Identification of polygonal faulting from legacy 3D seismic data in vintage Gulf of Mexico data using seismic attributes

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Abstract

We have analyzed a 1991 3D seismic data set located offshore Florida and applied seismic attribute analysis to identify geologic structures. Initially, the seismic data appear to have a high signal-to-noise-ratio, being of an older vintage of quality, and they appear to reveal variable-amplitude subparallel horizons. Additional geophysical analysis, including seismic attribute analysis, reveals that the data have excessive denoising and that the continuous features are actually a network of polygonal faults. The polygonal faults were identified in two tiers using variance, curvature, dip magnitude, and dip azimuth seismic attributes. Inline and crossline sections show continuous reflectors with a noisy appearance, where the polygonal faults are suppressed. In the variance time slices, the polygonal fault system forms a complex network that is not clearly imaged in the seismic amplitude data. The patterns of polygonal fault systems in this legacy data set are compared to more recently acquired 3D seismic data from Australia and New Zealand. It is relevant to emphasize the importance of seismic attribute analysis to improve accuracy of interpretations, and also to not dismiss older seismic data that have low-accuracy imaging because the variable-amplitude subparallel horizons might have a geologic origin.

Geological feature: Polygonal faults

Seismic appearance: Variable-amplitude plane-parallel horizons without clear discontinuities

Features with similar appearance: Seismic noise in stratigraphic sequences without brittle deformation

Age: Cenozoic

Location: Northern Gulf of Mexico

Seismic data: Survey B-01-91-MS obtained by the U.S. National Archive of Marine Seismic Surveys

Analysis tools: Geometric seismic attributes

Geologic background

The Gulf of Mexico Basin (Figure 1) was formed in the Late Triassic-Early Jurassic by an episode of crustal extension and seafloor spreading drifting away from the North American plate from the African and South American Plates (Salvador, 1987). During the initial phases of rifting, an extensive salt layer was deposited in the Mid-to-Late Jurassic age. The later tectonism and the continuous sediment loaded from the North American continent mobilized and deformed this salt sequence (Bryant et al., 1990; Milkov and Sassen, 2001). The consequence was the development of several large salt domes, which are separated by salt-withdrawal minibasins on the continental slope (Bryant et al., 1990; Milkov and Sassen, 2001). These salt structures improved the petroleum system by generating favorable hydrocarbon migration pathways through faults and structurally focusing hydrocarbon accumulation.

Polygonal fault arrays have been observed in the Gulf of Mexico from the shelf to the outer abyssal plain. Although some authors have noted the extensive occurrence of polygonal fault systems in the Gulf of Mexico, their stratigraphic occurrence, areal distribution, and the potential implications for basin exploration are still not well comprehended (Palmer, 2016). Regardless of the hypothesis of the genetic mechanism, there is an agreement that polygonal faults typically form (1) in sequences of very fine grained sediments, (2) in marine basins of >500 m water depth, and (3) at shallow burial depths (Cartwright et al., 2003; Goulty, 2008; Moscardelli et al., 2012).

Polygonal fault system meaning

Polygonal fault systems, due to their geometry, distribution, and kinematics, may increase the understanding of compositional variety in the rock in which they form and aid in locating sandstone-rich deepwater

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reservoirs, thereby reducing the exploratory risk (Jackson et al., 2014). Because polygonal fault systems are found in many hydrocarbon-bearing sedimentary basins, the study of their geometry and evolution might be a promising aid to assess reservoir presence and seal quality, particularly in deepwater basins (Turrini et al., 2017). Nevertheless, detailed studies focused on applying polygonal fault system mapping to deepwater reservoirs exploration are still lacking in the literature (Lonergan and Cartwright, 1999; Jackson et al., 2014; Turrini et al., 2017).

A good example of the seismic expression of polygonal faults developed in the Great South Basin, New Zealand, and off the Northwest Shelf of Australia is presented in Figure 2. In a modern 3D cube, seismic data polygonal faults appear as clear-cut amplitude discontinuities in the vertical slices. Although the Gulf of Mexico has been explored by the petroleum industry for decades and large amounts of geologic and geophysical information are available, the presence of polygonal faults in this area is not widely documented. Figure 2c displays an example of a Gulf of Mexico data set with unclear polygonal faults.

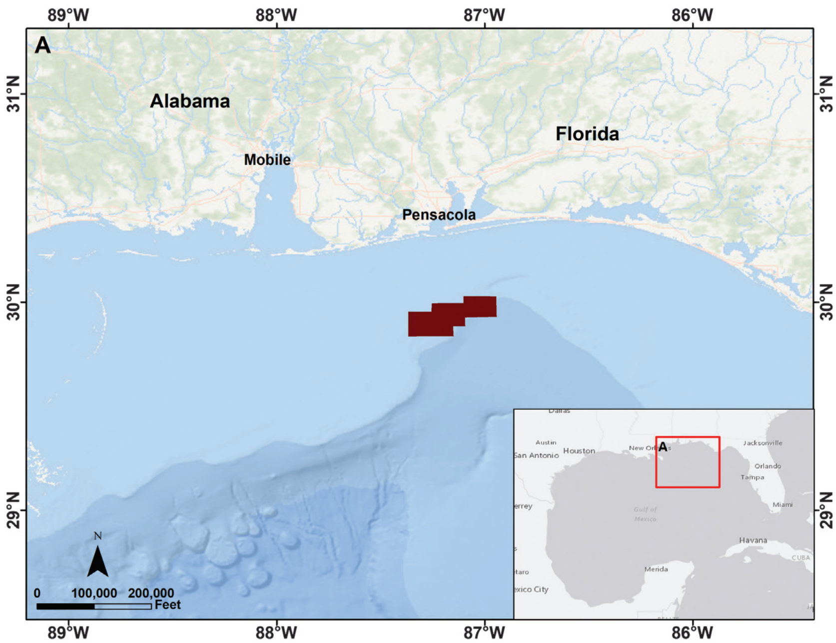

Figure 1. Gulf of Mexico Basin and the B-01-91-MS seismic survey (the brown polygon). The base map is a compilation of the geographic information system community available in ArcGIS software.

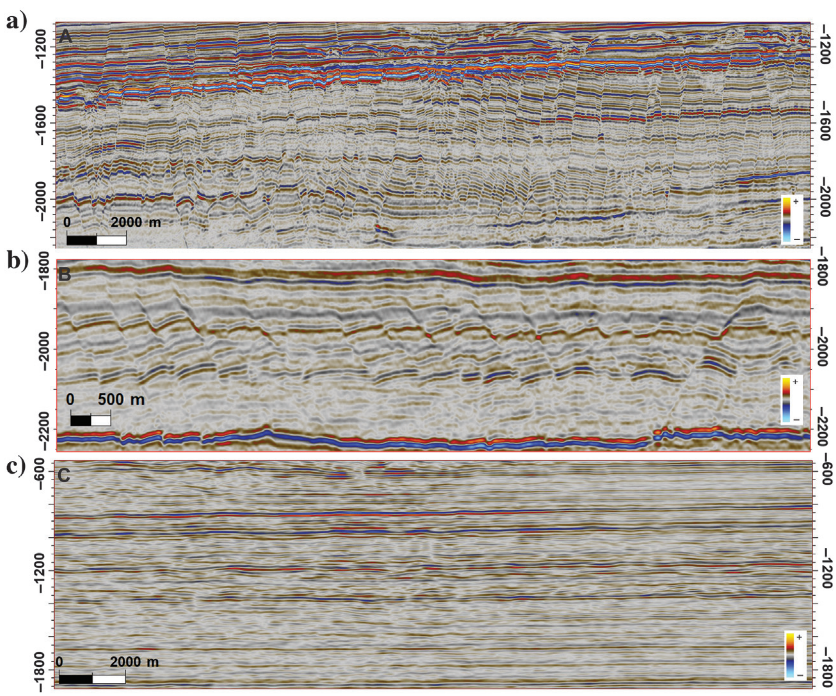

Figure 2. (a) Vertical section showing polygonal faults in the Great South Basin, New Zealand — BO_GSB3D seismic survey, (b) vertical section showing polygonal faults in Australia — Meo_NWS_3D seismic survey, and (c) Gulf of Mexico B-01-91-MS seismic survey. Vertical scale in two-way traveltime (ms TWT).

Attributes used to enhance polygonal faulting interpretation

Conventional seismic data interpretation was applied in the Gulf of Mexico data set. Looking at the vertical sections, small structures are almost imperceptible (Figure 3). Because seismic attributes are commonly used to accelerate and improve the interpretation of tectonic features in 3D seismic data, we first applied the variance, which is widely applied for structural analysis because it emphasizes the dissimilarities within the seismic data. The variance was calculated along the volumetric dip and azimuth to show only geologic structures and not structure-induced anomalies. So, when analyzing the variance in a time slice, we discover structures having the characteristics of polygonal faults (Figure 4). Because the common characteristics of polygonal faults are (1) layers bounded vertically — crossed with each other in the plane, (2) polygonal shape, (3) small fault throw, (4) varying strikes, and (5) small extending length (Ding et al., 2013); we investigate those structures using some geometric attributes.

Inspired by some studies that aimed to understand and interpret polygonal faulting configuration by using seismic attributes (Sun et al., 2010; Tellez et al., 2015; Alrefaee et al., 2018; Li et al., 2019), in addition to variance, we also generated the dip magnitude, curvature, and dip azimuth attributes/volumes to improve our interpretation. In Figure 3, note that, in the seismic amplitude volume, the appearance of the polygonal faults is not obvious and it can cause confusion with other types of features or even noise (e.g., weak amplitude signal and channels). Figure 4 displays the vertical seismic sections and time slices with the amplitude, as well as with the variance attribute generated at different time slices. To identify the polygonal faulting in this data set, the variance attribute is essential.

The variance and dip magnitude attributes delineate the polygonal shape associated with polygonal faulting (Figure 5). The shape of the faults was defined with high variance depicted in the red to dark-black color and high dip magnitude value (approximately 90°) shown in black. For this particular case, the variance attribute better delineates the polygonal faults compared to the dip magnitude because the variance calculation is sensitive to the waveform and lateral changes of the reflector amplitude, and, because the polygonal faults cause discontinuities in its lithology, they become easily detectable with variance. Meanwhile, the dip magnitude computes the deviation of a seismic reflector from a horizontal plane; it means that it is mainly useful when the faults cause layer movement on the fault plane.

The dip azimuth displayed the wide range of strikes, characteristic of polygonal faults (Figure 6). Polygonal faults do not have a preferred strike or dip direction because they are a multitude of normal faults, which in-

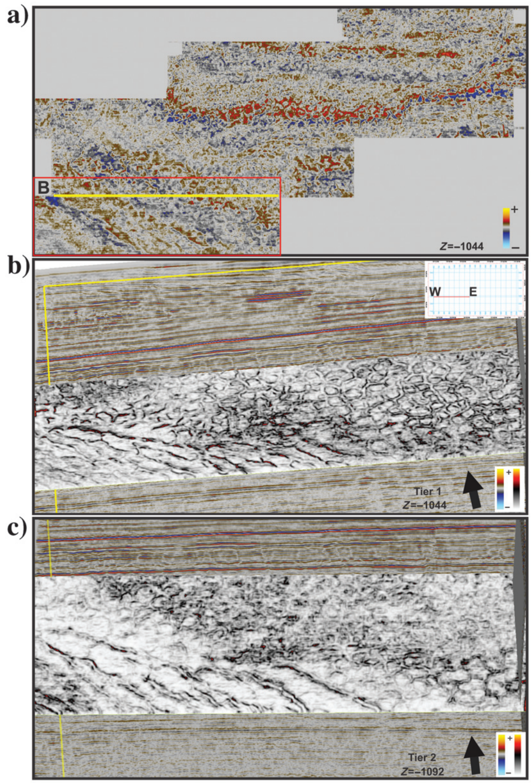

Figure 4. Gulf of Mexico data set: (a) time slice of amplitude extracted along the above red dashed line in Figure 3a, (b) time slice of the variance seismic attribute extracted along the above red dashed line in Figure 3a, and (c) horizon slice of the variance seismic attribute extracted along the below red dashed line in Figure 3a showing the polygonal fault system morphology. Vertical scale in TWT (ms).

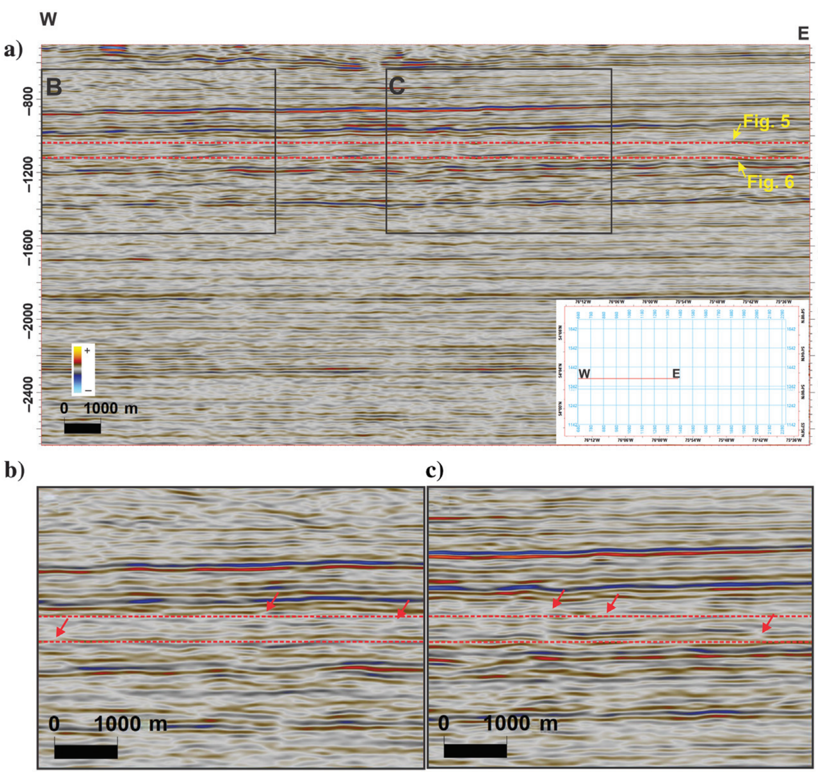

Figure 3. Gulf of Mexico data set used in this study: (a) plane-parallel sedimentary package in which the faults are poorly imaged, only being misinterpreted as random noise and (b and c) show red arrows in the polygonal faults. Notice that the red dashed lines are the time slices presented in Figures 4–6. Vertical scale in ms TWT.

tersect together (Watterson et al., 2000). In addition, the most-negative curvature (the blue colors; Figure 6) is a reliable attribute for imaging the shape of the studied features being well defined even in vintage or low-resolution seismic data. The fact that the most-negative curvature attribute is a good tool to image these polygonal faults could be related to their genesis, when the sediments were contracted forming low-relief spaces. However, a robust interpretation should be done to address relevant questions about the polygonal faults in the Gulf of Mexico, mainly about their genesis and how these structures can impact hydrocarbon exploration. For example, in the Songliao Basin, China, polygonal fault systems are migration pathways for hydrocarbons, and they significantly control the oil-water distribution (Ding et al., 2013).

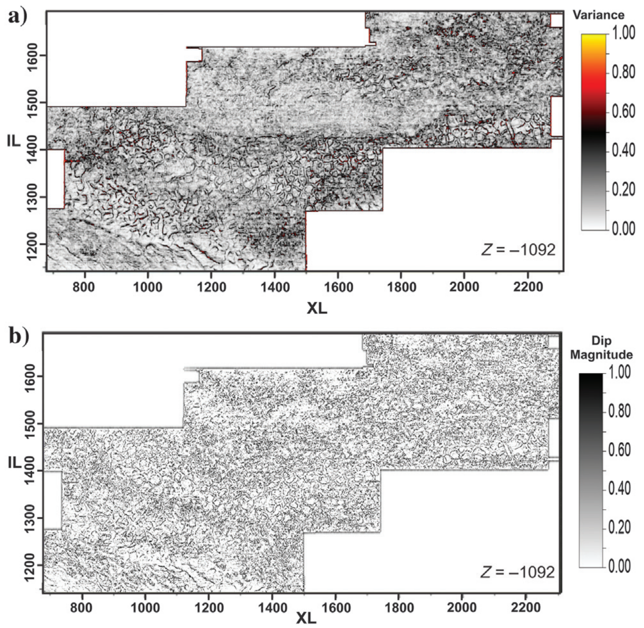

Figure 5. In time slice −1092 ms. (a) Variance and (b) dip magnitude attributes delineate the radial to polygonal patterns associated with polygonal faulting. The shape of the faults is defined with high variance depicted in the red to dark-black color and high dip value (approximately 90°) shown in black. Notice that for this particular case, variance better defines these structures than dip.

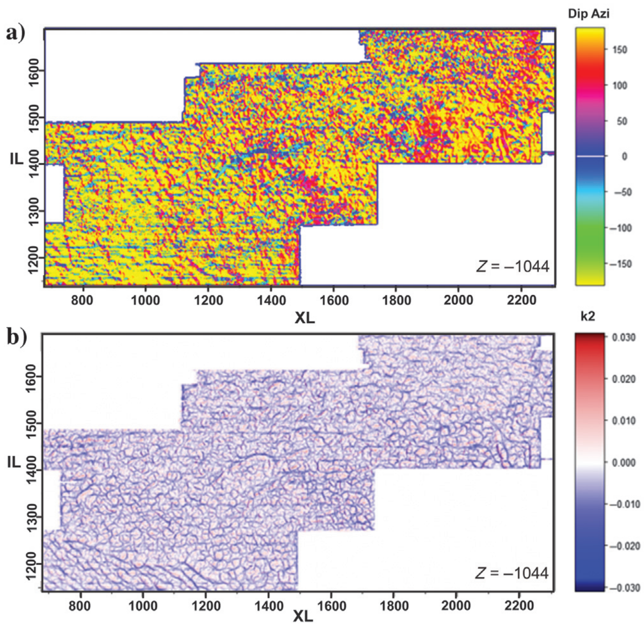

Figure 6. (a) Dip azimuth attribute showing the different orientation of the polygonal faults at the time slice −1044 ms. (b) Most-negative curvature (in blue) shows polygonal faulting shape.

Accordingly, we suggest the future development of an integrated 3D geologic model to investigate key factors in the genesis, evolution, and role of polygonal faults in the Gulf of Mexico petroleum system. Moreover, a more accurate interpretation using horizon slices could provide insights in the relationship between stratigraphic levels and the deformation affecting them. In this way, helping to constrain the potential effect of lithologic changes on polygonal fault distribution. Regarding this 1991 3D seismic data, the authors recommend reprocessing using modern seismic imaging techniques to prevent interpretation pitfalls by younger or less experienced interpreters.

Conclusion

Previous studies revealed that attributes such as variance and dip magnitude are powerful tools to interpret polygonal-like features. In our case, besides the latter attributes, we demonstrate that curvature (negative), in addition to dip azimuth aid in the interpretation of polygonal faults in a vintage 3D seismic data set. We noticed in this case study that seismic attributes perform well in extracting subtle and easy overlooked features in vintage data. Thus, vintage data should be carefully studied using tools such as seismic attributes that can help reveal structural features like polygonal faults that are not easily seen in an amplitude expression and that can be critical for oil and gas exploration and development. The insights presented here are a starting point to further studies about the polygonal faults in the Gulf of Mexico hydrocarbon province.

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Data and materials availability

Data associated with this research are available and can be accessed via the following URL: https://walrus.wr.usgs.gov/namss/survey/b-01-91-ms/.

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