Canadian Mineralogist
Vol. 21, pp. 647-654 (1983)

URANIUM IN OVERTHRUST ARCHEAN BASEMENT, BAHIA, BRAZIL

LYDIA M. LOBATO*, JOHN M. A. FORMAN AND KAZUO FUZIKAWA
Nuclebrás, Av. Presidente Wilson 231, Rio de Janeiro, Brazil 20030
WILLIAM S. FYFE AND ROBERT KERRICH
Department of Geology, University of Western Ontario, London, Ontario N5A 5B7

ABSTRACT

In the Lagoa Real region of western Bahia State, Brazil, basement acid gneisses of the São Francisco craton (3 Ga) show localized zones of uranium enrichment that in places attain ore grade. The enrichment occurs in linear shear-zones associated with retrograde metamorphism and extensive metasomatism of the amphibolite- to granulite-facies basement. Zones of uranium enrichment contain the mineral assemblage plagioclase–epidote–amphibole–aegirine–garnet typical of the epidote-amphibolite facies. Metasomatic processes include: oxidation, sodium addition, potassium depletion, quartz removal, and addition of U–V–Y and some *REE*. The typical product is dominated by albite and a sodic pyroxene. Oxygen-isotope data for quartz (-0.02‰), albite (-1.95‰), magnetite (-8.70‰) and pyroxene (-4.15‰) show that fluids involved were ~ -4‰ and that the major phase of alteration occurred near 500°C. This is confirmed by fluid-inclusion studies, which also show the presence of highly saline fluids. A model is proposed in which a slice of Archean basement (~15 km thick) has been thrust to the west over Proterozoic sediments. Isotopically light formation-brines carrying uranium have been expelled through hydrofractures into the hotter overthrust plate, causing the observed mineralogical and chemical changes. The rocks provide an example of mobilization of U and some trace elements from a saline, organic-matter-rich, low-temperature environment, with precipitation in response to rising temperatures.

Keywords: Archean basement, uranium, sodium metasomatism, overthrusting, Bahia, Brazil.

SOMMAIRE

Dans la région de Lagoa Real (partie occidentale de l'état de Bahia, Brésil), les gneiss acides du socle du craton São Francisco, vieux de 3 Ga, montrent des zones localisées d'enrichissement en uranium qui peuvent passer, localement, à la teneur d'un minerai. L'enrichissement est associé, le long de zones de cisaillement linéaires, à un métamorphisme rétrograde et à un métasomatisme des roches du socle, qui se trouvent dans le facies amphibolite et granulite. Dans la zone enrichie, on trouve l'assemblage plagioclase–épidote–amphibole–aegyrine–grenat, qui est typique du facies amphibolite à épidote. Les processus métasomatiques comprennent l'oxydation, l'addition de Na, la soustraction de K, le lessivage du quartz, et la venue de U, V, Y et de certaines terres rares. Le produit typique contient surtout l'albite et un pyroxène sodique. Les données sur les isotopes d'oxygène dans le quartz (-0.02‰), albite (-1.95‰), magnétite (-8.70‰) et pyroxène (-4.15‰) indiquent la coexistence d'une phase fluide de ~-4‰, et une température de métasomatisme voisine de 500°C. Ces conclusions concordent avec les résultats d'inclusions fluides, qui indiquent, de plus, la forte salinité de cette phase fluide. On propose comme modèle le chevauchement d'une écaille de socle archéen d'une épaisseur d'environ 15 km vers l'Ouest, par-dessus les sédiments protérozoïques. Les saumures de formation, qui étaient isotopiquement légères, et qui transportaient l'uranium, auraient été expulsées le long de fractures hydrauliques à travers l'écaille de socle, de température plus élevée, ce qui aurait causé les changements minéralogiques et chimiques observés. Ces roches montrent un exemple de mobilisation de l'uranium et de certains éléments en traces d'un milieu relativement salin, riche en matière organique et de basse température, suivi de précipitation dans un milieu à température ascendante.

(Traduit par la Rédaction)

Mots-clés: socle archéen, uranium, métasomatisme sodique, chevauchement, Bahia, Brésil.

INTRODUCTION

The major rock-formations of Bahia State comprise the São Francisco craton, which consists mainly of high-grade metamorphic rocks of the basement covered by a succession of younger sedimentary sequences (Figueiredo 1981). In the period 1976–77, a large number of radioactive anomalies were discovered in the central-southern part of the state, in the high-grade orthogneisses of the Paramirim complex (Raposo & Matos 1982, Jardim de Sá 1978). The Lagoa Real uranium deposit is located 50 km northeast of the town Caetité and constitutes an arcuate zone of 30 anomalies (Villaça & Hashizume 1982) associated with long tabular bodies of albitite.

Albitization and U enrichment of the gneisses are restricted to ductile shear-zones (Ramsay 1980) that transect those rocks. The shear zones are comparable to typical examples of shear zones cutting Archean

---

*Present address: Department of Geology, University of Western Ontario, London, Ontario N6A 5B7.

high-grade gneiss terranes, as described by Beach (1980). Pervasive retrograde metamorphism of host rocks is associated with the shear zones, and mineral transformations give place to a high-greenschist-facies assemblage with albite, aegirine-augite, garnet, hematite (from magnetite), epidote and chlorite (rare).

GEOLOGICAL SETTING

The central-south part of Bahia State in Brazil is dominated by rocks of the São Francisco craton (Almeida 1977). The craton occupies almost the entire state as well as parts of Minas Gerais, Goiás, Pernambuco and Sergipe states (Almeida 1977, Figueiredo 1980). In the area under study (Fig. 1), the rocks comprise Archean granulite- and upper-amphibolite-facies gneisses and migmatites of the Paramirim complex, Lower Proterozoic metavolcanic and metasedimentary sequences of the Urandi and Brumado belts, and a Middle Proterozoic supracrustal cover of the Espinhaço Supergroup (Inda & Barbosa 1978) (Fig. 1).

The Precambrian of the São Francisco craton has been affected by four major geotectonic cycles: Jequié (2.7 ± 0.2 Ga), Transamazonian (2.0 ± 0.2 Ga), Espinhaço (1.5 ± 0.2) and Brazilian cycles (0.7 ± 0.2 Ga) (Inda & Barbosa 1978). Rb/Sr whole-rock isochrons suggest that during the Jequié cycle, the high-grade terranes of the craton were formed and consolidated. Parts of the sialic Archean basement were reactivated during Transamazonian times. At the end of this cycle, sedimentation of Espinhaço basin was initiated (Jardim de Sá 1978). Lower Proterozoic metavolcanic and metasedimentary sequences of the Brumado (to the east) and Urandi belts (to the west of the area) are dominated by amphibolites, quartzites, banded iron-formations, gondites, marbles, mica schists and paragneisses (Geisel *et al.* 1980). The Espinhaço metasedimentary se-

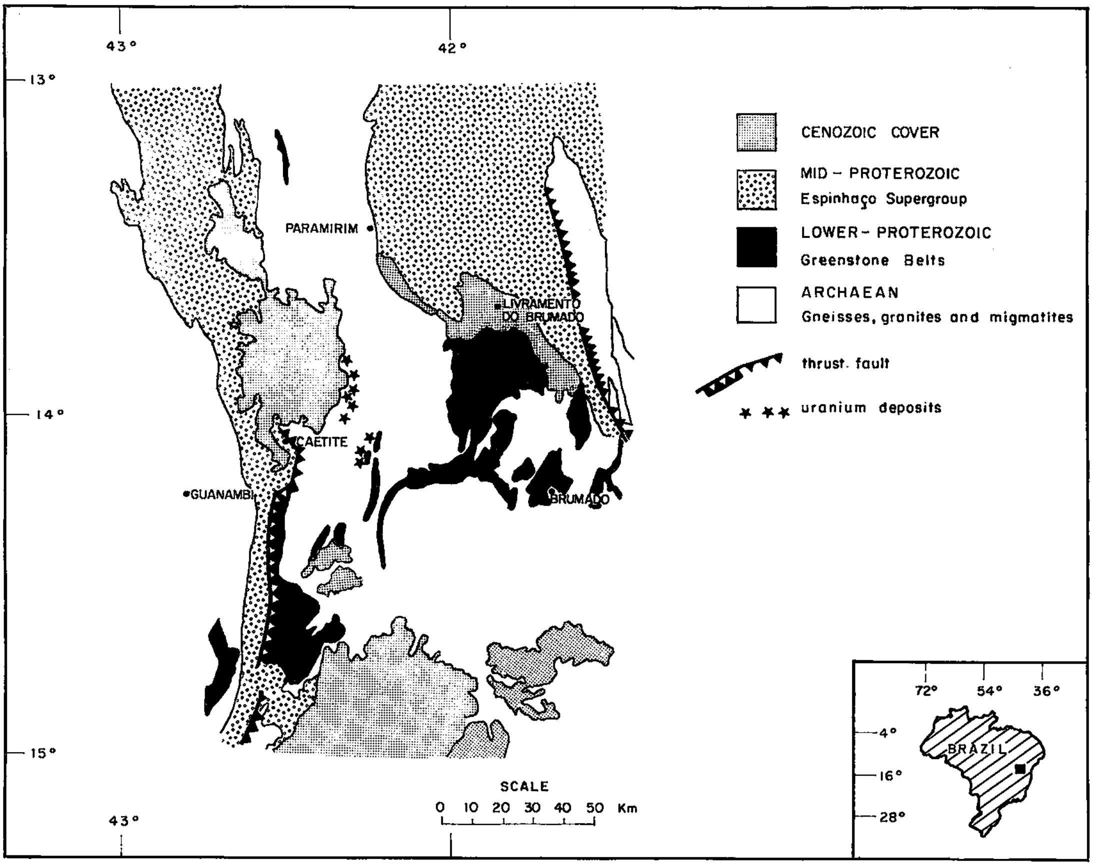

FIG. 1. Simplified geological map of the Lagoa Real region and surroundings, displaying the Archean gneisses, the lower Proterozoic greenstone belts, the middle Proterozoic Espinhaço Supergroup sedimentary sequence, thrusts and uranium deposits (modified after Inda & Barbosa 1978).

quence, to the west of the Lagoa Real region, forms a narrow belt from north of Boquira to Licínio de Almeida in the south (Fig. 1). Those rocks are characterized by acid volcanic rocks at the base, overlain by polymictic conglomerates and sandstones, with interlayered shales, graphitic rocks and orthoquartzites at the top of the sequence (Moutinho da Costa & Inda 1982). In particular, the lower and medium Espinhaço strata are intensely deformed, and some volcanic rocks appear strongly schistose.

PETROGRAPHIC ASPECTS

Metasomatic alteration in Lagoa Real is observed to extend over a band about 40 km wide and 100 km long, parallel to the regional strike. The uranium anomalies are confined to this band of metasomatic rocks, invariably associated with albitites.

The regional gneisses of the plutonic-migmatitic association have been transformed into albite-bearing gneisses and albitites (>70% albite). They can both show the same textural types as their parent gneisses. A striking feature of most altered rocks is the polygonal granoblastic texture (Fig. 2). In places, these open textures are modified by late cataclastic processes. Metasomatized shear-zones dip at about 35–90°; drilling has shown them to be rather uniform to depths of at least 800 m (Villaça & Hashizume 1982).

Both albite-rich gneisses and albitites share the same mineralogy, which commonly includes: plagioclase, pyroxene, garnet, amphibole, biotite, microcline, epidote, calcite, titanite and magnetite (partly altered to hematite). Accessory minerals include zircon, fluorite, allanite and chlorite; sulfides (pyrite, chalcopyrite) and muscovite are rare (Table 1).

The regional gneisses surrounding the area are coarse grained and rich in perthitic microcline, quartz, plagioclase, amphibole and biotite, with accessory titanite, apatite, zircon, ilmenite and fluorite (Table 1). Blocks of typical charnockites occur restrictedly, and mafic amphibolites occur in few places. Whereas porphyroclastic and granoblastic textures predominate, some gneisses show mylonitic and brecciated textures. The plagioclase of most gneisses is typically oligoclase, and the amphiboles are hornblende and ferrihastingsite (Table 2).

In zones of Na alteration, (1) microcline is replaced by plagioclase; (2) biotite and amphibole tend to disappear; pyroxene and garnet, together with

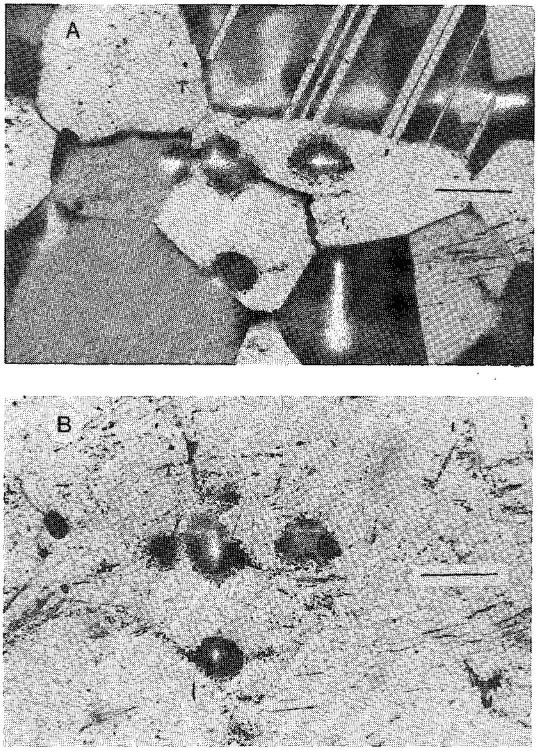

FIG. 2. Mineralized albitite. Grains of uraninite occur along grain boundaries of the polygonal albite and also as inclusions in the latter. A) crossed nicols, B) plane light. Scale bar is 0.1 mm.

TABLE 1. SELECTED MINERAL COMPOSITIONS

	Host Gneisses			Albitites						
	pl	am	bi	pl	pl	py	py	py	am	am
SiO_2	65.4	37.7	33.9	68.5	65.7	51.4	49.9	53.0	42.2	52.3
TiO_2		0.5	2.2			0.08	0.04	0.02	0.04	0.00
Al_2O_3	22.3	12.5	14.7	19.2	21.5	2.5	1.4	0.76	7.3	1.3
Cr_2O_3		0.00	0.05			0.00	0.06	0.01	0.10	0.12
FeO*		32.2	35.6			15.3	21.2	9.5	23.4	15.0
MnO		0.31	0.55			0.38	0.72	0.2	0.3	0.22
MgO		0.48	1.2			8.5	5.5	12.4	8.2	13.8
CaO	3.1	10.5	0.02	0.25	3.5	17.5	19.4	23.0	13.0	13.7
Na_2O	9.9	1.4	0.24	12.2	9.8	4.5	2.0	1.2	2.1	0.65
K_2O	0.22	2.1	9.3	0.09	0.26	0.02	0.03	0.01	1.2	0.20
Total	100.9	97.7	97.7	100.2	100.7	100.2	100.3	100.1	97.8	97.3

Abbreviations: pl plagioclase, am amphibole, bi biotite, py pyroxene. * Total Fe expressed as FeO.

TABLE 2. MINERAL ASSEMBLAGES IN THE REGIONAL GNEISSES AND IN THE ALBITIZED ROCKS, WITH MODAL COMPOSITIONS

Rock type	Sample no.	pl	mic	qz	am	bi	pyr	gar	ep	cal	tit	mg	ilm	all	chl	sul	flu	zir	ap	ur
Gneisses																				
	1460	20	60	15		5							x				x	x	x	
	1473	25	40	25	5			5	x	x	x							x	x	
	371	30	45	15	5	5				x	x		x				x	x	x	
Albitized Rocks																				
	18600	62	x	x	x		5	25	x	x	3	5			x		x	x	x	
	18760	95	x	x				4	x	x		x					x	x	x	1
	18510	80	x	x	x		3	10		5	x	1		x			x	x	x	1
	438	90	x	x	3	5			x	x	1	1				x	x	x	x	
	455	75					15	10	x		x			x				x	x	
	1454	45		x	15	x	3		35		2	x							x	x

x: accessory mineral; pl plagioclase, mic microcline, qz quartz, am amphibole, bi biotite, pyr pyroxene, gar garnet, ep epidote, cal calcite, tit titanite, mg magnetite, ilm ilmenite, all allanite, chl chlorite, sul sulfides, flu fluorite, zir zircon, ap apatite, ur uranium.

titanite and magnetite, are formed; (3) quartz is dissolved. In later phases, pyroxene is replaced by epidote or amphibole (or both), and magnetite is partly altered to hematite.

In the altered rocks, polygonal equigranular *plagioclase* occurs in 0.2 to 1.5 mm crystals commonly untwinned and rarely showing alteration to clay material. It can be present in quantities up to 90%. Preliminary microprobe studies of the plagioclase revealed compositions ranging from pure albite in some mineralized rocks to An_{1-15} (Table 2).

The mafic minerals tend to form concentrations and segregations; among these, *pyroxene* is the most important. The predominant pyroxene is aegirine-augite, which forms up to 25% in round and prismatic crystals. The crystals commonly show spotted inclusions of magnetite as well as intergrown titanite. Microprobe analysis of the pyroxene shows that its composition is fairly variable, attaining the diopside–hedenbergite series in a number of cases (Table 1). Zoned crystals have a Mg-rich core and a Na-, Fe^{3+}-rich rim (Lobato *et al.* 1983a). Pyroxene grains are commonly altered to amphibole, whose composition is variable as well.

Garnet is granoblastic and appears associated and intergrown with pyroxene. Although generically named andradite (two microprobe analyses show 75% of the andratite end-member), garnet also seems to be chemically variable in view of its variable optical properties.

Microcline is interstitial to plagioclase and amounts to less than 5%. Quartz forms fine inclusions in feldspar and rarely exceeds 3% of the rock.

Epidote (pistacite) is occasionally seen as fine crystals, after pyroxene and amphibole. A brownish yellow epidote, which in some cases shows anomalously low birefringence, occurs up to 30% in a few albitite samples; it is an alteration product after pyroxene. It forms fine granoblastic crystals. Preliminary ion-probe data show that it is also chemically variable; a few epidote grains studied were shown to contain significant amounts of U, Th, V, Y, La and Ce.

Granoblastic *calcite*, sparsely found in some albitite specimens, is generally associated with garnet. In places, calcite forms up to 10% of the rock and, like epidote, seems to have been formed in the late stages of alteration.

The samples of mineralized albitite are strongly enriched in sodium and depleted in potassium (Geisel *et al.* 1980) (Table 3). They occur in parallel layers averaging 6 m thick within the metasomatized zones, with no significant variations down dip to depths of 800 m (Raposo & Matos 1982). They show open "saccharoidal" replacement textures; highly sheared rocks are not mineralized. Mineralized albitites always show either one or more of the following minerals: pyroxene, amphibole, biotite, garnet, calcite, magnetite (altering to hematite). Uraninite occurs in round crystals 5–8 μm across, associated with mafic concentrations, but also interstitial to or included in albite (Fig. 2).

GEOCHEMICAL ASPECTS

Chemical data for selected samples are shown in Table 3. The regional rocks are typical of the granite–granodiorite family. The mineralogical changes undergone by the microcline-bearing gneisses reflect fundamental changes in rock chemistry. These changes are primarily related to microcline → albite transformation, as shown by mass-balance studies (Lobato *et al.* 1983b). Using the general metasomatic equation derived by Gresens (1967) and comparing the chemistry of four samples of host gneisses with thirteen samples of albitized rocks, one concludes that the K-feldspar → albite reaction was dominant throughout the alteration, with K_2O loss and Na_2O addition roughly

TABLE 3. MAJOR ELEMENT AND URANIUM DATA FOR HOST GNEISSES AND ALBITITES OF THE LAGOA REAL REGION

	Host gneisses					Albitites						
	34	37	33	7	8	10568	10670	18600	18580	18760	18510	17
SiO_2 (wt. %)	74.96	73.68	72.70	73.81	67.90	62.09	58.20	55.60	60.83	61.08	60.43	58.70
TiO_2	0.33	0.30	0.38	0.17	0.30	0.46	0.24	0.76	0.55	0.33	0.39	0.37
Al_2O_3	11.80	11.97	12.00	12.28	14.27	14.05	13.30	13.80	17.41	16.48	15.85	15.70
Fe_2O_3 (total Fe)	3.58	3.16	4.25	2.91	4.27	11.06	9.05	11.50	8.15	5.63	6.19	5.80
MnO	0.04	0.04	0.05	0.04	0.06	0.05	0.27	0.18	0.03	0.09	0.11	0.10
MgO	0.04	0.07	0.14	-	-	-	0.37	0.73	0.05	0.02	0.25	0.78
CaO	0.63	0.95	0.98	0.66	2.02	2.63	9.69	7.33	1.19	5.78	6.45	6.96
Na_2O	4.00	3.80	3.46	2.97	3.97	8.86	8.40	8.72	8.28	10.90	10.05	8.48
K_2O	4.54	4.85	4.63	6.42	6.00	0.31	0.59	1.30	3.93	0.27	0.40	0.59
P_2O_5	-	-	0.06	-	0.02	0.05	0.05	0.14	0.06	0.02	0.06	0.08
LOI	0.03	0.20	0.39	0.04	0.08	0.02	0.47	0.08	-	0.03	0.09	1.93
U (ppm)	3	7	4	5	3	5	7	14	25	2914	2464	3566

equivalent. SiO_2 removal has been shown to be about 10%.

Besides Na_2O and U enrichment (Table 3), the metasomatic rocks have been enriched in Pb, V and *REE* (Stein *et al.* 1980). Addition of oxygen is suggested by the overall change in Fe^{3+}/Fe^{2+} ratios of mineral phases.

The oxygen-isotope composition of country-rock gneisses, their deformed equivalents and U-mineralized counterparts within shear zones is reported in Table 4. Whole-rock δ values for the gneisses range from 7.2 to 10.2‰. The highest values are isotopically heavy compared to the $\delta^{18}O$ for primary igneous rocks of granodioritic composition (Taylor 1968), signifying either low-temperature hydrothermal alteration of a granodiorite precursor or, as an alternative, a high-^{18}O sedimentary component to the gneissic parental rocks. In gneisses, the $\delta^{18}O$ of quartz is relatively uniform at 11.3 to 12.1‰, as are the $\delta^{18}O$ of plagioclase (8.5 to 8.8‰) and magnetite (1.0 to 2.5‰). The quartz–oligoclase and quartz–magnetite fractionations are not concordant, indicating variable disturbance, during subsequent cooling, of isotopic equilibrium attained at maximum metamorphic temperatures.

In one specimen of deformed gneiss (sample 04), the quartz–oligoclase and quartz–magnetite fractionations are triply concordant, signifying a deformation temperature of 500 to 540°C. The calculated isotopic composition of water in equilibrium with quartz under the ambient conditions of deformation is 5.8 to 6.4‰. These results are consistent with the range of δ values for metamorphic fluids reported by Taylor (1974), and an interpretation in terms of metamorphic fluids indigenous to the gneisses is commensurate with the geological evidence.

Within the U-mineralized shear-zones, quartz, feldspar, pyroxene and magnetite all undergo a shift of about −10‰ relative to their δ values in the parental gneiss. Quartz–magnetite fractionations are in a

TABLE 4. THE OXYGEN-ISOTOPE COMPOSITION OF MINERAL SEPARATES AND WHOLE ROCKS FROM COUNTRY-ROCK GNEISS, AND URANIUM-MINERALIZED COUNTERPARTS WITHIN SHEAR ZONES

Sample description	Sample Number	$\delta^{18}O$ qz	$\delta^{18}O$ fsp	$\delta^{18}O$ pyr	$\delta^{18}O$ mt	$\delta^{18}O$ wr	Δ (qz-fsp)	Δ^{18} (qz-pyr)	Δ^{18} (qz-mt)	temp. °C	$\delta^{18}O$ fluid
GNEISS											
	0.1	12.15	9.85†		2.54	10.12	2.3		9.6		
quartz, oligoclase	0.2	10.87	8.50		1.03		2.4		9.8		
kspar, pyroxene, biotite,											
± magnetite	0.3	11.35	8.64		1.18	8.28	2.7		10.2		
	0.4	8.76	6.99	6.04	0.40		1.8	2.7	8.4		+6
	0.5	9.05	7.16			7.19	1.9				
	0.6	9.86	7.67				2.2				
ZONE OF U-MINERALIZATION											
	M1	-1.20	-2.63*		-9.47		1.4		8.3	540	-4
albite, pyroxene, quartz, magnetite	M2	+0.53	-1.37		-8.44		1.9		9.0	500	-3
	M3	-0.02	-1.75	-4.15	-8.70		1.7	4.1	8.7	520	-3

† $\delta^{18}O$ of oligoclase in the gneiss * δ^{18} of albite in uraniferous rocks, qz quartz, fsp feldspar,
pyr pyroxene, mt magnetite, wr whole rock. Values in °/₀₀.

narrow interval of 8.3 to 9.0‰, corresponding to isotopic temperatures of 500–540°C. In samples Ml and M2, coexisting quartz, albite and magnetite are triply concordant, and in sample M3, quartz, albite, pyroxene and magnetite are quadruply concordant, providing a rigorous criterion for retention of isotopic equilibrium in the mineralized rocks.

Following Bottinga & Javoy (1975), we assign concordant isotopic temperatures to those coexisting minerals for which T°C (quartz–albite), T°C (quartz–pyroxene), and T°C (quartz–magnetite) *etc.* agree to within an uncertainty in Δ (quartz–albite), Δ (quartz–pyroxene) *etc.*, where the error in mineral-pair fractionations $\epsilon_\Delta = \pm (\epsilon_\delta^2 + \epsilon_\delta^2)^{0.5} = \pm 0.23‰$ and the reproducibility of δ values, ϵ_δ, is $\pm 0.16‰$. Errors in temperatures calculated from quartz–magnetite fractionations amount to about ± 10°C. Isotopic temperatures have been calculated from mineral–water fractionations given in the following sources: O'Neil & Taylor (1967), Bottinga & Javoy (1973), Clayton *et al.* (1972), Friedman & O'Neil (1977) and Javoy (1977). Based on the temperature estimates and mineral δ-values, fluids implicated in the uranium mineralization have a $\delta^{18}O$ of -3 to -4‰, an isotopic signature consistent with meteoric water.

Preliminary study of the fluid inclusions in albite shows evidence for solutions of various salinities (1.5–23% NaCl), suggesting evolution of solutions during the metasomatic process (Fuzikawa 1980). Some of the inclusions studied froze at -60°C. When subsequently heated, they fused at -1.0°C, suggesting salinities in the order of 1.5% NaCl. Other inclusions, however, did not freeze down to -160°C, although some started to nucleate greenish crystals during the freezing process. In spite of lack of freezing of the inclusions, a salinity of about 23% NaCl was calculated. Fluid-inclusion data on late-stage calcite reveals the presence of hydrocarbons; CO_2 and CH_4 are also reported in fluid inclusions in albite (Fuzikawa 1982).

CONCLUSIONS

The trace element and uranium distribution in high-grade rocks has been a topic of special interest in the geochemistry of the Archean; a number of workers seem to agree that granulitic rocks show a characteristic depletion in U (Heier 1973, Atal *et al.* 1978).

The striking geochemical characteristics of the Lagoa Real region call for a mechanism that can account for the highly abnormal U concentrations in a portion of the high-grade metamorphic terrane typical of that considered to be continental basement. The recharge of uranium accompanies pervasive metasomatism during tectonic processes that returned the basement rocks to the surface.

The major metasomatic changes in the area are the replacement of K-feldspar by albitic plagioclase, removal of silica, enrichment of U and oxidation.

Removal of about 10% silica *via* solution of quartz is readily explained by fluids moving up a temperature gradient. Such fluids could not come from a magmatic source, for they would certainly precipitate silica. Given conditions of fluid pressure and temperature (4 kbar, 500°C) (Lobato *et al.* 1983a), with a quartz solubility of 0.65% (Fyfe *et al.* 1978), the minimum water: rock ratio is 40, considering that the density of the parent rock is 2.68 g/cm^3 (Lobato *et al.* 1983b).

It has been shown by workers in the region that uranium is associated with high degrees of Na alteration (*e.g.*, Geisel *et al.* 1980, Villaça & Hashizume 1982, Raposo & Matos 1982). Nevertheless, mineralization is also observed to occur in association with albitite characterized by a Ca-rich assemblage (albite, diopside, garnet, calcite and wollastonite). Oxidation of Fe-Mg minerals is extensive, and U precipitation occurred in response to water–rock interaction. Reduction of uranyl ion by ferrous iron may be very effective at high temperatures (Nash *et al.* 1981).

Shear zones developed in deep-seated basement during the Proterozoic are considered to be initiated in the source area by the metasomatic fluids propagating in response to $P_{fluid} > P_{load}$(Beach 1976). They developed as channels for upward flow of fluid *via* intense hydraulic fractures.

We suggest that shear zones were initiated in a metamorphic regime under low water–rock ratio (see O-isotope studies). Shear zones then acted as conduits for large amounts of low-^{18}O fluids *via* hydrofracturing. The fluids are considered to have been derived by dewatering of sedimentary formations. A mechanism involving tectonic emplacement of large portions of the basement over colder, wet rocks, as suggested by Beach (1976), seems adequate and is consistent with regional structures.

The presence of ductile and brittle overthrusting processes has been shown to be common in Proterozoic tectonics (Bridgwater *et al.* 1973). Recent detailed seismic studies of deep continental structures (Cook *et al.* 1980, Matthews 1982) have shown ubiquitous thrust-structures. Present knowledge in the Lagoa Real region is also consistent with a thrust model where the Archean has been emplaced over the Proterozoic sediments of the Espinhaço sequence (Lobato *et al.* 1983a). The high temperatures at the base of the thrust, as shown by oxygen-isotope data, could be consistent with mechanisms discussed by Hyndman (1980) and Allis (1981). The updoming and uplifting of the Paramirim complex, with resulting faulted blocks, are suggested by Jardim de Sá (1978) and Moutinho da Costa & Inda (1982) to have occurred in Proterozoic times. Overthrusting of the volcanosedimentary sequences, along with reverse folding of the Espinhaço lower strata, have been recognized in the region (Moutinho da Costa & Inda 1982) (Fig. 1).

This mechanism would provide release of fluids from the underthrust sediments under high fluid-pressures. Fluids would travel up a thermal gradient, explaining oxidation, removal of quartz and retrometamorphism.

ACKNOWLEDGEMENTS

We thank Nuclebrás geologists and staff in general for their support in providing all necessary material for the research, especially all those involved with the Lagoa Real Project. L. Lobato also thanks Pronuclear and Nuclebrás for continuing financial support. Part of the microprobe analyses required for this paper were performed by R. L. Barnett. Ion-probe data were provided by Dr. W. Nesbitt. We also thank the referees, who offered critical comments that greatly improved the paper.

REFERENCES

ALLIS, R.G. (1981): Continental underthrusting beneath the Southern Alps of New Zealand. *Geology* **9**, 303-307.

ALMEIDA, F.F.M. (1977): O craton do São Francisco. *Rev. Brasileira Geociencias* **7**, 349-364.

ATAL, B.S., BHALLA, N.S., LALL, Y., MAHADEVAN, T.M. & UDAS, G.R. (1978): Radioactive elemental distribution in the granulite terrains and Dharwar schist belts of Peninsular India. *In* Archean Geochemistry (B.F. Windley & S.M. Naqvi, eds.). Elsevier, Amsterdam.

BEACH, A. (1976): The interrelations of fluid transport, deformation, geochemistry and heat flow in early Proterozoic shear zones in the Lewisian complex. *R. Soc. Lond. Phil. Trans.* **A.280**, 569-604.

______ (1980): Retrogressive metamorphic processes in shear zones with special reference to the Lewisian complex. *J. Struct. Geol.* **2**, 257-263.

BOTTINGA, Y. & JAVOY, M. (1973): Comments on oxygen isotope geothermometry. *Earth Planet. Sci. Lett.* **20**, 250-265.

______ & ______ (1975): Oxygen isotope partitioning among the minerals in igneous and metamorphic rocks. *Rev. Geophys. Space Phys.* **13**, 401-418.

BRIDGWATER, D., ESCHER, A. & WATTERSON, J. (1973): Tectonic displacements and thermal activity in two contrasting Proterozoic mobile belts from Greenland. *R. Soc. Lond. Phil. Trans.* **A.273**, 513-533.

CLAYTON, R.N., O'NEIL, J.R. & MAYEDA, T.K. (1972): Oxygen isotope exchange between quartz and water. *J. Geophys. Res.* **77**, 3057-3067.

COOK, A., BROWN, L.D. & OLIVER, J.E. (1980): The southern Appalachians and the growth of continents. *Sci. Amer.* **243(4)**, 156-168.

FIGUEIREDO, M.C.H. (1980): *Geochemistry of High-Grade Metamorphic Rocks, Northeastern Bahia, Brazil.* Ph.D. thesis, Univ. Western Ontario, London, Ontario.

______ (1981): Geoquímica das rochas metamórficas de alto Grau do nordeste da Bahia-Brasil. *Geol. Rec. Mineral Est. Bahia* **4**, 1-71.

FRIEDMAN, I. & O'NEIL, J.R. (1977): Compilation of stable isotope fractionation factors of geochemical interest. *U.S. Geol. Surv. Prof. Pap.* **440 KK.**

FUZIKAWA, K. (1980): Estudos preliminares de inclusoes fluidas em albita dos albititos do projeto Lagoa Real, Caetité, BA, Brasil. *Anais XXXI Congr. Bras. Geol. (Santa Catarina)* **4**, 2038-2049.

______ (1982): Alguns carbonatos do distrito uranífero de Lagoa Real, Bahia: estudos de inclusões fluidas e isótopos estáveis. *Anais XXXII Congr. Bras. Geol. (Salvador)* **5**, 2072-2085.

FYFE, W.S., PRICE, N.J. & THOMPSON, A.B. (1978): *Fluids in the Earth's Crust, their Significance in Metamorphic, Tectonic and Chemical Transport Processes.* Elsevier, Amsterdam.

GEISEL, E., RAPOSO, C., ALVES, J.V., DE BRITO, W. & VASCONCELOS, J.G. (1980): O distrito uranífero de Lagoa Real, Bahia. *Anais XXXI Congr. Bras. Geol. (Santa Catarina)* **3**, 1499-1510.

GRESENS, R.L. (1967): Composition–volume relationship of metasomatism. *Chem. Geol.* **2**, 47-65.

HEIER, K.S. (1973): Geochemistry of granulite facies rocks and problems of their origin. *R. Soc. Lond. Phil. Trans.* **A.273**, 429-442.

HYNDMAN, D.W. (1980): Bitterroot Dome – Sapphire tectonic block, an example of a plutonic-core gneiss–dome complex with its detached suprastructure. *Geol. Soc. Amer. Mem.* **153**, 427-443.

INDA, H.A.V. & BARBOSA, J.F. (1978): *Texto Explicativo para o Mapa Geológico do Estado da Bahia.* Secretaria das Minas e Energia, Estado da Bahia, Salvador.

JARDIM DE SÁ, E.F. (1978): *Geologia da Chapada Diamantina e faixa Santo Onofre, Bahia, e Geoquímica do Vulcanismo Ácido Associado.* M.Sc. thesis, Universidade Federal da Bahia, Salvador, Brazil.

JAVOY, M. (1977): Stable isotopes and geothermometry. *J. Geol. Soc. Lond.* **133**, 609-636.

LOBATO, L.M., FORMAN, J.M.A., FYFE, W.S., KERRICH, R. & BARNETT, R.L. (1983a): Uranium enrichment in Archaean crustal basement associated with overthrusting. *Nature* **303**, 235-237.

———, ———, FUZIKAWA, K., FYFE, W.S. & KERRICH, R. (1983b): Uranium enrichment in Archean basement: Lagoa Real, Brazil. *Rev. Brasileira Geociencias* **12**, 484-486.

MATTHEWS, D.H. (1982): BIRPS: deep seismic reflection profiling around the British Isles. *Nature* **298**, 709-710.

MOUTINHO DA COSTA, L.A., co-ordinator (1976): *Projeto Leste do Tocantins-Oeste do Rio São Francisco.* Relatorio Final, Dep. Nac. Prod. Mineral/Comp. Pesq. Rec. Minerais/PROSPEC (Rio de Janeiro), **1A.**

——— & INDA, H.A.V. (1982): O aulacógeno do Espinhaço. *Ciencias da Terra* **2**, 13-18.

NASH, J.T., GRANGER, H.C. & ADAMS, S.S. (1981): Geology and concepts of genesis of important types of uranium deposits. *Econ. Geol., 75th Anniv. vol.*, 63-116.

O'NEIL, J.R. & TAYLOR, H.P. (1967): The oxygen isotope and cation exchange chemistry of feldspars: *Amer. Mineral.* **52**, 1414-1437.

RAMSAY, J.G. (1980): Shear zone geometry: a review. *J. Struct. Geol.* **2**, 83-99.

RAPOSO, C. & MATOS, E.C. (1982): Distrito uranífero de Lagoa Real, "A história de um exemplo". *Anais XXXII Congr. Bras. Geol. (Salvador)* **5**, 2035-2047.

STEIN, J.H., NETTO, A.M., DRUMMOND, D. & ANGEIRAS, A.G. (1980): Nota preliminar sobre os processos de albitização uranífera de Lagoa Real (Bahia) e sua comparação com os da URSS e Suécia. *Anais XXXII Congr. Bras. Geol. (Santa Catarina)* **3**, 1758-1775.

TAYLOR, H.P., JR. (1968): The oxygen isotope geochemistry of igneous rocks. *Contr. Mineral. Petrology* **19**, 1-71.

——— (1974): The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition. *Econ. Geol.* **69**, 843-883.

VILLAÇA, J.N. & HASHIZUME, B.K. (1982): Distrito uranífero de Lago Real - reservas e potencial. *Anais XXXII Congr. Bras. Geol. (Salvador)* **5**, 2048-2061.

Received December 1, 1982, revised manuscript accepted April 22, 1983.