

ISOSTATIC STATE OF THE UPPER RHINE GRABEN

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ABSTRACT

In any particular region isostatic anomalies point out the balance degree, establishing the excess or deficit of compensating masses. Nevertheless the distribution of these masses is not unique. Current isostatic models consider a simple dipolar mass configuration. The performance of predictive isostatic anomaly derived from an extensional crustal model, compensated in the Airy's system, is analyzed for a sedimentary basin with intracrustal anomalous masses, settled on an anomalous lithospheric mantle. The gravimetric analysis for two cross sections of the Upper Rhine graben, is based on all the geophysical information available for this region: seismic results (reflection and refraction) and a remarkable thermal anomaly derived from several geophysical studies. The calculated isostatic anomalies and predictive vertical movements indicate: i- that nowadays the state is close to the isostatic balance both at north and south of the Rhine graben; ii- the future vanishing of the thermal anomaly in the southern section will cause thermal subsidence; iii- in qualitative terms, simple dipolar isostatic models are adequate for the predictive vertical movability evaluations.

RESUMEN

Las anomalías isostáticas para una región en particular señalan el grado de balance, estableciendo el excedente o defecto de masas de compensación pero no su distribución de manera unívoca. Los modelos isostáticos usuales consideran una configuración de masas de dipolo simple. Analizamos aquí la eficiencia predictiva de la anomalía isostática, calculada a partir de un modelo cortical distensivo compensado en el sistema de Airy, para una cuenca sedimentaria con masas anómalas intracorticales y emplazada sobre un manto litosférico también anómalo. El análisis gravimétrico, para dos secciones transversales al graben del Rhin Superior, se basa en la información geofísica existente para esa región: resultados sísmicos (reflexión y refracción) y una significativa anomalía termal inferida a partir de diversos estudios geofísicos. Las anomalías isostáticas y la movilidad vertical predictiva calculadas indican: i- el estado actual cercano al equilibrio isostático en el norte y sur del graben; ii- la futura desactivación de la anomalía calórica en la sección sur, provocará sin duda subsidencia térmica; iii- los modelos isostáticos de dipolo simple son cualitativamente adecuados para las evaluaciones de movilidad vertical predictiva.

1. INTRODUCTION

The principle of isostasy establishes an equilibrium between visible masses and not visible ones, so that uniform pressure exists at some compensation level. In this context, topographic signals (excesses) hypothetically determine both location and magnitude of compensating masses, after assuming a balance system, such as Airy's one, through the well understood case of the mountain masses (i. e. the Andes). Dealing with sedimentary basins of extensive origin, if isostasy holds, the gravity field on a m_b mass (assumed negative) is not a simple or monopole gravity effect (g_b). It is a combined or dipole gravity effect of that mass and its deeper m_r antiroot (positive in this case). Referring to Figure 1-a-, we see that the total dipolar gravity field (g_T) is:

$$g_T = g_b - g_r,$$

where g_r is the gravity effect of the antiroot, and g_T is usually negative.

The total vertical load $q(x)$ can be obtained by integrating the product of g and all the density contrasts $\Delta\alpha$ respect to z , within anomalous lithosphere as well as within the basin, compared with a column of normal lithosphere (unstretched and homogeneous), so that:

$$q(x) = \int_0^L \Delta\sigma(z) g dz, \quad (1)$$

where L denotes the lithosphere thickness up to compensation depth and g the mean acceleration of gravity. Therefore, we can obtain the degree of imbalance ($q(x) \neq 0$) or balance ($q(x) = 0$) of the masses, for any assumed isostatic system.

Following this analysis, the isostatic anomalies (IA) have been used to determine the isostatic level on a crustal scale, and moreover to predict future potential vertical motions for different orogenic structures. The isostatic correction ('IC' = $-g_r$) is algebraically added to the Bouguer gravity anomaly (BA) constituting the isostatic anomaly (IA = BA \pm IC). After that, the amount of these vertical motions can be computed. Particularly, this methodology, applied to the case of Argentine sedimentary basins, was developed by Introcaso (1993), who assumed that only m_b and m_r masses are involved, at a compensation depth at normal Moho level.

The purpose of this paper is to investigate the case of both crust and lithospheric mantle being anomalous. We specifically analyze the isostatic level of the Upper Rhine graben for which intracrustal anomalous masses and hot lithosphere have been recognized. The study is carried out along two profiles perpendicular to the graben, which show strongly differentiated geological and geophysical characteristics. The results, supported by numerous geophysical data, make it possible to assess the efficiency of simple isostatic models compared with more complex ones.

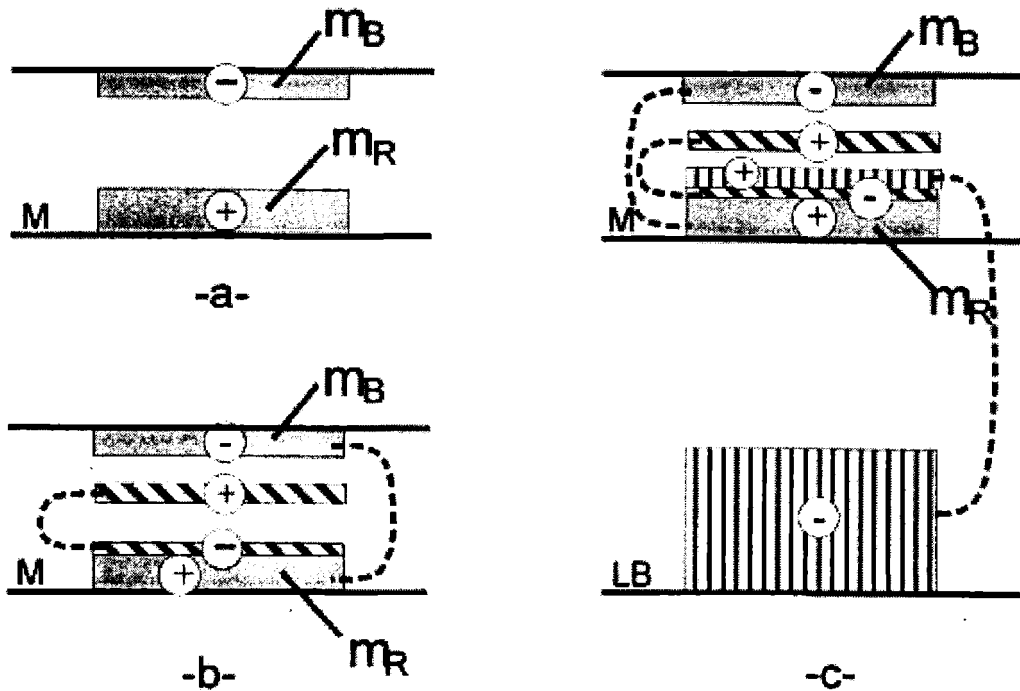


Figure 1. Theoretical isostatic dipolar models in the Airy's concept. Graphical representations sketch hypothetical subsurface masses with contrary sign antiroots. Compensation of masses is obtained by means of changing Moho depths. a- Simple dipolar model. b- double dipole due to mass excesses in crust; c- treble dipole involving anomalous masses located in crust and in lithospheric mantle. m_B : sedimentary infill (deficiency of mass); m_R : antiroot or compensating mass at Moho level; LB: lithospheric base.

2. MODELING SECTIONS

The Upper Rhine graben trending north-northeast between Basel (Switzerland) to Frankfurt (Germany) is about 300 km long, and 40 ± 5 km average wide. The Rhine graben is the most pronounced surface expression of an extended continental rift system and a seismically active zone (Faber *et al.*, 1994) crossing the crust and upper mantle of Central Europe.

Subsidence in the Rhine graben started during the late Eocene and was accompanied by the uplifts of its borders, which exposed the crystalline basement in some sectors (Campos Enriquez *et al.*, 1992). The graben evolution has not been homogeneous in time and space: the subsidence has been stronger in the northern part contrasting with a faster uplift

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in the south. The evolution models proposed at present incorporate either symmetric homogeneous extension or asymmetric heterogeneous extension (McKenzie, 1978; Wernicke, 1985). Villemin *et al.* (1986) have proposed evolutionary models incorporating both mechanisms. It has been defined as a transtensional impactogen that was near to the Alpine collision orogen, formed on the subducting European plate in a peripheral-foreland setting (Sengör, 1993). We have considered two gravity profiles 'CE' and 'WK' oriented normal to the graben axis (Fig. 2) to be studied.

A contour map for the depth of the M-discontinuity (Fuchs, 1987) derived from seismic reflection and refraction experiments, indicates crustal thinning under the Rhine. The uplifted M reaches its shallowest depth of about 24 km in the southern graben apex (Zeis, 1990).

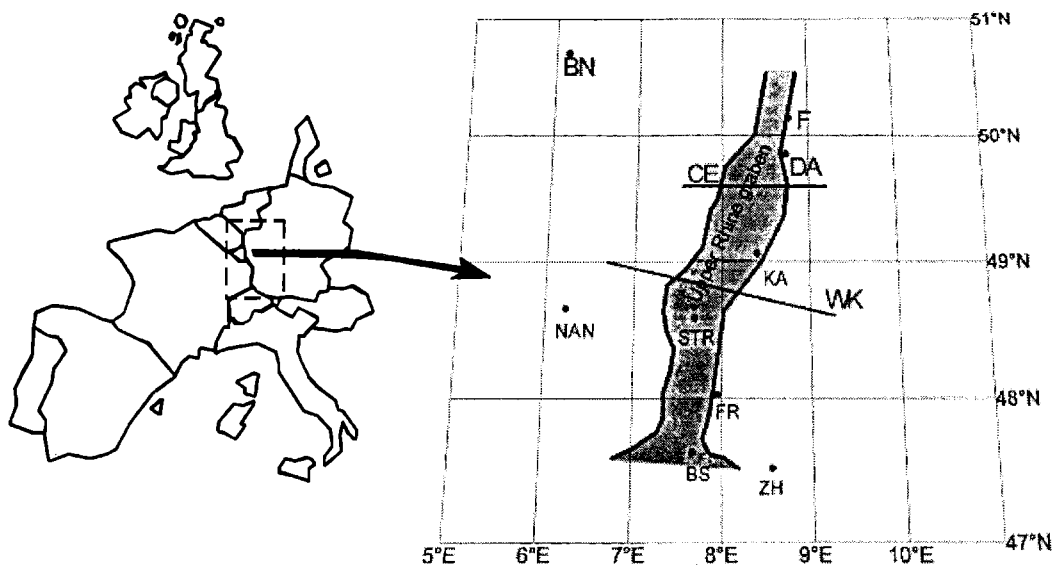


Figure 2: Map of the Upper Rhine graben. Position of gravity profiles CE (Campos Enriquez., 1992) and WK (Werner and Kahle, 1980) is shown. BN: Bonn, BS: Basel, F: Frankfurt, DA: Darmstadt, FR: Freiburg, KA: Karlsruhe, NAN: Nancy, STR: Strasbourg, ZH: Zurich

Heat flow data in the WK profile area report significant local anomalous values: 105-118 mW m⁻² (Morgan, 1982; Lysak, 1987). This lateral changes in temperature can contribute to the gravity field and to the isostatic balance. Compensation depths at the lithosphere base of the graben are suggested by Berbabé (1981) and Hellinger and Sclater (1983). Werner and Kahle (1980) calculated a kinematic model for temperature distribution underneath the

Rhine by modeling a thermal anomaly between 48° N and 49° N latitudes. According to this model the top of the astenosphere reaches a depth of nearly 60 km under the graben axis and progressively dips down to normal levels of about 140 km, at distances greater than 100 km respect to the center. This model is supported by seismic studies and geomagnetic and magnetotelluric soundings (Fuchs, 1986; Hermance, 1982).

The geometry, depth and density of the complete sedimentary infill are well known at different cross sections (geological studies and seismic information; e.g. Campos Enriquez ., 1992). Heterogeneous crust has also been revealed (Kahle and Werner, 1980; Campos Enriquez ., 1992).

The spectral analysis of the observed Bouguer anomalies in each section (CE and WK), carried on to determine their probable source depths, has proved that the gravity responses in this area hold wavelength compatible with the following mean compensation depths: - for the area of section CE, an intermediate interface ($z_1 \approx 33$ km) and a shallow interface ($z_2 \approx 3$ km); - for the region of section WK, a deep interface ($z_1 \approx 70$ km), an intermediate interface ($z_2 \approx 23$ km) and a shallow interface ($z_3 \approx 6$ km). By comparing our results with the available information previously described, we have decided that the deeper interface may be due to the lithospheric anomalous mantle, the intermediate interface may be due to the anomalous lower crust and the Moho discontinuity, and the shallow interface could be related to the sediment thickness.

3. SIMPLE ISOSTATIC DIPOLE

The observed gravity data digitized at an interval of 5 km, thickness and density of the sedimentary infill (derived from seismic velocities) were taken from Campos Enriquez . (1992) for the section CE and from Kahle and Werner (1980) for the section WK.

By modeling the simple isostatic dipole, we have computed the predictive antiroot in the Airy's concept at Moho level, from the geometry and effective density of the sedimentary infill, according to:

$$\Delta R' = \frac{\sigma_{cs} - \sigma_s}{\sigma_m - \sigma_{ci}} \cdot h_s, \quad (2)$$

where $\Delta R'$ is the antiroot in km, h_s is the thickness of sedimentary infill in km, σ_s is the effective density of sedimentary infill ($\sigma_s = 2.24$ g/cm³), σ_{cs} is the upper crust density ($\sigma_{cs} = 2.67$ g/cm³), σ_{ci} is the lower crust density ($\sigma_{ci} = 2.9$ g/cm³) and σ_m is the upper mantle density ($\sigma_m = 3.3$ g/cm³).

The 2D gravity effect of the antiroot defined according to (2) was computed

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(Rasmussen and Pedersen, 1979) using $\Delta\sigma = 0.4 \text{ g/cm}^3$ the lower crust-upper mantle density contrast (Campos Enriquez ., 1992) and $T = 30 \text{ km}$ the reference crust (Zeis ., 1990). The IA calculated isostatic anomalies on profiles are shown in Figures 3 and 4. There, we can see that:

- Section CE (see Fig. 3a): the BA observed Bouguer anomaly is negative over the graben (-33 mGal minimum). The removal of the gravity effect of sedimentary infill from the observed gravity anomaly makes it positive (+20 mGal maximum). Strictly speaking, nearly compensation state would be inferred from the slightly positive IA anomaly on the deepest part of the graben. However, anomalies ranging within $\pm 10 \text{ mGal}$ have usually been considered as indicators of isostatic compensation (Woollard, 1969). The pressure analysis would indicate a slight energy excess ($\Delta P = +76.5 \text{ bar}$), therefore future subsidence in this region should be expected.

- Section WK (see Fig. 4a): the observed BA on the graben axis reaches -25 mGal which is reduced to -3.5 mGal when the infill gravity effect, thinner than in the previous section CE, is removed. The isostatic anomaly is negative adopting reduced values on the graben (-7 mGal). The slight undercompensation process inferred from $IA < 0$ has also been indicated by the slight deficiency in pressures ($\Delta P = -4.4 \text{ bar}$).

4. MULTIPLE ISOSTATIC DIPOLE

Following the idea of the previous case, when anomalous crustal or subcrustal masses exist, they could be taken into account to evaluate the balance state of masses by requiring that pressures in vertical columns should be the same at the compensation level. Dipolar schema for this case (equivalent dipoles) are graphically shown in Figures 1b and 1c. Besides, the isostatic condition can be written in terms of the density distribution in the crust like this:

$$\int_0^z \Delta\sigma(z) dz = 0,$$

where g must be the same, and then the isostatic anomaly is zero ($IA = 0$). Furthermore, Bouguer anomaly generally indicates the effect of disturbing masses below the high reference surface. If they were considered to compute a predicted antiroot, an improved isostatic anomaly AI' would be obtained, although at first, it must not be so different to those calculated from a simple dipolar model. Knowledge of velocities and seismic depths, heat flow data, MT sounding, among others, combined with regional gravity values, contribute to consider other sources involved in compensation, above or below M , and besides it contributes to a better interpretation of the structure and evolution of studied orogenic system.

Thus, to determine the ‘new’ isostatic anomalies, we consider the following masses:

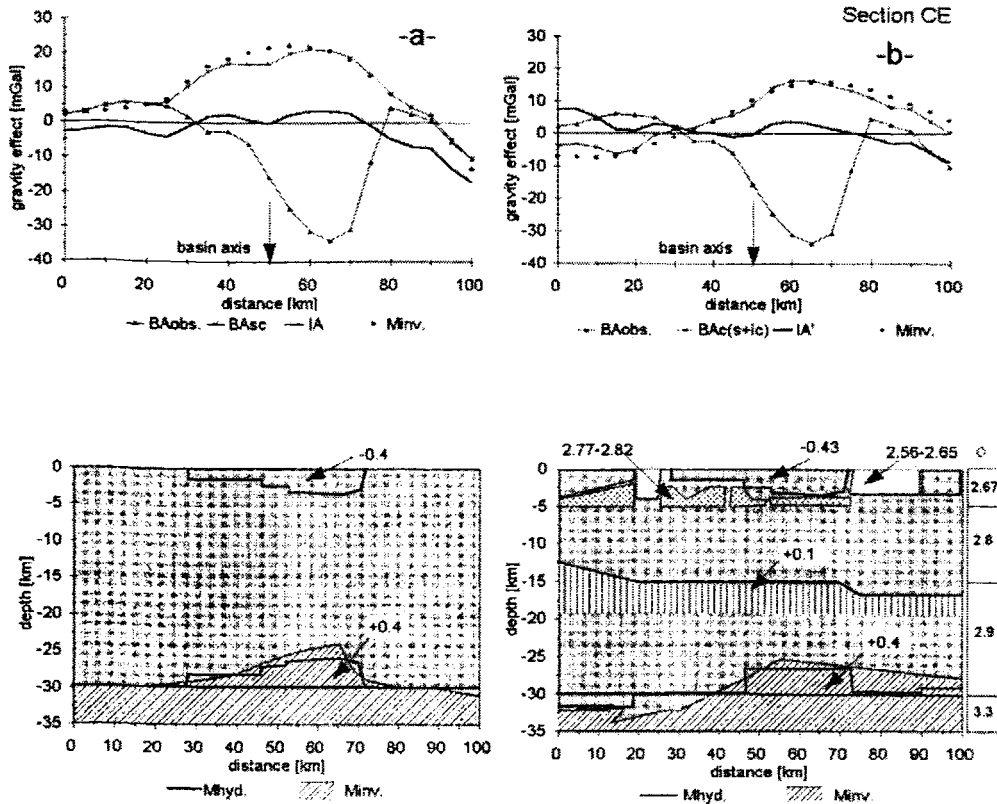


Figure 3: Isostatic analysis considering an extensive crustal model compensated in the Airy’s system, of the gravity section CE crossing the northern part of the Upper Rhine. -a- Simple dipolar isostatic model. -b- Multiple dipolar isostatic model. BAobs.: Observed Bouguer gravity anomalies; BAsc= BAobs. + gravity effect of the sedimentary basin infill; BAsc(s+ic)= BAsc + gravity effects of the minor subsedimentary bodies (see inset at the bottom plot -b-) + gravity effect of the anomalous middle crust; IA: isostatic anomaly for a simple model of Airy; IA’: isostatic anomaly for an improved isostatic model by considering the anomalous middle crust. M_{hyd} : hydrostatical Moho undulations; M_{inv} : resulting crustal model derived from the 2D gravity anomalies inversion (BAsc in the case -a-; BAsc(s+ic) in the case -b-). This profile reveals a present nearly balanced isostatic state at Moho level. All consigned masses and densities (in g/cm^3) are the ones informed by Campos Enriquez., 1992.

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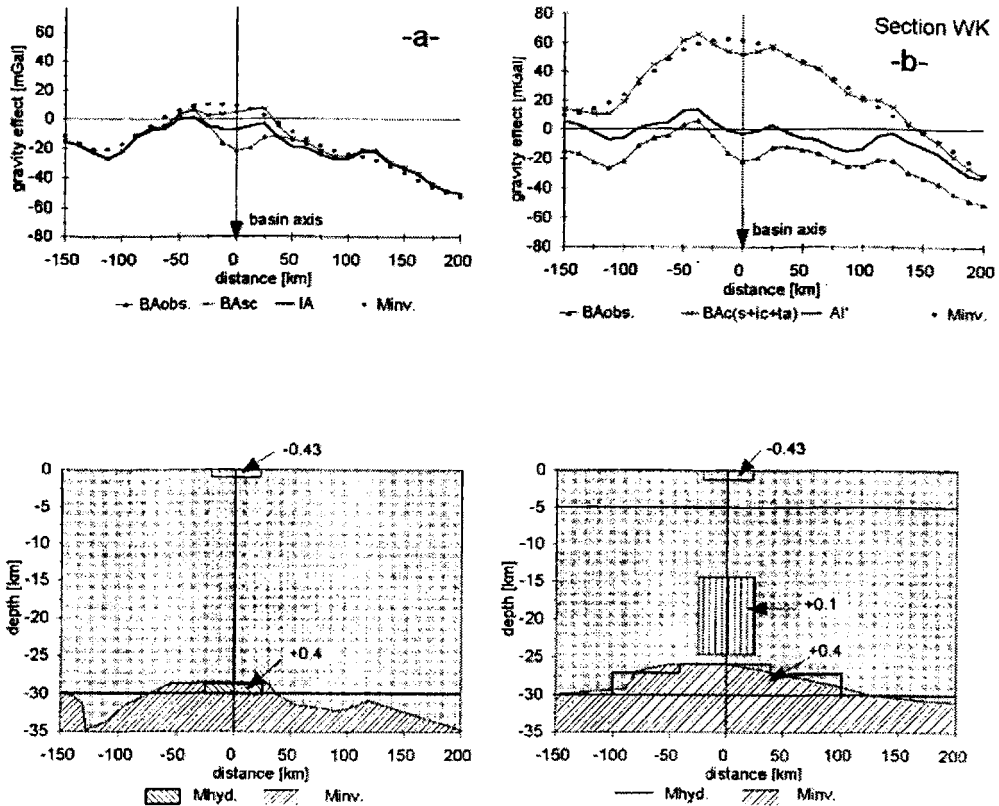


Figure 4: Isostatic analysis considering an extensive crustal model compensated in the Airy's system, of the gravity section WK crossing the southern part of the Upper Rhine. -a- Simple dipolar isostatic model. -b- Multiple dipolar isostatic model. BAobs.: Observed Bouguer gravity anomalies; BASc= Baobs. + gravity effect of the sedimentary basin infill; BAc(s+ic+ta)= BASc + gravity effects of the minor subsedimentary bodies (see inset at the bottom -b-) + gravity effect of the anomalous middle crust + gravity effect of the thermal anomaly sketched in plot -c-; IA: isostatic anomaly for a simple model of Airy; IA': isostatic anomaly for an improved isostatic model by considering the anomalous middle crust (see the text) and lithospheric mantle heating. M_{hyd} : hydrostatical Moho undulations; M_{inv} : resulting crustal model derived from the 2D gravity anomalies inversion (BASc in the case -a-; BAc(s+ic+ta) in the case -b-). This profile reveals a present nearly balanced isostatic state at lithospheric base level. All consigned masses and densities (in g/cm^3) are the ones informed by Werner and Kahle (1980) and Campos Enriquez. (1992).

- Section CE. The sedimentary infill (3.4 km maximum thickness) and a difference in crust thickness to both sides of the graben, which is located at intermedium crustal levels. It has been proposed using the travel times derived from reflection seismic findings (Campos Enriquez ., 1992).

- Section WK. In this case, implicated masses were: the sedimentary infill (1.5 km maximum thickness), anomalous lower crust and an asthenospheric upwelling beneath the graben axis. Denser lower crust ($\Delta\sigma = +0.12 \text{ g/cm}^3$) have been postulated by Kahle and Werner (1980) and Werner . (1982), based on seismic refraction data. By modeling the lithospheric thinning beneath the graben axis, we have considered the Werner and Kahle's kinematic model (1980). To do so we have assumed $\Delta\sigma = -0.034 \text{ g/cm}^3$ density deficit ($\Delta\sigma = \sigma_0 \alpha \Delta T$) with $\alpha = 3 \times 10^{-5} \text{ 1/}^\circ\text{C}$ thermal volume expansion coefficient, $\Delta T = 350 \text{ }^\circ\text{C}$ lateral temperature differences, and $\sigma_0 = 3.3 \text{ g/cm}^3$ density for $T = 0^\circ\text{C}$. Figure 5 shows this thermal anomaly.

By calculating the predicted hydrostatic Moho we have postulated that pressures should be the same according to equation (1), at Moho level for the section CE and at the lithospheric base for the section WK. In this approach every balanced column involves all the masses previously described.

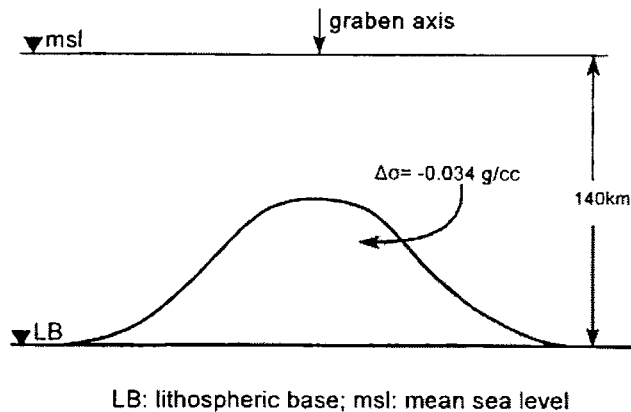


Figure 5: Scheme of the lithospheric thermal anomaly modeled for the section WK (after Werner and Kahle,1980). (without scale).

The (IA) resulting isostatic anomalies in both sections (Figs. 3b and 4b) show a clear agreement with the computed ones from our simplest former model. The deficiency of masses inferred from the negative isostatic anomalies to both sides of the graben have been partially

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removed due to a lack of control. $IA < 0$ on the eastern side of the section WK, may be at most caused by downbending of the crust in the Alpine foreland due to topographic loading of the Alps (Kooi ., 1992). Also in this section, exposed granites to both sides to the graben (Sengör, 1993), can contribute to explain these mass deficiencies.

The obtained results (see Figs. 3 and 4) determine that the more complicated models (or multiple dipole) provide isostatic anomalies (AI') no so different from the calculated ones (AI) for the simplified models. Thus, we inferred that a simple Airy's model (or simple dipole) is suitable for establishing the compensation degree for this extensive sedimentary basin.

The close fitting between the Moho undulations ($M_{inv.}$), derived from the 2D Bouguer gravity inversion (Figs. 3 and 4), and the respective hydrostatic Moho depths ($M_{hyd.}$) clearly supports the reduced subsidence in present predicted by $IA = 0$. Therefore, nowadays the Upper Rhine graben is almost in a compensation state. On the other hand, if we predictively approach, in some future time the thermal anomaly would be totally absent. So, at that moment this region should be subsided 1.8 km to hold the compensation in the section WK.

5. CONCLUSIONS

When quantifying the isostatic anomalies computed with a system inspired on the Airy's isostasy, the isostatic state of the Upper Rhine graben was analyzed. The study was carried out on two cross sections located at different latitudes. Isostatic anomalies and a gravity inversion crustal model of both sections, were calculated by means of: a- a simple dipole model and b- a multiple dipole model. They have showed similar resulting anomalies.

In the former (a-), the isostatic correction was computed postulating the same pressure at Moho level. Total loading involved the infill graben and its antirroot.

For the latter (b-), anomalous masses both in middle crust and in lithospheric mantle were added. The last one was considered only for the section WK. Spectral analysis of the observed gravity anomalies combined with other geophysical findings were taken to define this improved model. Compensation states at Moho level for the section CE and at lithospheric base for the section WK were considered.

In sum, the present study of the Upper Rhine graben indicates:

- 1- a compensation state close to the mass balance;
- 2- simple crustal models suitable to evaluate the isostatic state;
- 3- as a consequence of the extinction of the thermal anomaly, the basin should be subsided 1.8 km on the southernmost section WK, to regain the balance in future time.

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