3D Inversion and Interpretation of Geophysical Anomalies Related to the Tapira Alkaline Complex- MG

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Abstract

The Tapira Alkaline Complexis the southernmost of a series of intrusions containing carbonatites in the Alto Paranaíba region, MG. The gammaspectrometric and magnetometric data used for this study are from aerosurveys acquired by CODEMIG on the so called 'Area 7'. Reduction to the Pole and Anomalous Magnetic Field Amplitude methods were applied to the aeromagnetic data, aiming to minimize or to attenuate the remanent component before performing 3D inversion. The 3D models were compared with the one obtained by the inversion of the ground gravity data achieved for the alkaline. The gammaspectrometric data were used to identify the signature of the main structures in the studied region, so as to analyze the radiometric response of the alkaline's outcrops.

Introduction

In this work the gammaspectrometric response of Tapira Alkaline Complexis analyzed and compared with the geological information of the region. Dickson and Scott (1997) show that outcrops of mafic and ultramafic rocks have uranium and thorium activity higher than the embedding rock, thus allowing easy identification of the alkaline's radiometric signature. Moreover, the intrusion is located in the Brasília Folding Belt, which is marked by the presence of a thrust fault, assigning a characteristic radiometric response for the region.

The deposits of magmatic origin were responsible for 10 to 20% of the world production of phosphate in the last 10 years (SOUZA, 2009). In addition of phosphate, the alkaline complexes have potential for exploration of niobium, titanium and rare earth elements (REE).

Because of its economic importance, once identified the presence of the body, the following step was to determine its volume and geometry in subsurface.

Since the magnetic response of Tapira alkaline presents a very strong remanent magnetization, three techniques that allow to minimize or to attenuate the influence of the magnetization direction in the data were applied and their results compared before the inversion. The techniques considered are: Reduction to the Pole (RTP) considering algorithms developed by Baranov (1957) and Fedi et al. (1994), and the Amplitude of the Anomalous Magnetic Field (AAMF) presented by Shearer (2005).

The 3D models obtained from the aeromagnetic data reduced by the cited methods were compared to the geological information and to the gravity model from the ground survey data (RIBEIRO, 2008), to choose the model that better represents the response of the intrusion in subsurface. Based on this the approximate volume of the intrusion and its depth were calculated.

Geology

According to Silva et al. (2006), in the region of Tapira, the Brasília Folding Belt shows four different lithotectonic domains, all of them thrust faulted and interlayered (Figure 1). The lower and upper layers are interpreted as structures derived from rocks originated in a distal continental platform, having as main source sediments from the San Francisco Craton of paleoproterozoic age. Rocks from the upper layer were originated from deposits of a continental slope or flat oceanic floor environment, being the Craton of San Francisco the sediments' source with paleo- and mesoproterozoic age. The overall metamorphism was not synchronous, which is expected for an overthrust system.

The Tapira Alkaline Complexhas an elliptical shape, and is composed by several intrusions of silicate plutonic-rocks and of carbonatites in a lesser amount (Figure 2).

According to Brod et al. (2005), two units of ultramafic rocks can be recognized in the Complex: B1 and B2. These autors also identified five episodes of carbonatite activity. The most recent intrusion (C1) occurs in region B1. The carbonatites of C2 are mainly related to the intrusion of syenites (S). C3 and C4 are lesser calcium-carbonatites intrusions. Dolomite-rich carbonatites are recurrent in the late-stage dykes (C5).

Using K-Ar method in muscovite, Sonoki and Garda (1988) obtained ages of 85.5 and 87.2 My placing the intrusion event in the Late Cretaceous.

Gravity Survey

Over the dome, the gravity stations were measured along the access roads and paths, being the distance between two measurements of about 1 km. In the adjacent areas (away from the center of the anomaly) the measurements were performed at 2 km from each other, and further at 4 km, in order to obtain a larger area to calculate the regional field.

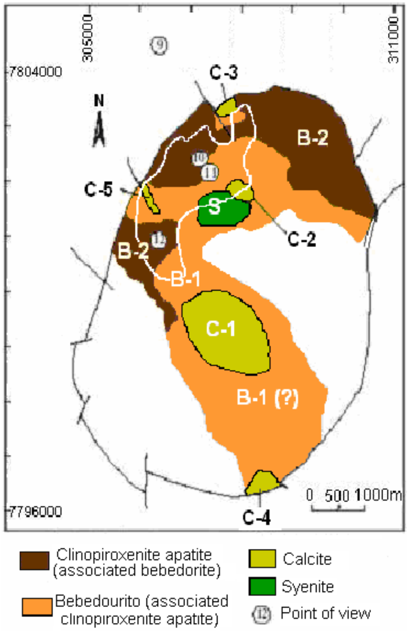

Figure 2. Geological sketch of the Tapira Alkaline Complex. Modified from Brod (2005).

A map with gravity stations measured along the study region is shown in figure 3.

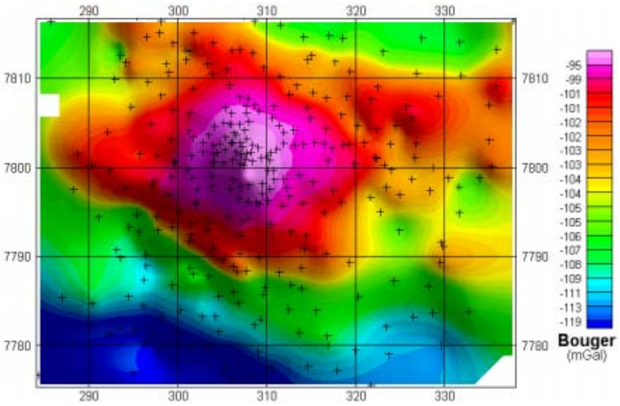

Figure 3. Complete Bouguer anomaly map with the distribution of stations (black crosses) measured along the studied area.

Aerosurvey

The aerosurvey performed by CODEMIG was flown at a height of 100m above the ground, with spacing between flight-lines and control-lines of 400m and 800m respectively.

The gammaspectrometric data were obtained considering four energy windows: potassium (1.37 to 1.57 MeV), thorium (1.66 to 1.86 MeV), uranium (2.41 to 2.81 MeV) and total count (concerning to the emission of gamma rays observed in the energy range of 0.41 to 2.81 MeV).

The gammaspectrometric data processing followed the procedure recommended by the International Atomic Energy Agency (IAEA, 1991). The gamma-ray spectrometry were corrected for aircraft and cosmic background, radon background, height discrepancies and Compton's effect.

The removal of the International Geomagnetic Reference Field (IGRF) was performed using the software routines included in Oasis Montaj 6.4.2 (Geosoft, 1994), which consist of the definition of trend surface representing the international geomagnetic field in the study area. To calculate this surface, a height of 1000 m was considered, referred to the year 2005 and updated for 2006 (year the aerosurvey was accomplished).

The magnetic data had also been corrected for diurnal variation and parallax error.

Method and Data Reduction

Gammaspectrometric Data

The main sources of gamma rays detected at earth's surface come from the natural decay of potassium (^{40}K) and the elements from uranium's (^{238}U) and thorium's (^{232}Th) series present in the composition of most rocks (Dickin, 1995). However, this emission can be detected only for a limited thickness of the superficial layer of rocks (about 30 to 40 cm), considering the density and loss of energy necessary for gamma rays traverse the rocks.

Each element is associated with a radiometric channel of energy. Gamma rays emitted from potassium (^{40}K) decay around the energy peak of 1.46 MeV. The isotopes ^{238}U and ^{232}Th do not emit gamma radiation; the concentration of these elements is estimated from the radiation released by the products of their radioactive decay: ^{214}Bi (uranium's decay) and ^{208}Tl (thorium's decay). The energies of these elements delineate peaks of 1.76 and 2.615 MeV respectively.

The ternary map resultant form the decay of these elements is shown in figure 4.

Gravity Data

The calculation of gravity anomalies at each station takes into account the measures of gravity, altitude, tidal effect (Longman, 1959), and the theoretical value of gravity calculated for the reference geoid. The free air anomaly (or Faye) is:

$$\Delta g_F = \Delta g_{obs} - \gamma(\varphi) + 0.3086.h \qquad (1),$$

where Δg_{obs} is the free air anomaly, Δg_{obs} the observed gravity, $\gamma(\varphi)$ is the value of reference's gravity defined by GRS67 (Geodetic References System 1967), φ the geodetic latitude and h the orthometric height of the gravity station.

The Bouguer anomaly (Δg_B) is defined by:

$$\Delta g_B = \Delta g_F - 0.1119.h \qquad (2).$$

The Bouguer anomaly corrected for the gravitational effect of topography is named Complete Bouguer Anomaly and is given by:

$$\Delta g_{BC} = \Delta g_B + C_R \qquad (3),$$

where C_R is the gravitational effect of topographic masses in gravimetric station, defined by:

$$C_R = G.\rho.\iint \left(\frac{1}{\sqrt{(x-x_0)^2 + (y-y_0)^2}} \right) dxdy -$$

$$- G.\rho.\iint \left(\frac{1}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + (h(x,y)-h_0)}} \right) dxdy \qquad (4),$$

for ρ as the mass density of the topographic relief, x_0 and y_0 are respectively the x and y coordinates of the gravimetric station, h_0 as the orthometric height of gravimetric station and h(x,y) as the orthometric height of the relief.

The map of Complete Bouguer Anomaly obtained for the Tapira Alkaline Complexis shown in figure 3.

To separate the regional-residual components of gravity field the method of polynomial fit developed by Beltrão et al. (1991) was applied. The filtered surface of regional data was performed with a robust polynomial of first degree (RIBEIRO, 2008). The map resulting from this filtering is shown in figure 5.

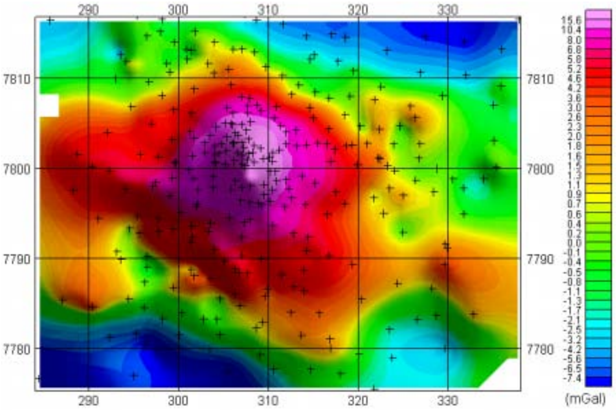

Figure 5. Residual Bouguer anomaly map with the distribution of stations (black crosses) measured along the studied area.

Magnetic Data Reduction

The magnetic field strength (H) is given by Am^{-1} (SI) being its unit value equivalent to the field generated in the center of a circular wire of radius r, through which passes a current i:

$$H = \frac{i}{2r} \qquad (5).$$

The magnetic permeability (μ) is given by the ratio between magnetic induction (B) an magnetic field (H), defined by (BLAKELY, 1995):

$$B = \mu.H \qquad (6).$$

The induced magnetization (M_i) is the response to charges of subatomic material (protons and electrons) due to an applied external field, and it is defined by:

$$M_i = \chi.H \qquad (7),$$

where χ is the susceptibility. In the absence of an external magnetic field, the induced magnetization is null. However, ferromagnetic materials can retain a magnetization even in the absence of external magnetic field. This magnetization is called remanent (BLAKELY, 1995). The total magnetization of a rock (M) is considered as the vector sum of induced (M_i) and remanent magnetization (M_r):

$$M = M_i + M_r \qquad (8).$$

The total magnetic field observed for the studied area is presented in figure 6.

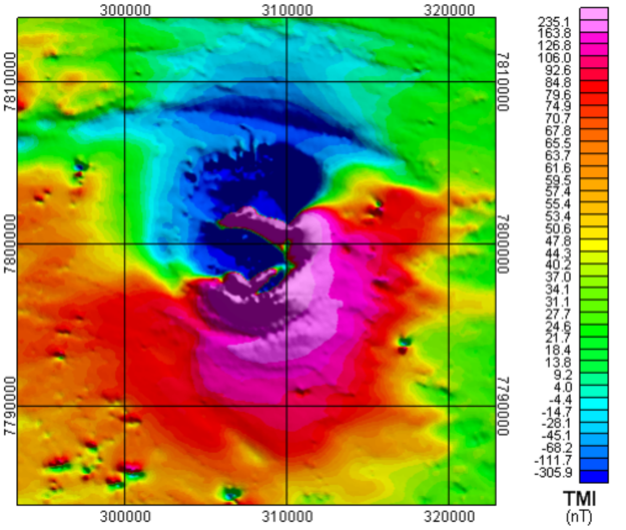

Figure 6. Map of total magnetic field observed for the studied area.

Anomalous Magnetic Field Amplitude

According to Shearer (2005), the Anomalous Magnetic Field Amplitude (AMFA) has a weak dependence of magnetization direction and, therefore, the difference of the remanent magnetization direction to the geomagnetic field's has little or no influence over its results. It's defined by:

$$B_a = \left\| \vec{B}_a \right\| = \sqrt{B_x^2 + B_y^2 + B_z^2} \qquad (9),$$

where B_x, B_y e B_z are the components of the magnetic field in the Cartesian coordinate system. The AMFA map is shown in figure 7.

Reduction to the Pole (RTP)

Reduction to the Pole (RTP), defined by Baranov (1957), use a filter operator that adjust the magnetic data to a state of vertical polarization, observed only in the magnetic poles. The formula used by Oasis Montaj 6.4.2 to this filtering is given by:

$$L(\theta) = \frac{[sen(I) - i.\cos(I).\cos(D-\theta)]^2}{[sen^2(Ia) + \cos^2(Ia).\cos^2(D-\theta)][sen^2(I) + \cos^2(I).\cos^2(D-\theta)]} \qquad (10),$$

where I is the magnetic inclination, I_a the slope of the amplitude correction, D is the magnetic declination and θ is the direction of the wave number.

However, according to Cooper and Cowan (2005), RTP produces errouneous results when applied to magnetic anomalies with remanent magnetization of unknown direction. As alternative, this filtering was calculated through an algorithm developed by Fedi et al. (1994). In the last one, the total inclination and declination (I_M, D_M) can be calculated from an RTP operator for different combinations of inclination and declination (IT, DT), observing the variation of the anomaly as defined in function of these.

Map resultant from this method is shown in figure 8.

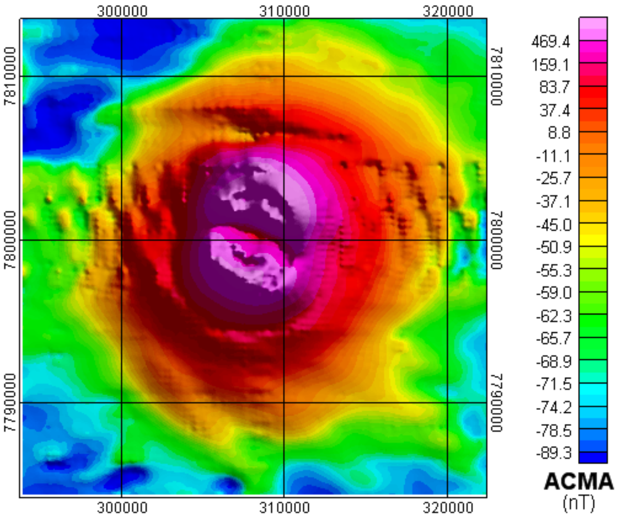

Figure 7. Anomalous Magnetic Field Amplitude map.

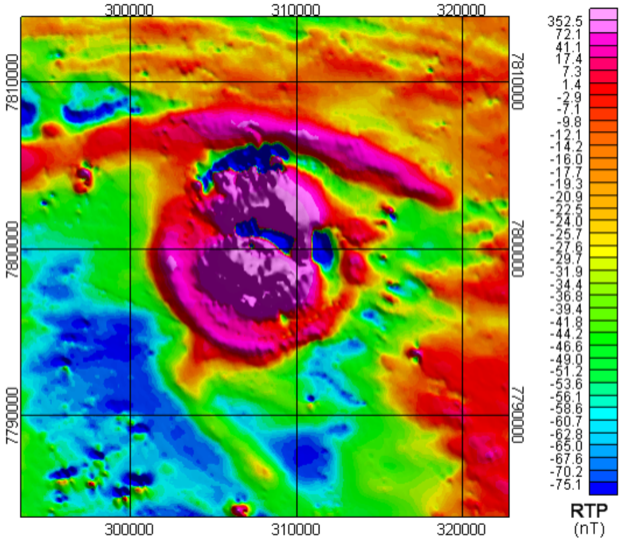

Figure 8. Reduction to the magnetic pole map calculated by algorithm developed by Fedi et al. (1994).

Inversion of Gravimetric and Magnetic Data

The 3D model composed from gravity and magnetic data are shown in figure 9, 10 and 11. The MAG3D (2002) and GRAV3D (2002) software, developed by Geophysical Inversion Facility (GIF) at University of British Columbia (UBC), were used to perform these inversions. Figures 12 and 13 show the superposition of the 3D magnetic models with that obtained by the inversion of gravity data.

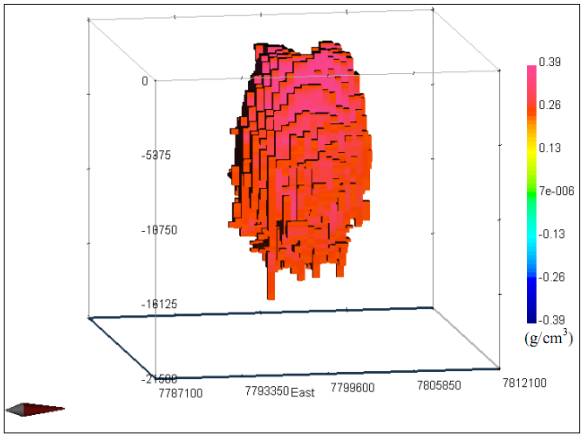

Figure 9. 3D model of density distribution obtained by the inversion of gravity data.

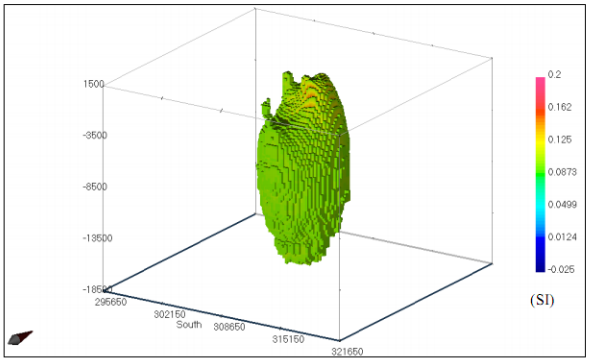

Figure 10. 3D model of susceptibility distribution obtained by the inversion of AMFA data.

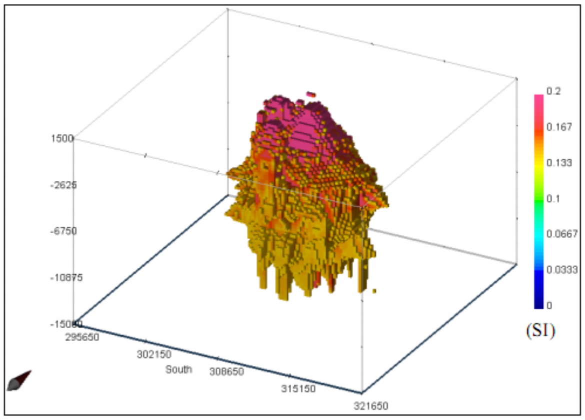

Figure 11. 3D model of susceptibility distribution obtained by the inversion of RTP data.

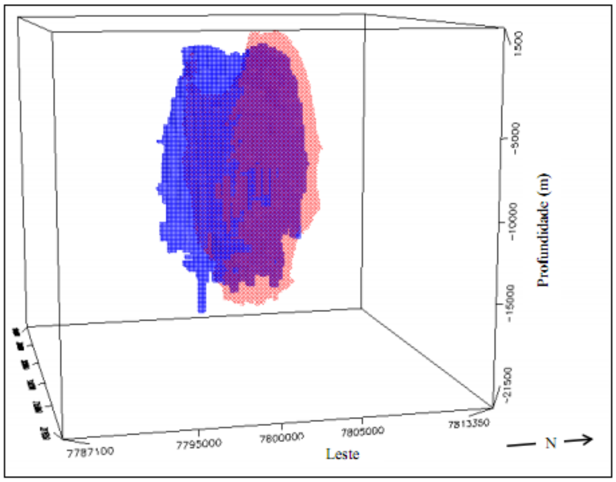

Figure 12. Superposition of the 3D model generated by the inversion of AMFA (red) and gravity data (blue).

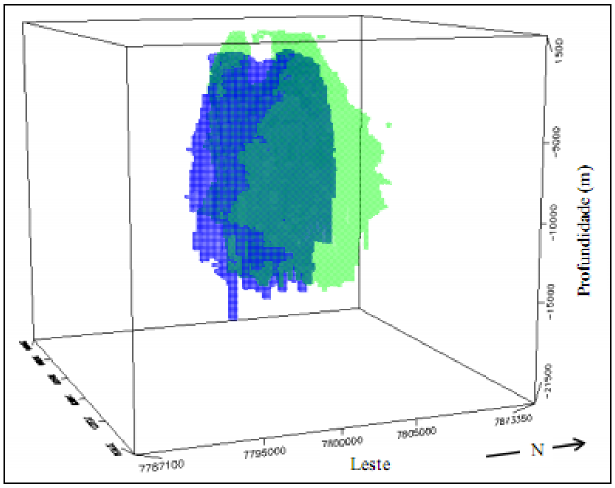

Figure 13. Superposition of the 3D model generated by the inversion of RTP (green) and gravity data (blue).

Table 1 shows the main properties of the models produced by the inversion of gravity and magnetic data.

Results and Conclusions

Comparing the ternary map with the local geology map it is possible to identify the gammaspectrometric response associated with the main surface lithologies of the region.

The ternary map shows an anomaly with high counts of thorium and uranium associated with Tapira alkaline.

The gamma ray spectrometry method allows to identify points associated to the Phanerozoic cover at east of the intrusion, not indicated in the geological map. To confirm this observation *in situ* observations are required.

Table 1. Properties of the models produced by the inversion of gravity and magnetic data.

	AMFA	RTP	GRAVITY
Depth (km)	17.0	16.0	16.5
Volume (km^3)	639.81	660.69	622.99
Susceptibility (SI)	0.117	0.145	-
Density (g/cm^3)	-	-	0.26

The average density observed for the pyroxenite is of 3.0 g/cm^3, while the carbonatite is about 2.71 g/cm^3 (RIBEIRO and MANTOVANI, 2008). The density assigned to the embedding rock is 2.67 g/cm^3.

The range for density contrast found by gravity model (Figure 9) between the intrusion and the embedding rock is 0.26 to 0.39 g/cm^3, which is consistent with the expected value by the literature.

The susceptibility expected for the embedding rock ranges between 0.01 to 0.05 (SI), while for pyroxenite it is approximately 0.125 (SI – TELFORD et al., 1990). The inversion through the AMFA and RTP methods supplied values of susceptibility contrast of 0.117 and 0.145, respectively.

Comparing the depth values and the volume obtained by gravity and magnetic models, and observing the superposition of 3D models, it is possible to conclude that the magnetic method which obtained the best approximation of the subsurface behavior was the AMFA.

The RTP method implemented by the Fedi et al. (1994) algorithm probably would present a better response to the reduction of the field if applied to a case were the remanent magnetic anomaly has a simpler arrangement.

Acknowledgments

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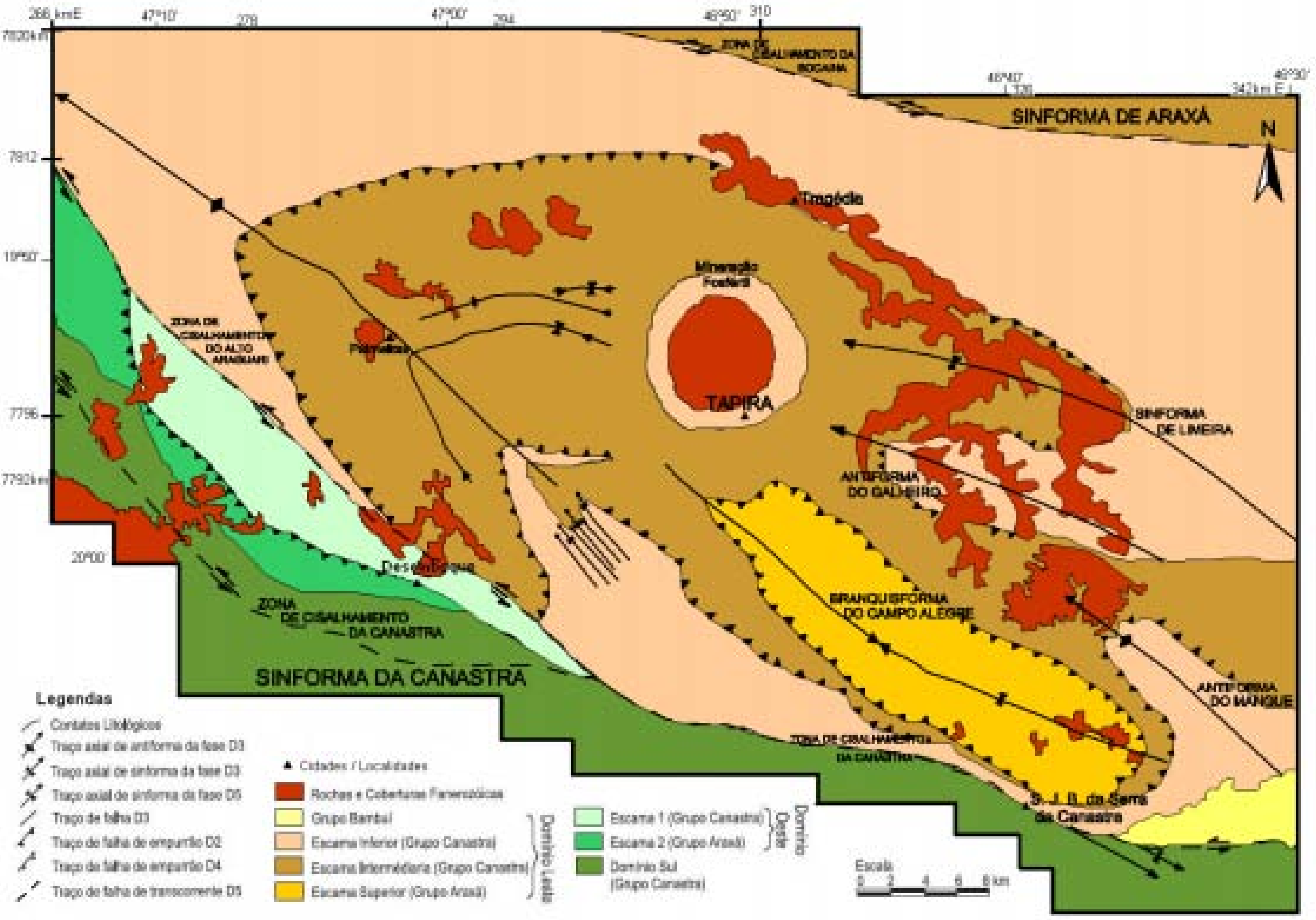

Figure 1. Geological map of the Tapira region, Minas Gerais. Modified from Silva (2003).

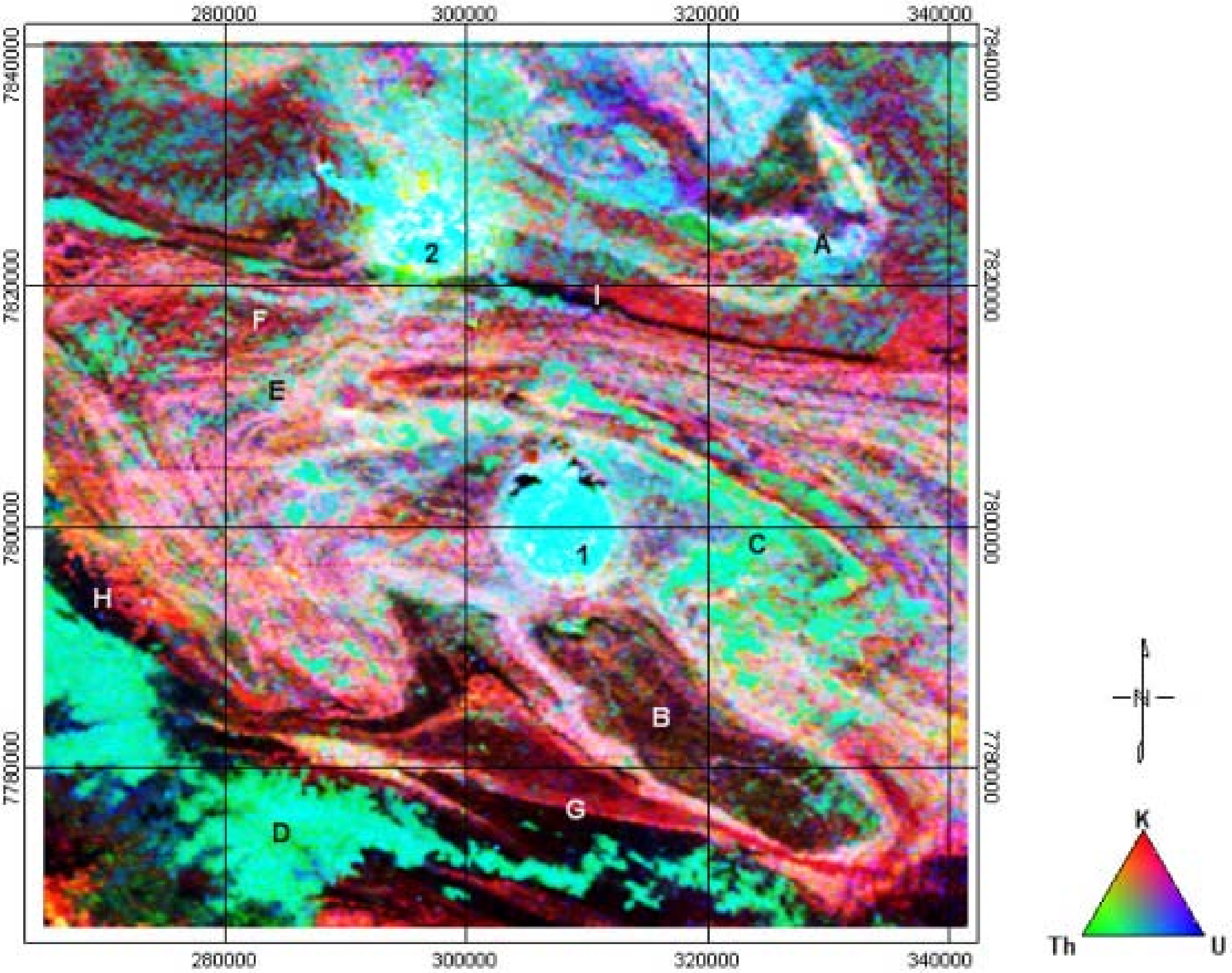

Figure 4. Ternary radiometric map with color (R,G,B) = (K, Th, U). The indices 1 and 2 show the location of the Tapira and Araxá alkaline complexes, respectively. A – Araxá synform, B – upper scale Canastra Group, C and D – Phanerozoic cover, E – intermediate scale and F – lower scale of Canastra Group, G – Shear zone of Canastra, H – Shear Zone of Alto Araguari, I – Bocaina Shear Zone.