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ISOSTATIC SYSTEMS AND TECTONIC MECHANISMS PRESENT IN ARGENTINA

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ABSTRACT

It is well known the diversity of geological structures present in Argentina. This makes it possible to analyze the vertical mobility throughout five selected cases in which different isostatic systems act. They are: Airy (+), (-) for an Andean section compensated on 33° S; Airy (-), (+) for the decompensated Salado basin; regional (or Vening-Meinesz's) to explain - although partially - the imperfect compensation of the Córdoba ranges; Airy and Pratt (thermal) systems combined to explain the Andean section compensated on 25° S; and Rudzki (+), (-) to explain - in part - the decompensation of the 50°20' S Austral basin section.

At the same time, we have considered the following mechanisms: shortening (on the Andes and Córdoba Ranges); thermal expansion (that we add to the Andean section on 25° S); stretching, thermal deactivation and load subsidence and load subsidence on the Salado and Austral basins.

By analyzing not only the compensation level but also either the most adequate isostatic system or the involved mechanisms, a better understanding of the origin and evolution of each structure can be achieved.

RESUMEN

Es bien conocida la diversidad de estructuras geológicas presentes en Argentina. Ello hace posible analizar el movilismo vertical a través de cinco casos seleccionados en los cuales operan diferentes sistemas isostáticos; a saber: Airy (+), (-) para una sección Andina compensada en 33° S; Airy (-), (+) para la cuenca descompensada del Salado; regional (o de Vening-Meinesz) para explicar - aunque sólo parcialmente - la compensación imperfecta de la Sierra de Córdoba; Airy y Pratt (térmica) combinadas para explicar la sección andina compensada en 25° S; y Rudzki (+), (-) para explicar en parte la descompensación de la sección en 50° 20' S de la cuenca austral.

Hemos contemplado al mismo tiempo los siguientes mecanismos aportamientos (en los andes y en la Sierra de Córdoba); expansión térmica (que agregamos a la sección andina en 25° S); estiramientos, desactivación térmica y subsidencia por carga en las cuencas del Salado y Austral.

Analizando no sólo el grado de compensación sino además tanto el sistema isostático más adecuado como los mecanismos involucrados, puede lograrse un mejor conocimiento de la génesis y evolución de cada estructura.

1. INTRODUCTION

The different isostatic systems demand to compensate the heterogenities of the masses located on the upper part of the crust, with equivalent masses below them. These masses, called compensating masses, are located at different depths, sometimes reaching deep levels in the upper mantle. The beginning and evolution of the different geological structures are entailed to:(1) the isostatic system characteristics, and (2) the compensation level that was reached. It is because of this, that it is important to recognize (1) and (2) while analyzing a structure by means of geophysical data, particularly by means of gravity. We start by describing the different isostatic systems mentioned in this paper, using the idea of dipolar distribution.

Dipole moment: It is known that two magnetic masses -m, +m making up a dipole originate a potential on external points ($r_1 \sim r_2$; r_1(or r_2)>>d) (Fig. 1):

$$V_P=\eta\nabla\left(\frac{1}{r}\right) z=\eta\,(\partial/\partial n)\left(\frac{1}{r}\right) \qquad (1)$$

where η is the magnetic moment: m x d. If we take gravitational masses -m and +m instead of magnetic masses, the expression (1) will become:

$$V_P=M(\partial/\partial n)\left(\frac{1}{r}\right)$$

where M = m x d: dipole moment.

From a dipole unit we can generalize the case of the potential of double layer. However, we concentrate our attention on the dipole moment related to different isostatic mechanisms treated in this paper. If we have a column with topographic mass +m and compensation mass -m and density σ separated by a distance d, (Fig. 2), we will have a distribution with dipole moment:

$$M=m\times d=((\sigma\times s\times h)/s)\times d=\sigma\times h\times d=\frac{h}{2}+T_n+\frac{R}{2}$$

The condition d → 0 is relatively well satisfied if d is small compared with the distance to the station.

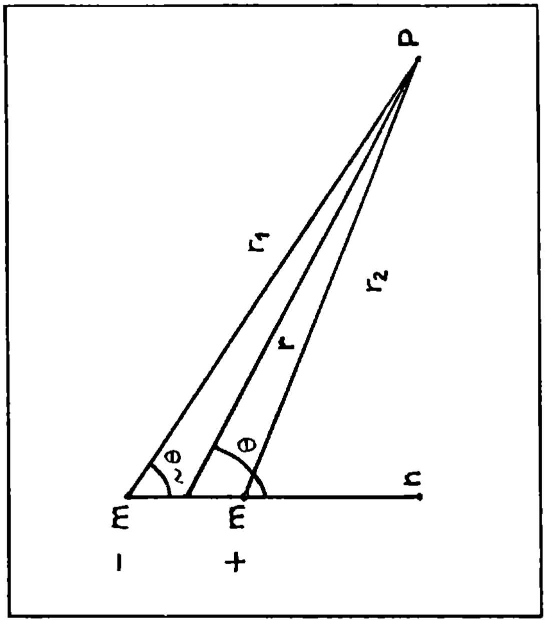

Fig. 1. Potential Vp of a dipole with $r_1 \sim r_2 \sim r$ and r_1 or $r_2 >> d$

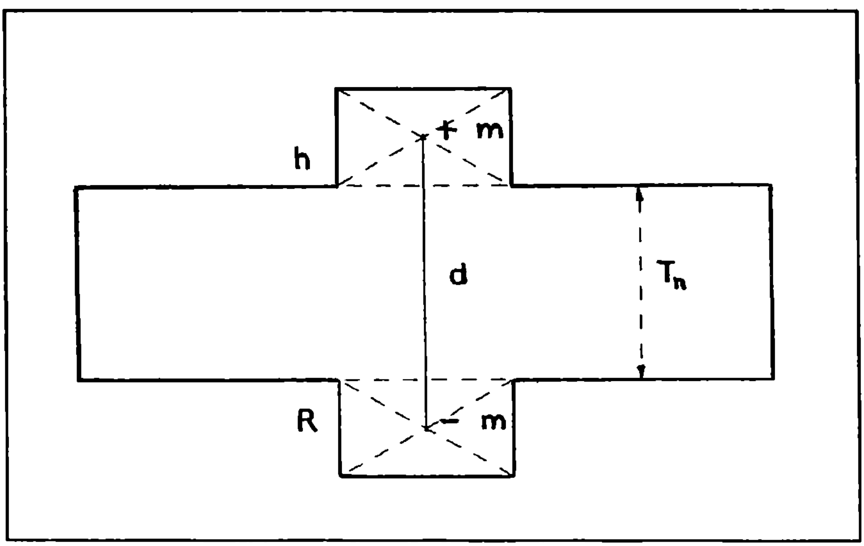

Fig. 2. Topographic mass + m and compensation mass - m separated by a distance d.

2. ISOSTATIC SYSTEMS

For different reductions we will have (Heiskanen and Moritz, 1965):(a) Pratt-Hayford: d=(h+H)/2; (b_1) Airy-Heiskanen (continent):d=Tn+(h+R)/2; (b_2) Airy-Heiskanen (ocean): d'=T_n-(h'+R')/2; (c) Rudzki (inversion): d=h (Fig. 3).

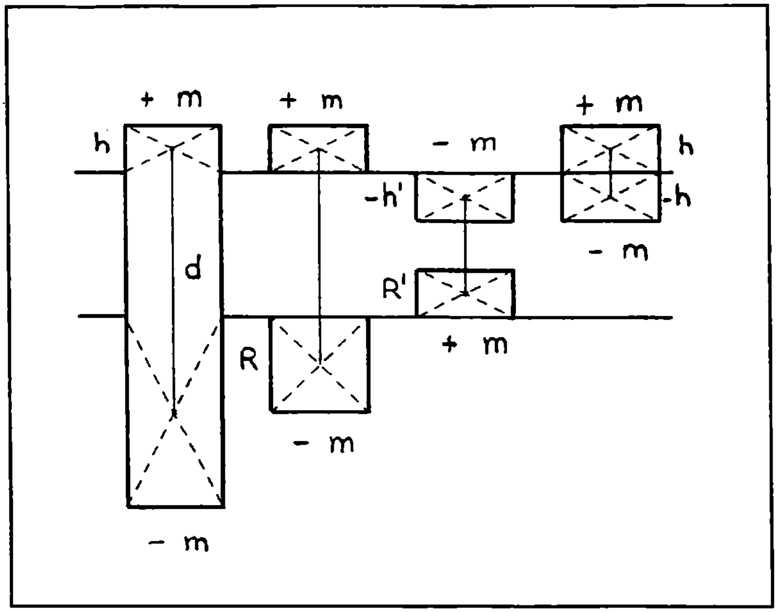

Fig. 3. Isostatic compensation systems: a (Pratt), b_1 and b_2 (Airy), c (Rudzki).

We have already analyzed the dipole moment ,ή = σ.h.d for continental areas. Instead of this, for oceanic areas we will have:

$$\mu=-h'(\sigma-\sigma_\omega)\,d'$$

where σ_ω is the water density. In the case of a sedimentary basin:

$$\mu=-h'(\sigma-\sigma_s)\,d'$$

where σ_S is the sediments' density.

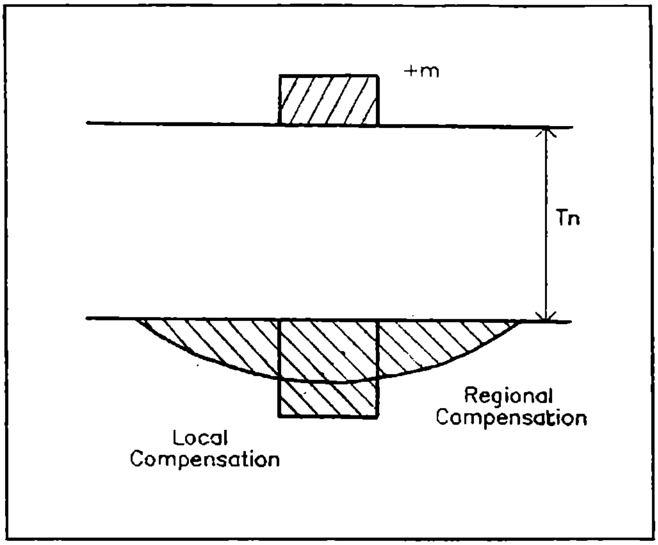

Fig. 4. Local compensation (Airy) and regional (V. Meinesz) of a topographic mass + m.

We have just considered the case of compensated columns. The regional (flexural) system of Vening-Meinesz distributes the compensation on a root of less amplitude, although distributed in the same way that the flexure and elastic beam suffers when loaded with a mass + m (Fig. 4). Next, we will see mechanisms that - keeping the isostatic equilibrium - originate uplifting and subsidence.

3. UPPER MANTLE MATERIALS HEATING AND COOLING

This mechanism keeps the isostatic equilibrium at the bottom of the normal lithosphere expanding (uplifting) the upper mantle column in presence of anomalous heating and depressing it in case of cooling. We assume the following initial conditions: "normal" crustal thickness: T_n= 30 km; thermal lithospheric thickness: L= 100 km; crustal density: σ_C=2.9 g/cm^3; upper mantle density: σ_m= 3.3 g/cm^3; thermal expansion coefficient: α=3x10^{-5} 1/°C. So, the upper mantle density variations $\Delta\sigma$ each ± 100 °C of the thermal anomaly, ΔT will be:

$$\Delta\sigma = \pm\sigma\alpha\Delta T = \pm 3.3\times 10^{-5}\times 100°C\,1/°C\,g/cm^3 = \pm 0.01\,g/cm^3$$

The expression that leads the ascension or descent of the 70 km mantle column that supports a crust 30 km thick and keeps pressures at a depth of 100 km is:

$$70(1-(3.30/(3.30\pm n\Delta\sigma)))$$

where n=1,2,3,4 and 5; and $\Delta\sigma$ = 0.01 g/cm^3. Fig. 5 shows the elevations ρ_e and depressing ρ_d of the lithospherical column in presence of anomalous heating (density defects) and cooling (density excesses).

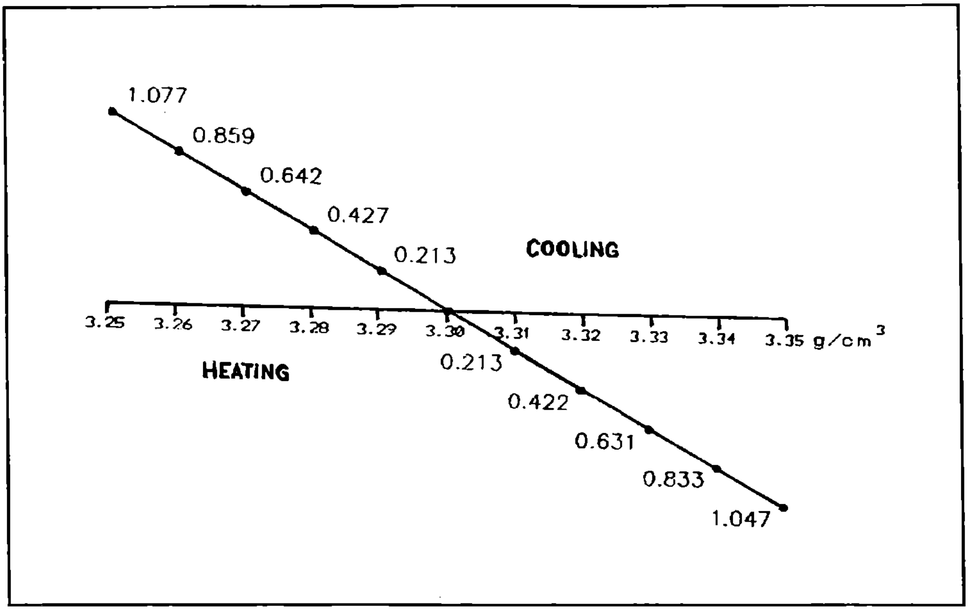

Fig. 5. Left: elevation of the upper mantle column with L_m= 70 km (and of the whole lithosphere) 100 km thick, in presence of density increasing by heating. Right: Depressing of the same column in presence of cooling.

4. CRUSTAL ATTENUATION AND THICKENING

This mechanism keeps the isostatic equilibrium at the crust, producing subsidence in the case of attenuation and elevation in the case of thickening. In order to study these effects, we assume the following initial conditions: σ_c= 2.9 g/cm^3; σ_m= 3.3 g/cm^3; crustal thickness T_i=30 km ± nx5 km, where n is varying from 1 to 4 in the case of attenuation (with n=4: T_n= 10 km; below this value in 9.375 (= 30 / 3.2) the crust could break (Le Pichon et al., 1981). In the case of thickening, n varies from 1 to 7 (for n=7: T_n= 65 km which is the case of many Andean segments (Introcaso et al.,1992). The expression used here is:

$$\rho' = 5n(1-2.9/3.3)) = \pm n0.606$$

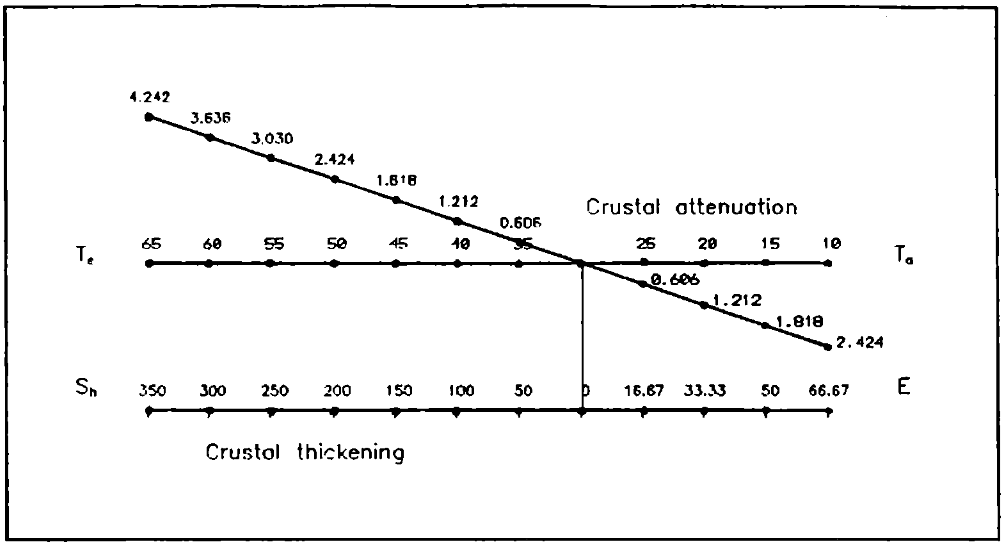

Fig. 6. *Left*: Elevations originated by crustal thickening T_e due to shortening S_h (on abscissas, calculated with a crustal width $\acute{\omega}_0$= 300 km). *Right*: Subsidence originated by crustal attenuation T_a on abscissas due to stretching S_t with a width $\acute{\omega}'_0$ = 100 km.

Fig. 6 shows the mentioned changes. All the columns show equality of pressure at a depth of 60.758 km, reached by the maximum thickening. We should also consider the mechanisms that thicken and attenuate the crust. Thickening is usually entailed with shortening Sh (for example on the Andes). So, for a width $\acute{\omega}_0$= 300 km, the shortened sector:

$$S_h = (\varpi_0 \times (T_e - T_n)) / T_n = (300 \times (T_e - 30)) / 30$$

where T_n= 30 km, T_e=T_i= 30 + 5n. For example, if T_e is 65 km, it will become S_h= (300 x 35) / 30= 350 km. It is also usual to entail crustal attenuation with stretching S_t. If the stretched sector width is $\acute{\omega}'_0$= 100 km, stretching will be:

$$S_t = (\varpi_0 \times (T_n - T_a)) / T_n = (100 \times (30 - T_a)) / 30$$

where T_n= 30 km, T_a=T_i=30-5n. For example, if T_a is 15 km, it will become S_t= (100 x 15) / 30 = 50 km.

5. CRUSTAL DENSITY CHANGES

Increasing of crustal density keeping T_n and σ_m produces subsidence, while decreasing of crustal density without changes in T_n and σ_m produces elevations. In both processes the isostatic equilibrium is kept in the Airy System. At the maximum reached depth (density 2.95 g/cm^3) every column equals pressures.

With the following initial conditions: T_n= 30 km (constant), σ_m= 3.3 g/cm^3 (constant) and varying σ_c according to σ'_c = (2.9 + n 0.01) g/cm^3, with n= 1, 2, ..., 5 we will have the variation graphic (Fig. 7).

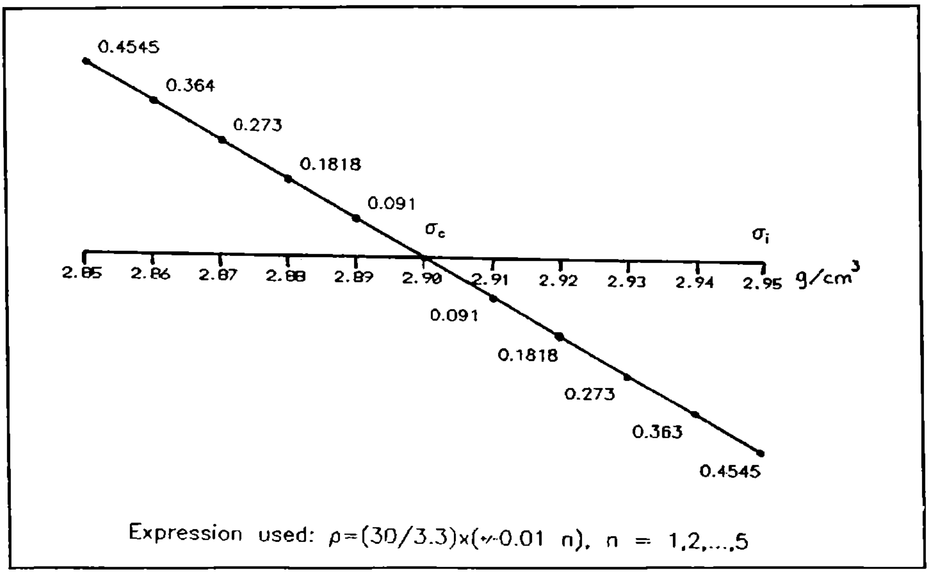

Fig. 7. *Left:* Elevations produced on a crust with density excesses and where T_n is constant. The crust lies on a mantle in which σ_m is constant. *Right*: Subsidence produced on a crust with density excesses, where T_n and σ_m are constant.

6. SUBSIDENCE BY SEDIMENTARY LOAD

One of the mechanisms contributing to the evolution (subsidence) of a sedimentary basin is the load of sediments. The process - controlled by isostasy under the Airy hypothesis - needs to have an initial trench produced, for example, by stretching.

With the following initial conditions obtained from Fig. 6, paragraph b): S_0 varying between 0.606 km; 1.212 km; 1.818 km and 2.424 km, the basin would develop to its whole fulfilling of sediments with density σ_S= 2.35 g/cm³ descending respectively to 2.10 km; 4.21 km; 6.315 km and 8.42 km (Fig. 8). We have used the expression proposed by Introcaso (1980):

$$S_T = S_0 / (1 - \sigma_S / \sigma_m)$$

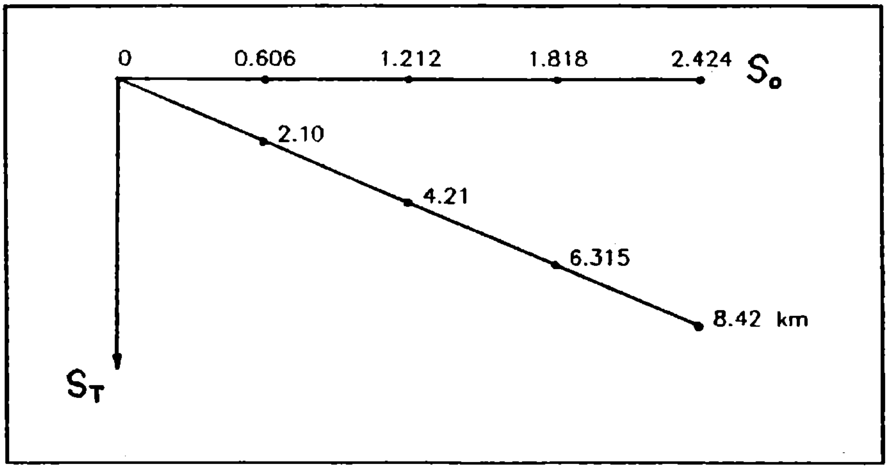

Fig. 8. Sedimentary load on an Airy system increases subsidence in $(1-\sigma_S/\sigma_m)^{-1}$

We have found and analyzed some examples in Argentina (see locations at Fig. 9) where the isostatic behavior is adapted - at least partially - to the different compensation hypothesis we have pointed out. They are:

♦ Andes Cuyanos where - as the isostatic anomalies indicate - compensation would take place in a system like b_1 (Fig. 3) (Airy-Heiskanen, + m_T-m_R) at the bottom of the crust and agreeing with seismic data; + m_T-m_R= 0.

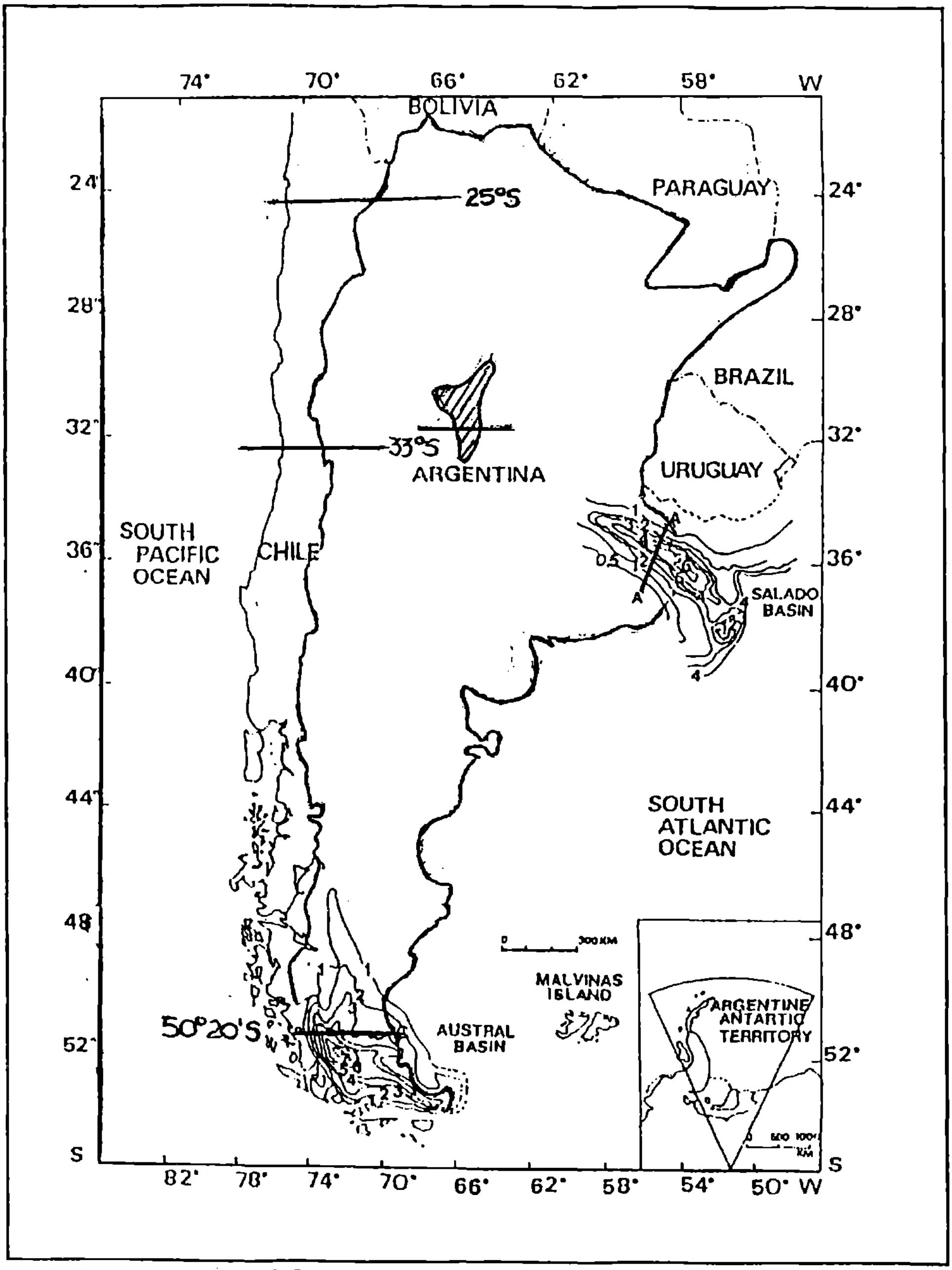

Fig. 9. Location of the five analyzed gravity sections

♦Central Andes where compensation - pointed out by small isostatic anomalies - would take place at a depth of 140 km involving a combination of systems (a) Pratt-Heyford, and (b) Airy-Heiskanen (Fig. 3). So, the Andean exceeding mass + m_T is compensated by means of the deficits originated by the crustal root $-m_R$ and the thermal root $-m_c$; $m_T - m_C - m_R = 0$ (Fig. 10).

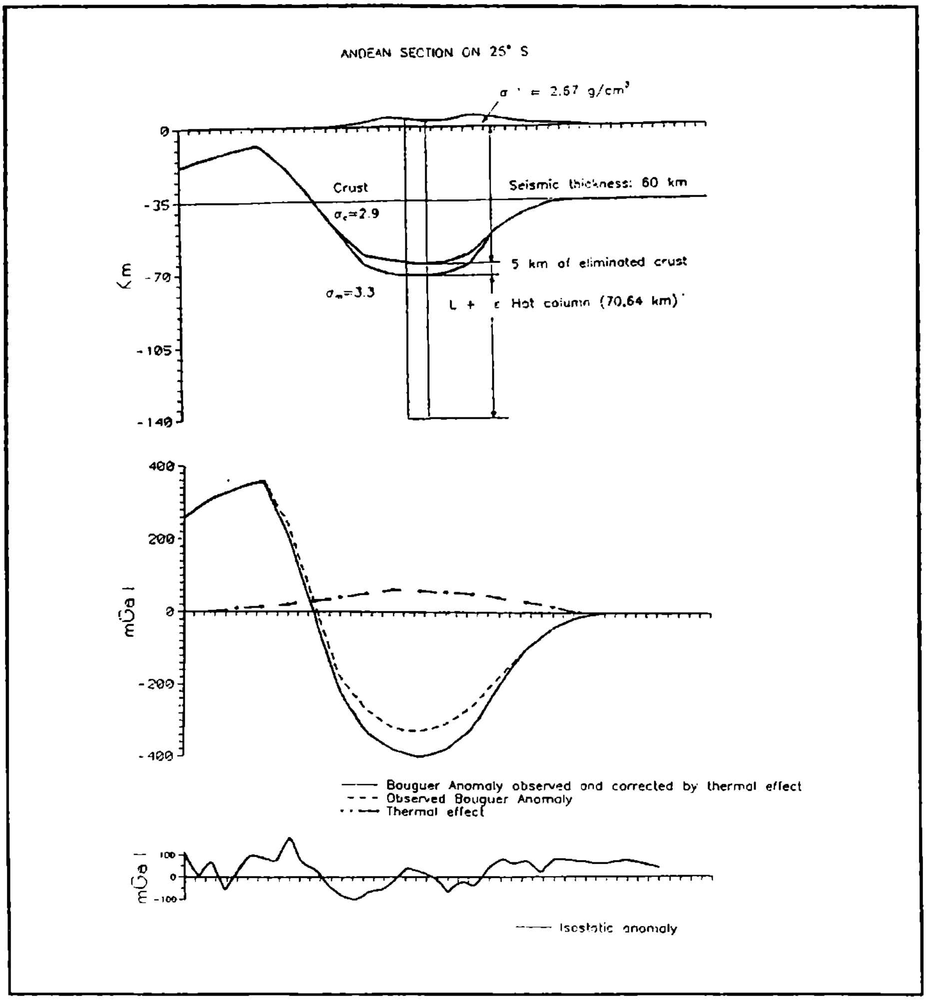

Fig. 10. *Top*: Crustal model that explains the observed Bouguer Anomaly by means of a combination of a 25 km crustal root (agreeing with the maximum seismic depth of 60 km) and thermal expansion on the lithospheric mantle. *In the middle*: Observed Bouguer Anomaly (ABo) and Bouguer Anomaly observed and corrected by the thermal effect. *Bottom*: Isostatic Anomaly. Source: Introcaso, A. (1993).

♦ Salado basin, whose significatively positive isostatic anomaly in the Airy system (-m,+ m), would indicate decompensation -m+ m > 0, excess of crustal density, or a combination of both.

♦ Northwards the Austral basin, whose isostatic anomaly in the Airy system is positive. However, the setting of the materials located over the crystalline basement, allows us to analyze the possibility of partial compensation on the upper crust (Rudzki system +m, -m) although + m - m > 0. So, + m is integrated with the masses located over the sea level and the masses excess inside the crust, while - m involves sediments below the sea level and a probable small root.

♦ Córdoba range does not seem to respond neither to a compensation system like the Airy one nor to a regional system like the Vening-Meinesz's one. The range appears decompensated (the isostatic anomaly is positive, increasing from west to east); + m - m > 0.

Fig. 11 shows columns that equal pressures at a depth of 120 km. They constitute models to begin the analysis of different structures of Argentina treated in this paper. In every case, the analysis of isostatic compensation must be done together with the genetic mechanisms and evolutions involved in the compensation systems. They must be consistent with the studied structures.

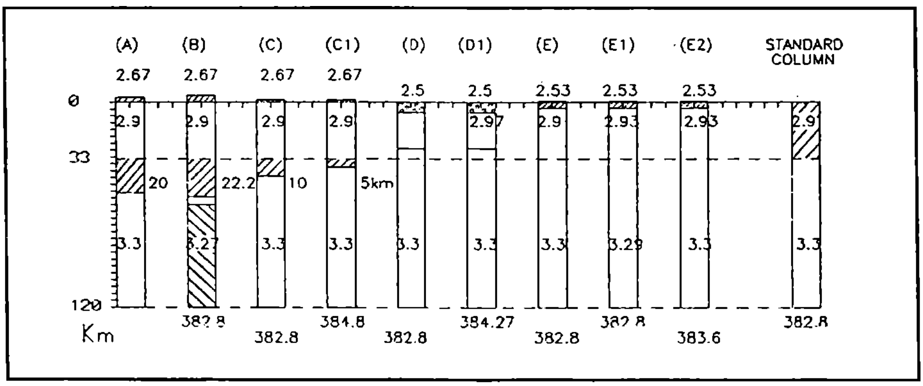

Fig. 11. Columns that equal pressures at a depth of 120 km. To the right, the standard column. All the columns have been thought to begin the study of the following sections: Andes on 33° S (Column A); Andes on 24° S (Column B); Córdoba Range (Columns C, isostatically compensated and C1 undercompensated); Salado Basin (Columns D isostatically compensated and D1 overcompensated); Austral Basin (columns E and E1 isostatically compensated). The densities: 2.67, 2.9, etc. are expressed in g/cm^3. Below each column there are pressures (with unitary gravity) expressed in 10^5 dyn/cm^2.

So, at the Central Andes (25° S latitude; Fig. 11 column B and Fig. 10) the isostatic anomalies at the Airy system are minimum compared with the significative Bouguer anomalies (AB) whose maximum is over - 400 mGal. The seismic-crustal model presents a maximum M depth of 60 km (Schmidt, 1993). The AB inversion in a crustal system like the Airy one gives a maximum M of 65 km. But a combination of a 60 km crustal root (in agreement with the seismic model) and the lithospheric expansion by heating of the lower half of the 70 km thermal lithosphere (Isacks, 1988) satisfies the observed Bouguer anomaly (Introcaso, 1993), Mechanisms correspond to Fig. 6 and Fig. 5. Two mechanisms would so explain the Andean uplift: shortening of about 250 km (Isacks, 1988) and thermal uplifting. From an isostatic point of view, two mechanisms are acting: Airy one on the crust and thermal one (Pratt) on the lithospheric mantle.

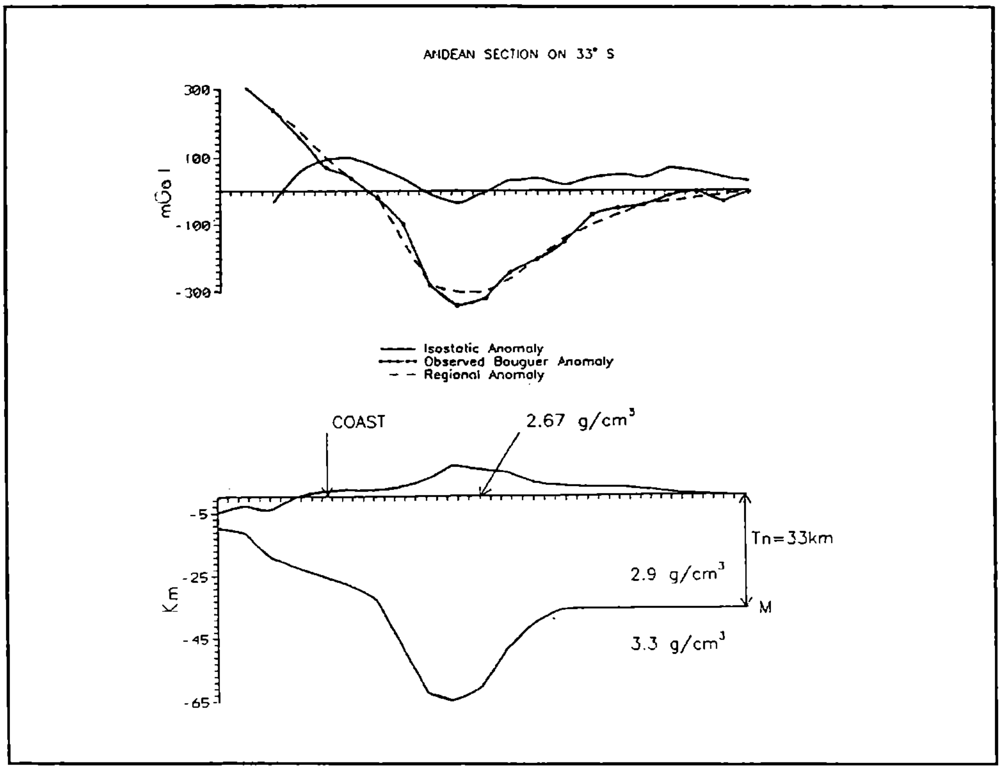

Fig. 12. Crustal gravity model on 33° S. Top: Observed Bouguer Anomaly; Regional Anomaly and Isostatic Anomaly. Bottom: Crustal model obtained by gravimetric inversion. <u>Source</u>: Introcaso et al. (1992).

At the Andes Cuyanos (33° S, Fig. 11 A and Fig. 12) the isostatic anomalies are also minimum, while the AB inversion with maximum values of -300 mGal produces a maximum M of 65 km, agreeing with the seismic model of Pardo-Fuenzalida (1988). Shortenings of 130 km justify the whole Andean uplifting in a process controlled by the Airy system (Introcaso et al., 1992). The involved mechanism can be seen in Fig. 6 (left).

At the Salado basin, a cross section shows a positive Bouguer anomaly with a maximum of + 55 mGal located over the basin axis (Fig. 11 D and D1 and Fig. 13). From the theoretical model of Introcaso (1993) we observe: (a) an isostatic anomaly of + 65 mGal, pointing out overcompensation or antiroot excess; (b) stretching E = 33.71 km, with β 1.5 that justifies the crustal attenuation; (c) the possibility that the gravity effect could be entailed with the crustal density excess is not discarded. The mechanisms involved can be seen in Fig. 5 (heating 3.25 g/cm^3 to cooling 3.30 g/cm^3), 6 (right), 7 (right) and 8 (for each value σ mantle).

This basin, entailed with the South Atlantic Ocean opening 125 Ma ago and classified as a model of aulacogenic evolution (Introcaso-Ramos, 1984) must continue its subsidence until the isostatic anomaly is eliminated. On the Austral basin section located at 50° 20' S (Fig. 11 E, E1 and E2 and Fig. 14) Bouguer anomalies are negative with a maximum of aprox. - 30 mGal, while the isostatic anomalies on the Airy system have values of more than + 40 mGal. This usually indicates crustal attenuation. Besides, as it was just pointed out, the setting of the load located over the bottom of the basin would imply an analysis in the Rudzki isostatic system (+ m_T over the sea level, compensated by - m_S immediately below). Such compensation is produced imperfectly. In fact, it does not exist a consistent correlation neither between wave lengths nor between the masses m_T and m_S of the basin topography. So, m_S is only 29 % of m_T according to the isostatic anomaly sign. Three mechanisms: crustal attenuation, cooling and sedimentary loading are present in this basin, with the possibility of keeping on subsiding (see Fig. 5,6 and 8). From the present model of the basin (see columns E1 and E2 in Fig. 11) that involves 4 km of sediments, subsedimentary attenuated crust, negative Bouguer anomaly, basic materials intruded in the crust, in view of the probable heating present, we have done an acceptable retroprediction from column E1, finding - for the initial conditions: attenuation by stretching ($\beta \sim 1.3$) and heating of the lithospherical mantle. Then cooling happens, with subsidence and sedimentary load, and crustal thickening by basic material intrusion. On the Córdoba range, and according to Lion-Introcaso (1987, Fig. 11 C and C1 and Fig. 15), the isostatic anomaly in the Airy system is positive (increasing eastwards until reaching + 50 mGal). So, compensating root in the Airy system (Fig. 2) is too big. On the other hand, a flexural system, or V. Meinesz (Fig. 4) with T_n= 33 km, D = 3.8 x 10^{30} dyn x cm, does not satisfy the observed Bouguer anomaly neither in amplitude (it is too small) nor in wave length.

Compression forces could retain the descending vertical movement that the Airy

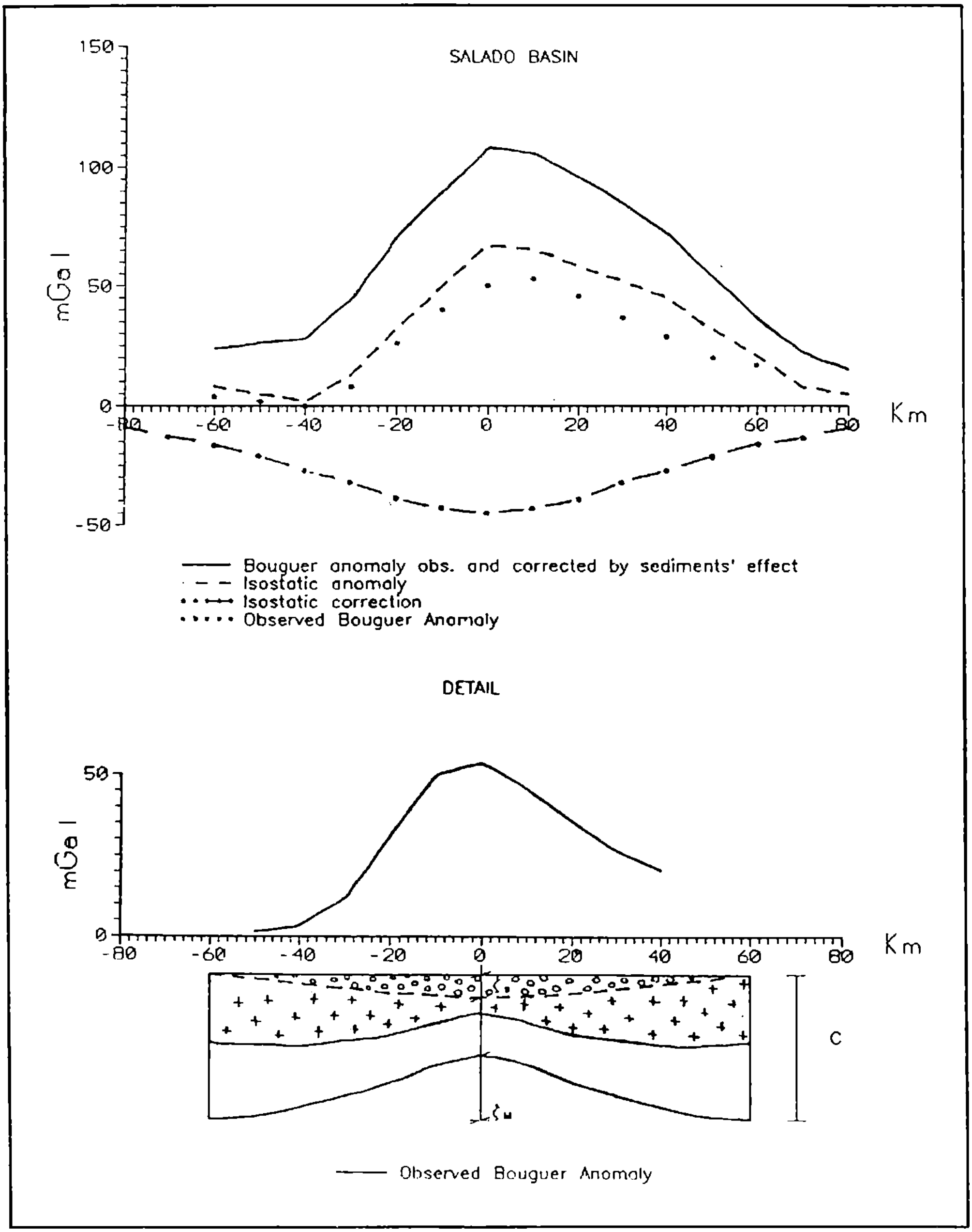

Fig. 13. Gravity Anomalies over the Salado Basin: Observed Bouguer Anomaly (ABo); ABo corrected by sedimentary filling effect (ABo + Ces); Isostatic Correction (Cl); Isostatic Anomaly (Al = ABo + Ces - Cl). Source: Introcaso and Ramos (1984). *Detail:* Crustal model of the Salado Basin ρ_M (antiroot) >> ρ_S (sedim) C: crustal thickness.

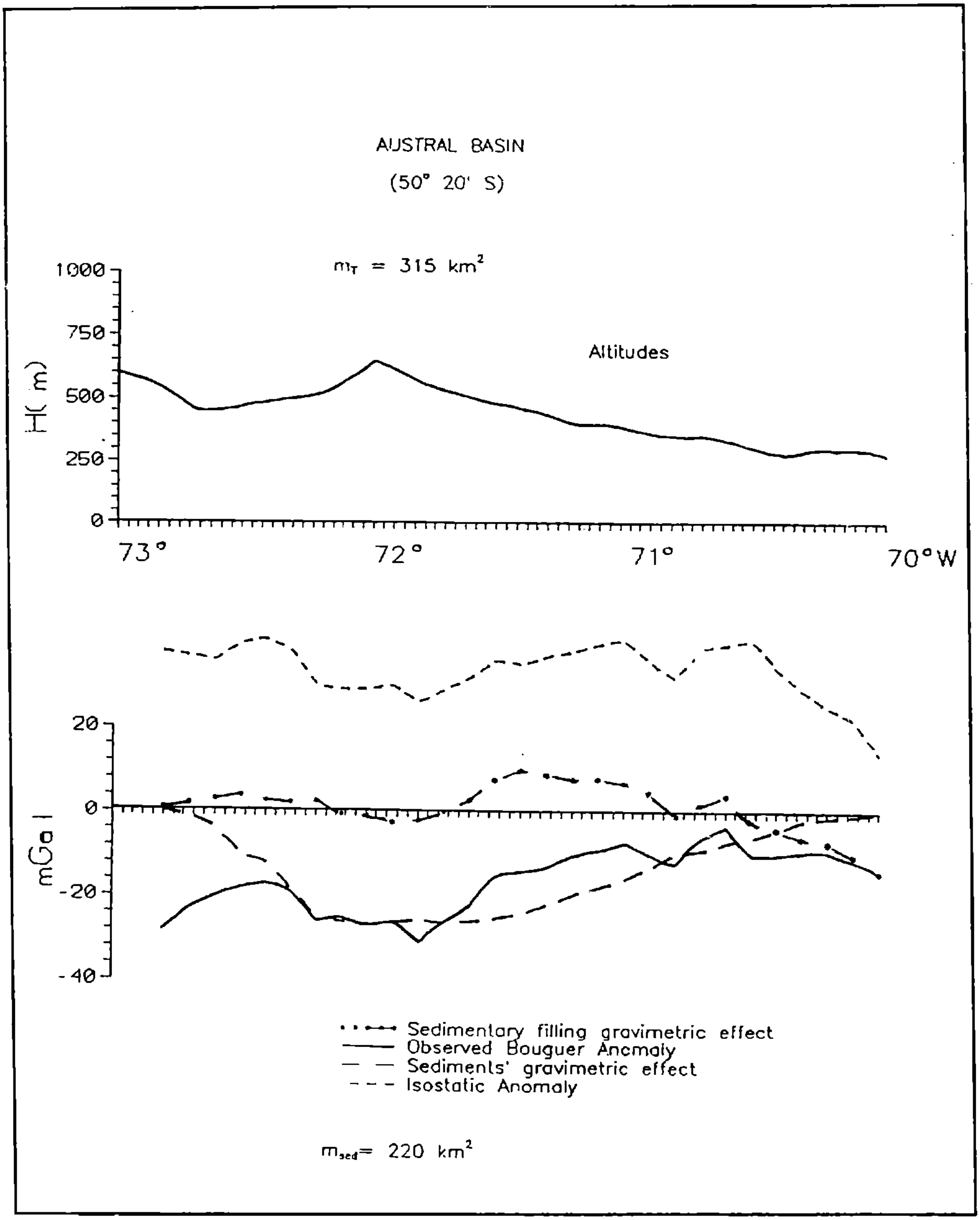

Fig . 14. *Top:* Medium altimetry over the analyzed section. *Bottom*: Observed Bouguer Anomaly (ABo) over the northern part of the Austral Basin (50°20'S). Source: Kraemer, Robles and Introcaso (unpublished). Gravimetric effect of the sedimentary filling (Egs); Bouguer Anomaly (ABo) ob served and corrected by the sediments' effect (Egs) and the crustal root on the west (Erc).

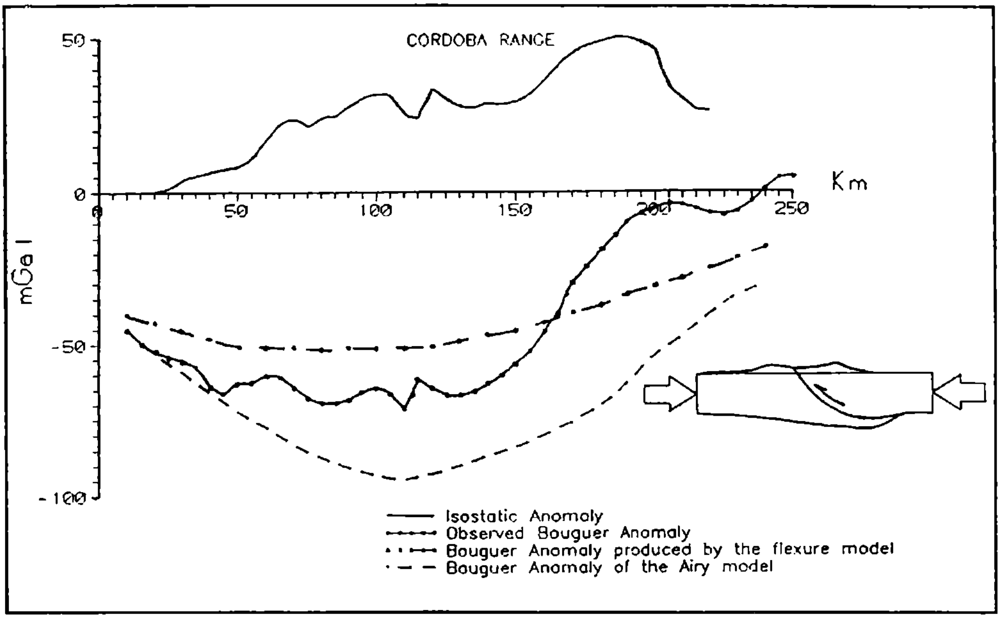

Fig. 15. Observed BouguerAnomaly (ABo); BouguerAnomaly produced by the flexure model (ABf): $\sigma = 2.7$ g/cm^3; $T_n = 35$ km; D = 3.81 x 10^{30} dyn.cm; Bouguer Anomaly of the Airy model (ABa): $T_n = 35$ km; $\Delta\sigma = 0.39$ g/cm^3; averaged altitudes on segments 60 km wide; D = 0. Source: Lion and Introcaso (1987).

system proposes, while if the flexural system is modified with $T_n = 15$ km and D = 3.8 x 10^{30} dyn x cm, the Bouguer anomaly amplitude can be reproduced, although the wave length cannot. A viscoelastic model better agrees with the observed results (Miranda, Silvia - personal communication). Isostasy regulates all the time the anomalous masses + m, - m and - m, +m distribution. So, it acts every time a mechanism tends to alter the normal masses distribution. For example, in the case of the Andes, each 10 mm of crustal thickening produced by shortening, 8.8 mm are located on the compensating root and 1.2 mm on the Andean emergent. In the same way, if the 1.2 mm were eliminated by erosion, it would be necessary to diminish the root thickness in 8.8 mm to keep the isostatic balance.

If the elevation mechanism happened to be the lithospheric expansion, as in the Central Andes, every 10 mm of elevation, the mantle heating would produce a decreasing of density of 0.5 x 10^{-5} g/cm^3 in presence of an anomalous heating of ~ 5 x 10^{-2} °C. In this case, the compensation depth would be the bottom of the thermal lithosphere.

Taking now the stretching as an attenuation factor, in the case of a sedimentary basin we will also have that every 10 mm of crustal attenuation, crust would decrease 1.2 mm leaving an antiroot of 8.8 mm. Every time the sediments fill the basin there will be subsidence in a convergent process that contains repetitions, always controlled by isostasy.

The cooling of the mantle is another probable mechanism that increases subsidence. This time, the isostatic control would be at the level of the bottom of the lithospheric mantle.

7. CONCLUSIONS

We have pointed out that the explanation of the origin and evolution of the different geological structures needs: (a) To define the sign and rate of the isostatic compensation; for this purpose, the Airy system (± m, ± m) is usually used. (b) To find the type of the isostatic system or systems involved (Airy, regional or Vening-Meinesz, thermal or Pratt, etc.). (c) To analyze the previous mechanisms involved in these processes (shortenings, stretchings, etc.).

Throughout five examples of different structures in Argentina, we have carried out an analysis involving items (a), (b) and (c) just mentioned.

Only one of the models analyzed here (Andean section on 33°S) expresses - in general terms - compensation in the classical Airy system. The Andean uplift by crustal thickening can be justified by means of an only mechanism: crustal shortening of 130 km, controlled by the just pointed out isostatic system. The bottom of the crust M defined by means of seismicity and gravity, presents good consistency.

The Andean section on 25° S, also isostatically compensated, involves a combination of two isostatic systems: Airy (imperfect) on the crust, and Pratt on the lower half of the thermal lithosphere. The crustal thickness of the gravity model is only 60 km, agreeing with the seismic results. The crustal root corresponding to that thickness justifies 85 % of the observed Bouguer anomaly with a maximum of aprox. -340 mGal. The rest (- 60 mGal) is justified by the thermal effect on the lithospheric mantle.

To justify the origin of the Salado basin, we have proposed: crustal attenuation by stretching and increase of temperature from the base of the thermal lithosphere. For the evolution of the basin still in subsiding process - as it is shown by the positive isostatic anomaly, we have considered the following mechanisms: sediments load, upper mantle cooling and subsidence anomalous pulses related to velocity changes of the continental derive.

For the section that crosses the Austral basin at 50° 20' S, we have found a gravity exceeding (positive isostatic anomaly) that shows the possibility of subsidence. Crustal stretching, sedimentary load and cooling should be considered in the study of the basin.

The distribution of the load located over the crystalline basement suggests an imperfect compensation in the Rudzki system.

Finally, the Córdoba range presents a positive isostatic anomaly. Crustal shortening that is solved over a listric failure without a defined isostatic control, explains the range uplift. The isostatic mechanisms seem to be inhibited by strong compensation.

We point out, at last, that the isostatic anomalies should be calculated to determine the sign and level of compensation of the studied structures. But we must go further trying to find in each case the most adequate isostatic compensation system. They contain the vertical mobility mechanisms that regulate the masses distribution at depth.Other mechanisms: compressive shortenings, tractional stretchings, derived from horizontal stresses, precede the isostatic control.

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