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Gravity Data Support for Large-Scale Silicate Liquid Immiscibility in the Triunfo Batholith, Northeastern Brazil

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Abstract

The Triunfo batholith, located in the Transverse Zone of Borborema Province in northeastern Brazil, consists of ultrapotassic alkali-feldspar syenite containing comagmatic alkali pyroxenite inclusions, and cut by synplutonic alkali pyroxenite dikes. Field, chemical, mineralogical and isotopic studies on rocks of this batholith have led to the hypothesis that coexisting syenite and pyroxenite melts were produced by large-scale liquid immiscibility from a parent mafic syenitic magma. A model for the spatial distribution of the unmixed syenitic and pyroxenitic melts proposed that volumetrically subordinate but denser pyroxenite underlies the main syenite body.

In this study, three gravity traverses along the major and minor axes of the batholith were carried out. The spatial distribution hypothesis was tested using direct and inverse gravity modeling, which suggested that a 200 m thick pyroxenite layer with a total width of 8.5 km forms the base of the batholith whose geometric form is intermediate between that of a laccolith and a lopolith.

Introduction

MANY PETROGENETIC studies do not take into account the volume and architecture of the pluton, or the form of magma emplacement in relation to the host rocks and associated structures. The basic shape of a pluton can indicate the number of conduits involved in the filling of the magma chamber, whereas the study of the emplacement form relative to the host rocks or structures can help in the understanding of the intrusion process. These parameters can be investigated using direct methods, such as stratigraphic drill holes, or indirectly, using geophysical methods. The use of gravity methods requires a density contrast between the intrusive bodies and their host rocks that affects the gravity values.

This study presents and discusses gravity data for the Neoproterozoic Triunfo syenite, a pluton that intruded metamorphic rocks of the Alto Pajeú foldbelt in the Transverse Zone of Borborema Province, northeastern Brazil. The data were used to test the hypothesis that the exposed syenitic pluton is underlain by a denser pyroxenite layer, formed by liquid immiscibility from a mafic syenite magma, as suggested by Ferreira et al. (1994). The large area of exposure (~600 km^2), excellent outcrops, relatively homogeneous lithological composition, and possible presence of a denser pyroxenitic body hidden at the base of the intrusion make it an ideal target for geophysical investigation and modeling. This study aims to model the shape, internal structure, and emplacement mode of the Triunfo batholith, and hence to test the hypothesis that large-scale liquid immiscibility has was the main process responsible for the formation of the coeval syenite and pyroxenite.

The Triunfo Batholith

The 572 Ma-old Triunfo batholith (Ferreira et al., 1994) is a well-exposed pluton intrusive into gneisses along its eastern border, a high-K calc alkalic granitoid at its northern contact, and low-grade metapelites on its western portion, next to the contact between the Alto Pajeú and Riacho Gravatá terranes of northeastern Brazil (Fig. 1). Petrological studies (Ferreira and Sial, 1993; Ferreira et al., 1994) revealed two unique characteristics: it is the largest known ultrapotassic pluton in Borborema

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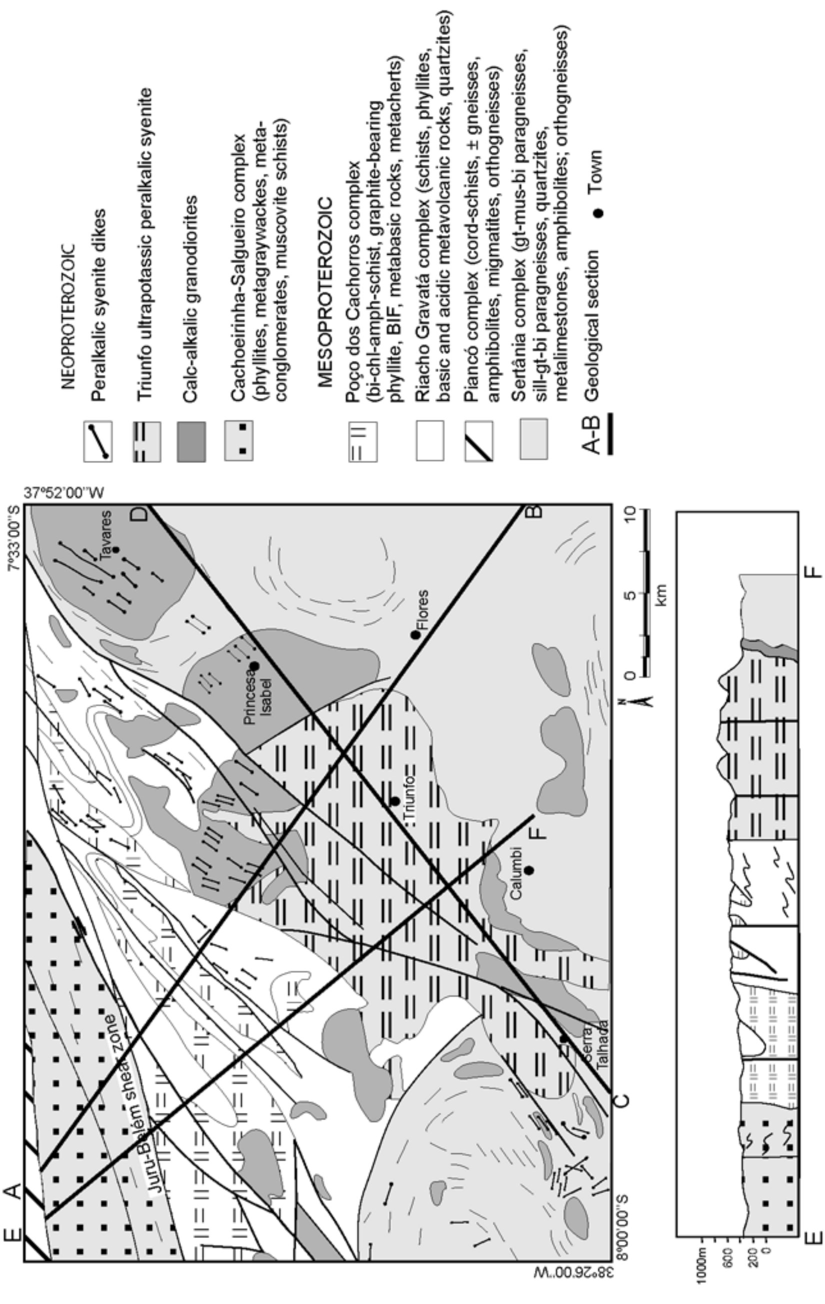

FIG. 1. Geologic map of the study area, modified from Gomes (1999).

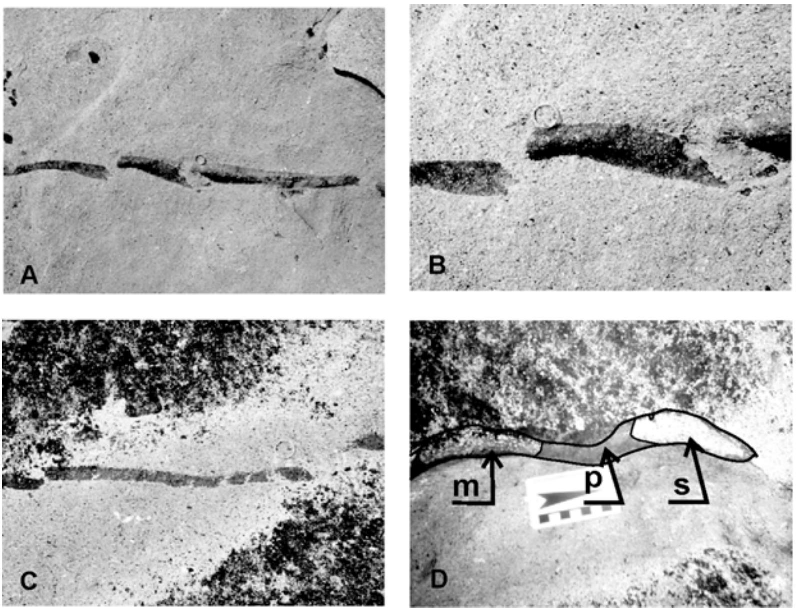

FIG. 2. Features of coexistence of pyroxenite and syenite melts at the Triunfo batholith. A. Disrupted synplutonic pyroxenite dike intruding the Triunfo syenite. B. Synplutonic pyroxenite dike with sharp contacts and rounded or cuspate ends typical of liquid-liquid contact. C. Curved disrupted synplutonic pyroxenite dike intruding the syenite. D. Synplutonic dike in which a mixed rock (m) with typical emulsion-like texture divides to form pyroxenite (p) and syenite (s).

Province, and it apparently formed by liquid immiscibility that generated syenite and pyroxenite melts in one of the few known natural examples of large-scale silicate liquid immiscibility.

The pluton is mainly composed of alkali-feldspar syenite and alkalic pyroxenite, which occurs as comagmatic inclusions, and as synplutonic and late-stage dikes intrusive during a phase of fracture propagation (Ferreira et al., 1994). The inclusions are rather small, ranging from about 1 cm to 1 m in diameter, and have rounded outlines with sharp crenulated contacts that provide evidence for contrasting viscosities, but which present no evidence for quenching (ibid.). The dikes are narrow (up to 10 cm wide) and long (up to 5 m long) (Figs. 2A–2C). Within each inclusion the texture is rather uniform, with a random orientation of grains, although orientation of pyroxene grains parallel to flow foliation is common. In most cases, the two melts have retained their identity with almost no mechanical mixing or chemical diffusion, probably due to differences in their viscosities. However, rare inclusions of a "mixed" rock with an emulsion-like texture that consists of mutually interstitial syenite and pyroxenite are present (Fig. 2D) (ibid.).

Both host syenite and alkalic pyroxenite inclusions and dikes are medium-grained rocks possessing the same mineral assemblage, although with different proportions. They are composed of orthoclase/microcline and clinopyroxene as major phases; titanite, apatite, and blue amphibole formed at the expense of the pyroxene, and rare quartz and albite are accessory phases. The compositions of clinopyroxene (weakly zoned aegirine-augite), and of amphibole (K-rich richterite) in the three rock types and in the mixed rock overlap, suggesting that chemical equilibrium between syenite and pyroxenite occurred. This is one of the requirements for two liquids to constitute an immiscible pair (Ferreira and Sial, 1993).

The host syenite, alkali pyroxenite inclusions, and dikes as well as the mixed rock have similar chondrite-normalized REE patterns with negative slopes and no Eu anomalyies; the total REE in the pyroxenite is greater than in the syenite. Whole-rock variation diagrams using silica as fractionation index show linear trends with a compositional gap between syenite and alkali pyroxenite, whereas the composition of the mixed rock is intermediate between the two end members. The syenite and pyroxenite have high $\delta^{18}O$ values (average whole

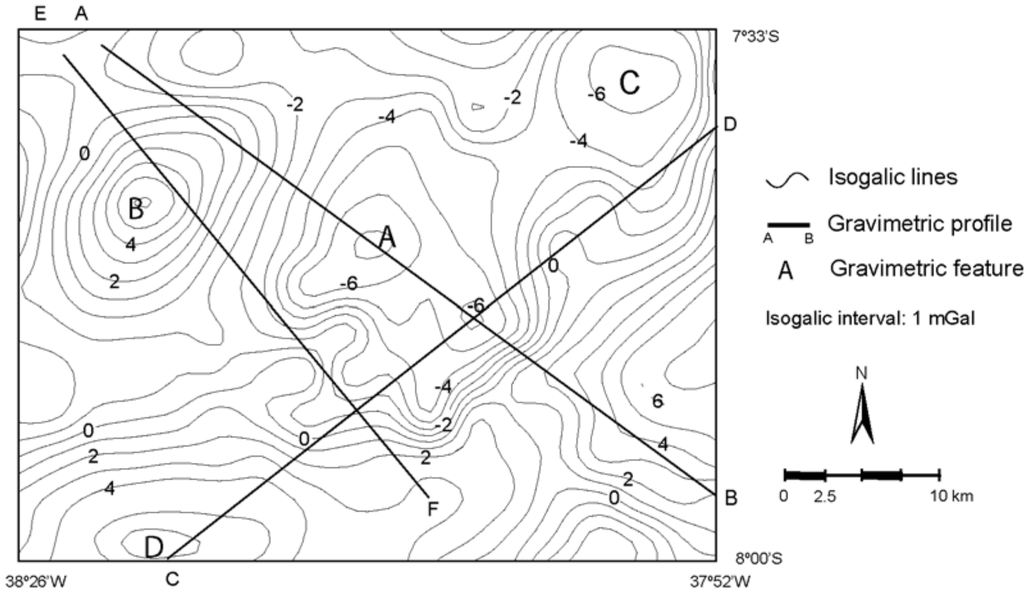

FIG. 3. Residual gravity map for the area of study. A–B, C–D and E–F are the studied gravity profiles.

rock +8.0‰$_{SMOW}$, corrected from pyroxene), high initial $^{87}Sr/^{86}Sr$ (around 0.710), and strongly negative eNd (ca. –20) (Ferreira et al., 1994).

Taken together, the field and geochemical characteristics of the Triunfo pluton indicate that chemical equilibrium was reached among the three rock types, and strongly suggest that the syenite and alkalic pyroxenite were formed by the unmixing of a mafic syenite magma. The mixed rock represents the frozen-in beginning of the process. The immiscibility probably occurred shortly before emplacement, and the denser pyroxenitic melt would have accumulated below the less dense syenitic melt (Ferreira and Sial, 1993; Ferreira et al., 1994).

Studies on anisotropy of magnetic susceptibility and microstructures of the Triunfo pluton indicated that the likely shape of the batholith approaches that of a laccolith, with magma flowing along a horizontal plane, as the planar-linear structures are mostly subhorizontal (Archanjo, 1994). The lack of stacked lineations suggests that only the upper portion of the batholith is currently exposed.

Geophysical Approach

A network of auxiliary bases was established relative to the first-order station, located at the town of Patos, about 150 km northwest from the town of Triunfo. It included 335 gravity stations on the Triunfo batholith and surrounding areas, with an average distance between stations of about 1.5 km.

A detailed gravity survey was carried out (Fig. 3) using a LaCoste & Romberg gravimeter, model G-994, with a precision of ± 0.01 mgal. The generated data were reduced according to procedures described by Sá et al. (1993). Values of the Bouguer anomaly are referred to the Brazilian fundamental gravity network (Rede Gravimétrica Fundamental Brasileira—RGFB-ON1987) with a precision around ± 0.5 mgal. Latitude was corrected using the 1967 International Gravity formula as reference, and a Bouguer density of 2.67 gr/cm^2. The densities of 65 samples of rocks from the Triunfo batholith and adjacent units were determined.

The relative altitudes were determined using six altimeters and two psychrometers, which allowed measurements within an error of about 1 m in the final altimetric corrections, after barometric and temperature corrections were applied. The barometric survey was made using the simple-base method, coupled with counter-leveling in the more topographically rugged areas.

Residual and regional gravity maps were generated from the field Bouguer map, which was obtained by interpolation, and was calculated using a computer program developed by Beltrão et al. (1991),

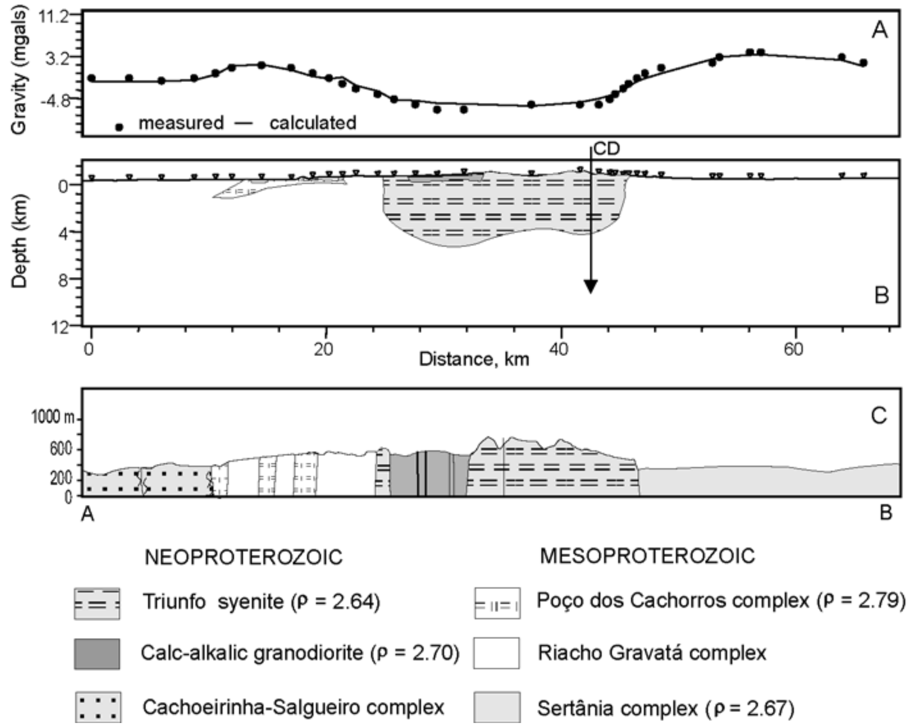

FIG. 4. AB1 gravity model: in this model a pyroxenite body at the base of the batholith is not taken into account. The modeling indicates that the Triunfo batholith has an approximate depth of 5 km and two points of maximum gravity values.

considering the degree 6 as reference. For this study, only the residual field map was used. Gravity modeling was done using the method of direct and indirect analyses through the application of version 5.0 of the Oasis-Montaj system, and version 4.4 of the GM-System, which provides 2D models.

The residual gravity data were modeled considering two superposed bodies: (a) one body outcrops, has negative density contrast relative to the host rocks and overlies a second body; (b) a second body has positive density contrast in relation to the host rock.

Results

Four distinct gravity anomalies are evident in the residual map of Figure 4. The most prominent anomaly (A in Fig. 3) is concordant with the NNE-SSW regional structural trend, with the largest axis about 20 km long. This is a negative anomaly of almost –7 mgal, which together with another nearby high-intensity negative anomaly of –6 mgal can be related to the Triunfo batholith. A second anomaly, at the northwestern portion of the studied area (B in Fig. 3), has an oval shape about 20 km long along its major axis, with positive values of up to +6 mgal, and appears to be related to the basic to ultrabasic metavolcanic rocks of the Poço dos Cachorros complex described by Gomes (1999). The third anomaly (C in Fig. 3) has negative values down to –6 mgal, is concordant with the regional structural trend, and can be related to the Tavares granitic pluton. The southwestern portion of the studied area is characterized by a semicircular positive anomaly of almost +7 mgal (D in Fig. 3), which can be related to amphibolite intercalations in the Sertânia complex.

Gravity Profiles and Modeling

Inasmuch as there is no unique interpretation for the field analysis, it is necessary to select information and to define constraining parameters before modeling. The gravity modeling of the Triunfo pluton and host rocks was initially done using the method of direct adjustment followed by application

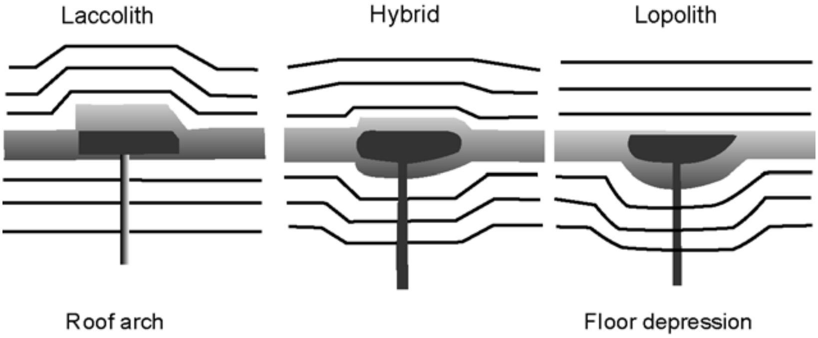

FIG. 5. Models of emplacement for tabular granitoids according to Cruden's classification (1998). Upwarping characterizes a laccolith, while downwarping characterizes a lopolith. A hybrid plutonic body shows an intermediate situation between these two types (adapted from Cruden, 1998).

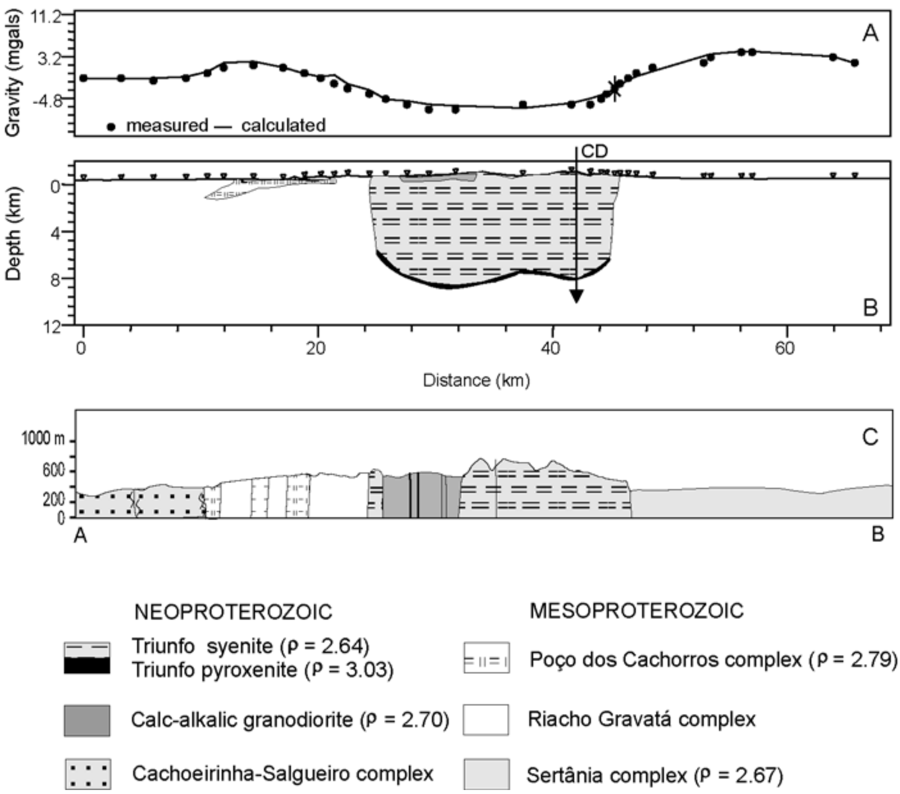

FIG. 6. AB2 gravity model in which the presence of a pyroxenite body at the base of the Triunfo batholith is taken into account. Modeling indicates that the batholith has maximum depth of 8.3 km.

of the inversion method to the preliminary model obtained. Densities of the syenite and pyroxenite, geological contacts, the present level of exposure of the batholith approximately corresponding to its original roof (Ferreira and Sial, 1993), and published petrological, structural, and geophysical information were taken into account in the modeling.

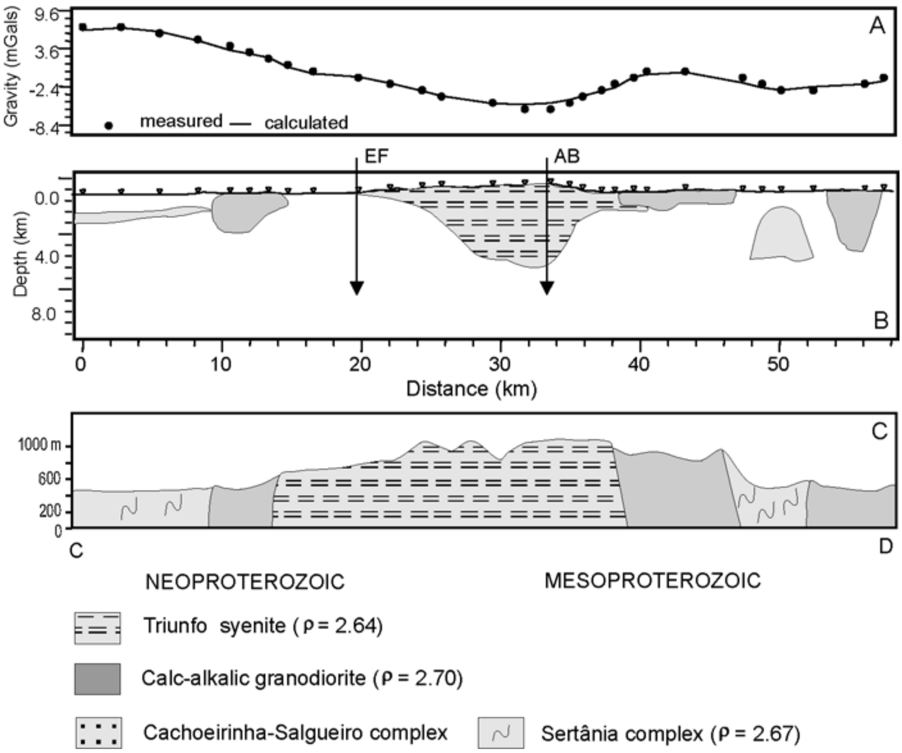

FIG. 7. CD1 gravity model. The presence of a pyroxenite body at the base of the Triunfo batholith is not taken into account. Modeling indicates an average thickness of only 30 m for the syenite body.

Three gravity profiles were carried out, indicated in Figure 3. The A–B profile extends for 68.5 km in the N45°W-S45°E direction. The second profile, labeled C–D, has an N40°E–S40°W direction, extends for 57.5 km, and is longitudinal to the Triunfo batholith, whereas the third profile, labeled E-F, is close to the A-B profile. The gravity data for the three profiles are discussed below.

A–B profile

AB1 model. Figure 4A represents gravity profile modeling showing the measured and calculated gravity curves, assuming that the observed anomaly can be accounted for by a single rock type (that is, a possible pyroxenite layer below the syenite is not considered). The application of inversions in this profile allowed a better adjustment of the measured and calculated curves. The adjustment of the two gravity curves shown is good, and correlates well with major rock units, except for the central and southeastern regions, which require the presence of additional rock types and structures other than those used in this model.

The obtained gravity profile (Fig. 4B) is compatible with the presence of the Triunfo pluton in the center of the modeled region, with a lateral extension of ca. 20 km and a maximum thickness of 6 km in the region corresponding to the –7 mgal gravity anomaly. This interpretation is compatible with the geological section shown in Figure 4C. The top of the batholith is in high topographic relief (up to 1200 m above sea level), so that the shape of the batholith can be considered to be hybrid according to Cruden's (1998) classification (Fig. 5). In this model, the batholith initially would have undergone a slight upward doming as well as late shearing, which occurred during the final stage of emplacement (Archanjo and Vauchez, 1997). This led to the collapse of the magma chamber, producing a set of fractures or faults that served as conduits for the ascent of syenite and pyroxenite melts to form the dikes. The thickness/lateral extension ratio and

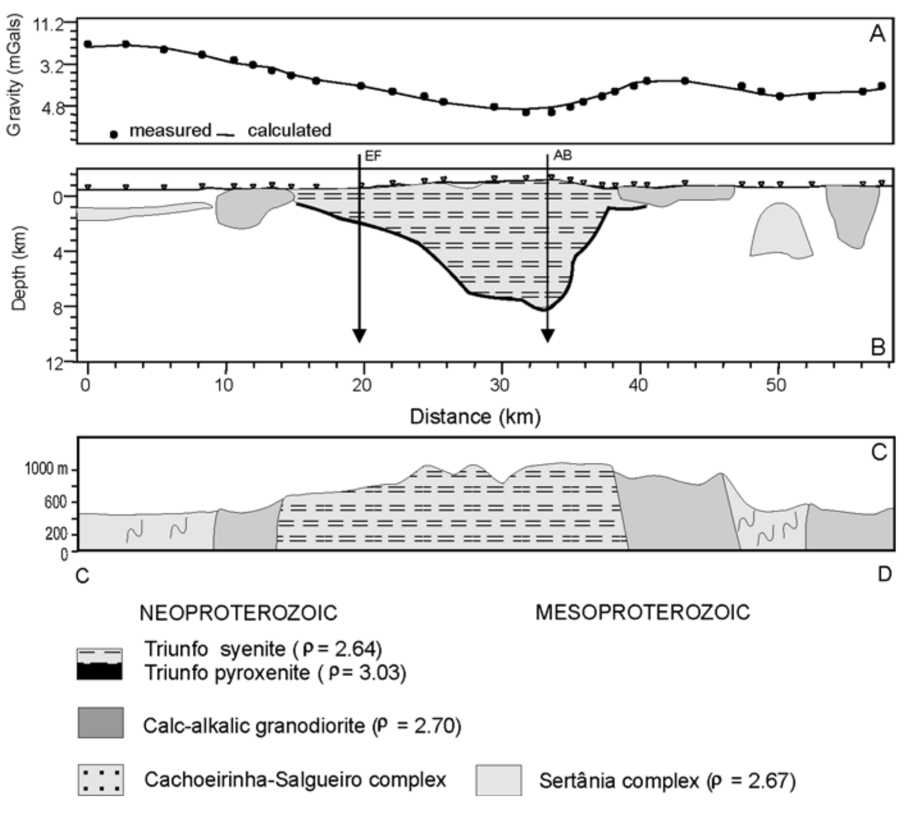

FIG. 8. CD2 gravity model. This model indicates the presence of a 0.2 m thick pyroxenite body, approximately longitudinal to the batholith, and passing through the point of highest gravity value in this pluton. Upwarping of the upper surface of the body is evident from this profile.

external shape of the batholith suggest that its geometry is similar to that of a lopolith (Fig. 5). This configuration is even better represented in the Triunfo CD model described below.

AB2 model. In this model, a pyroxenite body at the base of the batholiths is considered (Fig. 6). This model indicates a similar general shape for the batholith as in that of AB1 model. The pyroxenite has an average thickness of 0.2 km and the syenite, 8.3 km, reaching a maximum of 8.5 km.

C–D profile

CD1 model. This model was performed for a comparison with the AB1 model, in which no pyroxenite body is present at the base of the batholith. The calculated and measured gravity curves (Fig. 7A) have the same adjustment as in the AB1 model, but the batholith is thinner (around 4.3 km) at km 33, the point of intersection with the AB1 model, compatible with the thickness obtained in that model.

The main difference is present in the stretch between 14 and 22 km, where the syenite has a thickness of only 10–30 m. These values are repeated at the intersection with the gravity profile EF at km 19, as described in the next section. At this point, the altimetric level is 900 m. Considering that the Triunfo batholith has considerable topographic relief compared with the host rocks whose average topographic level is about 670 m, about 230 m of syenite is exposed. The inferred average thickness of 30 m for the syenite body is very much smaller than expected if the contact between the rock types is assumed to be tabular. This model, therefore, is not supported either by geologic or topographic evidence (Fig. 7C), and the expected presence of a thicker layer in the central portion of the batholith is also not indicated.

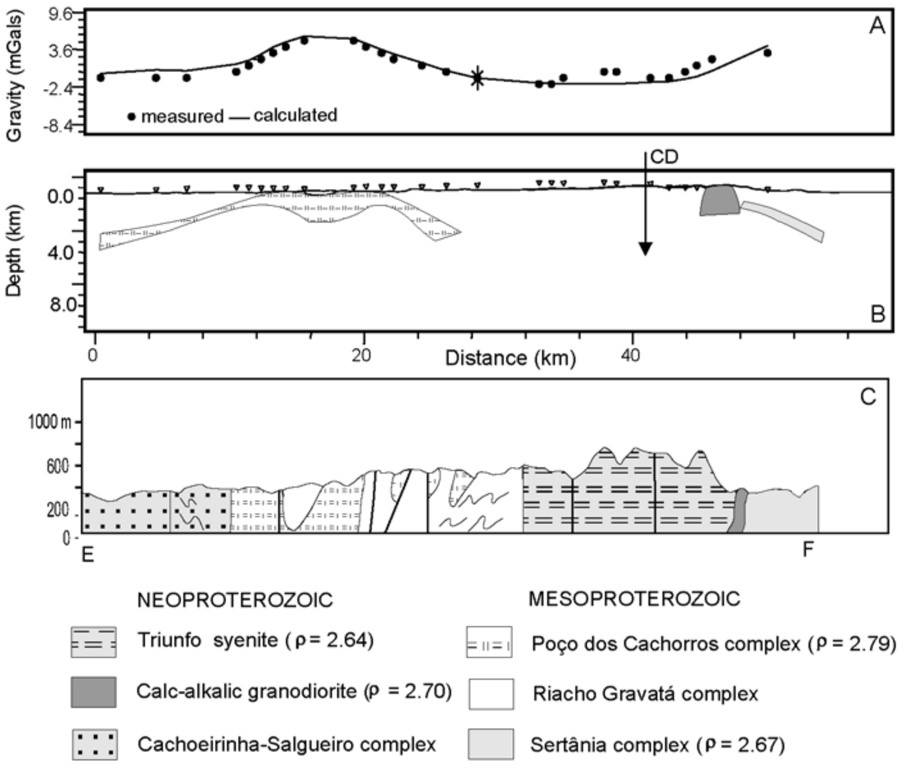

FIG. 9. EF1 gravity model. The presence of a pyroxenite body at the base of the Triunfo batholith is not taken into account. The modeling indicates maximum thickness of the syenite of only 25 m, incompatible with the geological evidence at km 42, at the intersection with model CD.

CD2 model. Assuming that a pyroxenite body is present in the subsurface, and using the same parameters of the AB2 model, the resulting model indicates that the syenite has a thickness of 8.37 km, whereas the pyroxenite is 0.18 km thick at km 32 of the studied profile, at its intersection with the A-B profile (Fig. 8B). The syenite and pyroxenite bodies have inferred thicknesses of 2.2 and 0.3 km, respectively, at km 20, the intersection with the profile E-F. These values are compatible with those obtained in the other profiles.

This model has a similar geometry to that inferred in the AB2 model, with the top curved upward and a depression at the base. However, in this model the pluton is more elongated, with only one maximum gravity value at km 32, suggesting that this point may correspond to one of the magma conduits. This model fits well with the geological cross-section as shown in Figure 8C.

E–F profile

EF1 model. This model does not take into account the presence of a pyroxenite body at the base of the syenite. Solutions are conflicting (Fig. 9). The measured and calculated curves present regular adjustment at only two gravity stations. Correlation between the model (Fig. 9B) and most other rock units of the geological profile is only fair (Fig. 9C). In this model, the syenite is only 25 m thick at km 42. Attempts at adjusting the curves at other points results in the elimination of the syenite body. This model shows more clearly than the CD1 model the necessity for the presence of a rock denser than the syenite in the batholith.

EF2 model. For this model it was assumed that pyroxenite is present in the subsurface. Modeling was performed directly using the same parameters used in the other profiles. This modeling indicates that the syenite and pyroxenite bodies have average

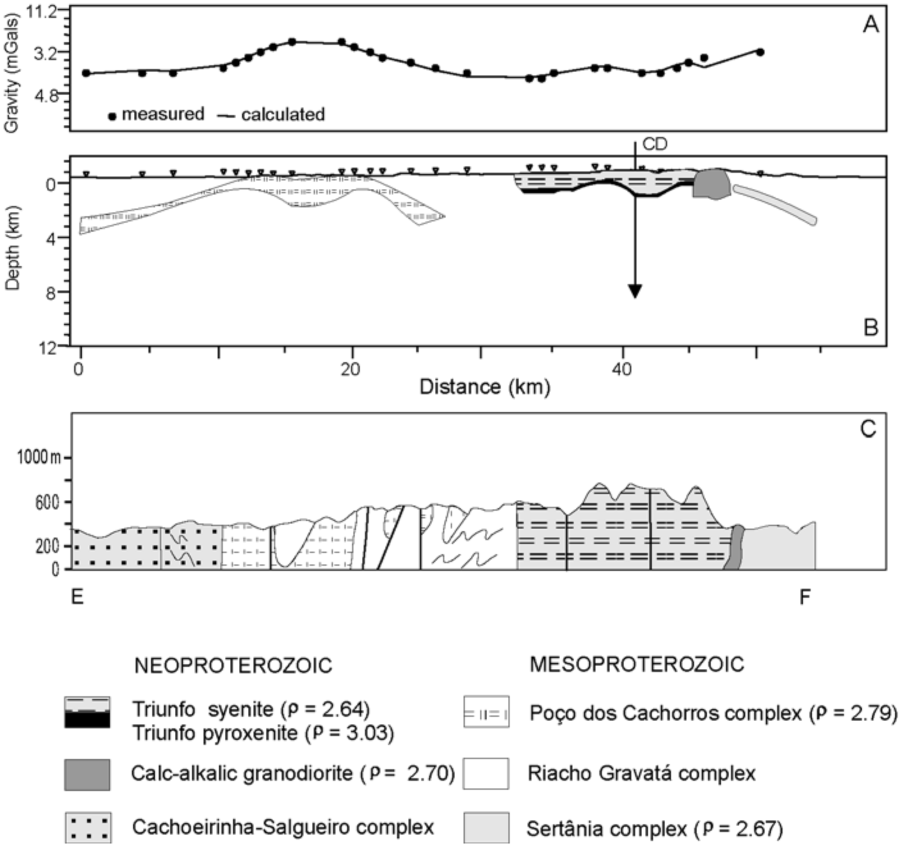

FIG. 10. EF2 gravity model. The presence of a 0.2 km thick pyroxenite within the Triunfo batholith is taken into account. A 2.3 km thickness at the point of intersection with the CD profile, besides field evidence, corroborates the presence of a pyroxenite body within the syenitic batholith underneath this point.

thickness of 2.2 and 0.3 km, respectively, at the intersection point with the CD profile at km 40 (Fig. 10). Good adjustment is obtained at most of the points. The inferred shape of the batholith using this model is similar to that of the AB2 model as to the depression of its base, and the presence of subvertical shear zones, but the shape is more tabular, having only one point of maximum inflexion at km 42. There is a fair correlation between the model (Fig. 10B) and the geological profile (Fig. 10C).

Conclusions

The consistency of gravity modeling of the three different profiles described here suggests the following:

1. The AB1, CD1, and EF1 gravity models that do not take into account the presence of a pyroxenite body below the voluminous syenite body do not match the inferences of previous detailed petrological studies. On the contrary, models that require a denser layer below the syenite body fit the gravity data much better.

2. The AB2 model requires the presence of a 200 m thick pyroxenite body, the top of which is slightly arched and its base depressed, due to vertical compaction. The top and the base of the batholith have modeled lateral extensions of 20 km, and its maximum thickness is 8.5 km. The shape is intermediate between a laccolith and a lopolith, and could be considered as an autochthonous hybrid;

3. There are two magma feeding conduits, at the places where the batholith has the greatest thick-

ness, at Espírito Santo northeast of Triunfo, and north of Santa Cruz da Baixa Verde village in the center of the pluton.

The issues addressed in this study can be refined or reassessed using other geophysical approaches. The magnetic method, in particular, could be of great importance for fully understanding the shape and composition of the Triunfo batholith. The present gravity data are well explained by—and are compatible with—the petrogenetic model that invokes liquid immiscibility as the main process that led to the formation of the coexisting ultrapotassic syenite and subordinate pyroxenite in the Triunfo batholith.

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