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Gravimetric modeling of the Parguaza granitic intrusion, Guyana Precambrian Shield, southwestern Venezuela using geochronological constraints

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RESUMEN

En este trabajo se llevó a cabo una interpretación integrada de datos gravimétricos y geocronológicos, para la intrusión de Parguaza en el Escudo Precámbrico de Guayana (suroeste de Venezuela). Aparentemente existe un patrón de enfriamiento inverso dentro de esta intrusión; sin embargo la poca información geológica y geofísica en el área representa un serio obstáculo en la interpretación de los datos gravimétricos. Basándonos en la correlación positiva que se observa entre las edades de Rb/Sr en roca total y la anomalía residual de Bouguer, se puede argumentar que los contrastes de densidad en esta intrusión están ligados a la temperatura y, por consiguiente, a la cristalización de las distintas fases minerales. Esta hipótesis se corrobora con medidas directas de la densidad realizadas sobre muestras de mano y con datos geoquímicos que señalan la existencia de marcadas diferencias composicionales dentro de la intrusión. De esta forma, se propone aquí un simple modelo gravimétrico en dos dimensiones acotado por la geología de superficie, las edades aparentes de Rb/Sr en roca total y la anomalía residual de Bouguer. El modelado gravimétrico, a lo largo de un perfil que corta la parte central del plutón, parece indicar la existencia de un sistema complejo de bloques tectónicos, algunos levantados y otros hundidos. Basándonos en este modelado se propone aquí un patrón de "horsts" y "grabens" que explicaría el enfriamiento inverso como resultado de los contrastes geológicos y geocronológicos que se observan al cruzar las fallas que separan los distintos bloques.

PALABRAS CLAVE: Granito Rapakivi, anomalía residual de Bouguer, modelado gravimétrico, patrón de enfriamiento, edades aparentes.

ABSTRACT

A combined gravimetric and geochronological interpretation of the Parguaza intrusion in the Guayana shield, southwestern Venezuela, indicates that there is a pattern of inverse cooling within this pluton. Based on a positive correlation between Rb/Sr whole rock apparent ages and residual Bouguer anomaly, density contrasts over the Parguaza intrusion are linked to temperature and crystallization of mineral phases. This hypothesis is supported by density measurements on hand samples and by independent geochemical evidence. A simple 2D gravity model is constrained by surface geology, Rb/Sr apparent ages (whole rock) and residual Bouguer anomalies. Gravimetric modeling implies a model of horsts and grabens that accounts for inverse zoning of the intrusion as a result of geological and age contrasts across the faults.

KEY WORDS: Rapakivi granite, residual Bouguer anomaly, gravimetric modelling, cooling pattern, apparent ages.

INTRODUCTION

The Parguaza granites of the Venezuelan Guayana shield are massive coarse-grained rocks with U/Pb zircon ages of 1500 ± 25 Ga (Gaudette *et al*., 1978). These granites represent the largest rapakivi intrusion in the world. Unraveling their geological history should lead to a better picture of the tectonic evolution of the Guayana shield. Most of the hypotheses concerning the tectonic evolution of this intrusion are based on scarce geological information or indirect geochemical, radiometric and paleomagnetic evidence (Gaudette *et al*., 1978; Gaudette and Olszewski, 1985; Gibbs and Barron, 1993; Mirón Valdespino and Costanzo-Álvarez, 1997).

Gaudette *et al*. (1978) suggest that the Parguaza intrusion originated by within-plate extension about 1500 to 1400 Ma in a large part of the northwestern and southern Guayana shield. Rifting was accompanied by high temperature gradients, slow migration of hot materials from subcrustal depths and deep faulting through the lithosphere. The emplacement of the pluton was caused by anatexis due to burial and volcanism-related heat flow from the sides and the base of a down-thrown block of trondhjemitic or charnockitic composition that developed in one of these extensional structures.

Gaudette and Olszewski (1985) and Gibbs and Barron (1993) propose an alternative model to explain the origin of the Parguaza intrusion. They suggest that the emplacement of these rocks was the last stage of the Trans-Amazonian episode, a 1500 Ma subduction that occurred along a convergent plate boundary. The suture is manifested by a long north-trending belt of sediments metamorphosed into the lower greenschist facies. According to this model, the Parguaza granites would be an intrusion resulting from plate subduction. Such a tectonic setting appears to be viable to explain the generation of large volumes of magma.

Mirón Valdespino and Costanzo Álvarez (1997) have reported an unusual pattern of inverse zoning of apparent ages for this pluton. A map of "chrontours" or contours of equal cooling age (Piper, 1980), was constructed by combining paleomagnetic and Rb/Sr data (whole rock apparent ages) available for this area. Later extension, after the intrusion had cooled down, would result in a system of NW-trending horsts and grabens, cutting through the pluton.

We present a gravimetric interpretation of a transect located in the central part of the Parguaza intrusion (Figure 1). The interpretation is made by matching the gravity anomaly profile, observed along a linear traverse, with the calculated anomaly profile from an assumed model of the structure. Since the final adjusted model is not unique, it is constrained by surface mapping and sometimes by seismic data. However, in inaccessible Precambrian terrains such as the Guyana shield, the lack of seismic, rock density and geological information adds some difficulties to gravimetric interpretations.

In a pilot gravimetric study of the Parguaza intrusion (Wynn, 1993), along a transect located south of Puerto Ayacucho, Amazonas State, Venezuela, surface geology and radar imaging information were the main constraints. Parguaza was modeled as a 15 km thick prism-like body, with a density contrast of 0.064 g/cc, buried 6.84 km below the surface, dipping 61° SW and with an upper surface of 87 x 42 km.

In this study we refine the subsurface model of Parguaza by combining gravimetric data with surface geology information and Rb/Sr whole rock apparent ages.

GEOLOGICAL SETTING

The northern Amazonas state, in southwestern Venezuela, is part of the Guyana-Brazilian shield of northern South America.

Cuchivero Province in the Guayana Shield, is composed of a high percentage of plutonic rocks and subordinate metavolcanic and metasedimentary rocks. The most distinctive feature of this province is the northwesterly strike (Figure 1) that contrasts with the northeasterly structural trends of older regions (Gaudette *et al.,* 1978).

Geological maps of Cuchivero (Bellizia *et al.*, 1976; Wynn *et al.*, 1993) show a large area of granitic intrusions known as the undifferentiated "Parguazan intrusions". These are referred here as the Parguaza Igneous Complex (PIC). From geochronological evidence (Hurley *et al.*, 1977; Olszewski *et al.*, 1977; Gaudette *et al.*, 1978; Barrios and Rivas, 1980; Barrios, 1983; Barrios *et al.*, 1985; Gaudette and Olszewski, 1985) it is known that the intrusions of the PIC are the youngest in this geological province. It seems reasonable to assume that they have not been intruded subsequently by intrusions large enough to result in regional reheating.

The Parguaza intrusion or pluton is located in the northwestern section of the PIC. This pluton is formed by massive, coarse-grained rocks, with a U/Pb zircon age of 1500 ± 25 Ma (Gaudette *et al.*,1978). About 10% of their feldspar phenocrysts show multiple zoning and, in contrast with most rapakivi granites, the K-feldspar is microcline perthite instead of orthoclase. Epidote and chlorite are absent. These rocks show no visible sign of metamorphism subsequent to emplacement (Gaudette *et al.*,1978).

After the Parguaza episode, there was little activity in the shield other than the extensional and vertical movements associated with the aftermath of subduction (Gibbs and Barron, 1993). Deposition of sediments and volcanic activity were followed by block-faulting and mafic magmatism that have dominated the geology of the shield since middle Proterozoic times.

GRAVIMETRY

Gravimetric data were obtained from the Venezuelan gravimetric network (USB database, Graterol, 1993). It was acquired during the 1980's and compiled by Universidad Simón Bolívar and INTEVEP S. A. There are 1153 stations along rivers and few roads in the study area. Measurements at these stations were made using a LaCoste and Romberg (G-441) gravimeter, which was calibrated prior and during the survey. All measurements were tied to secondary base stations placed nearby or at bench marks. Vertical positions were obtained using an altimeter calibrated at nearby bench marks which gave statistical errors less than 3 m. No GPS technique was available at the time of the survey. Bouguer anomalies were calculated assuming a surface standard density of 2.67 g/cc. The spatial coverage of

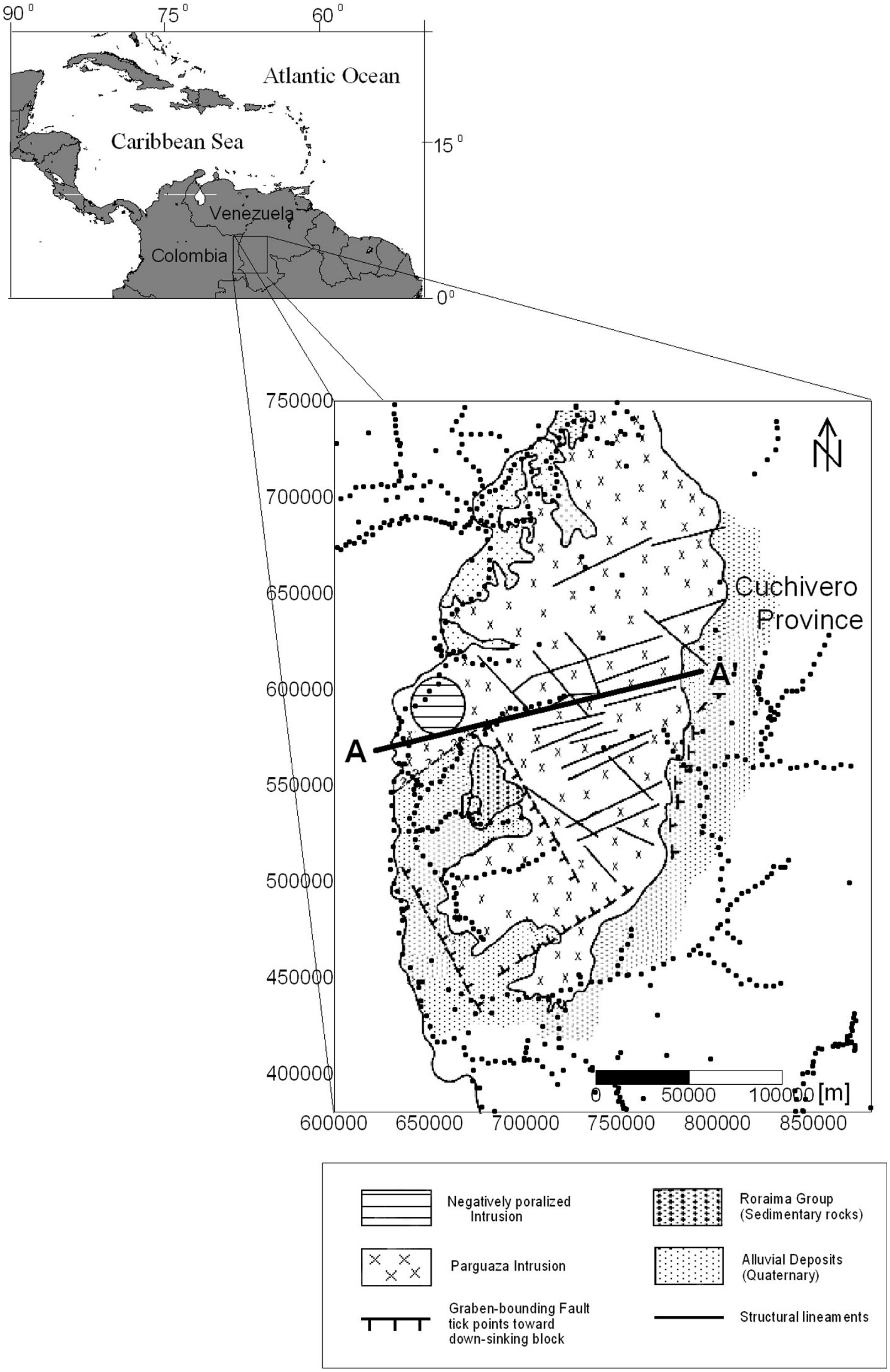

Fig. 1. Geologic and tectonic map of the Parguaza intrusion after Wynn *et al*. (1993) showing the transect used in this study. Also shown: the location of the gravimetric posts and the most important geological features of the intrusive complex, namely: structural lineaments, the sediments of the Roraima group and Quaternary alluvial deposits. Coordinates in this map are UTM Zone 20.

these stations is approximately 112,000 km^2 and their distribution over the pluton was controlled by the availability of access.

The Bouguer anomaly (BA) signal contains regional and residual components. The regional anomalies are not related to possible geological structures to be interpreted, in other words "it is what you take out of the data to make what is left look like the structure" (Nettleton, 1954 and 1962). The process of separating the residual and regional anomalies means separating narrow anomalies (i.e. residual) from broad ones (i.e. regional). The technique used for the regional residual separation in gravity interpretation depends on the geology of the area, quality of the gravity data and the geological features of interest. The regional field was removed using a first order polynomial approximation in order to obtain a residual gravity anomaly used to model the gravity effect of the Parguaza intrusion. We have chosen this method because is simple, robust and correlates well with the coverage of the data and the dimension of the study area. The residual Bouguer anomaly map shown in Figure 2 was generated applying the method of minimum curvature and using a 10x10 km-grid.

The gravity modeling is restricted to one transect (AA'), which goes across the regional strike of the Parguaza intrusion. The rationale behind the choice of this profile obeys to the distribution of gravimetric anomalies that are cut by it (i.e. the best possible coverage) and the geological map of this intrusion, which reveals the presence of a system of structural lineaments (Figure1).

The residual Bouguer anomaly map shows the following features (Figure 2):

- Gravimetric gradients roughly oriented along two mutually orthogonal directions. The NS-strike is much larger than the EW-trend.
- A gravimetric gradient at the eastern end of the study area.
- The NS-striking gravimetric gradient characterized by higher values of the Residual Bouguer anomaly. This is most likely associated with bodies of high density.
- The EW-striking gravimetric gradients show lower Residual Bouguer anomaly values, which are most likely associated with crustal units of low density and/or sediments.

GEOCHRONOLOGICAL CONSTRAINTS

Barrios *et al*. (1985) presented a comprehensive compilation of the geochronological results available for the study area (Hurley *et al.,* 1977; Olszewski *et al.,* 1977; Gaudette *et al*., 1978; Barrios and Rivas, 1980, Barrios, 1983 and Gaudette and Olszewski, 1985) consisting mainly of whole rock Rb/Sr data. Following the method of Hurley *et al.* (1977), Olszewski *et al*. (1977) and Gaudette *et al*. (1978), they assigned Rb/Sr apparent ages to samples from a total of 19 sites across the intrusive complex, assuming a comagmatic origin for the Parguaza intrusion and a $^{87}Sr/^{86}Sr$ initial ratio of 0.705. A better estimate of the $^{87}Sr/^{86}Sr$ initial ratio for a Proterozoic granite would be 0.7004 (Gaudette *et al.,* 1978), but any of these Rb/Sr initial ratios yields the same pattern of relative cooling ages within the Parguaza intrusion. Cooling over periods of hundreds of millions of years requires deep burial and a very slow rise through isotherms, or differential uplift of individual blocks due to faulting. Rapakivi textures are thought to be the outcome of extremely slow cooling, with large differences of ages, within a single intrusion (Dempster *et al.,* 1994).

By integrating Rb/Sr apparent ages with paleomagnetic results, Mirón Valdespino and Costanzo-Álvarez (1997) have constructed a map of chrontours in which positive gradients represent the oldest areas of the intrusion, and valleys are the younger ones.

This map shows a conspicuous NW-trending region of high apparent ages flanked by zones of younger ages (Figure 15 in Mirón Valdespino and Costanzo Álvarez, 1997). It is important to point out that whole rock Rb/Sr apparent ages can be highly susceptible to perturbation by younger events, and can often represent mixed ages due to contamination. Additionally, the limited number of data points on which this chrontour map was constructed, is rather scarce evidence to support the pattern of cooling proposed for the intrusion.

However, there is more evidence for an unusual age distribution over Parguaza. Geochemical evidence suggests compositional inverse zoning for this intrusion. Mendoza *et al.* (1977) have reported a systematic increase of alkali ($Na_2O + K_2O$) versus SiO_2 percentage, from granodiorite to granite-like rocks, away from what seems to be the center of the pluton. Rock magnetic data also yield evidence for inverse textural zoning across the intrusion. Site-average Königsberger ratios and their corresponding relative errors indicate that magnetite grain sizes vary from coarse-grained at the margins, down to fine-grained at the center of the mapped surface expression of the Parguaza intrusion (Mirón Valdespino and Costanzo Álvarez, 1997).

We have overlapped this geochronological information on the contour map of the residual Bouguer anomaly (Figure 2). Some of the highest Rb/Sr age values roughly coincide with zones of maximum residual Bouguer anoma-

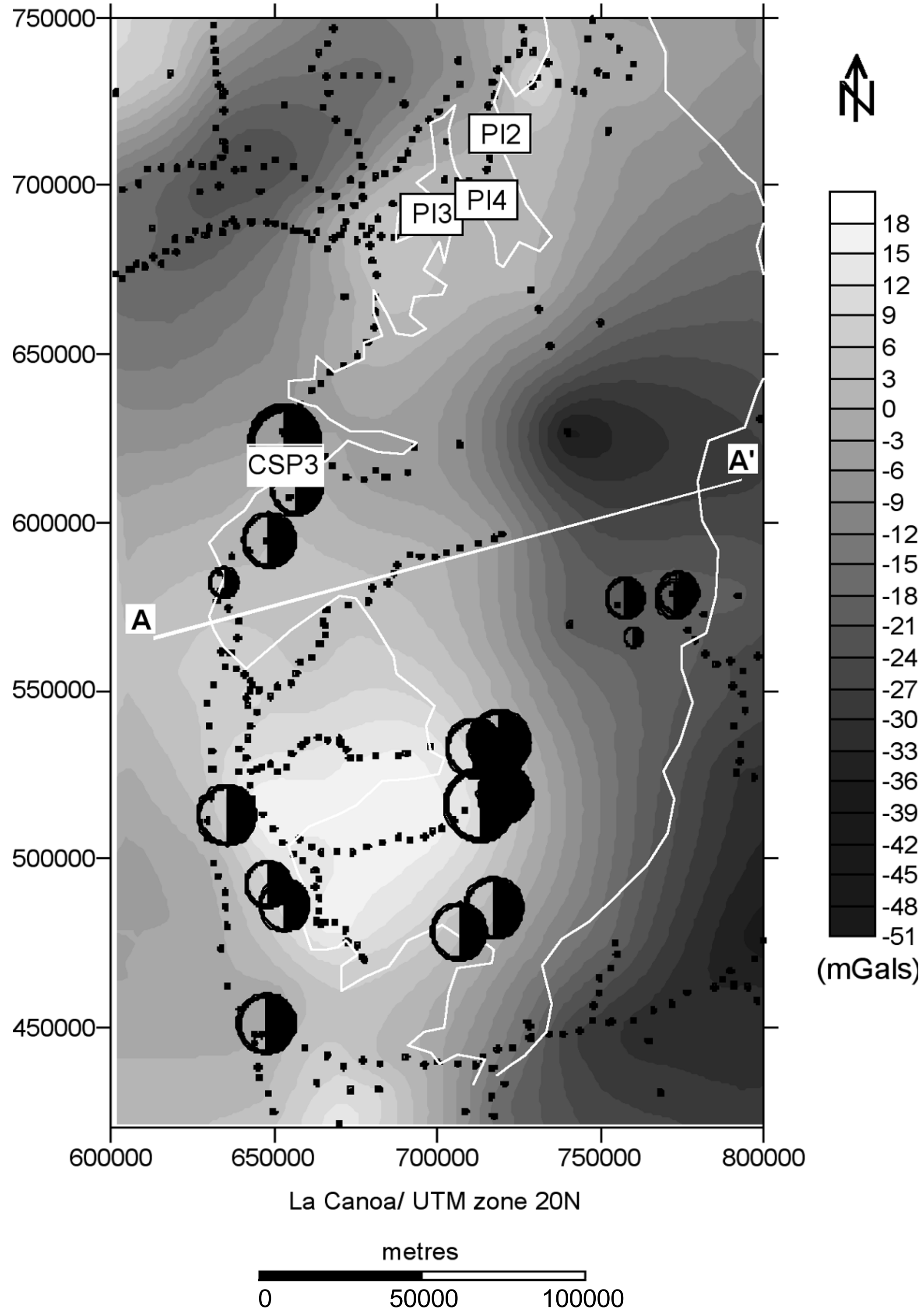

Fig. 2. Residual Bouguer anomaly map of the Parguaza intrusion showing the transect of this study (white line), the gravimetric stations (black points) and the Rb/Sr sites. These last ones are indicated by bubbles (◑) whose sizes are directly proportional to their ages ranging between 1200 and 1500 Ma (Rb/Sr whole rock apparent ages after Barrios *et al.*, 1985). A sketch of the Parguaza pluton is shown in the background (white countour) as well as the location of paleomagnetic sites PI3, PI2, PI4 and CSP3 (after Mirón-Valdespino and Costanzo-Álvarez, 1997) where direct density measurements were carried out for this study.

lies. Bubble sizes for the Rb/Sr data are directly proportional to apparent ages ranging between about 1200 to 1500 Ma.

Figure 3 shows a crossplot of residual Bouguer anomaly versus Rb/Sr apparent ages with an increasing trend between these two independent data sets. Such a trend is not entirely clearcut due to the lack of Rb/Sr ages at the interval of residual Bouguer anomalies between ≈ -5 to –15 mGals and problems associated to the use of whole rock Rb/Sr apparent ages. However, from Figure 3 it appears that density distribution within the pluton is mainly related to temperature and crystallization of mineral phases. Based on mineral physics and thermodynamics, a close relationship between density and temperature has been suggested for different geodynamic processes such as subduction, rifting and mantle dynamics (i.e. Birch 1968; Kanamori *et al.* 1968; Dumitru, 1991; Katsura, 1995; Iwamori, 1997; Kincaid and Sacks, 1997; Ita and King, 1998; and Hauck *et al.,* 1999). In this study we have used a density distribution that fits to the inverse cooling pattern described in previous works (i.e. Mendoza *et al.,* 1977 and Mirón Valdespino and Costanzo-Álvarez, 1997), as well as to the evidence provided by Figure 3. The older the cooling the higher the density of rock.

DISCUSSION

The structural model and the observed and calculated residual Bouguer anomalies across the intrusion are presented in Figure 4.

There are no density data available for the Parguaza outcrops in the inaccessible area where most of the gravimetric stations are located. Direct density measurements were performed on 18 hand specimens collected at the locations (i.e. sites PI3, PI2, PI4 and CSP3 shown in Figure 2) previously sampled by Mirón-Valdespino and Costanzo-Álvarez (1997). According to that study, paleomagnetic evidence indicates that rocks from site PI3 cooled long after those from locations PI2, PI4 and CSP3. Average densities, measured for these two groups of sites, are 2.6 ± 0.1 g/cc and 2.8 ± 0.3 g/cc respectively. We have taken these values as average densities of younger and older surface expressions of the Parguaza intrusion. For the country rock we worked with a density of 2.7 g/cc taken as average for the continental crust (Grow and Bowin, 1975).

In Figure 4 the gravimetric inversion shows an approximately 8 km-thick funnel-shaped layered intrusion. The western block displays variations of density with depth grading from a maximum of 2.8 g/cc (outermost layer) down to 2.73 g/cc (innermost bottom layers). The value assigned to the bottom layer is constrained by the density contrast previously used by Wynn (1993). The average of the two extreme densities in this block differs by 0.06 g/cc when compared with the country rock. The cross section of Figure 4 shows a 6 km-thick eastern block with an average density of 2.6 g/cc. According to this interpretation both blocks are flanked by normal faults with an eastern sedimentary basin, of approximately 500 m depth, composed of Quaternary alluvial deposits.

Ultimately an agreement between the gravimetric model of Figure 4 and the pattern of inverse cooling, evidenced by geochronological, geochemical and paleomagnetic data, would be expected.

Mirón Valdespino and Costanzo Álvarez (1997) argue that an inverse cooling pattern of the Parguaza intrusion might be due to slow progressive cooling of the pluton from its center towards its margins, or to differential intrusive pulses separated by long time-intervals or subsequent thermal events that have affected the pluton margins after emplacement.

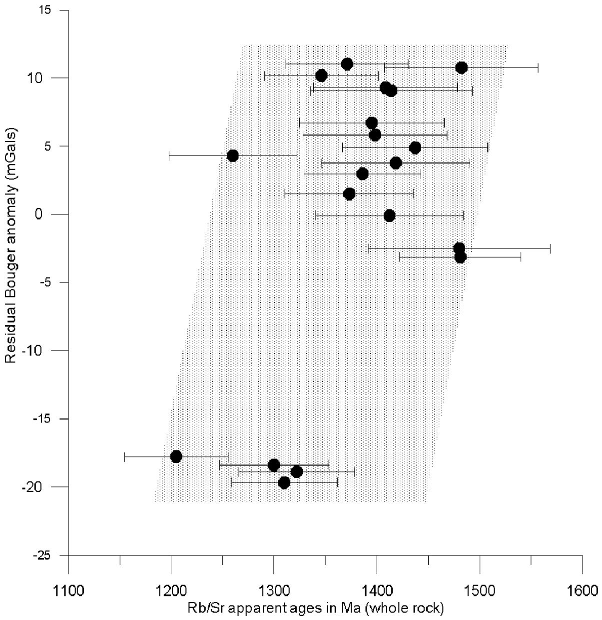

Fig. 3. Crossplot of residual Bouguer anomaly versus Rb/Sr apparent ages suggesting a progressive trend between these two independent data sets. Error bars reflect the analytical errors of 3.6% and 0.3% over the $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios respectively (Barrios *et al.*, 1985), propagated through the calculation of the Rb/Sr apparent ages. The observed trend is not completely reliable because the lack of ages for the interval of residual Bouguer anomaly between ≈ –15 and –5 mGals and problems inherent with the use of whole rock apparent ages. However, this plot seems to indicate that density distribution within the pluton is related to temperature and crystallization of mineral phases.

Slow and progressive cooling of the pluton, from its center towards its margins (inverse cooling) seems unlikely. On the other hand, differential intrusive pulses separated by long time-intervals require that Rb-Sr whole rock apparent ages should be regarded as model ages of crustal extraction similar to those proposed by Dickin and McNutt (1989, 1991) for the various lithotectonic domains in the Central Gneiss Belt (Grenville Province, Canada). However, there is manifold evidence that suggests that Parguaza is a single and slowly cooled intrusion. For instance, only two mutually exclusive primary paleomagnetic components are found at different sites within the pluton (Mirón Valdespino and Costanzo Álvarez, 1997) and there is petrological continuity across the intrusion (Mendoza 1974, 1976; Bangerter, 1985; Menendez *et al.,* 1985).

Subsequent thermal events may have affected the margins of the pluton after its emplacement. Geological contacts and nearby fractures can act as conduits for fluid circulation. Thus, it might be possible that the core rocks were largely unaffected by a thermal event. According to Mendoza *et al*. (1977) and Martín (1974) the only orogenic event in Venezuela during Precambrian times, after the intrusion of the Parguaza rapakivi granites, is the Nickerian event (ca. 1250 Ma). It is also reported by Gaudette *et al*. (1978) as a thermal event that affected the Parguaza area at about 1190 Ma. Yet, there is no clear evidence for alteration or metamorphism in the Parguaza intrusion (e.g. Mendoza *et al.,* 1977, Bangerter, 1985).

In order to reconcile our gravimetric model with evidence for inverse zoning within the Parguaza intrusion, we propose a chain of structural events illustrated in Figure 5. The inverse age-pattern of the Parguaza intrusion may be the outcome of extension resulting in a system of horsts and grabens cutting through the normal zoning of the pluton. These structures could yield the actual age-pattern observed on surface, namely:

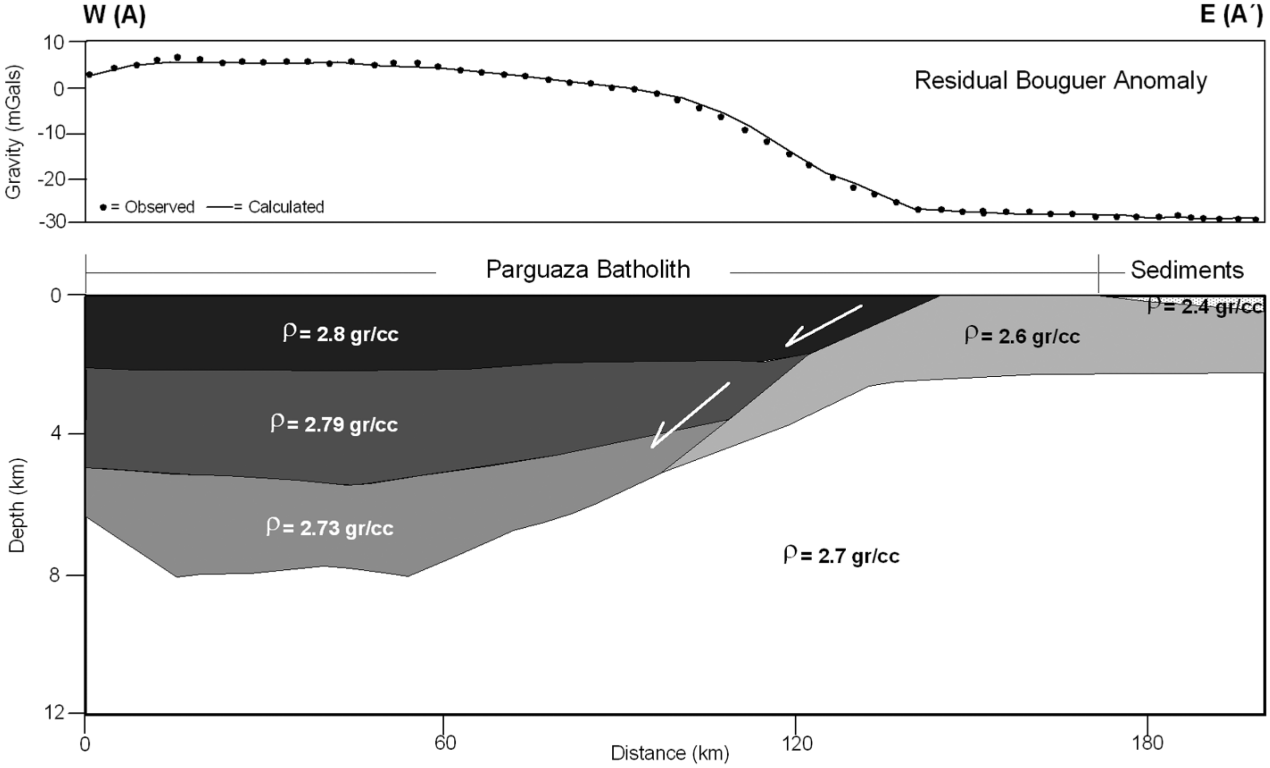

Fig. 4. A simple 2D gravimetric model along cross-section AA'. In this model the residual Bouguer anomaly is calculated and compared with the observed residual Bouguer anomaly in order to model the gravity effect down to a depth of 12 km. In the model the funnel-shaped Parguaza pluton is shown as an approximately 8 km thick layered intrusion in which the western block has a variation of densities with depth from 2.80 g/cc (density measured on surface for older Parguaza rocks) to 2.73 g/cc. On the other hand, the eastern block shows a density of 2.6 g/cc (density measured on surface for younger Parguaza rocks). The country rock has been assigned a density of 2.70 g/cc, whereas the eastern sedimentary basin was assigned 2.4 g/cc. The average density of the western block differs in approximately 0.06 g/cm by comparison with the country rock. This value roughly coincides with the density contrast used in the gravimetric model by Wynn (1993).

1. Intrusion ca. 1.5 Ga: Parguaza is emplaced as the result of a NE-trending subduction process (Figure 5a). It probably cooled slowly with a normal internal zoning, namely, the core of the pluton is younger and more felsic than its margins (Figure 5b). This also agrees with the progressive decrease of density with depth, in the western block, that comes out from the gravimetric model of Figure 4, namely a more mafic, aphanitic and higher density surface (margin of the pluton) progressing towards a felsic, phaneritic and lower density bottom (core).

2. Extension episodes (Precambrian to Mesozoic): NW-SE and E-W extension divided the pluton into fault-bounded blocks (Figure 5c).

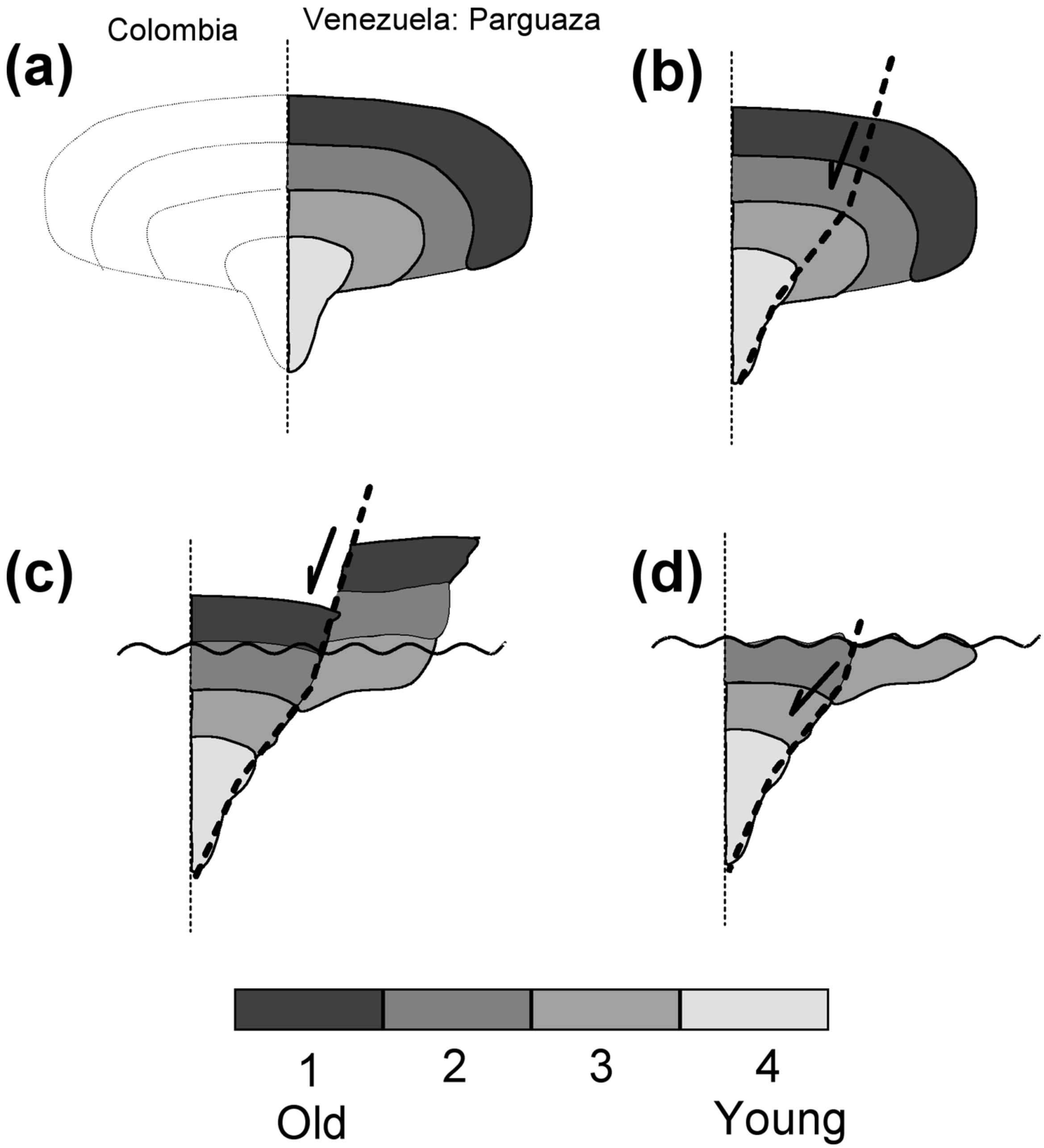

Fig. 5. A sketch of a four-stage tectonic model describing the geological history of the Parguaza intrusion: a) The pluton is emplaced as the result of the last stage of the Trans-Amazonian subduction. b) and c) After the Parguaza intrusion has cooled down NW-SE and E-W extension divided the pluton into fault-bounded blocks. d) The surface has been eroded resulting in a relatively flat topography and displaying present-day apparent inverse cooling pattern.

3. Present: The surface has been eroded resulting into a relatively flat topography. Erosion has flattened the surface by removing only the uplifted regions (edges of the pluton) and leaving the central part unaffected (namely the down-thrown block). This would produce at surface, an apparent pattern of inverse zoning (Figure 5c).

According to Gibbs and Barron (1993) the origin of the intracratonic Parguaza intrusion (ca 1500 Ma) can be related to the last stage of the Trans-Amazonian subduction. Extensional tectonics controlled the development of the Parguaza area after cooling had been completed. Extensional-vertical movements could have been produced either by normal faulting, in the aftermath of subduction, or by the development of a system of horst and grabens.

According to the structural data for the Precambrian basement in southeastern Venezuela, there are two main trends of normal faulting and lineaments in the Guayana shield. These trends coincide with those recognized at the Parguaza intrusion (Figure 1), namely a NW-SE-striking set of faults (as a response to a NE SW-striking extension regime) and an almost E-W striking set of faults (as a response to a N-S-striking extension regime). In general northeasterly-striking faults seem to be disrupted by their northwesterly counterparts implying that the later are younger. It is difficult to establish absolute age brackets for these structural trends, however, varied geological evidence seems to indicate that the extensional evolution of the Precambrian basement in southeastern Venezuela took place during a long period that lasts from Precambrian up to Cretaceous times (e.g. De Rojas, 1987, Wynn *et al*., 1993, Gibbs and Barron 1993, Parnaud *et al*. 1995). The E-W-striking Espino graben (eastern Venezuelan basin), as well as the Takutu graben (northwestern Brazil), seem to date from a Jurassic Barremian rifting period related to the separation of South America from Africa. Consequently, the age of the system of NW-SE-striking horsts and grabens, modeled by gravity inversion in this study, would be possibly bracketed between Paleozoic prerifting and Jurassic-Barremian rifting episodes.

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