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Depth estimation to crystalline basement in the valley of La Paz, Baja California Sur, Mexico

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Resumen

Con base en datos gravimétricos se estimó la profundidad al basamento cristalino en el valle de La Paz, Baja California Sur, y con apoyo de la anomalía aeromagnética se interpretó la geometría de la fosa tectónica que subyace al valle. En la separación regional-residual de los datos de gravedad, se consideró el efecto regional como un plano horizontal. Para estimar la profundidad al basamento se utilizó la fórmula para el cálculo de la gravedad en un punto sobre una capa horizontal de extensión infinita, con un contraste de densidad de 0.66 g/cm³ de acuerdo a las características generales del basamento y del relleno sedimentario. Con la profundidad al basamento obtenida a partir de un perfil magnético de otro estudio se normalizaron las profundidades estimadas. Se modelaron dos secciones para evaluar el procedimiento.

La profundidad al basamento en el valle de La Paz varía desde 100 a 500 m en el este y centro-sur, a más de 1500 m al NNE, NW y oeste. Es evidente la existencia de un graben delimitado por dos lineamientos principales, uno al este con orientación casi N-S y el otro al oeste con rumbo SSE-NNW, los cuales se atribuyen a las fallas La Paz y El Carrizal respectivamente. El graben presenta un basculamiento en dirección WNW.

Palabras clave: Gravedad, magnetismo, profundidad al basamento, graben, fallas, Baja California Sur.

Abstract

Based on gravity data, the depth to crystalline basement in the valley of La Paz, Baja California Sur was estimated. Geometry of the tectonic depression that underlies the valley was interpreted with support of the aeromagnetic anomaly. For regional-residual separation of gravity data, regional effect was considered as a horizontal plane. In order to estimate depth to basement, the formula for the calculation of gravity in a point over a horizontal layer of infinite extension was used. A density contrast of 0.66 g/cm³ was used, based on the general characteristics of basement and sedimentary infill. Estimated depths were normalized to a depth to basement obtained in a magnetic profile from another study. Two sections were modeled to evaluate the procedure.

The depth to basement in the valley of La Paz ranges from 100 to 500 m on the east and the center-south, to more than 1500 m to the NNE, NW and west. A graben delimited by two main lineaments is evident, one lineament extends on the east with a N-S direction, and the other on the west with a SSE-NNW orientation, which are respectively attributed to the La Paz and El Carrizal faults. The graben is tilted towards the WNW.

Key words: Gravity, magnetics, basement depth, graben, faults, Baja California Sur.

Introduction

The city of La Paz is located in the southern end of the peninsula of Baja California, Mexico. For many years, source of water supply for population and agriculture has been obtained from groundwater exploitation of the aquifer of the valley of La Paz, which geologically corresponds to a graben (Hausback, 1984, in Alvarez *et al*., 1997). Due to exhaustive pumping since 1977, groundwater level has descended approximately 30 cm/year (CNA, 1999), increasing risk of salt water intrusion contamination.

In order to characterize the hydrogeological conditions of the aquifer, among other parameters, it is necessary to determine its extension and depth. This article presents results of a research project whose objectives are related to the availability of groundwater in the valley of La Paz.

Limited geophysical work has been made in this zone, most important being the geoelectrical sounding that give support to geohydrological studies. Since the 70's, federal institutions in charge of water administration have contracted several companies such as GEOFIMEX (1971); INGESA (1972); ROASA (1981); ADI Construcciones, S.A. de C.V. (1997); CIGSA, S. A. de C. V. (2001), among others, which have made geohydrological and geophysical studies and exploratory drilling.

In spite of the effort made in the above mentioned studies, none have defined the crystalline basement of the basin, even in the exploratory drilling made by INGESA (1972) up to 700 m, or the electromagnetic soundings carried out by CIGSA (2001) with penetrations of 500 m in the middle of the valley.

In 1986 the Secretaría de Agricultura y Recursos Hidráulicos (SARH), Universidad Nacional Autónoma de México (UNAM) and Universidad Autónoma de Baja California Sur (UABCS) made a geohydrological and geophysical study of the aquifer of La Paz and El Carrizal. The geoelectrical soundings penetrated to a depth of 500 m, without detecting the basement.

Arzate (1986) reported a geoelectrical and magnetic study between the valleys of La Paz and El Carrizal. He located the La Paz and El Carrizal faults, and estimated the depth to basement in the south of the valley of La Paz near the town of San Pedro.

CIGSA (2001) presented a summary and reinterpretation of geohydrological and geophysical information. They made electromagnetic transitory soundings (EMT) and generated a stratigraphic model of the aquifer, as well as a structural interpretation through aerial photography and geological cartography, with which they identified some faults in the valley of La Paz.

Among the geological and tectonic regional studies we refer to Beal (1948); Gastil *et al.* (1979); Hausback (1984); Lonsdale (1989); Munguía *et al.* (1992); Ramos (1998); Fletcher and Munguía (2000). In regional geophysics there are the magnetic studies by Hilde (1963); gravity studies by Harrison and Mathur (1964) and Couch *et al.* (1981); and gravity and magnetic by Gallardo *et al.* (2005).

Study area

The hydrologic basin that forms the valley of La Paz is located between the 23° 45' to 24° 14' north and 110° 12' to 110° 35' west (Fig. 1), shaped by a series of superficial runoffs that cover an area of approximately 1,500 km^2 (CNA, 1997).

Climate is predominantly dry with annual average temperatures of 20 to 26°C, reaching a maximum in July, August and September of up to 45°C. Annual average rainfall in the basin is 265 mm (CNA, 2005) occurs mostly in the summer, with the highest values in August and September. At the end of summer tropical storms and cyclones are present allowing the recharge of the aquifer.

Geological setting

The valley of La Paz is formed in a graben with N-S orientation, limited to the east by the La Paz fault and to the west by the El Carrizal fault. Both faults spread from the coast of the Gulf of California down to the surrounding area of Todos Santos, located on the Pacific coast. Northern limit for both faults is not defined, and southern limit probably is located near Todos Santos (Alvarez *et al.* 1997) where they converge (Fig. 2).

Geology of the basin of La Paz-El Carrizal is characterized by a sequence of marine sediments and alluvial recent fans formed by conglomerates, sandstones and shales. Towards the NNW of the valley the Middle Tertiary to Recent sequence is formed by: San Gregorio Formation (Late Oligocene–Early Miocene) with an alternation of tuffy sandstones, silty shales, mudstones, conglomeratic sandstones and fosforite inter-bedded layers; San Isidro Formation (Early Miocene) formed by glauconitic sandstones, conglomerates, shales and some pink colored rhyolitic tuff layers; and Comondu Formation (Late Miocene) formed by sandstones and volcanic conglomerates, rhyolitic tuffs, andesitic lahars and lava flows. Towards the NNE, emerge rocks from Cretaceous to Recent that constitute the sierras Las Cruces and El Novillo (Fig. 2), formed by intrusive rocks such as granite and tonalite.

In the surroundings of the city of La Paz is found a sequence of volcanic and sedimentary rocks. This is considered the youngest unit of the Comondu Formation (Hausback, 1984, in Alvarez *et al.*, 1997), composed of tuffs, lavas, volcanic breccias and agglomerates. In this area the granitic and volcanic rocks are separated by the La Paz fault (Fig. 2), that contributed to the formation of the valleys of El Coyote and La Paz. This area is covered by alluvial fans composed by conglomerates, sands, silts and clays.

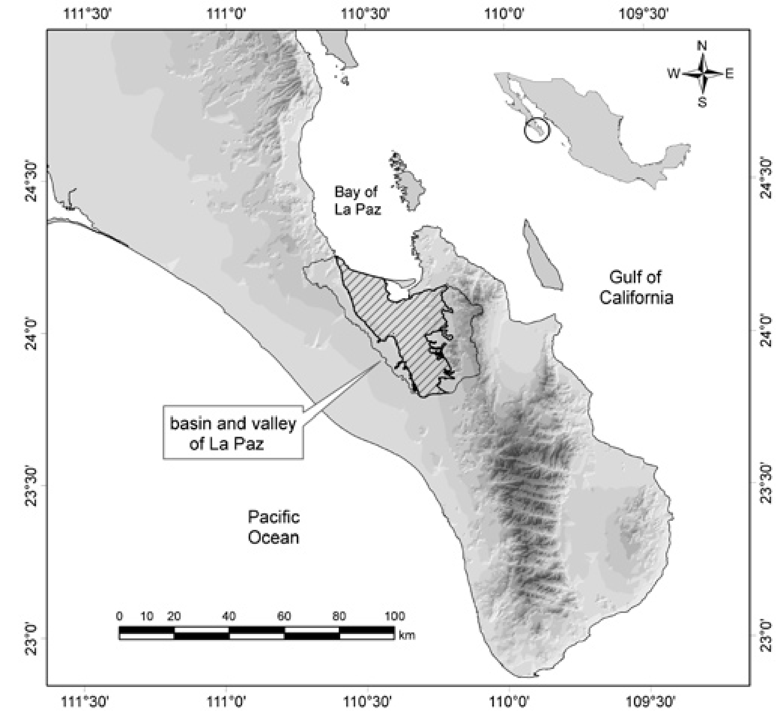


Fig. 1. Location of the study area. It is shown the basin (black line perimeter) and the valley of La Paz (shaded area).

Methods

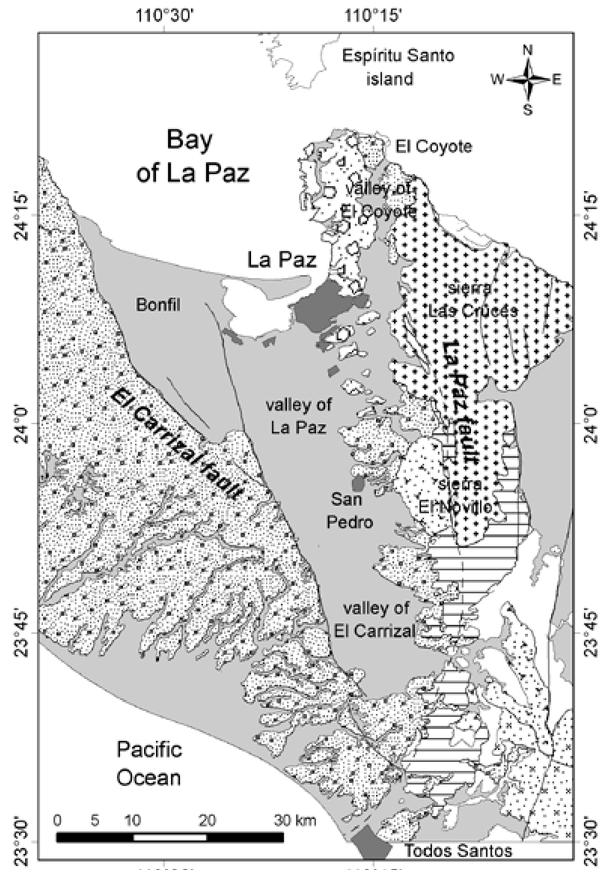
It is important to mention that the basement of the valley of La Paz, for geohydrological purposes, is constitutted by a volcanic sequence formed by tuffs, agglomerates and breccias (CIGSA, 2001) with slightly permeable characteristics, which possibly is the base of the aquifer. In this study, the basement to be considered is the crystalline granitic rock that limits the basin at depth.

Gravity data

For the field survey a La Coste and Romberg gravimeter model G-599 was used. All field data were referred to a base station (gravity station, Topographic chart G12D83, INEGI, 1982), located at the base of the shaft flag of the government building in the city of La Paz. Readings were taken in a total of 554 stations distributed in 20 profiles, with a spacing between stations of 300 to 1800 m (Fig.3). Station location was obtained with GPS (Garmin III) in decimal geographical coordinates, with reference to NAD27 Datum.

Data corrections as drift, latitude, elevation (free air and Bouguer) and terrain, were made following Dobrin (1976), Telford *et al*. (1982) and Hurtado and Urrutia (2007). In order to calculate the free air and Bouguer corrections, a terrain elevation model (TEM) with 20 m pixel was constructed (Fig. 3). Elevation contours spaced every 10 and 20 m were obtained from topography charts of INEGI (1998-2003). Density of rocks and sediments on gravity stations were assigned directly from the geology map of INEGI (1983). According to the type of rock or sediment, density values were taken from density tables of Dobrin (1976) and Telford *et al*. (1982).

Terrain correction was made with the program of Ballina (1990). For this correction it was also used a TEM, but with a spatial resolution of 1 km (according to the program specifications). To generate the TEM for areas outside the continental margin, there were used the bathymetric contours of the lagoon, Bay of La Paz and Gulf of California, obtained from the nautical charts of Secretaría de Marina (1976) and the DMAH/TC (1984). A density map was generated from the geology map of INEGI (1983), with same spatial resolution as the TEM. The program of Ballina (1990) selects internally from the input grid, a grid of 40 x 40 km (divided into an outer and inner zones) placing the station at the center of it. The inner zone considers the sub-zone D to F, and the outer zone considers sub-zones G to M, compared with the template model for terrain correction of Hammer (1939, in Dobrin, 1976). Each grid cell contains information of elevation and density. Density in the marine area was



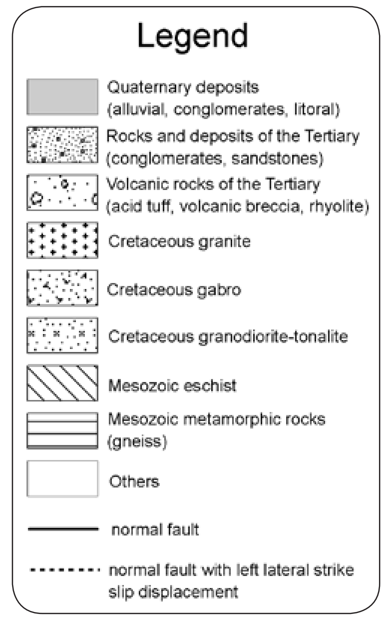


Fig. 2. Geological - structural map of the valley of La Paz - El Carrizal. Modified from the geological charts F12-3-5-6 and G12-10-11 (INEGI, 1983) and Alvarez *et al*. (1997).

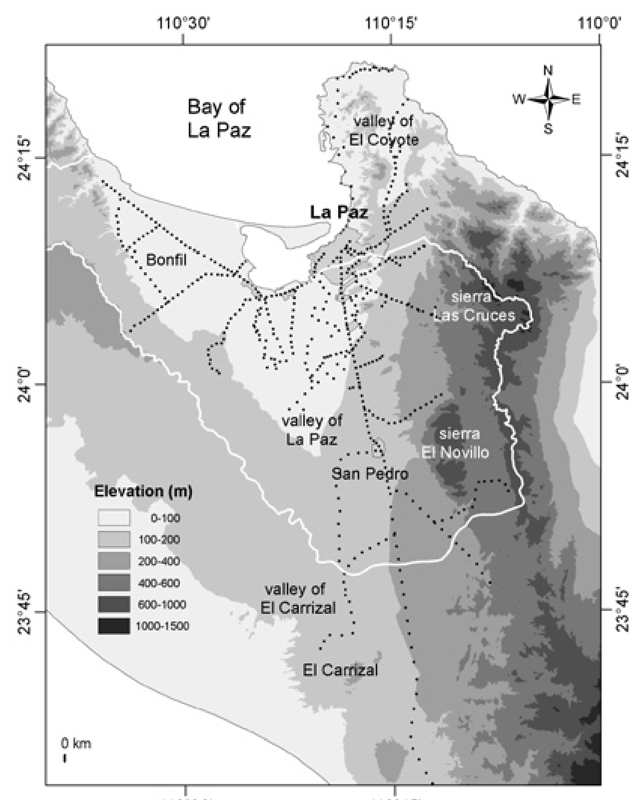


Fig. 3. Distribution of gravity stations (points) and terrain elevation model (TEM) in the valley of La Paz - El Carrizal. It is shown the perimeter of the basin (white line polygon).

considered equal to one. The same process was performed at each station.

Calculations were made using Excel spreadsheets that contained the formulas. ArcView 3.2 (Geographical Information System) program was used to manage digital thematic layers, for interpolation, and to generate the TEM and the density map.

Bouguer anomaly = observed gravity – (latitude correction) + free air correction – (Bouguer correction) + terrain correction.

The observed gravity in the previous formula was calculated for field stations, adding correction from drift and tides. For details of all corrections and calculations to obtain Bouguer anomaly, refer to Telford *et al*. (1982), Hinze *et al*. (2005), and Cruz (2007).

Values of Bouguer anomaly were interpolated to obtain contour map every 2 mGal (Fig. 4).

From Bouguer anomaly map (Fig. 4) it can be observed that higher values are located towards center, east and south of the area, while lower values are distributed to the SE, north, west and NW. Higher values correlate with outcrops of Sierra Las Cruces and Sierra El Novillo located to the east, with shallow basement in the center of the map near San Pedro, and to the south near El carrizal. Lower values are located to the SE, north (valley of El Coyote) and NW (at Bonfil). Three gravity highs are observed: to the east, south of Sierra Las Cruces; to the center at San Pedro; and to the SE near El Carrizal. A gravity low is observed to the NW in the Bonfil area. Gravity contours show three main lineaments: one to the NW with a SE-NW orientation, that could be attributed to the El Carrizal Fault; another lineament with a N-S orientation in the center-north of the map, possibly attributed to a normal fault; and the other located to the NE with a N-S orientation, that could be attributed to the La Paz fault. There is a lack of data due to difficulty of conducting gravity surveys throughout the entire area, making it difficult to define some features and lineaments.

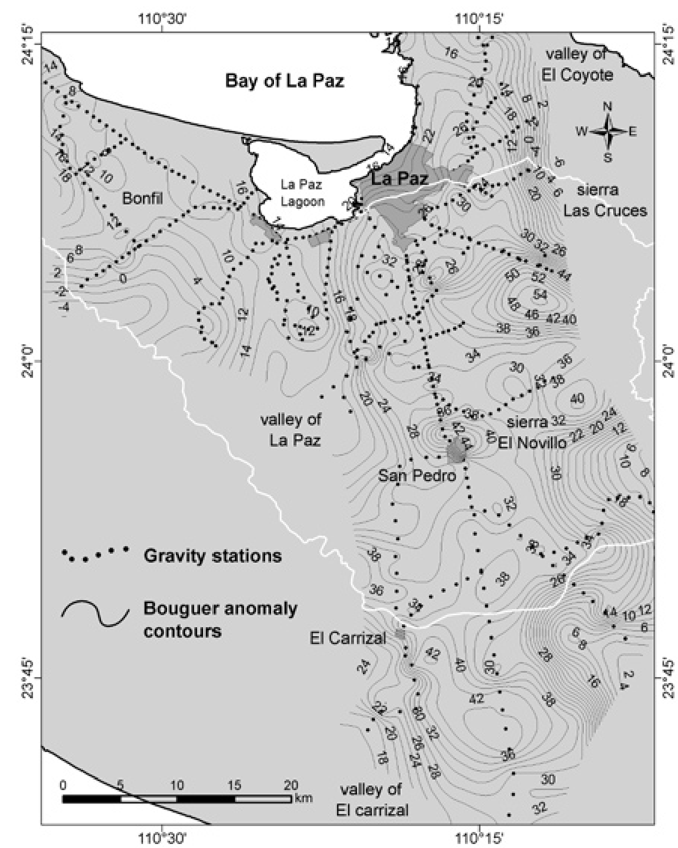


Fig. 4. Bouguer gravity anomaly contours and distribution of gravity stations (points) in the valley of La Paz - El Carrizal. It is shown the perimeter of the basin (white line polygon).

Aeromagnetic data

Aeromagnetic data were acquired from the Consejo de Recursos Minerales (CRM, 1972), cover an area of approximately 6500 km^2. Correction of data including diurnal variation and geomagnetic field (IGRF-1995) were made by CRM. Distance between flight lines is 1 km, at a height of 300 m. Data are UTM projected, referred to NAD27 Datum.

All data were subsampled every 500 m to obtain a regular grid to generate a contour map (every 100 nT) of magnetic anomaly (Fig. 5). This map was used to support the interpretation of gravity data.

Magnetic anomalies with positive values are located near the mountains (hills) located to the NE, east and SE of the basin of La Paz, in the Sierra Las Cruces and El Novillo. By contrast, the negative anomalies are located across the flat area (valleys of La Paz, El Carrizal, El Coyote and Bonfil). The highest negative values are located in the central and western part of the basin. Beyond the boundaries of the basin, the negative anomaly increases towards the east, but decreases towards the west.

Three magnetic lows are observed in the magnetic anomaly map (Fig. 5): one is located to the SW of the basin, another to the NW near the area of Bonfil, and the other towards the valley of El Coyote.

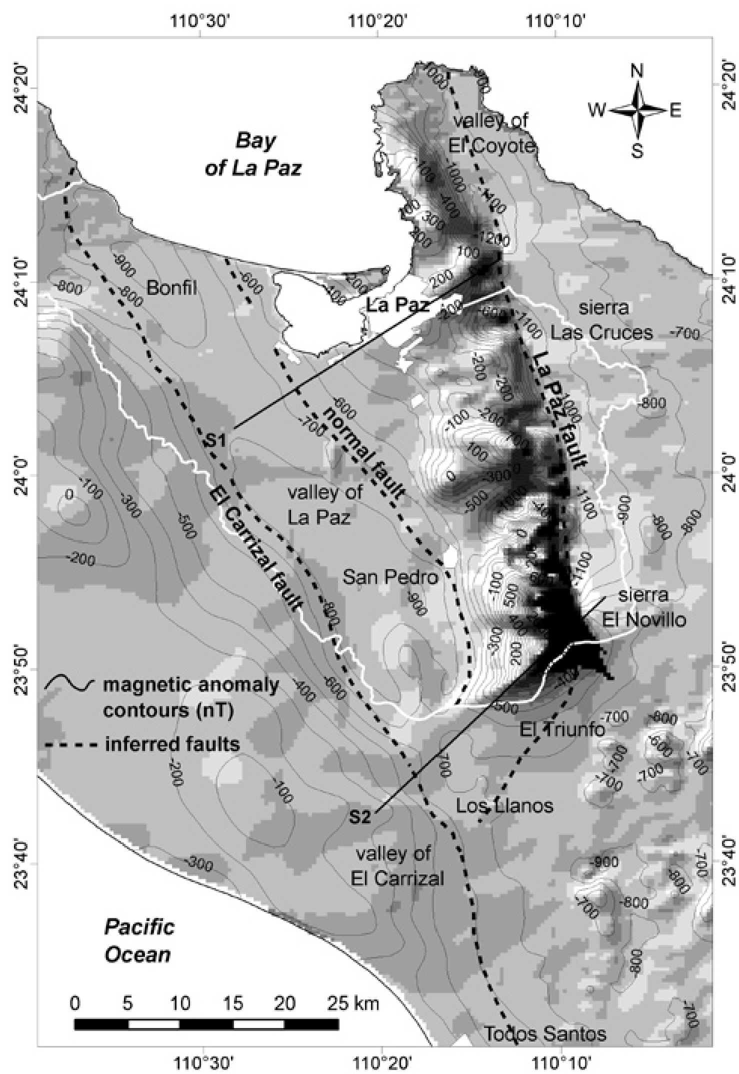


Fig. 5. Map of magnetic anomaly contours in the valley of La Paz-El Carrizal. It is shown the inferred trace of the La Paz and El Carrizal faults, an intermediate normal fault (black dotted line), the perimeter of the basin (white line polygon) and the gravity modelled sections (S1 and S2).

The magnetic contours show three main lineaments: one to the west and SW of the map with a SE-NW orientation, wich could be attributed to the El Carrizal fault; another lineament with the same orientation in the middle of the map, possibly attributed to a normal fault; and the other, although not well defined, located east of the map with a SSE-NNW orientation, which may be attributed to the La Paz fault.

Regional-residual separation (gravity data)

A graphical method was used to separate regional and residual anomalies. Residual gravity anomaly was obtained by fitting a virtual horizontal plane, substracting a value to Bouguer gravity anomaly. Similar procedure was carried out by Ali and Whiteley (1981).

New data were interpolated to obtain a residual anomaly contour map (Fig. 6).

Estimation of depth to basement

Estimation was made with residual anomaly, applying the formula for the estimation of gravity in a point over a horizontal plane of infinite extension (Carmichael and George, 1977):

$$\Delta h \text{ (m)} = [\ (\Delta g / 1000) / (2\pi \text{ x } G \text{ x } \Delta\rho)\ ] / 100,$$

where:

Δh = depth in meters
Δg = residual anomaly in mGal
G = universal gravity constant (6.67 x 10-8 dyne cm^2 /g^2)
$\Delta\rho$ = density contrast (0.66 g/cm^3).

Density contrast was calculated from saturated alluvium (most of the material that fills the sedimentary basin) with a density of 1.98 g/cm^3, and the grantic rock (basement at depth) with a density of 2.64 g/cm^3. These densities were obtained from the table of densities for igneous and sedimentary rocks of Telford *et al*. (1982).

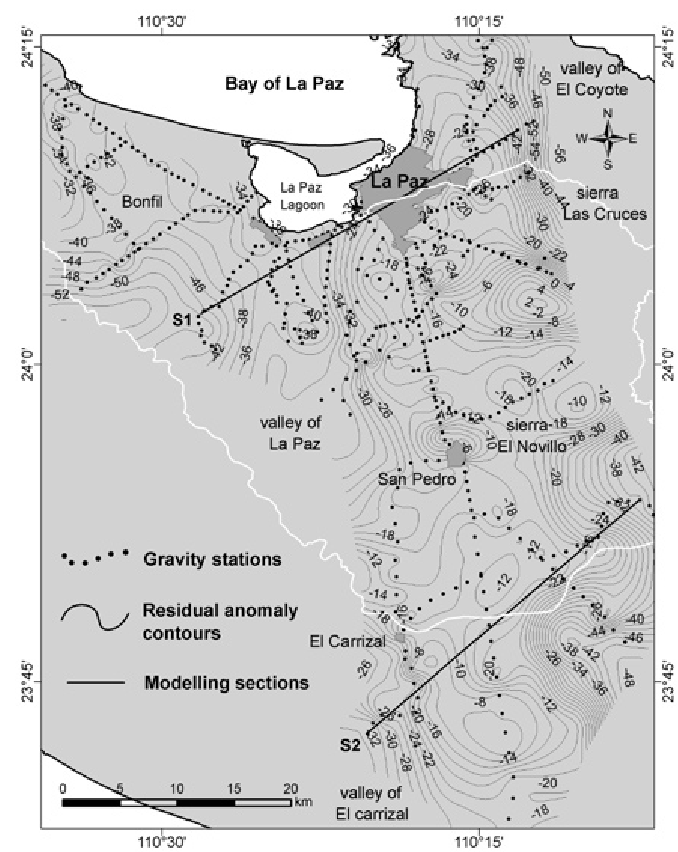


Fig. 6. Residual anomaly gravity contours, gravity stations (points), and location of modelling sections (S1 and S2) in the valley of La Paz - El Carrizal. It is shown the perimeter of the basin (white line polygon).

In this study some field stations located near the town of San Pedro (Fig. 6), 20 km south of La Paz, coincide with a magnetic profile of another study in the same area (Arzate, 1986), where depth to basement was estimated in 180 m. This depth was used to normalize the previously estimated depths. Then by interpolation, a contour map of depth to basement was constructed (Fig. 7).

Uncertainties of this calculation depend on the depth to basement used to normalize the data. If there is an error with this depth previously calculated, it will affect estimations made, but uncertainty will exist until it is carried out a drilling to the basement, or some other detailed geophysical survey.

Modelling

Two sections perpendicular to the residual anomaly were modelled (Fig. 8). Sections were placed north and south of the valley. It was used the program of Webring (1985), which models a structural profile from prisms in 2D. A density contrast of 0.66 g/cm³ was used.

Couch *et al*. (1981) in a gravity and magnetic study of the Baja California peninsula and the Gulf of California, the section that crosses the isthmus of La Paz (from the Pacific Ocean to the Gulf of California) used modelling densities of 2.4 g/cm³ for the overlying sedimentary rocks, and 2.67 g/cm³ for the batholitic rocks. The density

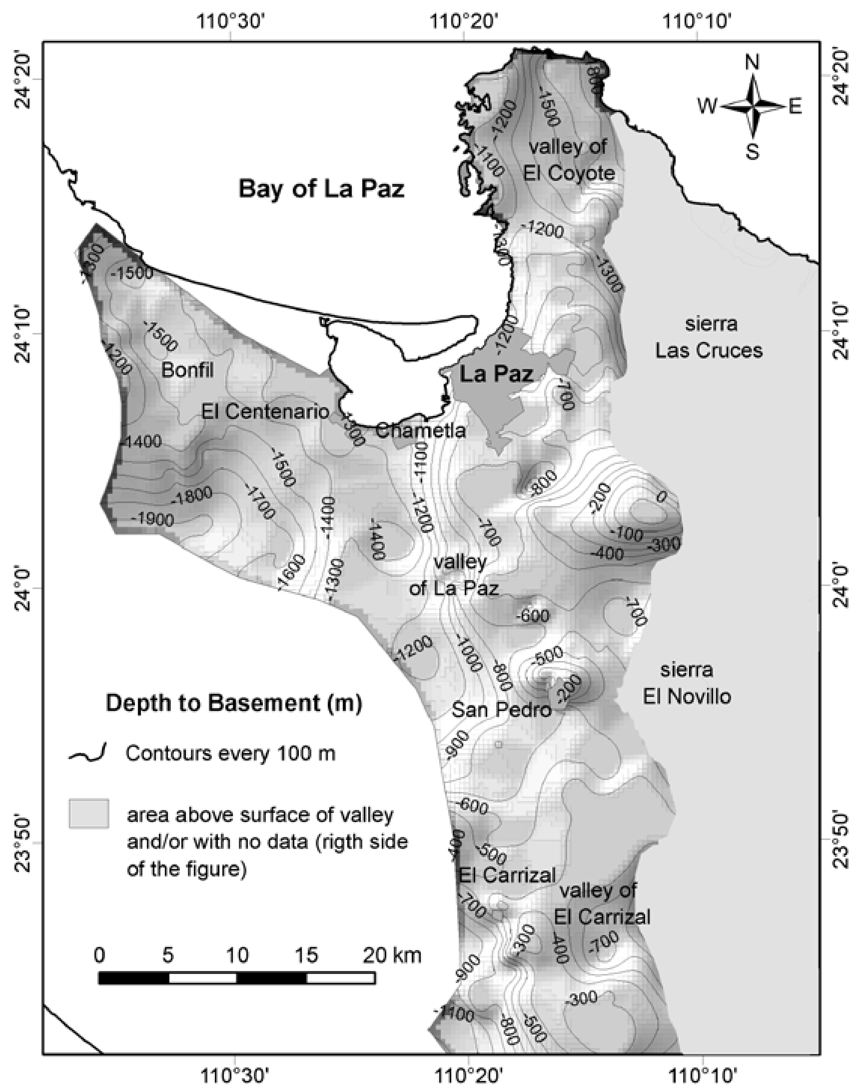


Fig. 7. Map of depth to the basement in the valley of La Paz.

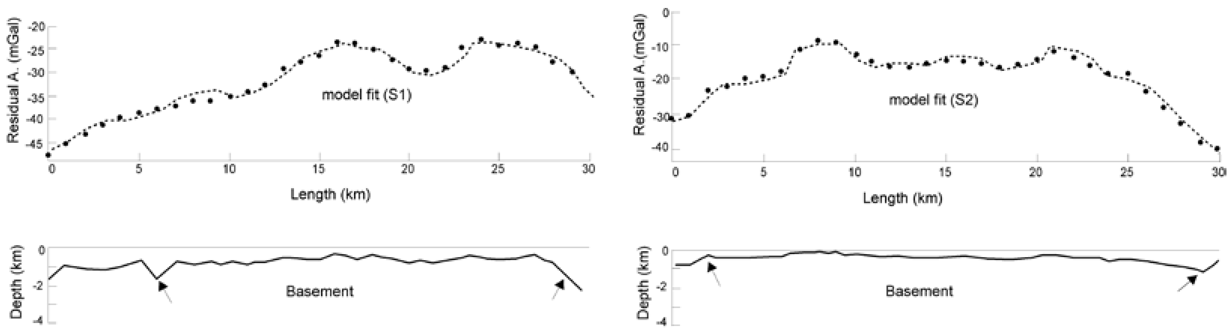


Fig. 8. Graphic of modelling sections (S1 and S2). Points represent the residual anomaly, dotted line shows the model fit, and the estimated depth is identified by the solid line below the graph. The arrows are positioned at the place of possible faults. These sections are shown in Figs. 5 and 6.

contrast used in that study was lower than that used in this work. On the other hand, Gallardo *et al.* (2005) using regional gravity data, delimited the sub-superficial layers of the southern Baja California peninsula. They assigned a density contrast of 0.67 g/cm^3, from 2.0 g/cm^3 to the superficial layer of sediments and 2.67 g/cm^3 to the uppercrust. The density contrast used in this study was nearly equal to ours.

Results and discussion

Depth to basement

Bouguer anomaly and magnetic anomaly maps (Figs. 4 and 5) appear similar, having a close correlation with the highs and lows that represent basement topography. In both maps you can observe highs on the east side, lows in the middle, and lows and highs to the west.

Because a poor coverage of gravity stations due to difficulty of conducting gravity surveys throughout the entire area, the observed contour trends and gradients toward the NE, center and NW are not well defined in the map (Fig. 4). The magnetic anomaly covers a wider extension (Fig. 5), therefore it was used as a support for the interpretation of gravity data.

From the map of depth to basement obtained with gravity data (Fig. 7), the granitic basement is shallower (0 to 200 m) to the east of the valley of La Paz, where it arises in the sierra Las Cruces and El Novillo. To the south and south-east, near the towns of San Pedro and El Carrizal it ranges from 200 to 500 m, and is deeper (1,500 m) towards the west, NNW (Bonfil) and NNE at the valley of El Coyote (Fig. 7). This graben structure is tilted to the WNW, as it can also be seen in the modelled section S1 (Fig. 8) that shows an increasing depth in the same direction, and possibly to the north.

In the modelled sections using the estimated depths to the basement and the residual anomaly (Fig. 8), the model showed a good correlation.

Results are consistent with the regional study of Couch *et al.* (1981), who found that the basement deepens towards the Bay of La Paz. The results are similar to the gravity and magnetic model of Gallardo *et al.* (2005), who estimated shallow depths of intrusive igneous rock located to the east, to even more than 1.5 km towards the NNW and NNE of the valley.

Geological structure from potential field data

Based on the magnetic anomaly map (Fig. 5) some lineaments can be observed, and It can be defined the trace of the El Carrizal fault to the west of the valley, the La Paz fault to the east, and another fault in the middle.

In the modelled gravity sections (Fig. 8) it is observed a feature that suggests the presence of these faults (position of the arrows). The section S1 crosses the La Paz fault on its eastern side, and on the western side crosses a fault still unnamed. The section S2 crosses both, the La Paz and the El Carrizal faults. The location of these sections can also be seen in Fig. 5.

The common geological maps of this area (Fig. 2) assume that the trace of the La Paz fault extends from the Pacific Ocean (south of the valley) passing trough the north of the town of Todos Santos, up to the bathymetric scarp located to the north at the east side of Espiritu Santo island. The La Paz fault (Fig. 2) is a left-lateral strike slip and normal displacement fault (CIGSA, 2001) with a north-south trend. On the other hand, the trace of El Carrizal fault extends from the north of Todos Santos up to the Bay of La Paz. This fault is divided in two axes with no definition of wich is the main lineament of the fault. The

El Carrizal fault (Fig. 2) is a normal displacement fault (Gaitán, 1986; CIGSA, 2001) with a NNW-SSE trend.

Compared to the above, the gradients observed in the magnetic anomaly map (Fig. 5) suggests that the trace of the La Paz fault extends from Los Llanos (southerly) located SW of El Triunfo, to the El Coyote, at north (Fig. 5). While the El Carrizal fault extends down from to the Pacific Ocean, passing trough the NNE of Todos Santos, up to the Bay of La Paz (northerly).

It is suggested that the graben that forms the valley of La Paz-El Carrizal has a triangular shape, due to its wedge towards the south (Fig. 5). The El Carrizal fault could be the main fault, and the La Paz fault a secondary one. The graben has a feature almost in the middle of this two faults due to a fault with the fallen block towards the west. Aranda and Pérez (1997) define the El Carrizal fault as a normal type with the fallen block eastward, which indicates that the deeper part of the graben is between these two faults.

Conclusions

1-Basement in the valley of La Paz has an irregular geometry. Shallower to central-east and south of the valley, and deeper towards the west, NNW and NNE, with a regional tilting towards the WNW and to the Bay of La Paz.

2- Estimated depths to the granitic basement obtained with gravity data, range from 0 to 200 m to the east of the valley of La Paz, where it arises in the sierra Las Cruces and El Novillo. To the south and south-east, near San Pedro and El Carrizal, range from 200 to 500 m, and is deeper (1,500 m) towards the west, NNW and NNE of the valley.

3- From magnetic anomaly map and residual anomaly modelled sections, the La Paz and El Carrizal faults which delimit the eastern and western flanks of the graben and another fault in the middle, are documented.

4-Trace of the El Carrizal fault extends from the Bay of La Paz down to the Pacific Ocean, and the La Paz fault extends from the valley of El Coyote towards the SW, but is truncated near El Triunfo, where it joints with the El Carrizal fault forming a triangular graben.

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