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RADIOGENIC HEAT PRODUCTION FROM SÃO FRANCISCO CRATON: POSSIBLE LINK TO ARCHAEAN CRUSTAL STABILITY

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A summary of the measured radiogenic heat production values from crystalline basement rocks of São Francisco craton, where radiometric data yield Archaean to Lower Proterozoic ages, and surrounding Lower Proterozoic folded regions is presented. The data, especially those from the high grade metamorphic terranes of Caraiba, Itabuna, Jequié, Jacobina and Pouso Alegre show that the values are highly variable (0.78 to 2.7 $\mu W/m^3$). Relatively high heat production values of 1.89 to 2.7 $\mu W/m^3$ were encountered in the Archaean granulite of Itabuna and Jequié. Presence of high heat production values in Jequié may be interpreted as representing relict primary geochemical character, little modified during metamorphim. Relatively low heat production values were encountered in granulite terranes of Caraiba and north of Pouso Alegre, whereas the amphibolite terrane of Jacobina seems to be characterized by intermediate values. Thus, the variability of heat production appears to be largely related to the original chemistry of the rock type and the nature of the fluids that participated in the metamorphic events. It can not be generalised as solely due to the type of metamorphism. Crustal temperatures were calculated for these five areas assuming possible forms of vertical distribution of radiogenic heat production. The results show considerable variations in the thermal regime of the Archaean crust within the São Francisco craton. This seems to imply that survival of Archaean crust in cratonic areas may not be directly related to the depletion of radioactive elements. Other mechanisms such as dehydration and participation of CO_2 fluids during metamorphism may have played a significant role in raising the melting point of lower crust, thereby contributing to the tectonic stability of cratonic areas since Archaean times.

Apresenta-se um resumo dos valores de produção de calor medidos em rochas de embasamento cristalino do Cráton do São Francisco, onde dados radiométricos estabelecem idades do Arqueano e do Proterozóico Inferior, e das regiões circundantes de dobramentos proterozóicos. Os dados, especialmente os obtidos nos terrenos com alto grau de metamorfismo de Caraiba, Itabuna, Jequie, Jacobina e Pouso Alegre, mostram valores muito variáveis (0.78 a 2.7 $\mu W/m^3$). Valores relativamente altos de produção de calor, de 1,8 a 2,7 $\mu W/m^3$ foram encontrados nos granulitos arqueanos de Jequié e Itabuna. A presença de altos valores de produção de calor em Jequié pode ser interpretada como representativa do caracter geoquímico primário preservado, pouco modificado durante o metamorfismo. Valores relativamente baixos de produção de calor foram encontrados nos terrenos granulíticos de Caraíba e ao norte de Pouso Alegre, ao passo que o terreno anfibolítico de Jacobina parece caracterizar-se por valores intermediários.

Portanto, a variabilidade da produção de calor parece ser, em grande parte, relacionada com a química original do tipo de rocha e da natureza dos fluídos que participaram dos eventos metamórficos. Essa variabilidade não pode ser generalizada como sendo devida exclusivamente ao tipo de metamorfismo. Temperaturas crustais foram calculadas nessas cinco áreas, assumindo-se formas possíveis de distribuição vertical da produção de calor radiogênico. Os resultados mostram variações consideráveis no regime térmico da crosta arqueana no cráton do São Francisco. Esses resultados parecem implicar em que a preservação da crosta arqueana em áreas cratonicas pode não estar diretamente relacionada com o empobrecimento em elementos radiativos. Outros mecanismos como perda de água e a participação de fluídos com

CO_2 durante o metamorfismo podem ter tido uma participação importante no aumento da temperatura de fusão da crosta inferior, contribuindo dessa forma, para a estabilidade tectônica de áreas cratônicas desde os tempos arqueanos.

(Traduzido pela Revista)

INTRODUCTION

The origin and the evolution of the continental crust is a matter of great interest and subject of serious discussion. The two important models proposed for the evolution of the crust involve steady state (Armstrong, 1968, 1981) and continuous growth (Hurley & Rand 1969; Moorbath, 1978; McCoulloch & Wasserburg, 1978), the latter model being largely supported by isotopic data. Among the different epochs of crustal growths identified, the period around the Archaean Proterozoic boundary (3000-2500Ma) was a major turning point in the crustal evolution during which 50 to 80% of the present crustal mass was generated (Kroner, 1985). It has been inferred that the post Archaean crust differs in chemical composition from the Archaean crust especially with regard to radioactive elements (Taylor & McLennan 1982; Weaver & Tarney 1984). The low abundance of the radioactive elements and its attendant heat production in the Archaean continental crust is considered by Morgan (1985) as an important factor for the crustal stabilization.

In the São Francisco craton (a major tectonic domain in the Brazilian platform), where basement rocks seem to have formed in the Archaean and Early Proterozoic, measured radiogenic heat production values are assembled for different terranes in the craton and in the surrounding Lower Proterozoic folded regions. The data are discussed in relation to the chemistry of the rock types, nature and type of metamorphism and their implication on the stabilization and survival of the ancient crust.

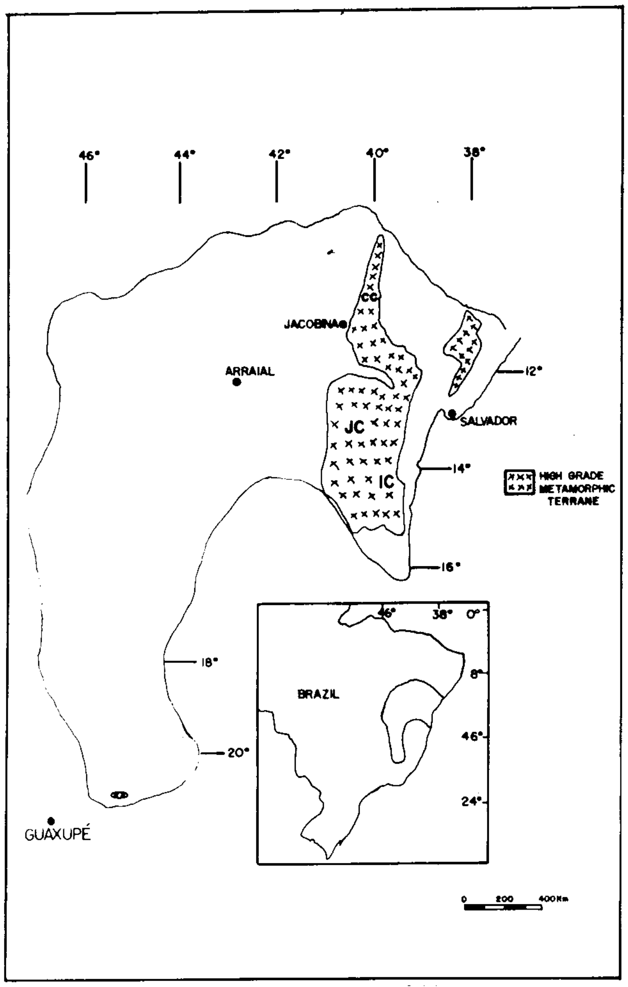

Figure 1 — Sketch map of São Francisco craton with sample locations CC — Caraiba Complex, JC — Jequié Complex, IC — Itabuna Complex.

GENERAL GEOLOGY

The São Francisco craton, occupying a major part of the states of Bahia, eastern parts of Minas Gerais and nothern parts of Espírito Santo, as shown in Fig. 1, is covered mainly by Late and Middle Proterozoic sedimentary and metasedimentary sequences of Bambui, Una and Espinhaço. The Archaean and Lower Proterozoic basement to these sequences can be observed in a very large terrane in Central and Eastern Bahia State and in an area at the southern tip of the craton, S.W. of Belo Horizonte, Minas Gerais. The three major types of the geological formations in these areas are Archaean granite-greenstone terranes, Lower Proterozoic supercrustals and medium to high grade metamorphic belts.

From the geochronological data and geotectonic features, Brito Neves et al. (1980) suggested a central stable Archaean cratonic area (covered by Chapada Diamantina Group) bordered by two Lower Proterozoic mobile belts on the east and the west. Along these belts remnant nucleii of granulite belts like Jequié-Mutuipe and Santa Isabel showing Archaean ages can be identified (Cordani & Iyer, 1979; Mascarenhas et al. 1985). The geological evolution of the craton, as envisaged by Cordani & Brito Neves (1982), invokes the formation of an extensive and stratified crustal mass by Late Archaean. Such a crust, according to these authors was made up of granulite facies rocks in its lower part and the erosional surface should have been at a level compatible with a granite-greenstone terranes found today. Superimposition of ensialic belts over the Archaean continent, as well as some addition from the mantle took place during the Late Proterozoic events, the most important one being Trans-Amazonian. After the Trans-Amazonian event the infrastructure of the Lower Proterozoic mobile belts along with extensive portions of granulite facies rocks, got exposed at surface probably by uplift. The erosion rates for most of the area in the São Francisco craton seem to have been low since the Lower Proterozoic and the exposed crustal levels seem to have remained unaltered to a large extent.

The radiogenic heat production data of high grade metamorphic terranes in the São Francisco craton and surrounding regions are assembled here. The regional geology of these regions can be obtained from the works of Cordani & Iyer (1979), Figueiredo (1980; 1982); Fernandes (1982). Mascarenhas et al. (1985). Table 1 lists the geological, geochronological, geotectonic and geochemical details of the various areas from where the data are assembled (Iyer et al., 1987).

SURFACE RADIOGENIC HEAT PRODUCTION DATA

Surface radiogenic heat production data, reported for different localities mentioned above, have been assembled and listed in Table 2. Most rock formations belong to amphibolite to granulite facies and the values vary from 0.81 to 2,7 $\mu W/m^3$, reflecting the heterogeneity in the chemistry of the original rock types as well as the nature of fractionation of radioactive elements, especially uranium, during high grade metamorphism. The regional depletion of uranium during high grade metamorphism is controlled by the type of the site of uranium, its solubility in metamorphic fluids, which in turn depends on FO_2, $a_H{}^+$, nature and concentration of complexing agent, temperature and relative volume of the fluid that passed through the rocks. According to Rudnick et al. (1985) the degree of U and Th depletion will depend on the position of these elements in the protolith, the presence of fluid phase and the stability of various accessory phases during granulite facies metamorphism. Haack (1983) estimated that average heat production value for the granulite facies rocks to be 0.721 $\mu W/m^3$. In the São Francisco craton, Archaean granulites of Jequié and the Lower Proterozoic granulites of Itabuna yield much higher values, the reasons for this have been discussed by Iyer et al. (1984). According to these

Table 1 – General characteristics of high grade metamorphic terranes of São Francisco Craton and neighbouring Belts

GEOLOGICAL UNIT	AREA	ROCK TYPE	GEOCHRONOLOGICAL EVOLUTION	GEOTECTONIC SIGNIFICANCE	GEOCHEMICAL FEATURES
JEQUIÉ, BAHIA	very large	banded granulites (partly migmatised felsic types predominate	Early Archaean protoliths with about 2700 Ma high grade event rejuvenation at 2000-1800 Ma	cratonic region (exposed lower crust)	granitic chemistry with undepleted LILE conc.
ITABUNA, BAHIA	very large	felsic to mafic granulites, calc-silicates and banded iron formation intercalations	probable Early Proterozoic high grade metamorphic event	internal zone of metamorphic belt	heterogeneous with depleted LILE conc.
CARAIBA, BAHIA	large	banded, felsic to intermediate gneisses and granulites highly migmatised	Late Archaean rejuvenated at 2100 Ma	internal zone of metamorphic belt	granodioritic tonalitic composition remobilisation of LILE
JACOBINA, BAHIA	medium	quartzites, pelitic schists upper amphibolite facies gneisses migmatised	Late Archaean rejuvenated at 2100 Ma	internal zone of metamorphic belt	granitic chemistry of gneisses
ARRAIAL, BAHIA	large	quartzites quartz-biotite schists iron formation, dolomites	Late Archaean rejuvenated at Early Proterozoic	internal zone of metamorphic belt	
GUAXUPÉ	large	charnockites, enderbites, mafic granulites, minor pelitic gneisses	Proterozoic with rejuvenation at 700 Ma	crustal blocks in collision belts	

medium = $(200-1000)km^2$ large = $(1000-10.000)km^2$ very large = > $10.000\ km^2$ LILE = large ion lithophile element.

authors, the higher radioactive element distribution, concentrated along the fractures, margins and cleavage zircon, apatite and monazite reflects the original chemistry of the rocks being little modified during metamorphism. From fission track studies, Dostal & Capedri (1978) showed that uranium is mainly concentrated along the fractures, margins and cleavage planes in amphibolite facies rocks, whereas in granulites it is concentrated in accessory minerals. Thus in a prograde metamorphic reaction uranium, not located in the accessory minerals in the amphibolite facies, is lost and thus granulites appear depleted.

Table 2 – Surface radiogenic heat production data from São Francisco Craton and surrounding areas.

GEOLOGICAL UNIT	RADIOGENIC HEAT PRODUCTIVITY µW/m³	REFERENCE
JEQUIÉ GRANULITES	2.7 (28)*	Sighinolfi et al (1981) Iyer et al (1984)
ITABUNA GRANULITES	1.89 (19)	Sighinolfi & Sakai (1977)
CARAIBA GRANULITES	0.78 (10)	Vitorello (1978)
JACOBINA		
Metasediments	1.6 (02)	Vitorello (1978)
Gneisses	0.9 (02)	Vitorello (1978)
ARRAIAL		
Biotite Schists	2.0 (04)	Vitorello (1978)
GUAXUPÉ		
Granulites	0.81 (14)	Fernandes (1982)
Amphibolite Gneisses	1.08 (14)	Fernandes (1982)

* In the brackets are given number of rock samples analysed.

An attempt to estimate the temperature distribution with depth for the regions mentioned above, based on the heat flow radiogenic heat production data and thermal conductivities of the rocks, is made. Studies by Heier & Adams (1964) show that near surface heat production must be strongly fractionated upward in the crust. Vitorello et al. (1980) proposed a tentative linear relation between heat flow density and near surface heat production for eastern highlands of Brazil with a depth parameter 13.1 ± 7mW/m². Hamza (1980) pointed out the possibility of two different heat flow provinces (São Francisco craton and Proterozoic folded regions) with different depth parameters. In the present work calculation of the temperature distribution for the different areas is made based on two types of assumed distribution of radioactive elements in the crust.

1 — radiogenic heat production is constant for the first ten kilometers (the step model)
2 — the radiogenic heat production decreases with depth (the exponential model).

The equations used for the calculations are presented in Hamza (1982), Hamza & Easton (1983). The equations are derived taking into account the influence of temperature on the thermal conductivity of the rocks. The distribution diagrams (Fig. 2 for step model and Fig. 3 for exponential model) for different regions up to the depth limits of 10 km, show that the temperature increment with depth is higher for exponential distribution than for uniform layer (step) distribution. The geotherms for Jequié, Arraial and Itabuna are less steeper than those of other areas, i.e. for a given depth the temperatures obtained are much lower. In this model lower geotherms are obtained for areas with higher radiogenic heat production. Morgan (1985) elaborated hypothetical geotherms for stable continental lithosphere for different amounts and distribution of crustal heat production, assuming constant conductivities for the crust and the mantle. For the different regions studies by the present authors such geotherms show that Jequié and Itabuna with higher radiogenic heat production values will have steeper geotherms in relation to other areas. In either case, the range of geotherms calculated for different areas probably reflects the complex nature of the crustal distribution of the heat producing elements as well as the reduced heat flow. More data are necessary from different localities to define better the geotherms as well as the crustal distribution of radioactive elements.

SURVIVAL OF THE ARCHAEAN CONTINENTAL CRUST

Recently Morgan (1985) suggested that the survival of the Archaean continental crust may be related to its low radiogenic heat production which makes it less susceptible to orogenic reworking. According to above author "either Archaean crustal generation was by a mechanism that perhaps fortuitously produced only low heat production crust, or all high production crust was reworked by orogenesis during the Archaean and did not stabilize in significant volumes until the earliest Proterozoic, perhaps in association with a reduction in mantle temperatures and mean heat flow".

The granulite terranes of Jequié, Caraiba, Itabuna and Guaxupé represent lower crustal materials. In Jequié mineral geothermometric and geobarometric data seem to indicate that these rocks have been subjected to pressure conditions corresponding to crustal depths of 20 — 30 km with temperatures of 750 - 800°C. The geochronological data seem to show that the rocks are Early Archaean with an inherited chemistry little modified (Iyer et al., 1984). Isotopic ages in the range of

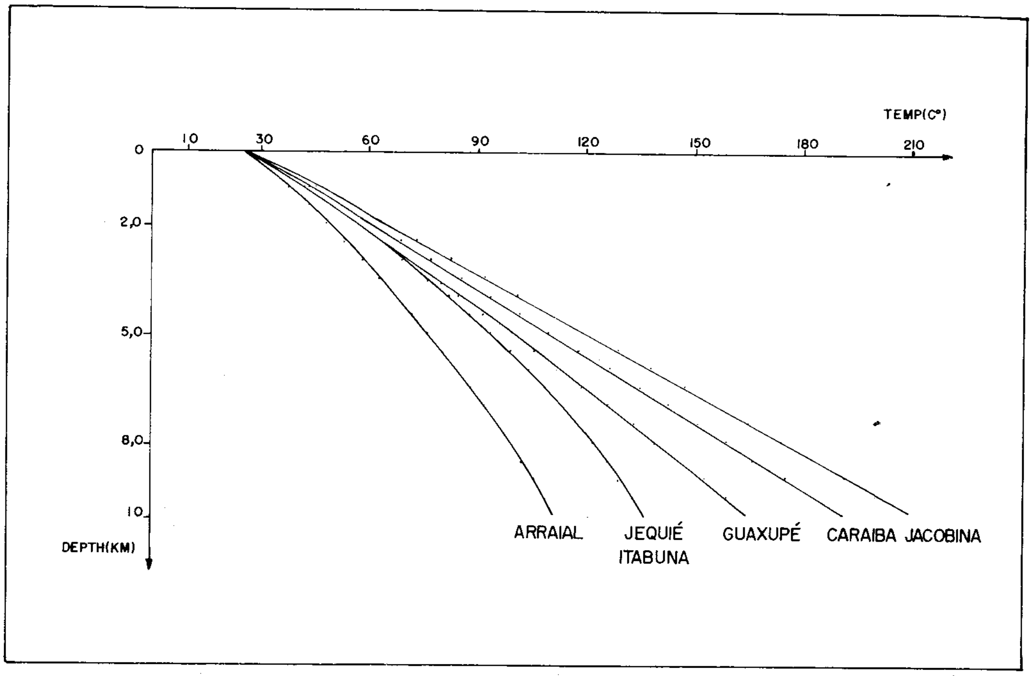

Figure 2 — Geotherms calculated for different localities assuming a constant heat production (Step model).

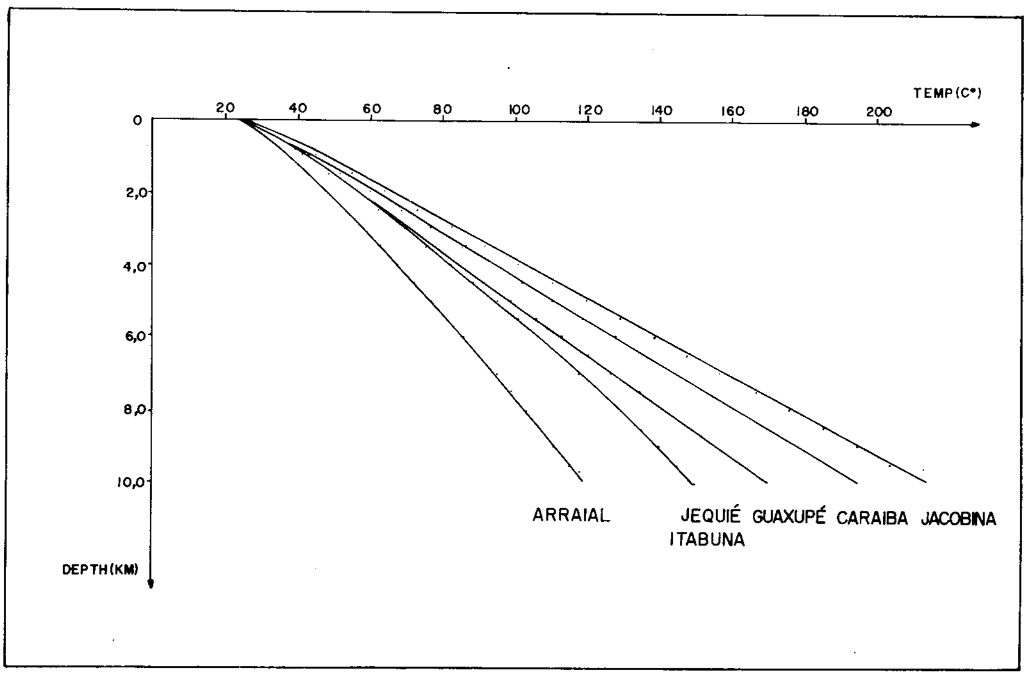

Figure 3 — Geotherms calculated for different localities assuming that heat production decreases with depth (exponential model).

3200 - 3000 Ma are preserved in Mutuipe region from where the radiogenic heat production data presented here are obtained. Thus, the presence of Archaean lower crustal nucleii at least in parts of Jequié is an indication that the cratonic regions in this complex have been stable since that time, despite their higher radiogenic heat production value. It is interesting to note in this connection the suggestion of Taylor & McLennan (1982) to a protracted event from 3200 to 2500 Ma for the Archaean-Proterozoic boundary depending on the location. This suggestion is based on the wide spread initiation of K-rich magmatism in South

Africa in Early Archaean. However, in Brazil, so far no indication for such widespread magmatism have been observed. Weaver & Tarney (1983) have observed that some Archaean granulites of South India are relatively enriched in radioactive elements.

It appears that, though the low radiogenic heat production may have played an important role in the stabilization of the early crust, we can not underestimate other features which may be of equal, if not, more importance. The presence of CO_2 rich inclusions in granulite facies rocks has been documented by several investigators eg. Touret (1971, 1981, 1985), Newton et al. (1980). The role of these fluids in the formation of the granulite facies rocks is a subject matter of great debate (Touret, 1985). However, the relative "dryness" of the granulite facies assemblages, due to dehydration during the metamorphism, is a factor to be considered, as dehydration raises the melting point of the lower crustal rocks, leading to the crustal stability. The model of cratonic root zone or "tectosphere" (Jordan 1975 a, b; Davies, 1979) extending to a great depth and acting as a thermal buffer between the crust and the deeper convecting mantle is an interesting hypothesis for the stability and survival of Archaean crust. Vitorello (1978) postulated the existence of a thick lithosphere of about 400 km beneath the Brazilian platform. A calculation based on the method of Oxburg (1981) showed that in Jequié lithosphere is at least 150 km thicker than the old oceanic crust (Iyer et al., 1984).

CONCLUSIONS

The radiogenic heat production values from different high grade metamorphic terranes of São Francisco craton and adjacent regions show that the variation may be explained in terms of the chemistry of the original rock types, the type of the metamorphism, nature of the fluids that participated in the transformation. The survival of the Archaean terranes in São Francisco craton may be an indication that factors other than radioactive element concentrations have also played a vital role in the stabilization and future preservation.

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