AMPLITUDE VARIATION WITH OFFSET APPLICATION HISTORY IN MIDDLE EAST AND NORTH AFRICAN BASINS

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ABSTRACT

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The assumption behind Amplitude Variation with Offset (AVO) concept is that amplitude changes (either decrease or increase) with offset can be related to rock physical properties and pore-fluid content. The technique has been widely deployed in the Gulf of Mexico, and has proved to be an excellent indicator of hydrocarbons and lithology. Over the past 40 years, several studies have shown that AVO responses of gas sands differ by geologic setting. These responses have been observed in many locations around the globe, some in basins similar to the Mexican Gulf such as the North Sea, South Canada, but others are in different geological settings than the Gulf setting. In this study we review some examples from North African and Middle Eastern basins. We discuss the occurrence of AVO anomalies and the successful application of the technique for detecting and delineating hydrocarbon reservoirs. Furthermore, we illustrate case studies where the technique was used for carbonate and naturally fractured reservoirs exploration and characterization. The case histories illustrated in the study demonstrate that AVO technique is applicable in different geological settings and environments including old and deep sand reservoirs in North Africa and the Middle East. Once calibrated to the local geology, AVO can perform well even in geological conditions that differ from the Gulf of Mexico where the technique was first developed and successfully implemented.

KEY WORDS: AVO anomaly, hydrocarbons reservoir, Gulf of Mexico, North Africa, Middle East.

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INTRODUCTION

The concept behind Amplitude Variation with Offset (AVO) assumes that amplitude changes with respect to offset or angle are related to rock physical properties and pore-fluid content (Ostrander, 1984). The AVO theory was first developed by Ostrander (1984), who demonstrated that seismic expressions of hydrocarbon-bearing sands vary in anomalous fashion with increasing offset; and this variation can be directly related to the change in Poisson's ratio (σ) or to the ratio of P-wave to S-wave velocity (V_P/V_S). Later, Rutherford and William (1989) demonstrated that AVO responses of gas sands differ by geologic setting. The authors have classified AVO amplitude anomalies based on their geologic settings into three classes Class I, II and III. With addition of Class IV AVO setting by Castagna et al. (1998), essentially all geologic settings were accounted for in clastic environments (Roden et al., 2014). Fig. 1 shows the different AVO classes' amplitude variation with offsets. From shallow, and young to deep, and old

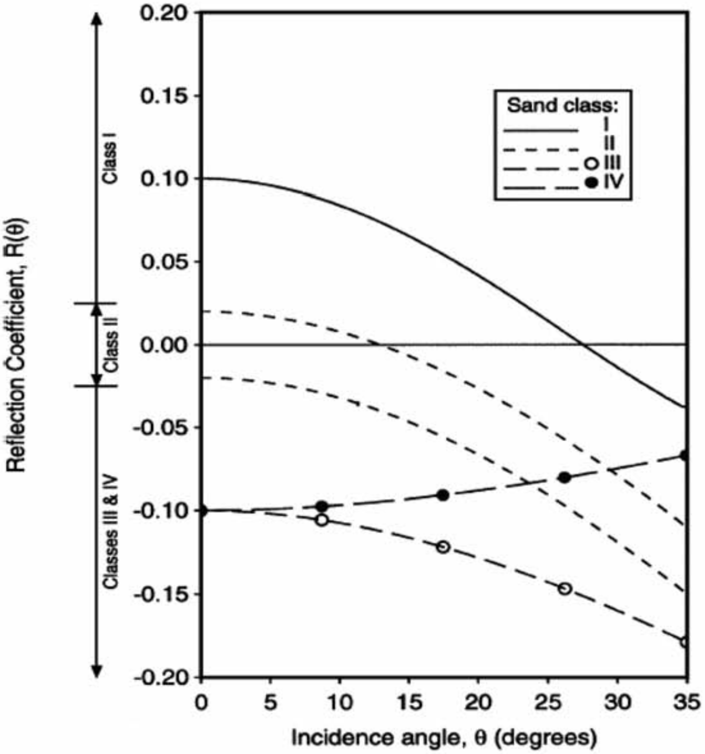

Fig. 1. Plan wave reflection coefficient at the top of each gas sand according to Williams and Rutherford (1984) classification. Class IV is added by Castagna et al. (1998).

formations one can start by AVO Class III gas sands. This class is the first and best known among all classes. It involves unconsolidated sands with porosities greater than 25%, usually Tertiary in age. They are characterized by a gross interval velocity that is usually less than 2,650 m/sec (Roden et al., 2005). Gas and oil zones associated with Class III appear as bright spots on stack section and offset or angle stacks (Fig. 2). Initially, Class III targets were exclusively identified offshore; however, as a result of improved seismic data quality, they are more frequently observed onshore (Roden et al., 2005). Class IV gas sands share the same characteristics as Class III, except that their reflection amplitude decreases with increasing offset because they are overlain by harder shale, silt or carbonate formations with higher shear velocity (Castagna et al., 1998).

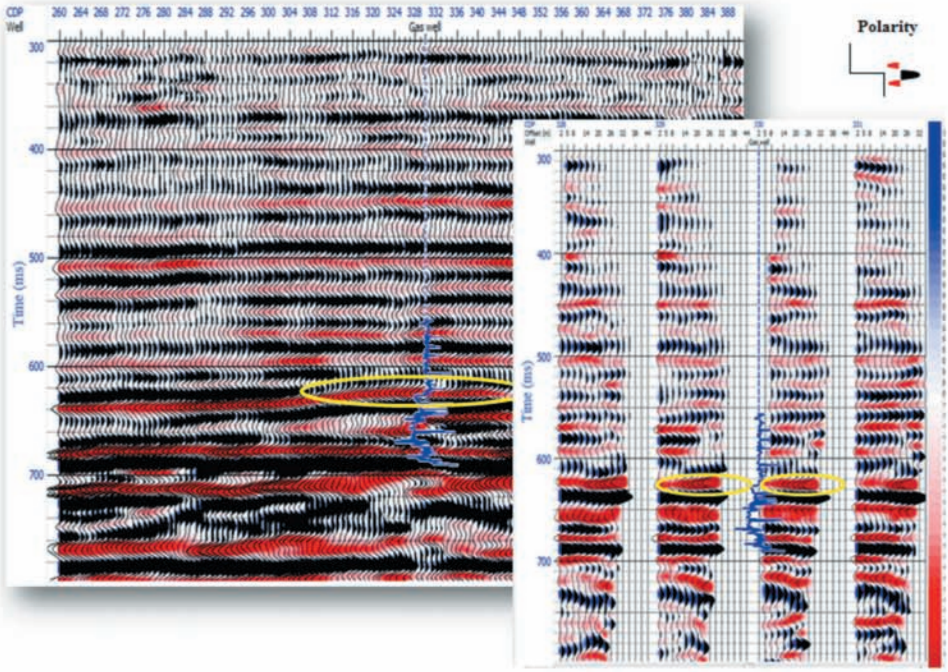

Fig. 2. Stack section showing typical bright spot associated with gas-bearing sand reservoir of tertiary age from a shallow gas field in central Alberta, Canada. Clear negative amplitude anomaly (read) at 650 ms followed by strong positive peak. Gathers at the well location shows anomalous amplitude changes. Peaks indicate increase in impedance while troughs show impedance decrease.

AVO Class II gas sands are moderately consolidated sand generally, have porosities of 15% to 25%. Their gross interval velocities are found in range of 2,650 m/sec to 3,650 m/sec (Roden et al., 2005). The acoustic impedances of these gas sands and encasing shale are approximately equal. AVO response is strongly negative with increasing offset distance or angle (Rutherford and William, 1989).

The last type is AVO Class I gas sands. These gas sands are consolidated, and have generally porosities of less than 15%. They have gross interval velocities that are usually greater than 3,650 m/sec. On stack seismic data, large positive amplitude for a wet sand decreases to a smaller positive amplitude for a gas sand. Class I reservoirs are usually identified onshore in old and compacted rock settings, e.g., Mesozoic and Paleozoic rocks (Roden et al., 2005, 2014).

From the literature, these AVO anomalies are seen in the Sacramento Valley (Gabay, 1990), Louisiana (Hoopes and Aber, 1989), southern Texas (Burnett, 1990), the North Sea (Snyder et al., 1989; Strudley, 1990), the Arabian Gulf (Chiburis et al., 1993; Castagna and Backus, 1993), Alaska (Zimmerman and Fahmy, 1990), and Italy (Mazzotti, 1990). Other AVO anomalies have also been observed in North Africa (Dalla et al., 1997; Wigger at al., 1997; Bellili et al., 2002; Kassouri and Djaffer, 2003; Marten et al., 2004). These successful case studies prove that the technique is applicable worldwide.

AVO technology was initially developed and successfully implemented for hydrocarbon detection in isotropic media; however, with the advent of seismic technologies, anisotropy has received a great degree of consideration (Russell, 2014). Significant effort has been made to study amplitude changes with respect to azimuthally anisotropic variations in both carbonate and clastic reservoirs (Al-Shuhail, 2004; Neves et al., 2004; Chopra and Castagna, 2014; Russell, 2014).

In this study we review some successful applications and case histories of the AVO technique in North Africa and the Arabian Peninsula. Some interesting old and recent examples are highlighted.

AVO analysis and inversion for hydrocarbon detection and reservoir characterization

Since the publication of the Zoeppritz equations' approximations, attentions have been drawn to exploit these simplified forms to analyze prestack data in order to recognize AVO signatures and classes. Some of these approximations (e.g., Aki and Richards, 1980; Shuey,1985; Fatti et al., 1994) have been used to predict AVO expressions associated with reservoir rocks, and to tie synthetic to recorded seismic gathers (AVO modeling). This has significantly contributed to seismic data acquisition design, as well as to prestack seismic data processing and interpretation (Li et al., 2007). Fig. 3

illustrates AVO gradient analysis performed to real and synthetic data. The synthetic data is generated using Aki and Richard (1980) approximation. Other approximations (e.g., Fatti et al., 1994; Connolly, 1999) were used to invert the seismic prestack data for V_P,V_S and density data (AVO inversion).

Geophysicists divide AVO-related approaches into seismic reflectivity-based methods and impedance-based methods (Russell, 2014). Reflectivity methods include for example, near and far-offset stacks, intercept versus gradient analysis, and fluid factor. These methods are qualitative and are commonly performed on both real and synthetic data. Impedance based methods are more advanced and quantitative. The latter methods involve: P- and S-impedance inversion (Hampson et al., 2005), Lambda-Mu-Rho (Goodway et al., 1997), Elastic impedance and Poisson impedance (Connolly, 1999). This rich variety of sub-techniques has made the AVO a popular technique with applicability to many different basins worldwide.

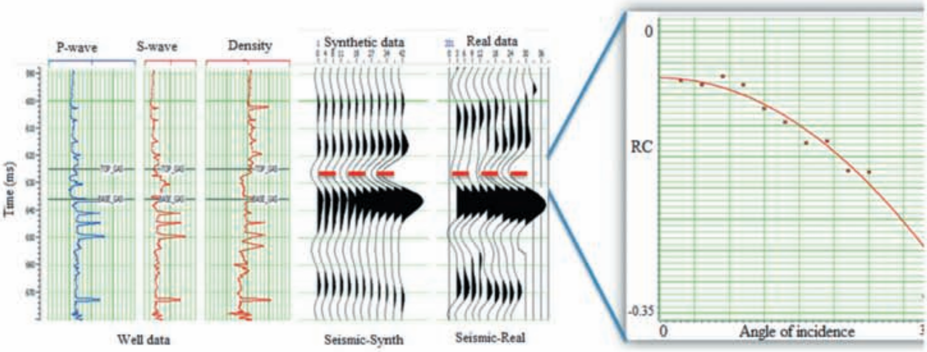

Fig. 3. Real prestack gather along with a synthetic gather calculated from well data (P-wave, S-wave and density logs) using Aki-Richard approximation. Negative amplitude is observed at zero angles (intercept) which increases in magnitude with angle (AVO class III) on both data. The target is gas-sand reservoir of tertiary age from Alberta, Canada.

AVO responses variation with depth and age of rocks

AVO classes are mainly defined by their intercept or seismic amplitude at normal incidence recorded at the top of the hydrocarbon charged formations (Hilterman, 2001). With continued deposition, the compaction of sand and shale causes acoustic impedances to increase with depth and age; however these impedances normally increase at different rates (Avseth et al., 2003). For young and shallow clastic rocks, sands typically have lower impedance than shale; but for older and deeper clastic rocks, sands have higher impedance than shale (Brown, 2010). While Class I and Class II sands are characterized by their higher impedance relative to their encasing shale, Class III and Class IV sands exhibit lower impedance compared to their embedding shale formations. Fig. 4 displays the intercept change as a result of formation depth. It is important to note that the presence of hydrocarbons in shallow formations can result in a substantial decrease in impedance (Chopra and Castagna, 2014). In fact, with the introduction of the gas into the pores, the rock experiences a reduction in bulk density and velocity. However, this is not the case in deep formations where consolidation can mask all expressions produced by fluid saturating the targeted sandstones. The deposition of the sandstones to very deep interval is commonly followed by increase in clay content that occludes porosity, reduce permeability, and increase velocity (Roden et al., 2014). As a result, their matrix compaction dominates their seismic response, making it more difficult to observe reflection characters caused by pore fluid changes (Chopra and Castagna, 2014). Thus, there is no wonder that one can find different AVO anomalies with different contrasts in impedance from target depth to another within the same field (Avseth et al., 2003).

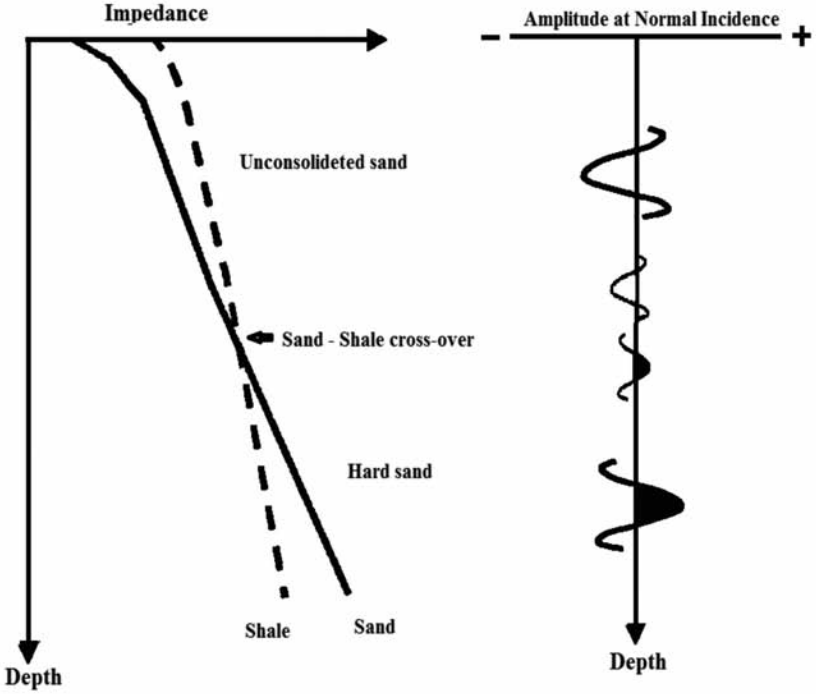

Fig. 4. Schematic depth trends of sand and shale impedances. Seismic amplitude changes in magnitude and polarity as we go from shallow and soft sands to the deep and hard sands. The depth trends can vary from basin to basin (Modified after Avseth et al., 2005).

AVO applications for fractured reservoir characterization

Fractures are defined as cracks in rocks that typically have apertures of a few millimeters or less. They usually show little or no displacement along their faces. As fractures are so much smaller than seismic waves, which typically have a wavelength of tens of meters, the seismic methods are only capable of detecting the cumulative effect of swarms of aligned fractures which must be close to vertical. Fortunately, these conditions frequently exist in fractured reservoirs (Gray, 2008). In such reservoirs, natural fractures often control reservoir permeability (fluid mobility) and porosity (storage); therefore knowledge of their location, orientation, density and connectivity is essential for optimized hydrocarbon production. Seismically, fractures can be manifested in the azimuthal variations of velocity, travel time, frequency content of seismic traces, and AVO. In fact, vertically aligned compliant (gas-filled) fractures in a reservoir will decrease the interval P-wave velocity for waves traveling normal to the fractures. In contrast, P-waves propagating parallel to the fractures are relatively insensitive to their existence and their filling components. Therefore, one should expect to observe distinct variations in AVO gradients parallel or normal to fracture orientation, a phenomena known as amplitude variation with offset and azimuth (AVOA)) (Ruger and Tsvankin, 1997; Russell, 2014). Identifying these signatures can allow geoscientist to detect and characterize fractures in subsurface formations.

AVO EXPRESSIONS IN OLD AND COMPACT RESERVOIR ROCKS OF NORTH AFRICA

Several case studies from North Africa have documented the use of amplitude change as an indicator of gas sands (Dalla et al., 1997; Wigger et al., 1997; Roberts et al., 2005; Bellili et al., 2002; Kassouri and Djaffer, 2003). In several Algerian fields, most of the encountered hydrocarbon reservoirs are highly consolidated, Mesozoic to Paleozoic-aged formations (Echikh, 2003). AVO Class I anomalies have been observed in Lower Devonian gas reservoir of Illizi basin, southeastern Algeria. The targeted zone was deep, thin, and high impedance sandstone. Petrophysical study followed by AVO attributes analysis and inversion led to a successful drilling in the area (Chegrouche et al., 2013; Farfour et al., 2013). Bellili et al., (2002) have also observed AVO Class I "dim spot" anomaly occurred in an Emsian (Lower Devonian) gas reservoir of the Ahnet-Timimoun Basin as well as in a relatively younger reservoir (Carboniferous in age) in Hassi Rmel gas field, Algeria. Some Paleozoic intracratonic basins (e.g., Mouydir-Oued Mya, and Sbaa, Algeria) that have similar regional geology and same primary reservoirs (Devonian sandstones) may also show similar anomalies (Echikh, 2003). The successful application of AVO has also been documented in other Cambro-Ordovician and Carboniferous gas-charged sandstone formations in several known Algerian fields (Fig. 5) including

Allal dome (Bellahcene and Mouggari, 2003), Ain-Saleh and Sbaa fields (Bellili et al., 2002; Kassouri and Djaffer, 2003). In contrast to other AVO classes, Class I sands are found to be the most challenging to identify because they do not yield bright spots or noticeable change in amplitude with offset (Hilterman et al., 2000). They rather show amplitude decrease that may fall below the noise level at far offset (Chopra and Castagna, 2014). For these cases, AVO attributes computation is often followed by more thorough AVO analysis where V_P/V_S and Poisson's ratio are incorporated (Hilterman, 2001). In addition, the knowledge of the local geology is critical.

Fig. 5. Some Algerian fields where AVO was successfully implemented (Modified after Hassaim and Bellahcene 2005). The fields belong to Illizi basin (Bellili et al., 2002, Bellahcen and Mouggari, 2003), Sbaa basin, Ahnet basin (Bellili et al., 2002, Kassouri and Djaffer, 2003).

Substitution modeling accounting for mineralogy, clay content, porosity, cementation, fluid properties, pressure, depth, and compaction must all be considered (Roden et al., 2014).

In the offshore Nile Delta the observed anomalies are different. Successful applications of AVO have resulted in several new and important discoveries (Dalla et al., 1997; Wigger et al., 1997; Roberts et al., 2005; Leveille et al., 2007). Interesting AVO anomalies have been identified in the shallow, young, and unconsolidated rocks of several fields (e.g., Abu Sir and AlBahig (Roberts et al., 2005), Abu Madi (Dalla et al., 1997), Ha'apy (Wigger et al., 1997), and Scarab (Mohammed et al., 2014). These conditions with the high porosity of sands are ideal for geological formations to express their fluid content response in seismic images. Bright spots associated with gas, and flat spots associated with gas-water contact (GWC) are common in the fields of these basins (Dalla et al., 1997; Roberts, 2005).

However, in one of the above fields (Ha'apy), a challenging AVO anomaly with Class I characteristics has been observed in Tertiary rocks of deeper formations with AVO class III anomalies were observed in the reservoirs immediately above (Wingger et al., 1997; Marten et al., 2004). Rock property analysis of the pre-Pliocene aged sediments indicated that these Class I sands have higher acoustic impedance relative to shale at zero-offset, and remain hard at far-offsets (Marten et al., 2004). The primary production interval in these fields was from Miocene-aged reservoirs at depths ranging from 3500 to 4500 m. In fact, despite their young age (Tertiary), their burial at deeper intervals has resulted in significant increase in impedance compared to their surroundings (Marten et al., 2004).

DETECTION OF HYDROCARBONS IN MIDDLE EAST CLASTIC AND CARBONATE RESERVOIRS USING AVO

Clastics

AVO anomalies due to hydrocarbons have been recognized in Middle East basins since the 1980s in the pioneering work of Chiburis (1984 and 1987) who developed a special AVO analysis technique to estimate amplitude variations associated with hydrocarbons. The technique could successfully predict the presence and distribution of hydrocarbons in 26 out of 27 cases confirmed by successful drillings in central and eastern Saudi Arabia as well as in the Arabian Gulf (Chiburis et al., 1993). Note that these successful cases are from different fields onshore and offshore. Offshore areas were found in the Arabian Gulf at depths greater than 2000 m while onshore targets were at depths exceeding 4000 m (Castagna and Backus, 1993).

Following the classification of Rutherford and Williams (1989), most AVO anomalies identified by Chiburis (1984, 1987) were characterized by negative amplitudes that either decreased in magnitude (Class IV) or increased (Class II and III) with offset. Over the last decade, different modern AVO analysis and inversion techniques have been successfully tested in the region (Neves et al., 2004; Rahati et al., 2011; Daghistani, et al., 2012; Hu et al., 2013; Almustafa and Giroldi, 2010, 2013). AVO inversions have confirmed the presence of the AVO anomalies and their classifications, and have shown that gas sands in many of these fields are characterized by their low impedance compared to their surrounding rocks (e.g., the Permo-Carboniferous fluvial-aeolian Unayzah sandstones and shallow marine shelf sandstones of the Devonian Jauf) (Sorkhabi, 2010). Note that Unayzah formation belongs to very widespread prospective sandstones that can be encountered in central and eastern Saudi Arabia, Qatar, the United Arab Emirates, and Oman.

Despite their significant age (mostly Mesozoic to Paleozoic) and significant deep burial (3000 to 5000 m), gas sands in these areas commonly show AVO class III and Class IV anomalies. A shared characteristic of most Class III and IV reservoirs is their high porosity (Al-Mustafa and Giroldi, 2010, 2013) which makes their seismic responses directly reflect their pore fluid contents (Roden et al., 2014). It was indeed the presence of numerous porous zones, in conjunction with large subtle closures and obvious richness of source materials that made the Arabian Peninsula so unique in terms of the discovery of large petroleum reserves.

Carbonates

Carbonates are the most difficult lithology for applying quantitative seismic analysis techniques. Their rapid lateral variations in porosity and permeability, which are mainly controlled by changes in depositional facies and diagenesis, pose always challenges for geophysicists (Tsuneyama et al., 2003). Historically, one of the first applications of AVO was to search for carbonate reservoirs in the Middle East. In fact, AVO has led to several giant hydrocarbons discoveries in carbonate formations of the region (Chubiris 1984, 1987 and Castagna and Backus, 1993).

In the past few decades, increased understanding of the physical properties of carbonate rocks, has led to adjusted AVO techniques for the identification of new carbonate reservoirs (Li et al., 2003). Interestingly, the dolomitization processes appears to help the fracturing of carbonate rocks, such that their behaviors due to gas saturation is similar to that of sandstones. Namely, P-wave velocities and the V_P/V_S ratio decrease, while S-wave velocities increase slightly as a result of decreased density, but with less sensitivity to fluid than is observed for limestone (Li et al., 2003).

Recently, several published studies have also revealed the successful use of AVO analysis and inversion in Middle Eastern carbonate fields. AVO inversions were successfully tested on carbonate reservoirs, offshore Abu Dhabi to estimate fluid effect and reservoir porosity (Tsuneyama et al., 2003; Ikawa et al., 2008; Ishiyama et al., 2010). Promising results have also been obtained from the Upper Jurassic Arab D formation, the most prolific carbonate reservoir in eastern Saudi Arabia, and from the Permian Khuff in the Uthmaniyah sector of the Ghawar field (Dasgupta et al., 2001; Keho et al., 2009; Macrides and Dey, 2010; AlMuhaidib, 2012) (Fig. 6). It is worth noting that Arab (A, B, C, and D) carbonate reservoirs are widely distributed in the area, extending from Saudi Arabia through Bahrain, and from Qatar to offshore Abu Dhabi.

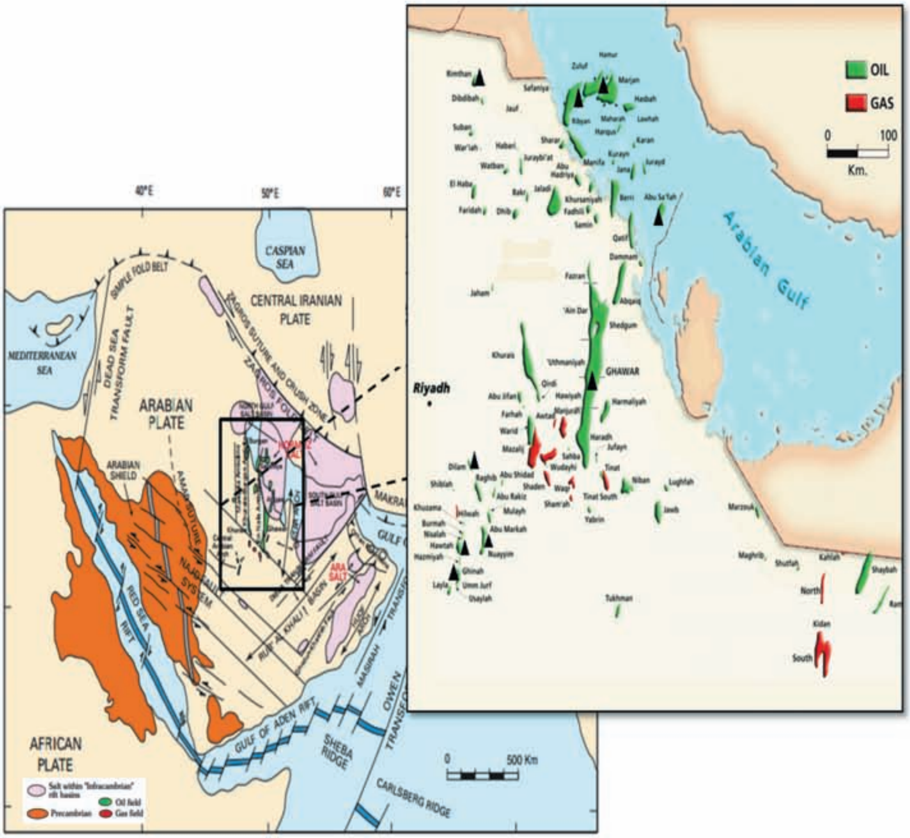

Fig. 6. Examples of Saudi fields where AVO was successfully utilized to detect potential hydrocarbon reservoirs. Anomalies were observed in the giant Ghawar field (Chiburis et al., 1993) in the eastern and other northern and southern fields (Neves et al., 2004, Hu et al., 2013, Al-Mustapha and Giroldi, 2010, 2013).

AVO IN STUDYING NATURALLY FRACTURED RESERVOIRS IN NORTH AFRICA AND THE MIDDLE EAST

Several studies have highlighted successful uses of the AVOA in Egypt, Algeria and Tunisia (e.g., Sousa, 1996; Tod et al., 2007; Davison et al., 2011; etc.). Over the last decade, AVOA has also been widely used and successfully employed in the Middle East; for example, Unayzah tight gas sands of Ghawar Field are extensively studied fractured zones in Saudi Arabia. Theses sands are typical for their great depth, tightness and anisotropy. In such reservoirs to recover greater amounts of production, horizontal wells should be drilled through a maximum number of open fractures. AVOA was a key tool in achieving this objective in Neves et al., (2004), Al-Hawas et al. (2003), Al-Marzoug et al. (2006), among many others. Interestingly, the technique has been successful and work very well even for fractured carbonate reservoir detection and characterization in the region; for example the Arab D and Hanifa carbonate reservoirs of Saudi Arabia (Al-Dajani, 2008), and the offshore reservoirs of Abu Dhabi (Roberts et al., 2001 ; Liu et al., 2010). Fig. 7, for example, shows the results of AVOA analysis of prestack seismic data over the Unayzah sandstone of Saudi Arabia (Table 1). The results agree with well-log data, and show East-West trending fractures in this reservoir.

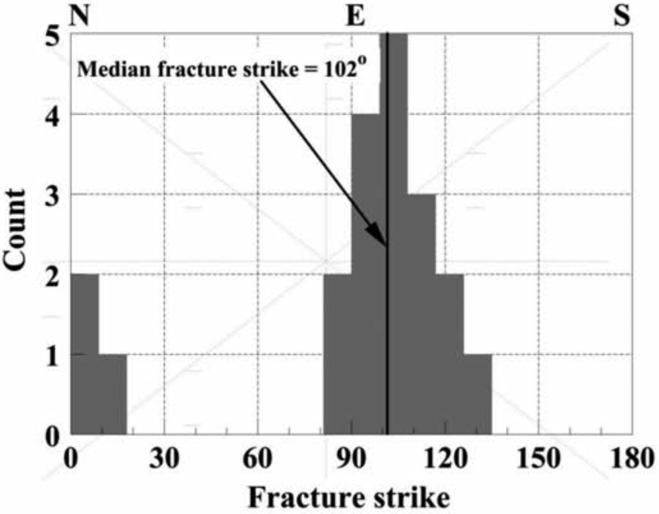

Fig. 7. Fracture orientation defined using the method of Al-Shuhail (2004). This analysis shows that the median AVOA fracture orientation has a strike of 102° (solid vertical line), which agrees with well-log data that show generally East-West-trending fractures in this area.

Table 1. AVOA data reported by Neves et al. (2004) along six azimuths in the Unayzah sandstone of Saudi Arabia.

Azimuth range	Measured AVO intercept	Measured AVO gradient
0-30	-0.1163	-0.0980
30-60	-0.3730	-0.0069
60-90	-0.4152	+0.0093
90-120	-0.4394	+0.0117
120-150	-0.2903	-0.0152
150-180	-0.2162	-0.0637

DISCUSSION AND CONCLUSIONS

AVO has grown from a bright spot detection technique to include a multitude of sub-techniques, each with their own assumptions. Old techniques are based on the analysis and computation of seismic reflection coefficient series. More recent techniques are based on the inversion of prestack gathers and analysis of some type of seismic impedance. All the techniques use Zoeppritz equations and their approximations to relate seismic responses changes with respect to offsets and physical properties.

Geophysicists classify AVO responses of hydrocarbon-charged reservoirs to well defined classes to ease their recognition and interpretation. Tables 2 and 3 summarize some AVO anomalies identified in North African and Middle Eastern basins. The anomalies are compared with their equivalent from the Gulf of Mexico. The tables show that some of reservoirs exhibit seismic responses similar to those of the Gulf of Mexico; however, there are other reservoirs with AVO anomalies that have a different geology.

The major factors controlling seismic response of hydrocarbon-bearing formations are their lithology (e.g., sand, shale or carbonate), porosity, fluid content, depth and age of the rock. However, experience showed that for both clastic and carbonate rocks, the petrophysical properties of the reservoir are the primary drivers of AVO phenomena, with geological conditions (e.g., age, depth) representing only indirectly contributing factors. This has been clearly seen in Saudi Arabian reservoirs where old formations (Jurassic to Devonian) show AVO anomalies that are more typical of young and shallow rocks elsewhere due mainly to their high porosity which reaches 25% at 3000 to 5000 m in depth. Changes of compaction rate of sand-shale successions with depth can result in different AVO anomalies with different polarity within the same field.

Table 2. AVO anomalies and their relevant conditions from G.O.M.

Basin	Shallow	Deep	Porosity	Age	Onshore	offshore	AVO class
G.O.M (Roden et al., 2005)		+	<15%	Paleozoic	+		I
	+		15% to 20%	Tertiary	+		II
	+		> 25%	Tertiary		+	III
North Africa (Dalla et al., 1997; Bellili et al., 2002; Marten et al., 2004)	+		<15%	Tertiary		+	I
		+	<15%	Paleozoic	+		I
		+	<15%	Mesozoic	+		I
		+	<15%	Paleozoic	+		II
	+		> 25%	Tertiary		+	III

Table 3. AVO anomalies with geologic settings from G.O.M and from the Middle East.

Basin	Shallow	Deep	Porosity	Age	Offshore	Onshore	AVO class
G.O.M (Roden et al., 2005)	+		> 25%	Tertiary	+		III, IV
		+	> 15%	Mesozoic			II
Middle East (Hu et al., 2013; Al-Mustafa and Giroldi, 2010, 2013)		+	> 20%	Mesozoic	+		III, IV

The case studies highlighted in this study show that AVO technique is applicable across many different geological settings and environments including consolidated and deep reservoirs in North Africa and Middle East.

Once calibrated to the local geology, the AVO technique can lead to successful detection and characterization of hydrocarbon-charged sediments. It is important, however, to note that despite its success, AVO has also led to numerous dry holes in basins around the world (e.g., Gulf of Mexico, the North Sea). To increase confidence and understand uncertainties involved in AVO interpretations, exploration companies perform risk assessment analyses to properly evaluate prospects in their drilling portfolio.

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