A gravity chart to quickly evaluate the probable contribution of lithospheric heating to the isostatic balance in the central Andes

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Abstract. The existence of a strong lithospheric heating beneath the Central Andes has been recognized by many authors. Isacks proposed in 1988 a mechanism that combines crustal thickening and lithospheric heating to justify both the Andean build up and its isostatic behaviour. With the purpose of including gravity in such a model, we present here a chart that simplifies the calculation of isostatic corrections for the thermal hypothesis (Pratt system). This chart was constructed from the 3-D gravity effect on a spherical earth of a thermal lithospheric "root" 400 km wide, extending between nearly 70 and 140 km depth, and whose flanks conform to the Nazca Plate subduction angle. The density contrast was assumed to be +30 kg/m^3. The largest isostatic-thermal correction exceeds +59 mGal (about 1/7 of the maximum Bouguer anomaly in the area), and a corrected Bouguer anomaly can be obtained by adding chart corrections to the observed values. Thus, via gravity inversion of this anomaly, a better determination of the real crustal root and the isostatic condition at the bottom of the lithosphere is possible. The observed Bouguer anomaly reaches about -400 mGal in the Central Andes. Of this maximum value, -60 mGal may be justified by means of expansive thermal effects taking place in the lower half of the lithoshpere. The remaining -340 mGal correspond to a crustal root of 25 km due to orogenic shortening. Thus, the two classical hypotheses (Airy in the crust and Pratt in the lithosphere) are combined to explain the isostatic balance in this Andean sector. This gravity model is consistent with the seismic crustal results in an Andean section at latitude 24.5° south.

1. Introduction

There are two recognized mechanisms for isostatic compensation: the Pratt or thermal mech-

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anism (Pratt, 1859), and the Vening Meinesz, also called the regional or flexural mechanism (Vening Meinesz, 1939). Many authors have studied this compensation system (for example, Brotchie and Silvester, 1969; Walcott, 1970a; Watts et al., 1975; Mc Adoo and Martin, 1984; Diez Rodriguez and Pacino, 1986; Sheffels and Mc Nutt, 1986). Other investigators have also worked on schemes connected with viscoelastic processes (Walcott, 1970b; Beaumont and Sweedey, 1978; Clark et al., 1978, among others).

It should be mentioned that the Airy mechanism (Airy, 1855) is only a particular case of flexure, as Walcott (1970c) noted. Let us say, therefore, that a major part of the Andes conforms, approximately, to the Airy mechanism. Yañez et al. (1993) have also pointed out that the isostatic behaviour of Andean sections in the northernmost sectors of Argentina and Chile is better explained by an Airy model than by a flexural one.

The level at which the isostatic compensation takes place is another important factor. Woollard (1969) showed that in some areas the isostatic compensation is achieved at the crust - mantle level by means of a hydrostatic mechanism; whereas, in others, the redistribution of mass takes place at greater depths, which would correspond to the Pratt compensation level. He considered a depth of 105 km. Magnitsky and Kalashnikova (1970) proposed that the changes in the surface level are due to variations in the asthenospheric system. By that time they attributed those variations to changes in the low velocity zone, due to heat flow and olivine-spinel transformations at a depth of about 400 km. Dorman and Lewis (1972) proposed that the compensation occurs at depths of at least 400 km in the United States. The isostatic adjustment extends into the mantle to depths of 400 km or so.

By means of a chart of thermal corrections and an Andean gravity - seismic model at latitude 24.5° south, we will prove that the Central Andes seem to reflect an Airy system, combined - to a minor extent - with a lithospheric heating system (Pratt).

2. The thermal model

When heterogeneity in the earth's upper mantle was discovered, Hsü (1982) pointed out that the relationship between surface elevation and mantle density also had to be considered. So, besides the Airy isostasy, "thermal isostasy'' was invoked (Haxby et al., 1976; Oxburgh, 1982; Kogan et al., 1985, among many others). This idea was anticipated by Pratt (1859) when he formulated his isostatic model.

We have taken here the original idea of Pratt (1859), since there is probably a significant caloric anomaly beneath the Andes between latitudes 13°S and 27°S (Froidevaux and Isacks, 1984; Introcaso and Pacino, 1988; Isacks, 1988). This is revealed by the many active volcanoes located in the continental crust (Fig. 1). Wigger (1986), Schwarz et al. (1984), and Götze et al. (1987), have proved that, in the intermediate crust, the velocity of seismic waves decreases, while the electric conductivity increases significantly. This suggests the probable existence of partial melting and active magmatic chambers.

According to Wörner (1991), subduction of the Nazca Plate drags the oceanic crust into the mantle, together with part of the sediments covering it. This cool material is heated when it con-

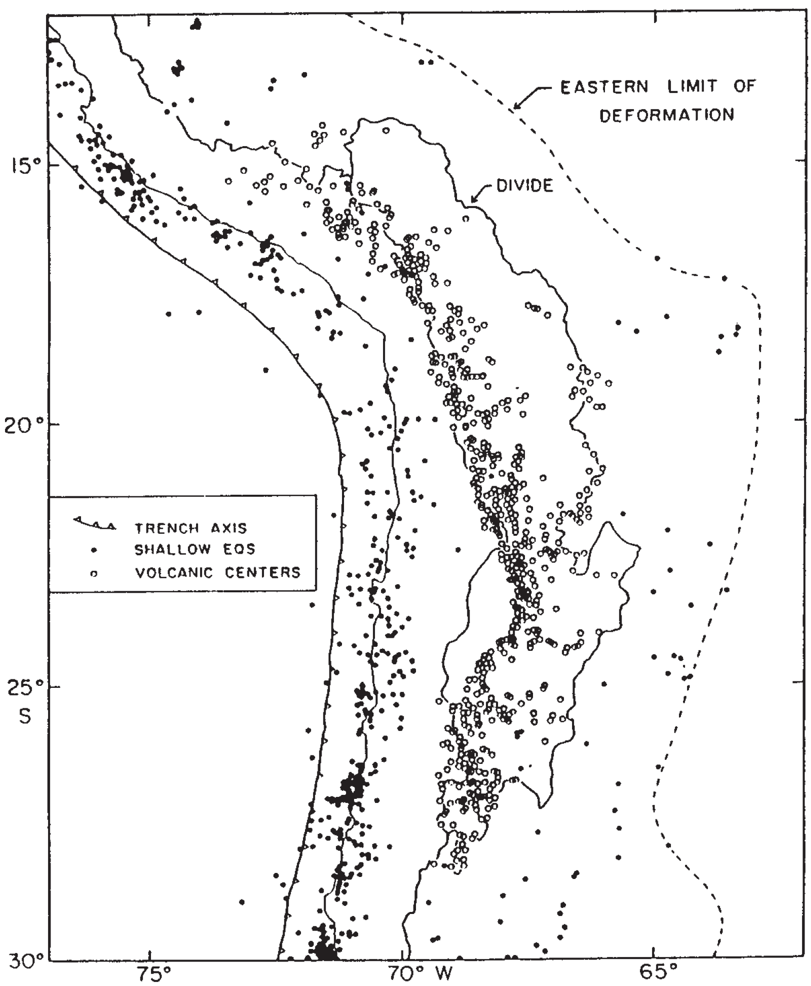

Fig. 1 - Shallow earthquakes (filled circles) and volcanic centers (open circles) in the Central Andes. The trench axes, the western South American coastline and the major drainage divides are depicted by solid lines (from Froidevaux and Isacks, 1984).

tacts the warm deeper mantle, and dehydratation reactions with water liberation towards the mantle of the South American Plate take place. This water reduces the melting temperature of some components and causes their partial melting, so that melted material ascends due to gravitational instability (Giesse and Reutter, 1987) and penetrates the crust. Once there, it may cool and crystallize generating large subterranean masses, the plutons, or it may generate the Andean volcanoes.

An important characteristic of the Benioff zone under the Peruvian and Chilean Andes is the presence of “aseismic gaps” at depths varying between 100 km and 200 km, depending on the slope of the subducted plate. These seismic silent zones exactly correspond, in a normal projection onto the surface, to the recent volcanic activity (Frutos, 1981). The aseismic gaps have been

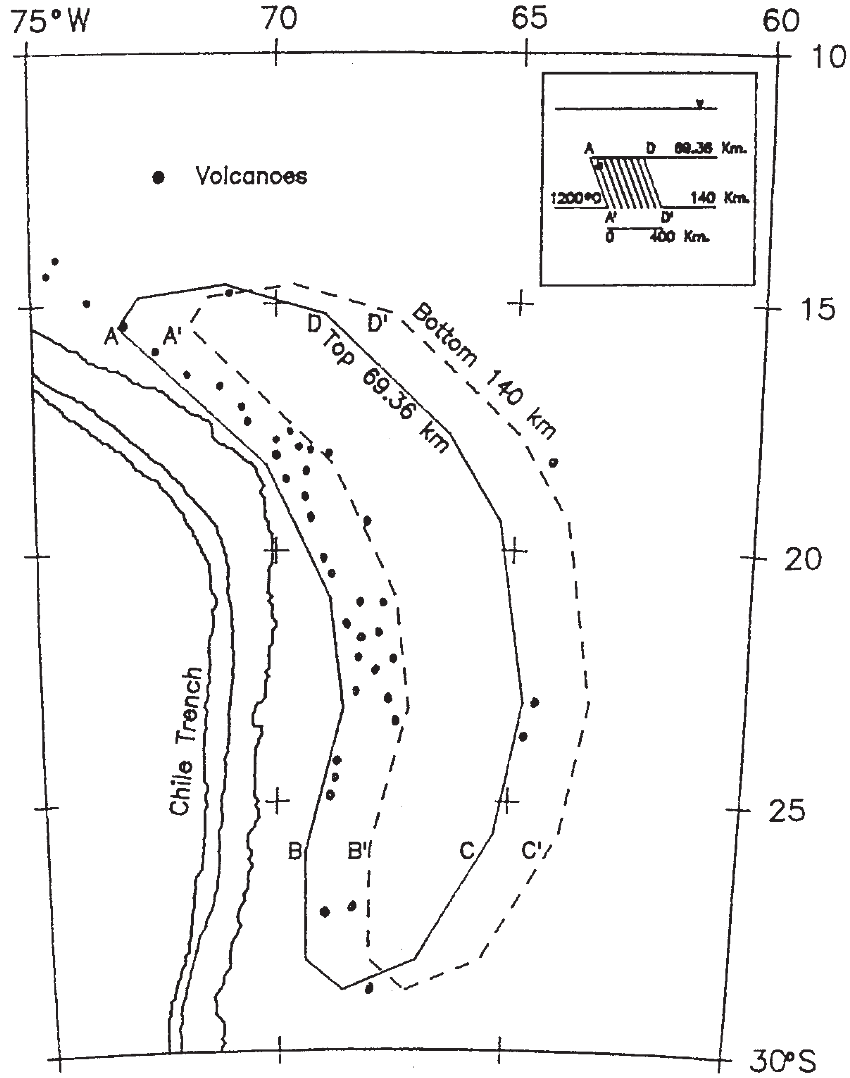

Fig. 2 - ABCD and A'B'C'D', top and bottom of the heated body at depths of 69.36 km and 140 km, respectively. Right and top, cross-section of the thermal root.

related to magma generation zones (Hamus and Vanek, 1978; Frutos and Oyarzun, 1980). Isacks (1988) assumed that the Altiplano-Puna has retained a significant thermal component since 27 Ma until the present, and he proposed a horizontal sectional areal of 28,000 km^2, while Kono et al. (1989) proposed a lithospheric heated area of 30,000 km^2 beneath the Peruvian Andes.

This significant heating beneath the Central Andes indicates the importance of thermal isostasy as a probable mechanism for partial build up in this Andean sector (Isacks, 1988; Introcaso, 1991). To work more efficiently, we prepared a chart of isostatic corrections using the thermal hypothesis. Since new, good quality, gravity data in this zone are today available (e.g., Fukao et al., 1989; Götze et al., 1990; Fairhead, 1991), this chart provides us with a quick way to separate the thermal gravity effect from other effects related to the Andean build up.

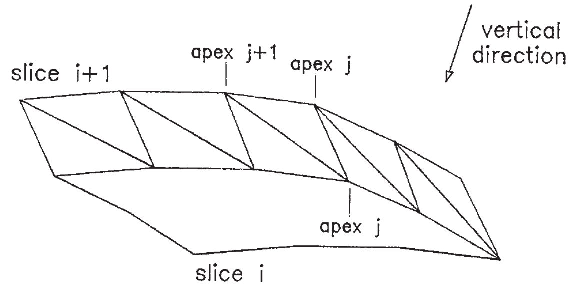

Fig. 3 - The causative body is approximated by a polyhedron defined by a series of slices at constant latitudes.

3. Some remarks on the adopted model

To locate the hot anomalous body, or "thermal lithospheric root", we start by surveying carefully the top of the subducted Nazca Plate between latitudes 13°S and 27°S using the curve that defines the Peru - Chile trench (Fig. 1). Part of this subducted surface, with constant dip of 25°, located between depths of nearly 70 and 140 km (Froidevaux and Isacks, 1984; Isacks, 1988), defines the slope of both flanks of the hot anomalous body (see in Fig. 2 the parallelism between AB and A'B', and between DC and D'C', and their equidistant positions with respect to the Peru - Chile trench).

The change in the thermal lithospheric thickness is then due to the ascent of the 1200°C geothermal boundary from 140 km to 70 km, as may be clearly seen in the top right inset of Fig. 2.

According to Isacks (1988), the "thermal root" width is AD = A'D' (Fig. 2). Both the top and bottom of the "thermal root" are also in good agreement with the 3,000 m altitude contour. Its longitudinal extension from 13°S to 27°S coincides with the distribution of Quaternary vulcanism.

Let us now calculate the anomalous density produced by the heating. The ascent of the 1200°C geotherm from 140 km to 70 km depths means that the average temperature variation in the lower half of the thermal lithosphere is

$$\overline{\Delta T} = 1/2\,(1200°\mathrm{C} - 600°\mathrm{C}) = 300°\mathrm{C}.$$

Thus, we infer the anomalous density in kg/m^3 from

$$\Delta\sigma_c = \sigma_L \times \alpha \times \overline{\Delta T}$$

where σ_L is the lithospheric density = 3300 kg/m^3; α is the thermal expansion coefficient = 3×10^{-5} (°C)$^{-1}$, and ΔT = 300°C. In this way we have a density deficit $\Delta\sigma_c$ = 29.7 kg/m^3-30 kg/m^3. With this value, and assuming a lithospheric thickness L = 140 km., the surface elevation due to the thermal expansion is

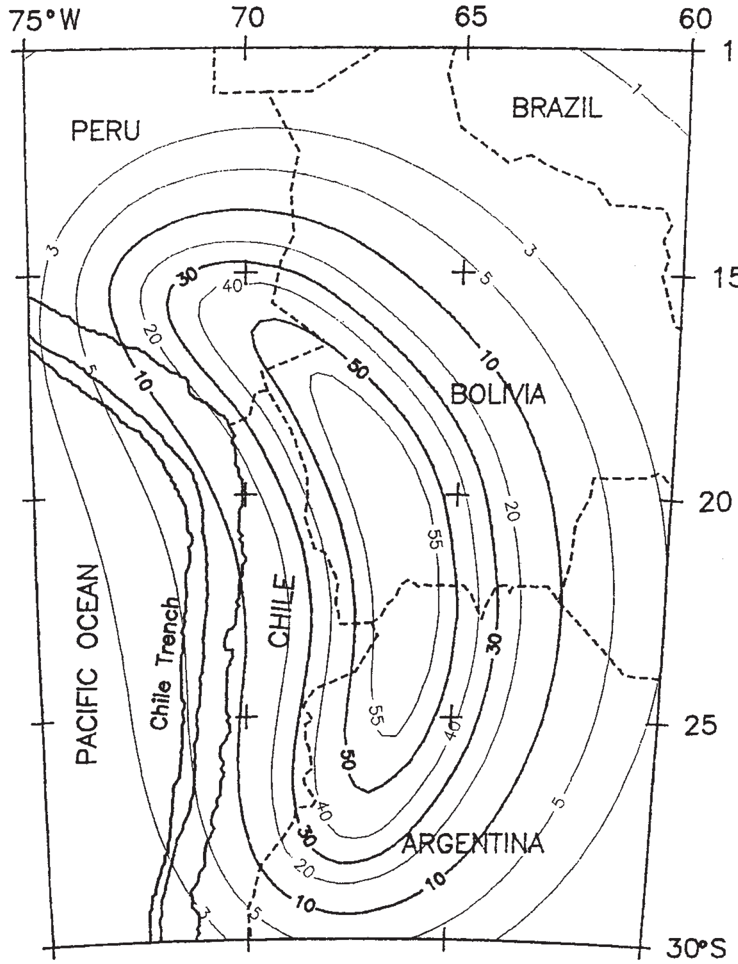

Fig. 4 - Chart of isostatic gravity corrections for thermal hypothesis (contours in mGal).

$$S = \alpha \times L / 2 \times \overline{\Delta T} = 0.630\,\text{km},$$

which is consistent with the expression

$$S = \frac{\Delta\sigma_m}{\Delta\sigma_m^{'}} \times \frac{L}{2} = 0.642\ \text{km},$$

with $\Delta\sigma_m = 30$ kg/m^3; $\sigma_m = 3270$ kg/m^3; and $L/2 = 70$ km. This last expression is taken from Hayford (1909). Both expressions equalize pressures at the bottom of the lithosphere between a standard column at sea level and an abnormally heated column which loses density and expands, raising the topographic surface.

Note that the deficit of density in the anomalous lithospheric “root” is -30 kg/m^3, but the chart for thermal isostatic corrections must be calculated for $\Delta\sigma = +30$ kg/m^3.

Finally, let us say that the heating mechanism may at most justify only 60% of the 4 km alti-

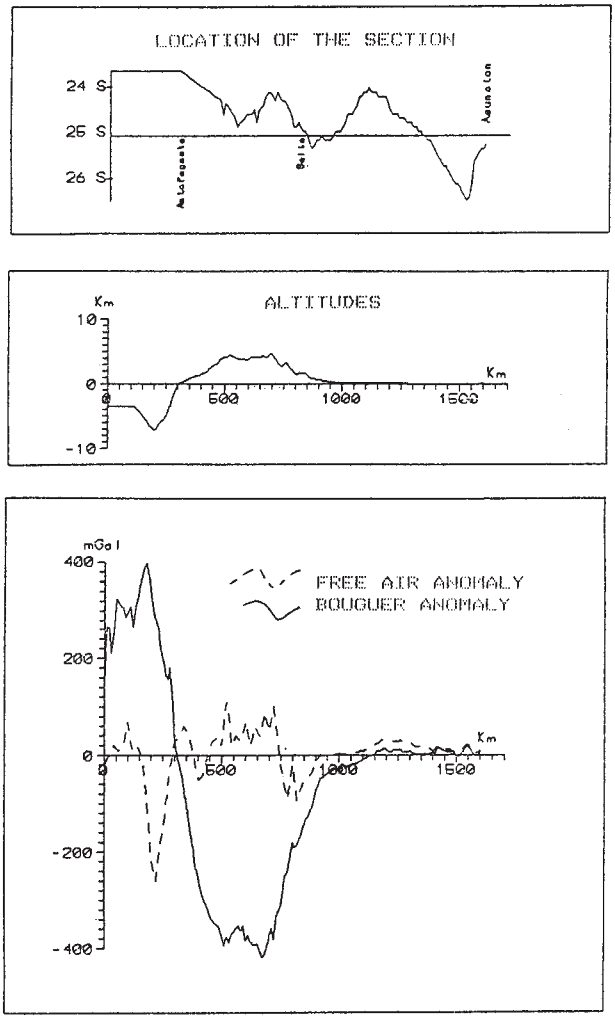

Fig. 5 - Location of the section. Altitudes, Free Air and Boguer anomaly profiles.

tude of the Altiplano. In fact, if we assume that the 1200°C geotherm rises to the surface, the mean thermal anomaly over the whole lithosphere with thickness L would be ΔT’ = 1200°C/2 = 600°C. With $\alpha = 3\times10^{-5}$ $(°C)^{-1}$, L = 140 km, and ΔT’ = 600°C, the highest elevation would be S=2.52 km. So, the thermal mechanism alone is not strong enough to justify the complete elevation of this Andean Segment.

4. Development of the chart of isostatic corrections

With the anomalous body already defined and the density contrast assumed to be +30 kg/m^3, the gravity correction was computed on a grid of 46x61 stations located between longitudes 60° and 75° west and between latitudes 10° and 30° south. The separation was 20’ in both directions,

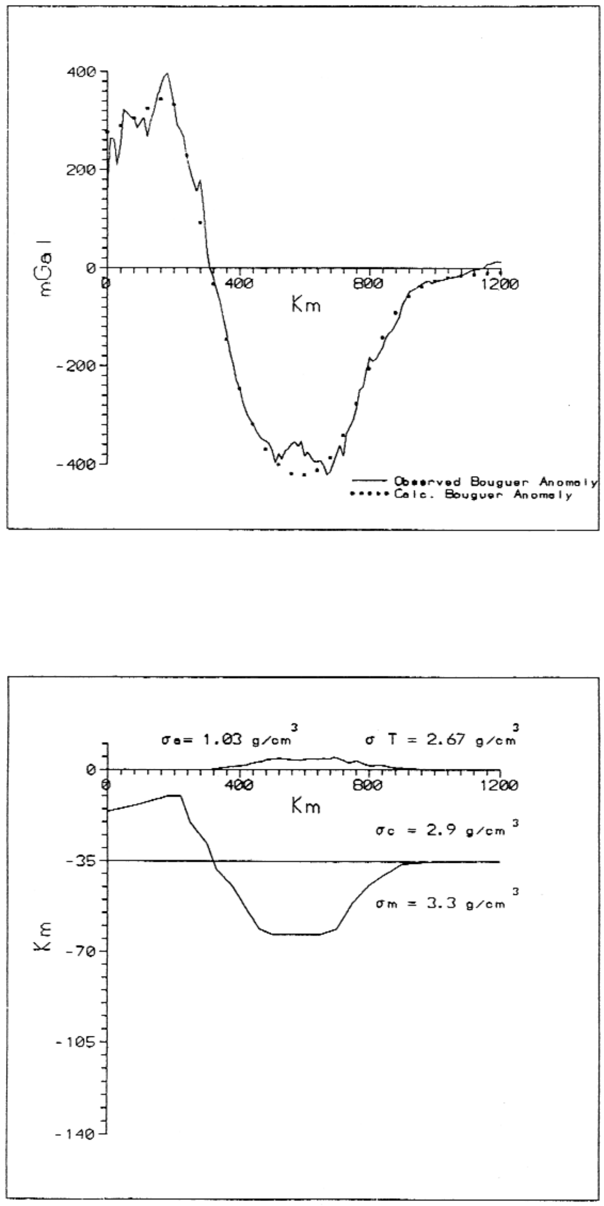

Fig. 6 - Observed Bouguer anomaly from Fig. 5. and calculated Bouguer anomaly (or regional anomaly) from the model below.

and the stations were considered at their real topographic heights, extracted from a global computer file.

The homogeneous source of the gravity effects presented in this paper is approximated by a polyhedral body, and the basic guidelines for assembling such a model are given in the paper by Barnett (1976). The polyhedron is defined by apices placed around a series of slices through the body.

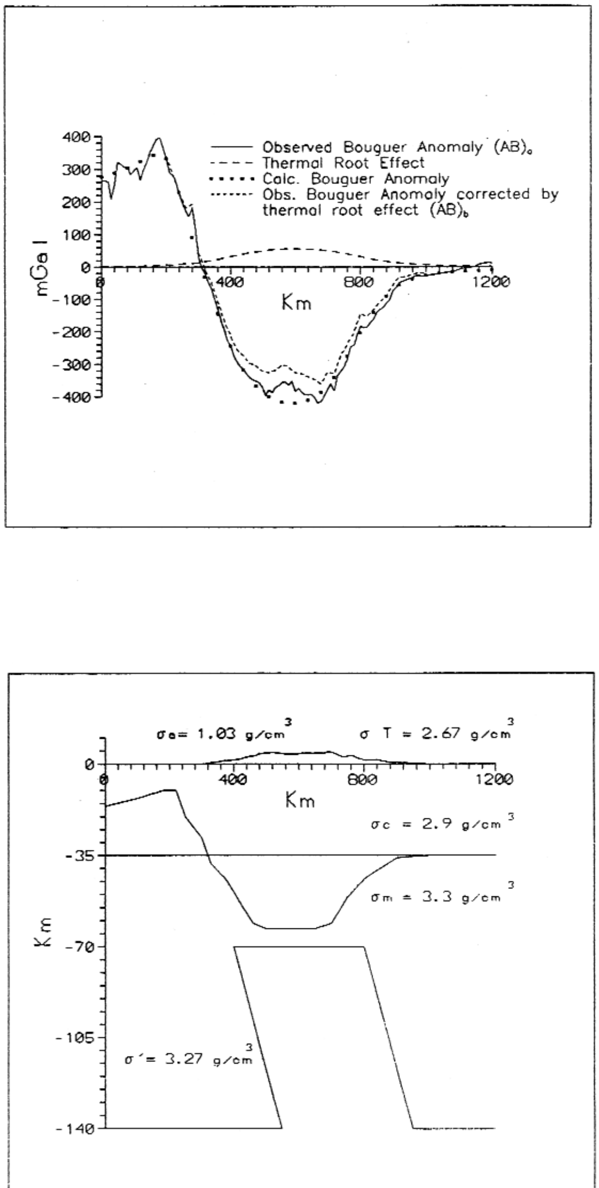

Fig. 7 - Observed Bouguer anomaly from Fig. 5, thermal root effect from the chart in Fig. 4, corrected Bouguer anomaly and calculated Bouguer anomaly from the model below (thermal and crustal root gravity effects).

As our body has an elongated shape in the N-S direction, we construct a series of 16 slices, each at constant latitude, separated by a distance of about 1°. Ten apices define the contours of the slices, and they are not planar, since latitude is kept constant (Fig. 3).

In order to assess to what extent the influence of the earth's curvature is important at the scale of this work, we repeat the calculations using a flat-earth model. There are many ways to

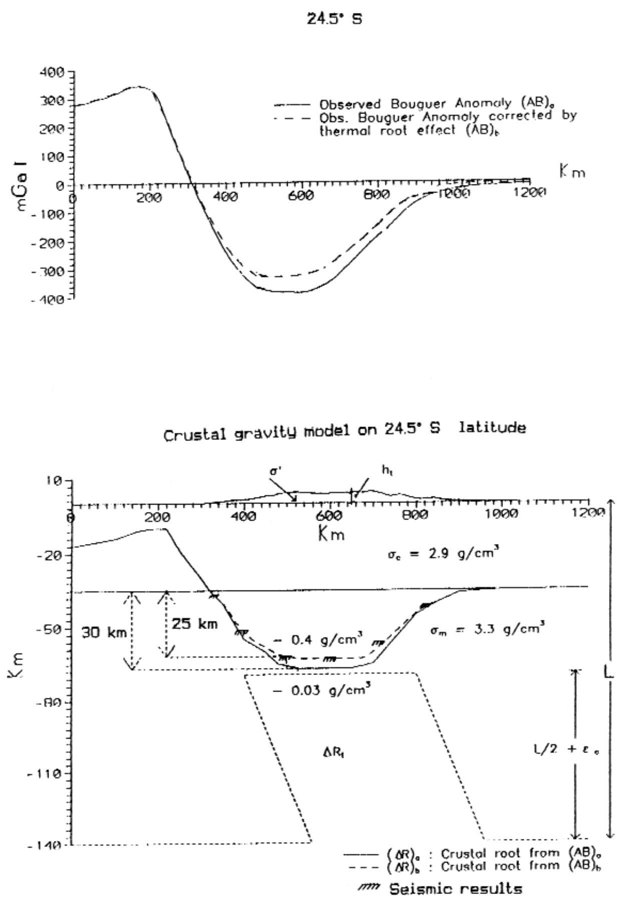

Fig. 8 - Gravity-seismic model at latitude 24.5° south explaining the isostatic balance by means of a combination of both a crustal root 25 km thick and a thermal root located in the lower half of the lithosphere.

"flatten'' a real earth representation; here we choose a coarse model, in which latitudes in degrees are converted into kilometers simply by multiplying by 111.2 (the distance in km between two parallels located one degree apart), and longitudes by 104.5 (the analogous distance in km between two meridians at the mean latitude of 20°). The calculations now simplify, since the tops and bottoms of the slices are horizontal and only four vertices are needed to define them. Moreover, the slices are planar and vertical, thus allowing gravity computation to be performed by the method developed by Guspì et al. (1987), which makes the rotation of coordinates required by more general methods for polyhedra unnecessary.

The differences between flat and spherical model results, about one mGal, are not very significant. As the earth's curvature is itself a "long wavelength phenomenon'', it interacts only weakly with the short to medium wavelength features of the geopotential (Vermeer, 1992).

The result, represented as a map in Fig. 4, is the gravity isostatic correction chart for the Central Andes using Pratt's hypothesis. As we can see, the distribution of the contour lines is nearly concentric, following approximately the shape of the physical model, with very small values in the surroundings of the body and a peak of 59 mGal at its center.

5. Example and conclusions

To illustrate the use of the chart in Fig. 4, we considered a W-E gravity section approximately centered at latitude 25°S, which starts east of the Chile trench and ends at Clorinda city (Argentina), at the boundary with Paraguay (Pacino, 1991). Profile location, altitudes, Free Air and Bouguer anomalies are represented in Fig. 5. The regional anomaly was calculated using spectral analysis (Introcaso and Guspì, unpublished).

Assuming a normal crustal thickness of 35 km (Kono et al., 1989), a density contrast between crust and upper mantle of -400 kg/m^3 (Introcaso et al., 1992) and the whole Bouguer anomaly caused by crustal thickening under the Airy hypothesis, a simple crustal model with about 30 km of maximum root would be obtained by 2D gravity inversion (see Fig. 6).

Consider now Pratt's thermal isostasy to justify part of the Andean build up at these latitudes, and take the values for the gravity corrections from the chart in Fig. 4. The corresponding curve in Fig. 7 is then subtracted from the observed Bouguer anomaly (Fig. 7) to obtain the corrected Bouguer anomaly (Fig. 7), which is used to calculate the crustal root. After inverting the corrected anomaly with the same crustal parameters assumed before, we obtain a crustal root with a maximum thickness of 25 km.

So, we can analyze the isostatic balance for the Central Andes in two ways: (a), by means of a thickened crust caused by orogenic shortening; and (b), by means of a combination of crustal thickening and lithospheric heating (thermal expansion).

The model from Isacks (1988), which, as the author pointed out, is not the only possible model, also distributes the compensation in the Central Andes between a crust with 65 km of maximum thickening, density σ_c=2930 kg/m^3 and normal crustal thickness T_n=40 km, laying over an upper mantle with density σ_m=3320 kg/m^3, and a lithospheric thermal "root" as the one considered here. This model assumes isostatic compensation, but does not involve the analysis of gravity data.

We added gravity data to Isacks' (1988) proposal, and constructed a chart of isostatic corrections that makes the study easier, since it allows us to easily separate gravity effects in the observed Bouguer anomaly (such as the lithospheric heating effect) from those due to crustal thickening.

In our example, the choice between the results of one or the other procedure is easier, since the seismic data available for this Andean segment (Fig. 8) permit us to locate the maximum M depth at 60 km (Schmitz et al., 1993). So, the "crustal root" obtained from seismic methods is consistent with that defined by the combination of both mechanisms (crustal thickening and lithospheric heating).

Finally, we point out that the isostatic analysis performed here is neither the only one possible (Grow and Bowin, 1975; Isacks, 1988), nor the most complete one (Introcaso and Pacino, 1988); however, it is more general than the classic one (related only to crustal thickening), since it considers the constraint imposed by the gravity anomalies as well.

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