Integration of High-Resolution Gravity and Depth-Migrated Seismic Data for Studies of Subsalt Plays in the Gulf of Mexico

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Abstract: The main goal of the present work was the modeling of structures related to salt tectonics and the visualization of the sedimentary rocks below these geologic structures, for the evaluation of a possible subsalt play. The main subsurface imaging method used in petroleum exploration is seismic reflection because it offers better spatial resolution than other geophysical methods; however subsurface salt bodies challenge the applicability of seismic reflection imaging. The new techniques of marine seismic research including depth migration increased spatial resolution, demonstrating its efficacy in better visualizing subsalt reflectors and better modeling halokinetic structures, especially for actual stratigraphic and structural thicknesses. Using a generalized density vs. depth curve for the deep-water Gulf of Mexico, a series of sensitivity models have been constructed for a salt lens. The present work shows the results of the integration of reflection seismic data with potential-field methods at high resolution as applied to the Cuenca Salina del Istmo (southern Gulf of Mexico).

Keywords: Seismic reflection, Salt tectonics, Gravity and magnetic methods, Gulf of Mexico.

1. INTRODUCTION

The Gulf of Mexico is a semicircular and overfilled basin [1], approximately 1500 km in diameter (Figure 1). It lies between the North American plate and the Yucatan Block. Its sedimentary cover reaches up to 10-15 km of thickness, with depositional ages ranging from late Triassic to Holocene [2]. The deep-water Gulf of Mexico is characterized by a great oil and gas potential.

One of the important parts of this potential, sub-salt plays, are widespread phenomena in this area. Interpretation of seismic lines evidenced the existence of early halokinetic activity, whereas most studies conducted on field data showed salt movement appearing mainly during the latest periods when several diapiric structures were formed in the Cuenca Salina del Istmo (Figure 2). Montgomery and Moore [3] report that exploration for deep-water sandstone reservoirs beneath allochthonous salt in the Gulf of Mexico represents a major new frontier play in North America. Although many studies have been undertaken to better understand this sub-salt petroleum system, the fundamental problem of sub-salt seismic imaging remains the key challenge, even with the latest acquisition and processing technologies available [4]. There are different problems in the seismic processing and interpretation. The high acoustic impedance contrast is one of these problems.

![Figure 1: Distribution of the salt in the Gulf of Mexico [1].](image-url)
Miocene, sandstone sections reflect subsalt deep-water paleoenvironments and advance deep-water depositional models. Through integration of reflection seismic, gravity and magnetic data, better imaging of the sub-salt environment may be achieved.

2. GEOLOGICAL SETTING

The study area occupies about 590 square km and is situated in the western part of La Cuenca Salina del Istmo, 130 km NW from the city Ciudad Del Carmen, Campeche state, Mexico (Figure 2). This zone forms part of the continental platform [6] in the Campeche shelf, western Gulf of Mexico. The Salina del Istmo Basin contains Mexico’s oldest oil fields, which have been exploited for the last 80 years. Several hundred million barrels of liquid and gaseous hydrocarbons have been extracted from the sandstone formations, which were deposited during Early Miocene time [7]. Salt sheets exist at various stratigraphic levels and have overridden sandstone fairways on the present-day outer continental shelf and upper slope [3]. Bird et al. [1] summarized the Mesozoic tectonic and geologic events that occurred in the history of the Gulf of Mexico in the Table 1. The stratigraphic sequence is constituted by siliceous, siliciclastic and carbonate sedimentary rocks that vary in age from Pleistocene to Kimmeridgian (Upper Jurassic), and are commonly intruded by bodies of salt [6,8,9].

3. GEOPHYSICAL DATA

The acquisition of seismic data in the study area was carried out by the Compañía General de Geofísica (C. G. G.) between August and December 2004. The set-up of the multi-channel seismic acquisition system on the geophysical research vessel and basic fundamentals of reflection are shown on the Figure 3. High-resolution gravity data were acquired by the companies COMESA and FUGRO. The data were observed at sea level simultaneously with the seismic survey, making a network with a spacing at 50 m intervals. Geomagnetic data were obtained by the Servicio Geológico Mexicano under the agreement with Pemex (Petroleos Mexicanos). The data were obtained at the flight height of 300 m above sea level and a separation of the pri-

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Table 1: Summary of Gulf of Mexico Formation Events (Modified from [1,2,9-13])

<table>
<thead>
<tr>
<th>Rifting Begins</th>
<th>Salt Deposition</th>
<th>Yucatan Rotation Begins</th>
<th>Sea-Floor Spreading Begins</th>
<th>Sea-Floor Spreading Ends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Triassic to Early Jurassic (200-230 Ma)</td>
<td>Callovian – early Oxfordian to Kimmeridgian (150-160-168 Ma)</td>
<td>Late Middle Jurassic (160 Ma)</td>
<td>Callovian – Kimmeridgian (150-160 Ma)</td>
<td>Berriasian – early part of Late Jurassic (137.85-140 Ma)</td>
</tr>
</tbody>
</table>
mary lines of 3 km. There are 4 wells within the study area. Well logs were used for identification of reflectors and their stratigraphic interpretation.

The seismic interpretation was performed with Landmark’s Seisworks software. As a first step, the migration in depth with the Kirchhoff algorithms and wave equation was performed [14–17]. The mapping of 13 horizons was established, within which seismic sequence’s limits and well-controlled horizons were proposed. As a result, several seismic lines were chosen to perform the modeling and integration with the high-resolution gravity and magnetic data. In this paper we show two of these lines (Line 1400 and Line 1500).

Figures 4 and 5 show the reflection seismic lines 1400 and 1500, which were migrated to depth and interpreted (Figure 4A, Figure 5A). It is possible to see the horizons of the Tertiary, Mesozoic age, as well as the depth and sub-salt horizons (possibly Pre-Jurassic). Evaporite domes here are marked with pink color (Figure 4B, Figure 5B). These domes are situated at different stratigraphic levels and are characterized by different dimensions. In these seismic sections we can appreciate the tectonic complexity of the area due to the great salt activity derived from the compressive events of the Mesozoic; the presence of reverse faulting of possible Oxfordian origin is shown. The faults can serve as possible migration routes for the evacuation of the salt. The depositional age of the salt is probably Callovian [6], but salt dome emplacement occurred during Cenozoic time. It is possible that these salt domes are currently active; they are affecting sediments located very close to the seafloor.

Stratigraphic interpretation of the seismic data [18-20] in the study area had shown the existence of numerous sedimentary sequences, separated by seismic horizons. Correlation between them was made using the well data. There are 9 horizons, which are mapped exclusively by seismic data, and 4 horizons with well-log control.

Table 2 shows the velocities in these seismic stratigraphic formations [21] corresponding to densities, calculated using Gardner’s Equation [22], other density-velocity relationships, and the use of available empirical data (e.g. velocity logs, gamma-gamma density logs, etc.).

4. GEOLOGICAL INTERPRETATION

There are different goals, which researchers try to approach through integration and joint inversion of geophysical data [23]. In reservoir geophysics one of the important cases is the development of appropriate facilities where deep drilling can be achieved followed by the best completion technology. At the same time,
one of the general aspects is the development and management of reservoir dimensions and properties [24]. In this work we tried to develop the geological model that best fits the reservoir dynamics thanks to the salt movement, with the aim to guarantee an accurate approach to subsurface geometry.

Figure 4: Line 1400 of the seismic cube. A – Seismic line migrated to depth using the Kirchhoff algorithm; B – The same line interpreted. In this seismic section we can appreciate the tectonic complexity of the area due to the great saline activity derived from the compressive events of the Mesozoic; the presence of reverse faulting of possible Oxfordian age is shown.

Figure 5: Line 1500 of the seismic cube. A – Seismic line migrated to depth using the Kirchhoff algorithm; B – The same line interpreted. In this seismic section we can appreciate the tectonic complexity of the area due to the great saline activity derived from the compressive events of the Mesozoic; it is shown the presence of inverse faulting of the possible Oxfordian origin.
Table 2: Correlation between Densities and velocities, Cuenca Del Istmo, Gulf of Mexico

<table>
<thead>
<tr>
<th>Formation</th>
<th>Density (g/cm³)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H_FM</td>
<td>2.0</td>
<td>1750</td>
</tr>
<tr>
<td>H_10</td>
<td>2.15</td>
<td>2330</td>
</tr>
<tr>
<td>H_30</td>
<td>2.20</td>
<td>2550</td>
</tr>
<tr>
<td>H_40</td>
<td>2.21</td>
<td>2600</td>
</tr>
<tr>
<td>H_50</td>
<td>2.23</td>
<td>2700</td>
</tr>
<tr>
<td>H_Ps</td>
<td>2.30</td>
<td>3050</td>
</tr>
<tr>
<td>H_TITOKIMER</td>
<td>2.58</td>
<td>4900</td>
</tr>
<tr>
<td>H_OXFORD</td>
<td>2.66</td>
<td>5450</td>
</tr>
<tr>
<td>SAL_AUTOCTONA</td>
<td>2.18</td>
<td>4600</td>
</tr>
<tr>
<td>LECHOS ROJOS</td>
<td>2.68</td>
<td>5500</td>
</tr>
<tr>
<td>BASAMENTO</td>
<td>2.75</td>
<td>6100</td>
</tr>
<tr>
<td>SAL_ALOCTONA</td>
<td>2.19</td>
<td>4600</td>
</tr>
</tbody>
</table>

2D gravimetric and geomagnetic modeling allows evaluating if the saline bodies interpreted with the seismic are adequate [25]. The appropriate densities and magnetic susceptibilities for each seismic formation were used according to Table 2. During the gravity and magnetic modeling we carried out the adjustment of the observed and calculated curves, taking as a base the seismic section migrated to depth. To propose the adjusted geophysical model with observed gravity and magnetic data, the depth and relief calculation of the crystalline (magnetic) basement was performed using Werner and Euler algorithms [26-30]. A full 2-D view of an integrated seismic-gravity-magnetic model with well control is shown in Figures 6 and 7.

Figures 6 and 7 show the result of this process. The green curves (Figures 6A, 6B, 7A, 7B) represent the observed gravimetric and magnetic fields. The red curves correspond to the anomalies calculated for the proposed model (Figures 6C, 7C) by the seismic interpretation (Figures 4B, 5B). The dotted black line in Figures 6A, 6B, 7A and 7B represents the equality between the observed and calculated anomaly, and this should be almost horizontal when both anomalies coincide. The effect of equality of these curves, which we can see on the Figures 6 and 7, shows that the proposed seismic models (Figures 4B, 5B) after adjustment using potential field data, correspond to real position of subsalt structures (Figures 6C, 7C).

5. DISCUSSION AND CONCLUSIONS

The present work shows how high-resolution potential field methods (gravity and magnetic) can support
marine reflection seismic data obtained and processed using modern enhancement techniques. Integration of potential field methods with depth-migrated seismic data has demonstrated its efficacy in producing a better visualization of both subsalt reflectors and better modeling of the halokinetic structures, especially in their possible real thicknesses. Due to the mobility of salt domes, space has been generated for the formation of mini-basins (Figure 8). It is possible to propose that the possible plays on sandy horizons were formed in these Tertiary mini-basins at the flanks of the salt domes. It is important to note that in the regional model for the study area, obtained from the joint interpretation of seismic, gravity and magnetic data, important reflectors are present below the economic basement. These deep pre-Jurassic reflectors (Figures 6C, 7C) could be of great economic interest. As a result of detailed integration, a new basement map has been created from high-resolution gravity, aeromagnetic data and Pre Stack Depth Migrated (PSDM) seismic data. These data were used to predict spatial distribution of the autochthonous salt bodies, densities and magnetic property distribution.

It was shown the reframing of the basement, which was approved through the simulation of gravity and magnetic fields. It was shown too that the base of this basement is located at depths below 8 thousand meters. These depths support the hypothesis of the existence (presence) of pre-Jurassic sub-salt sediments within the study area [5]. The results of this study can provide clues to potential prospects and leads in the area. The data can also be used for seismic attribute analysis and quality enhancement. The results of these models quantitatively demonstrate the need for accurate gravity and magnetic data in deep water salt modeling.

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and useful suggestions that helped to substantially improve the paper.

Figure 8: Seismic profile, which shows the thinning out of proposed. Tertiary plays with presence of sand (Figure 8A point 1 and Figure 8B point 2). The point 3 (Figure 8A) marks the presence of a Tertiary mini-basin.

REFERENCES


