Interpretation of aeromagnetic data using GIS to evaluate the geotectonic regime of the Sabinas Basin

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ABSTRACT

The study presents the use of Geographic Information System (GIS) to assess the geotectonic regimen of the Sabinas Basin. Initially, the GIS database was designed using geological and geophysical information (total magnetic field reduced to the pole). Subsequently, 2D models of the basin were obtained along 4 profiles running on a north-south direction. The implementation of GIS enables a geological-geophysical interpretation generating various thematic maps that overlap the magnetic map during interpretation. The analysis of overlapping maps enables the identification of areas with different geotectonic regimes in the Sabinas Basin, as well as the relationship between these environments and mineralization. The qualitative and quantitative interpretation of the aeromagnetic data obtained for the total magnetic field reduced to the pole delineate uplifted basement areas as well as shallower blocks within them. This paper presents the location of both the basin’s deepest zones and its probable faults, which can be linked to the block boundaries. The faults zones and block boundaries correspond to the main mineral deposits found in the basin. Finally, the geotectonic regime of some sectors of the basin is detailed in order to reaffirm the results obtained by the interpretation of aeromagnetic data.

RESUMEN

Se presenta el uso de un Sistemas de Información Geográfica para evaluar el régimen geotectónico de la Cuenca de Sabinas. Inicialmente se llevó a cabo el diseño de la base de datos del Sistema de Información Geográfica, teniendo en cuenta las características de la información geológica y geofísica (campo magnético total reducido al polo). Posteriormente se obtienen modelos 2D de la cuenca a lo largo de 4 perfiles con direcciones norte-sur. A partir de la implementación del Sistema de Información Geográfica, se logró una interpretación geológica-geofísica, generando diversos mapas temáticos que se superpusieron al mapa magnético durante dicha interpretación. El análisis de los mapas superpuestos permitió identificar áreas con diferente régimen geotectónico dentro de la Cuenca de Sabinas, así como la relación de esas áreas con mineralizaciones. A partir de la interpretación cualitativa y cuantitativa de los datos del campo magnético total reducido al polo se delimitan áreas levantadas del basamento de la cuenca y los bloques más someros dentro de las mismas. También se localizan las zonas más profundas de la cuenca y probables fallas, que pueden estar vinculadas con los límites de los bloques. Las zonas de fallas y los límites de bloques están relacionados con los principales depósitos minerales de la cuenca. Por último, se detalla el régimen geotectónico de algunos sectores de la cuenca, para reafirmar los resultados de la interpretación de los datos aeromagnéticos.
1. Introduction

The efficient interpretation of geophysical data requires the knowledge and appropriate use of geological information, especially information represented on geological maps. Magnetometry is a geophysical method usually used in regional geological studies. The surface and subterranean distribution of different rocks types and geological structures provide the basis for the behavior of magnetic field (Telford et al., 1990). In sedimentary basins, the magnetic field is principally related to the crystalline basement, which is generally composed of igneous and metamorphic rocks which have a very high magnetic effect (Vázquez et al., 1990; Gunn, 1997). Deformations in the sedimentary infill of the basin may be related to their basement dynamics, which are linked to faults that cause uplifted or depressed blocks (Gunn, 1997).

The magnetic method has been used for the mineral exploration in the Sabinas Basin, which is located in northeastern Mexico (Figure 1) (Pascacio-Toledo, 2001). The deposits of metallic and nonmetallic minerals found in this basin, comprise mainly coal, fluorite, celestine, Pb-Zn-Ag and hydrocarbons (Eguiluz de Antuñano, 2001; Corona-Esquivel et al., 2006; González-Sánchez et al., 2007, 2015).

![Figure 1. Location of the study area (a section of the geological map of Nueva Rosita). Light gray line indicates the border with the Sabinas Basin. Modified from Martínez-Rodríguez et al. (2008).](image)

In the interpretation of magnetic data, it is very important to have the geological maps to identify the distribution of igneous rocks, geological structures and mineralized areas which can be linked to positive anomalies in the magnetic field. These geological maps also show the surface distribution of rocks that can be classified as diamagnetic, paramagnetic or ferromagnetic, according to their magnetic susceptibility values. Once those geological characteristics are known, they can be the behavior of the magnetic fields. GIS techniques are widely used to integrate geological and geophysical data, because they provide effective tools for managing geo-referenced information by enabling the correlation and comparison of different types of information. The graphical, numerical and text information can be combined using these tools (Ziaii et al., 2010; Kheniri et al., 2013). For example, in this study, fault locations (graphical information) with their respective names (text information), with values of magnetic anomalies (numerical data) can be combined, generating several maps of interpretation.

This research presents an example of using GIS, combined with other tools, to use maps to interpret geophysical data, taking as an example, the aeromagnetic data reduced to pole obtained for the Nueva Rosita area, in order to assess the geotectonic regime in this section of the Sabinas Basin, located in northeastern Mexico (Figure 1).

2. Geological setting

The study region is located in the Sabinas Basin in northeastern Mexico (Figure 1). This basin forms part of a rift associated with the opening of the Gulf of Mexico (Eguiluz de Antuñano, 2001). This structure originated as a rift-type graben limited by paleotectonic and paleogeographic blocks, such as the Coahuila block to the southwest (SW), the Tamaulipas block to the northeast (NE), and the Burro-Peyotes blocks to the north (N) (Figure 2). The San Marcos and La Bavia faults are deep regional structures that separate the blocks of the basin (Chávez-Cabello et al., 2005).

![Figure 2. Structural configuration and tectonic features of northeastern Mexico (Coahuila and adjacent areas). Rectangle indicates the study area. Taken from Chávez-Cabello et al. (2005).](image)

The Sabinas Basin is filled with different types of sedimentary rock, principally limestone, sandstone, shale, conglomerate, limolite and gypsum, accumulated during the Mesozoic and Cenozoic (Eguiluz de Antuñano, 2001; González-Sánchez et al., 2007). In the Late Cretaceous, the Laramide orogeny altered the sedimentary regime in the region and caused deformation in all sedimentary sequences (Eguiluz de Antuñano, 2001). This orogeny was also accompanied by various magmatic events which generated different types of igneous rocks during the Middle Eocene (basic, intermediate and acidic rocks), constituting some intrusive bodies that outcrop in the Candela-Monclova intrusive belt located to the southeast of the Sabinas Basin (Chávez-Cabello et al., 2011).

The geological map of Nueva Rosita (Martínez-Rodríguez et al., 2008) is located in the Sabinas Basin (Figure 2 and 3). Outcrops of sedimentary rocks are found in the entire area covered by the map, aside from the central-north part of the map, named Esperanzas-Kakanapo lava, in which volcanic rocks outcrop (Martínez-Rodríguez et al., 2008). Various anticline and syncline folds are observed in this region, whose axes lie northwest-southeast (NW-SE). Also there are also several fault systems following the same direction. Some of the identified anticline folds being heavily eroded, such as the Obayos anticline (Figure 3). A high level of erosion in this structure causes outcropping in the majority of the sedimentary Mesozoic sequence (Martínez-Rodríguez et al., 2008). Metallic and nonmetallic mineral deposits can also be found in this area (Figure 3). The nonmetallic mineralization mainly comprises coal (Corona-Esquivel et al., 2006), barite, celestine, fluorite and hydrocarbons, whereas Ag-Pb-Zn comprises the most significant metallic mineralization (González-Sánchez et al., 2007, 2015). The deposits of barite, celestine, fluorite and Ag-Pb-Zn are Mississippi Valley-Type (MVT) mineral deposits (González-Sánchez et al., 2007).
3. Methodology

The GIS database structure was designed to include geological and geophysical information from previous research undertaken by Martínez-Rodríguez et al. (2008) and SGM (2000), as well as, results of the interpretation of geophysical data. The structure of the database included the objects considered (geological information, tectonic, aeromagnetic data, etc.), as well as the type of object (areal, vector or point) its attributes (name, rock types, mineralization, values of the magnetic field, etc.) and type of field (integer, logical and character). Subsequently, the input of geological and geophysical data was performed under the categories of object type, attribute and field type. The representation and management of all the information was made in the geographical coordinate system. The geological and geophysical interpretation was carried out in the final stage of GIS management, overlapping and comparing the set of geological and geophysical information used. The geological information is based on the geological map of Nueva Rosita to a scale of 1:250,000 (Martínez-Rodríguez et al., 2008). This geological map provided information pertaining to outcrops of geological formations, tectonic features and other mining-related information. The geophysical data includes total aeromagnetic field data taken on a 1:250,000 scale by the SGM (2000) using a G-B22A optically pumped cesium vapor magnetometer with a sensitivity of 0.01 nT. The flight lines were measured on a north-south direction, with a spacing of 1000 m and a height above average terrain of 300 m. The geomagnetic field in the center of the measured area had an intensity of 4730 nT, an inclination of 56°19’ and declination of 7ο31’. Initially aeromagnetic data were reduced to the pole using the Talwani method (Talwani, 1965). This method calculates magnetic anomalies produced by arbitrarily two-dimensional bodies, represented by irregularly shaped polygons in a cross-section. Two groups of rocks were used in the modeling, the first composed by igneous rocks taken from the basement of the basin, with an average magnetic susceptibility of 13x10⁻³ SI, while the second group includes the sedimentary rocks taken from the basin presented an average magnetic susceptibility of 0 SI. Subsequently, several graphical entities were defined on the magnetic map (contour lines, areas, alignments and points) entities which were exported into the MapInfo and ArcGIS software for inclusion in the GIS database. The entities were then compared with surface geological information to determine their probable relationship with the behavior of the magnetic field. Various thematic maps (e.g. rock types, geological age and tectonic regime) were also generated in the MapInfo and ArcGIS software. These maps were exported to the Surfer software for comparison with the magnetic map.

Two sectors of the study area were selected in order to assess the detail of the geotectonic regime, using the results of the interpretation of the aeromagnetic data. The first sector is located in an area of uplifted blocks in the basement, while the second sector is located inside an area of depressions in the basement.

4. Results and Discussion

4.1. Use of GIS to assess the geotectonic regime using aeromagnetic data reduced to the pole

From the description and analysis of the aeromagnetic data reduced to the pole, positive anomalous zones are shown as elongated mainly on a NW-SE direction (Figure 4). This zone occupies the biggest area of the map (bounded by the contour line with the value 0 nT). As it is considered that the behavior of the magnetic field mainly correspond to the basement rocks of the Sabinas Basin (Pascacio-Toledo, 2001), this area is characterized by uplifted basement blocks (Vázquez et al., 1990; Gunn, 1997) composed of igneous and metamorphic rocks (Pascacio-Toledo, 2001; Jacobo-Albarrán et al., 2011).

Before beginning the process of managing the GIS, the description and analysis of the magnetic map was performed using Surfer software. A quantitative interpretation of aeromagnetic data using 2D forward modeling was performed during this first stage. This interpretation was carried out along 4 profiles on a north-south direction, thus located in the area in which the main anomalies are found, in order to calculate the depths of the basement and determine any possible subsurface structures. Forward modeling was undertaken using Mag2dc software (Cooper, 2003) which calculates the magnetic field anomalies by means of the Talwani method (Talwani, 1965). This method calculates magnetic anomalies produced by arbitrarily two-dimensional bodies, represented by irregularly shaped polygons in a cross-section. Two groups of rocks were used in the modeling, the first composed by igneous rocks taken from the basement of the basin, with an average magnetic susceptibility of 13x10⁻³ SI, while the second group includes the sedimentary rocks taken from the basin presented an average magnetic susceptibility of 0 SI. Subsequently, several graphical entities were defined on the magnetic map (contour lines, areas, alignments and points) entities which were exported into the MapInfo and ArcGIS software for inclusion in the GIS database. The entities were then compared with surface geological information to determine their probable relationship with the behavior of the magnetic field. Various thematic maps (e.g. rock types, geological age and tectonic regime) were also generated in the MapInfo and ArcGIS software. These maps were exported to the Surfer software for comparison with the magnetic map.

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The 2D models obtained from the 4 profiles show the depths of the basin as varying from 1.5 and 9 km. The deepest zone of the basin is located at the southern end of the P4 profile, while the shallower zone is located in the P2 profile, in the Obayos area. The basement geometry of the basin suggests several faults, which suggest the probable presence of graben and horst. This later structure may be related to the uplifted basement blocks (Figure 5). These results suggest that the 160 nT are contour lines delimit the areas of the basement where the blocks themselves are presumed to be shallower; whereas the contour lines with the value 240 nT indicate the shallower parts of these blocks. Theoretically, the negative values for the magnetic field should correspond to with the deep zones of the basin (Vázquez et al., 1990), namely the depressed blocks of the basement. Using the 2D models (Figure 5) revealed that the areas with negative values were delimited by isolines of -80 nT, which should define the deepest parts of the basin (Figure 4). Within these areas, the isolines with a value of -100 nT indicate the areas of the basin with the greatest thickness of sedimentary rock, thus indicating that the basement rock is deeper.

The shaded relief map of the aeromagnetic data shows various alignments along the NW-SE and NE-SW trajectories (Figure 6). Most alignments can also be identified in the 2D models (Figure 5), alignments which have been associated with deep faults delimiting the basement blocks (Cruz-Falcón et al., 2010). Contour lines and magnetic alignments were exported to the GIS and subsequently compared with geological information (e.g., outcrops of different types of rocks, faults and location of mineral deposits). The MapInfo software shows the exported vectors overlapping on the geological map (Figure 3). The comparison of the geological and geophysical information allows the causes for the behavior of the magnetic field to be inferred. The shallower blocks of the basement sometimes cause changes in the sedimentary cover, as seen in the blocks located in the central and NW end of the study region and identified by the letters A and B in Figure 3. Both of these blocks form part of the Obayos anticline and the Santa Rosa Range, with the shape and direction of Block A forming part of the Obayos anticline and following the direction of the fold axis. The NW end of this geological structure is truncated by Block B, which follows a different direction (NE-SW) similar to the Santa Rosa Range. The comparison of the magnetic map with the map of rock types shows that the basaltic have little influence on the behavior of the magnetic field (Figure 7) as they do not generate a magnetic anomaly due to their very low thickness (an average of approximately 3 meters). These outcrops are located on the edges of uplifted blocks and apparently correspond to faults that follow the alignments of the magnetic field (Figure 3 and 6). Such faults may constitute pathways through which lava spills occurred in this area, volcanic events which occurred during the Pliocene-Pleistocene (Martínez-Rodríguez et al., 2008) and indicate the recent active nature of these presumed faults.
According to the locations of the main geological structures (folds and faults), the axes of the big anticlines are located on the edges of what appear to be uplifted blocks (Figure 6). Sometimes these axes of folds and small sections of faults correspond to the NW-SE magnetic alignments.

With Figure 6 showing all barite, manganese and Pb-Zn mines as located on the edges of the supposed blocks and apparently corresponding to the faults, the magnetic map shows one important feature of these MVT-Type mineral deposits, namely their proximity to large fault systems (González-Sánchez et al., 2007). Furthermore, most of the coal mines are located on the edges of these blocks or in areas of the basin of intermediate depth. This result demonstrates the effect of the remobilization of the basement on the structural configuration of the region, a remobilization which caused shallow coal seams to be formed.

Comparing the ages of the rock with the magnetic map (Figure 8) reaffirms the relationship between the basement and the tectonic deformations, as most of the areas with high magnetic field values and corresponding to the uplifted blocks of the basement are surrounded by outcrops of Mesozoic rocks, generally very folded and eroded.

4.2. Details of the geotectonic regime in two sectors of the Sabinas Basin.

Using the above results, this section presents the details of the geotectonic regime in two sectors of the Sabinas Basin, sectors referred to hereafter as Example 1 and Example 2 (Figure 9). Detailed analysis was undertaken in these sectors to confirm the results of the interpretation of the aeromagnetic data, which suggested uplifted and depressed basement blocks. The following analytical steps and results are described below.

4.2.1. Management of databases

Initially the magnetic field data were interpolated to create a map in raster format, which was classified into five classes of relevance taking into account the different ranges of the magnetic map indicate by the contour lines in Figure 4. These contour lines delineate the areas with different levels of the tectonic regime of the basin. The map depicts each of the classes and the different attributes of the tectonic regime, as well as the corresponding effect on the basin (Table 1). Classes 1 and 2 present negative values for the magnetic field and include the zones of the basin in which predominates the tectonic regime of subsidence, which is recorded at great depths, mainly in the zones of corresponding to Class 1. The zones presenting an uprising tectonic regime are indicated in three classes, with positive values for the magnetic field that indicate a different order of uprising for the basement blocks.

<table>
<thead>
<tr>
<th>Classes</th>
<th>Magnetic field values (nT)</th>
<th>Attribute of tectonic regime</th>
<th>Response in the basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>≤-100</td>
<td>Subsidence</td>
<td>Deeper zones of the basin (larger thick sediments)</td>
</tr>
<tr>
<td>2</td>
<td>-99 to -80</td>
<td>Subsidence</td>
<td>Deep zones of the basin</td>
</tr>
<tr>
<td>3</td>
<td>0 to 159</td>
<td>Uprising</td>
<td>Uprising the basement of the basin</td>
</tr>
<tr>
<td>4</td>
<td>160 to 239</td>
<td>Uprising</td>
<td>More uplifted blocks of the basement</td>
</tr>
<tr>
<td>5</td>
<td>≥240</td>
<td>Uprising</td>
<td>Shallower areas of uplifted blocks</td>
</tr>
</tbody>
</table>

The characteristics of some of these areas are detailed in the two examples shown below.

4.2.2. Example 1.

The geotectonic regime map in the Sabinas Basin (Figure 10) indicate that the sector represented by Example 1 is located within a positive magnetic field anomaly (Figures 3 and 9) representing one of the sectors of more uplifted blocks of the basement in the basin. In the inside of this sector is also delimited the shallower area of the block. The spatial analysis results for the shallower area of the uplifted block in this sector are shown in Table 2. The combination of geotectonic regime map with the geological map indicates that in this area predominate Cretaceous rocks on the surface (Figure 10), with mainly Late Cretaceous covering more than 69% of the area (Table 2). This indicates uplift and the erosion of the youngest geological formations, according to the results of other studies (Buccolini et al., 2014; Wu et al., 2014). This uprising regimen is corroborated by the presence of Holocene colluvial sediments formed by piedmont deposits covering 27% of the area, with the few alluvial deposits identified in the area revealing a sector of uprising, where erosion processes predominate compared to cumulative processes. This approach is validated by other research results (Shikakura, 2012; Medvedev and Harst, 2015).

<table>
<thead>
<tr>
<th>Age</th>
<th>Type of rocks and sediments</th>
<th>Area (km²)</th>
<th>% of area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td>Colluvium</td>
<td>10.66</td>
<td>27.04</td>
</tr>
<tr>
<td></td>
<td>Alluvium</td>
<td>0.43</td>
<td>1.09</td>
</tr>
<tr>
<td>Late Cretaceous</td>
<td>Sedimentary</td>
<td>27.64</td>
<td>69.64</td>
</tr>
<tr>
<td>Early Cretaceous</td>
<td>Sedimentary</td>
<td>0.88</td>
<td>2.33</td>
</tr>
</tbody>
</table>

Table 2. Spatial distribution of the shallower area of uplifted blocks in the sector for Example 1.
GIS. A remobilization of the basement in the Sabinas Basin during the Laramide orogeny is evidenced from the relationship between the magnetic field and the geological structures. This relationship suggests that, during the orogeny, various deep fault systems were reactivated, thus dividing the basement into blocks which were uplifted, causing deformations in the sedimentary filling of the basin. The development of thematic maps using GIS, such as maps drawn based on rock type, age and tectonics, enables an accurate and precise comparison with the aeromagnetic data. The main structural deformations observed on the surface, as well as the principal areas with mineral deposits and lava spills, correspond to the edges of the presumed uplifted blocks of the basement. The results enabled researchers to detail the geotectonic regime in two sectors within the study area, which are linked to uprisings and subsidence in the basin. A prevalence of erosion processes were identified in the sector where uprisings were recorded in the basin whereas the cumulative processes predominate in the sector showing subsidence. The analysis conducted here on the tectonic regime in two sectors supports the concept pertaining to the dynamics identified in the basement blocks, which indicated uplifted and depressed blocks, suggested by the interpretation of the aeromagnetic data.

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