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The efficiency of seismic attributes to differentiate between massive and non-massive carbonate successions for hydrocarbon exploration activity

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ABSTRACT

The present work investigates the efficiency of applying volume seismic attributes to differentiate between massive and non-massive carbonate sedimentary successions on using seismic data. The main objective of this work is to provide a pre-drilling technique to recognize the porous carbonate section (probable hydrocarbon reservoirs) based on seismic data. A case study from the Upper Cretaceous – Eocene carbonate successions of Abu Gharadig Basin, northern Western Desert of Egypt has been tested in this work. The qualitative interpretations of the well-log data of four available wells distributed in the study area, namely; AG-2, AG-5, AG-6 and AG-15 wells, has confirmed that the Upper Cretaceous Khoman A Member represents the massive carbonate section whereas the Eocene Apollonia Formation represents the non-massive carbonate unit. The present work have proved that the most promising seismic attributes capable of differentiating between massive and non-massive carbonate sequences are; Root Mean Square (RMS) Amplitude, Envelope (Reflection Strength), Instantaneous Frequency, Chaos, Local Flatness and Relative Acoustic Impedance.

1. Introduction

Seismic attributes are defined as parameters and measurements derived from seismic data such as the time, amplitude, frequency and attenuation of the seismic waves (Sheriff, 1994; Coren et al., 2001; Chopra and Marfurt, 2005). These attributes have long been used to provide information and details about the geologic structures, lithology, stratigraphy and reservoir properties on seismic sections (Taner, 2001; Chopra and Marfurt, 2005; Azevedo and Pereira, 2009). They represent powerful tools in prediction, characterization and monitoring of hydrocarbon reservoir (Chen and Sidney, 1997). However, the most important application of seismic attributes is to get information from the raw seismic data which is not readily apparent (Anees, 2013). The rapid progress in seismic attributes started after the using of 3D seismic data and the colored seismic profiles (Barnes, 2001; Chopra and Marfurt, 2005). Seismic attributes are controlled by various components of the seismic wavelet including; phase, amplitude and frequency. The phase content is helpful in seismic stratigraphic interpretation by examine the reflectors shape, geometry and continuity. While, the amplitude derived attributes are useful in providing structural details by providing physical parameters about the subsurface such as velocity, acoustic impedance, reflection coefficient, and absorption effect. However, the attributes based on the frequency are helpful in evaluating reservoir properties (Taner, 2001; Brown, 2001; Chopra and Marfurt, 2005).

Petrel-Software of Schlumberger Company is a worldwide software deals with seismic data. It includes a comprehensive package of seismic attributes used in hydrocarbon reservoir modeling in order to decrease the uncertainty and also to substitute the lack of the available seismic data (Sheline, 2005; Azevedo and Pereira, 2009). This package is classified into surface and volume categories depending on the input data. Volume attributes are used where two time horizons are defined as upper and lower boundaries. However, the surface attributes is used in a single horizon (Azevedo and Pereira, 2009). The most important role for the seismic interpreter who deals with the seismic attributes analysis is that, after finding one attribute shows the feature he wants to examine, he should not stop searching through the rest of the available attributes. This is because the interpreter should

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correlate between the different results based on using different attributes which displaying the feature of his interest in order to decrease the uncertainty (Chopra and Marfurt, 2005).

Porous carbonates that are associated with reefs, shoals, and ramps usually form excellent hydrocarbon reservoirs. They often represent stratigraphic traps if they are sealed by low-permeable rocks such as shales or evaporites (Chopra and Marfurt, 2007). Much of seismic exploration has been focused on determining locations and geometries of subsurface carbonate rocks such as reefs that have unusual porosity and permeability. Carbonate-on-carbonate reflections, such as those resulted from the interface between a porous grainstone and a nonporous carbonate mudstone, generally create lower reflectivity and lower resolution than those created within siliciclastic sequences. Also the dissolution and karstification digenesis processes within carbonates cause some modifications on the seismic reflector geometries. These reasons create big problems for the interpreters who dealing with carbonate successions on seismic data (Chopra and Marfurt, 2007). Carbonates rocks are deformed as brittle substances during lithification, thus they fracture more easily than the siliciclastics. In this concern, Chopra and Marfurt (2007) stated that unless the original connected pores have not been preserved between or within carbonate particles, carbonate reservoir will need open fractures to be able to hold and produce hydrocarbons.

Status of Abu Gharadig Basin carbonates

Abu Gharadig Basin is an elliptical E-W Mesozoic rift basin and extends for about 300 km representing the largest basin in the northern Western Desert (Demerdash et al., 1984; Abdel Aal and Moustafa, 1988). The basin subsidence continued during the Late Cretaceous - Early Tertiary times accompanied by compressional tectonic phase started by Santonian time leading to the development of several NE-SW oriented anticlines which are the main hydrocarbon traps in the basin (Moustafa, 2008). The Upper Cretaceous lithostratigraphy in Abu Gharadig Basin (Fig. 1) ends upwards by the carbonates of the Santonian-Maastrichtian Khoman Formation which was deposited under open marine outer shelf conditions. Khoman Formation is subdivided into two members; an upper Khoman A Memeber (Companian- Maastrichtian) and lower Khoman B Member (Sanrtonian), (Moustafa, 2008). The upper Khoman A Member consists of fine-grained white chalky massive limestone and massive dolomite, lacking any adequate reservoir properties (Mahsoub et al., 2012) and is almost devoid of any pores in thin sections (Soltan et al., 2013). Moreover, the scanning electron micrography for core samples represent the Khoman Formation confirm that the chalky limestone of this member is fractured and filled with calcite crystals (Kassab et al., 2013). On the other hand, the lower Khoman B Member is composed of argillaceous limestone with shale intercalations. The above Upper Createaceous carbonates are unconformably overlain by the Eocene Apollonia Formation. The latter is essentially composed of shallow marine carbonates (EGPC, 1992). Sousa and Badri (1996) applied various amplitude inversions for porosity mapping of the reservoir and amplitude variations with offset (AVO) techniques in order to evaluate the hydrocarbon prospectively of the Apollonia Limestone. They concluded that the Apollonia carbonate causes losing of the drilling fluid due to the presence of open fractures. In general words, in most of the Western Desert's sedimentary basins, including Abu Gharadig Basin, the limestone of the upper Khoman A Member displays sealing action, whereas the Eocene Apollonia limestone has reservoir characteristics (i.e. porous and permeable) as shown in Fig. 1. The Apollonia Limestone represents a promising hydrocarbon reservoir in the nearly future for many petroleum companies working in the Northern Western Desert such as Qarun Petroleum Company due to the presence of fractures (Personal Communication).

The present work focuses on the comparison between the massive carbonate (represented herein by the upper Khoman A Member) and the porous carbonate (represented herein by the Apollonia Formation) by testing some seismic attributes. This will enable distinguishing which of these attributes will provide the best contrast between the massive and porous limestones. So, the best value of this work is to examine the efficiency of some seismic attributes in distinguishing the porous carbonate sequences which may hold hydrocarbon from the massive units before the drilling step. Since the present work is concerning only on the application of the seismic attributes not the attributes themselves, the definitions and the derived mathematical formula for each one will be out of the scope of this work.

2. Study areas, available data and methodological approach

The study area is located at the central part of Abu Gharadig Basin in the northern Western Desert of Egypt (Fig. 2A). This area is covered by fifteen 2D seismic reflection profiles, tied by five wells, namely; AG-2, AG-5, AG-6, AG-15 and SWAG-1 (Fig. 2B).

Only the composite log for SWAG-1 well is available. The available well log data for AG-2 well includes; Sonic (DT), Gamma Ray (GR), Deep Resistivity (RD), Medium Resistivity (RM) and Density (RHOB). However, the obtained data for AG-5 contains Sonic (DT), Deep Resistivity (RD), Medium Resistivity (RM) and Shallow Resistivity (RS). The data for AG-6 well constitutes of Sonic (DT), Gamma Ray (GR), Deep Resistivity (RD), Medium Resistivity (RM), Shallow Resistivity (RS) and Density (RHOB). The present data for AG-15 well includes AG-6 data constitutes of Sonic (DT), Deep Resistivity (RD), Medium Resistivity (RM) and Shallow Resistivity (RS).

A qualitative interpretation for the shapes of the available log curve has been done to compare between the carbonates of Khoman A (massive carbonate unit) and Apollonia Limestone (non-massive carbonate unit), with special care on the examination of the presence of pores or fractures in each unit. This comparison was followed by the application of different seismic attributes on the available seismic data to confirm the conclusions extracted through the qualitative interpretation of the well data. Moreover the applied attributes were compared with each other to determine the best attribute that can play significant role in differentiation between the two carbonate units.

Petrel is a designed software by Schlumberger Company and is considered the most common software used in seismic interpretation in the majority of petroleum companies all over the world. Petrel software contains two packages of seismic attributes; volume package which concerns with units bounded by two surfaces and surface attributes which applied to enhance only surfaces. The Volume attributes in Petrel Software includes three libraries; seismic signal processing library, complex trace attribute library and stratigraphic attributes library. Various seismic volume attributes from the different libraries of Petrel Software have been applied in the present work as illustrated in Table 1.

3. Results

3.1. Qualitative well-logs interpretation

Based upon the lithologic composite log of SWAG-1 well, the limestone of the Apollonia formation is tannish brown, occasionally tannish gray and crypto-crystalline to very fine-crystalline; moderately hard; glauconitic. However, the limestone of the Khoman A Member is tannish white, off white, milky white; crypto-crystalline to fine-crystalline; moderately hard to hard and chalky. It is of worth mentioning that the variation in the massiveness

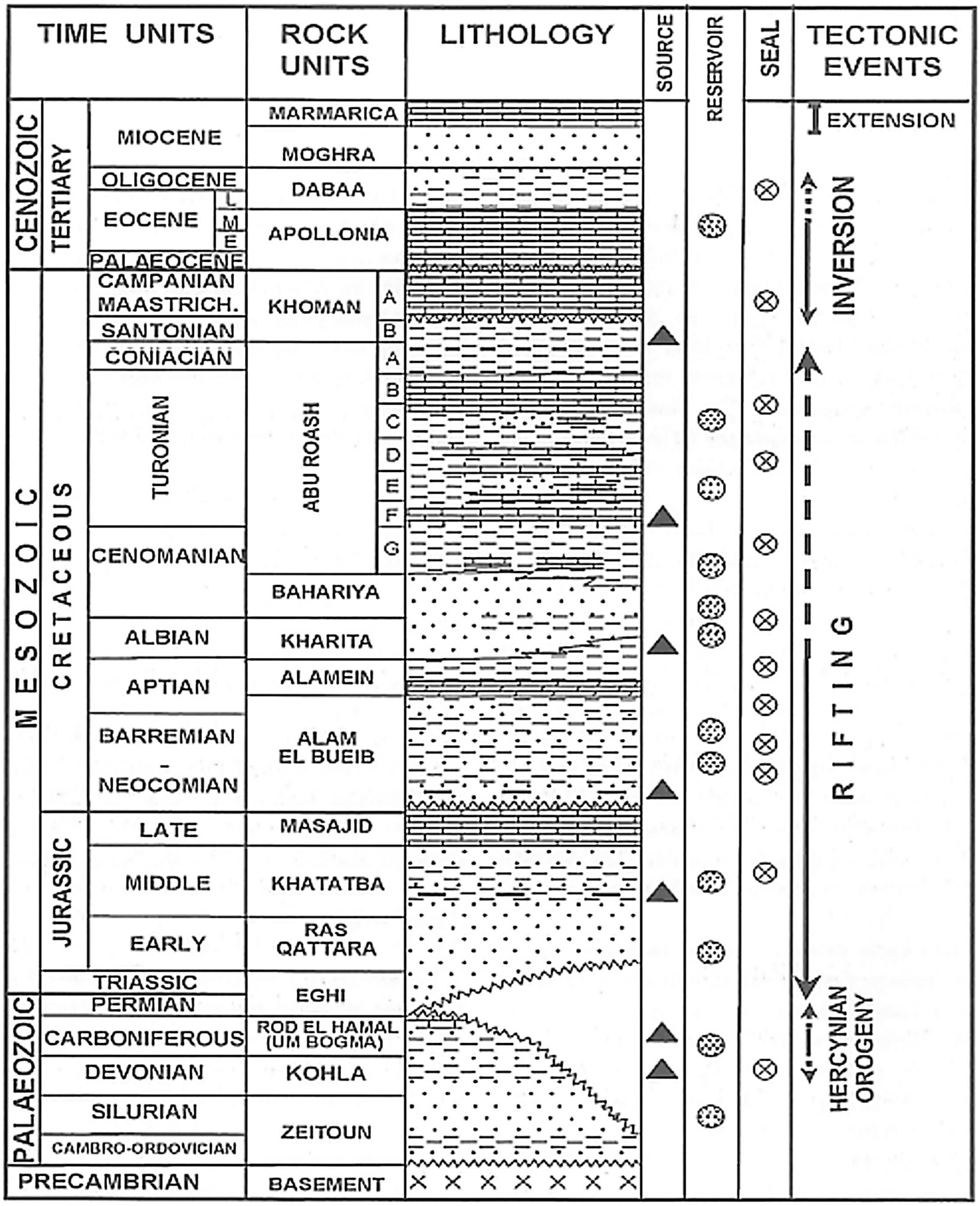

Fig. 1. Regional stratigraphic column of the northern part of the Egyptian Western Desert including El-Gindi Basin (modified by Moustafa, 2008 after Schlumberger, 1984, 1995 and EGPC, 1992).

between both rock units can be observed through inspection of the rate of penetration (R.O.P.) track in SWAG-1 well. This rate recorded 4 and 5 per 5 feet against the Apollonia limestone unit, whereas it varies between 5 and 10 min per 5 feet against the Khoman A limestone unit. This marked (R.O.P.) difference is attributed to the presence of effective porosity in the Apollonia Formation, even formed during deposition (primary porosity types) or after the deposition such as fracture or dolomitization (secondary porosity types).

The visual description of the available well log curves for AG-2, AG-5wells (Fig. 3) and AG-6, AG-15 wells (Fig. 4) wells has been done to judge the presence or the absence of pores within the Khoman A and Apollonia limestone. The qualitative examination for all well logging data displays lower values in sonic log opposite to the Khoman A limestone rather than Apollonia limestone (Figs. 3 and 4). This suggests that the Khoman A unit is a massive carbonate unit causes the decrease in the delay time for the transmitted sonic waves through its entire carbonate. However, the Apollonia limestone unit contains pores which are responsible for the increase in the delay time. Also the shallow, medium and deep resistivity curves (RS, RM and RD) in each examined well display identical similarity (have the same values) in Khoman A unit indicating that there is no invasion for the drilling fluids through the limestone of Khoman A (Figs. 3 and 4). This confirms the absence of pores within the Khoman A succession. However the resistivity curves opposite the Apollonia limestone show relatively variations in their values (Figs. 3 and 4). These variations reflect the invasion of the drilling fluid through the open pores and confirm the presence of porosity and permeability in Apollonia limestone unit. On the other hand, the visual inspection for all well logging data displays higher values in density (RHOB curves) in AG-2 and AG-6

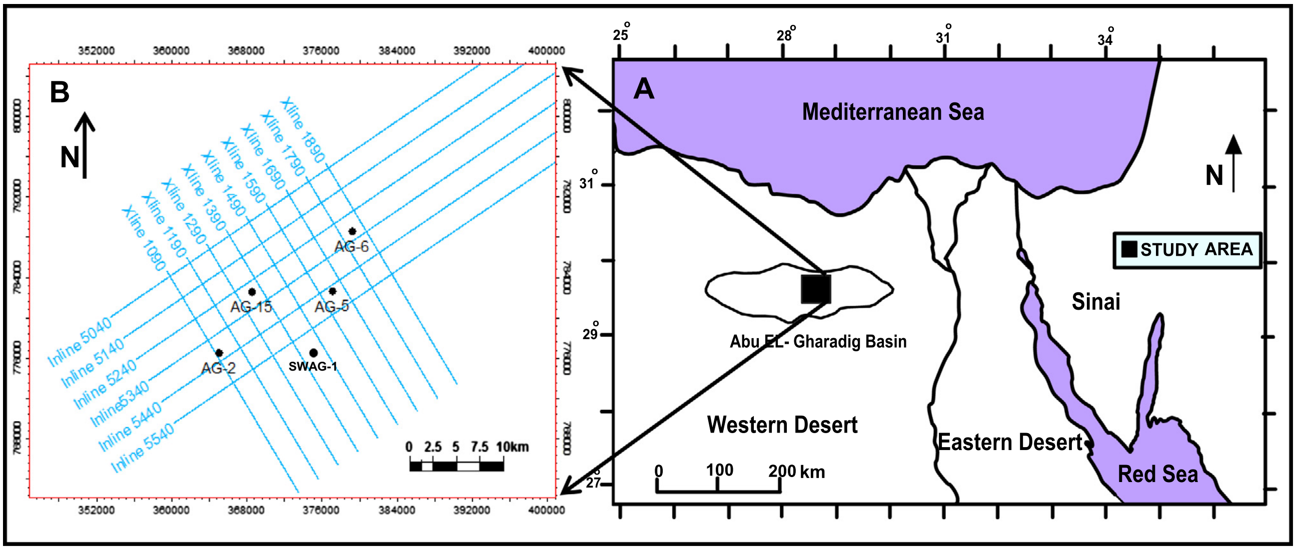

Fig. 2. Regional map of the Northern Western Desert showing the study area within Abu Gharadig Basin (A) with seismic lines and well locations (B).

Table 1
Summary of the most promising seismic attributes to differentiate between massive and non-massive carbonate sequences.

Applied attribute	Petrel library	Importance (*according to* Azevedo and Pereira, 2009)	Figure no.	Response to differentiate between massive and non-massive carbonate		
				Very good	Good	Fair
First derivative	Seismic signal processing attribute	Improve reflector sharpness	Fig. 5			√
Second derivative		Improves reflectors continuity and sharpness	Fig. 6			√
Trace automatic gain control (AGC)		Provide mild amplitudes to all the data	Fig. 7			√
Trace gradient		Distinguish between seismic units and can be correlated with areas with abrupt changes in lithologies related to differences in acoustic impedance	Fig. 8			√
Time gain		Increase of amplitudes with time	Fig. 9		√	
Reflection intensity		Distinguish between different type of lithologies	Fig. 10		√	
RMS amplitude		Gives information about the energy content of the seismic data	Fig. 11	√		
Apparent polarity	Complex trace attribute	Enhance continuity and lateral variations in lithology	Fig. 12			√
Instantaneous phase		Enhancing reflectors continuity, discontinuities, faults, pinch-outs and seismic stratigraphy patterns (e.g. onlaps and offlaps)	Fig. 13			√
Cosine of instantaneous phase		Improves reflectors continuity and enhances faults and stratigraphic boundaries, enhance stratigraphic terminations, lateral variations and seismic facies variations	Fig. 14			√
Instantaneous bandwidth		Improve changes in lithology	Fig. 15			√
Dominant frequency		Enhance lateral changes in geology	Fig. 16			√
Envelope (reflection strength)		Detect major and subtle lithological changes that may be difficult to interpret from the original seismic data	Fig. 17	√		
Instantaneous frequency		Enhance vertical and lateral variations of lithologies, detect fracture zones and as a Direct Hydrocarbon Indicator (DHI)	Fig. 18	√		
Iso-frequency	Stratigraphic attributes	Reveal subtle variations in lithology that may indicate stratigraphic traps for hydrocarbons	Fig. 19			√
Chaos		Enhance faults, discontinuities, salt bodies, and reflectors with chaotic texture which are often associated with channel infill or reef textures	Fig. 20	√		
Local flatness		Enhance faults and other vertical anomalies, gives information about the flatness of the local seismic signal	Fig. 21	√		
Relative acoustic impedance		Indicate sequences boundaries, unconformity surfaces and discontinuities, It may be also related with porosity within the formations and the presence of fluid content inside a hydrocarbon reservoir	Fig. 22	√		

wells (fourth track to the left) opposite the lithologic interval of Khoman A rather than the Apollonia carbonates (Figs. 3 and 4). The lower density of the Apollonia unit is attributed to the existence of the open pore spaces. Regarding to the lower gamma ray (GR) values opposite Khoman A interval in AG-6 well (Fig. 3) may be attributed to the deposition of the Khoman A chalky lime-

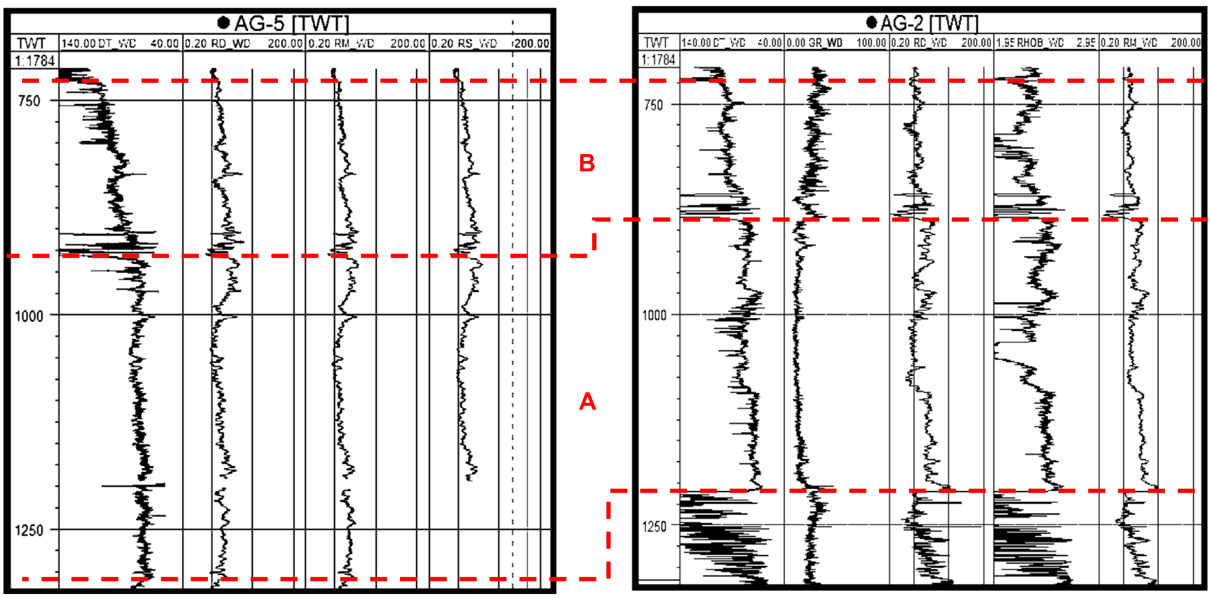

Fig. 3. Available well log suite for Khoman A Member (Unit A) and Apollonia Formation (Unit B) in AG-2 and AG-5 wells.

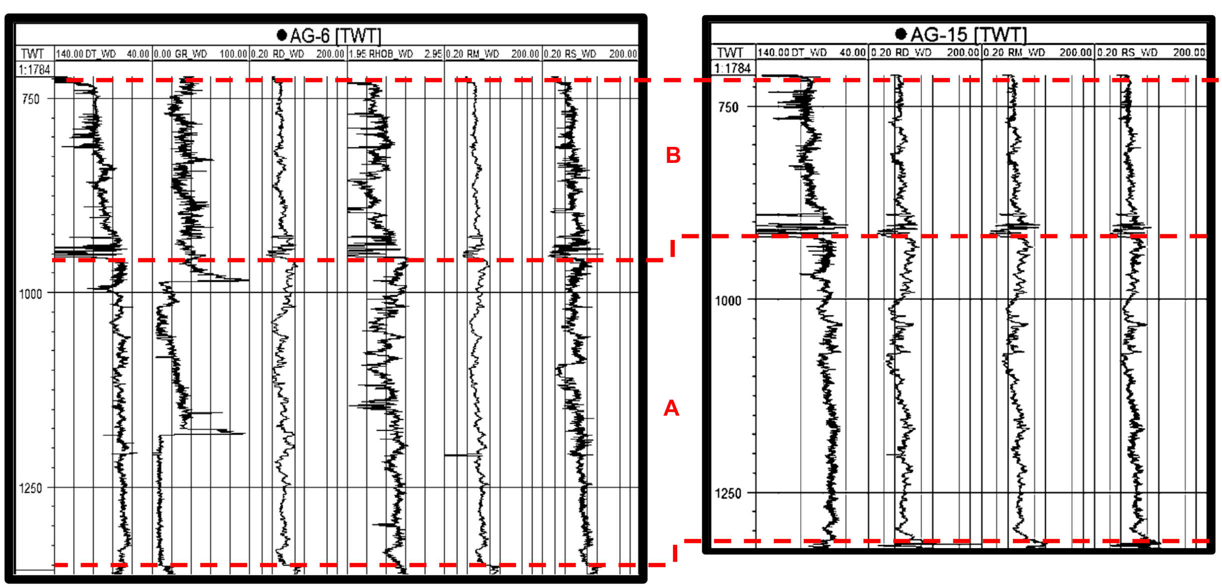

Fig. 4. Available well log suite for Khoman A Member (Unit A) and Apollonia Formation (Unit B) in AG-6 and AG-15 wells.

stone was far from mud contribution (clean limestone). While the increase in gamma ray opposite the Apollonia limestone may be due to the occurrence of some shale intercalations.

In conclusion, the above qualitative well logging interpretation confirms that the entire carbonate of Khoman A Member is massive unit, whereas the limestone of the Apollonia Formation is non-massive (porous) carbonate sequence.

3.2. Application of seismic attributes

The application of the different seismic attributes from the seismic signal processing library in Petrel Software has revealed that the first derivative, second derivative, trace Automatic Gain Control (AGC) and trace gradient attributes have no significant contrast between the examined massive limestone of Khoman A unit and the non-massive carbonates of Apollonia Formation (Figs. 5–8). All of these attributes clearly display the more continuous reflectors of the Khoman A unit relative to the highly broken seismic reflectors of the Apollonia limestone. The discontinuous reflectors in Apollonia unit (the non-massive carbonate unit) may be due to the presence of open pores (fractures) which led to the distortion of the seismic waves. The applied time gain attribute displays values around zero (white color background) in the non-massive Apollonia carbonate which may be considered as an indication for the presence of porous units (Fig. 9). The reflection intensity attribute exhibits observable lower values (pale blue colored background) in the non-massive Apollonia carbonate rather than the carbonate of Khoman A (Fig. 10). This may be attributed to the presence of pores which decrease the amount of the received reflections (decrease the reflection intensity). However, the appli-

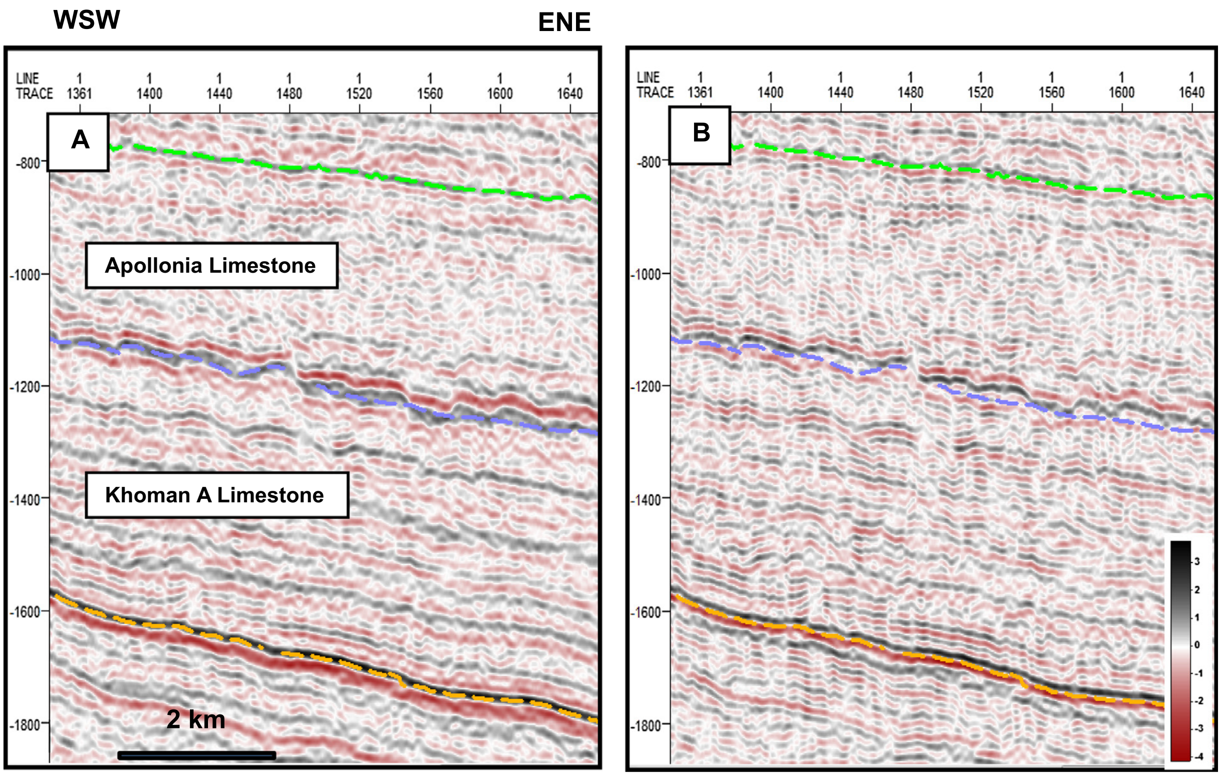

Fig. 5. (A) Original seismic line (INLINE 5240) and correspondent (B) first derivative attribute.

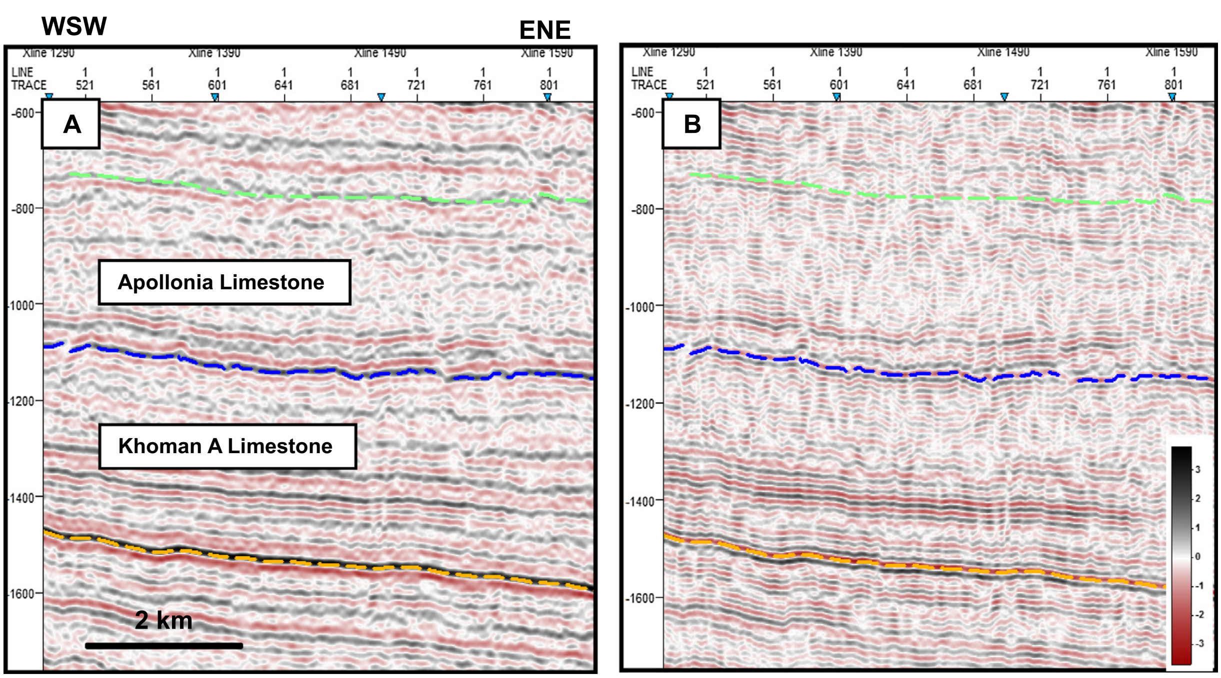

Fig. 6. (A) Original seismic line (INLINE 5040) and (B) computed second derivative attribute.

cation of Root Mean Square Amplitude (RMS Amplitude) attribute displays a distinct contrast between the Khoman A and the Apollonia limestones. The prevalence of the larger positive values (dark blue color) within the examined Apollonia limestone rather than Khoman A indicates that the Apollonia limestone is a more porous unit (Fig. 11). This result matches the findings of Azevedo and Pereira (2009) who reported that the high values of RMS amplitudes are commonly related to high porosity lithologies.

The applied seismic attributes from the complex trace package in Petrel software include; apparent polarity, instantaneous phase, cosine of instantaneous phase, instantaneous bandwidth, dominant frequency, envelope (reflection strength) and instantaneous

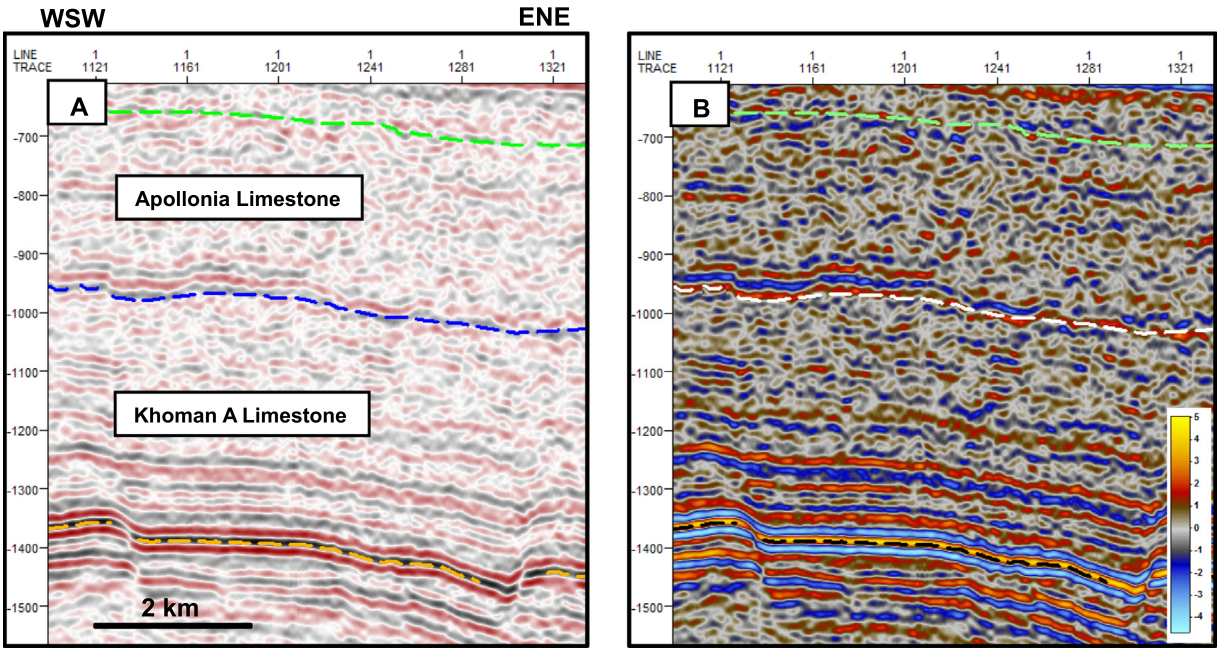

Fig. 7. (A) Original seismic data (INLINE 5440) and (B) extracted trace AGC attribute.

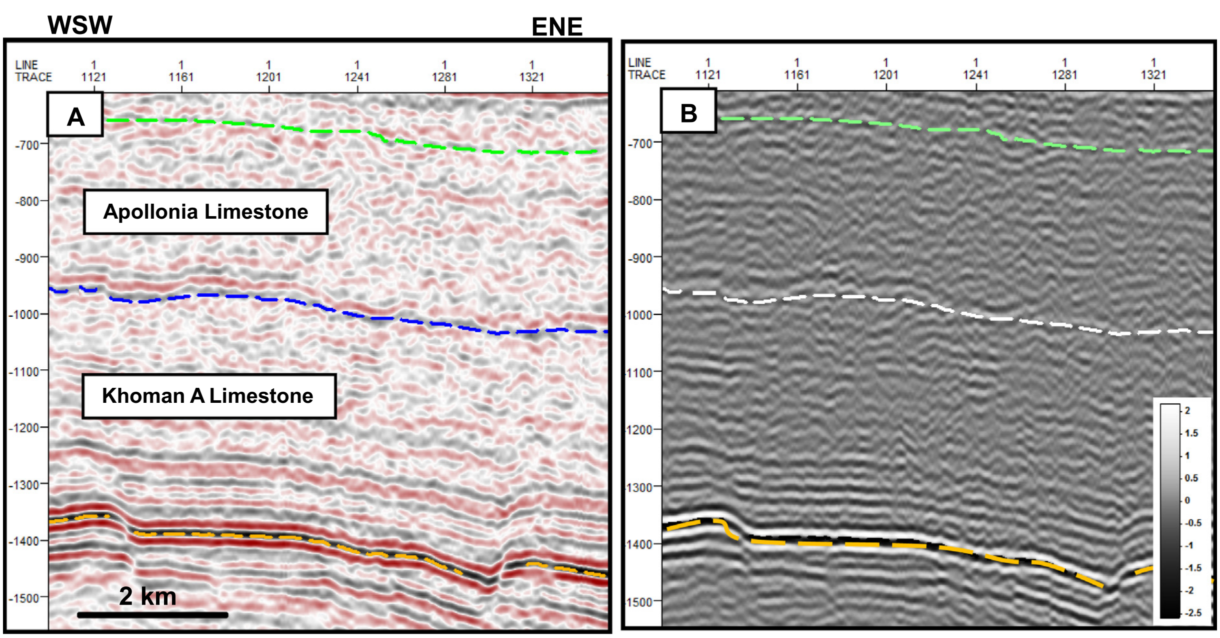

Fig. 8. (A) Original seismic data (INLINE 5440) and (B) trace gradient attribute.

frequency attributes as shown in Figs. 12–18. The attributes of apparent polarity, instantaneous phase, cosine of instantaneous phase, instantaneous bandwidth and dominant frequency seismic attributes didn't show a specific variation between the Apollonia and the Khoman A limestones (Figs. 12–16). All of these attributes just enhance the more continuous reflectors of the Khoman A succession in comparable to the divided seismic reflectors of the Apollonia limestone. However, the use of the envelope (reflection strength) and instantaneous frequency seismic attributes exhibit a significant difference between the two examined carbonate units (Figs. 17 and 18). The envelope attribute shows low values of reflection strength (pale blue color) in the majority of the non-massive unit (Apollonia carbonate) whereas, the spread of the low values is very limited within the massive Khoman A unit (Fig. 17). This may be attributed to the presence of the open pores within the Apollonia limestone which decrease the entire density and causing a reduction of the strength of the reflected seismic waves. Regarding to the instantaneous frequency seismic attribute, it displays spreading of the low values of instantaneous frequency (orange to red color) in the whole Apollonia limestone rather than in Khoman A limestone (Fig. 18). This is may be due to the presence of fractures in the Apollonia carbonate causing absorption effects which led to the low values of instantaneous frequency matching the findings of Azevedo and Pereira (2009).

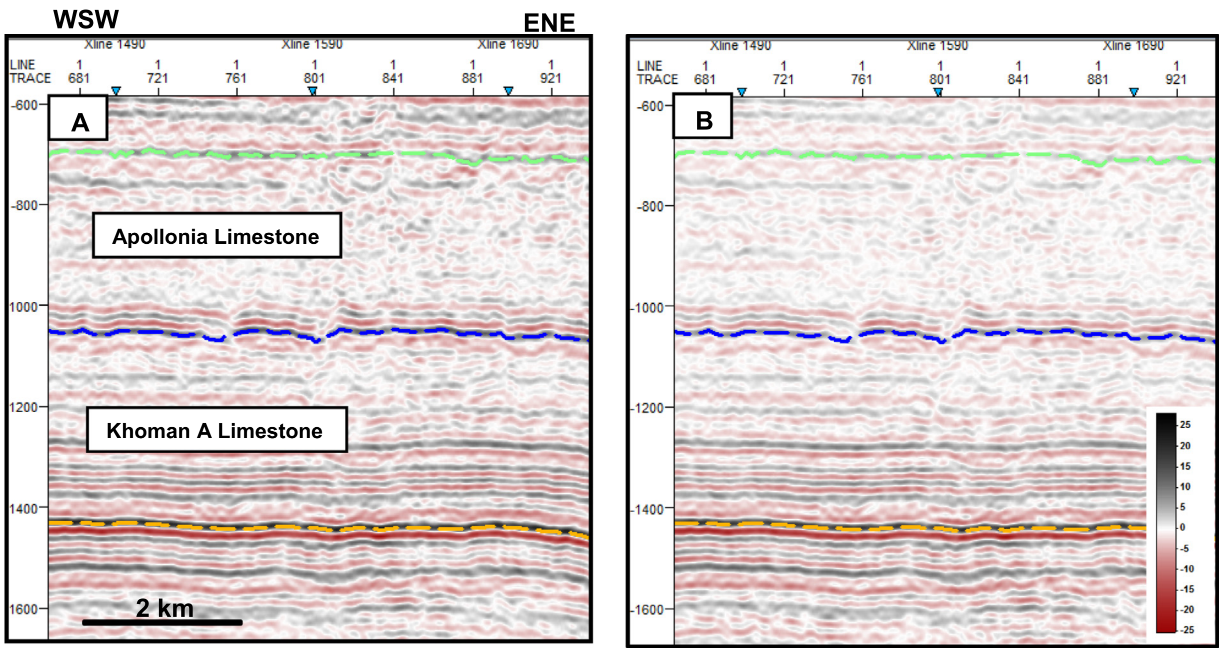

Fig. 9. Seismic sections comparing (A) the original seismic section (INLINE 5140) with (B) time gain attribute.

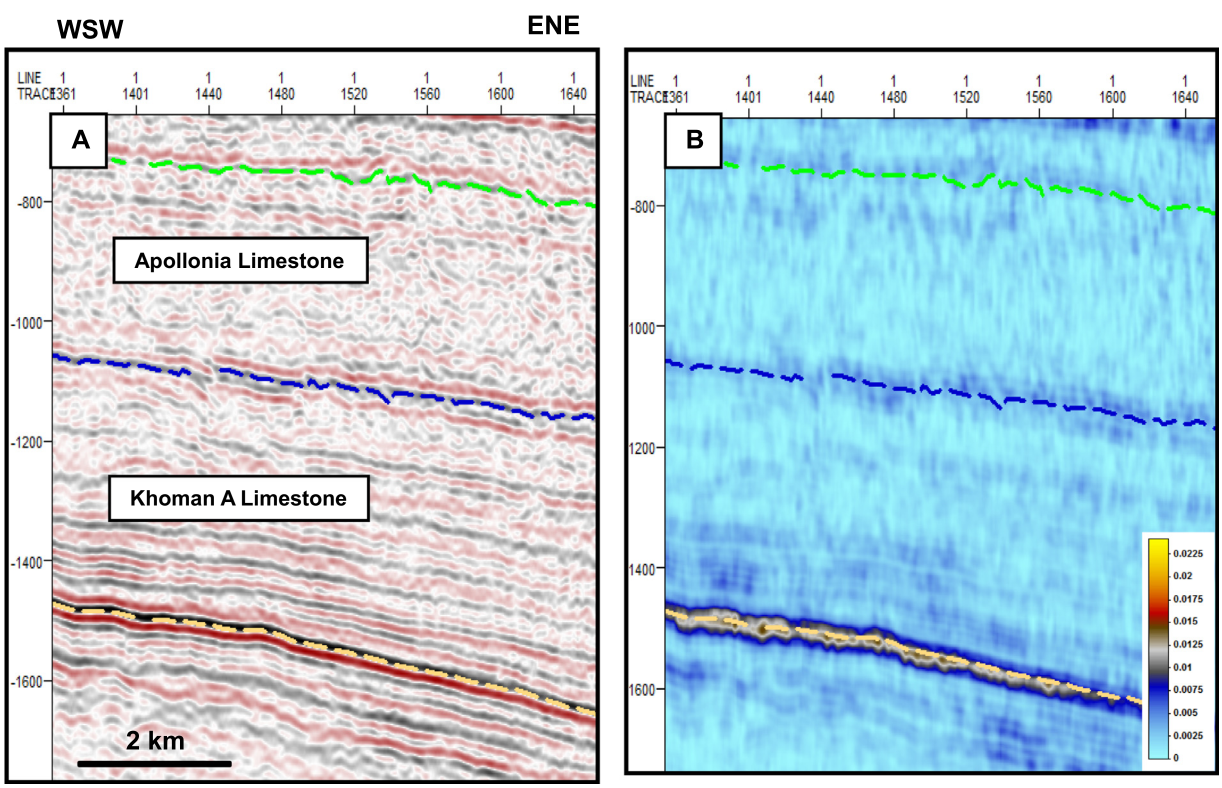

Fig. 10. (A) Original seismic section (INLINE 5340) and (B) reflection intensity output.

On the other hand, the applied seismic attributes from Stratigraphic Attributes Library in Petrel contain; iso-frequency, chaos, local flatness and relative acoustic impedance (Figs. 19–22). The iso-frequency attribute presents a highly mottled appearance in both investigated carbonate units. The lower values (blue in color) distribute over the surroundings yellow background (higher values) in the Khoman A and Apollonia units (Fig. 19). The chaos, local flatness and relative acoustic impedance attributes present observable contrast between the examined carbonates units (Figs. 20–22). In chaos attribute, the chaos is highly increased in the Apollonia limestone rather than the Khoman A unit forming a clear difference between both units (Fig. 20). Also, the local flatness attribute

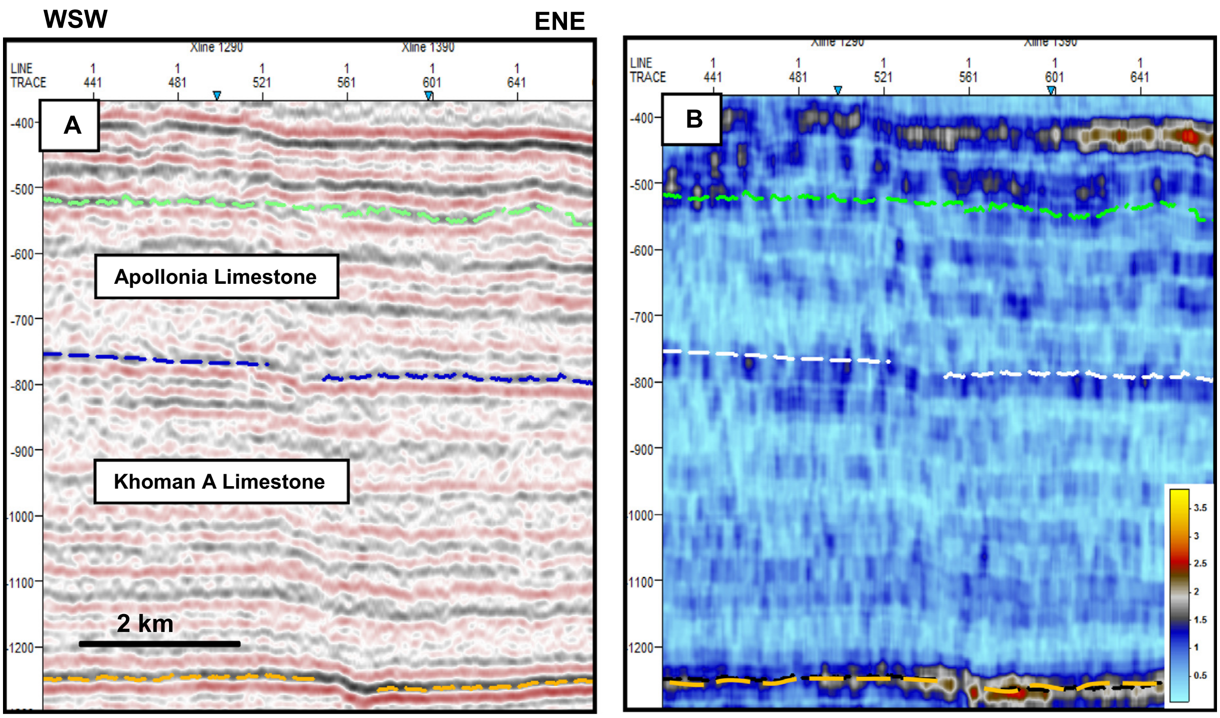

Fig. 11. (A) Seismic line (INLINE 5540) in original amplitude and (B) extracted RMS Amplitude attribute.

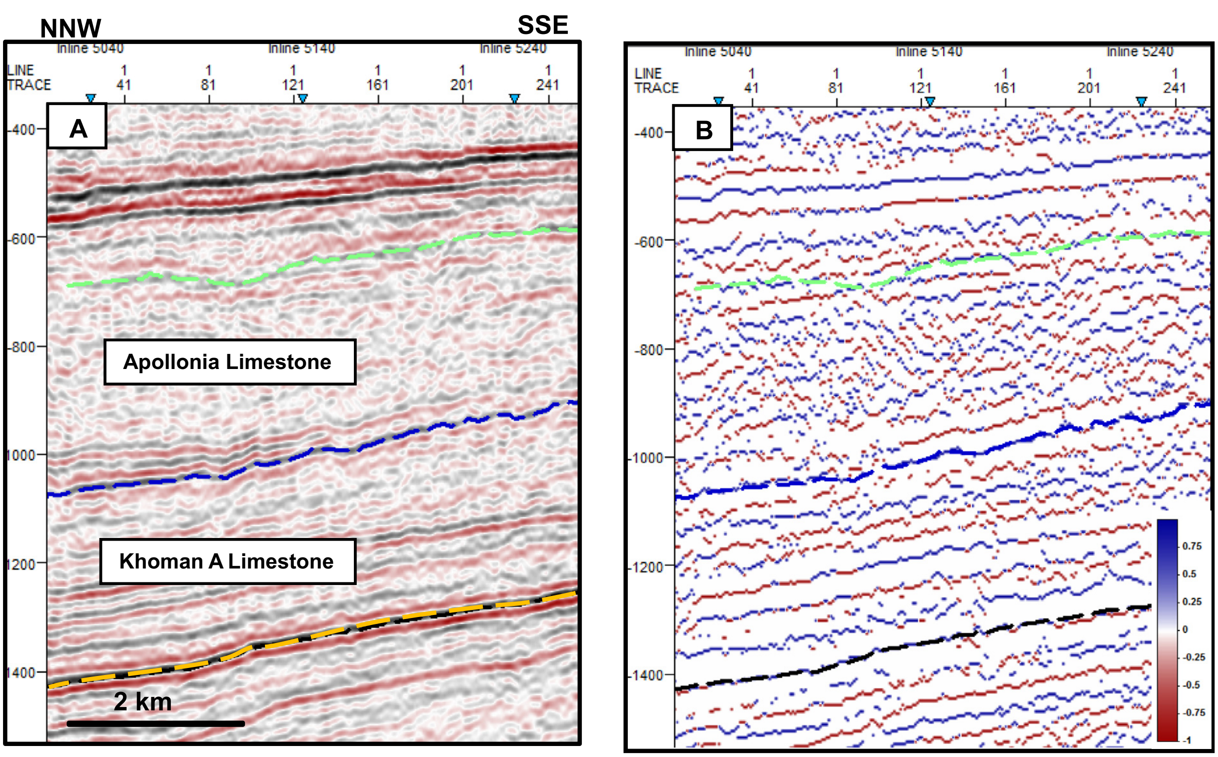

Fig. 12. (A) Seismic section (Xline1090) displaying original seismic data and (B) extracted apparent polarity attribute.

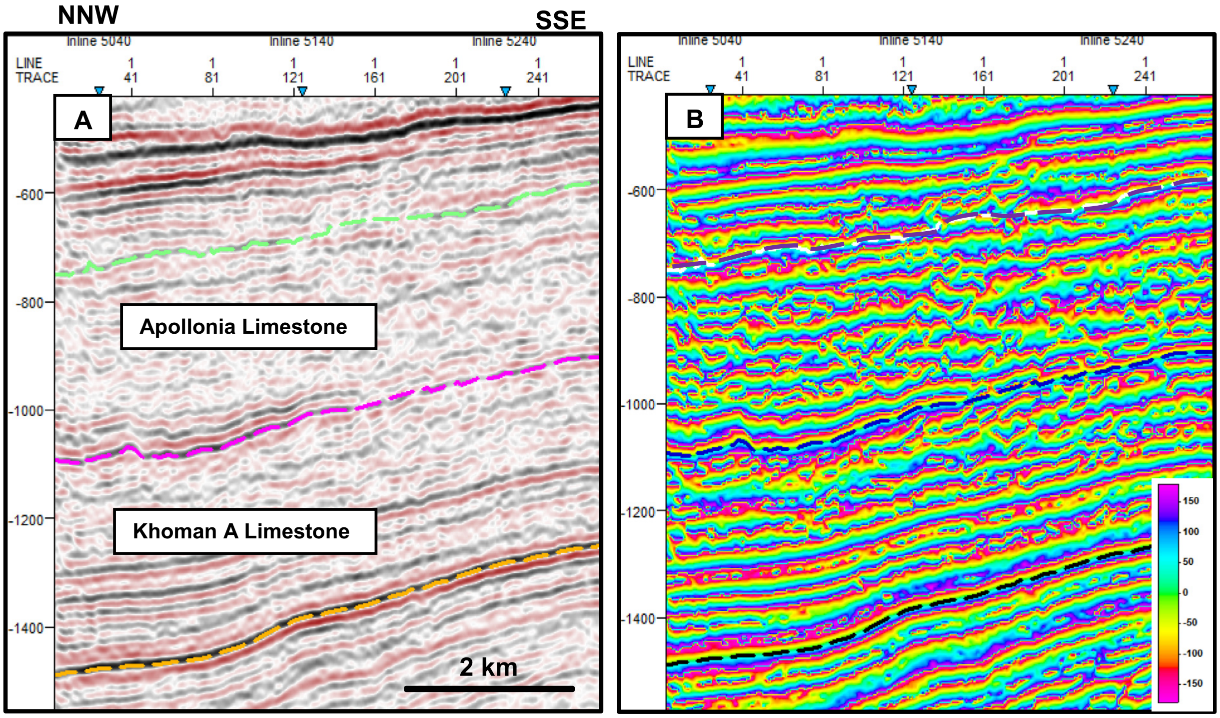

Fig. 13. (A) Original seismic plot (Xline1290) and (B) corresponding instantaneous phase seismic attribute.

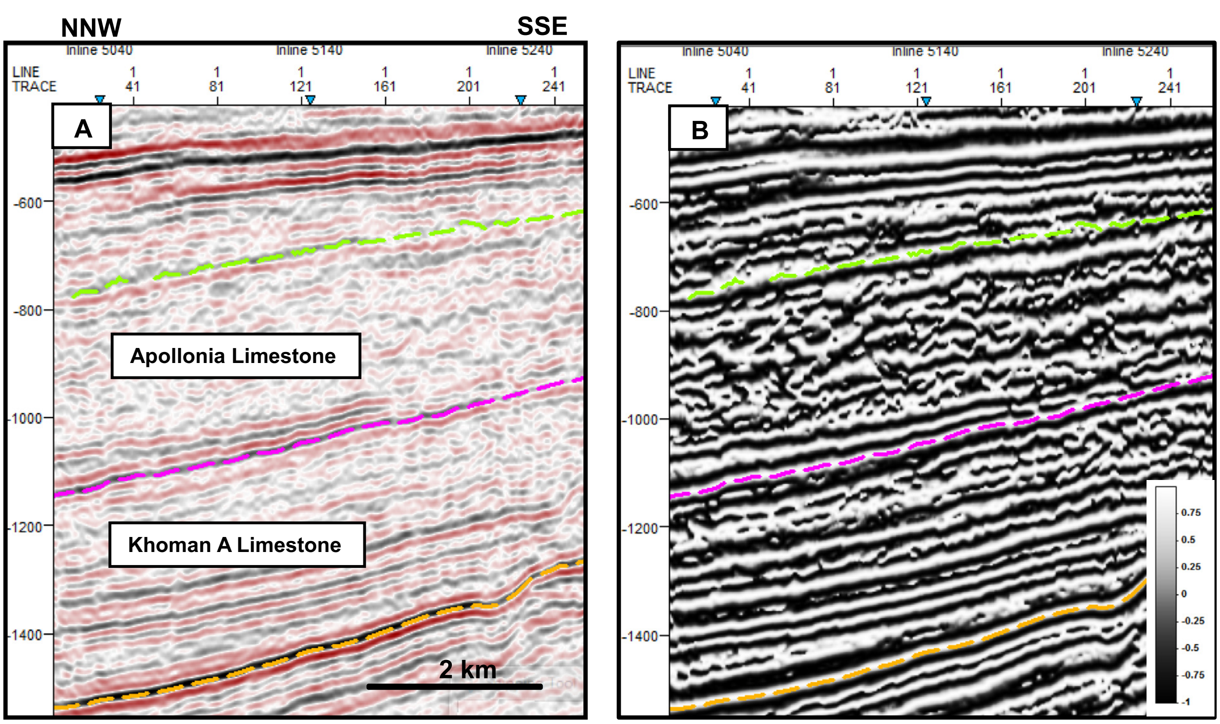

Fig. 14. (A) Original seismic data (Xline 1390) and (B) extracted cosine of phase attribute.

displays a distinguished dotted look in the Apollonia limestone and pure appearance in the lower unit of Khoman A (Fig. 21). The application of relative acoustic impedance attribute shows a distant variation between the lower Khoman A unit and the overlain Apollonia limestone. Khoman A unit contains higher positive (red) together with high negative (blue) values however, the majority of the Apollonia carbonate shows relative acoustic impedance values around zero values (between +1 and −1) causing the spread of

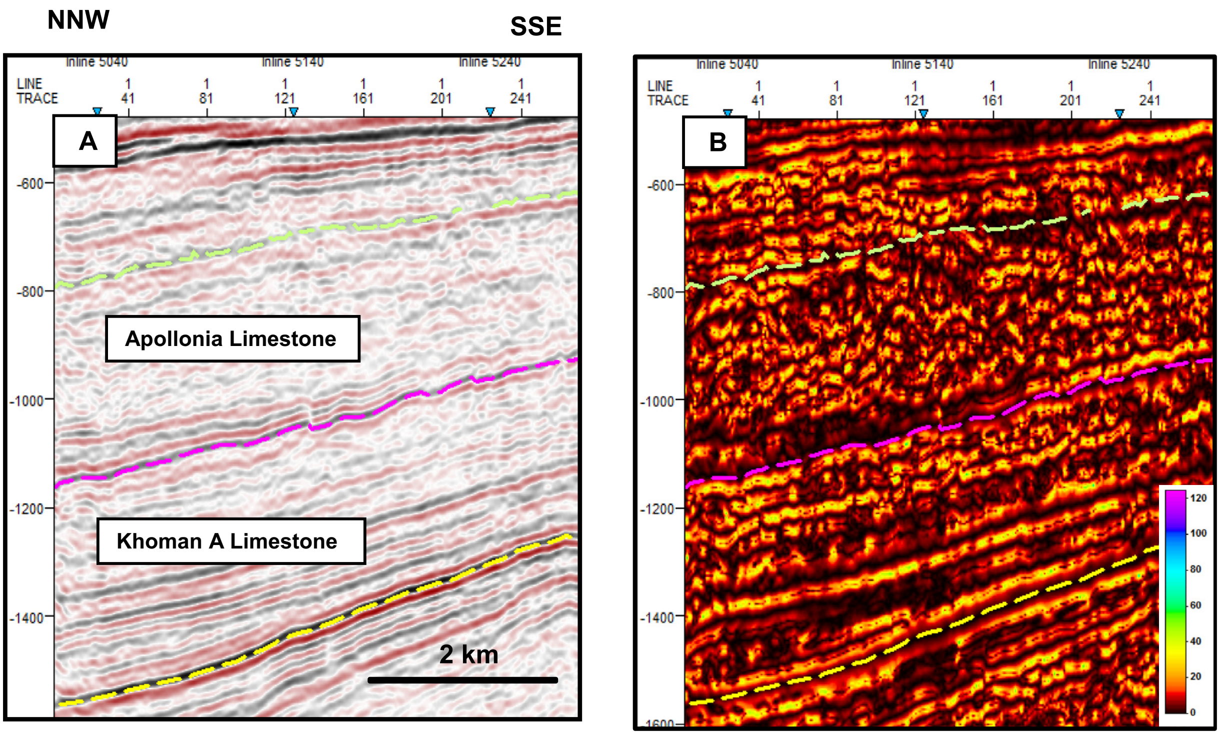

Fig. 15. (A) Original seismic section (Xline1490) and (B) instantaneous bandwidth output.

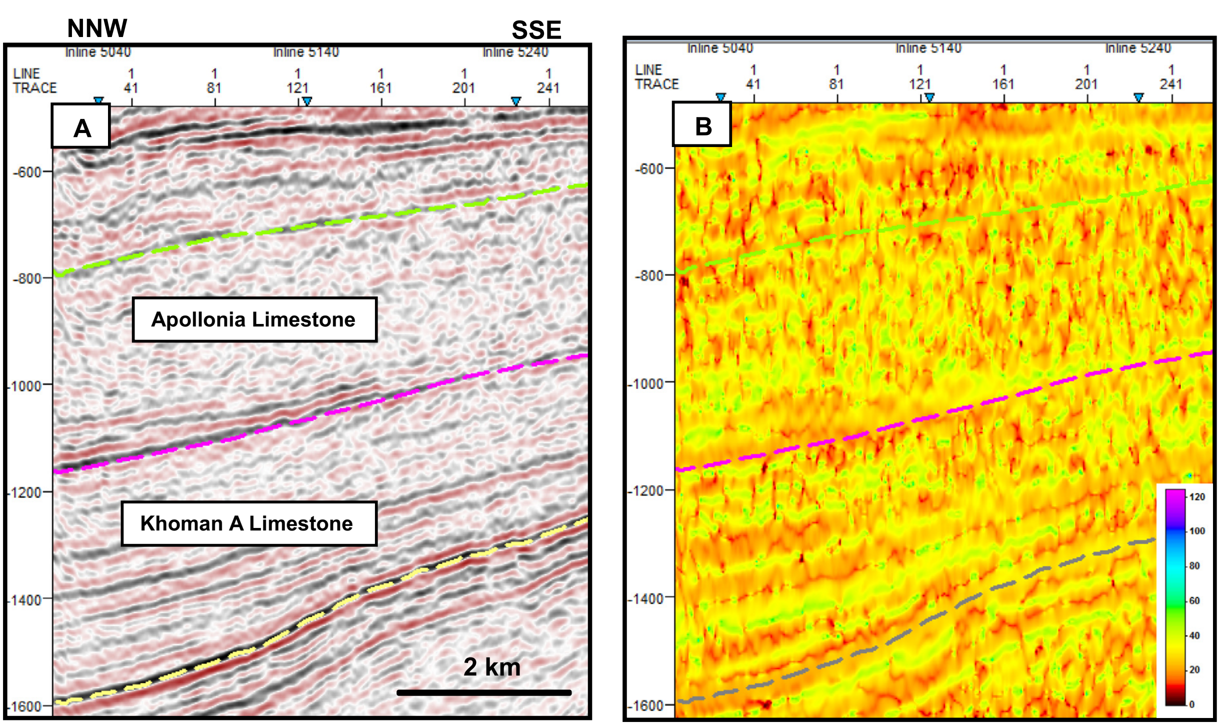

Fig. 16. (A) Original seismic line (Xline1590) and (B) correspondent dominant frequency attribute.

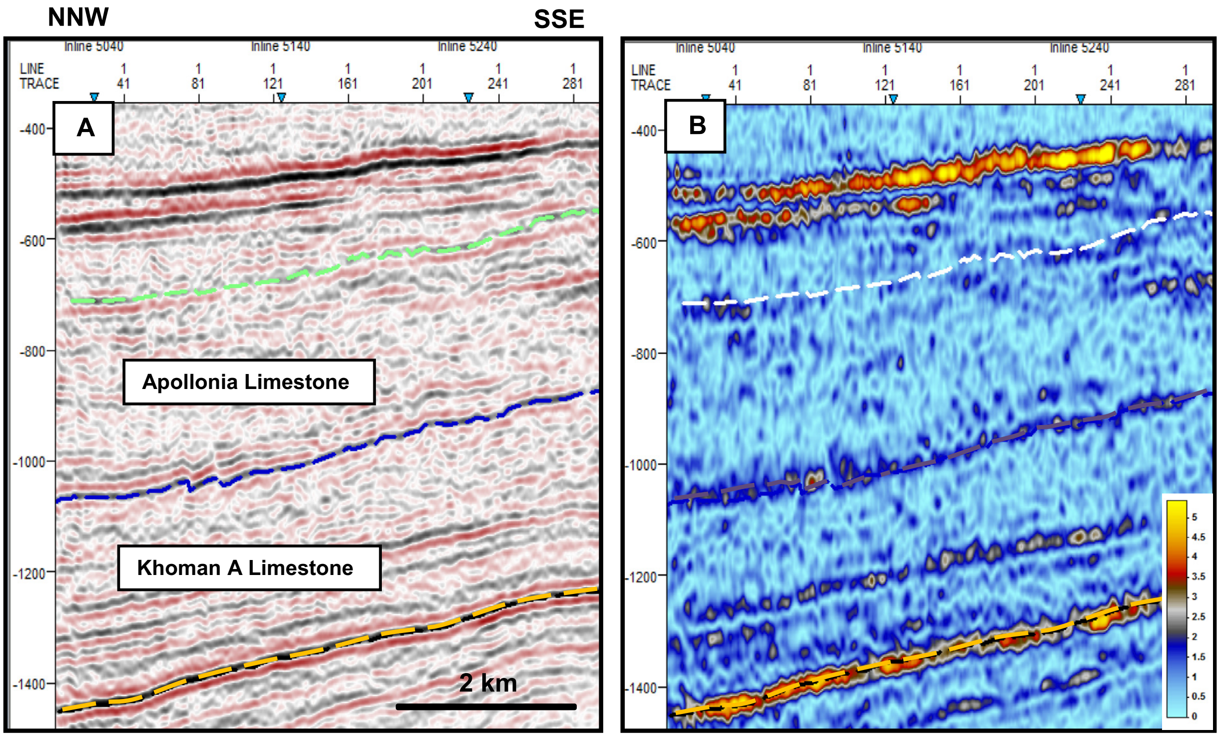

Fig. 17. (A) Original seismic data (Xline1190) and (B) extracted envelope attribute.

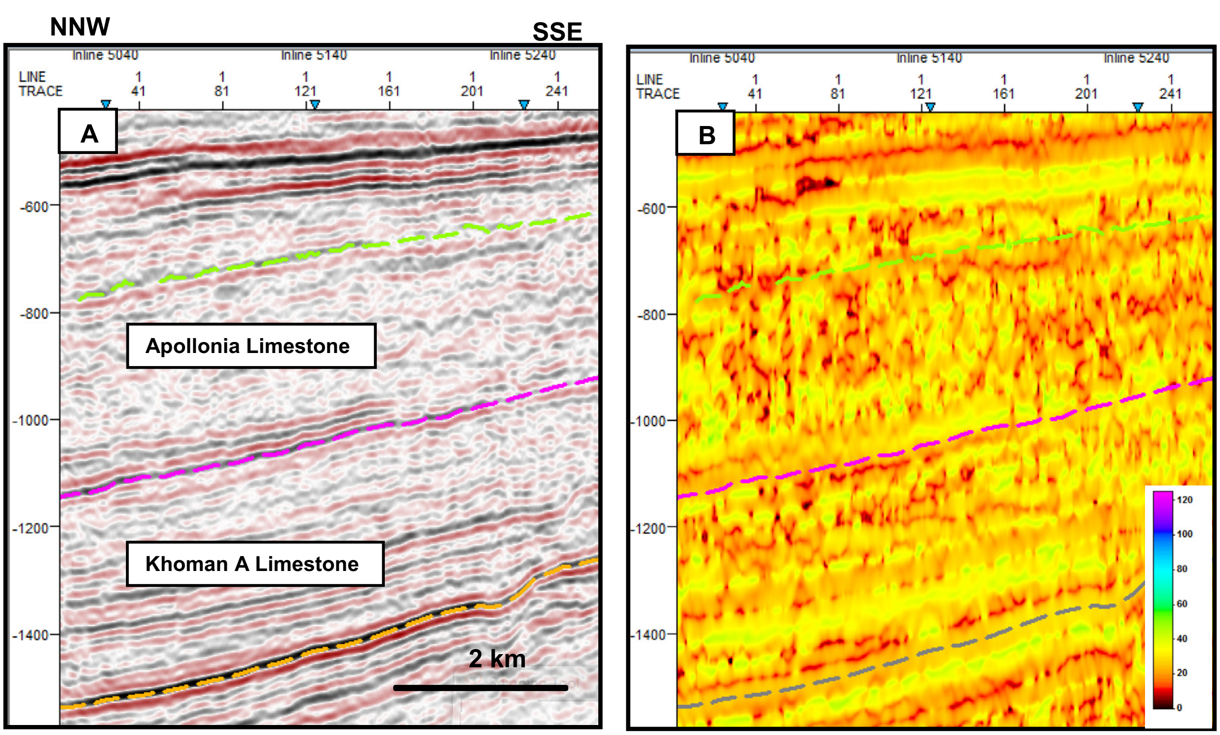

Fig. 18. (A) Original seismic line (Xline1390) and (B) correspondent instantaneous frequency seismic attribute.

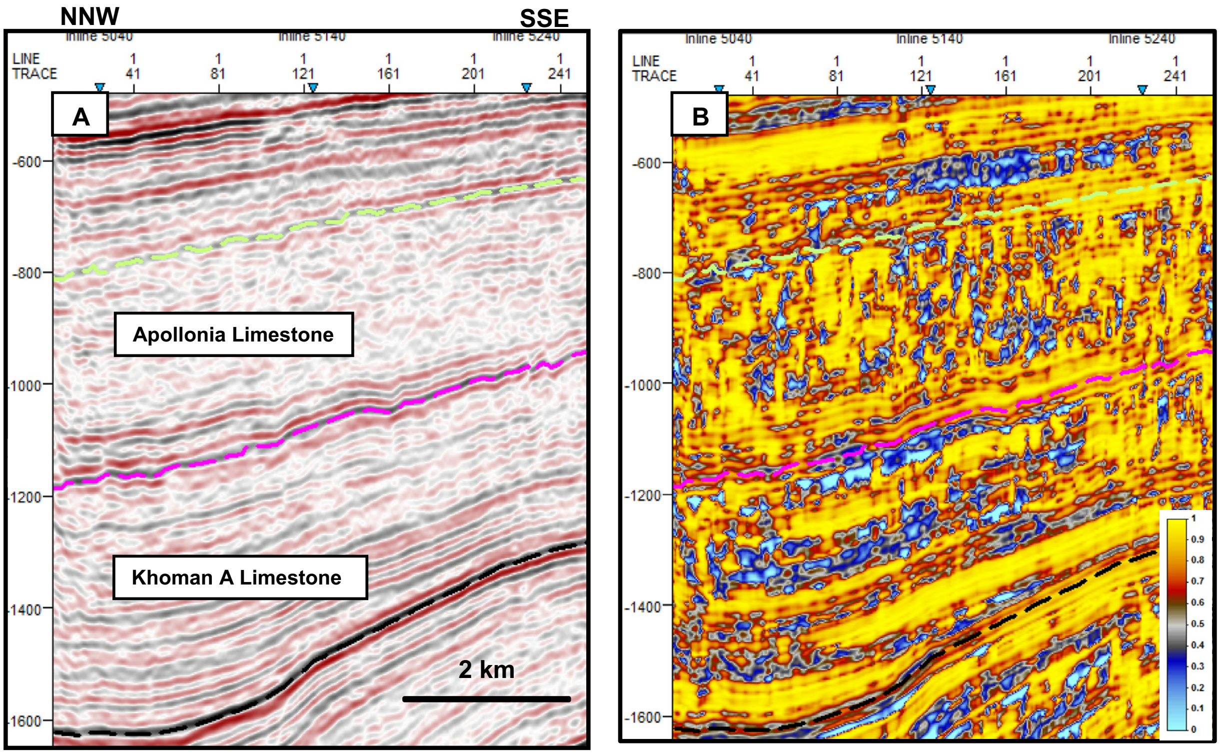

Fig. 19. (A) Seismic section (Xline1790) displayed as original and (B) corresponding iso-frequency seismic attribute.

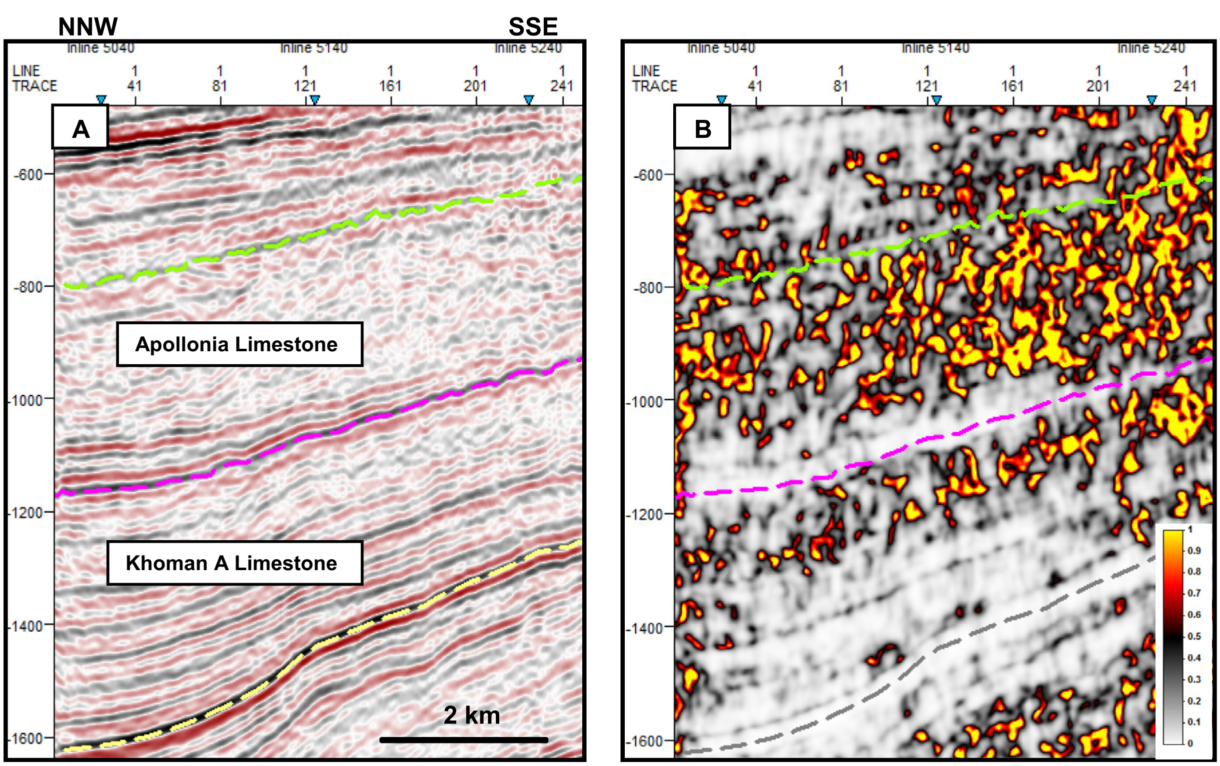

Fig. 20. (A) Original seismic line (Xline1690) and (B) correspondent chaos attribute.

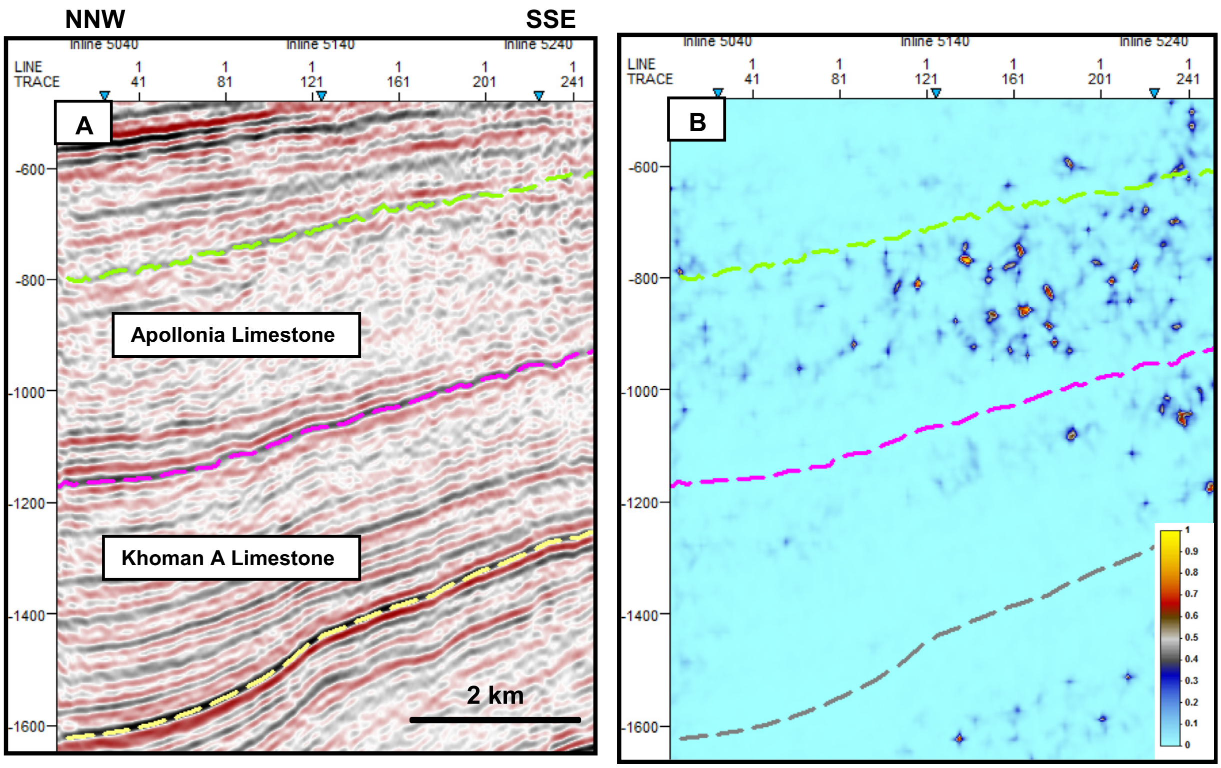

Fig. 21. (A) Seismic section (Xline1690) displayed as original and (B) corresponding Local flatness seismic attribute.

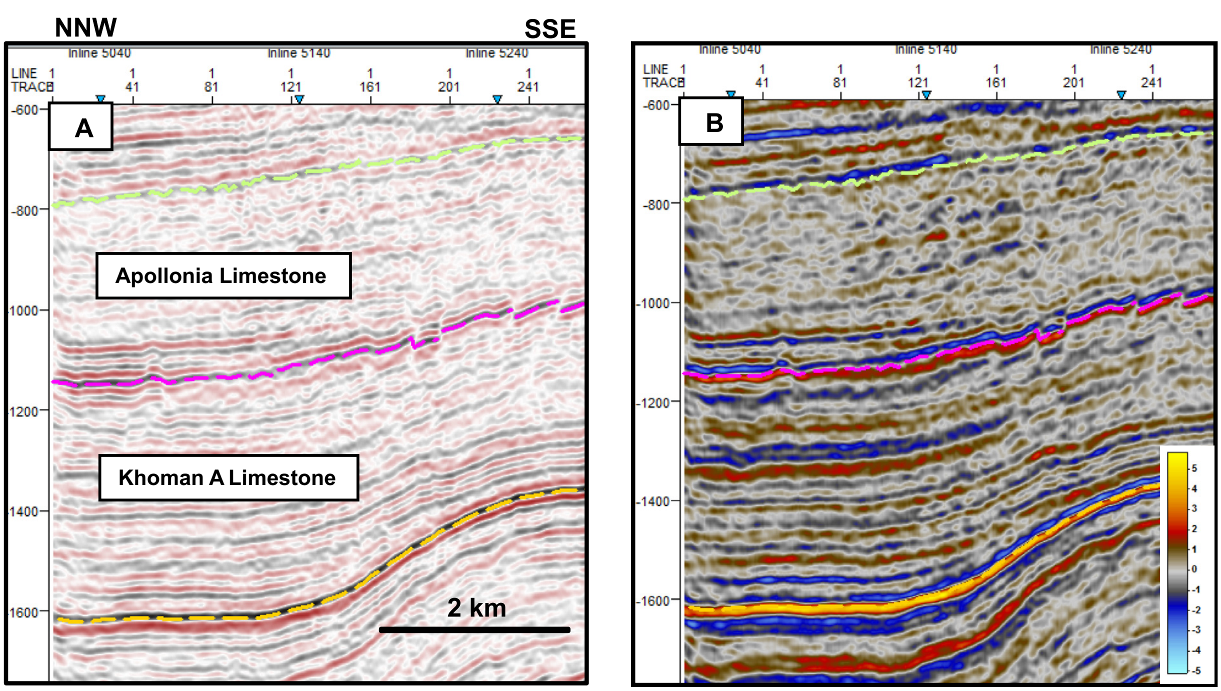

Fig. 22. (A) Original seismic line (Xline1890) and (B) corresponding relative acoustic impedance seismic attribute.

the gray color all over the seismic section (Fig. 22). This matches the findings of Azevedo and Pereira (2009) who considered the effect of porosity and the presence of fluid content inside a hydrocarbon reservoir are reasons led to contrast of relative acoustic impedance attribute between two units.

4. Conclusions

This study examines the possibility and the efficiency in applying different seismic attributes to distinguish the massive from the non-massive (porous) carbonate sequences on seismic sections.

The importance of this examination is to specify which of the investigated carbonate sequences may be porous to be able to hold potential fluids (hydrocarbon) within the pores before the drilling process. The results from this work have defined the optimum seismic attributes which give good contrast between massive and non-massive limestone bodies.

A case study from the Upper Cretaceous – Eocene carbonate successions in Abu Gharadig Basin in the northern Western Desert of Egypt has been used for this purpose. The Upper Cretaceous Khoman A Member represents the massive carbonate sequence and the Eocene Apollonia Formation displays the non-massive carbonate unit. Although both Khoman A and the Apollonia carbonates contain fractures, the fractures are only opened in the Apollonia limestone and filled with calcite crystals in Khoman A unit (Kassab et al., 2013). These fractures attributed to the effect of the compressional tectonic inversion in the Upper Cretaceous – Tertiary period which was followed by the rifting phase in the Miocene time (Moustafa, 2008). The qualitative interpretation of the available well-logging data in addition to many previous published works has confirmed the presence of pores (open fractures in this case) within the limestone of Apollonia Formation and the absence of pores (closed fractures) within the entire carbonate of the Khoman A Member.

The results of the present work define the most promising seismic attributes which successfully discriminated the massive (non-porous) limestone from the non-massive (porous) carbonate sequences. The best seismic attributes which display notable contrast (described by very good response in Table 1) between the massive and the non-massive carbonate units include; RMS Amplitude, Envelope (Reflection Strength), Instantaneous Frequency, Chaos, Local Flatness and Relative Acoustic Impedance. This work is highly recommend the application of the former seismic attributes on several massive and non-massive carbonate sections in different study areas to measure their efficiency in distinguishing the massive and non-massive carbonate sequences on seismic data.

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