)

	sapphirine	hypersthene	cordierite	spinel
SiO ₂	12.4	50.2	49.3	< 0.05
Al ₂ O ₃	60.7	7.6	33.9	61.5
ΣFeO	9.8	20.9	3.3	23.7
MgO	17.5	22.3	12.3	15.8
CaO	< 0.02	< 0.05	< 0.02	< 0.05
TiO ₂	< 0.05	0.06	–	< 0.05

The diagram of Figure 10 was constructed by Stormer (1973) based on the data of the Table 2. This diagram shows the possibility of sapphirine formation by addition of SiO₂ to spinel and removal of FeO and MgO, since Al₂O₃ variation is very small. Also cordierite may be formed by more intense silicification of spinel and sapphirine. Textural relations between these minerals show that really this process is verified in the rock. But the textural relations between sapphirine and spinel do not show

Figure 10 - Plotting of sapphirine (sa), cordierite (cd), hypersthene (hy), spinel (sp), enstatite (en), of Rio Vermelho in $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-(Fe,Mg)O}$ diagram (Stormer 1973)

clearly the formation of sapphirine from silicification of the last mineral. Both minerals are possibly "primary" minerals. Textural equilibrium between sapphirine and spinel was also observed by Morse & Talley (1971) in granulites of near Eilson Lake, Central Labrador, Canada.

The ex-solution of sapphirine from orthopyroxene is the origin admitted here for sapphirine. Then, the reaction between orthopyroxene and sapphirine in a Si supplying environment produced cordierite as rim between those minerals, and following the reaction: sapphirine + hypersthene + $\text{SiO}_2 \rightarrow$ cordierite + (Fe, Mg) O (removed). Also from the reaction between orthopyroxene and spinel, cordierite is formed and an appreciable amount of (Fe, Mg) O should be removed. This (Fe, Mg) O removed have contributed, probably to the biotite formation. The cordierite and biotite are probably products of retrograde metamorphism.

The presence of sapphirine indicates for the rocks containing this mineral a metamorphic condition of deeper parts of the crust, around 11 Kb and 1100°C according to Morse & Talley (1971). Stormer (1973) determined for granulitic rocks of Salvador a metamorphic conditions

of 5 to 8 Kb and 1000°C. If sapphirine is an ex-solution product, the use of this mineral in determining P-T conditions must be applied with caution.

Acknowledgements The author wishes to thank Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq for financial support and Zelinda M. A. N. Leão for reading and Elza M. C. Azevedo for typing of the manuscript.

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MANUSCRITO

Recebido em 27 de julho de 1984

Revisão aceita em 21 de fevereiro de 1985

... A descrição de um processo não é, contudo, uma lei, mas uma conjunção de proposições singulares. Esta aplicação confusa do termo "lei" não traz consequências importantes, a menos que nós procuremos montar predições e explicações em termos de uma "lei" de sucessão histórica. "Leis" de sucessão histórica neste sentido são raras, se não inexistentes em geologia. . .

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