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ARTICLE

Geochemistry and sedimentary provenance of the Upper Cretaceous Uberaba Formation (Southeastern Triângulo Mineiro, MG, Brazil)

Geoquímica e proveniência sedimentar da Formação Uberaba (sudeste do Triângulo Mineiro, MG)

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ABSTRACT: The campanian Uberaba Formation, which crops out around the homonymous town, is composed of greenish lithic sandstones and conglomerates with possible volcanoclastic contribution. In this unit, heavy minerals such as ilmenite, garnet, perovskite and magnetite, besides clinopyroxene, plagioclase, quartz, calcite and apatite, are found. The Uberaba Formation geochemistry is marked by high grades of Ba, Ta, La, Nb and Th, with flat (no Eu anomaly) and highly fractionated (La_N/Yb_N = ca. 128) chondrite-normalized rare earth elements. Mineral chemistry analyses of detrital garnets from the Uberaba Formation indicate the predominance of chorlomite with an affinity to crustal garnets (G3). The sedimentary provenance of the Uberaba Formation corresponds to a mixing of materials from the alkaline districts of the Alto Paranaíba and from the erosion of the Serra Geral Formation and the Canastra and Araxá groups. Diamond-producing conglomerates which crop out nearby, in Romaria, were considered by some authors as correlated to the Uberaba Formation. However, the composition of garnets recovered from those conglomerates is different, plotting in the field of mantle garnets (G9/G10). We consider, then, that those units are not correlated, and that the Uberaba Formation is not a possible source for the alluvial diamonds found in the homonymous river.

KEYWORDS: Uberaba Formation; Alkaline magmatism; Triângulo Mineiro; Provenance; Upper Cretaceous.

RESUMO: *A Formação Uberaba, de idade campaniana e ocorrência restrita à região da cidade homônima, é composta de arenitos líticos e conglomerados de cor esverdeada, com possível contribuição vulcanoclástica. Nessa unidade ocorrem minerais pesados como ilmenita, granada, perovskita e magnetita, além de clinopiroxênio, plagioclásio, quartzo, calcita e apatita. A Formação Uberaba é marcada geoquimicamente por altos teores em Ba, Ta, La, Nb e Th, com padrões de elementos terras raras normalizados ao condrito fortemente fracionados (La_N/Yb_N = ca. 128) e planos (sem anomalia de Eu). Análises de química mineral das granadas detríticas da Formação Uberaba indicam predominância de chorlomita com afinidade com granadas crustais (G3). A proveniência sedimentar da Formação Uberaba corresponde a uma mistura de materiais de distritos alcalinos do Alto Paranaíba e derivados da erosão da Formação Serra Geral e dos grupos Canastra e Araxá. Os conglomerados produtores de diamante que ocorrem proximamente, em Romaria, foram considerados por alguns autores como correlatos à Formação Uberaba, porém a composição das granadas retiradas desses conglomerados é bastante diferente, plotando no campo de granadas mantélicas (G9/G10). Descarta-se, dessa forma, correlação entre essas duas unidades, e a Formação Uberaba, portanto, não é uma fonte provável dos diamantes aluvionares encontrados no rio homônimo.*

PALAVRAS-CHAVE: *Formação Uberaba; Magmatismo Alcalino; Triângulo Mineiro; Proveniência; Cretáceo Superior.*

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INTRODUCTION

The discovery of alluvial diamonds in the Triângulo Mineiro (TM) and Alto Paranaíba (AP) regions, southeast Brazil, most specifically between the cities of Coromandel and Uberaba, has called the attention of researchers on the source area and sedimentary control of these deposits. The fact that some occurrences are located in alluvial deposits of the Uberaba River (Fig. 1), which occurs in the southern portion of the TM above a specific unit denominated Uberaba Formation, has brought some attention to this unit, as in the works of Hasui (1968), Barbosa *et al.* (1970), Barcelos (1984), Ferreira Jr. (1996), Ferreira Jr. and Gomes (1999), and Gravina *et al.* (2002).

The Uberaba Formation, with a mean thickness of 70 m and composed of sandstones and conglomerates, was deposited at ca. 80 Ma ago based on fossiliferous content (Huene 1939). It is stratigraphically the base of the Bauru Group, and its sandstones show a considerable amount of detrital perovskite. Some authors interpret a volcaniclastic origin for at least part of the unit, with further sedimentary reworking (Hasui 1968, Barcelos 1984, Fulfaro & Barcelos 1991, Goldberg 1995). Despite its importance for both the reconstruction of Cretaceous paleoenvironments and potential source for diamond-producing, the Uberaba Formation is one of the least studied units in the context of the Bauru Group.

This paper presents novel data on the Uberaba Formation, emphasizing its geological cartography, petrography, mineral chemistry and geochemical aspects. The main objective is to characterize its provenance and source areas. Besides, in the present paper, we analyze for the first time the potential of the unit as a source for the placer-type alluvial diamond deposits of the area, with respect to the great quantity of alluvial diamonds already recovered in the TM and AP (Campos 1891, Hussak 1891, Hussak

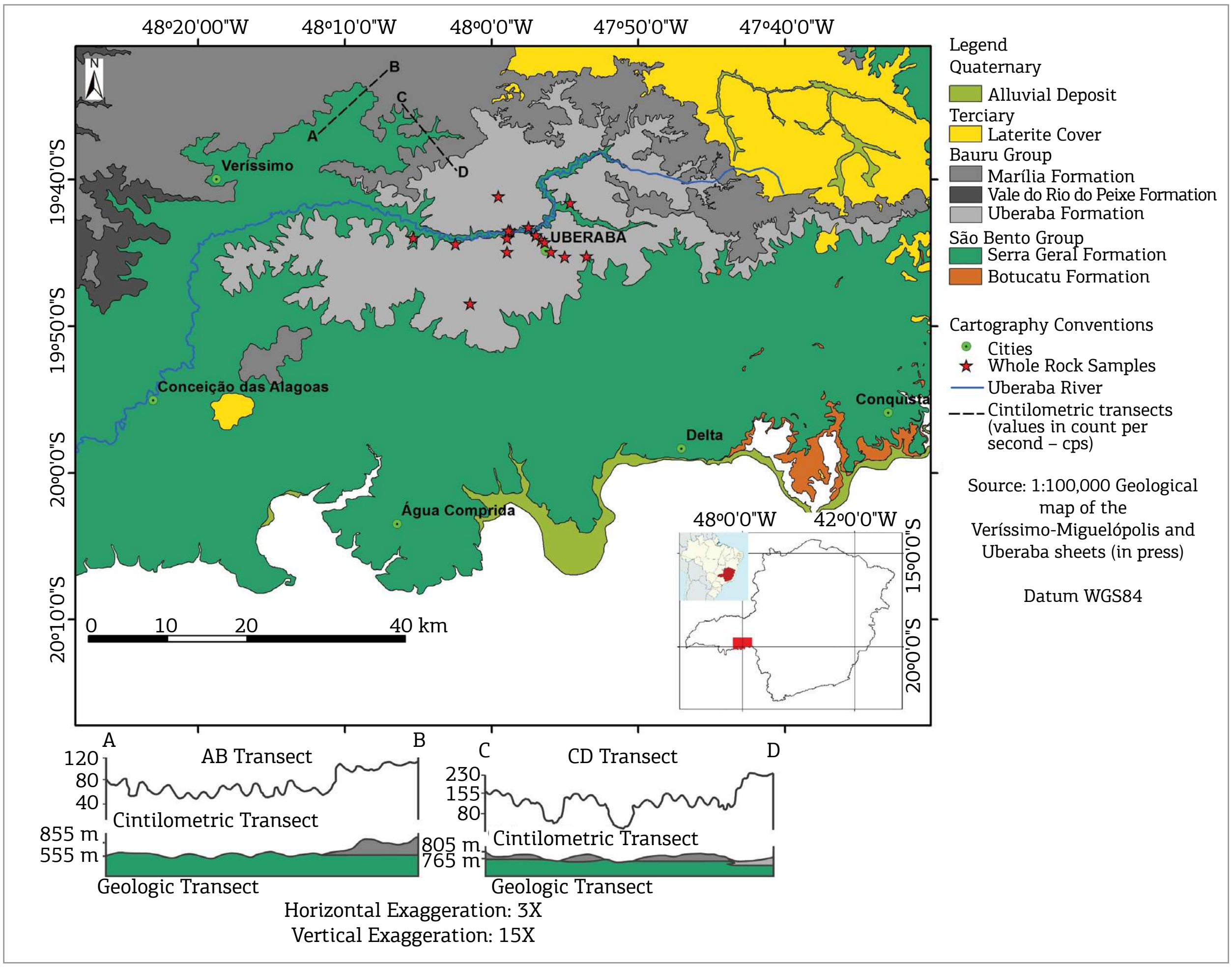


Figure 1. Integrated simplified geological map of the Veríssimo-Miguelópolis and Uberaba sheets (Ferreira *et al.* and Seer & Moraes, in press), produced within the Triângulo Mineiro mapping project CODEMIG/UFMG 2015-17. Scintillometric transects A-B and C-D and the location of samples collected for whole-rock geochemistry (red stars) are also shown.

1906, Karfunkel *et al.* 2014). In this respect, it is interesting that some authors correlate the Uberaba Formation to diamond-producing conglomerates, which crop out 95 km to the northeast, in the Romaria region (Ferreira Jr. 1996, Coelho 2010). The study of heavy minerals recovered from the Uberaba Formation, and their mineral chemistry will help in the definition of the provenance and potential for mineralization of this unit.

GEOLOGICAL CONTEXT

Bauru Group and Uberaba Formation

The Bauru Group presents approximately 370,000 km^2 or ca. 20% of the Paraná Basin (Barcelos 1984, Fernandes & Coimbra 2000), occurring in the states of Minas Gerais, Goiás, Mato Grosso do Sul, Paraná and São Paulo. This group is limited to the north by the Alto Paranaíba Arch, and corresponds to semi-arid system tract deposits, formed by alluvial fans, ephemeral fluvial systems and an endoreic palustrine zone (Milani *et al.* 2007).

Soares *et al.* (1980), based on paleontological and stratigraphic studies, suggest that the Bauru Group was deposited in the Aptian-Maastrichtian interval, as also proposed by Bertini (1993). The Uberaba Formation is considered as deposited in the Campanian (83.6 to 72.1 Ma), based on lithostratigraphic relationships with the Vale do Rio do Peixe and Marília formations, in addition to paleontological data (Huene 1939, Santucci & Bertini 2001) and paleomagnetic studies of Tamrat *et al.* (2002).

The Uberaba Formation belongs to the lower portion of the Bauru Group, in an erosive contact upon the Serra Geral Formation (Fig. 1). This contact is marked by the presence of a polymictic conglomerate with basalt, sandstone and claystone clasts (Hussak 1906). The upper contact with the Marília Formation is considered by some authors as also abrupt, marked by a silexite level and a conglomerate rich in quartz clasts (Seer & Moraes, in press), cimented by calcite (Barbosa 1934, Hasui 1968).

Hasui (1968), Barcelos (1984), Goldberg (1995), Ferreira Jr. (1996) and Batezelli (2003) interpret the Uberaba Formation as constituted predominantly by sedimentary rocks with volcaniclastic contribution, mostly coarse sandstones with a local greenish matrix of volcanic origin due presence of Ce oxides, arkoses and lithic sandstones, locally siltstones and mudstones (Fig. 2A), conglomerates and conglomeratic sandstones. Carbonate cementation might occur, as well as carbonate nodules. Macrofossils are common (Santucci & Bertini 2001), as well as bioturbation (Fig. 2B), cross bedding (Fig. 2C), plane-parallel bedding and some syn-depositional deformational structures such as flame structures and convolute fold structures.

Ferreira Jr. (1996) and Ferreira Jr. and Gomes (1999) describe the presence of clay minerals such as detrital illite and authigenic esmectite in the intergranular spaces and suggest their formation from volcanic ashes. On the other hand, Goldberg (1995) proposes a process of mechanic infiltration of fine-grained sediments transported in high stand periods and deposited by decantation over the sand deposits (sieve effect).

Silva *et al.* (1994) suggest that detrital components of the sandstones were sourced of basalts from the Serra Geral Formation, quartzites and schists from the Canastra, Ibiá and Araxá groups, and alkaline rocks from the Alto Paranaíba region.

The depositional setting of the Uberaba Formation is a matter of high debate, and some work hypothesis have been proposed, e.g., fluvial with little transport (Hasui 1968), fluvio-deltaic (Suguio 1980), meandering (Barcelos 1989) and braided (Ferreira Jr. & Guerra 1993, 1995, Batezelli 2003). However, a detailed sedimentological approach is necessary for this issue to be fully understood.

Besides the Uberaba Formation, the Vale do Rio do Peixe and Marília formations compose the Bauru Group in the studied area. The Vale do Rio do Peixe Formation is composed by fine to medium-grained reddish sandstones, with cross-bedded foresets of up to 3 m (Fernandes & Coimbra 2000). The Marília Formation, according to Almeida & Barbosa (1953) corresponds to conglomerates and coarse sandstones with calcite cementation, divided by Barcelos (1984) in three members: Ponte Alta (conglomerate sandstones and conglomerates, calcretes and silcretes), Serra da Galga (polimictic conglomerates with calcrete clasts) and Echaporã (fine to medium-grained sandstones). Other authors as Fernandes and Ribeiro (2015) and Batezelli and Ladeira (2016) consider only two members in this area (Serra da Galga and Ponte Alta).

The stratigraphic subdivision adopted in this paper is according Barcelos (1984) and Batezelli (2003) following the nomenclature of Vale do Rio do Peixe Formation from Fernandes and Coimbra 2000 (Fig. 3).

Diamonds in the Uberaba region

The diamond occurrences of the TM and AP regions are known for more than 250 years and correspond mostly to placer type deposits in the drainage gravels. There are some occurrences in rocks like Romaria's conglomerate and the Capacete Formation of the Mata da Corda Group (Fernandes *et al.* 2014). Some satellite minerals have been reported on the Uberaba Formation, such as Cr-diopside, picro-ilmenite and pyrope (Gravina *et al.* 2002). However, diamonds properly have not yet been found in the Uberaba Formation rocks, only within alluvium sediments such as along the Uberaba River. One of the authors (L.C.B.R.) saw a 9 carat diamond at the end of the 70's north of the Uberaba city recovered from gravels of the Uberaba River. According to information from *garimpeiros* (diggers) a 42 ct diamond has also been recovered from an alluvial deposit. To one of the co-authors (J.K.), several diggers reported the largest recovered stone in the headwaters of the Uberaba River gravel in the 60's ties that weigh 42 ct, and a second one of 34 ct. Karfunkel *et al.* (2014, 2015) discuss and put forwards some hypotheses to explain the origin of these gems, from local sources, or transported from long distances by extrusive rocks.

Ferreira Jr. (1996) proposes that kimberlitic intrusions were important in providing those minerals. In fact, they could represent some of the sources, but not the main source because up to now no diamondiferous kimberlite or lamproite intrusions were found with a volume that could provide the ca. 40 million carats of diamonds already recovered from drains in the TM (Karfunkel *et al.* 2015). Besides, most kimberlites and related rocks in the TM are of small size, sterile or with non-economic diamond concentrations (Karfunkel *et al.* 2015). Thus, the provenance of these gems and satellite minerals from kimberlites and lamproites for this region as main suppliers is contentious.

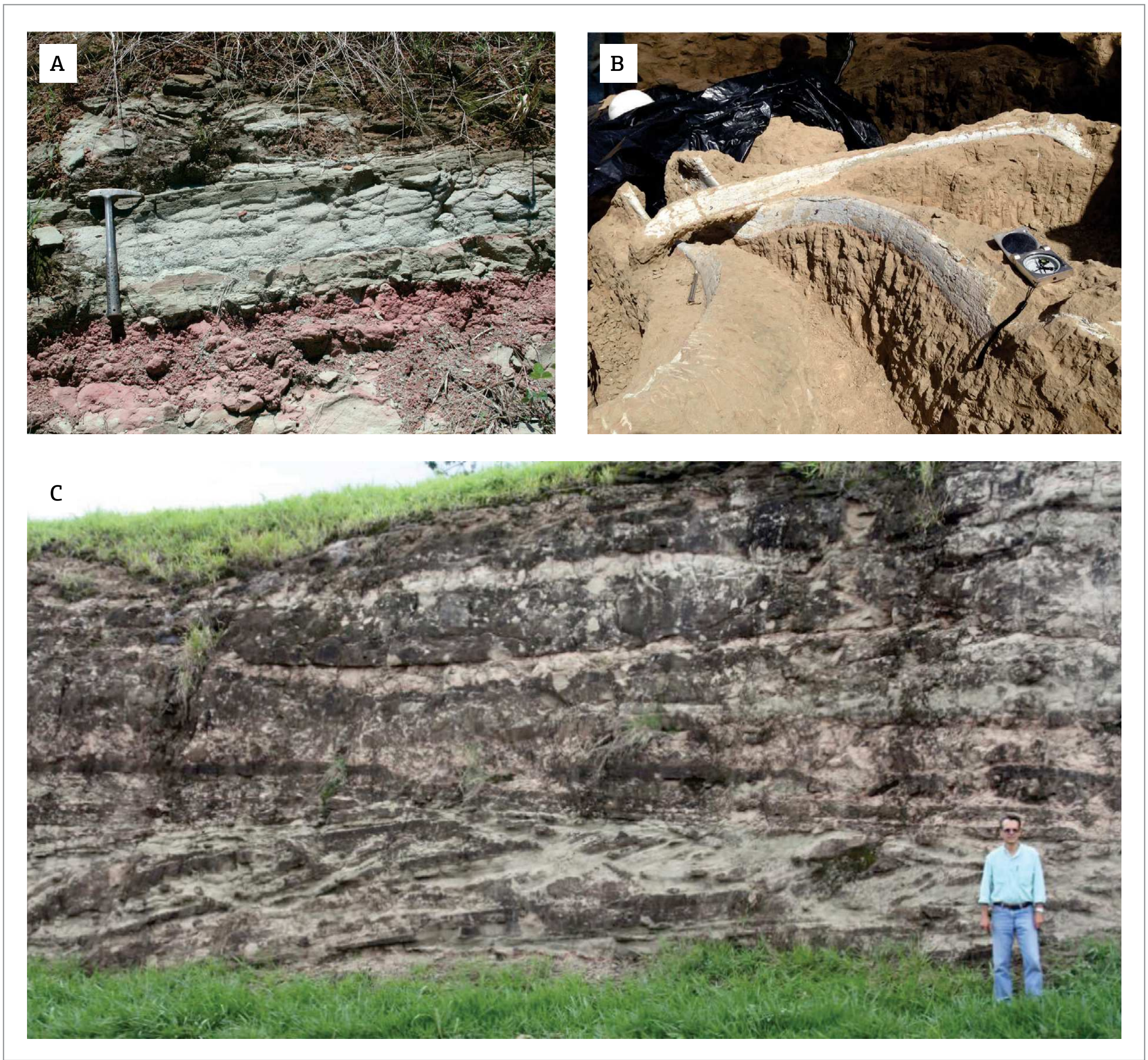


Figure 2. Field aspects of rocks from the Uberaba Formation: (A) red fine sandstone bed (below) in contact with green lithic green sandstone (above); (B) bone fossils (probably titanosaur ribs) found in excavation in the Uberaba town; (C) cross stratifications in likely channel deposits. Hammer is 42 cm long.

MATERIALS AND METHODS

Fieldwork for data and sample collection was conducted within the context of the Triângulo Mineiro CODEMIG/UFMG 2015–2017 mapping project, specifically within the context of Veríssimo/Miguelópolis and Uberaba 1:100.000 sheets. All of the authors were involved in the fieldwork stage. During the fieldwork, stratigraphic sections were made by L.M., H.S., D.Q. and F.C., with the collection of samples for petrographic, heavy minerals and chemical analyses.

Cartography of the Uberaba Formation was greatly aided by the utilization of aerogeophysical maps, mainly gamma spectrometric maps (U, Th and ternary K-Th-U maps in Fig. 4), from the program Levantamento Aerogeofísico do Estado de Minas Gerais 2010/2011 of CODEMIG, in a 1:500.000 scale. Also, scintillometric transects were produced by D.Q. and J.K. (Fig. 1). Those transects were made near the geological contacts between the various units in order to identify possible radiometric variations which could aid in the individualization of the units. A SC-132 hand scintillometer of Mount Sopris Instrument Co. was used for this purpose.

Separation of heavy minerals from selected samples was conducted at the Laboratório de Tratamento de Minérios, CEFET-MG – Campus Araxá. Samples were dried at 300ºC for two hours, then crushed in a jaw crusher, sorted, and then sieved utilizing 70# (210 μm) and 120# (125 μm) sieves. Samples were panned, and then magnetite was removed using a hand magnet. Finally, acid attack with 10% HCl has been carried out for 24 hours in Erlenmeyers. Heavy minerals were then separated by H.S., L.M. and F.V. using a binocular lens.

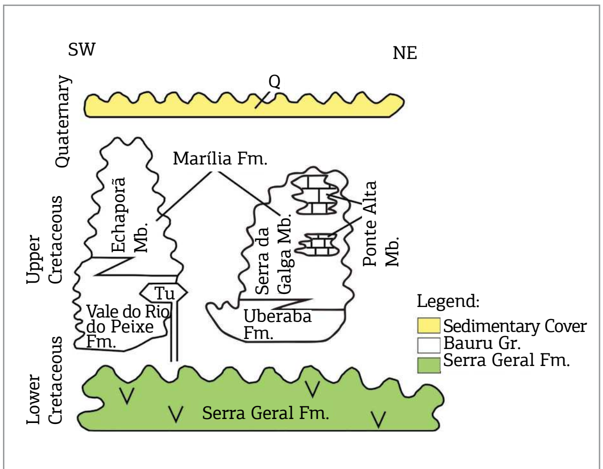


Figure 3. Lithostratigraphic chart of the Bauru basin, from Fernandes and Coimbra (2000).

Twenty-four samples were selected for petrographic analysis, from which five samples were selected for mineral chemistry analysis (samples V634, V620A and B, V631 and 7C). After covering of the polished thin sections with a fine carbon powder, they were subjected to quantitative and semi-quantitative analysis in a JEOL JXA-8900RL (WDS) microprobe at the Centro de Microscopia, Universidade Federal de Minas Gerais, using an acceleration tension of 15 kV and a beam current of 20 nA. Twelve oxides were determined for each analyzed point, and the grades were obtained using Ian Steele and Astimex collection standards.

After crushed and pulverized, 17 samples were sent for whole rock chemistry analysis at GEOSOL Laboratories, Brazil, and two other samples were sent to ACME Analytical Laboratories Ltda., Canada (sample location in Fig. 1). Major element grades were analyzed by ICP-MS (ACME) or ICP-OES (GEOSOL), and trace element grades were analyzed by ICP-MS in both laboratories after fusion with lithium metaborate/tetraborate and digestion with diluted nitric acid. Analytical errors are within 5% for oxides and 10–15% for trace elements. Base and precious metal grades were determined by digestion in Aqua Regia followed by ICP-MS analysis. The Loss On Ignition (LOI) was determined by the weighing difference after ignition at 1,000ºC.

RESULTS

Application of geophysics in the cartography of the Uberaba Formation

In the ternary K-Th-U gamma spectrometric map of the region an E-W trending area in the central portion exhibits high Th and U contents (Fig. 4A), corresponding to the outcrop area of the Uberaba Formation (whiter colors in Fig. 4A). In the Th channel map, the Uberaba Formation is characterized by values above 23,844 ppm (purple and pink shades in Fig. 4B), mainly due to the high perovskite content of the unit. In the U channel map, values above 1,430 ppm (red and pink shades in Fig. 4C) characterize the unit.

Another resource utilized in the mapping of the Uberaba Formation is scintillometric transects (Fig. 5). During the realization of those transects, the Uberaba Formation has shown high radiometric activity, with 250–350 cps (counts per second), while basalts of the Serra Geral Formation show average values around 50 cps and rocks of the Marília Formation around 110 cps. Thus, geophysical data improved considerably the cartography and recognition of the Uberaba Formation outcrop area. For geological mapping in flat lying

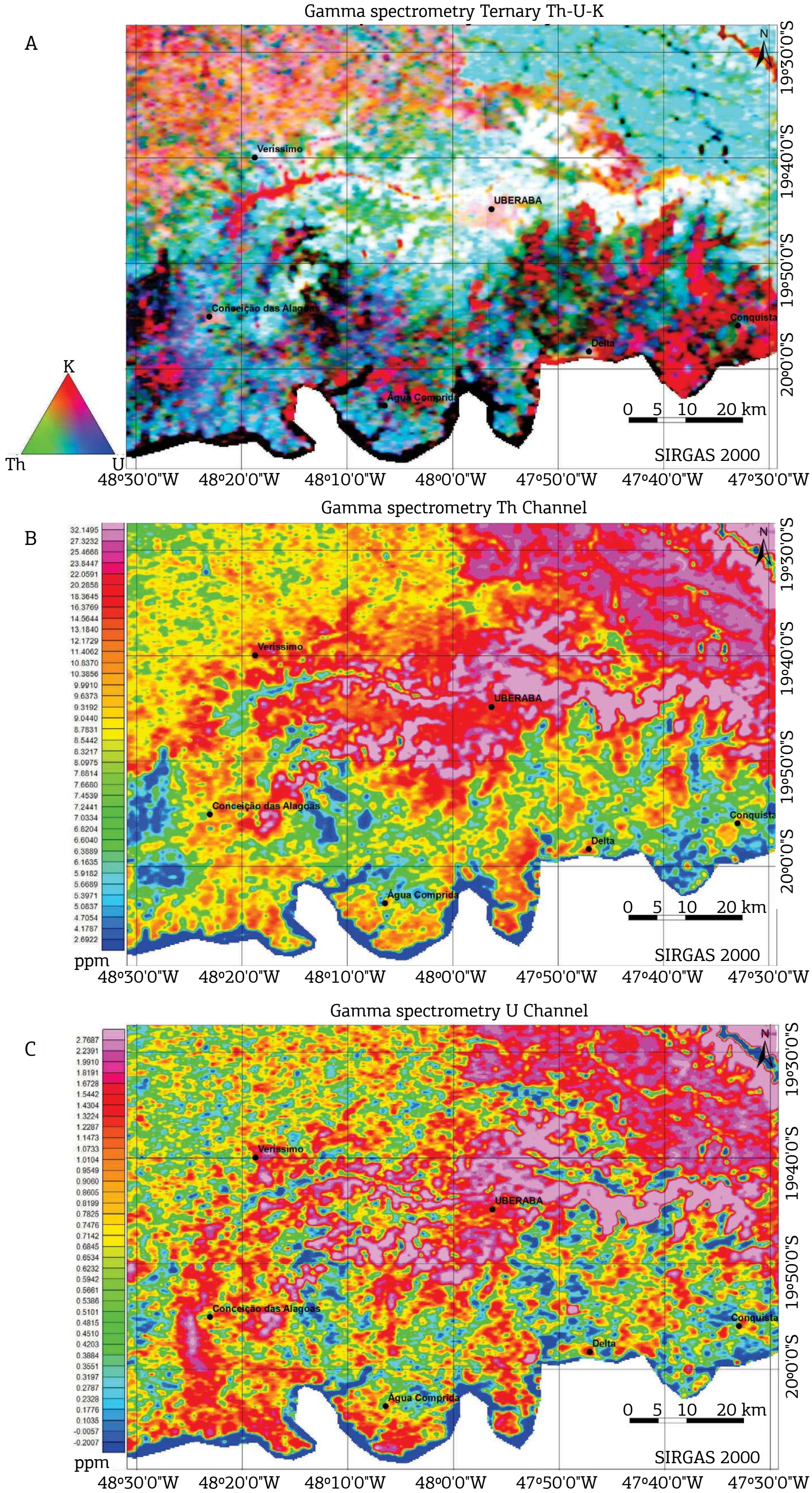


Figure 4. Geophysical maps of the Veríssimo-Miguelópolis and Uberaba sheets (data from CODEMIG, Geophysic Airborne Program 2010/2011): (A) gamma spectrometry, ternary plot Th-U-K; (B) gamma spectrometry, Th channel; (C) gamma spectrometry, U channel.

rock sequences with different backgrounds in vast regions covered by plantations like sugar cane and soya, this auxiliary method has been of great help.

In a ternary gamma spectrometric map of the eastern TM and AP (Fig. 5), the signature of the Uberaba Formation is comparable to that of the Mata da Corda Group (Guimarães 1964, Bryon 1999, Sgarbi *et al.* 2003). Both units show high Th and U grades as shown by the bluish colors in the map.

Sedimentological aspects

Three schematic stratigraphic columns were measured for a preliminary study of the Uberaba Formation sedimentary features. For each column, a group of sedimentary facies was described as follows.

In the MP01 column (Fig. 6), located in Randolfo Borges Junior Avenue corner with José Marçal Costa Street (190806 E/ 7815657 N; WGS84 23K), predominantly coarse facies can be recognized, marked by the occurrence of clast- and matrix-supported massive conglomerate, massive sandstone with clasts and medium-grained sandstone followed by a claystone bed. In the middle portion of the column, the sedimentary package is characterized by the presence of erosive surfaces. Above these, clast-rich sandstone and massive conglomerate have been observed, followed by a massive clast-rich sandstone that grades upwards to medium-grained sandstone. The top of the column is marked by conglomerate sandstone and medium-grained sandstone.

The MP02 column (Fig. 7), located in Randolfo Borges Junior Avenue closer to Florestan Fernandes Avenue (189948 E/ 7.816.650 N; WGS84 23 K), is characterized from base to top by normal graded facies with conglomerates grading to sandstones. Atop basalts of the Serra Geral Formation, massive matrix-supported conglomerates and sandstones with cross bedding are identified. Above an erosive surface, matrix-supported conglomerate occurs, followed by sandstone

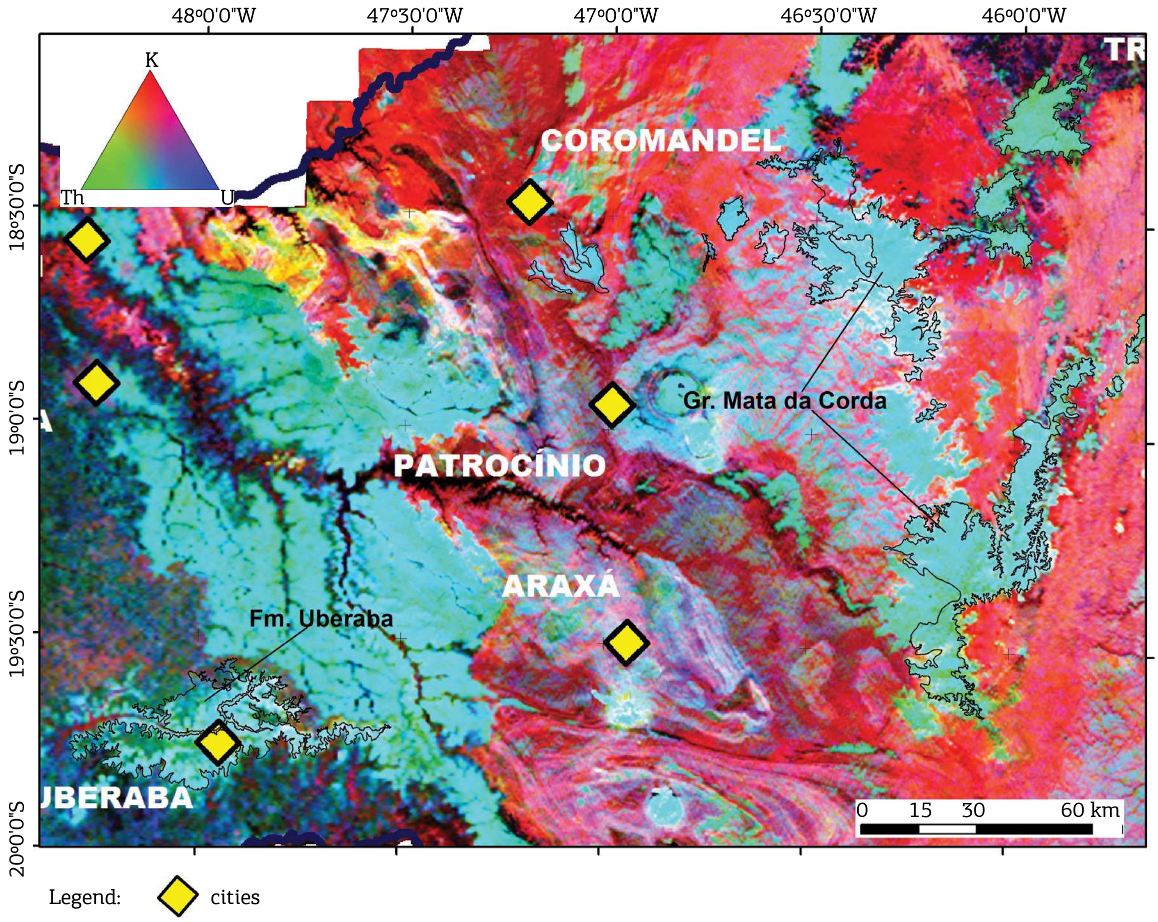


Figure 5. Ternary gamma spectrometric map of the eastern portion of the TM and AP regions, showing the outcrop areas of the Uberaba Formation and Mata da Corda Group (data from the Geophysics Airborne Program of CPRM/CODEMIG, 2006, Area 7).

with cross bedding and claystone beds. Above a second erosive surface, another layer of clast-supported conglomerate is followed by massive and cross-bedded sandstone. In the top of the sequence, also delimited by a basal erosive surface, matrix-supported conglomerate, massive and clast-rich sandstone occurs.

The base of column FU464 (Fig. 8), located in Leopoldino de Oliveira Avenue corner with José Pimentel Camargo Street (194297 E/ 7813016 N; WGS84 23 K), is marked by a claystone bed followed by a conglomerate sandstone above an erosive surface, showing decreasing-upwards grain size and grading to medium-grained cross-bedded sandstone. The upper portion of the column is marked by another matrix-supported conglomerate covering an erosive surface.

Petrography

The sandstones of the Uberaba Formation show a mean composition of ca. 40% quartz, ca. 40% lithic fragments and ca. 15% feldspars, characterizing them as lithic sandstones

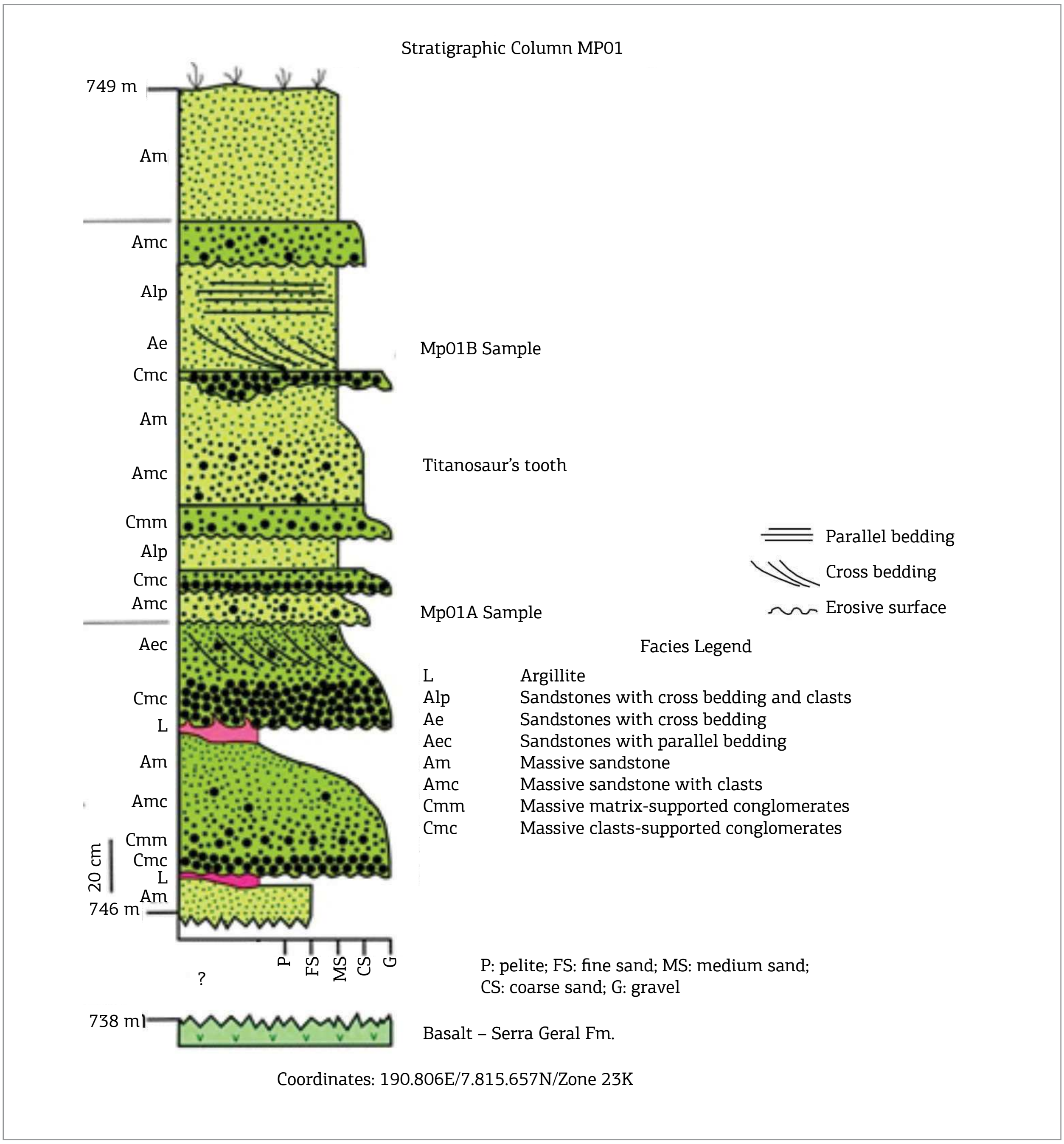


Figure 6. Stratigraphic column MP01.

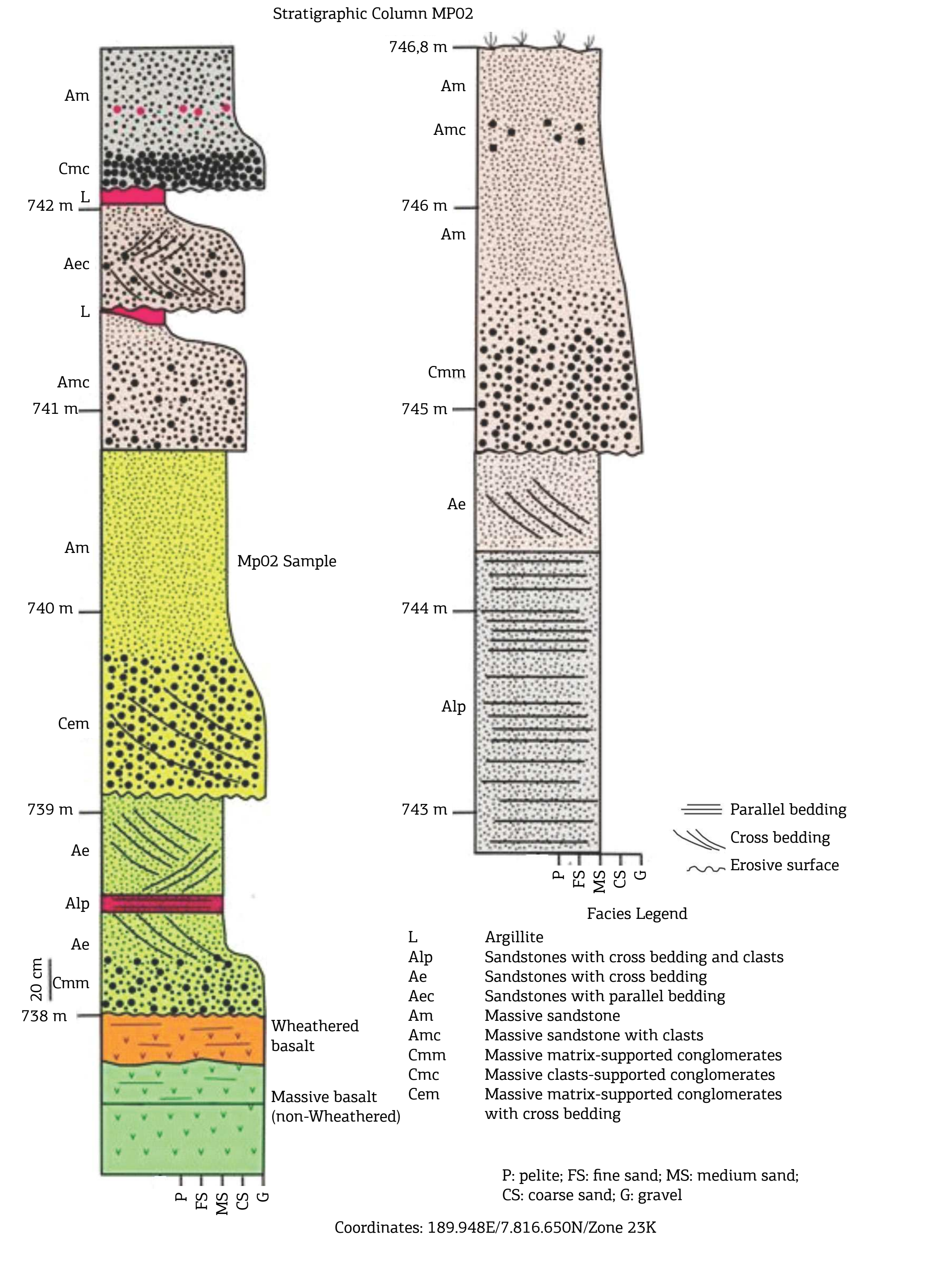


Figure 7. Stratigraphic column MP02.

or arkoses. Accessory minerals are olivine, pyroxene, titanite, apatite, phlogopite, garnet, perovskite and opaque minerals, generally up to 5%, but locally, in concentrated laminae, reaching up to 36% of the total rock.

Texturally the sandstones show a predominance of subangulous clasts of medium sphericity, with poor selection and carbonate cementation. The contact between the grains is punctual or normal, suggestive of a loose packing. Some of

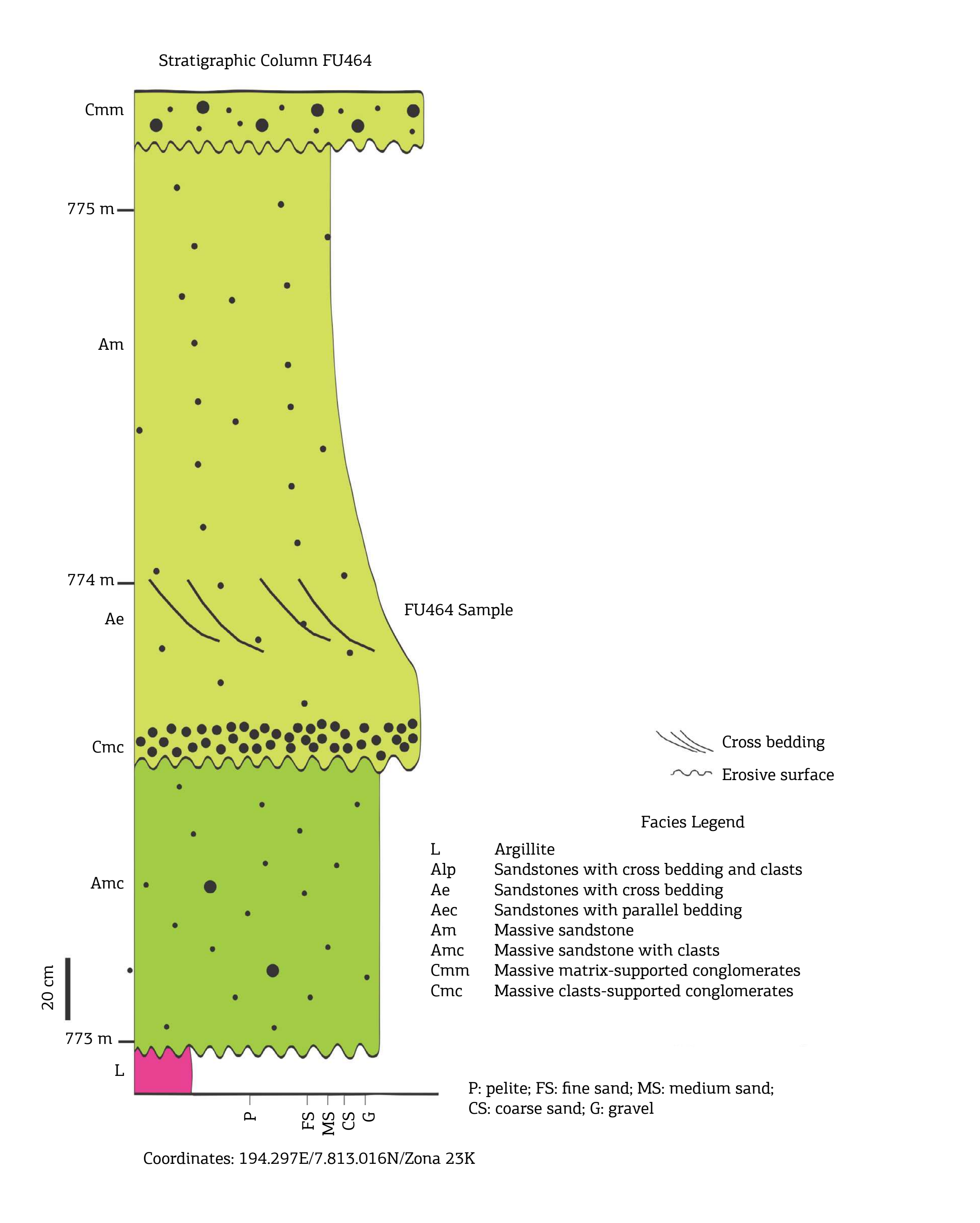


Figure 8. Stratigraphic column FU464.

the detrital grains show chemical alterations in the borders and corrosion gulfs (Fig. 9A and B) in varying sizes, from 0.1 mm to 0.5 mm.

Lithic fragments are generally constituted of basalt, quartzite, schist, phyllite and well-sorted sandstone (Fig. 9C–E). Feldspars are usually altered through sericitization and caulinization processes. Plagioclases are more common, but alkali-feldspars also occur. It is common to identify perovskite and garnet in the heavy mineral levels (Fig. 9F). In some samples, an amorphous, very fine greenish mass of clay minerals

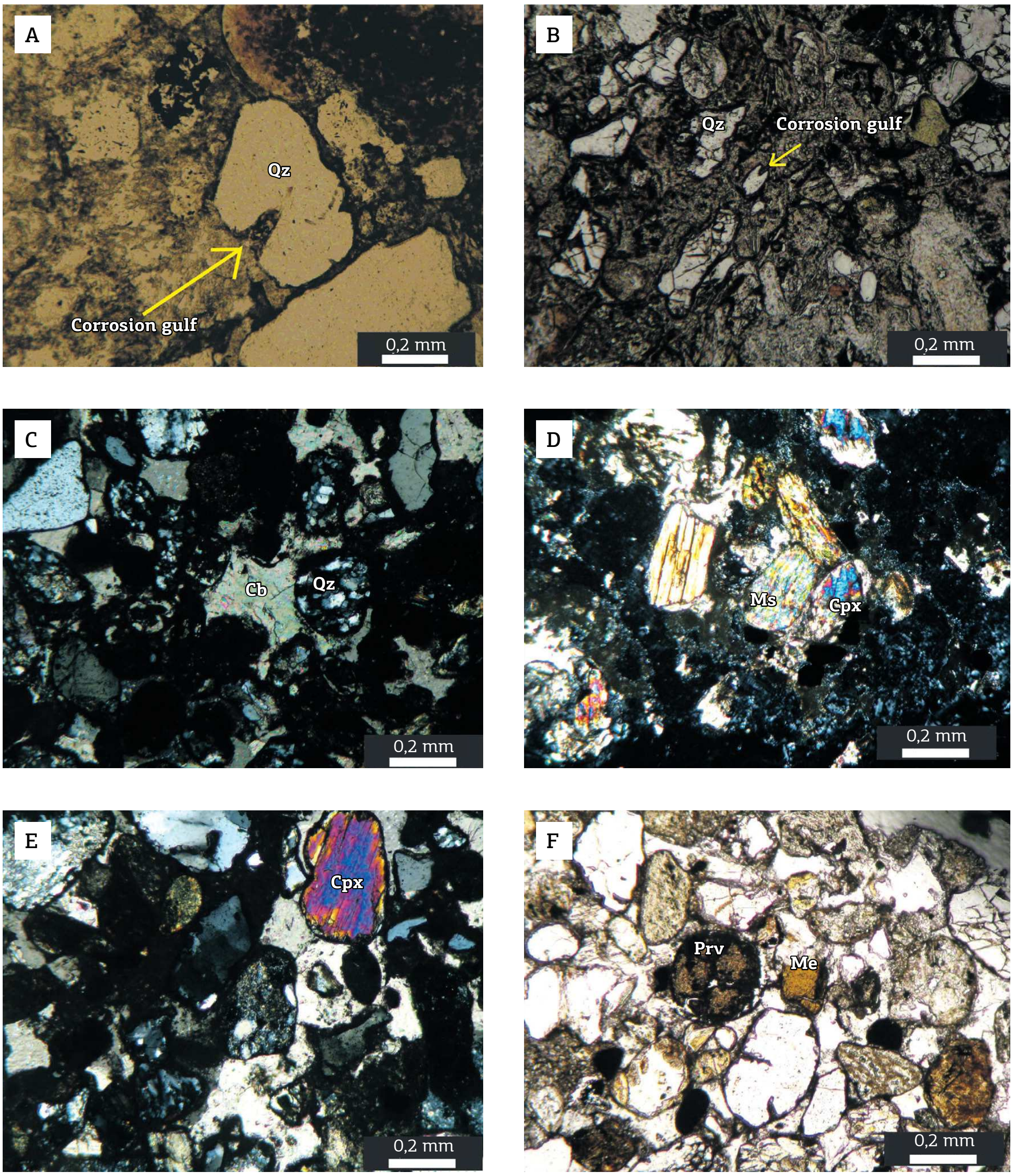


Figure 9. Photomicrographies of sandstones from the Uberaba Formation: (A and B) detail of quartz grains of probable volcanic origin, showing corrosion gulfs (Qz), uncrossed polarizers; (C) quartzite fragment (Qz) and carbonatic cement (Cb), crossed polarizers; (D) fragment of muscovite schist (MS) and clinopyroxene (Cpx), crossed polarizers; (E) clinopyroxene (Cpx), crossed polarizers; (F) perovskite (Prv) and melanite (Me), uncrossed polarizers.

is observed, filling the intergranular voids. This groundmass can reach up to ca. 25% of the total rock volume.

Heavy minerals

Two samples from MP02 site and three samples from MP04 were selected for separation of the heavy minerals. From those samples, magnetite, pyroxene, ilmenite, perovskite, monazite, epidote, rutile, apatite, and diopside were separated (Tab. 1). It is noteworthy that for most samples the magnetite concentration is much higher than the other minerals (ca. 75%). The main other heavy mineral is perovskite (ca. 70% of the clean concentrates), followed by pyroxene with ca. 20% and ilmenite around 7%. Other minerals such as monazite, epidote, rutile and apatite show minor contributions or are lacking in some samples.

Mineral Chemistry

Through quantitative and semi-quantitative (EDS) microprobe analysis a great variety of detrital minerals from the Uberaba Formation were characterized, such as ilmenite, perovskite, phlogopite, andradite, pumpellyite, augite and richterite, sanidine and diopside (Tab. 2). Semi-quantitative EDS analyses (Tab. 3) aided in the characterization of other minerals such as titanite, celadonite, zircon, apatite, anatase, rutile, phlogopite, allanite, illite, muscovite, glauconite and dolomite.

Analyses of perovskite (Tab. 2) were always performed in the nucleus of the grains, due to its small size. The analyzed perovskites are close to the ideal formule (final member $CaTiO_3$ with ca. 29.48% Ca and 35.22% Ti). Low grades of Na, between 0.04 and 0.62%, suggest low concentration of components such as loparite ($NaCeTi_2O_6$) and/or lueshite ($Na_2Nb_2O_6$). Considerable amounts of Fe, between 0.64 and 1.41%, might be related to solid solution of latrappite ($CaNb_{0.5}Fe_{0.5}O_3$). Th can reach up to 0.36% (Tab. 2), which reflects the characteristic gamma spectrometric responses of the Uberaba Formation (Fig. 4B). U, on the other hand, might be more correlated to celadonite in the rock matrix.

Detrital garnets of the Uberaba Formation are typically enriched in Ca (22.41 to 24.36%), Fe (19.58 to 20.34%) and Ti (2.12 to 3.54%), and show low Al (0.22 to 0.40%), Cr (0.04 to 0.22%) and Mn (0.02 to 0.08%), mostly classified as andradite. Ti and Fe enrichment of those garnets allows to further classify then as the andradite subtypes, mostly schorlomite and melanite (Deer *et al.* 1992).

The most common detrital mica of the Uberaba Formation is phlogopite. Chemistry analyses close between 77.23 e 91.25% because of the water preset in their mineral structure, which is not considered during the analyses. The phlogopites show Mg amounts between 11.74 and 16.84%, Fe between 4.32 and 6.64%, Al between 3.97 and 6.678%, and, lastly, Ti between 1.14 and 1.92% (Tab. 2). The majority of the phlogopites analyses belong to a solid solution series between tetra-ferriphlogopite and phlogopite.

Whole rock geochemistry

Nineteen samples were analyzed for whole rock geochemistry, and results are shown in Tables 4 and 5. The spatial distribution of those samples within the Uberaba Formation is shown in Fig. 1.

Table 1. Heavy mineral concentrated from Uberaba Formation.

		Samples				
	Mineral (%)	**MP02A**	**MP02C**	**MP04A**	**MP04B**	**MP04D**
	Heavy mineral total mass (g)	**1.9**	**5.89**	**16.47**	**13.81**	**23.29**
Heavy Minerals	Magnetite (%)	75.79	74.02	79.05	71.04	78.02
	Clean Concentrate (%)	24.21	25.98	20.95	28.96	21.98
Clean Concentrate	Pyroxene	9.84	19.39	24.52	20.43	25.78
	Illmenite	2.76	10.32			0.15
	Perovskite	85.53	61.56	75.3	79.56	72.85
	Monazite			0.16		0.9
	Epidote	0.3				
	Rutile	1.53				
	Apatite		7.29			
	Diopside		1.42			0.3

Samples show overall low SiO_2 (25.15 to 53.88%) and Al_2O_3 content (2.70 to 6.71%), and relatively high contents of CaO (2.34 to 29.18%), K_2O (2.85 to 6.97%), Fe_2O_3 (7.99 to 17.36% — locally reaching abnormal values up to 30%) and TiO_2 (3.82 to 13.23% — reaching up to 24%). P_2O_5 grades are between 0.58 and 1.48%, MgO between

Table 2. Mineral Chemistry from electron microprobe (%wt).

Na	Ti	Th	Si	Cr	U	Mg	Fe	Ca	Al	Mn	K	Total (%)	Minerals
0.02	3.37	0	14.99	0.06	0.12	0.46	20.06	24.36	0.22	0.22	0.02	63.88	Andradite
0.01	3.54	0	14.94	0.08	0	0.55	19.58	24.23	0.4	0.18	0.01	63.53	Andradite
0.07	2.38	0	15.72	0.05	0	0.42	20.11	22.41	0.27	0.11	0.01	61.54	Andradite
0.02	2.12	0	16.73	0.02	0.06	0.35	20.34	23.08	0.27	0.04	0	63.01	Andradite
0.75	0.67	0	25.36	0	0.03	9.68	3.55	16.95	0.07	0.06	0.01	57.13	Augite
0.05	1.69	0	15.89	0.07	0.73	11.74	5.78	0.51	3.97	0.3	3.22	43.94	Phlogopite
0.08	1.19	0.09	16.99	0	0.61	15.72	4.53	0.65	6.16	0.26	3.1	49.38	Phlogopite
0.04	1.92	0	16.16	0	0	15.24	6.64	1.21	5.22	0.11	4.46	51	Phlogopite
0.05	1.14	0	17.73	0.02	0.49	16.84	4.33	0.54	6.68	0.29	2.89	51	Phlogopite
0.23	0.32	0	24.51	0	0.08	10.86	2.57	17.82	0.08	0.08	0	56.55	Diopside
0.07	0.07	0.01	23.67	0	0	0.36	0.61	0.11	10.63	0	5.97	41.51	Illite
0.06	30.04	0	0	0.25	0	5.3	30.3	0.06	0	0.7	0.01	66.71	Ilmenite
0.02	33.55	0.01	0.03	0.1	0.05	7.01	17.94	0.65	0	2.99	0.05	62.4	Ilmenite
0.1	0	0	25.98	0	0	0.14	0.41	0.09	10.17	0	8.3	45.19	Muscovite
1	32.86	0.36	0	0	0	0	0.97	23.1	0.02	0	0.01	58.32	Perovskite
0.63	33.92	0.15	0.02	0	0.04	0	0.72	24.71	0.03	0.02	0.02	60.25	Perovskite
0.6	33.77	0.21	0.02	0	0.01	0.01	0.72	25.46	0.01	0	0.01	60.83	Perovskite
0.21	34.72	0.16	0.01	0	0	0	0.76	28.06	0.06	0	0.02	63.99	Perovskite
0.04	34.13	0.03	0.03	0	0.04	0.02	1.33	28.87	0.09	0.06	0.01	64.65	Perovskite
0.05	33.8	0.04	0.04	0	0	0.02	1.23	29	0.07	0	0.02	64.26	Perovskite
0.06	33.08	0.01	0.06	0.01	0.01	0.03	1.41	28.57	0.12	0.01	0.02	63.39	Perovskite
0.26	34.29	0.15	0.03	0.07	0	0	0.72	28.51	0.02	0	0.02	64.07	Perovskite
0.1	33.98	0.02	0.06	0.02	0	0.03	1.03	28.68	0.06	0.06	0.04	64.08	Perovskite
0.23	35.7	0	0.01	0	0.06	0	0.78	28.47	0.02	0.03	0.01	65.31	Perovskite
0.56	34.06	0.06	0.01	0	0	0	0.74	25.93	0.03	0.03	0.02	61.44	Perovskite
0.55	34.65	0.13	0.02	0.02	0	0.02	0.64	26.27	0.01	0.01	0.01	62.33	Perovskite
0.01	0.19	0	17.68	0.02	0	0.01	6.47	17.06	14.97	0.13	0.01	56.55	Pumpellyite
0	0.08	0	46.27	0	0	0	0	0.01	0.01	0.04	0	46.41	Quartz
6.62	0.54	0.01	26.44	0.03	0	2.57	18.93	5.78	0.09	0.28	0.01	61.29	Amphibole
5.46	0.37	0.02	24.2	0	0.03	2.61	16.96	6.77	0.06	0.45	0.02	56.94	Amphibole
0.34	0	0.04	28.29	0.05	0	0	0.02	0.01	10.08	0	11.96	50.78	Sanidine
0.11	25.37	0.03	6.08	0.16	0.08	0.07	13.74	7.66	0.03	0.67	0.04	54.03	Titanite
0.1	23.23	0	14.74	0	0.02	0	1.31	20.03	0.08	0.05	0.01	59.56	Titanite

3.59 and 11.38%) and Na_2O (0.08 to 0.28%), MnO (0.14 to 0.36%) and Cr_2O_3 (0.05 to 0.77%) are low.

Chondrite-normalized rare earth element (REE) patterns of the samples are characterized by a strong fractioning of the light rare earths (LREE) relative to the heavy rare earths (HREE), with La_N/Yb_N around 128 and La_N/Lu_N around 154. No relevant Eu anomalies are found, and the mean value of Eu/Eu* is 0.89. Thus, the chondrite-normalized patterns are flat with a steep incline towards HREE (LREE — enriched).

Chondrite-normalized (Thompson 1982) incompatible element plots for the Uberaba Formation (Fig. 10A) show a distinctive enrichment in Ta-Nb (positive Ta-Nb anomaly) and also Th enrichment (due to the presence of perovskite). P and Sr show, on the other hand, negative anomalies. North American Shale Composite (NASC)-normalized patterns (Taylor & McLennan 1995) present the same anomalies verified on the chondrite-normalized plots (Fig. 10B and 10C).

In the plots of Figs. 11 and 12, besides the samples of the Uberaba Formation, the fields which correspond to the plotting area of the alkaline complexes of the AP (Tapira, Araxá, Catalão I, Serra Negra and Salitre) are also plotted for comparison. In general, samples from the Uberaba Formation plot within the patterns of the AP complexes in Fig. 11, and there is a high overlap between the complexes, generally showing highly fractionated LREE and a positive Nb-Ta anomaly. The patterns which are closer to the Uberaba Formation are those of Tapira and Catalão. Fig. 12A shows a bi-variant plot of $SiO_2 \times MgO$. Those two variables are not correlated, and MgO is constant with higher SiO_2. In this diagram, some samples plot within the Serra Negra / Salitre and Tapira / Araxá fields, but away from Catalão I.

Figure 12B corresponds to a diagram proposed by Foley *et al.* (1987), which utilize CaO and Al_2O_3 grades. The Uberaba Formation samples are characterized by low Ca

Table 3. Mineral Chemistry from energy dispersive X-ray detector (EDS) analyzes (%wt).

Na	Ti	Si	Cr	Mg	Fe	Ca	Al	Mn	K	P	Ba	C	Zr	S	Ce	Mineral
0	0	15.75	0	0	8.02	6.24	0	0	0	4.15	0	0	0	0	17.62	Allanite
0	3.45	22.74	0	6.63	3.25	0	5.54	0	7.39	0	0	0	0	0	0	Alumino Celadonite
0	59.9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Anatase or Rutile
0	0	0	0	0	0	39.27	0	0	0	16.58	0	0	0	0	0	Apatite
0	0	0	0	0	0	0	0	0	0	0	46.14	0	0	23.35	0	Barite
0	0	21.59	0	10.3	0	0	7.18	0	7.09	0	0	0	0	0	0	Biotite
0	0	27.65	0	5.55	5.11	0	2.78	0	7.65	0	0	0	0	0	0	Celadonite
0	0	22.93	0	7.31	9.42	0	3.85	0	6.04	0	0	0	0	0	0	Celadonite
0	0	0	0	20.44	0	32.32	0	0	0	0	0	1.54	0	0	0	Dolomite
0	0	21.44	0	16.61	0	0	7.02	0	0	0	0	0	0	0	0	Phlogopite
0	0	23.07	0	7.27	9.36	0	3.82	0	6	0	0	0	0	0	0	Glauconite
0	0	21.02	0	2.35	0	0	17.05	0	5.53	0	0	0	0	0	0	Illite
0	0	21.31	0	3.06	0	0	16.58	0	7.27	0	0	0	0	0	0	Illite
0	0	21.2	0	0	0	0	15.76	0	9.42	0	0	0	0	0	0	Muscovite
0	0	28.4	0	0	0	0	10.01	0	10.1	0	0	0	0	0	0	Sanidine
0	12.98	19.55	0	0	0	21.84	0	0	0	0	0	0	0	0	0	Titanite
0	0	21.37	0	0	0	0	0	0	0	0	0	0	34.82	0	0	Zircon

and high Al_2O_3 as compared with the alkaline complexes, although the Serra Negra/Salitre complexes plot closer to the samples.

Figure 12C correlates the quantities of TiO_2 with SiO_2. This diagram shows elevated values for the Uberaba Formation, plotting closer to the Serra Negra/Salitre complexes, compared to the other alkaline complexes. The elevated SiO_2 and TiO_2 contents can again be correlated with detrital input from sandstones, quartzites and schists of the basement (SiO_2) and alkaline complexes (TiO_2).

Unlike major element-based diagrams, a trace-element diagram using the Th/Yb *vs*. Ta/Yb ratios (Wilson 1989) show a high geochemical affinity of the Uberaba Formation to the AP alkaline complexes, with an enriched-mantle like composition (Fig. 12D).

DISCUSSION

In order to discuss the possible source areas of the Uberaba Formation, we consider here three main distinct sources, two of them included in the nearby basement (Serra Geral Formation and Proterozoic units of the Canastra and Araxá groups), and the third represented by the alkaline-carbonatite complexes of the AP (Fig. 13). Rocks on the AP became exposed and began suffering erosion during the Meso/Neocretaceous with a positive reactivation (Costa 1963, Hasui 1968, Sad 1970). This reactivated high probably provided the detrital contribution during the Cretaceous sedimentation on the northeastern part of the Bauru Basin.

The Mata da Corda Group is another very important unit of the AP (Fig. 13). This group is composed of alkaline volcanics, pyroclastics and epiclastic rocks, with lamproitic,

Table 4. Whole rock analysis – Major elements (%wt).

Samples	Coordinate (X)	Coordinate (Y)	Zone	Al2O3	CaO	Cr_2O_3	Fe_2O_3	K_2O	MgO	MnO	Na_2O	P_2O_5	SiO_2	TiO_2
7C	191484	7815082	23K	4.86	10.95	0.13	15.85	5.89	9.7	0.19	0.12	1.49	42.35	8.48
FU442	194843	7819800	23K	4.85	11.12	0.26	12.09	5.71	8.99	0.15	0.18	0.69	48.92	7.05
FU460	191898	7814786	23K	6.11	27.04	0.12	8.69	6.15	4.99	0.16	0.18	0.71	41.79	4.07
FU464	194297	7813016	23K	5.58	9.45	0.25	13.34	6.06	7.48	0.17	0.28	0.89	49.14	7.36
HD04	196919	7813106	23K	5.68	9.37	0.21	13.55	6.53	8.14	0.19	0.24	0.84	48.39	6.86
HD05	192647	7813608	23K	4.66	10.49	0.17	15.79	6.02	10.25	0.19	0.17	0.92	43	8.35
MP01A	190806	7815657	23K	4.55	8.84	0.11	13.46	5.42	9.89	0.15	0.11	0.63	49.65	7.2
MP01B	190806	7815657	23K	2.84	12.44	0.11	15.65	4.59	9.59	9.59	0.1	0.85	31.56	12.69
MP02	189948	7816650	23K	4.78	25.7	0.05	7.99	4.71	7.5	0.15	0.16	0.76	44.38	3.82
MP04	187457	7815942	23K	4.57	12.03	0.1	10.65	4.43	11.39	0.14	0.08	0.58	42.8	13.23
V620A	811753	7807036	22K	3.53	4.94	0.77	25.19	4.1	8.25	0.23	0.13	0.72	35.74	16.41
V620B	811753	7807036	22K	5.88	21.52	0.2	12.02	6.29	8.69	0.18	<0.1	0.85	38.83	5.54
V631	187431	7813503	23K	4.63	15.1	0.22	15.79	4.89	10.16	0.19	0.15	0.94	38.78	9.15
V632	187401	7815231	23K	4.05	22.43	0.12	13.81	4.35	6.92	0.19	0.15	0.96	40.03	6.99
V633A	187490	7816065	23K	2.7	29.18	0.15	17.36	2.86	8.77	0.24	0.2	1.11	25.15	12.29
V633B	187490	7816065	23K	6.64	12.17	0.07	12.85	6.39	10.56	0.15	<0.1	1.32	45.16	4.69
V634	186272	7820493	23K	4.85	10.02	0.13	14.72	5.05	8.79	0.17	0.15	0.92	46.72	8.5
V648	810121	7814540	22K	6.71	2.34	0.18	14.85	6.97	5.6	0.16	0.18	0.89	53.88	8.23
V658	805109	7815396	22K	5.95	4.3	0.6	30.29	2.87	3.59	0.36	<0.1	0.59	27.21	24.23

kimberlitic and kamafugitic intrusions and clastic sedimentary rocks. Some minerals which are abundant in the Uberaba Formation are also common in the volcanic rocks of the Mata da Corda Group, such as olivine, clinopyroxene, magnetite, apatite, phlogopite and perovskite (Sgarbi *et al.* 2003). Freyberg (1934), studying the Capacete Formation of the Mata da Corda Group near Tiros, described a diamantiferous red conglomerate with fine matrix, which Rimann

Table 5. Whole rock analysis – rare earth element and trace elements (ppm).

Samples	7C	FU442	FU460	FU464	MP01A	MP02	V633A	V633B	V620A	V620B	V631	V632	V634	V648	V658	HD04	HD05	MP01B	MP04
Ba	1933	1805	1248	1164	1814	772	769	871	875	1032	1854	745	857	924	925	1426	1131	1575	901
Ce	723.1	983.1	550.9	996.7	775.7	824.4	1683	595.6	1871	1044	936.4	971.7	891.5	1234	3045	949.2	850	1485.1	1207.9
Co	50.7	43.1	30.2	40.9	53.2	31	45.8	39.1	76.9	37.2	47.8	43.2	64.7	81.5	98	44	51	55.2	32.8
Cs	1.24	0.94	1.17	1.14	1.06	0.81	0.63	1.59	0.69	1.45	1.26	0.81	0.99	1.45	0.52	1.33	0.84	0.6	0.5
Cu	76	40	37	49	60	42	64	71	74	53	62	54	65	77	108	57	63	48.8	37.3
Dy	9.55	14.13	8.54	13.61	8.49	22.03	35.4	12.63	20.37	15.64	12.79	21.44	10.45	15.95	74.99	10.81	12.29	14.81	13.26
Er	3.35	4.12	3	4.08	2.42	5.84	9.46	4.17	5.42	4.76	3.84	5.91	3.19	5.54	26.48	3.4	4.27	3.68	3.16
Eu	8.36	12.12	6.75	12.11	8.83	14.93	25.16	8.58	19.95	11.51	11.36	14.52	9.96	13.77	62.44	9.92	10.25	17.18	15.57
Ga	13.6	10.8	11.1	12.8	12.1	9.6	12	15.3	15.9	12.4	12.1	10.8	12.6	16.3	20.9	12.8	12.4	9.4	7.8
Gd	22.74	33.55	18.85	32.85	23.48	42.63	71.79	25.74	53.82	32.96	31.39	41.37	26.73	40.05	176.41	26.77	28.55	38.52	34.23
Hf	13.13	11.34	9.05	13.18	9.4	7.07	10.25	12.37	13.54	10.73	12.19	9.42	10.9	13.3	15.77	10.88	11.26	11.5	10.6
Ho	1.4	1.92	1.21	1.81	1.08	2.88	4.72	1.81	2.57	2.16	1.71	2.83	1.38	2.38	11.12	1.44	1.79	1.64	1.56
La	414.3	423.7	259.9	483.1	388.1	210.3	679.5	255.4	839.6	348.7	466.3	349	464.5	578	2517	430.3	429.7	695.4	561.5
Lu	0.3	0.3	0.26	0.31	0.18	0.28	0.39	0.32	0.31	0.33	0.26	0.29	0.24	0.4	1.99	0.28	0.27	0.28	0.25
Mo	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<0.1	0.1
Nb	304.96	286.66	150.37	364.61	244.89	118.53	421.2	155.8	638.44	177.11	311.34	210.58	291.43	346.08	>1000	330.09	266.48	450.2	478.8
Nd	293.5	372	215.2	400.8	307.9	297.2	652.7	227.2	704.1	303.6	369.3	344	351.3	460.5	2421	344.2	332.3	550.5	481.5
Ni	233	170	155	175	267	132	205	204	339	742	658	550	217	787	437	179	327	189	142.3
Pr	83.33	99.68	59.16	108.66	84.24	67.4	166.97	59.13	193.96	76.98	101.48	85.49	97.02	124.38	649.27	95.31	91.36	158.58	134.12
Rb	100.7	83.7	82.7	89.4	83.8	61	50	110.6	66.9	93.5	84.7	65.4	79.4	114.1	44.8	103.3	88.4	77.6	52.7
Sm	38	53.2	29.9	54.3	40.1	55.4	101.3	35.2	92.2	47.3	50.5	56.8	45.7	61	280.9	45.9	45.3	71.18	62.37
Sn	3.6	2.9	1.6	3.3	2.4	0.8	2.9	2.1	5.7	1.9	3.1	2.5	2.7	3.1	8.3	3	2.9	4	3
Sr	978	1148	830	976	1034	1634	2166	952	587	1425	1146	1360	1002	481	611	1125	1094	1312.1	905.6
Ta	19.68	19.3	8.96	20.66	18.57	6.97	27.81	7.99	48.27	11.71	20.75	14.04	20.7	22.39	74.54	18.31	18.45	35.7	44.1
Tb	2.33	3.52	2	3.37	2.26	4.88	8.02	2.77	5.38	3.59	3.14	4.76	2.66	3.93	18.04	2.69	2.95	3.57	3.41
Th	46.9	53	28.3	63.6	45.8	25	79	23.5	118.9	39	51.3	36.6	50.8	62.9	216.4	62.6	47.9	82.8	95
Tl	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.1	<0.1
Tm	0.38	0.41	0.33	0.42	0.24	0.54	0.83	0.45	0.51	0.47	0.4	0.51	0.33	0.57	2.77	0.37	0.42	0.38	0.4
U	2.76	4.22	2.72	5.21	2.56	1.89	4.09	2.65	9.82	2.45	3.33	2.87	3.67	4.01	15.64	4.88	2.49	3.5	6.5
V	143	164	79	173	122	121	314	92	337	89	169	219	156	259	604	137	156	234	312
W	13.6	88.2	57.8	47.3	88.8	85.8	16.8	9.7	23.5	6.4	21.7	51.1	79.7	172.9	56.9	48.9	28.7	9	4.4
Y	32.21	40.5	30.02	38.54	22.85	57.1	91.48	45.23	55.5	50.45	37.32	58.63	30.51	94.94	376.19	32.6	57.04	39	35.5
Yb	2.4	2.3	2	2.4	1.4	2.6	3.9	2.6	2.8	2.7	2.2	2.7	1.9	3	15.5	2.2	2.2	2.23	2.43
Zn	96	68	59	95	77	40	80	76	142	67	87	70	76	143	160	87	93	73	58
Zr	504	401	314	506	367	241	356	485	515	405	442	333	405	550	573	474	445	469.7	429.9

(1917, *in* Freyberg 1934) linked to kimberlite-picritic eruptive events and chrono-correlated with the Uberaba Formation. On the other hand, Batezelli and Ladeira (2016) suggest that the Capacete Formation is chrono-correlated with the Marília Formation. The $^{206}Pb/^{238}U$ perovskite ages of kamafugites from the Mata da Corda Group generally cluster in the 80–81 and 75–76 Ma age interval (Sgarbi *et al.* 2003). Thus, the Mata da Corda Group could be a correlative to the Uberaba Formation. This hypothesis needs to be checked by further geochronological studies.

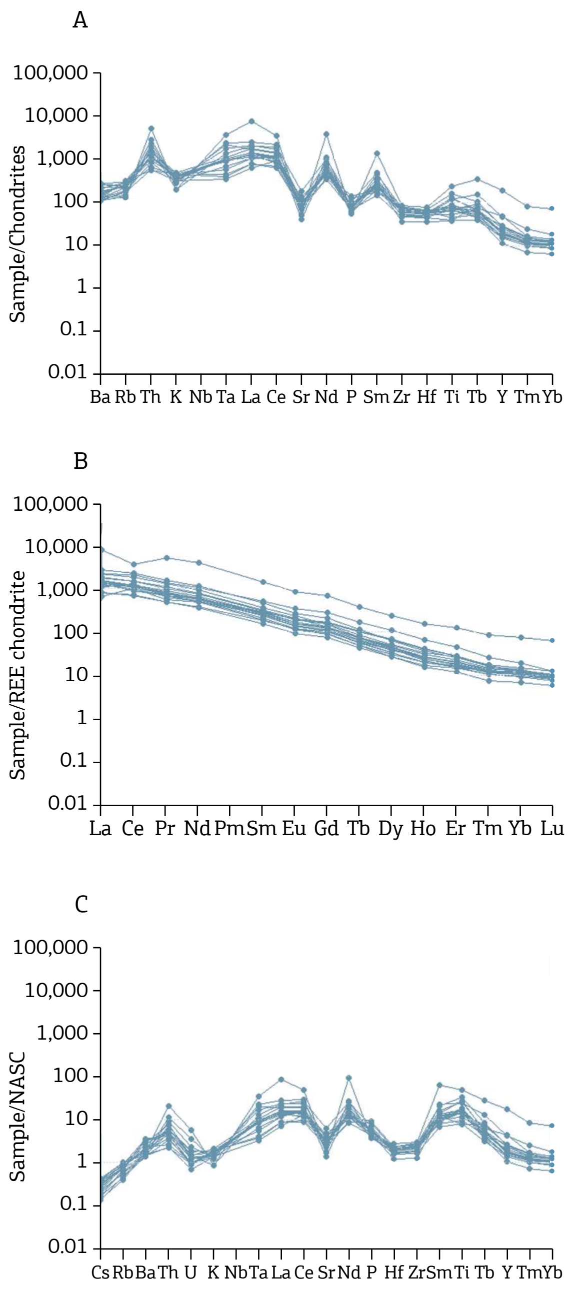
We also discuss the probable chrono-correlation of the Uberaba Formation with the diamond-bearing conglomerates of the Romaria region, which outcrops 95 km to the northeast of Uberaba, in isolated channels carved in the basement. The conglomerates of the Romaria region are very important diamond producers, having yielded thousands of carats, including large stones. The company GAR Mineração, Comércio, Importação e Exportação LTDA. explores diamonds in the so-called Tauá conglomerate of Romaria since 2014. Some authors have proposed that this conglomerate is chrono-correlated to the Uberaba Formation, but this hypothesis remains to be proved (Ferreira Jr. 1996, Gravina *et al.* 2002).

According to Bizzi *et al.* (1991, 1993), alkaline rocks of distinct ages occur in the AP, based on Rb-Sr phlogopite ages: Santonian (117–119 Ma) and Aptian (87–86 Ma). According to Huene (1939), the Uberaba Formation was deposited during the Campanian, ca. 80 Ma ago. Thus, this unit is contemporaneous or slightly younger than the alkaline-carbonatitic intrusion of the AP.

The anomalous concentration of clinopyroxene, plagioclase and Ti-bearing minerals in the Uberaba Formation lithic sandstones seems to be related to the erosion of the Serra Geral Formation, while schist and quartzite fragments are mostly related to the erosion of the Canastra and Araxá groups. Indeed an important component of erosion from the nearby basement, without considerable transport and sorting, is suggested by the subangulous clasts with medium sphericity.

The mineral chemistry of the Uberaba Formation detrital garnets and phlogopites are shown in Figs. 14 and 15, and compared with similar minerals in the alkaline complexes (Barbosa 2009, Brod *et al.* 2013) of the AP, along with mineral chemistry of samples from the Romaria region (Coelho 2010).

Chemical analyses of the detrital garnets of the Uberaba Formation indicate the presence of Ti-rich andradite, which is a common mineral in alkaline rocks (Keep & Russell 1992). This garnet variety is present in the Tapira (Brod 1999, Eberhardt 2014) and Salitre (Barbosa 2009) complexes. Fig. 14A shows a plot of Mg/(Mg+Fe) × Ca/(Ca+Mg) in garnets (Schulze 2003), and the corresponding fields of crustal *versus* mantellic garnets. Most of the garnets from Romaria show a mantle affiliation, while the Uberaba Formation and alkaline complexes garnets are mainly crustal. Fig. 14B shows a Mg/(Mg+Fe) × Cr_2O_3 plot (Schulze 2003), in which most garnets of the Romaria conglomerate shows a peridotitic



REE: rare earth element; NASC: North American Shale Composite.

Figure 10. Whole rock geochemistry plots for samples of the Uberaba Formation: (A) trace elements, chondrite-normalized after Thompson (1982); (B) REE, chondrite-normalized after Boynton (1984); (C) REE, NASC-normalized after Taylor and McLennan (1995).

composition, while those from the Uberaba Formation and alkaline complexes are more like eclogitic garnets.

Studies of garnet chemistry by Dawson and Stephens (1975), Grütter (1998) and Grütter *et al.* (2004) led to a classification based on the CaO and Cr_2O_3 contents in 13 groups (G0 to G12) (Fig. 14C). G0 corresponds to garnets of dubious origin. G1 and G2 are brown megacrystals; G3, G4, G5, G6 and G8 are garnets from eclogite xenoliths; G7, G9, G11 and G12 are from lherzolite xenoliths; G10 are garnets from harzburgite and possibly diamond-bearing rocks. In the diagram of Fig. 14C (Grütter *et al.* 2004), garnets from Romaria are mostly within the G9 (some within the G10) group, i.e., lherzolite-derived. Garnets from the Uberaba Formation and from the alkaline complexes, on the other hand, show significative quantities of Fe, Ca and Mn (ca. 1%), and low Cr, localized in the G3 field, from eclogitic xenoliths.

Plotting the mica analysis in a Mg × Fe × Ca diagram (Fig. 15a) makes possible the classification of the phlogopites. The small differences with respect to the phlogopite-annite series are due to the high Ti concentrations (mean 1.48%). A similar situation is observed for the phlogopites of the Tapira (Brod *et al.* 2001) and Serra Negra (Grasso 2010) complexes (Fig. 15A). In a Fe × Mg plot (Fig. 15B) the samples plot within the alkaline complexes trend. A subordinate substitution of Mg to Fe can be identified in this plot. According to Cordeiro *et al.* (2010), this substitution occurs in the Catalão I Complex and indicates distinct zoning patterns in the micas of the different rocks of the complex. The compositional variation of the Al_2O_3 and TiO_2 grades in micas, plotted in Fig. 15C, reflects the high grades of TiO_2 and low Al_2O_3, a signature that is similar to the one of the alkaline complexes.

Finally, a Ti × [Fe/(Fe+Mg)] diagram (Fig. 15D) shows the high Ti grades in analyzed phlogopites. This is accompanied by a raise in Fe/(Fe+Mg), a pattern which is very similar to that of phlogopites of the AP alkaline complexes.

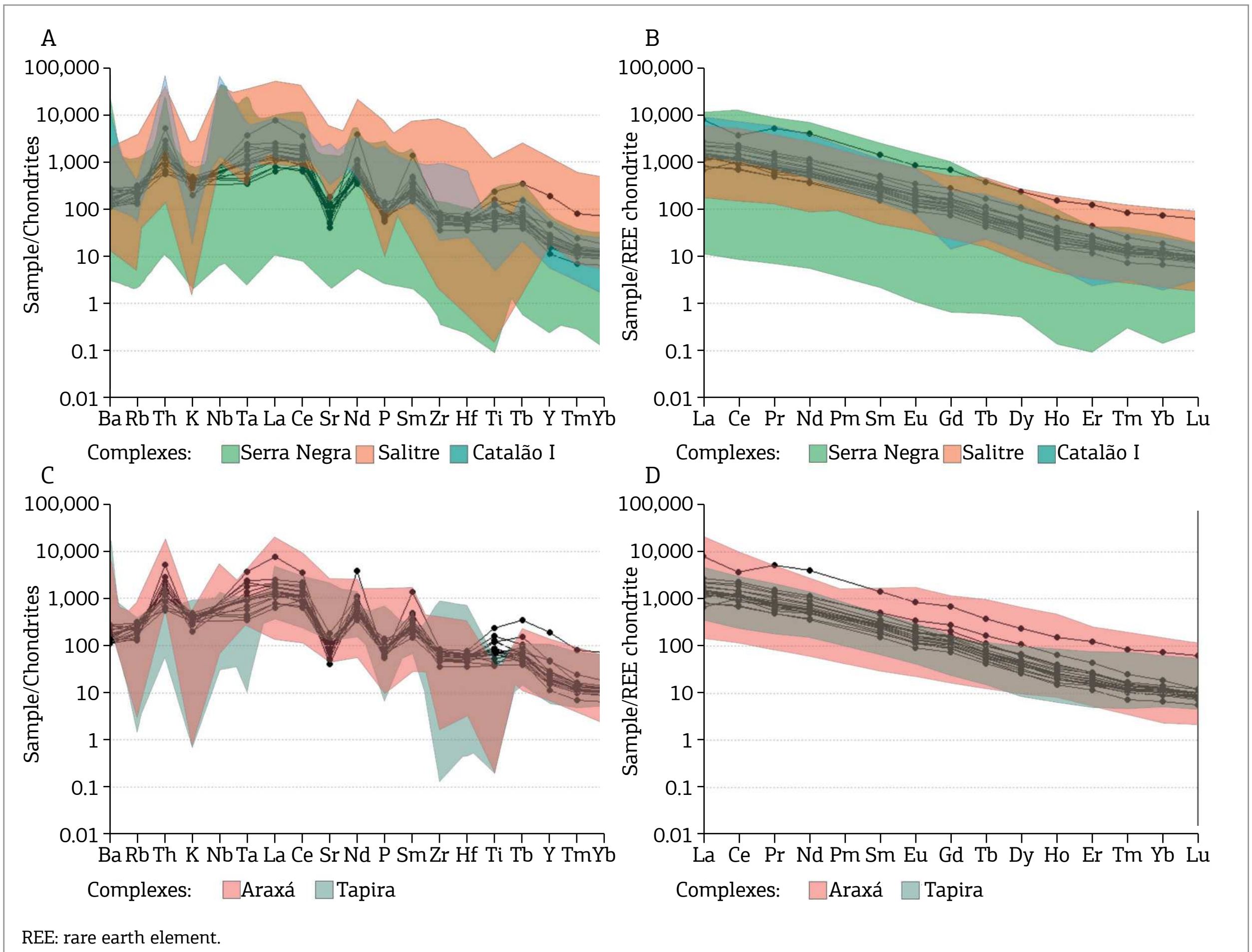


Figure 11. Compared whole rock geochemistry of the Uberaba Formation (line graphics) and AP alkaline complexes: (A) trace elements and (B) REE, chondrite-normalized after Thompson (1982) for the following alkaline complexes: Serra Negra (Grasso 2010), Salitre (Barbosa 2009) and Catalão I (Cordeiro *et al.* 2010); (C) trace elements and (D) REE, chondrite-normalized after Boynton (1984) for the following alkaline complexes: Araxá (Traversa *et al.* 2000) and Tapira (Brod *et al.* 2013).

Whole rock chemistry analyses of the Uberaba Formation sandstones also suggest a high influence of the alkaline complexes as source areas. This is mainly expressed in the high overall REE concentrations, heavily fractionated LREE, flat REE chondrite-normalized patterns (no Eu anomaly), Ta-Nb positive anomalies, and high Ti and Th concentrations from perovskite, a rare mineral in detrital rocks, but common in alkaline complexes.

The complexes of Serra Negra, Catalão I, Salitre, Araxá and Tapira share all of those characteristics, with high REE concentrations, fractionated LREE, Nb-Ta positive anomalies, etc. (Fig. 11). The smaller complexes, such as Catalão I, Araxá and Tapira, show little variation of the element concentrations resulting in limited fields in the plots (Fig. 11). The larger complexes, such as Serra Negra and Salitre, on the other hand, show a greater variability, leading to broader plotting fields (Fig. 11A and B).

Thus, between the studied complexes, the ones that most closely resemble the geochemical patterns of the Uberaba Formation are those of Catalão I and Tapira (Fig. 11C and D). The main difference is the negative Sr anomaly of the Uberaba Formation, which might be related to the leaching of this element

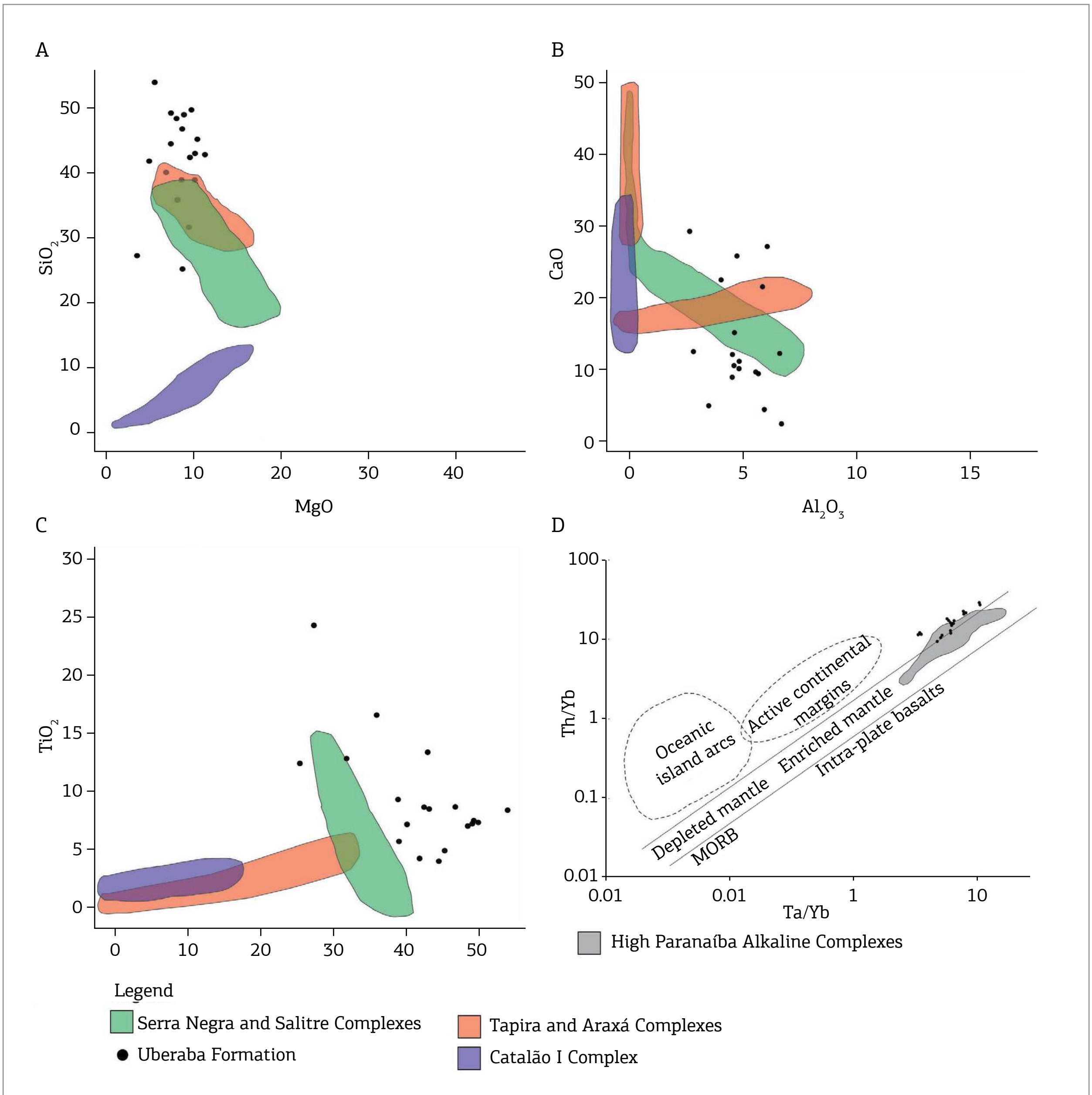


Figure 12. Geochemistry diagrams comparing the Uberaba Formation with AP alkaline complexes, in (A) $SiO_2 \times MgO$, (B) $CaO \times Al_2O_3$, (C) $TiO_2 \times SiO_2$ and (D) (Th/Yb)/(Ta/Yb).

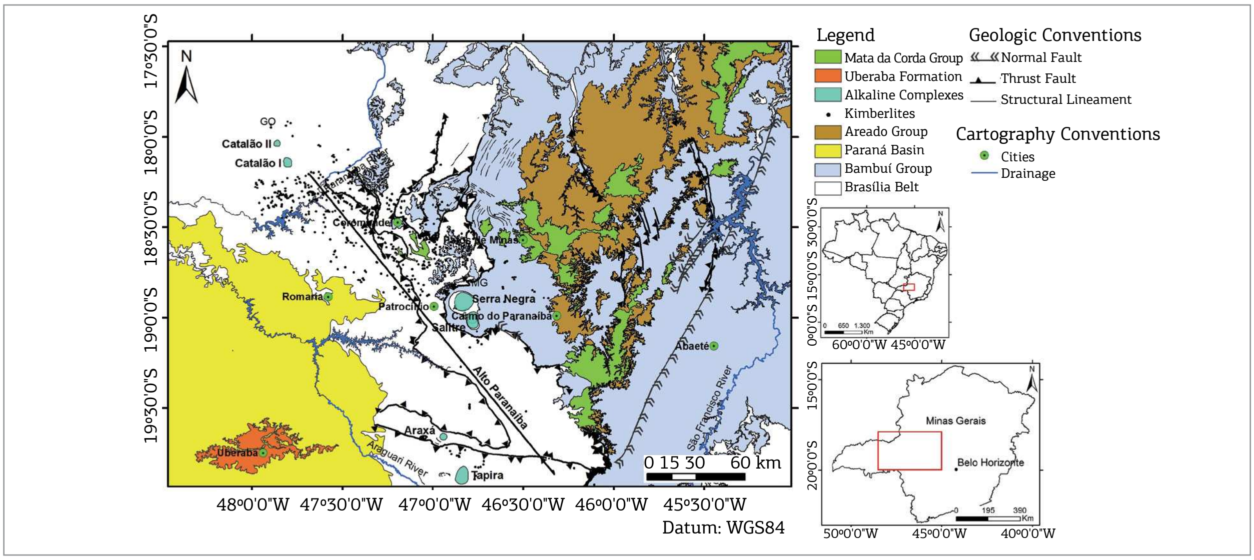


Figure 13. Geologic map of the AP (Alto Paranaíba). Adapted from Oliveira *et al.* (2004), with the locations of the alkaline complexes and the distribution of the Uberaba Formation.

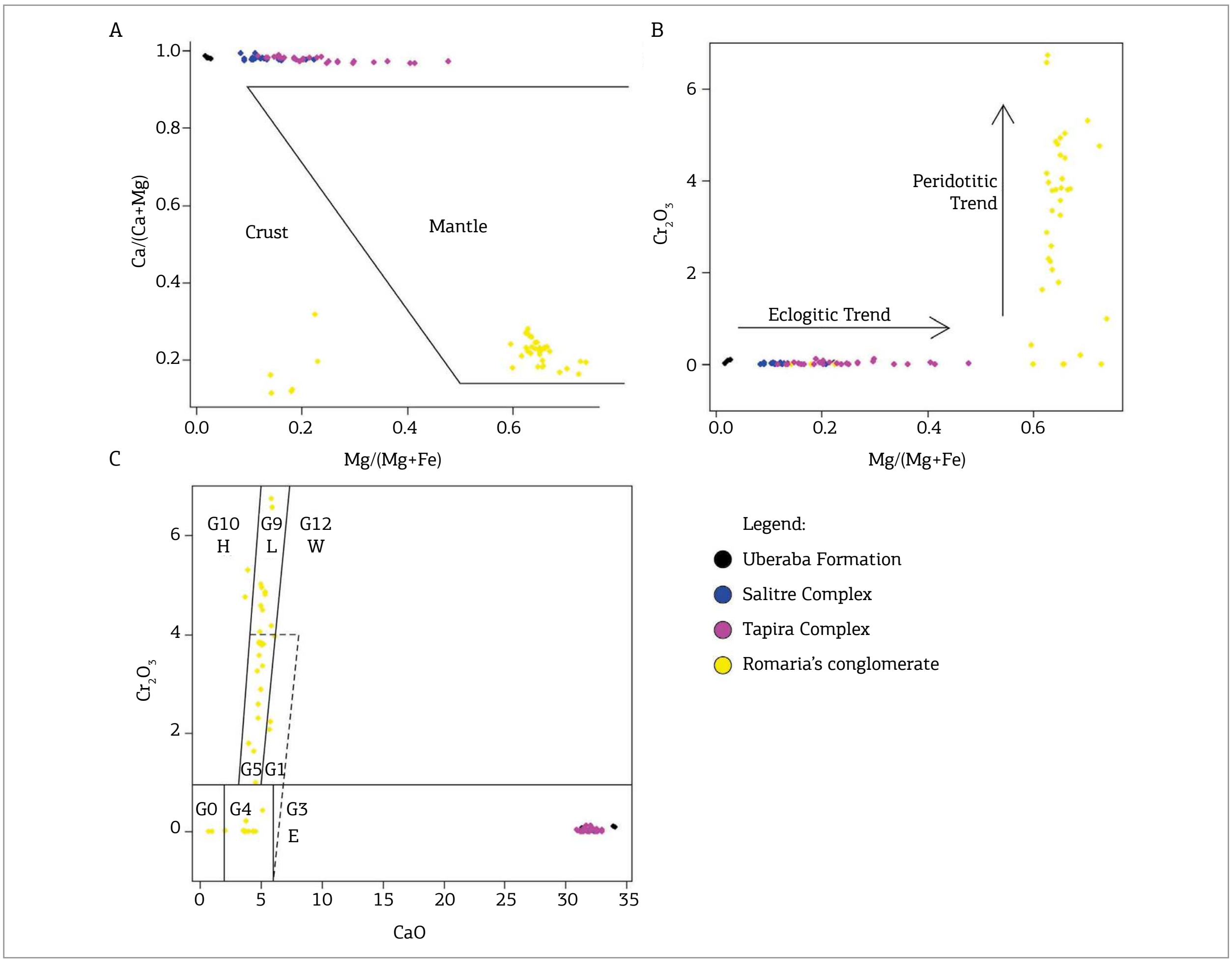


Figure 14. Mineral chemistry binary diagrams of garnets from Uberaba Formation comparing with garnets from alkaline complexes and from Romaria's diamantiferous conglomerate (Tauá): (A) [Mg/(Mg+Fe)] × [Ca/(Ca+Mg)] diagram after Schulze (2003) separating mantle-affiliation and crust-affiliation garnets; (B) Mg/(Mg+Fe) × Cr_2O_3 diagram after Schulze (2003) classifying garnet's evolutionary trends and (C) CaO × Cr_2O_3 diagram after Grütter *et al.* (2004) classifying garnet's provenance, H: harzburgite, L: lherzolite, W: werhlite and E: eclogite). Salitre mineral chemistry analysis from Barbosa (2009), Tapira from Brod *et al.* (2013) and Romaria from Coelho (2010).

during the carbonatic/dolomitic cementation. On the other hand, enrichment in Ti and Th is related to detrital perovskite.

According to Mitchell (1986), garnets are important indicators in the identification of kimberlites and their magma sources. The results obtained for detrital garnets of the Uberaba Formation confirm the presence of andradite garnet, of the schorlomite variety, which is rich in Ti, thus not indicating a kimberlitic source, as suggested by the plotting of the garnets in the eclogitic xenolith field in Fig. 14B. The contrary is observed in Romaria pyrope garnets, which indicate a kimberlitic source. Compared to the diamond-bearing conglomerates of Romaria, the Uberaba Formation provenance and sourcing is quite distinct (Fig. 14C).

CONCLUSIONS

According to the stratigraphic, petrographic, mineral chemistry and whole-rock geochemical data gathered for the Uberaba Formation, three main source areas can be

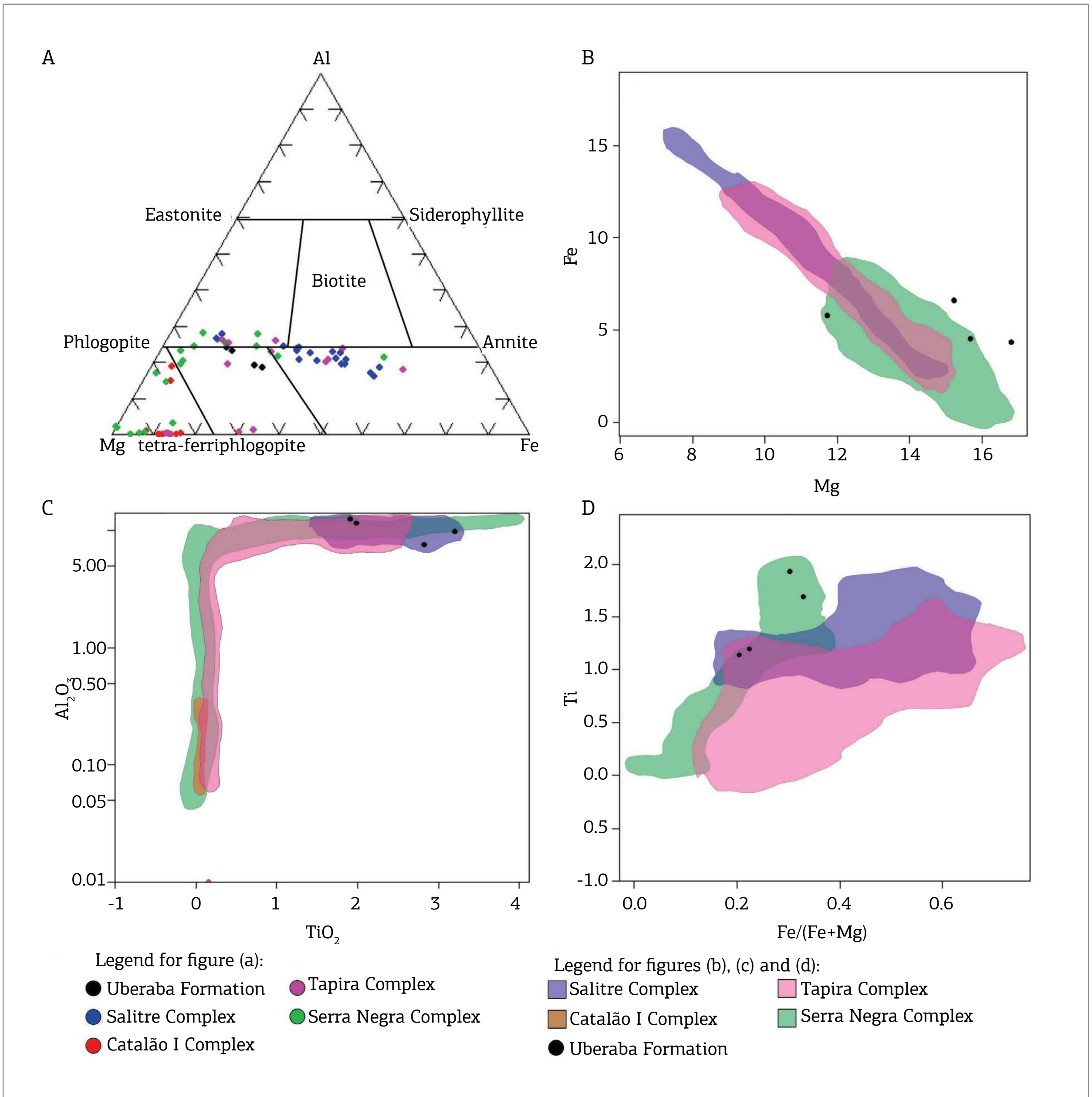


Figure 15. Mineral chemistry binary and ternary diagrams of phlogopites from the Uberaba Formation compared to phlogopites from some alkaline complexes of the AP: (A) Mg × Fe × Ca ternary diagram of micas classification; binary diagrams comparing phlogopites chemistry according to (B) Fe × Mg, (C) Al_2O_3 × TiO_2 e (D) Ti × [Fe/(Fe+Mg)].

recognized for the provenance of the lithic sandstones and conglomerates of this unit, which probably represents a braided fluvial system:

1. Precambrian rocks of the Araxá and Canastra groups;
2. basalts of the Serra Geral Formation;
3. alkaline rocks of the Catalão I, Catalão II, Serra Negra, Salitre, Tapira, and Araxá cretaceous intrusions and others similar rocks.

All of those units are exposed in the AP Arch, a basement high to the east of the Uberaba Formation outcrop area, which has been active during the Cretaceous.

The chemical composition of the Uberaba Formation rocks, which is very similar to that of the alkaline complexes (highly fractionated REE with La_N/Yb_N = ca. 128; positive Nb-Ta and Ba anomalies), and abundant detrital perovskite, suggests that the third source area was somewhat preponderant over the other two ones. The unit might also involve some syn-sedimentary volcanic or volcanoclastic activity as suggested by a greenish very fine matrix in some samples and fragments of quartz with corroded gulfs.

The chemical analysis of perovskite, garnet and phlogopite confirms that those minerals show similar composition as those ones found in the alkaline complexes of the AP. Garnets of the Uberaba Formation are mainly schorlomite, a Ti-rich variety of andradite, and plot in the field of eclogitic xenoliths (crustal garnets) in discriminatory diagrams. Thus, the unit is not prone to bear detrital diamond grains, as garnets are not indicative of a kimberlitic (mantellic) affiliation.

A chronocorrelation of the Uberaba Formation and the Mata da Corda Group, of around 80–75 Ma (Sgarbi *et al.* 2003) can be considered for investigation. The diamond-bearing Romaria conglomerate, however, shows a very distinct provenance pattern, bearing pyrope garnets which fall within the kimberlitic field in discriminatory diagrams. Thus, the Uberaba Formation is probably not correlated to the Romaria conglomerate. The geochemical and mineral chemistry features suggest that the Uberaba Formation was not a likely source for alluvial diamonds of the southeastern TM region. Thus, the quest for the source of those diamonds remains open.

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