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RECOGNITION OF STRIKE-SLIP FAULTS FROM SEISMIC DATA: EXAMPLE FROM NE SYRIA

M. Mansour[1], A.R. Moustafa[2], M. Yousef[2] and M. Soliman[1]*

(1)Tri-Ocean Energy Company, Cairo 11431, Egypt.
(2) Department of Geology, Ain Shams University, Cairo 11566, Egypt.
[*]Corresponding author (e-mail: geo_mansour89@yahoo.com)

تحديد صدوع الانزلاق المضربى باستخدام البيانات السيزمية: مثال من شمال شرق سوريا

الخلاصـــة: على الرغم من أن هناك صعوبة فى التعرف على صدوع الانزلاق المضربى بإستخدام البيانات التحت سطحية, لكن البيانات السيزميةثلاثية الأبعاد عالية الجودة بإمكانها التعرف على مثل هذه الأنواع من الصدوع. فى هذا البحث نلقى الضوء على تحديد صدوع الإنزلاق المضربى بإســتخدام البيانات السيزمية. ولأن إزاحة هذا الفالق تكون أفقية, فإن أفضل طريقة لعرض الازاحة المضربية تكون فى الخرائط او الشرائح السيزمية حيث يوجد ازاحة عرضية او مائلة مع تراكيب جيولوجية اخرى مثل الطيات. ويمكن ايضا التعرف على صدوع الانزلاق المضربى من وجود التركيب الزهرى المعقد او تركيب (التى بى). بالاضافة الى تغير الازاحة الظاهرية للصدع فى اتجاه المضرب من الازاحة العادية الى الازاحة المعكوسة.

ABSTRACT: *Although the recognition of strike-slip faults in subsurface data is difficult, good quality 3D seismic datacan be very usefulforidentifyingsuch faults. In this paper, we throw light on the identification of strike-slip faults from seismic data. Because fault slip is horizontal, strike–slip displacement is better displayed on horizon maps or seismic slices, where they transversely or obliquely offset other structural features like folds. Strike-slip faults may also be recognized by complex flower structures and/or teepee structures. In addition, changing the apparent fault displacement along the strike of the fault from normal to reverse may also indicate the presence of strike-slip movement.*

INTRODUCTION

Strike-slip faults are generally vertical or steeply dipping, and accommodate horizontal shear within the crust. The horizontal displacement on the fault is either dextral or sinistral. Strike slip faults are normally associated with other (second order) structures, which have en echelon arrangement, such as synthetic and antithetic strike-slip faults, folds and normal and reverse faults (Wilcox et al., 1973).Abu El-Ata and Helal (1985) presented some criteria for identification of strike-slip faults on seismic sections and maps. The purpose of this paper is top resent additional criteria for the identification of the strike-slip faults in seismic data.3D seismic data of NE Syriaafford an exceptional opportunity to document the structural features of strike-slip faults.

Geological Features of Strike-Slip Faults

The presence of a strike-slip fault is frequently indicated by en échelon arrays of fractures, faults, and folds in narrow elongated zones. In addition to truncating reference features, such as stratification, foliation, folds, dikes, sill, and other faults, strike-slip faults juxtapose rocks of dissimilar lithology, facies, age, origin, and structure (Sylvester, 1988).

The criteria for determination of the magnitude of horizontal displacement on a strike-slip fault are those that are least affected by the depth of erosion (Gabrielse, 1985). Ideally, the reference lines and surfaces should be at a high angle to the fault. In many other instances, a rare rock type or unique assemblage of rocks has been displaced from one side of a strike-slip fault to the other side, so that a minimum horizontal displacement may be determined by the distance, that the deposit has been removed from its source (Crowell, 1952).Juxtaposition of provinces having great dissimilarities in geochemistry or paleomagnetic orientations, together with the slicing of long slivers of oceanic crust, are evidences of strike-slip faulting in the Semangko fault zone (Page et al., 1979).

Indications of Strike-Slip Faulting from Seismic Data

Three-dimensional (3D) seismic data is a good tool to define strike-slip faults. In seismic sections, the strike-slip fault zones are characterized by complex flower structures. Flower structure is a system of faults that splay upward within a strike-slip fault zone (Harding, T.P., 1983),(Fig. 1). Such structures are normally characterized by steeply dipping to vertical faults nucleating from the main strike-slip fault. These faults show either dominantly extensional (negative flower structures) or compressional (positive flower structures) displacements. Flower structures mainly develop at the relay zones and the bends of strike-slip faults.

Strike-slip movement may also be identified on seismic sections by teepee structures. Teepee is a conical shape and the origin of this name is related to a tent shape used by the nomadic tribes/band governments of the Great Plains and Canadian Prairies in North America. Teepee structures appear above the strike-slip faults in seismic sections and are usually of narrow width, indicating local dip of the rocks away from the fault surface. In the study area of the Abu Khashab Field, NE Syria,a 3D seismic volume was interpreted and helped capture three main criteria of strike-slip faults in the area. These criteria are:

1. A faulted-syncline with left-lateral offset of the whole syncline on the time slice (Fig. 2).The time slice clearly indicates the left-lateral offset of the syncline.
2. Teepee structures along some portions of the faulttrace on vertical seismic sections, as shown in Figure(3), where the reflectors are pushed up along the fault plane on both sides of the fault forming a tent shape. Such geometry indicates pushing up of the rocks along the fault on both sides, due to horizontal slip on the fault.
3. Changing the apparent vertical displacement of the fault along its strike from normal to reverse or from reverse to normal (Fig. 4).Seismic section AA’ (Fig.4) shows apparent normal displacement of the reflectors by the fault, whereas section BB’ shows apparent zero slip of the reflectors, as if they are not faulted, despite the presence of the fault on the seismic slice at the area of this seismic section. Seismic section CC’ shows the southwestern continuation of the same fault, but with apparent reverse displacement. Such change of apparent displacement of the fault matches very well with the left-lateral offset of the syncline on both sides of the fault (Fig. 2) and both features provide good evidence for strike-slip displacement on the fault.

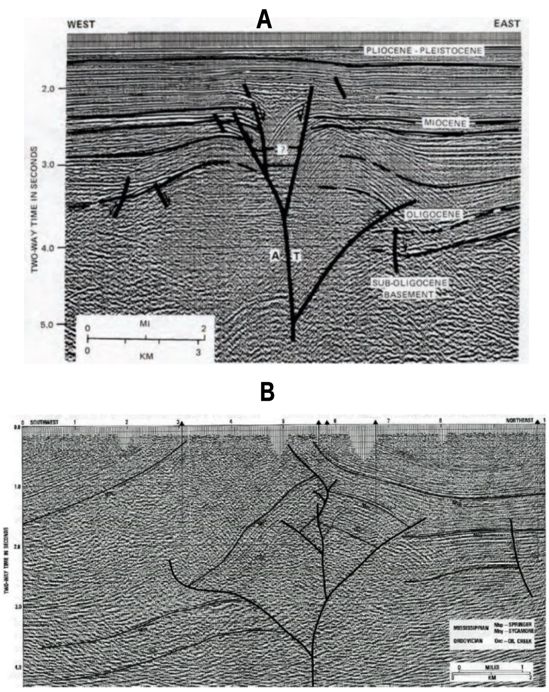


Fig. 1: Seismic sections showing negative (A) and positive (B) flower structures, after Harding (1983).

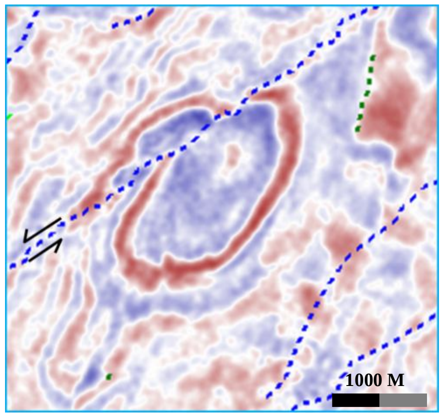


Fig. 2: Time slice @ 1700 milliseconds showing a faulted syncline which is left laterally displaced by the oblique-slip fault.

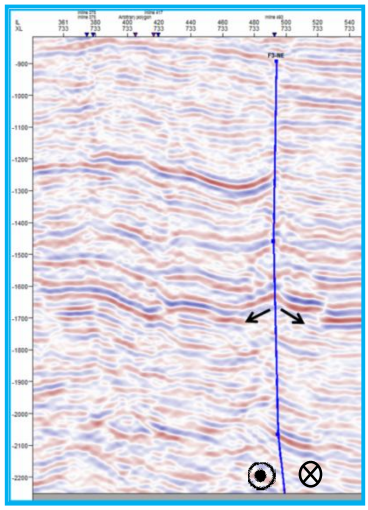
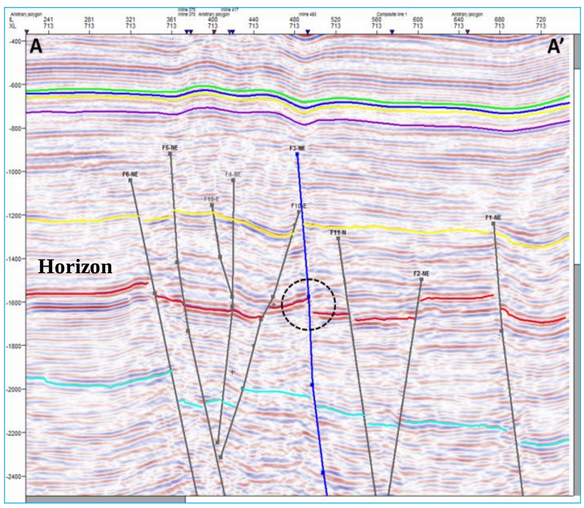


Fig. 3: Seismic section showing teepee structure along the fault.



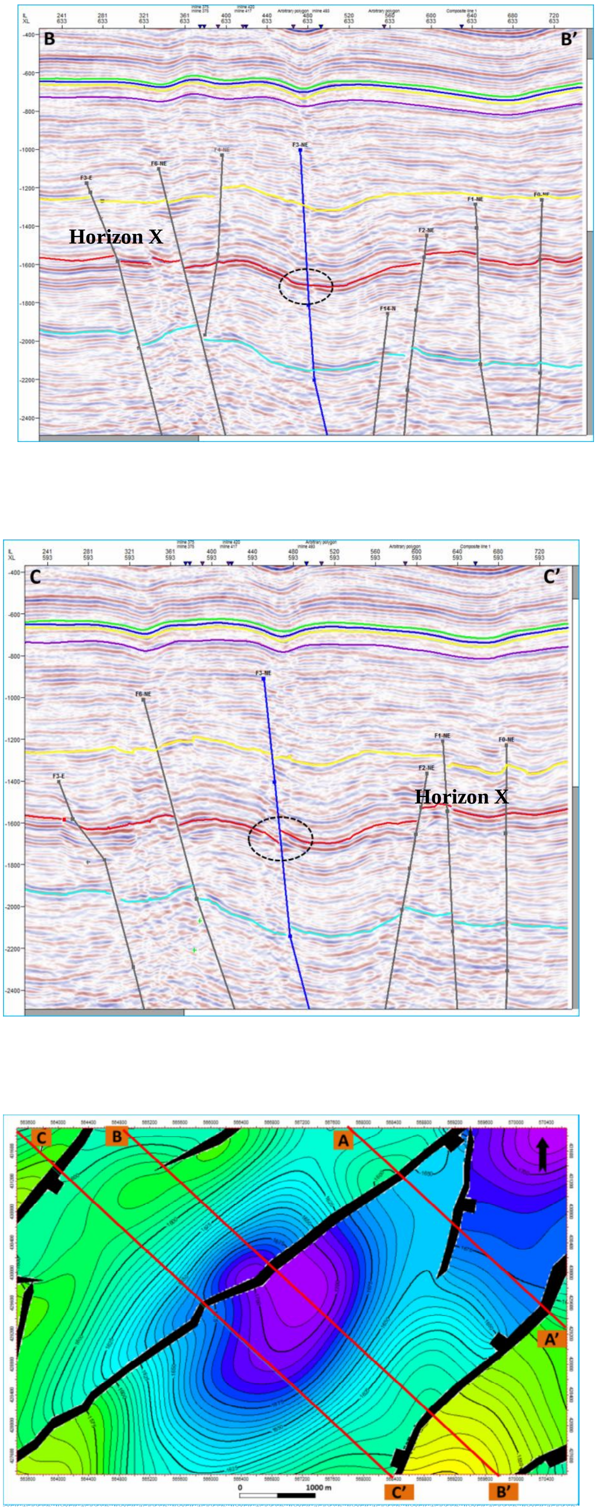


Fig. 4: Seismic section showing the change of apparent fault displacement along the strike of the fault. Section AA' shows apparent normal displacement of horizon x by one of the faults (encircled area), whereas section BB' shows no apparent displacement on the same fault and section CC' shows apparent reverse displacement. The map shows the two-way time structure of horizon X and the locations of the seismic sections.

CONCLUSIONS

Seismic data can be used to define strike-slip faults by the presence of flower structures, teepee structures and/or the change of apparent fault displacement along strike. In addition, time slices are very useful when other structures are laterally offset by the strike-slip fault, such as synclines or anticlines.

Acknowledgments:

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THE USE OF SEISMIC ATTRIBUTES FOR CONFIRMING THE SALT BODIES AT HILAL OIL FIELD, SOUTHERN GULF OF SUEZ, EGYPT

A. El-Werr[1], A. El-Sayed[1], A. Helaly[1], and C. Mahran[2]

1- Geophysics Department, Faculty of Science, Ain Shams University, Egypt.
2- Master of Science Thesis Student.

استخدام السمات السيزمية للتأكد من الاجسام الملحية في حقل هلال للبترول - جنوب خليج السويس ، مصر

الخلاصـــة: يتمثل التحدي في هذا البحث في معرفة وتحديد الطبقات الكامنة تحت طبقة الملح في الأعماق البعيدة وتمييز مناطق تواجد جسم الملح من الطبقات والتراكيب المجاورة له في القطاع الجيولوجى باستخدام السمات السيزمية. نادرا ما يتم التعرف على سطح قبة الملح على البيانات السيزمية لأنها لا تسفر عن انعكاس واضح المعالم و يرجع ذلك إلى تشوهات أسطح انعكاس سطح القبة الملحية، فضلا عن عدم وجود انعكاسات داخل جسم الملح نفسه. وعلاوة على ذلك، فإن الجسم الملح نفسه يحجب وجود الطبقات الكامنة تحته. ومع ذلك، تم استخدام كل هذه القرائن معا ووجدت هذه القرائن في حقل نفط هلال، جنوب خليج السويس، مصر، و استخدمت هذه السمات السيزمية لتحديد القبة الملحية السميكة وتمييزها عن التراكيب الجيولوجية المجاورة لهـــا والمحتوية على طبقة ملح أقل سمكا. وأثبتت هذه السمات انها مفيدة جدا في هذا التمييز و أيضا تحديد سطح الأنعكاس لتكوين خزان نوبيا في المستويات الأكثر عمقا.

ABSTRACT: *The challenge in this paper is to pick and identify the subsalt layers at deeper levels, and to discriminate the thick salt layer from the thin salt layer using seismic data volume. The border of the salt dome is rarely recognized on the seismic data, because it does not yield a clearly defined reflection, due to the distortions of the reflecting features inside the salt dome, as well as the absence of reflections within the salt body itself. However, strong amplitude reflection horizon is noticed inside the salt body, due to the presence of anhydrite layer. Moreover, the salt body masks the existence of the underlying layers in deeper depth levels. However, these criteria are all together found at Hilal Oil Field, Gulf of Suez, Egypt and they can be used to detect the thick salt body and to discriminate it from the neighboring thin salt layer and also to delineate the approximate location of the salt face in the evaluated seismic data volume.*

Seismic attributes were used and have proven to be very useful in the detection of the thick salt from the thin salt layer in the shallower depth levels. Seismic attributes, were also very helpful in detecting the underlying reflection horizon of the Nubia Formation in the deeper depth levels.

INTRODUCTION

Massive salt bodies can be both blessing and curse for oil companies exploring the depths. As salt movement helps to generate a wide variety of traps, the industry has had consistent success in discovering large hydrocarbon accumulations in their basins. Many of the exploration successes have been salt-related, and directly linked to the ability to image in and around the salt structures. A great deal of effort has been focused on imaging beneath complex salt in the Southern Gulf of Suez. Not only the subsalt imaging is a challenge to the oil industry, but also the discrimination of the salt from the non-salt layers is an important task.

Rock salt with a velocity of 14000 feet/sec is significantly faster than the surrounding sediments with typical velocity of 7000-10000 feet/sec, so that much energy is lost in passing through the salt, requiring a strong seismic source for the subsalt exploration. In exploration, complications due to salt (1) obscure the accurate definition of the trap, (2) distortion the image, making detailed stratigraphic and fault interpretation difficult, and (3) complicates our ability to make a geologic risk estimate.

Salt flow often produces anticlines and domes when thick salt deposits have been buried rapidly beneath relatively unconsolidated sediments. The sediments are compacted with depth and so increase their density, whereas the salt density remains constant. Thus, below some critical depths, the salt is less dense than the overlying sediments. Salt behaves like a very viscous fluid under sufficient pressure and the buoyancy may result in the salt flowing upward to form a salt dome, arching the overlying sediments and sometimes piercing through them.

Hilal Oil Field lies in the southern part of the Gulf of Suez region, Egypt. It is found between latitudes 27° 46´&27° 51´ N and longitudes 33° 42´&33° 47´ E, as shown in the study area location map (Fig. 1)EGPC, (1996). The stratigraphic succession of Hilal Oil Field (EGPC, 1996) is illustrated in Fig. (2).

The purpose of this study is to discriminate the thick salt body from the thin salt layer at shallower depth levels, and to pick and identify the subsalt layers at deeper levels.

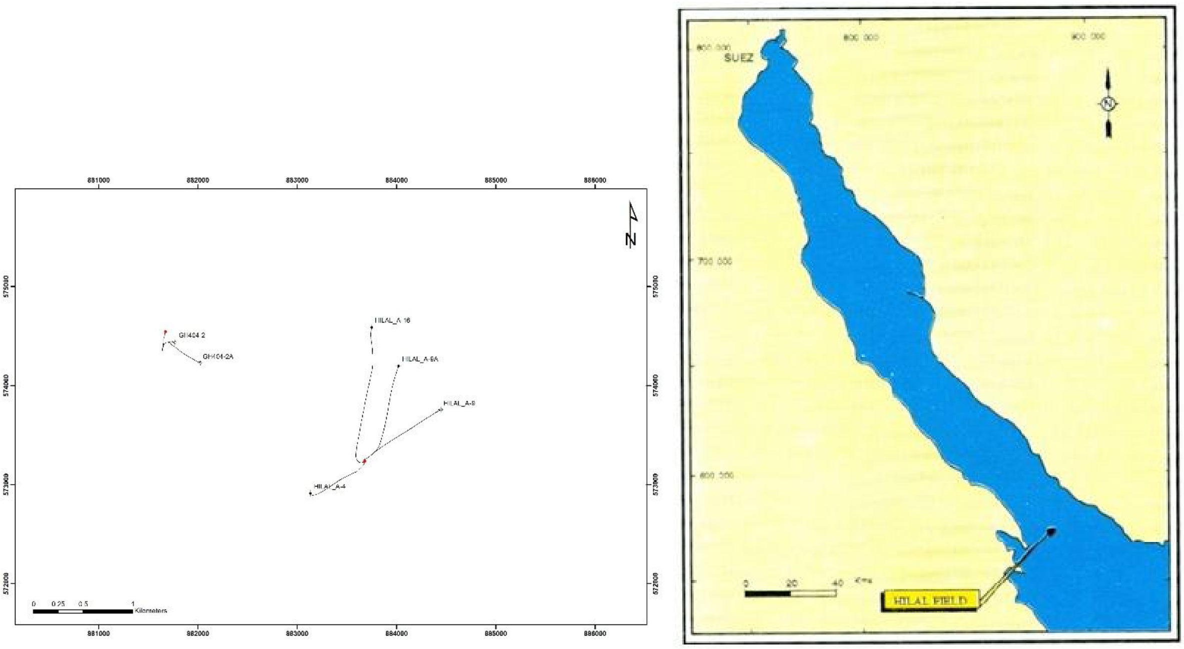


Fig. 1: Location map of Hilal Oil Field with rectangle showing the borehole location.

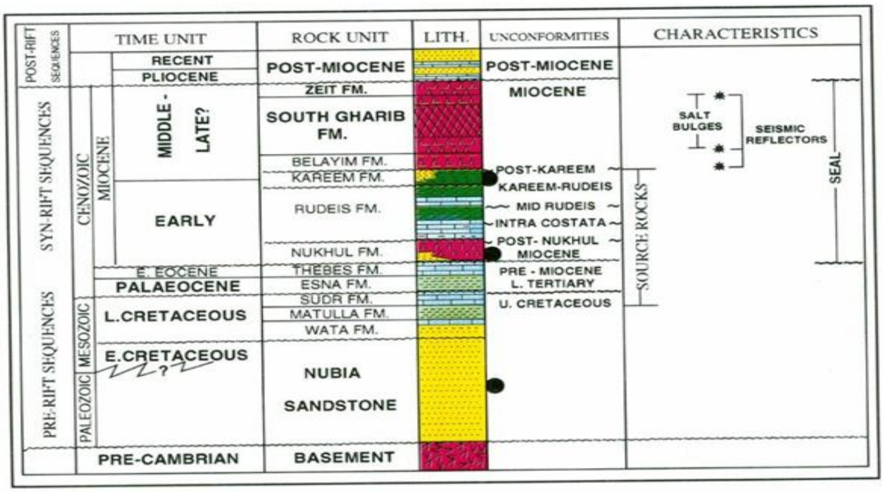


Fig. 2: Stratigraphic column of Hilal Field(after EGPC, 1996).

Seismic attributes were used and have proven to be very useful in the detection of the thick salt from the thin salt layer in the shallower depth level. Also, seismic attributes, were very helpful in detecting the underlying reflection horizons like Nubia Formation in the deeper depth levels.

Recognition of Salt Dome on *Vertical Seismic Sections:*

Fig. 3 shows an example of a salt dome feature on a crossline1636 with layers of anhydrite which clearly responsible for the strong events inside the salt body. The rim syncline formed around the dome flank stands out obviously on the right side at about 5528 ft depth level. The strata forming this syncline appear with strong amplitudes with South Gharib Formation thin salt layer sandwiched in between two anhydrite layers of Zeit and Balayem Formations. It is rare that, the salt surface itself yields a clearly defined reflection. However, the right salt surface (border) is clearly visible with major normal faults accompanying it. More generally, the distortions of reflecting layers above the dome and alongside it, as well as the apparent absence of reflections within the salt layers, are used to delineate the approximate location of the salt face. The salt body itself masks the existence of the underlying layers at deeper depth of 10400 ft (Nubia Formation).

Fig. (4) is a structure cross section at Hilal Oil Field after EGPC (1996) showing South Gharib Formation with thick salt body on the left side and a thin one on its right side.

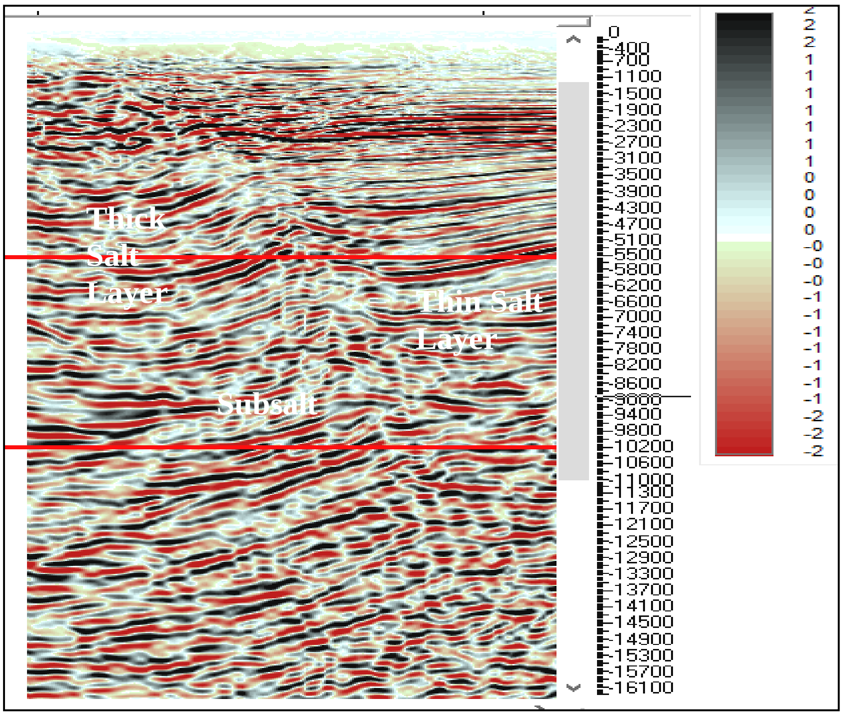


Fig. 3: Vertical seismic section (crossline 1636) with two red line marks at 5528 and 10200 ft.

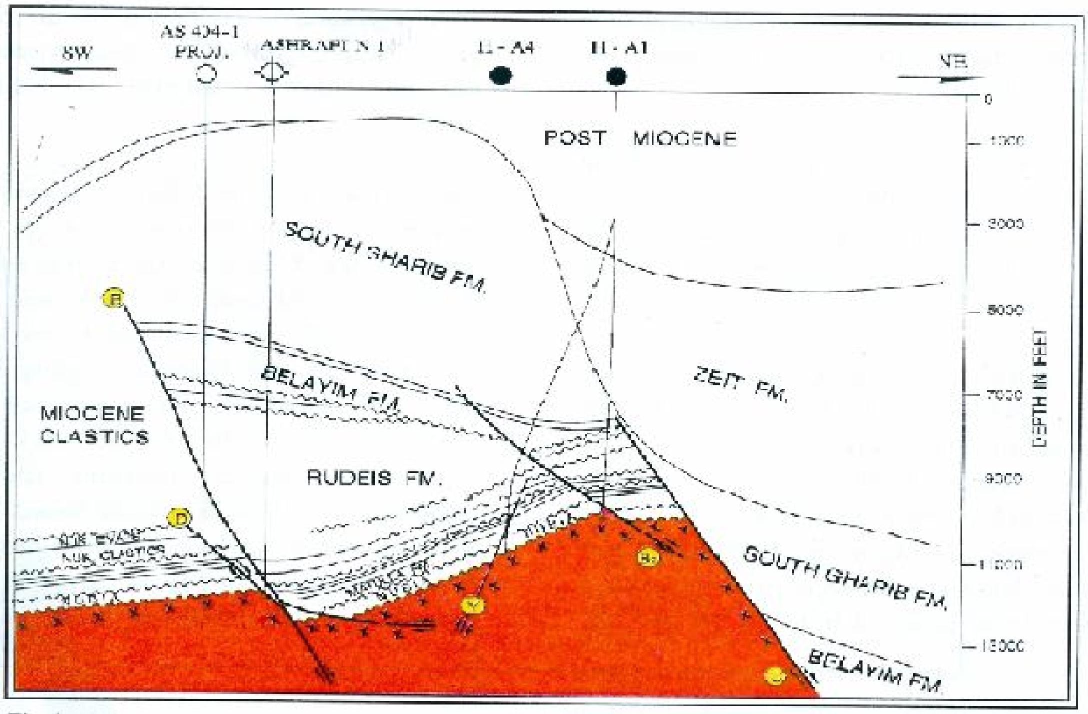


Fig. 4: Structure cross section of Hilal Oil Field (after EGPC, 1996).

Recognition of Salt Dome on *Depth Slice:*

Salt domes vary in their geometric shape, in relation to the slope of their sides and have distinctive mushroom shaped tops. The key features to recognize salt domes on depth slices are: 1- Oval shaped anomaly, without any reflections inside this feature, except at the top of the dome. 2- Oval shaped anomaly, with reflections from other horizons terminating at the salt dome outline.

Depth slice at shallower depth level of5528 ft (Fig. 5) shows the salt body at the left side and syncline strata at the right side. Depth slice (Fig. 6) at deeper depth level about 10400 ft crossing the Nubia Reservoir Formation shows the subsalt events with no clear waveform events. That is why we had to use the seismic attributes for detecting the masked subsalt layers.

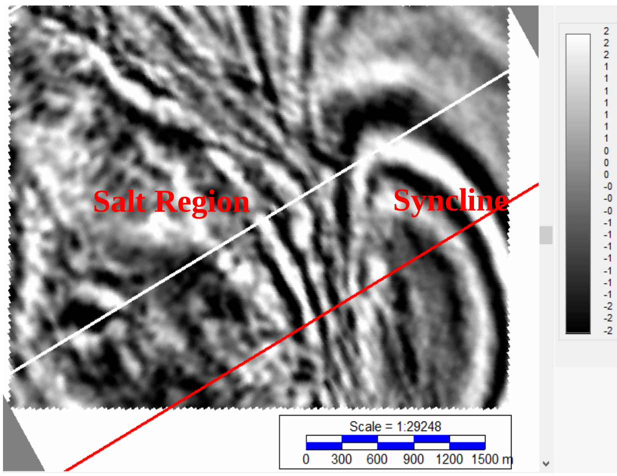


Fig. 5: Depth slice at 5528 ft, showing the salt body at the left and syncline at the right.

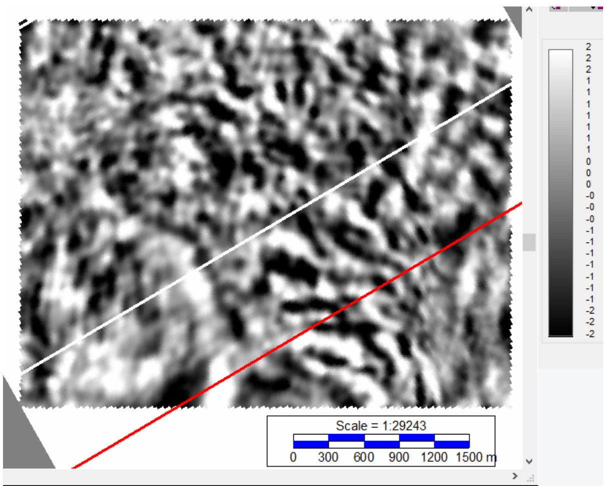
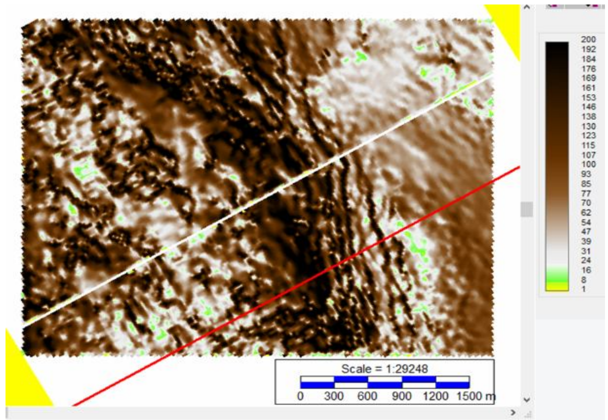


Fig. 6: Depth slice at 10400 ft, showing the subsalt layers with no clear reflection events.

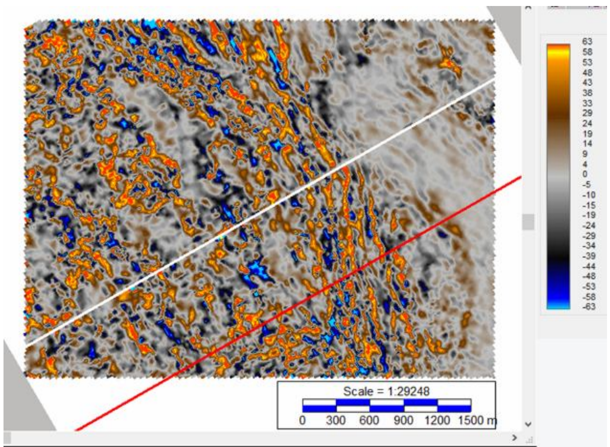
Different seismic attributes have been proposed by several researchers for salt detection. For example Chopra and Marfurt (2005), Berthelot et al. (2009, 2012and 2013) and Hegazy and AlRegib (2014). It is very clear from the vertical seismic section that, the texture of the non-salt layers exhibits strong directionality with small gradients in the (*x,y*) directions, while that of the salt feature lacks of directionality with higher magnitudes of gradients. Also, smoothness and event continuity are higher for the synclinelayers than that inside the salt body.

Seismic Attributes For Detecting Salt Dome:

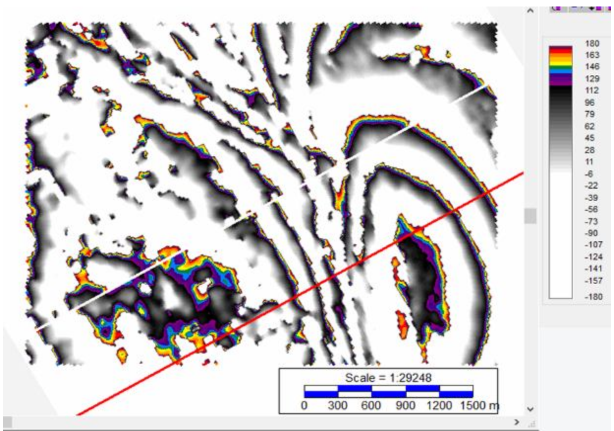
In this paper, the following types of seismic attributes: 1- dip of maximum similarity, 2- dip variance, 3- instantaneous phase and 4- event continuity were used for discriminating the thick salt structure from the synclinein shallower depth level (5528 ft),as shown in Fig. (7).



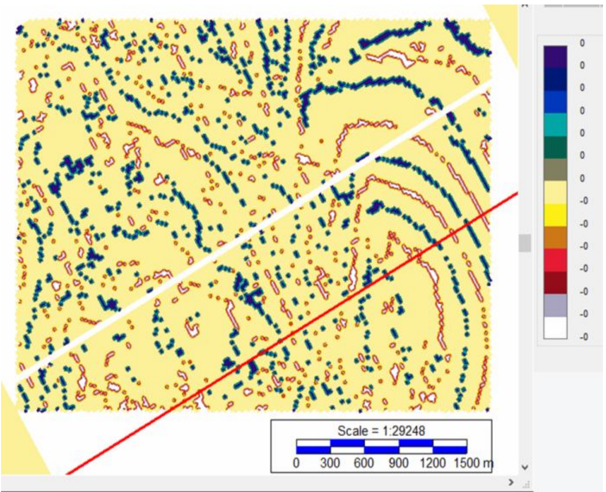
Dip of Maximum similarityslice attribute at depth 5528 ft.



Dip variance slice attribute at depth 5528 ft.



Instantaneous phase slice attribute at depth5528 ft.



Event continuity slice attribute at depth 5528 ft.

Fig. 7: Seismic attributes for depth slice 5528 ft showing good separation of salt from syncline regions.

Moreover, the instantaneous lateral continuity slice attribute at depth 5528 ft shows the predominant major fault trends NW-SE to the NNW-SSE in orange colors as shown in Fig. (8). Ayolabi and Adigun (2013) mentioned that the variance attribute showed better response to faults than any other attribute in their study area.

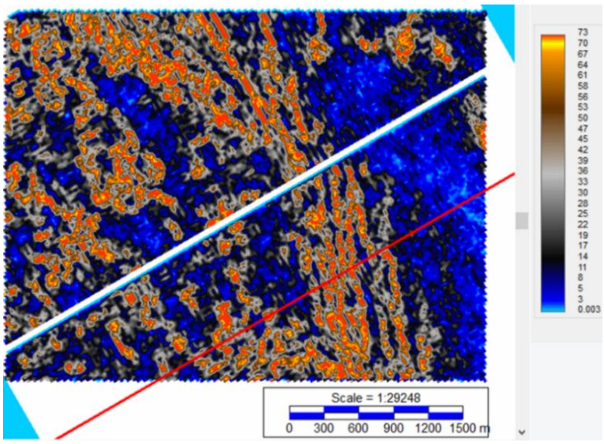


Fig. 8: Instantaneous lateral continuity slice attribute at depth 5528 ft showing faults in orange colors.

Fig. (9) is the final represent ationdelin eating the borders of the salt body surfaces from all sides, as deduced from the interpretation of the different kinds of seismic attributes shown on the crossline seismic section 1636.

The four types of seismic attributes mentioned above are applied for the deeper depth level at 10400 ft crossing Nubia Reservoir Formation aiming at manifesting the subsalt layers. It was found, three of them which are the dip of maximum similarity, dip variance, and event continuity seismic attributes did not show any clear waveform eventsin the horizontal depth slice at 10400 ft, as shown in Fig. (10).

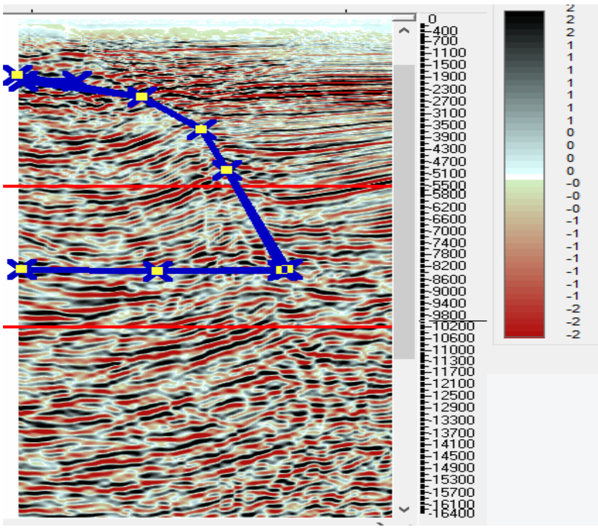
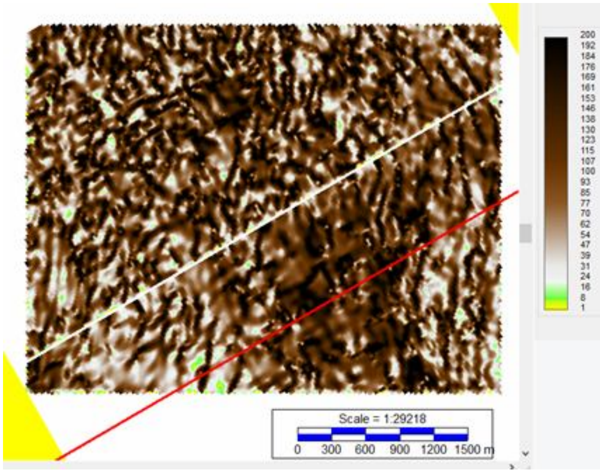
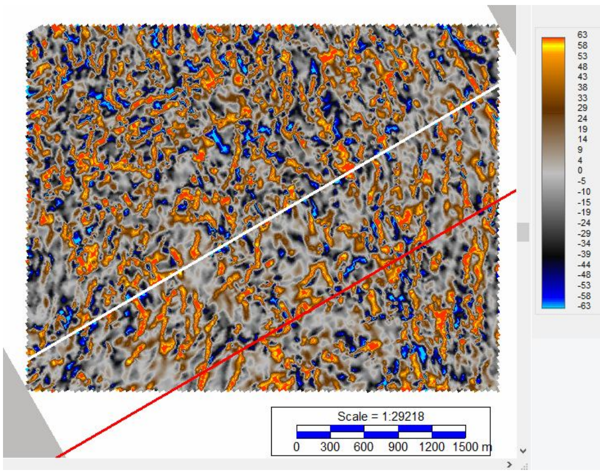


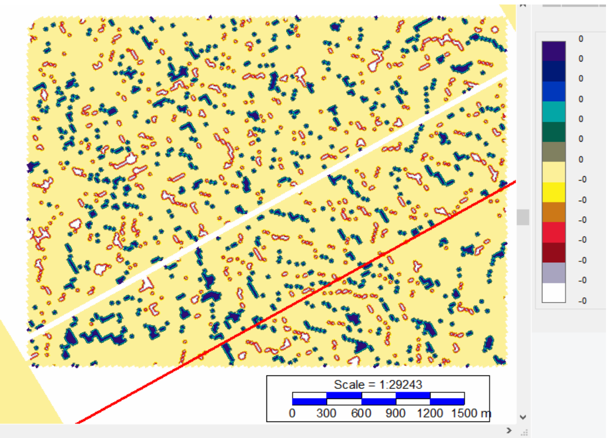
Fig. 9: Final borders delineating the salt body.



Dip of Maximum similarity slice attribute at depth 5528 ft.



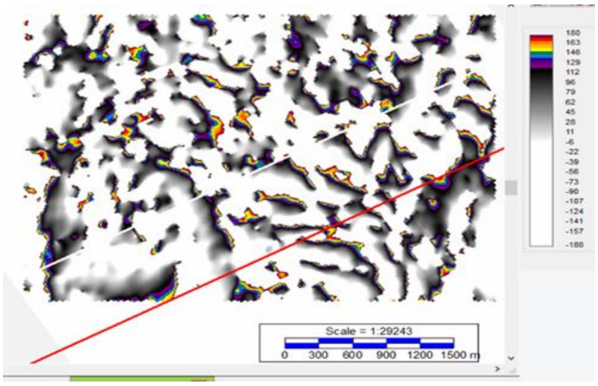
Dip variance slice attribute at depth 5528 ft.



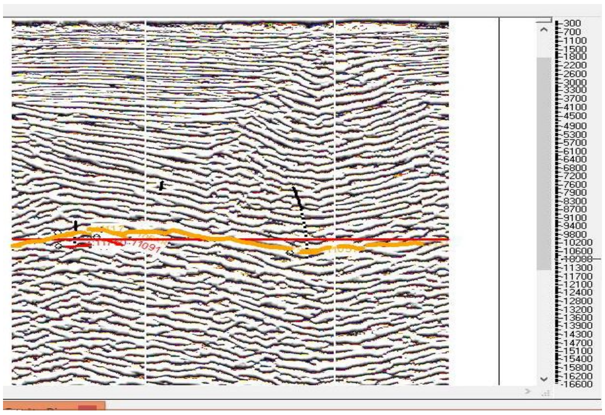
Event continuity slice attribute at depth 5528 ft.

Fig. 10: Different seismic attributes slices at depth 10400ftwith no clear reflection events of the subsalt layers.

However, the instantaneous phase attribute shows much more clear image with more continous reflection events in both of the horizontal slice 10400 ft attribute and the instantaneous phase attribute of the vertical arbitrary line A, as shown in Fig. (11).



A) Instantaneous phase attribute slice at depth 10400 ft.



B) Vertical arbitrary line A with clear subsalt picking of Nubia Formation top.

Fig. 11: A) Instantaneous phase attribute slice at depth 10400 ft, and B) Vertical arbitrary line Awith clear subsalt picking of Nubia Formation top.

That was a big challenge in solving the problem of picking of the top surfaces of Nubia Formation that were very difficult to pick in normal vertical seismic sections in Hilal Oil Field.

By this way, seismic attributes have proven to be very useful in detecting both salt body at shallower depth levels and also defining and picking the top surface of the Nubia Formation prospect beneath the salt body.

CONCLUSIONS

Seismic salt criteria were found and were responsible for detecting the salt dome and its neighboring valuable syncline. Seismic attributes provide a big favor of the discrimination of those two geologic features. The best selected four types of seismic attributes that have been carried out for delineating the locations of those geological features are the following: 1- dip of maximum similarity, 2- dip variance, 3- instantaneous phase and 4- event continuity. In addition, the instantaneous lateral continuity attribute shows the predominant major fault trends in the study area that are ranged from NW-SE to the NNW-SSE directions. Also, foridentifying and picking the top surface of the subsalt reflection horizon of the Nubia Formation at Hilal Oil Field at the southern part of the Gulf of Suez, the best type of attributes was instantaneous phase attribute.

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