Potential Field Data Guided Seismic Forward Modelling of Basement Structures: a Case Study from Offshore Nile Delta Basin

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SUMMARY

The offshore Nile Delta region has huge exploration potential, keeping in view the existing commercial oil and gas fields in and around this basin. The majority of the offshore Nile Delta basin is underexplored. Sparsity of geophysical data coverage and ambiguity in the interpretation of existing geophysical data have held back the exploration for many decades. In order to assess and evaluate the exploration potential, it is important to estimate the depth to the basement, the nature of basement and its topography. Identifying the basement reflector based on the current seismic data is challenging, because of limitations of the resolution and record length of the seismic data. Moreover, an estimation of sedimentary column is paramount for further detailed geological and geophysical investigations. The objective of the research is to perform seismic forward modelling of the basement reflector, guided by gravity and magnetic field data, and minimize the ambiguity involved in a single geophysical method of interpretation. The geophysical properties and their contrasts derived from seismic, gravity and magnetic methods of exploration are various criteria used in the integration and modelling process. Seismic stacking velocity data and depth values interpreted from gravity and magnetic field data are used in the modelling process. The uncertainty in modelling the basement character is assessed based on the stacking velocities and seismo-geological cross-sections interpreted from 2D seismic data, instead of cross-sections obtained from unreliable seismically derived depth data. The analysis of errors observed in the seismic data due to younger layer-cake reflections interfering with the basement reflector are analysed and the observed errors in the velocity models are accordingly reconciled based on the potential field data. The potential field data interpretation guiding the seismic forward modelling facilitates the redesign process of seismic data acquisition and processing in the hugely unexplored offshore Nile Delta basin in Egypt.

Key Words: Nile Delta Basin, Basement Reflector, Time Modelling, Gravity and Magnetic Data Integration, Risk Minimizing Interpretation

INTRODUCTION

The study area lies in the northern part of the offshore Nile Delta basin and geologically it is associated with a reworked clastic environment. The sediments are characterized by thick and quite recent wedging features that resulted the successive growth of abundant terrigenous sediments in the Late Miocene (Salem, 1976; Ross and Uchupi, 1977; Doherty et al. 1988). The oldest section penetrated is Mid-Jurassic as interpreted in the drilled well Mango-1 at a depth of 4440m (El Barkoky and Helal, 2002 and El Heiny and Enani, 1996). The general stratigraphic column in the offshore Nile Delta basin indicates deep and thick section from Palaeozoic to Recent. The drilled wells have not penetrated the Palaeozoic section, but seismic data indicate favourable seismic features associated with this geological formation. The study area is structurally affected by three major elements, sub-dividing the basin into three sub- basins (Figure 1), the eastern sub-basin, the central sub-basin and western sub-basin.

The previous researchers (El Barkoky and Helal, 2002) interpret salt related structural features including North Sinai structure (Moustafa, and Khalil, 1989 and 1990) with the existing geological modelling and interpretation. Dolson et al. (2000) present various issues on structural interpretation and business challenges of offshore basins in the Mediterranean region and its future exploration potentialities. Mekkawi et al. (2007) describe the structural interpretation of the Nile Delta basin using the seismic data. In the offshore part of the Nile Delta basin, the section is composed of mainly the clastic rocks with sporadic occurrence of non-clastic rocks of the upper Cretaceous and Messenian salt rocks. The subsurface structures in the offshore Nile Delta and its surrounding areas are mainly controlled by three major geologic factors (Gaullier et al. 2000): (1) the Nile River, as sediments source that accumulated along the Northeast African margin and the Levant basin (2) a thin layer of weak mobile Messinian evaporites flooring these sediments, and (3) the subduction regime, affecting the Eastern Mediterranean basin that led to shortening of the Mediterranean ridge and possibly the subsidence of the Herodotus Abyssal plain. The interactions between these three factors give the offshore Nile Delta area and its surroundings their unique geomorphological and structural configurations.

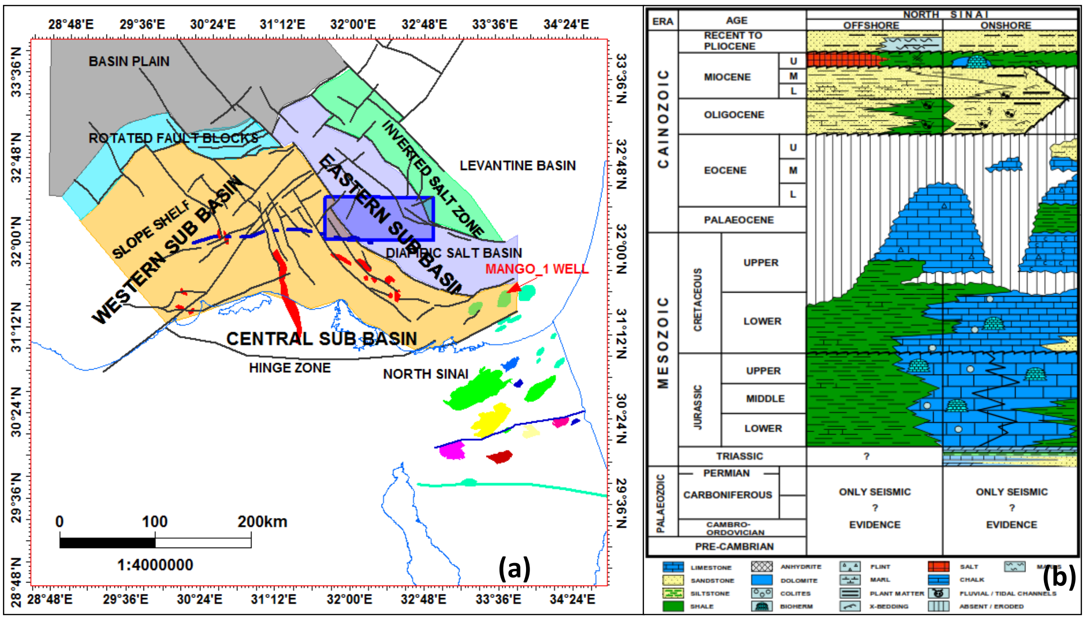

Figure 1: (a) Main structural elements of the Nile Delta basin (b) generalized chronostratigraphic column for northern onshore and offshore Sinai

As shown in Figure 1, the black solid lines are the main faults in the Nile-Delta basin, the coloured spots are the surface and subsurface Syrian arc system anticlines in and around the onshore and offshore Sinai and the red zones are the main producing fields in the Nile-Delta basin. The existing gravity and magnetic data have been investigated by Selim (2013), and is used as a basis for modelling, interpretation and analysis in the study area. The interpretation of magnetic data is very important in the salt areas such as the offshore part of the Nile Delta, since these data represent an additional tool to enhance the results obtained from seismic data degraded by the salt layers. The resultant depth maps exhibit a tolerable error range. In the current case study, the existing data are the only input in the modelling process. There is limited published literature on time/depth to the basement in the Nile Delta, due to the following reasons:

1. There is no indication of the basement reflector from drilled wells on the onshore part, where the basement is at shallow depths. It is very hard to interpret in the offshore part, where the basement has more than ten kilometers depth.
2. The unknown or ambiguous velocity models in the Nile Delta make it hard to estimate the depths and the behavior of the sedimentary rocks under these great depths.
3. There are no regional thickness maps of geological formations extended in the offshore area, thus underestimating the velocities in the region.
4. The seismic acquisition parameters are not optimum for imaging good quality seismic reflections at target levels, due to economic constraints of the projects. Especially, reaching 12 km of depth implies the length of streamer to reach 18 kms (with cable length=1.5 x depth).
5. Use of inadequate seismic data processing parameters at target levels, in particular the velocities used for stacking various seismic events, including deeper events are less accurate. Al Chalabi (1974) models and analyzes comprehensively the stacking and interval velocities on a horizontally layered earth media. Accordingly, the deeper events are focused while designing the processing parameters.

METHODOLOGIES

The Gravity and Magnetic Data Modelling

Integration of gravity and magnetic data suggest variety of structural features and major basement associated faults as interpreted from basement highs and lows, attributed from the map (Figures 2a and 2b). The continuous and multiple subsidence events are interpreted, which may have been causative to thicker sedimentation, associated with negative magnetic anomalies. Thick sediments overlie the basement structures in the study area. Magnetic data suggest smooth dipping of the basement from SW to NE. Analysis and interpretation of shelf-slope and deep-basin events suggest on-lapping patterns associated with gravity-flow deposits in the north and north easterly direction. Where basement structure is interpreted to have undergone major tectonic movement in the northerly direction, an increase in the magnetic intensity is observed. The depth to the basement, which is in the order of 1500m in the southern part of the study area, increases to 5000m in the northern part of the Nile Delta region. Overall depth to the basement is estimated to be 10km (Selim, 2013 and Saleh, 2013) as indicated in the preliminary investigations and inferred from the available seismic data and nearby drilled wells, which are corroborated by a number of seismic-geological cross sections taken in the southwest to north easterly direction. The gravity interpretation (Saleh, 2013) suggests 11km of depth to the basement. In the south, it is a stable platform area, but in the north-easterly direction, it is turned out to be with rotated fault blocks, which may have been affected by the deep-seated basement uplift including gravity gliding over the salted structures (Rybakov and Segev, 2004). The gravity data in the study area corroborates with E-W main bounding fault, which is deep-seated.

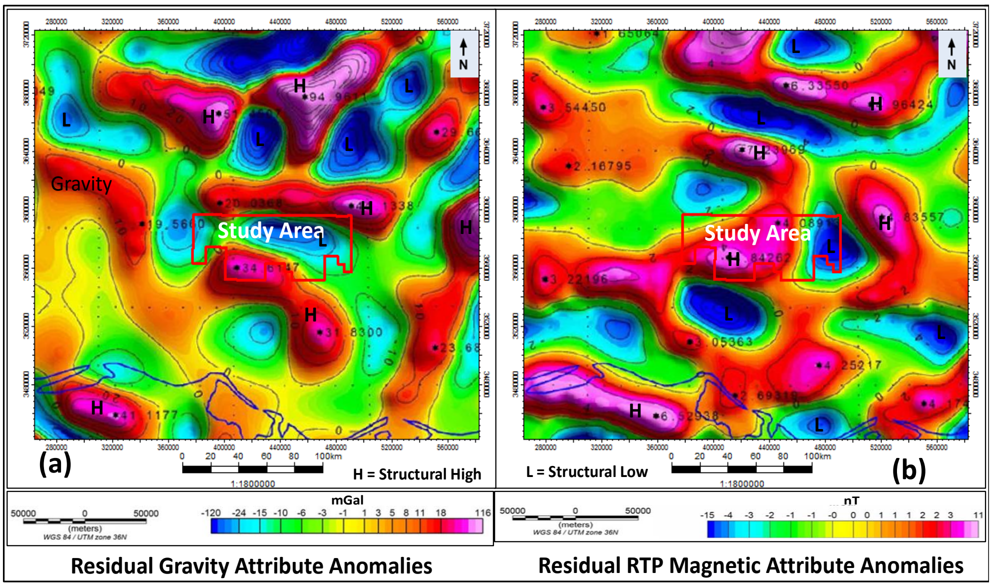

Figure 2: Study area, showing (a) gravity and (b) magnetic responses

The gravity and magnetic data further provide better definition of the tectonic features in the study area that support the seismic interpretation. The geomagnetic negative closure anomalies, along with elongated shape, low gradients, high relief and negative polarity attributes in the northern part of the Nile Delta basin (within the study area) suggest thicker sediments in the basin. Several polarity anomalies that are described by irregular shape, high sharpness and high gradients (Saleh, 2013) are interpreted in the central part of the area. Elongated shaped, negative polarity and low gradient anomalies are interpreted in the southern part of the study area. The spherical shape attributed anomalies, their closures with high gradient and sharp anomalies suggest thicker sediments in the Nile Delta basin. The Bouguer gravity anomaly map comprising of positive and negative gravities, which are striking in EW, ENE-WSW directions with minimum amplitudes suggests presence of thick sedimentary cover. Steep gradients of gravity anomalies with alternate negative and positive anomalies are interpreted in the central part of the map, which suggests the area is tectonically controlled by NE-SW and NW-SE trending structure anomalies.

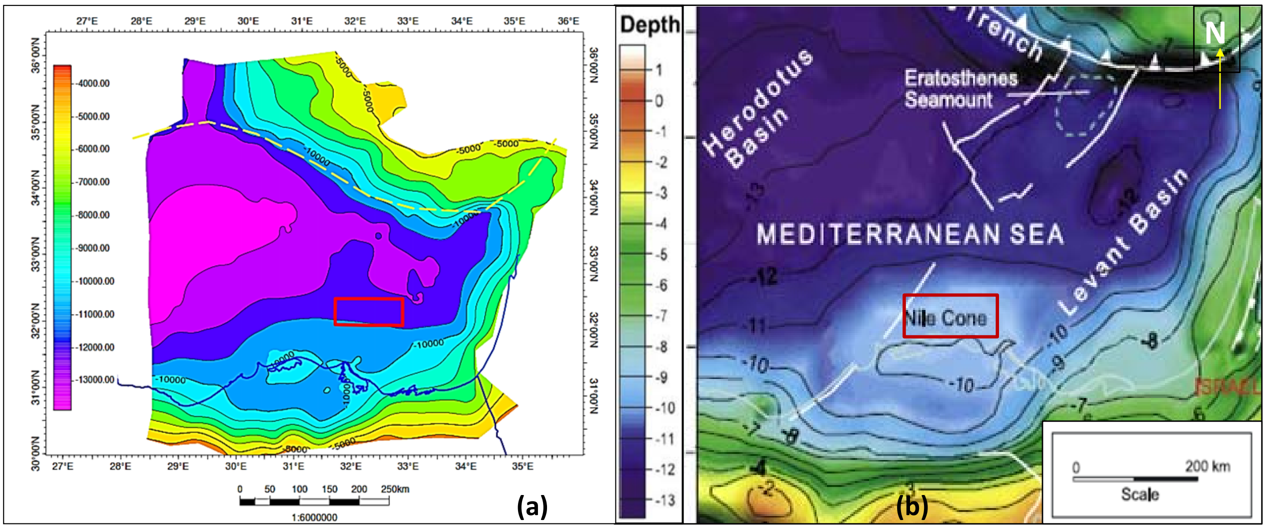

Figure.3: (a) Basement depth map, the area under study (the red rectangle) (b) the depth estimated

The available seismic data in the study area are reprocessed with optimum processing parameters, which further enhanced the seismic reflection character and its contrast, so that the basement reflector is interpreted with confidence using the existing seismic events. Only one stacking velocity function has been applied at CDP 1400, which is located at the middle part of the seismic section (Figure 4) that has NW-SE trending orientation. Sloth model is a slowness model, in which velocities in different layers are entered by (1/(v)^2), implying that sloth =1/(v)^2 where, v is the velocity in km/sec. For example, for a velocity 1500 m/sec, the sloth value is equal to 1 / (1.5*1.5) =0.44. This value is used in the velocity modelling and applied it in the seismic UNIX software. This velocity function is plotted to calculate the sloth trend at this location (Figure 5a). The key horizons digitized in the time-domain data are the sea bottom, top salt, bottom salt and basement, though there is ambiguity associated with the basement seismic character. Smoothed versions of the horizons are added as input in the modelling process (Figure 5b). Using these velocity trends, a depth structure map is computed at top of basement and is shown in Figure 3.

These depths are compared with the depths computed by gravity and magnetic responses on the 2D seismic profile. As described in the seismic forward modelling technique in Zelt and Ellis (1988), Zelt and Smith (1992), Anderson et al. (1995), Anderson and Cardimona (2002), Krebs (2004), Landro (2011) and Alaei (2012), using horizontal distance, vertical depth and layer acoustic impedance attributes, a geological model is transformed into a synthetic seismic reflection model that characterize the horizontal distance, 2-way travel time and seismic reflection amplitudes. Synthetic seismic records are generated both before and after the acquisition of reflection seismic field data (Anderson and Cardimona, 2002). The input data include depth-velocity cross section and the two-way time section of the modelled data. The depth-velocity cross section details are the critical factors in the accuracy and efficiency of the modelling process.

The work flow is as follows:

1. The smoothed version of the digitized key horizons from time section (the interval from mud line to the base-salt) are used as constant velocity value (2000 m/sec), as input in the depth modelling process,
2. The velocity of the interval from base-salt to basement is calculated from the stacking velocity function.
3. An ambiguous seismic basement horizon is constructed based on the resultant seismic data to test the result.

The 2D seismic line is located in the deepest part of the basin and very close to the new exploration activity area, in the eastern block of the Mediterranean region. The yellow dashed line as shown in Figure 3a is the Euro-African subduction zone. The seismic profile existing within the vicinity of gravity and magnetic data is used in the modelling and thus interpretation of the ambiguous or questionable basement reflector is carried out and it is highlighted as red horizon in Figure 4, which is that of a Cretaceous age.

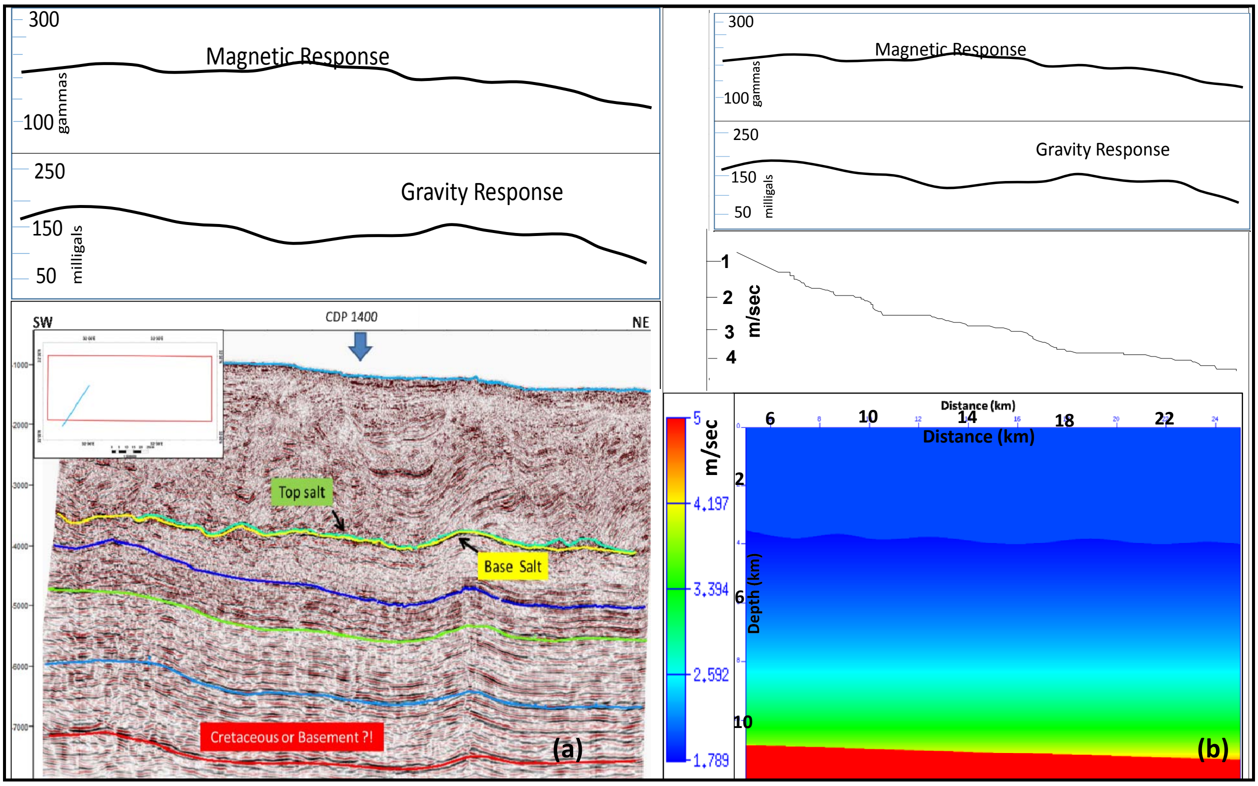

Figure.4: 2D seismic section, showing the (a) questionable basement horizon and (b) its reconciliation from gravity, magnetic and stacking velocity responses

The time values associated with mud line (shallowest blue reflector) are increasing towards north-eastern part of the study area. The shallow section of Pliocene- Pleistocene has nearly constant thickness in which, the salt layer (section between pale blue and yellow reflector) has thin and constant thickness. The range of the time-thickness of this layer is 20-25ms. The deepest section that has a reflector around 7sec is affected by series of faults. This reflector is the main target in the modelling process. The mud line at the bottom of salt reflector is digitized and it is an input horizon with velocity 2000 m/sec used in modelling process. The computed depth map as shown in Figure 3a is digitized for further modelling and analysis.

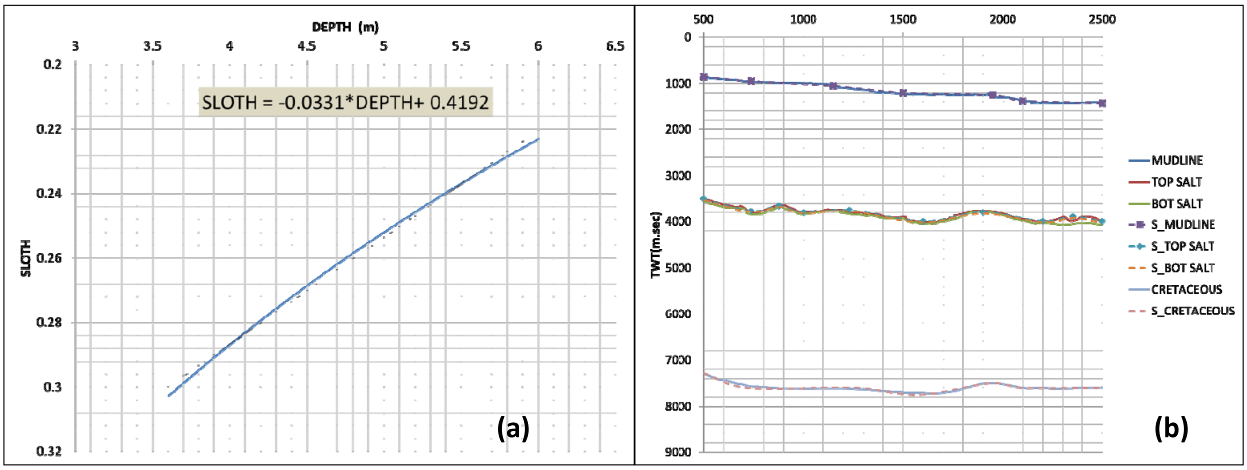

Figure.5: (a) Sloth ($1/V^2_{km}$) - depth relationship of the CMP 1400; (b): Smoothed versions of the digitized horizon

The sloth initial value is very small compared with the time value of the target zone (Figure 4). The reference point in this case has the base salt point at the CMP 1400 location (depth = 3600 m, velocity = 1817 m/sec and sloth value = 0.30289). The smoothed horizons are very close to the original ones Figures 6a and 6b.

Seismic Velocity Modelling

Three main horizons are used in modelling the velocities. Two of them are extracted from time section (the first being, the mud line horizon and the second is the base-salt horizon). For deeper horizons below the salt, the velocity is unknown and for this purpose the average velocity equation is used to minimize the error. The constant velocity 2000 m/sec is applied to keep the reflections as they are without any change, but replacing the velocity values of the water (1500 m/sec), shallow sedimentary section (2000 m/sec) and the salt (4500 m/sec) subsequently affecting the mudline horizon.

The model is subdivided into two main parts, the shallow or constant velocity section (2000 m/sec) and the deeper with variable velocity part. The maximum velocity is 4200m/s, which is interpreted to be a very high velocity value for sedimentary rocks in the area under study. This value calculated as shown in Figure 5 (the red area) has basement velocity 5000 m/sec. The third horizon is the top of basement layer, extracted from magnetic depth to basement map. The velocity of the base-salt basement interval is extracted from the stacking velocity point depth-velocity relationship. The reference point in this case is the base-salt point at the CMP location (depth = 3600, velocity = 1817 m/sec and sloth value = 0.30289). The average sloth depth relation for the interval is corrected and this relation is converted to Sloth=-0.0331*Depth+0.4192. The sloth value computed 0.4192, corresponds to 1544 m/sec, which may be a velocity of a horizon within Pliocene-Pleistocene sequence, which has Sloth= -0.0331*Depth+0.30289.

RESULTS AND DISCUSSIONS

Using the input velocity model (Figure 6a and 6b), a seismic section is modelled. As expected the shallow two horizons mud-line and base salt are located at their input time values. The basement horizon appears to be at deeper-time close to 10 seconds, the questionable horizon appears (blue line in Figure 6b) at shallower times, implying that the horizon is not associated with the basement or the gravity/magnetic data derived depth to basement may be incorrect.

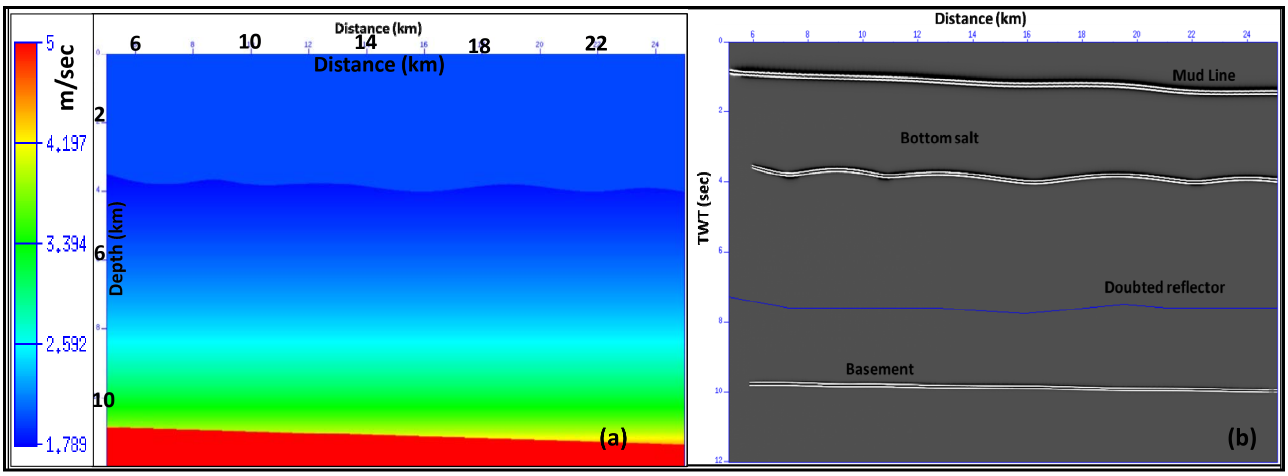

Figure.6: (a) the input velocity model (b) modelled seismic section

The shallow reflections are located at their correspondent time locations in the time sections and the questionable horizon is appearing at shallower location than the basement reflector. Two possible main sources of errors of the data used in the modelling process are:

1- The errors are analysed in the estimation of top of the basement. The expected error is 10 % shallower or deeper than the used values. For this reason another case is simulated by decreasing the depths 10% using the same velocity model. The result of the modelling is the shallower basement reflector as seen in Figures 7a and 7b. The deepest sedimentary section has lower velocity than the original with maximum values at the most right edge of the model close to 3270m/sec. The shallow reflections are located at their target times in the time sections and the basement horizon is apparently appearing at shallower location than the original case.

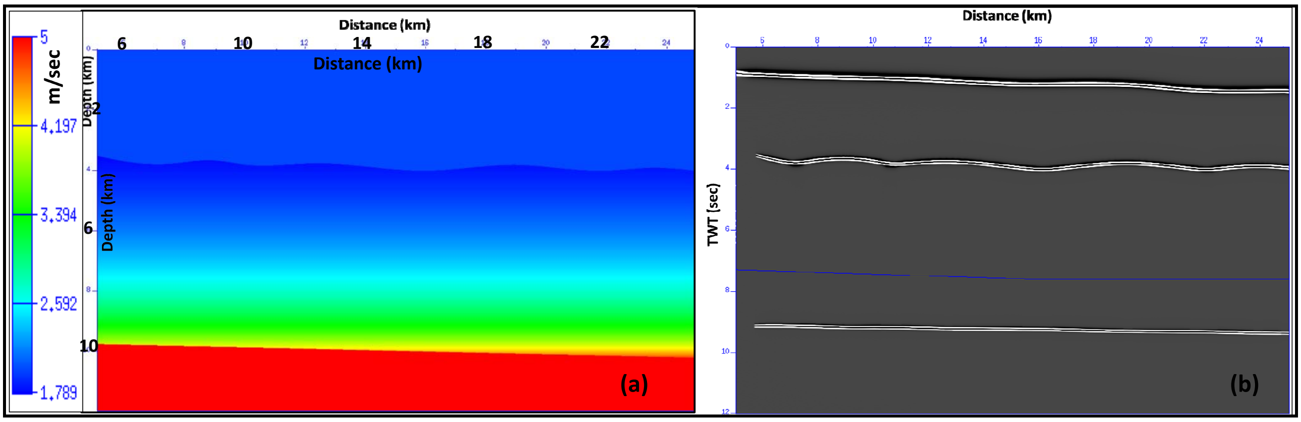

Figure.7: (a) The input velocity model for 10% shallower basement, using the same velocity model of the original case (b) modelled seismic section for shallower basement case

2- The velocity of the deeper section is higher than the estimated velocity function. To maximize this effect, the velocity is applied with 10% shallow basement case. The highest velocity value is obtained by applying the highest horizon velocity in the area under study, which is close to 4200 m/sec at deeper part of the section as shown in Figures 8a and 8b.

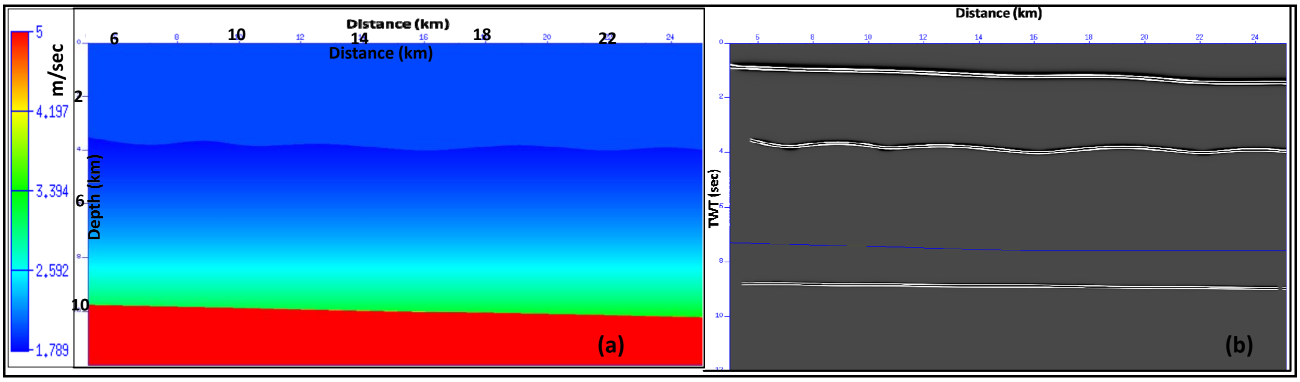

Figure.8: (a) The input velocity model for 10% shallower basement, using higher velocity function than the original case (b) modelled seismic section for shallower basement-higher velocity case

The deepest sedimentary section has higher velocity than the original with maximum values at the most right edge of the model close to 4200m/sec. This model is generated using the equation Sloth= -0.04*Depth+0.30289 instead of the original Sloth= -0.0331*Depth+0.30289. The input velocity model for this case is shown in Figure 8; the basement reflector is shallower than the previous cases and become closer to the doubted or questionable reflector. The comparison between different cases is presented in the Figure 9.

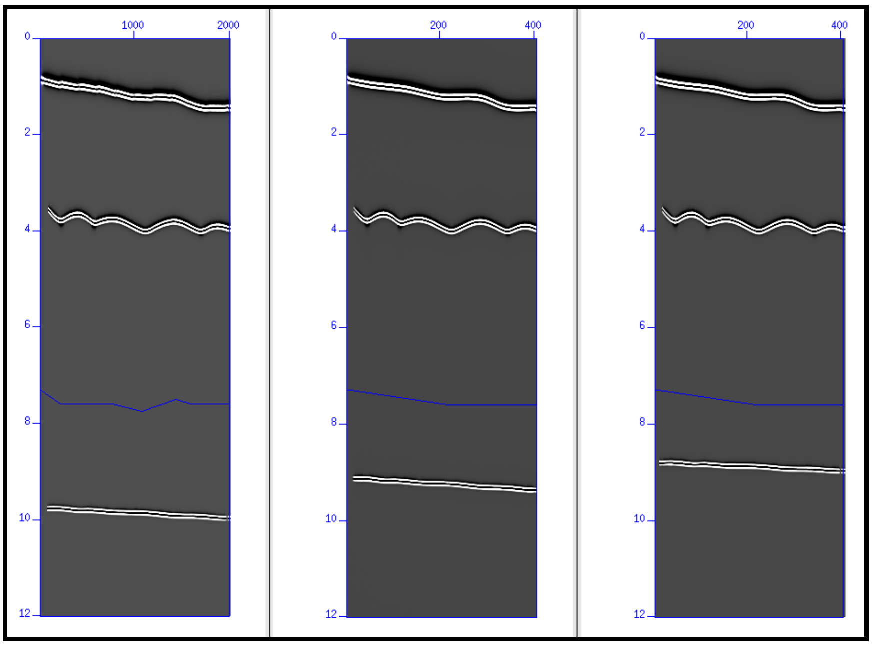

Figure.9: the different modelled cases of the basement reflector

As shown in Figure 9, the left panel shows the original case, the middle panel is with 10 % shallower reflector with the same velocity model of the original and the right panel displays with 10% percent higher velocity model, the last case with the shallow basement reflector. In all cases, there is clear separation between the basement reflector and the questioned reflector. In addition, the depth to the basement estimated by the forward seismic modelling corroborates with the depth estimated by Rybakov and Segev (2004) as shown in Figure 3b.

CONCLUSIONS

1. The study presents alternate methods of modelling between time and depth attributes to model the deeper horizons
2. The seismic modelling of the basement layer successed in the offshore Nile Delta to differentiate between the basement and the shallower reflections.
3. The seismic forward modelling is an important tool in the exploration of wild areas, such as offshore Nile delta.
4. The deep section of the offshore Nile delta has relatively mild velocity section.
5. The expected difference between the stacking velocity and well data pull the time of the basement horizon much deeper.
6. According to the modelling result of the baseemnt reflector, the acquisition parameters will be changed to allow the recording of the deeper horizons, for example the recording of the basement reflector needs at least 20 seconds listening time to record the reflected sweep.

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