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Geophysical Modeling of the Surroundings of La Popa Basin, NE Mexico, with Gravity and Magnetic Data

Vsevolod Yutsis¹, Antonio Tamez Ponce² and Konstantin Krivosheya¹

¹*Universidad Autónoma de Nuevo León, Facultad de Ciencias de la Tierra, Linares, N.L.,*

²*Posgrado en Ciencias Geológicas, Facultad de Ciencias de la Tierra, Universidad Autónoma de Nuevo León, Linares, N.L. Mexico*

1. Introduction

Northeast Mexico is in essence the juncture of two distinctly different tectono-stratigraphic provinces, the eastern Gulf of Mexico (Coastal Plane, Sierra Madre Oriental) province and the western Pacific Mexico (Rivera plate, Meso-American trench, Sierra Madre Occidental) province (Goldhammer & Johnson, 2001). Tectonic evolution of northeast Mexico was dominated by divergent-margin regime associated with the opening of the Gulf of Mexico and overprinted by non-igneous Laramide orogenic effects (Pindell et al., 1988). The structural grain of northeast Mexico consists of Triassic to Liassic fault-controlled basement blocks, the development of which reflects in part late Paleozoic orogenic patterns of metamorphism and igneous intrusion (Wilson, 1990). Several tectonic provinces may be recognized by interpretation of the basement and sediment cover: Coahuila Block, La Popa Basin, Sabinas Basin, Burgos Basin, Sierra Madre Oriental (Monterrey Trough), and Parras Basin (Yutsis et al., 2009, Fig. 1).

Mojave-Sonora Megashear and San Marcos Fault (Chavez-Cabello et al., 2007) are two principal fault zones crossing the northeast Mexico in NW-SE direction.

La Popa Basin is located on the foreland of the Sierra Madre Oriental, 85 km northwest of the city of Monterrey, N.L., northeast of Parras Basin and south of the Sabinas Basin (Fig. 2).

The basin's development is greatly defined by salt tectonics, and is of great interest to the petroleum industry (Hudec and Jackson, 2007; Jønen, 2007), due to the fact that many of oil reservoirs in the world are located in salt basins (e.g. Gulf of Mexico, the Persian Gulf, the North Sea, Lower Congo Basin, Campos Basin, etc.) (Warren et al., 1999). La Popa Basin is the best analogue of the Gulf of Mexico (Willis, 2001). Although no oil or gas deposits were found in it so far, understanding of its structure and geological evolution can be applied to similar areas whether they are located in the continent or offshore.

The Bouguer gravity and the total field aeromagnetic data were supplied by Geological Survey of Mexico (SGM), Pemex Exploration and Prospecting, published data (Mickus et al., 1999), and authors field works (Yutsis et al., 2009, Tamez et al., 2010, in press).

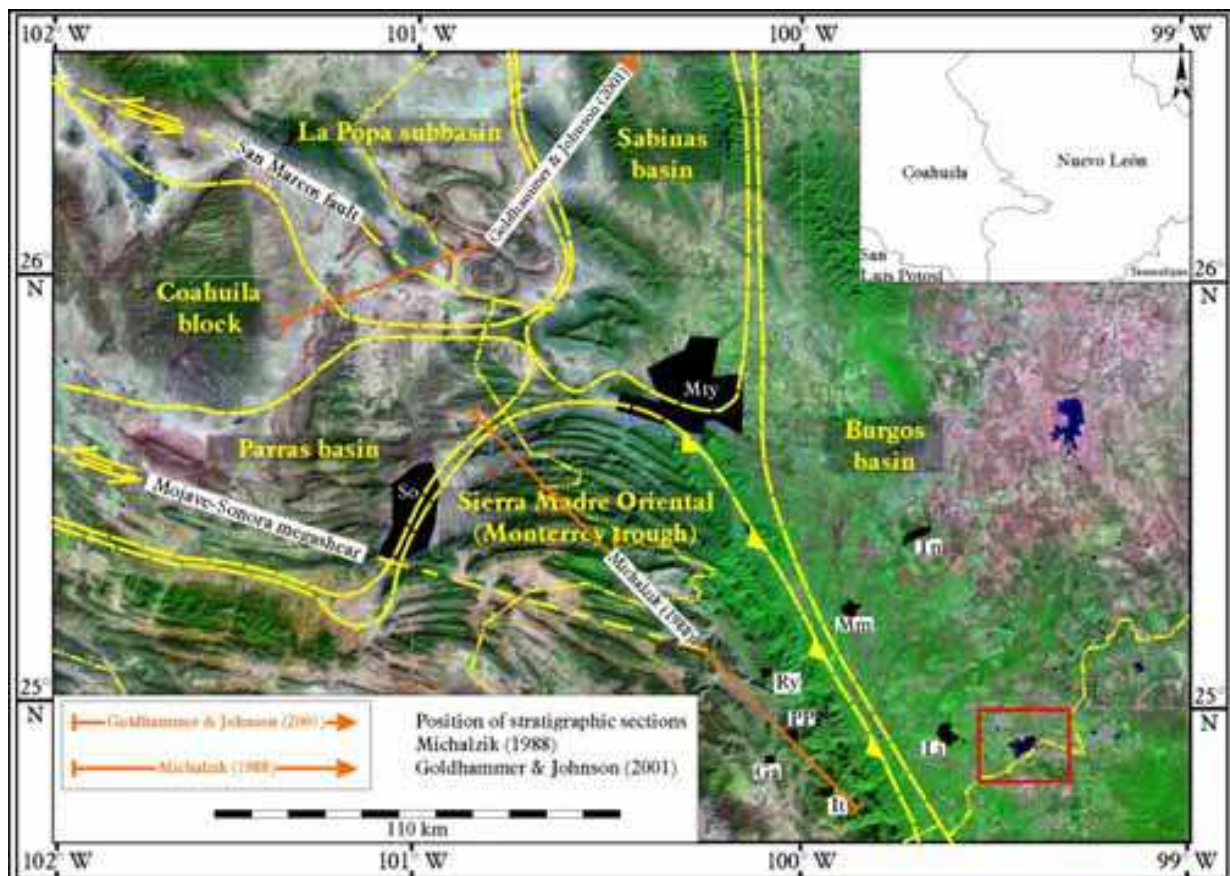


Fig. 1. Location of study area in context with major and geologic elements (basins and blocks; orange lines; abbreviations: Mty: Monterrey, So: Saltillo, Tn: Terán, Mm: Montemorelos, Li: Linares, It: Iturbide, Ga: Galeana, PP: Potrero Prieto y Ry: Rayones; satellite image: worldwind.arc.nasa.gov; political limits in the upper right corner)

2. Geological setting and paleogeography evolution

Geological formations of the NE Mexico range from the Proterozoic crystalline basement to Tertiary sedimentary rocks and Quaternary deposits. Middle Jurassic through Upper Cretaceous tectonic and sedimentary evolution in this area is mainly defined by divergent-margin process/ regime associated with the opening of the Gulf of Mexico, and overprinted by nonigneous Laramide orogenic effects. Generally the stratigraphic evolution is interpreted to be dominated mainly by eustasy as thick regional accommodation cycles can be correlated throughout the Gulf of Mexico (Goldhammer & Johnson 2001).

The stratigraphic and structural configuration of Northeastern Mexico reflects it's a complex tectonic evolution. It initiated in the Permian-Triassic with the Ouachita-Marathon orogenic event, followed closely by Late Triassic to Middle Jurassic rifting of Pangea, subsequent opening of the Gulf of Mexico, and passive-margin development through the Late Cretaceous. It culminated with Laramide foreland deformation through the early Tertiary with local associated evaporite tectonism. The structural core of Northeastern Mexico consists of Triassic to Liassic basement fault blocks whose development reflects in part late Paleozoic orogenic events of metamorphism and intrusive magmatism. These early Mesozoic fault blocks in turn controlled Late Jurassic and Cretaceous sedimentation, and also strongly influenced Laramide structural patterns and foreland basin deposition.

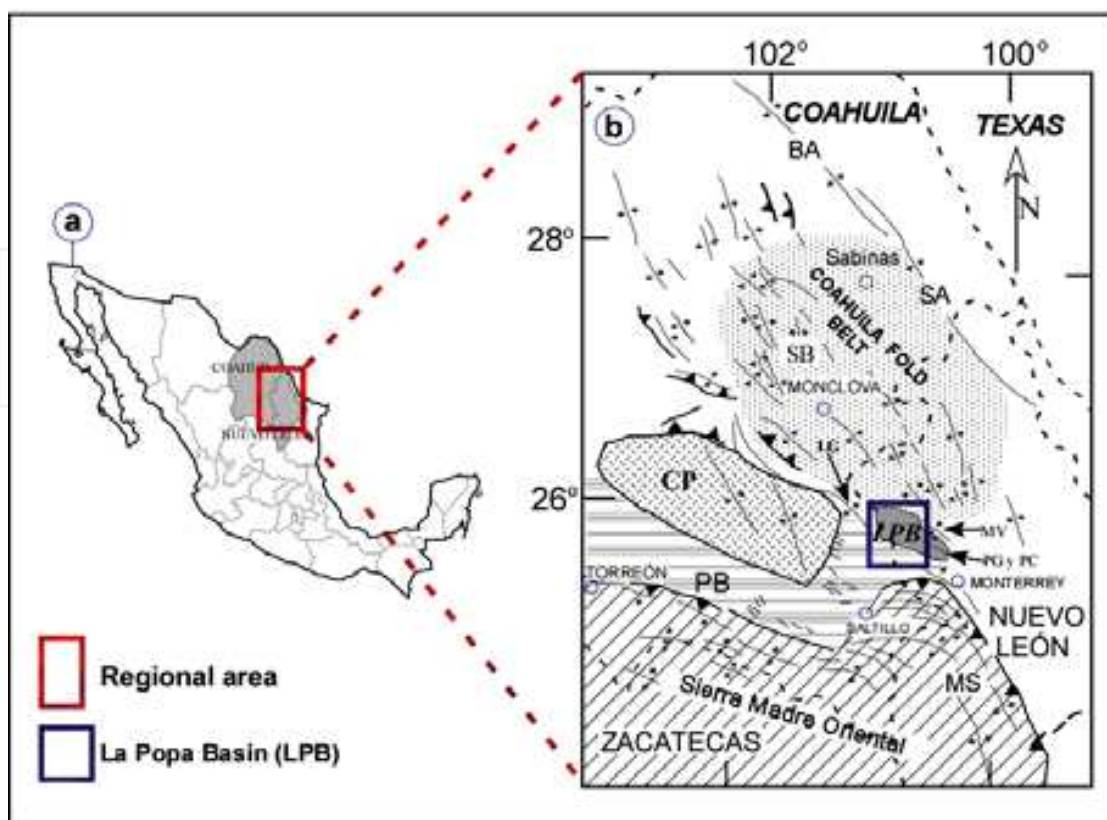


Fig. 2. (a) Location of foreland of Sierra Madre Oriental in northeastern Mexico and (b) La Popa Basin in the foreland. Explanation: CP, Coahuila Platform; LG, La Gavia anticline; LPB, La Popa Basin; MS, Monterrey Salient of Sierra Madre fold belt; PC, detachment fold at Potrero Chico; PG, detachment fold at Potrero de García; MV, detachment fold at Sierra Minas Viejas; PB, Parras Basin; SB, Sabinas Basin; SA, Salado arch; BA, Burro arch. Inset blue rectangle in La Popa (Lawton et al., 2001)

Rifting and initial segmentation of Pangea are evidenced by attenuated basement in Northeastern Mexico expressed as basement highs (Coahuila Block, Burro-Salado Arch, Tamaulipas Arch) and lows (Sabinas Basin, the “Monterrey trough”; Fig. 1). These shallow, rigid basement blocks are held up primarily by granite to granodiorite intrusions of Permo-Triassic age, created south of the Ouachita-Marathon orogenic belt by closure of Gondwana and North America and stranded by subsequent rifting (Goldhammer & Johnson 2001).

The Sierra Madre Oriental folds and thrust belt is of Laramide age (Late Cretaceous to Eocene). The belt is characterized by elongated anticlines that trend east to west, curving to the south (further east). The anticlines have very steep, vertical limbs, and some are overturned to the north. Folds are arranged in a series of nappes and may be bounded by thrusts. The deformed section consists of essentially the entire Upper Triassic to Cretaceous rift to passive-margin sequence (e.g., Prost et al. 1994, Gray & Johnson 1995, Marrett & Arranda-García 1999).

Late Cretaceous to Early Tertiary foreland basins include the Parras, La Popa, and Burgos Basins (Fig. 1). The Parras Basin is confined between the Coahuila block and the Sierra Madre front. The sediments in these basins consist of nearly 5000 m of Campanian to Maastrichtian shallow marine and deltaic terrigenous siliciclastics of the Difunta group and up to 10000 m in the Burgos basin (Lawton et al. 2001, Ortiz-Ubilla & Tolson 2004).

2.1 Mesozoic sedimentation

The Gulf of Mexico depicts a Mesozoic divergent margin basin formed through rifting and extension of Pangea, followed by breakup, seafloor spreading, and migration of various cooling and thermally subsiding tectonic plates (further reading Buffler & Sawyer 1985; Pindell 1985; Pindell & Barrett 1990).

During Triassic to Middle Jurassic (pre-Callovian) times, red beds associated with volcanism accumulated in fault-bounded graben systems, to which Mixon et al. (1959) assigned a Late Triassic age. These deposits unconformably overlie Late Paleozoic metasedimentary or Permo-Triassic granite basement. Thicknesses are in the order of 300 to 2000 m, restricted to rift basins (Michalzik 1988; Goldhammer & Johnson 2001).

Widespread Jurassic evaporite deposition occurring in the whole Gulf of Mexico area continues into the more restricted portions of Sabinas Basin and “Monterrey trough” (Fig. 1). In the Monterrey-Salttillo area, the Minas Viejas evaporite outcrops as deformed masses of gypsum unconformably overlying the Huizachal red beds and/ or Paleozoic basement.

In Northeastern Mexico, the La Caja Formation is of Kimmeridgian to mid-Berriasian age and consists of rhythmically bedded, thin, calcareous shales, siltstones, and fine sandstones, with thin limestones toward the base. Locally, the La Casita Formation (of late Kimmeridgian to Hauterivian age), shows a period of major clastic influx. Age and thickness of these sedimentary packages vary geographically, in part as a function of proximity to the exposed Coahuila block and Tamaulipas arch.

The Taraises Formation is the Lower Cretaceous (mid Berriasian through Hauterivian) deeper-water, offshore facies equivalent to the middle and upper units of the La Casita and consists of rhythmic-bedded, black, cherty, pelagic lime mudstones and intercalated shales.

Goldhammer & Johnson (2001) do not report a clastic influence during the Lower Cretaceous (Taraises Formation) derived from Tamaulipas arch, however, Michalzik (1988), Ocampo-Díaz (2007) and Ocampo-Díaz et al. (in review) can prove a clastic influence to the Galeana, Potrero Prieto and Rayones areas coming from a contemporaneous paleo-high. These clastic intercalations may also have influenced the subsurface in the study area.

From Hauterivian to early Aptian, the enormous carbonate platform system of Northeastern Mexico maintains a low-relief, reef-rimmed shelf margin with a platform interior shallow-marine facies. The carbonate strata of this Cupido Formation (700 to 1200 m) predominates today's Sierra Madre Oriental.

The Lower Tamaulipas Formation (late Hauterivian to early Aptian) is the basinal equivalent to the Cupido Formation and crops out primarily to the south and east of the Monterrey-Salttillo area. It consists of up to 600 m of dark gray to black, thin- to medium-bedded, cherty lime mudstones to wackestones. The La Peña Formation separates the Cupido/ Lower Tamaulipas Formations from the overlying upper Tamaulipas Formation. The formation varies in thickness from a few meters to 200 m (Goldhammer & Johnson 2001), and consists of thin-bedded, dark, argillaceous, cherty limestones and black shales.

The upper Tamaulipas Formation (Albian; 100 to 200 m thick) is the basinal equivalent of the Aurora Formation (Fig. 2). Outcropping basinal facies are assigned to the Cuesta del Cura Formation which is latest Albian to Cenomanian and consists of 60 m deep-water carbonates and shales. The Agua Nueva and the San Felipe Formations result from the upfolding diachronous Laramide phase of deformation (from the end of Cenomanian) and the displacement of the depocenter towards the Gulf of Mexico (Smith 1981; Winker & Buffler 1988; Ice 1981; Goldhammer & Johnson 2001). This package of deep-water deposits averages 300 to 400 m in thickness and consists of pelagic lime mudstones to

wackestones. At the time of their deposition, the Sierra Madre Oriental fold belt developed and migrated from west to east. In Northeastern Mexico, Maastrichtian foreland basins developed in front of the advancing Sierra Madre (e. g. Sabinas area, La Popa, Parras and Burgos Basins).

2.2 Digital elevation model

As the geographical situation of the studied area in the north of the Sierra Madre fold belt entails a lack of outcrops, thicknesses and facies of the different stratigraphic units (mainly igneous and sedimentary Mesozoic and Tertiary rocks and Quaternary soils; Lawton et al., 2001) had to be estimated and substantiated by geophysical and satellite data.

Digital Elevation Model (DEM) taken from The Consortium for Spatial Information (www.csi.cgiar.org) was used to compare the surface structures and basement blocks (Figs. 2, 3).

This model consists of a database of 72,202,000 points and covers the major structures such as La Popa Basin and its surrounding structures: The Monterrey Silent, anticlines Minas Viejas, Potrero Garcia, Potrero Chico, Las Gomas - Bustamante, La Gavia, Enmedio, Lapazos - Sabinas, Coahuila Island, Parras Basin, Sabinas Basin, and Monclova Island (Eguiluz, 2001), and Candela - Monclova Intrusive Belt (Fig. 2). Figure 3 shows main geological structures distinct in the Digital Elevation Model.

2.3 Surface geology

The surface of study area is formed by blocks of marine sediments deposited between the Middle-Late Jurassic and Cretaceous (Fig. 3) (Padilla y Sanchez, 1986, Salvador, 1987, Pindell et al., 1988; Winkler and Buffler, 1988; Wilson, 1990, Pindell and Barrett, 1990 and Dickinson and Lawton, 2001), and the deformation observed in these blocks and in many parts of northeastern Mexico is complicated by evaporite sequences (Minas Viejas Formation), local incorporation of the basement in the deformation, and by reactivation of some basement faults such as San Marcos Fault (Padilla y Sanchez, 1986 and McKee et al., 1990). Part of this fault is covered by the gravity and magnetic data (Yutsis et al., 2009).

Foreland La Popa Basin is located in front of the Monterrey Silent as part of the Sierra Madre Oriental, a province that represents the structural high. The Parras Basin is located west of the Monterrey Silent and South Coahuila Block, which in turn is adjacent to the Sabine Basin in the northern part of the area. La Popa and the Parras Basin's sedimentary rocks contain fine-grained siliciclastic deep-water carbonates of Late Cretaceous - Early Tertiary age. These units overlie carbonates of Early Cretaceous platform. Late Cretaceous rocks underlie the Difunta Group and the Parras shale (McBride et al., 1974, Vega-Vera and Perrilliat, 1989 and Ye, 1997). This sedimentary sequence was deposited in front of the Sierra Madre Oriental during Laramide Orogeny (Vega-Vera and Perrilliat, 1989, Vega-Vera et al., 1989 and Ye, 1997). There are also some tectonic blocks or Permo-Triassic paleo-highs such as the Coahuila block (Tardy, 1980 and Charleston, 1981), the Monclova Island, representing basement high (Golhammer and Johnson, 2001).

The most important fault in this area is the San Marcos Fault, which was defined by Charleston (1981), who suggested the lateral movement along it in the Late Jurassic and normal fault behavior in the Early Cretaceous. In addition, the San Marcos Fault structurally separates the Coahuila Block and Coahuila Folded Belt (McKee and Jones, 1990); within the latter there are a number of intrusive bodies of nearly EW orientation which in general are called Intrusive Belt Candela-Monclova (Fig. 3).

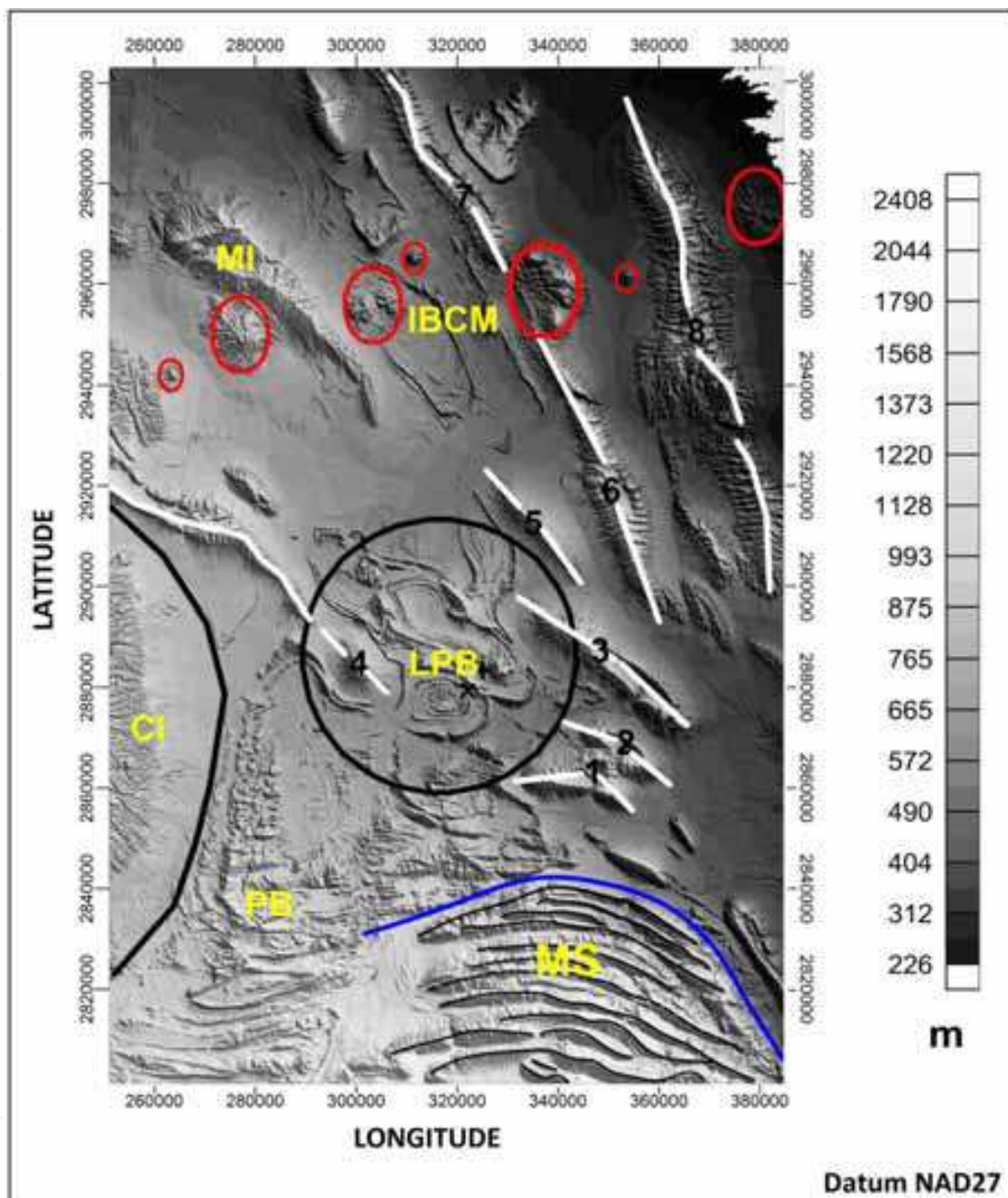


Fig. 3. Geological structures recognized in the Digital Elevation Model: CM, Monterrey Silent, CP, Parras Basin, CI, Coahuila Island, CLP, La Popa Basin, IM, Monclova Island, CICM, Candela-Monclova Intrusive Belt (circled in red). Anticlines: 1- Potrero Garcia, Potrero Chico 2 - 3 - Minas Viejas, 4 - En Medio, 5 – La Gavia, 6 - Las Gomas, 7 – Bustamante, 8 - Lapazos – Sabinas

3. Gravity and aeromagnetic data

Gravity data used in this study consists of a database of 9857 measured points on the surface with a 500 m interval (Fig. 4). This data analysis prompted to recognize the Mesozoic sedimentary features. It was also confirmed that the basement of La Popa Basin is composed by evaporates of the Minas Viejas Formation.

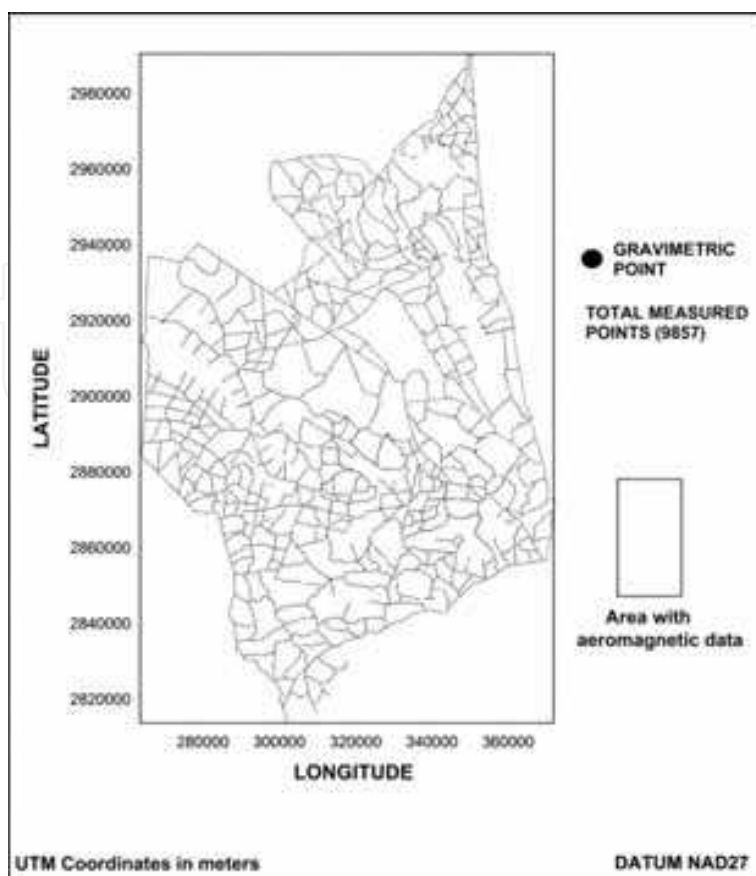


Fig. 4. Area covered by gravity net (total 9857 measurements). The same region and all blank parts are covered by aeromagnetic data grid

The total-field aeromagnetic data were supplied by the Mexican Geological Service (EMS), with the International Geomagnetic Reference Field removed. This method was used because its principle is based on changes in the magnetic properties of rocks in the subsurface (Reynolds et al., 1990 and Blakely, 1995). To correlate the aeromagnetic map with the crystalline basement, we examined the contrast of the physical property of sedimentary and igneous rocks.

The area of gravity and aeromagnetic data is located between coordinates 260000 E and 375000 E, 2810000 N and 29900000 N (UTM coordinates in meters, DATUM: NAD 27) but information is lacking for some parts.

3.1 Bouguer gravity

The complete Bouguer anomaly map was obtained using a density of 2.4 g/cm³ which was obtained using the method of Nettleton. Terrain correction was applied according to the method of Hammer (Burger, 1992) as there is variation in elevations from 300 to 1500 m. This gravity map shows that the values from west to east are more negative in a range of -43 to -165 milligals (Fig. 5b), which is interpreted as a change in cortical thickness between 33 to 38 km by Bartolini et al. (2001). Also, the regional-residual separation of the Bouguer anomaly was applied (Reynolds, 2007). In order to analyze the structures, the shallow residual Bouguer anomalies were used. They were obtained by applying a high pass filter with a cutoff wavelength of 50.000 m to the map of the Bouguer anomalies, which resulted in a map with values ranging from 5 to -17 mGals (Fig. 5d).

This showed that negative residual gravity anomalies are concentrated at the peripheries of La Popa Basin marking their border, and bounded by some blocks of Permo-Triassic basement such as Coahuila Block, Monclova Island, the Arch de Tamaulipas, Tamaulipas Archipelago (Goldhammer and Johnson, 2001). This phenomena is possible to explain taking into account that salt being initially deposited in the Upper Jurassic, later began to spreading to the periphery of the basin.

It is also noted that these minimums are surrounded by gravimetric maximum reflecting the density contrast between salt and denser rocks such as limestone, shale and sandstone.

3.2 Residual Bouguer anomaly

To study shallow bodies in the area we analyzed the map of residual Bouguer anomaly. It was observed that gravimetric minima ranging from -2 to -17 mGals almost perfectly match with some anticlines such as the anticlines Potrero Garcia, Potrero Chico, Minas Viejas, Las Gomas - Bustamante and the anticline La Gavia (Fig. 5d), Since the anticlines are considered to be nucleated by evaporites, the gravity minima may correlate with some of the most important accumulations of evaporites in the area under study.

3.3 Magnetic anomaly

The analysis of the crystalline basement of the study area was done using magnetic anomaly map. The total-field magnetic data were supplied by the SGM, with the International Geomagnetic Reference Field removed. The sedimentary cover in the NE of Mexico is generally considered to be almost non-magnetic, and the anomalies are sourced overwhelmingly in the crystalline basement. Local intra-sedimentary anomaly sources may be related to depositional concentrations of magnetic minerals in some clastic rocks, or to secondary magnetization of sedimentary rocks by circulating brines. Analysis of the total magnetic anomaly map, with variations in the range of 252 to -89 nT, shows that the La Popa Basin is characterized by magnetic minimum with values ranging from -8 to -14 nT; these minimums are found throughout the central part of the map in the E-W direction. The observed high magnetic values, ranging from 10 to 200 nT, increase to the northern part of the basin, and the southern part of the map are characterized by the low magnetic field. In addition, an isolated high can be clearly seen in the southern part of the La Popa Basin.

This analysis shows that La Popa Basin can be limited to the north and south by high magnetic fields (Fig. 6a).

The aeromagnetic map shows a quiet magnetic field in the area of the Basin. The general trend of the magnetic field reduced to pole is NW-SE in which background anomalies of northeast trend are obviously traced. However, local magnetic anomalies have mosaic character and, being morphologically extended in a NE direction, they are grouped in chains of northwest trend. The analysis of magnetic data allows assuming a series of linear elements focused in a NW direction. The NE part of the area is occupied by a series of positive magnetic anomalies intensively up to 120-160 nT. The maximum of this anomalies is the same as of gravity high (Fig. 5,6).

4. Regional geological-geophysical models

Geophysical data interpretation includes two-dimensional gravity and magnetic modeling. The observed anomalies contain the effects of both shallow and deep bodies, reflected in the gravity response as the sum of short and long wavelengths. We performed the separation of

regional and residual components of the Bouguer anomaly and magnetic anomaly, to conduct a qualitative analysis, and selected two profiles were selected for 2.5D modeling which represent the study area to a maximum depth of 15 km.

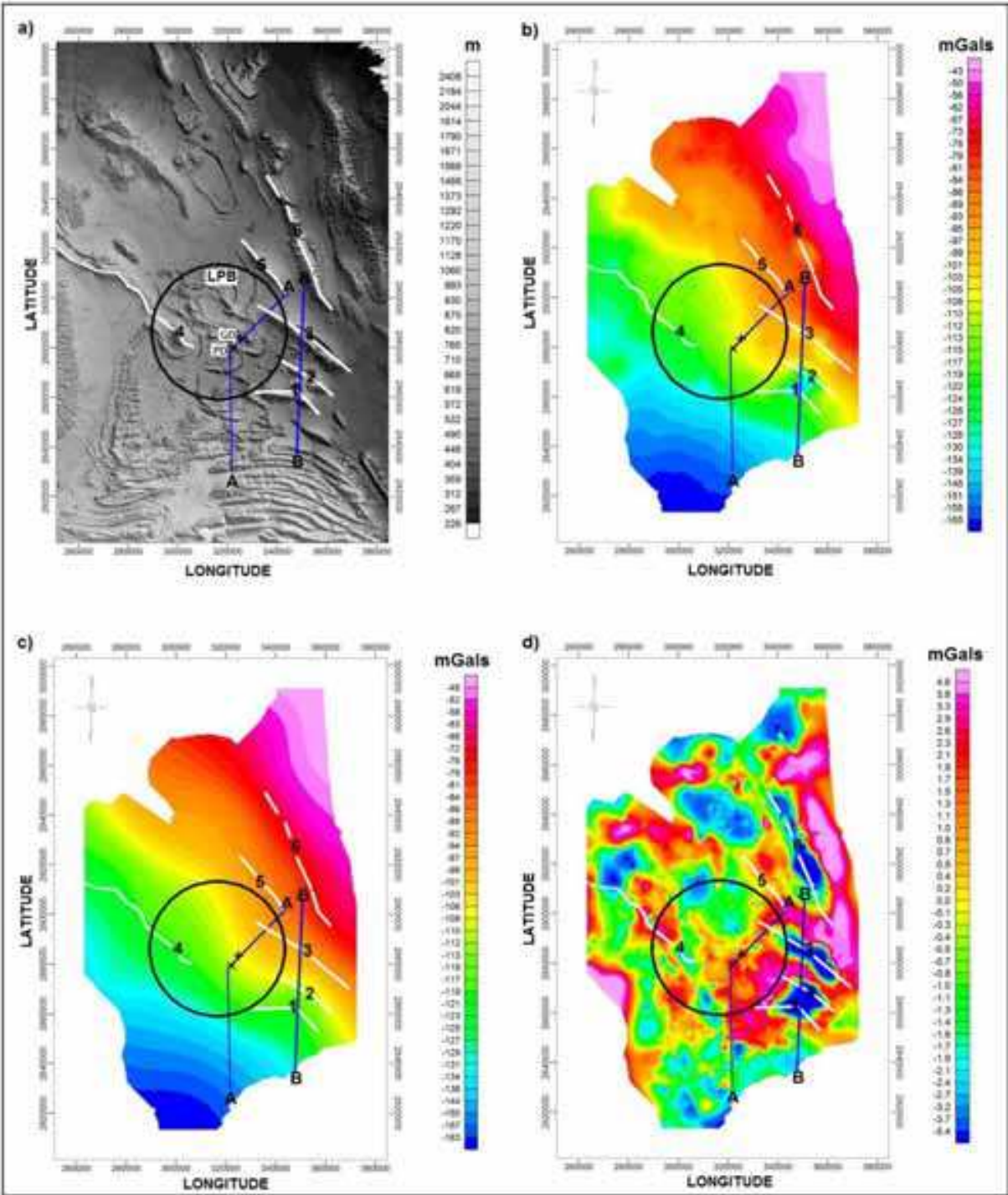


Fig. 5. a) Digital elevation model where: La Popa Basin (LPB), the Diapirs El Gordo (DG) and El Papalote (DP), profiles (A - A ') and (B - B ') as well as some anticlines (see Figure 2 for the names of the numbered structures). b) Map of the Bouguer anomaly 2.4 g/ cm3, c) Map of regional anomaly obtained from the Bouguer anomaly, d) Map of residual anomaly obtained from the Bouguer anomaly

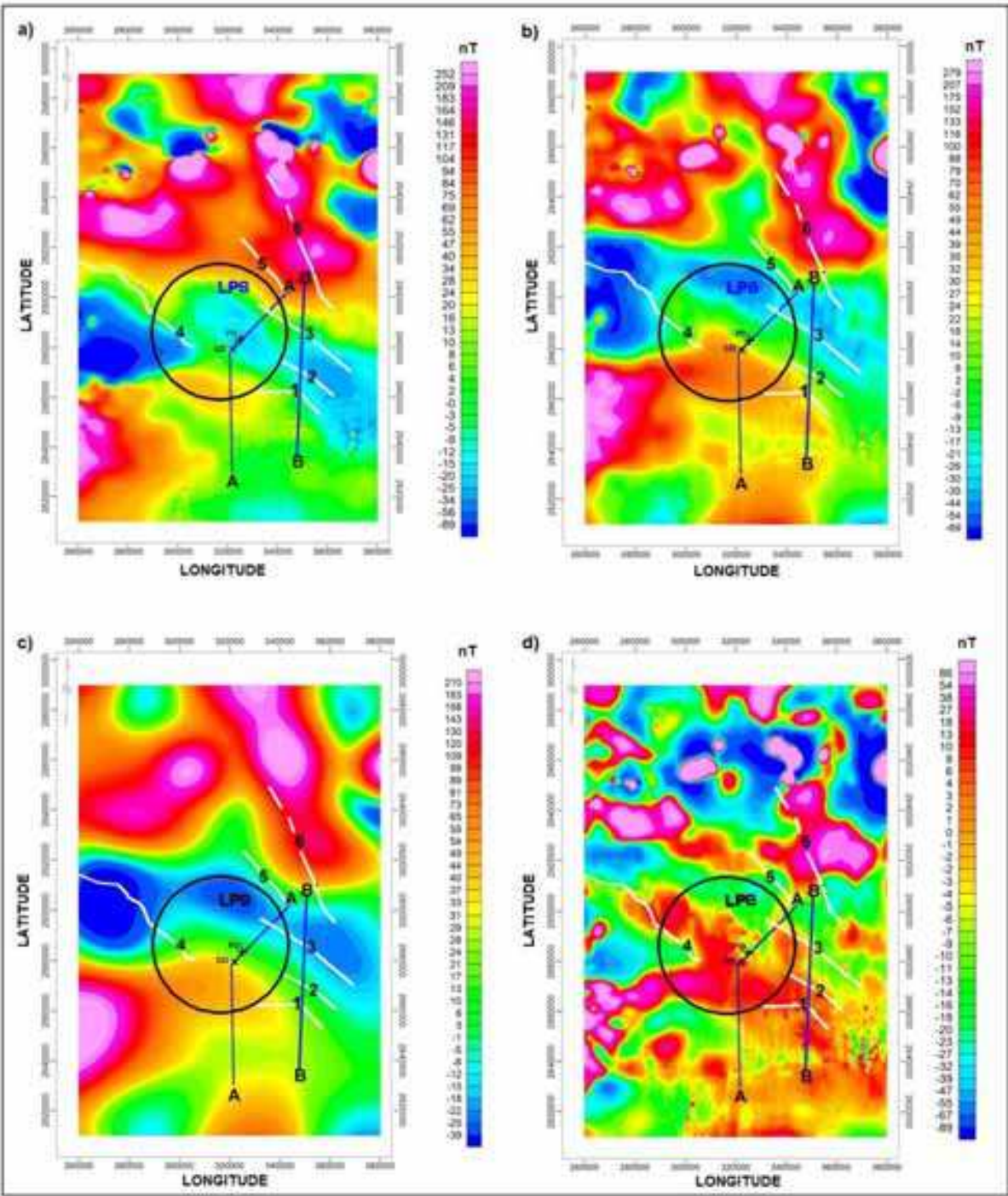


Fig. 6. a) Map of the total magnetic anomaly which is located La Popa Basin (LPB) within which are the diapirs El Gordo (GD) and El Papalote (PD), profiles (A - A ') and (B - B ') as well as some anticlines (see Figure 2 for the names of the numbered structures). b) Total magnetic anomaly map reduced to pole, c) Map of the regional component obtained from total magnetic anomaly reduced to pole, d) Map of the residual component obtained from total magnetic anomaly reduced to pole

The models presented here were developed based on the total magnetic anomaly, Bouguer anomaly and residual Bouguer anomaly, and were supported by the work of Aranda et al. (2008), who provided a compilation of published structural sections by Echanove (1962),

Padilla and Sanchez (1982), Gray et al. (2001), Millán-Garrido (2004), Higuera et al. (2005) and Latta and Anastasio, (2007).

To highlight local anomalies, the regional component of the gravity or magnetic anomaly field is commonly subtracted from the data, generating a residual map. The definition of regional vs. local anomalies is subjective. Regional-local separation can be achieved by band pass wavelength filtering, but as previously mentioned, this procedure requires assuming the cut-off wavelengths, which can smear the separation due to non-vertical filter roll-off, and can contaminate the data by Gibbs ringing. It is more intuitive to compute from the gridded data the best-fit smooth surface, of an optimal low order, and then remove that smooth surface as the regional component. Good results in northern Mexico, including La Popa Basin, are obtained by subtracting from the data a third-order best-fit surface. Gravity data benefited from this procedure the most, whereas no significant improvement was obtained for the magnetic data.

The procedure and technology of data interpretation was generally described in publications of one of the co-authors (Yutsis et al. 2004; Yutsis et al. 2009). In this case the data were extracted from the complete Bouguer anomaly chart and magnetic anomaly map. The profiles were located across and along the structural elements of the La Popa Basin. The resulting models obtained are shown in Figs. 7-8.

The gravity line demonstrates a significant elevation of anomaly from -33 mGal in the SW up to -24 mGal in the NE part of the profile. It is possible to recognize a zone of relatively high gravity gradient in the south part of the model. This zone is also characterized by topographic low.

Magnetic anomaly showing amplitudes between -250 and -150 nT. The central part of the model (corresponding to the central part of the Basin area) is characterized by relatively high intensive anomalies. The highest magnetic anomaly is located in the NE part of the basin. Two high-gradient zones are located in the same areas as topography and gravity irregularities.

Integrated geological-geophysical interpretation was based on gravity and magnetic models constructed using Geosoft and WingLink software.

4.1 Selected profiles for modeling

The methodology to select two modeled profiles consisted on the selection of representative structures of the area of study and to that they could also verify if the structural sections compiled by Aranda et al. (2008) agree with the geophysical response observed in these structures.

Later, they were located on the MDE and gravity and magnetic maps that represent the effect of the structures that cross the profiles; with this it was possible to select the maps that isolate the effect of deep structures by gravity and to see the effect of Mesozoic sedimentary block and the magnetic response of the crystalline basement.

The profile A - A' (Fig. 7) extends from the far North of the Curvature of Monterrey, the northeast part of the Parras Basin, the El Gordo and El Papalote diapirs in the La Popa Basin, ending in the marginal part of the Minas Viejas anticline. The profile B - B' (Fig.8) crosses the anticlines of Potrero Garcia, Potrero Chico and Minas Viejas (Fig. 6a).

4.2 Model (A-A'), "detached diapirs"

The profile A - A' (Fig. 7) is representative of the area as it allows us to observe 6 styles of folding in northeastern Mexico coexisting. Anticline Los Muertos corresponds to a fold-off of Jurassic evaporites, the anticline Venado of the Parras Basin suggests a hybrid fold, where

you firstly had a fold-off, and then its northern flank elevation is modified by salt developing a drape fold. The Delgado syncline developed by evacuation of evaporites, the anticlines El Lobo and El Gordo are a fold hybrid, where structure possibly was formed by a wall halo-kinetic salt and subsequently amended during contraction to a fold of two detached diapirs, one on each side of it (El Gordo y El Papalote). The halo-kinetic structure La Soldadura (Giles and Lawton, 1999) has been considered as a wall of salt (La Popa Fold), and finally the model proposes a basement inversion which should help the La Soldadura development (Aranda et al., 2008).

The model shows that the Mesozoic sedimentary sequence lies on the salt. This sequence is altered by the plastic properties of salt and its incompressibility prompting the inversion of densities in the area causing this migration to the periphery of the La Popa Basin,

4.3 Model (B-B'), "cut off anticlines"

The profile B - B' (Fig. 8) is located east of the La Popa Basin, crossing perpendicularly the anticlines of Potrero Garcia, Potrero Chico and Minas Viejas, which represent folds in the Jurassic evaporites of the Minas Viejas Formation. Similar structures have been reported in the Sabinas Basin by Peterson-Rodriguez et al. (2008).

The Bouguer anomaly map was used for this model, because the anticlines of interest correspond to high frequency negative anomalies related to shallow bodies, specifically the accumulation of evaporites in the cores of the structures.

The total magnetic anomaly reduced to pole for the crystalline basement mapping was used. This information was supported by structural sections constructed by Aranda et al. (2008) based on the work of Gray et al (2001) and Latta and Anastasio (2007), as well as lithological map of the basement (Albarran et al., 2008).

The cores of anticlines covered by this profile are eroded, so we combined information of the evaporite outcrops, data of the well Minas Viejas 1, which drilled a section of evaporites of 4.500 m (Lawton et al., 2001) and interpretation of the low values of the residual Bouguer anomaly. Finally, we obtained the thickness of evaporite at the core of the anticlines more than 4 km (Potrero Chico, Potrero Garcia anticlines). The anticline Minas Viejas also shows in its core a thickness of more than 5 km and a length of 1 km. The morphology of the basement in the model corresponds to a graben-like depression, being composed of schist and granite (Fig. 8).

5. Conclusions and discussion

Gravity data in the northeast Mexico basins are sensitive to local vertical offsets across high-angle faults, where rocks with different densities are juxtaposed. Yet, high densities in some Mesozoic sedimentary rocks just above the basement may smear out the subtle gravity traces of basement faults. Notably, in the Coahuila block in northwestern part of the area, where vertical basement-fault offsets reach tens and hundreds of meters, the associated gravity anomalies are not strong.

The total-field magnetic data were used, with the International Geomagnetic Reference Field removed. The sedimentary cover in northeast Mexico is generally considered to be almost non-magnetic, and the anomalies are sourced overwhelmingly in the crystalline basement.

Local intra-sedimentary anomaly sources may be related to depositional concentrations of magnetic minerals in some clastic rocks, or to secondary magnetization of sedimentary rocks by circulating brines.

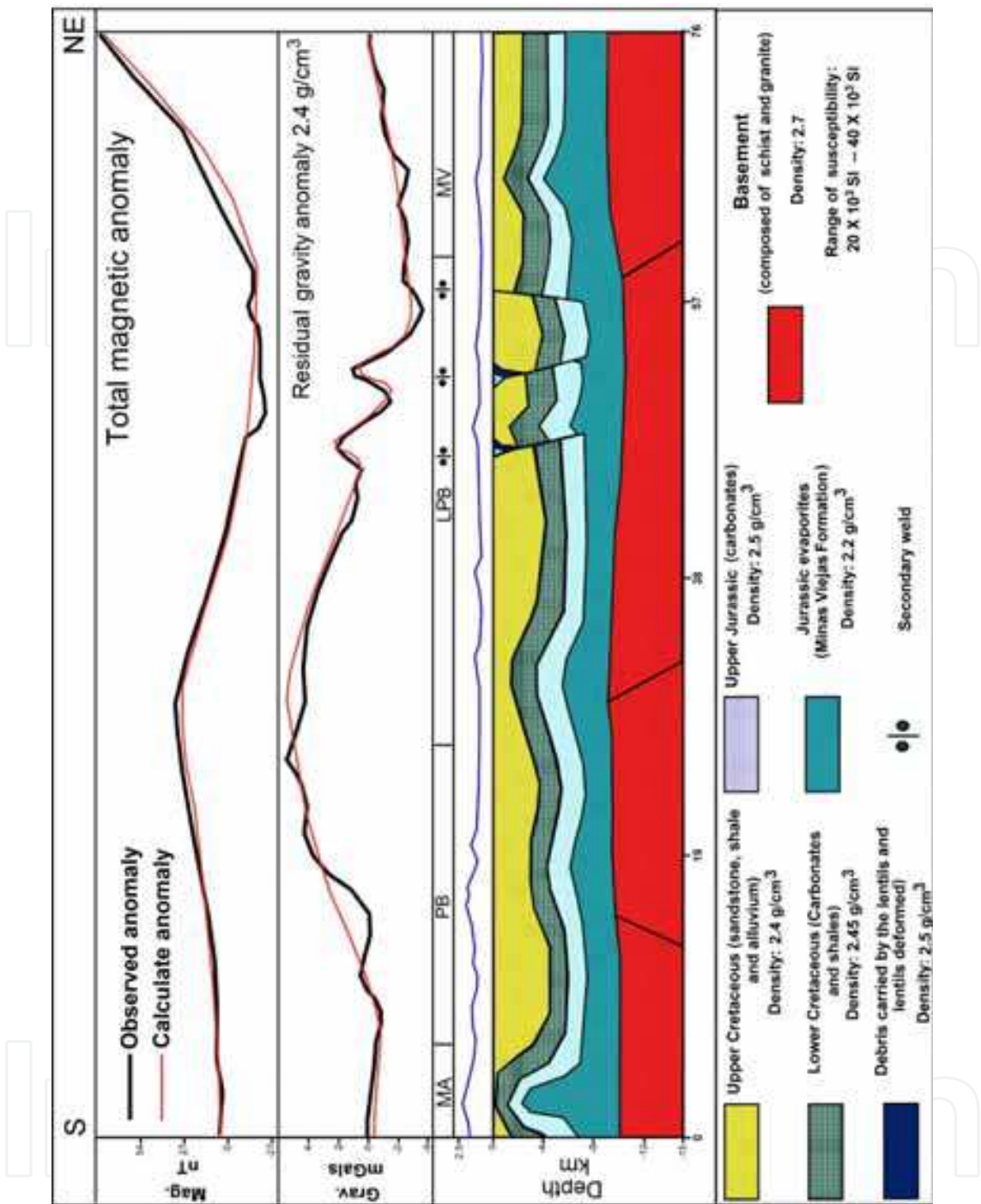


Fig. 7. Geological-geophysical model 2.5D (detached diapirs), by inversion of the total magnetic anomaly and the residual Bouguer anomaly 2.4 g/ cm³, Abbreviations: AM, anticline of Los Muertos, PB, Parras Basin , LPB, La Popa Basin, MV, anticline Minas Viejas

Steep, straight faults are commonly expressed as subtle potential-field lineaments, which can be gradient zones, alignments of separate local anomalies of various types and shapes, aligned breaks or discontinuities in the anomaly pattern, and so on. Many large magnetic and gravity anomalies represent the ductile, ancient, healed basement structures, obscuring the desirable subtle features. Subtlety of the desirable lineaments need detailed data processing, using a wide range of anomaly-enhancement techniques and display parameters. So data

processing includes Fourier transformation, wave-length filters, upward and down ward continuation, vertical and horizontal derivates, analytic signal analysis, etc.

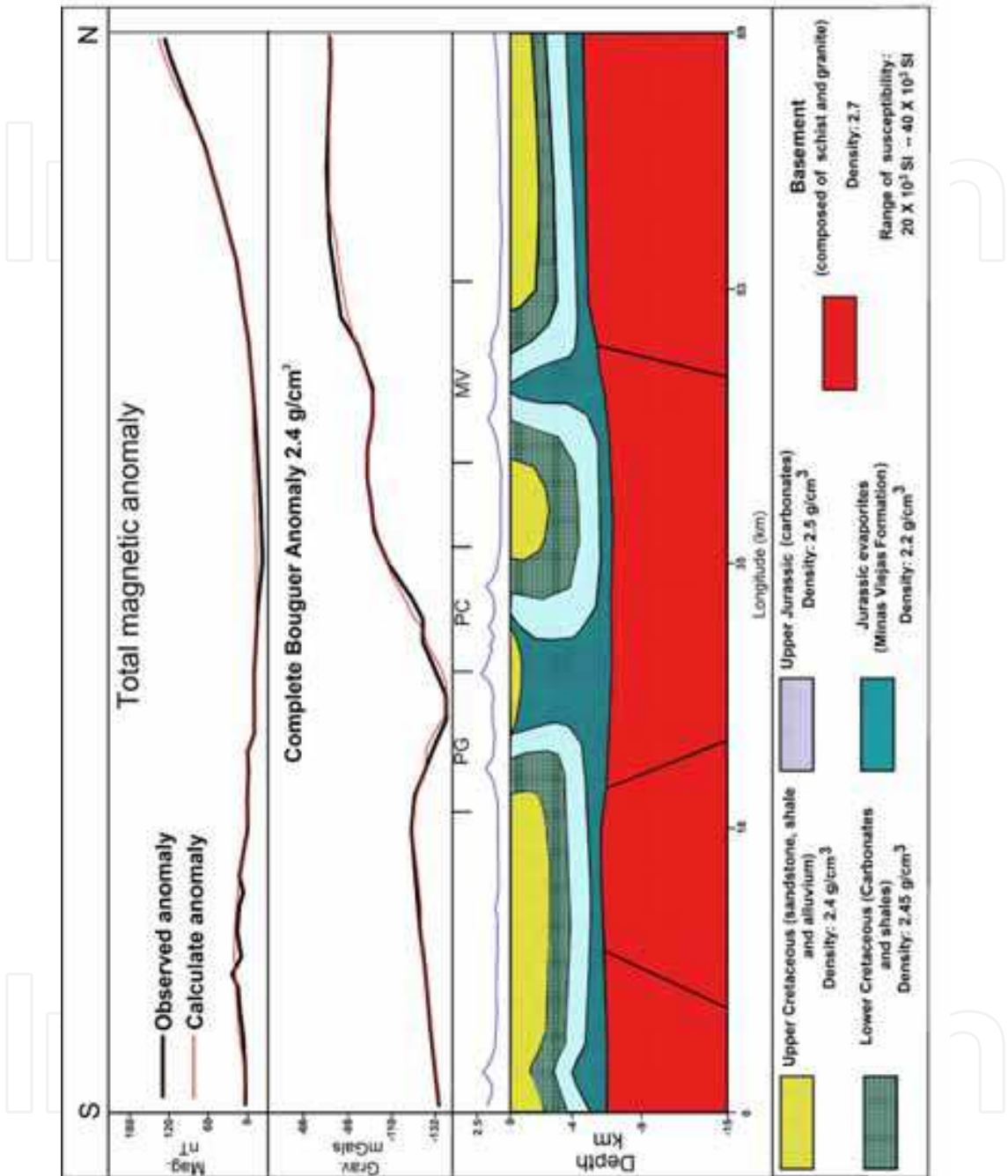


Fig. 8. Geological-geophysical 2.5D model (detachment anticline), by inversion of the complete Bouguer anomaly 2.4g/ cm³ and total magnetic anomaly. Abbreviations: PG, Potrero Garcia anticline; PC, Potrero Chico anticline; MV, Minas Viejas anticline

The qualitative analysis of geophysical potential field data and its relation to the geological structures in the area of study shows that some of the residual minima of the Bouguer gravity are related to the topographic highs and generally positive tectonic features, specifically to anticlines such as Potrero de García, Minas Viejas and Potrero Chico. It is well known that the nucleus of anticlines here are characterized by accumulation of evaporates,

so we propose that the observed gravity minima correspond to the most important accumulations of salt in the area. This phenomenon is shown in model (B - B'). Also, it was discovered that these minima are located on the peripheries of La Popa Basin, so it is proposed that the La Popa Basin acted as the depocenter of salt sedimentation during Late Jurassic and finally "salt basement" was formed. Then more recent Mesozoic sedimentary rocks were deposited on the salt basement and caused a significant lithostatic pressure. Then, due to such physical properties of evaporites as plasticity and investment, salt began to migrate to the periphery of La Popa Basin.

Folds in the Minas Viejas Formation delineate the structures of some sub-domes and indicate the possibility that it is still rising.

Evidence of significant accumulation of salt is shown by the diapirs El Gordo, El Papalote (the model A - A') that are detached diapirs with debris and lentil at the edges.

Magnetic analysis showed that the La Popa Basin is bounded on the north and south by magnetic highs and it may be modeled as graben-like depression. This model corresponds to the hypothesis of Aranda et al. (2008) and Hernandez (2008) who named this structure as Jurassic Pit.

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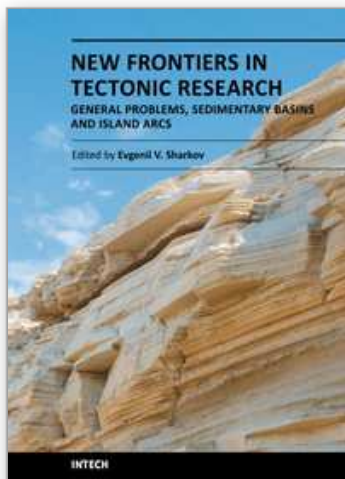
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