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Improvement of Gulf of Suez subsurface image under the salt layers through re-processing of seismic data- a case study

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ABSTRACT
Advanced technology in processing the old seismic data in the Gulf of Suez (G.O.S) has been used and applied using new parameters to emphasise the optimisation of geological structures and stratigraphic units as much as possible. The primary reflections in Gulf of Suez have low frequency while multiple reflections have higher frequency where there is a high reflection contrast in the shallow section represented by Zeit Formation due to alternation of shale and anhydrite that generates a lot of multiple reflections. The deeper formations will be affected by low-frequency reflections resulted from the incident energy itself with the common attenuation parameters such as transmission loss, adsorption, and spherical spreading of waves. Otherwise, the data in the Gulf of Suez suffer from a lot of loss mechanism from the salt of South Gharib Formation and anhydrite of Zeit Formation. In this study, new software are adapted to apply new technology in processing and analysis of seismic data such as VISTA 11 software from GEDCO company. After a lot of iterations of all seismic data parameters, seismic flows and parameters have been chosen to retain the primary frequency contents and relative amplitude while suppressing multiples energy. The reprocessing produced seismic sections with the increased temporal and spatial seismic resolution, facilitating more accurate interpretation of the data. Enhanced imaging of both the salt structures and the sub-salt sequence has been achieved, which in turn leads to a more and better understanding of salt deformation and improve the mapping of structural subdivisions within the study area.

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1. Introduction

The Gulf of Suez is a subsidence area within the stable shelf and the northern part of the Arabo-Nubian shield. Great accumulation of sediments from this fast subsiding depression was interrupted many times by tectonic events accompanied by general regional uplift with subsequent erosion. It is an intra-continental, late Oligocene rifted basin but was originally formed during the early Palaeozoic as a narrow embayment of the Tethys that was intensively rejuvenated during the rifting phase of the great East African rift system in the Palaeocene. (Abudeif et al., 2016; Bosworth and McClay 2001; Lashin and Abd El-Aal 2004; D'Agosto et al. 2008; Abd El-Naby et al. 2010; Attia et al. 2015) It can be described as a rejuvenated, slightly accurate NW-SE trending rifted graben, which separates the shield of central Sinai from that of the Eastern Desert of Egypt and extends from latitude 27° 15′ to 30° N and 32°10′ to 34°E embracing a total length of 350 km with average width ranging between 30 and 80 km, and average water depth of 160 ft.

1.1. Exploration history

North Ramadan (NR) oil field is one of the main fields in the Gulf of Suez area. A 3D seismic marine survey was conducted by Western Geophysical Company for SHELL EGYPT NV in 1997. However, the North Ramadan oil field concession acquired a 3D survey by CGG Veritas for IPR Energy Sea Inc and processed by the same company from December 2007 till July 2008. The seismic data used in this study is represented by the 3D survey acquired in 1997 for SHELL EGYPT NV and obtained from the EGPC. The North Ramadan concession has a total area of about 290 km^2 and is surrounded by some prolific producing oil fields (such as Ras Fanar and South Gharib to west, North July to the south, South Belayim to the southeast) and opposite marine field to Ras Gharib city in the Gulf of Suez (Figure 1). Total potential resources in the block are estimated to exceed 200 MMBO.

1.2. Geologic setting

Different parts of the Gulf of Suez have different geological histories. The succession, facies changes and the relationships of the different blocks that comprise the Gulf of Suez are quite variable so that no single area in the Gulf is found to be wholly representative of the stratigraphy or the structure of the entire region (Said 1962; Steen and Helmy 1982).

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Figure 1. Location map of North Ramadan oil field plotted on Google Earth and Seismic Line (Yellow Line) in the middle of the area and also two wells (E-Gharib and C4-A1).

The generalised litho-stratigraphic column within the North Ramadan oil field shown in (Figure 2), for which three depositional phases are generally assumed (Attia et al. 2015).

(1) The deposition of formations ranging in age from a postulated Pre-Carboniferous to Eocene. These formations which include the Nubia Sandstone are important as reservoir rocks and to a lesser extent as source rocks.
(2) The second phase is represented by the Lower Miocene and is characterised by its overall excellent qualities as source, reservoir and seal rocks.
(3) The third phase, of Upper-Middle Miocene to Upper Miocene and Pliocene age in essence (basically), closes the depositional history of the Suez graben area.

South Gharib and Zeit formations have been considered in this study. South Gharib Formation lies stratigraphically in the middle part of the Ras Malaab Group and represents the maximum development of the lagoonal phase during the Miocene sedimentary cycle. South Gharib Formation consists of a limited number of thick massive rock salt and hard anhydrite beds with markedly thin intercalation of shale and sandstone. Zeit Formation represents the topmost formation of Ras Malaab Group of Miocene in the Gulf of Suez region, it overlies conformably South Gharib evaporites and underlies unconformably Pliocene coarse clastics and consists of sandstone, shale, anhydrite and salt which increase in the lower part of Zeit Formation which indicate alternating close and open lagoonal environment (Attia et al. 2015).

The effect of salt diaper structures is one of the most serious problems facing explorations activities. The salt layer has significantly high velocity, which causes a large velocity contrast with the surrounding layers. If the target horizon lies above the salt layer, the problem will decrease a little bit is the time of migration will be acceptable. However, if the target horizon is beneath the salt diapir, then there is a complex overburden problem and it will be difficult to image the target horizon with acceptable accuracy (EGPC, 1996).

In the Late Mesozoic to Early Tertiary time, the Red Sea graben system had developed as a result of early rifting between the African and Arabian plates. This faulting was locally accompanied by intensive basaltic intrusions and resulted in tilting of fault blocks in the form of half grabens. The main bounding normal faults of the tilted blocks show an original dip angle of 60 degree (Meshref 1990).

Dickinson (1974) stated that the development of rifted continental margins may span five stages: Pre-rift arch,

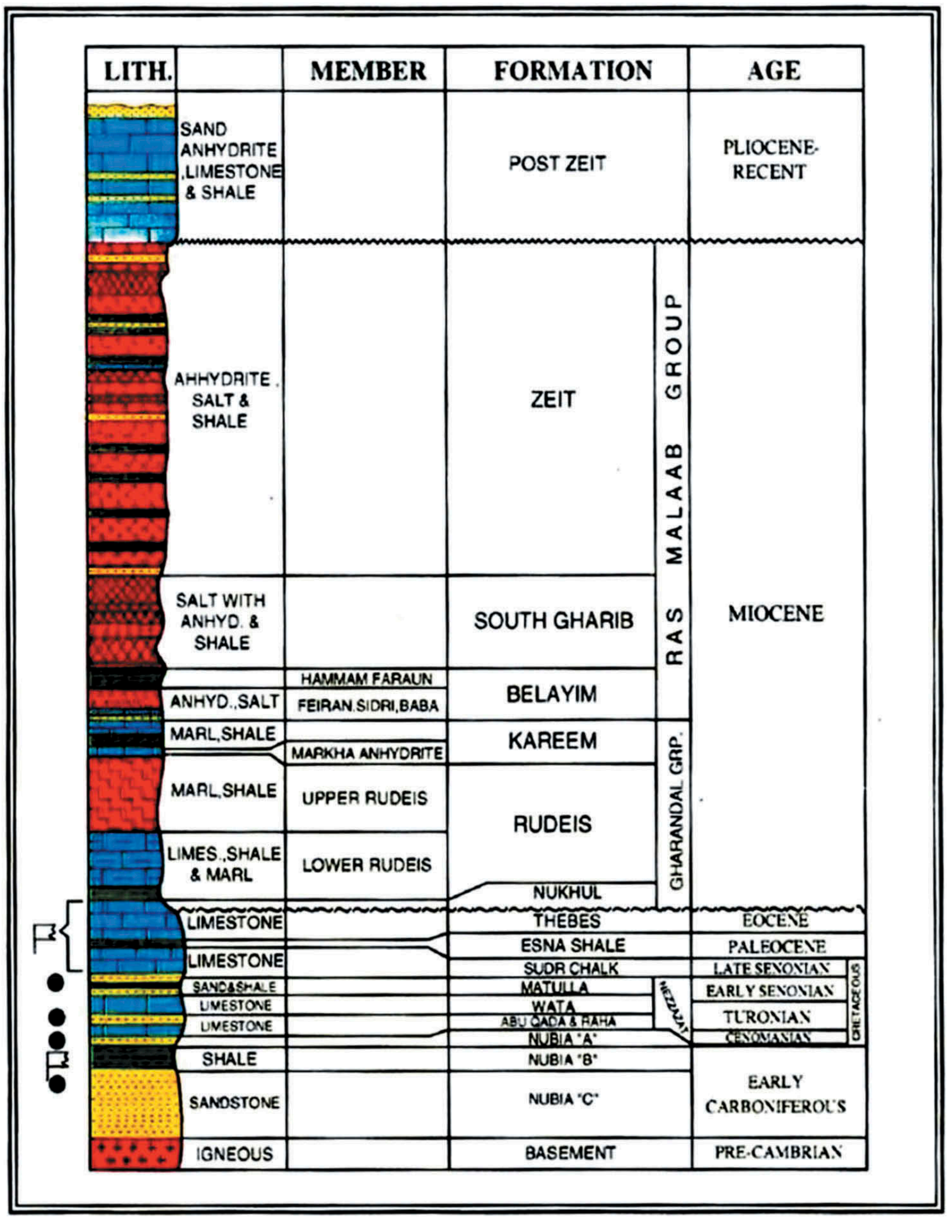

Figure 2. Stratigraphic column of North Ramadan Oil field with Source and Reservoir rocks (EGPC (Egyptian General Petroleum Corporation) 1996).

rift valley, proto-oceanic gulf, narrow ocean, and open ocean. During the Late Eocene-Oligocene, the Red Sea as a part of the graben system further opened by 60–70 km lateral displacement but in the direction of the Aqaba fault system creating the Gulf of Aqaba while the Gulf of Suez remained relatively stable. The spreading in the Red Sea continued and the Sinai block moved together with Arabian plate leading to reactivation of the initial listric graben faults in the Gulf of Suez. This reactivation led to a further tilt and rotation of the earlier fault blocks and deposition of thick asymmetric wedges of Miocene age (Patton et al. 1994).

As the block rotation continued during Miocene time, extensional movements prevailed and tilting of fault-bounded blocks compensated the extension. With an active horizontal extension, more thinning of the earth's crust took place due to the rotation of blocks; this resulted in decreasing the dip angle of the main bounding normal faults, in some cases up to 40 degree as deduced from well data (Meshref 1990). The rift reaches its maximum width (80 km) and depth during the lower Miocene time, as shown by the overall extension of open marine facies, known as the Rudeis Formation (Chenet and Letouzey 1983). The direction of block rotation was not constant along the strike of the gulf due to the regional reversal of the dip regime along the strike. Accordingly, the tilted blocks would be expected to rotate more towards the southwest in the northern and southern provinces of the gulf and more to the northeast in the central province of the gulf (Meshref 1990).

The Gulf of Suez is currently subdivided into three structural provinces according to their structural setting and regional dip direction; Northern Province,

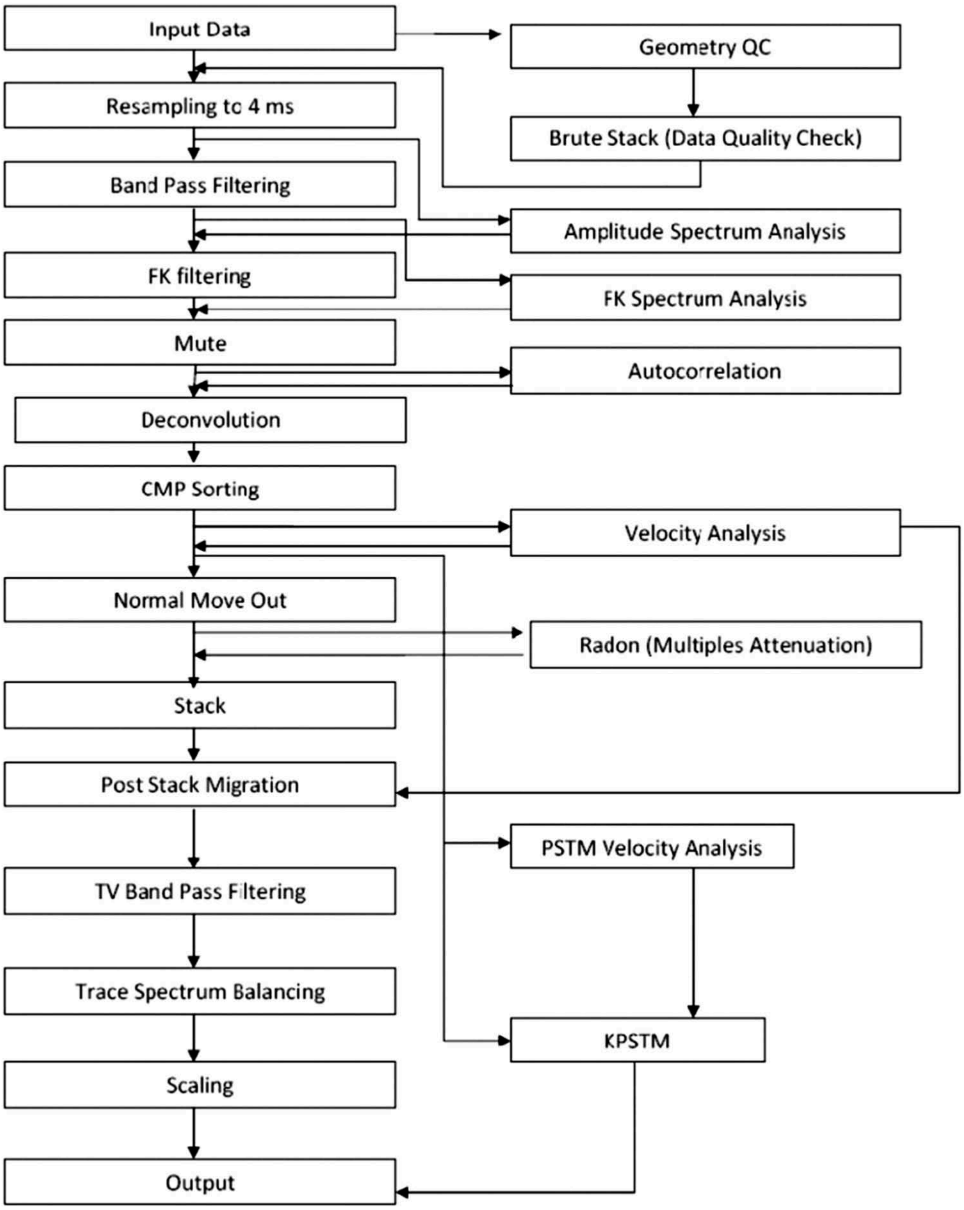

Figure 3. Seismic data processing flow chart.

Central Province and the Southern Province (Meshref et al. 1976).

The Northern Province represents the north part of the Gulf of Suez and is bounded by Galala Hinge Zone that extends from south Galala Plateau to the offshore ASL oil field and is characterised by high structural features" Galala Plateau Westward" with a regional dip of strata in the southwest direction. The Central Province occupies the central part of the Gulf of Suez and is characterised by the pre-Miocene shallow structures underlying the Miocene sediments with a regional dip in the northeast direction. The Southern Province lies to the south of the Morgan Hinge zone which pass from the north of Esh El Mellaha to Ras Shukheir and is characterised by the occurrence of surface outcrops of Miocene, pre-Miocene sediments and basement rocks with a regional dip of strata in the southwest direction as in Northern Province.

1.3. Wave characterisation

The primary reflections in Gulf of Suez have low frequency while multiple reflections have higher frequency content where there is a high reflection contrast in the shallow section represented in Zeit Formation due to alternation of shale and anhydrite that generates a lot of multiples reflections. The deeper formations will be affected by low-frequency reflections resulted from the incident energy itself with the common attenuation parameters such as transmission loss, adsorption, and spherical spreading of waves. Otherwise, the data in the Gulf of Suez suffer from a lot of loss mechanism from the salt of South Gharib

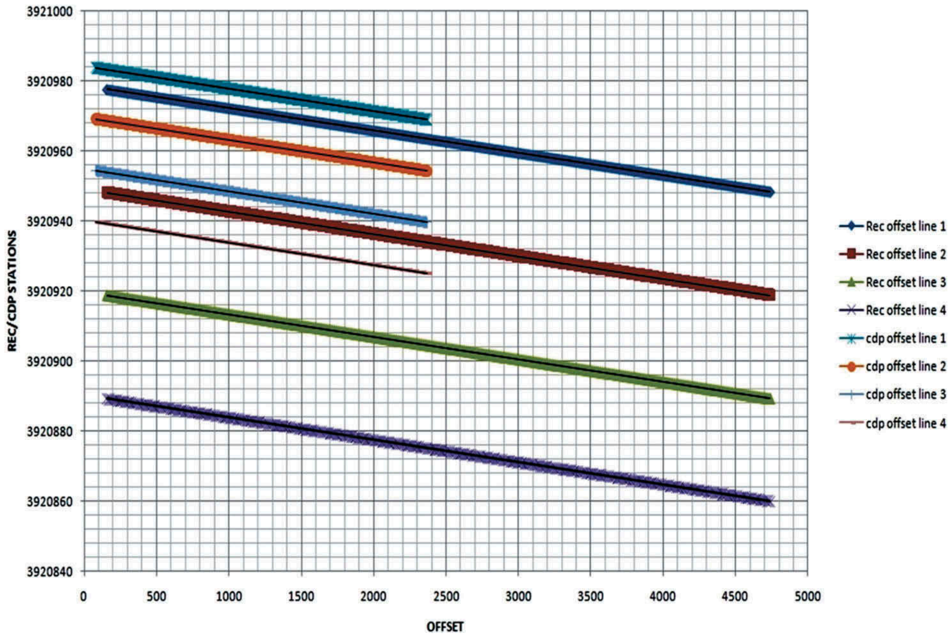

Figure 4. Relationship between the receivers and CDP offset.

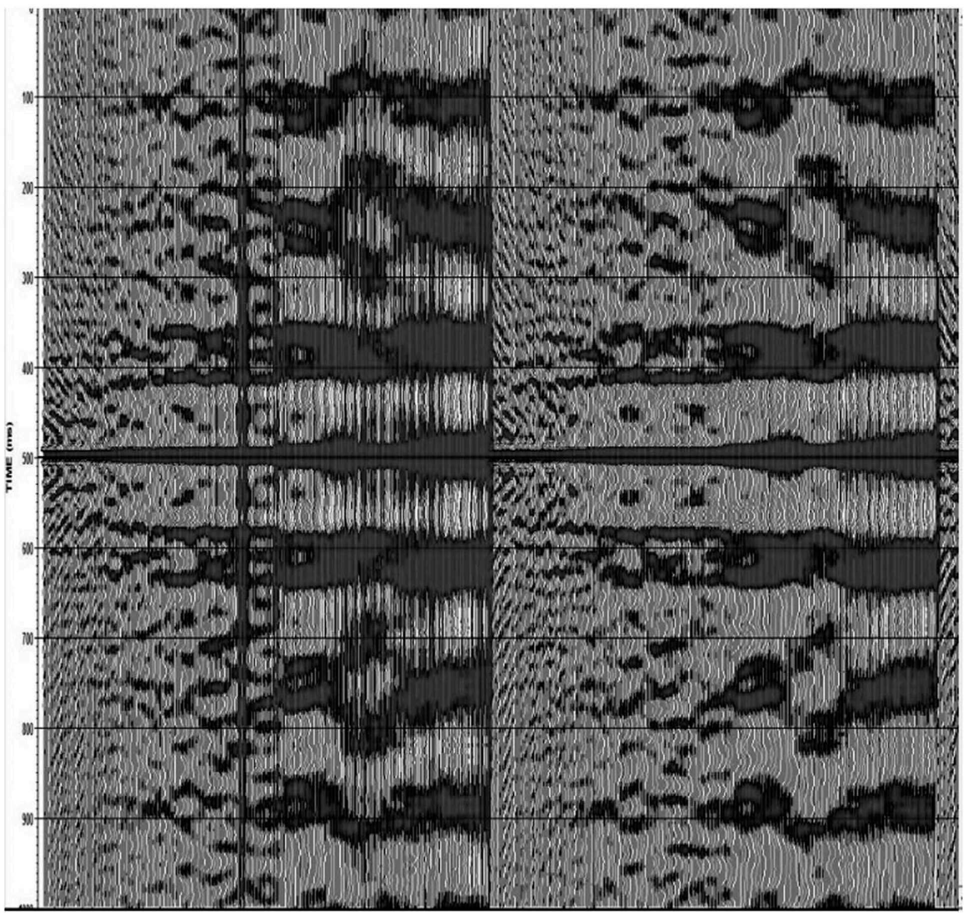

Figure 5. Autocorrelogram showing the multiples in raw data.

Formation and anhydrite of Zeit Formation. The Miocene Evaporite sections have three forces been identified as the main cause of the major seismic exploration problem since they show a highly cyclic layering. The consequences and effects of cyclic layering on the seismic response of the subsurface are demonstrated. This leads then directly to the topic of this study; how to overcome these difficulties.

Zakaria (1998) concluded that seismic processing flows and parameters must be chosen to retain the primary frequency content and the relative amplitude while suppressing multiple energy because the

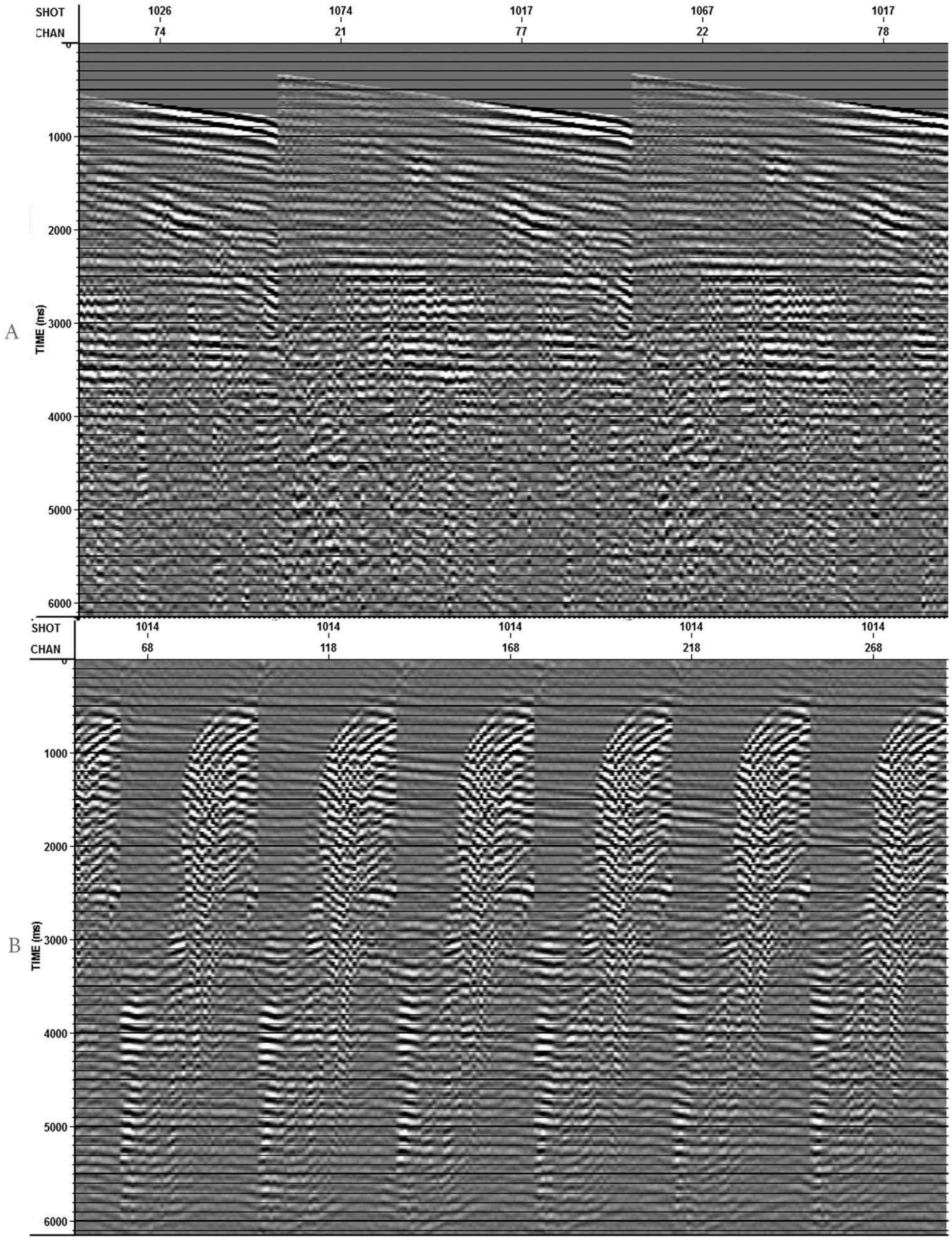

Figure 6. (a) Raw seismic data in CMP sort and (b) The multiple extracted from the raw data by Radon Transform.

multiple energy prevents the optimisation of structure and stratigraphic from seismic data. Also, the reasonable velocity analysis picking leading to; enhance the reservoir reflections, emphasising the seismic sequences which make the seismic stratigraphy interpretation available in the Gulf of Suez.

2. Materials and methods

The seismic line was examined through the processing of the raw 2D seismic data in the direction of NW-SE by plotting the area corners, wells, the first point and endpoint of the seismic line on Google Earth. It was found that each parameter lies in its position related to others (Figure 1).

The seismic survey shot during 1997 with cable length 2600 metres and the record length was 6 sec. using an air gun's array fired every 25 metres (the same source fires every 50 m in Flip-Flop mode) into 368 channels to get 46 fold according to the equation:

$$N_{FOLD} = (N_{CHAN} * G_{INT})/(2 * SP_{INT})$$

Where:

N_{FOLD}: number of fold
N_{CHAN}: number of channel or groups
G_{INT}: group interval
SP_{INT}: shot point interval

The processing sequence applied on the old data was Amplitude recovery, Low Cut Filter, Trace Editing, Missing traces interpolation, Swell noise attenuation in shot and Receiver domain, Seismic interference noise attenuation, Gun and cable static correction, Zero phasing and De-absorption, Tau-P de-convolution, Velocity analysis 1 km X 1 km,

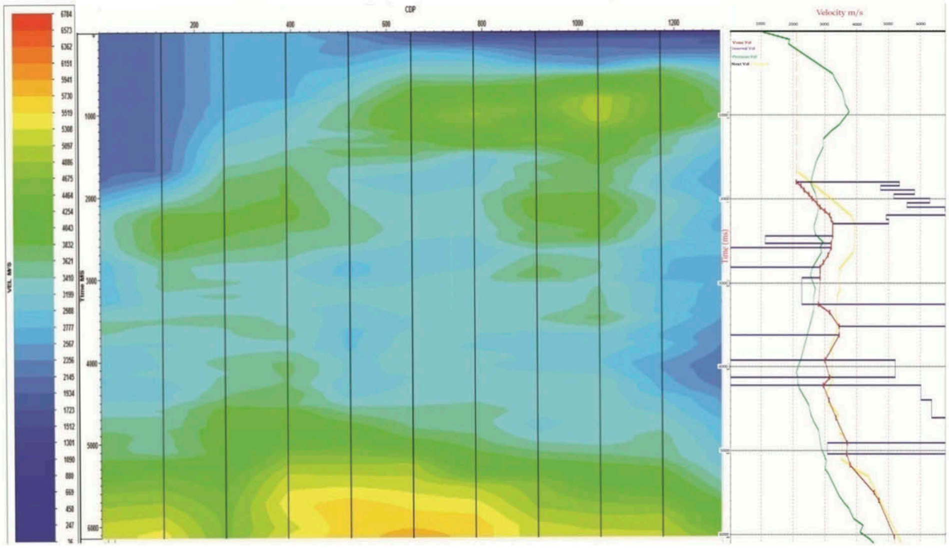

Figure 7. (a) Velocity field and (b) RMS Velocity and interval velocity curves of North Ramadan Field.

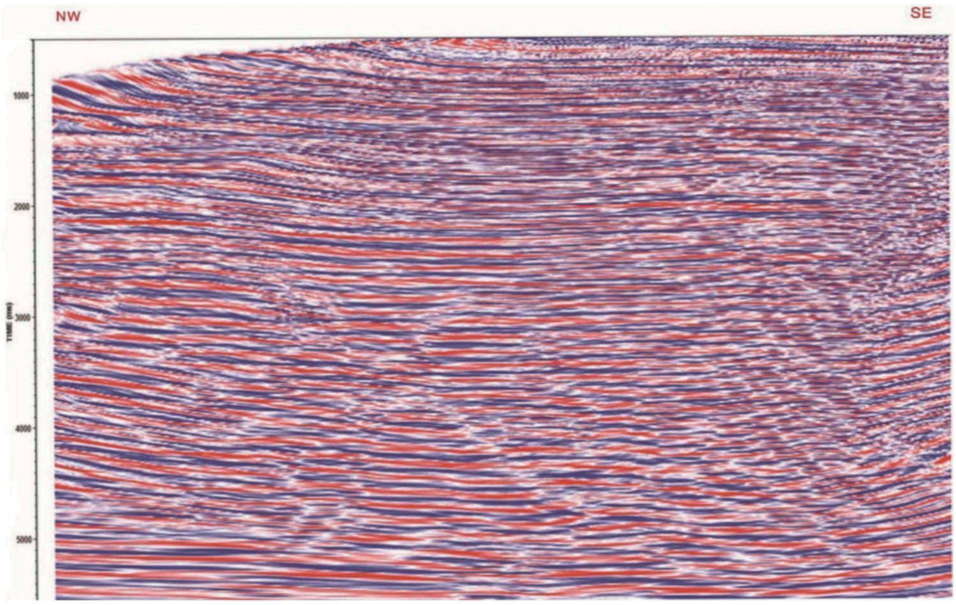

Figure 8. Final seismic section (NW-SE) of length 6.2 km.

Radon De-multiple, Shot and channel Gain correction, Regularisation and missing trace interpolation, Kirchhoff time migration for high density automatic velocity picking, Automatic high density velocity picking, Pre-Stack Time Migration for velocity picking with additional percentage scans, Velocity Analysis, Pre-Stack Time Migration, Precondition for automatic residual NMO, Residual NMO, Radon de-multiple, Mute and final stack, De-absorption, spectral balance and RNA, Foot imprints removal, TVF and scaling.

In this study, new programs have been adapted to apply advanced approach in processing and analysis of seismic data such as VISTA 11 program from GEDCO company for processing, after a lot of iterations of all seismic data parameters, seismic flows (Figure 3) and parameters were chosen to retain the primary frequencies content and relative amplitude while suppressing multiples energy. The reprocessing sequence is then divided into four essential stages that applied to the seismic data to get the final stacked section. The first one is geometry quality control (QC) which makes overall check on the positions of lines, shots, and receivers. The second stage is the de-noising stage in which the processor tries to remove the noise as possible as it can. The third one is the stacking with the velocity analysis needed for it. The final stage is the migration either on the stacked section or pre-stack migration.

The recording time length was 6 sec with a sample rate 2 msec. counting 3073 samples for each trace from 351,808 traces with a total size of 4.12 GB of data. The streamers were tested using the Navigation file on

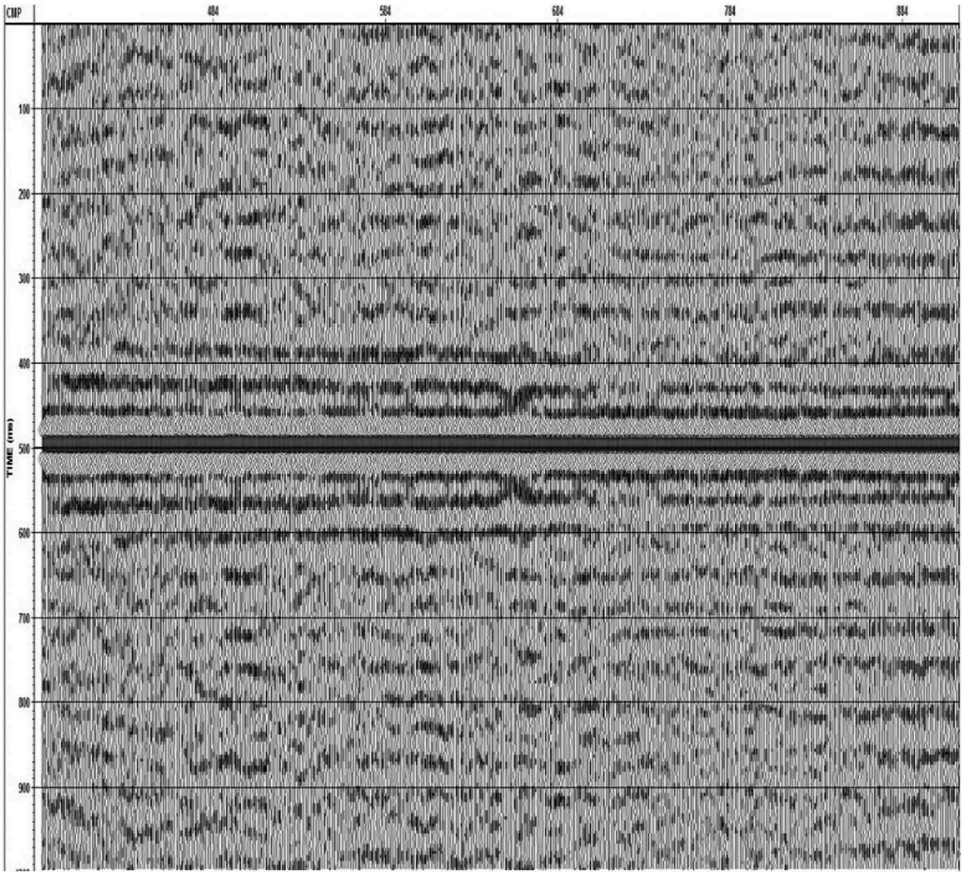

Figure 9. Autocorrelogram in the final section.

Micro Soft Excel (MS Excel) for their positions and relationship to each other and the relationship between the receivers and CDP offset (distance to shot point) (Figure 4). The depth of shots and receivers with a velocity of the water have also been used to draw the water bottom line on the seismic section using the following equation.

The static shift time = ((source depth+ cable depth) *2000)/1500

Predictive deconvolution can be very effective at suppressing short period multiple reflections (reverberations) with periods of less than around 300 ms (Yilmaz 2001). In the studied area, the large number of alternations of anhydrite with shale of Zeit Formation and salt of South Gharib Formation make the Predictive deconvolution more effective. The operator length is tested for 94, 192, 240, 280 and 300 m/sec while the prediction lag extracted from the autocorrelogram (Figure 5) of raw data is 80 msec., while the predictive gap is tested for 24, 32, 44 msec. Another tool has been used to remove the multiple which is the Radon Transform that is applied on raw seismic data (Figure 6(a)) in CMP domain to decompose the data into plane wave components; this decomposition allows waves which travel with different slowness to be separated. This means that the signal and multiple will separate from each other due to different slowness. Then, the inverse Radon transform is required to get the data back to the time-space domain after processing in the plane wave domain but with multiples free after extracting the multiple from the data (Figure 6(b)).

The process of calculating seismic velocity, typically by using common midpoint data. Successful stacking, time migration and depth migration require proper velocity field inputs (Figure 7(a)). Velocity analysis was conducted at locations interval of 1–2 km but with the specific locations selected so results are relatively free of structural or other complications. The locations for velocity analysis are usually determined from a study of the near-trace section output by the prior processing pass. In this study, the output of velocity picking along the seismic line by 300 metres interval show the velocity field along the line. By interpreting the velocity field, we will see that the velocity values increase downward rapidly, then decrease and increase again slowly, this is called velocity inversion as shown in (Figure 7(b)). This phenomenon is common in the Gulf of Suez because; first, increasing the velocity in shallow sections due to alternation between anhydrite, salt, and shale in Zeit and South Gharib formations, then it decreases due to disappearing of salt and anhydrite in deep formations. The velocity increases again due to the increase of compaction but this increase in velocity is slow and normal down to the end of the section. Moreover, the data is filtered by a sequence

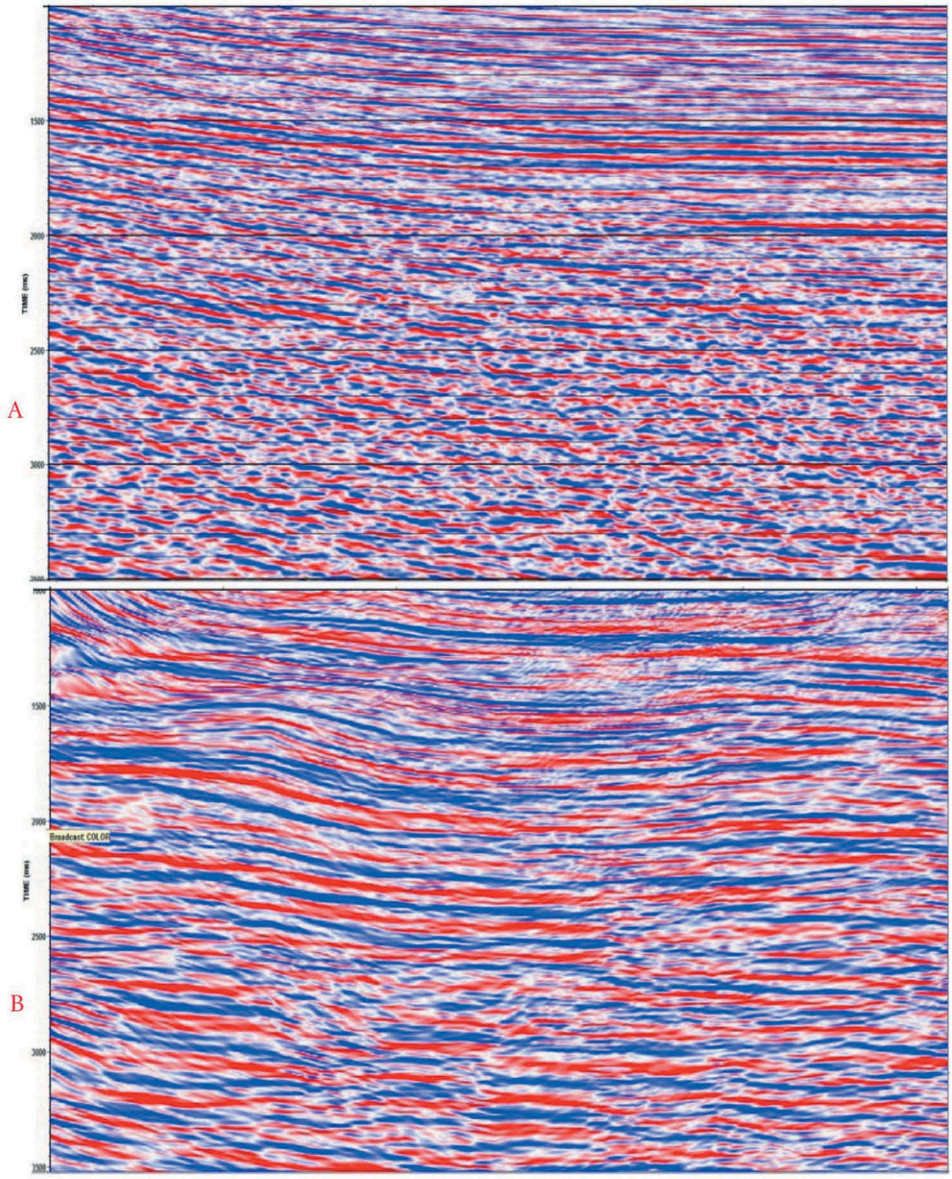

Figure 10. (a) Old processed section (NW-SE) and (b) Reprocessed final section (NW-SE).

of narrow bandpass filters to yield a filter panel is used to ascertain how the frequency content varies with arrival times and to determine subsequent filtering parameters.

Once the velocity model has been constructed, the seismic line is stacked and migrated with the velocity model and its arbitrary percentages. Typical, percentages will vary from 90% to 105% of the original velocity model then the most appealing section is chosen.

3. Results and discussion

The most proliferous reservoirs in the Gulf of Suez are the Miocene clastics and Pre-Miocene formations. The majority of these traps are of structural type. In the quest for additional hydrocarbon accumulations stratigraphic traps will need to be identified. Seismic stratigraphic and structural enhancement will help in the exploration of these subtle traps. Seismic data suffer from a multitude of problems where the primary reflections have low frequency while multiple reflections have higher frequency content. This will be realised from the reflectivity function of the different wells in the studied area (Zakaria 1998) where there is a high reflection contrast in the shallow section generated from the alternation of shale and anhydrite of Zeit Formation. This will generate a lot of multiples in the field data which in turn affect the deeper formations of low-frequency reflections. This low-frequency energy reflected from the deeper formations due to the incident energy itself suffers from a lot of loss mechanism from the salt of South Gharib Formation and anhydrite of Zeit Formation. With the need for seismic stratigraphic and structural enhancement, seismic processing flow and parameters have been chosen to retain the primary frequency

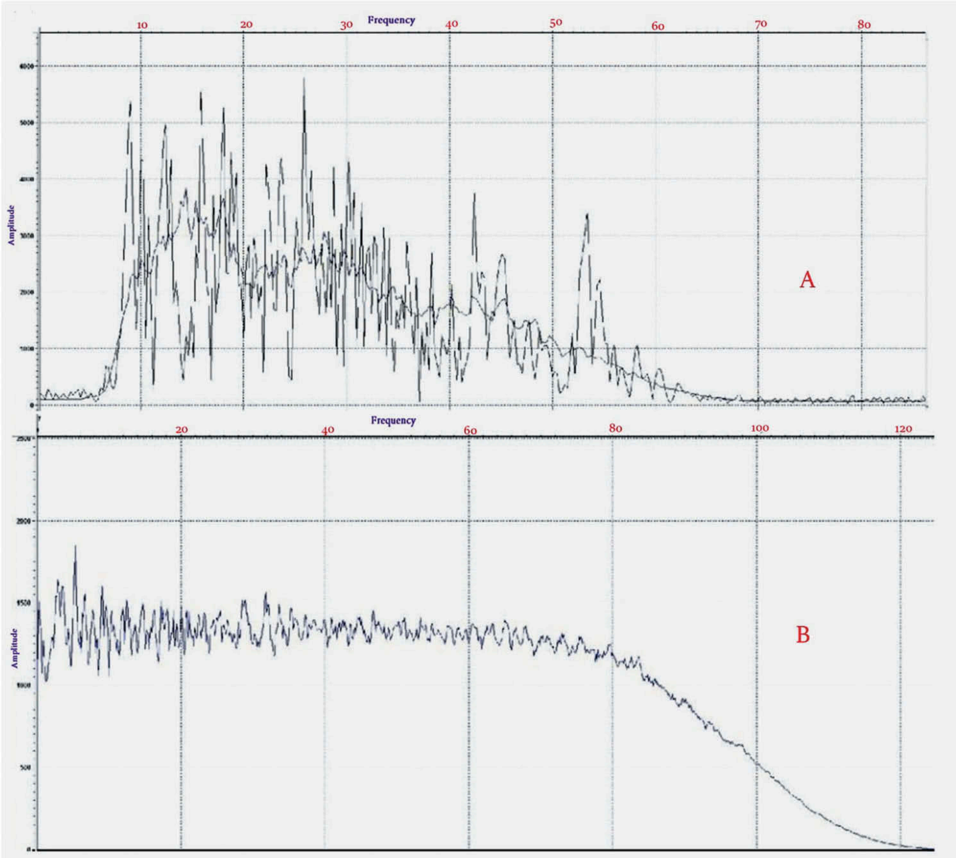

Figure 11. (a) Amplitude vs Frequency spectrum obtained frequencies content for old processed section and (b) Amplitude vs Frequency spectrum obtained frequencies content for the Reprocessed section.

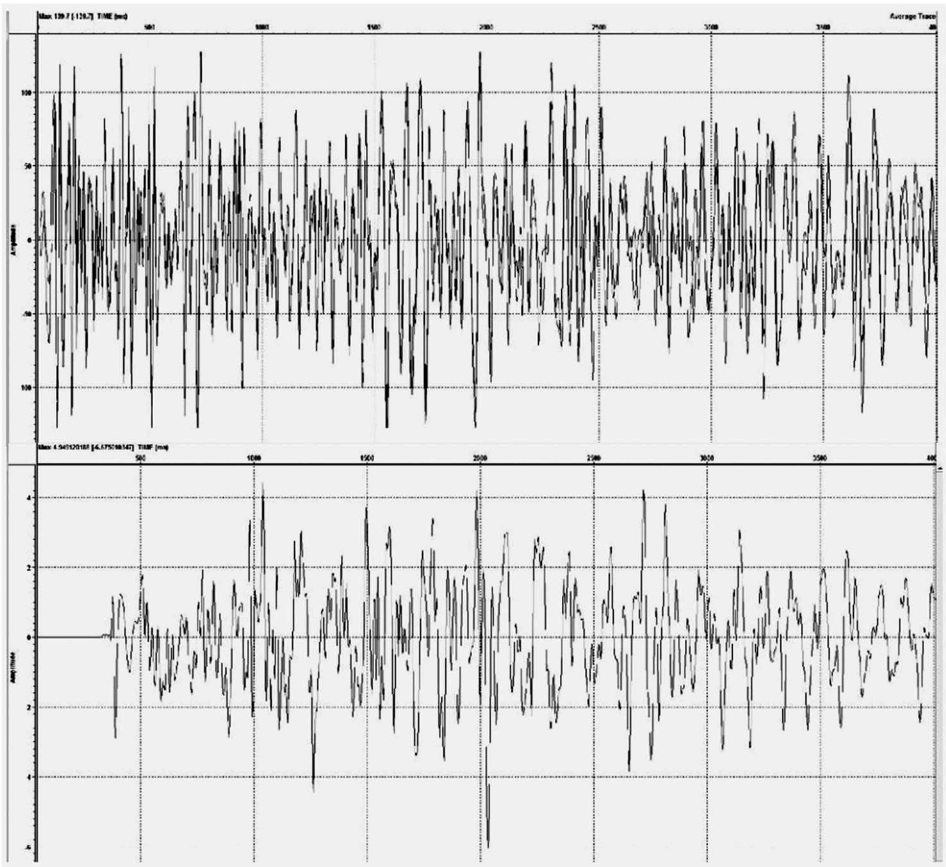

Figure 12. (a) Amplitude strength along the recording time for old processed section and (b) Amplitude strength along the recording time for the Reprocessed section.

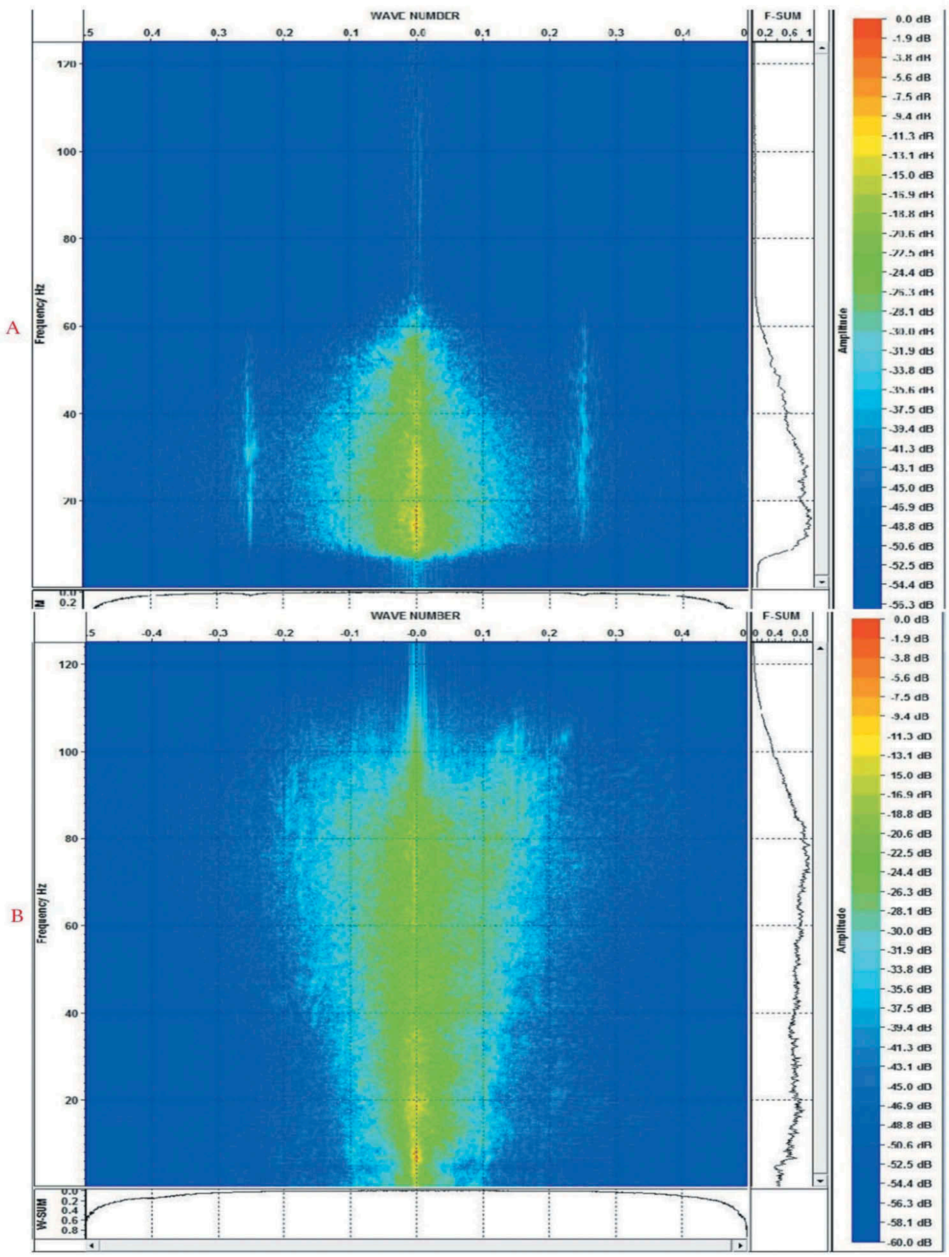

Figure 13. (a) F-k analysis for old processed seismic section and (b) F-k analysis for Reprocessed seismic section.

content and the relative amplitude producing the final section (Figure 8), while suppressing the multiples energy as shown on the autocorrelogram for the final section (Figure 9). These primary frequencies and energy are lost during the acquisition stage due to waveshape changing factors.

The stacked data can then be migrated and used as input to other processes such as attributes analysis. Velocity information has to be input to migrate the data. This velocity information is usually based on the stacking velocity measurements, especially where dips are not extreme, even though the optimum velocity for migration is usually different from that for stacking. Because processing usually involves a number of successive passes and because the decision on processing parameters has to be made between passes, there is a minimum turnaround time for most processing.

3.1. Comparison between old and new seismic products

By comparing the results of the two seismic processing methods, differences became obvious (Figure 10(a,b)). This comparison shows two images; the first image shows the old migrated post-stack data, and the second image shows the new migrated pre-stack data. For the second image, a velocity field updated by residual analysis was applied.

3.2. Comparison of frequency content

By analysing the frequency content in the old and new seismic processed data. The new seismic contain all the low frequency which comes from under the salt layers (Zeit and South Gharib formations), that one of the goals

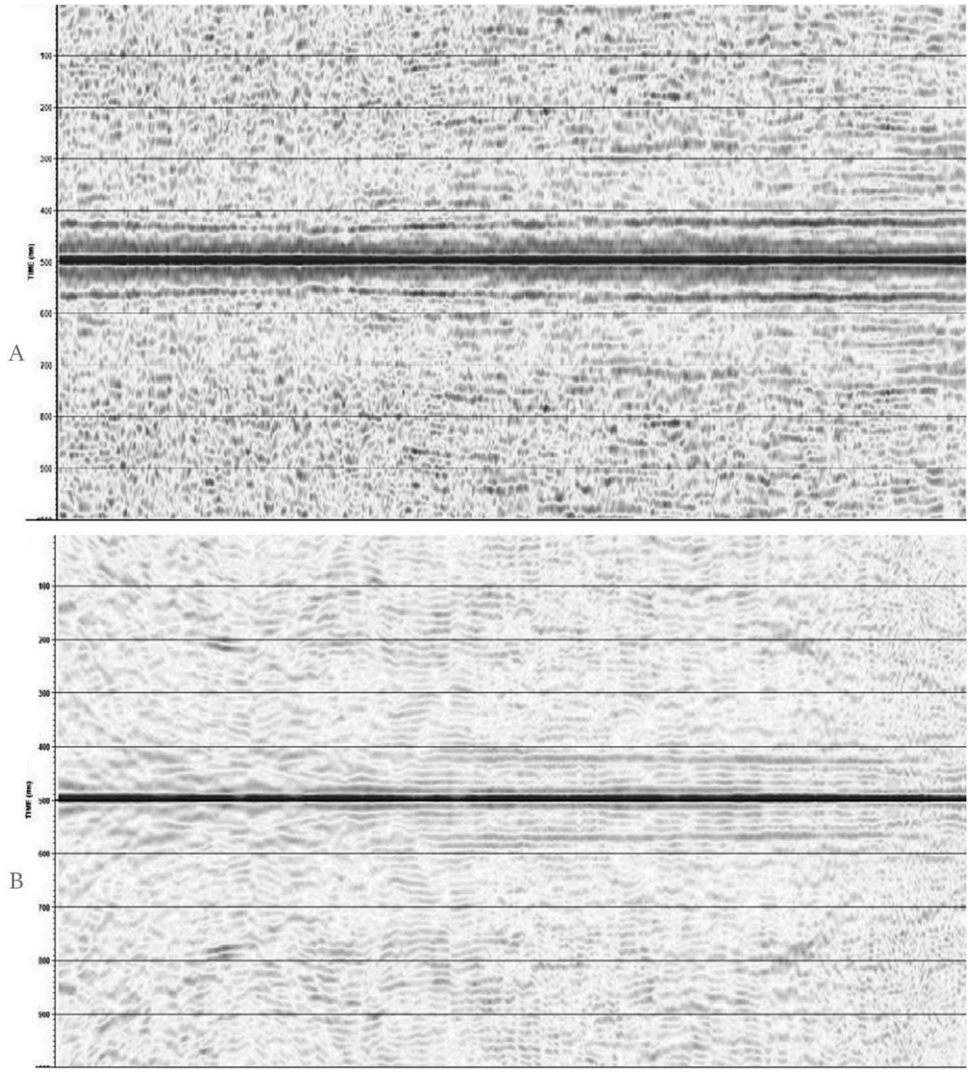

Figure 14. (a) Autocorrelogram for old processed seismic section obtain the multiples content and (b) Autocorrelogram for the Reprocessed seismic section obtain the multiples content.

of this study. This is to bring all low frequencies which represents the deep formations beneath the salt layers. However, the old seismic cut the low frequency beneath 8 Hz. and high frequency above 62 Hz. This means that the reprocessed data contain more frequency than the old processed data which means more events and more information content than the old one (Figure 11(a,b)).

3.3. Comparison between the recoveries of the amplitude signal

One of the most essential steps of processing is amplitude recovery and this step is applied more than one time either on shot gather or on migrated final section aimed to improve the appearance of events and treatment the loss of seismic energy either by natural processes during the acquisition or during the processing sequence applied on the data. This step is simple with the same applying procedure either on the old or new seismic data (Figure 12(a,b)).

3.4. Comparison between output velocities

There are a lot of events that have a low-velocity effect such as water and multiples that can appear in the FK-domain, so when we see the final seismic data in FK-domain, we can analyse the low velocities events. Here, the old and new seismic data appears with no low-velocity events (Figure 13(a,b)).

3.5. Comparison between multiples contents

Multiples contents appear for any seismic data when applying autocorrelation on it. Therefore during the processing sequence, we apply autocorrelation many times for example before and after Radon, and before and after stack to show the effect of these steps on multiples attenuation. The autocorrelation process was applied to the old and new seismic sections to compare the contents of the multiple in each data set. It is found that there is good multiples attenuation in both data sets either the old or new ones (Figure 14(a,b)).

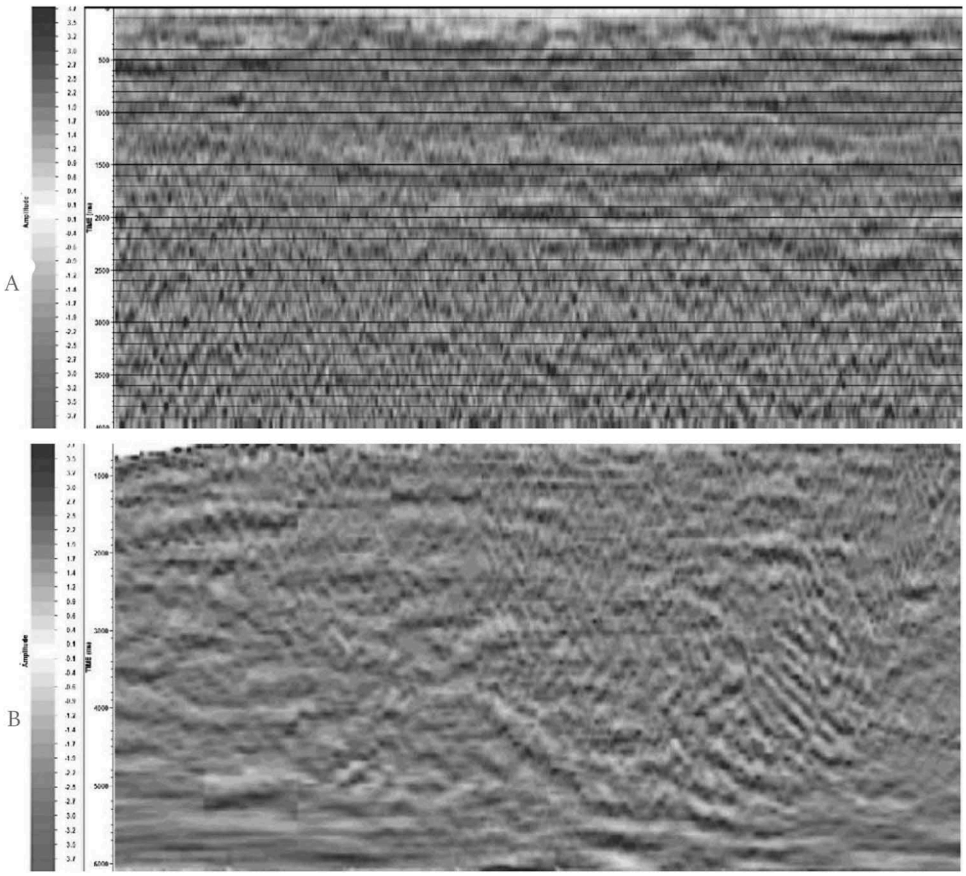

Figure 15. (a) S/N ration analysis window for old processed section and (b) S/N ration analysis window for reprocessed section.

3.6. Comparison between signals to noise S/N ratio

One of the analyses available to apply on the seismic section in any stage through the processing is Signal to noise S/N ratio as a type of quality control on the processes done and its effect in removing the noise from the data. When we applied this on the old and new seismic section, we found that the S/N ratio stacked the final section is very high for both old and new processed sections but it is more clear in the new one (Figure 15(a,b)).

3.7. Conclusion

The proposed reprocessing flow produced seismic sections with an increased temporal and spatial seismic resolution, facilitating a more accurate interpretation of the data. Enhanced imaging of both the salt structures and the sub-salt sequence has been achieved, which in turn leads to a better understanding of salt deformation and improve the mapping of structural subdivisions within the study area.

When the new processed section is compared with the old processed one, we notice the difference in resolution, frequency, signal to noise (S/N) ratio and continuity of the events. Reasonable velocity picking and reliable velocity information along the seismic line with the following benefits:

- Emphasises the seismic sequence interpretation.
- The reprocessed seismic data still suffer from multiples interference especially in the Pre-Miocene formations, but velocity-dependent multiples removal methods like the Radon method might help in multiples removal.
- Application of de-reverberation is very effective in increasing the seismic data resolution.
- The application of these new techniques and parameters in seismic data processing makes it possible to interpret seismic data stratigraphically as well as structurally in the Gulf of Suez.
- Inversion in seismic velocity in the Gulf of Suez helps in delineating the different velocity formations if the seismic data quality is free enough from noise and multiples.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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