PS Polygonal Fault System in the Great South Basin, New Zealand*

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Abstract

Polygonal faults are a network of layer-bound normal faults arranged in polygonal geometry. A polygonal fault system was identified from 3D seismic data in the Great South Basin, New Zealand. The lithology of the strata bounding the polygonal fault system is shale and siltstone, which is typical for most polygonal fault systems identified globally.

This study applies an advanced fault skeletonization method to 3D seismic data of the Great South Basin. Seismic attributes, such as coherence, are used to delineate faults. A new fault advancement and skeletonization workflow is applied to sharpen structural and stratigraphic discontinuities and smear the incoherent noise on coherence. Fault images are co-render enhanced with the fault dip magnitude and dip azimuth to map the geometry of the polygonal fault system.

The tectonic control on the formation of the faults is studied by comparing the orientation of the faults to the NE-SW trend of the major structures in this study area. In addition, a 3D model of the polygonal faults is produced. The maximum displacement on polygonal faults and the displacement on a single fault are measured and analyzed; these show that the displacement diminishes laterally towards the fault ends and the nucleation of the fault is near the base tip of the fault. Previous studies have attributed the formation of the polygonal faults to four main mechanisms: density inversion, syneresis, gravitational loading, and diagenetically induced shear failure. In this study, the density inversion model is favored for the genetic mechanism for polygonal fault system because of folding of the hanging wall layer and the nucleation point near the base tip of the fault.

Polygonal fault system in the Great South Basin, New Zealand

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Introduction

The Great South basin is located off the southeast coast of the South Island, New Zealand.The Great South basin formed as a result of Late Cretaceous rifting during Gondwanaland breakup of Australia, Antarctica and New Zealand. This resulted in a NE-SW trending normal fault system defining horst, graben and half-graben structures.

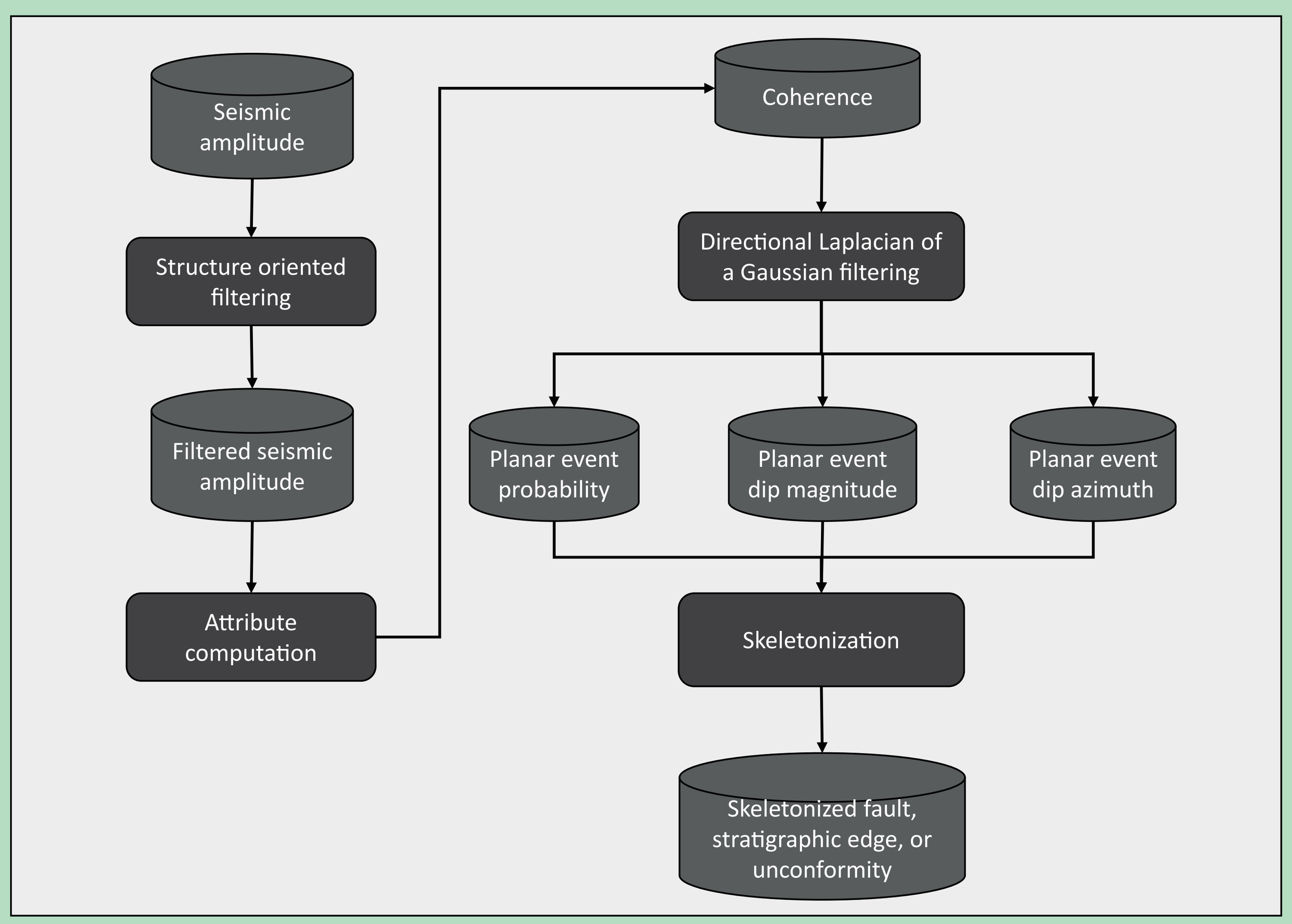
Polygonal faults are a network of layer-bound normal faults arranged in polygonal geometry. A polygonal fault system was identified from 3D seismic data in the Great South Basin, New Zealand. The lithology of the strata bounding the polygonal fault system is shale and siltstone, which is typical for most polygonal fault systems identified globally. This study applies an advanced fault skeletonization method to the 3D seismic data of the Great South Basin. Seismic attributes, such as coherence, are used to delineate faults. A new fault advancement and skeletonization workflow are applied to sharpen structural and stratigraphic discontinuities and smear the incoherent noise on coherence. Fault images are co-render enhanced with the fault dip magnitude and dip azimuth to map the geometry of the polygonal fault system.

The tectonic control on the formation of the faults is studied by building the rose diagram of the fault system and comparing it to the major structures in this study area. In addition, a 3D model of the polygonal faults is produced. The maximum displacement on polygonal faults and the displacement on a single fault are measured and analyzed.

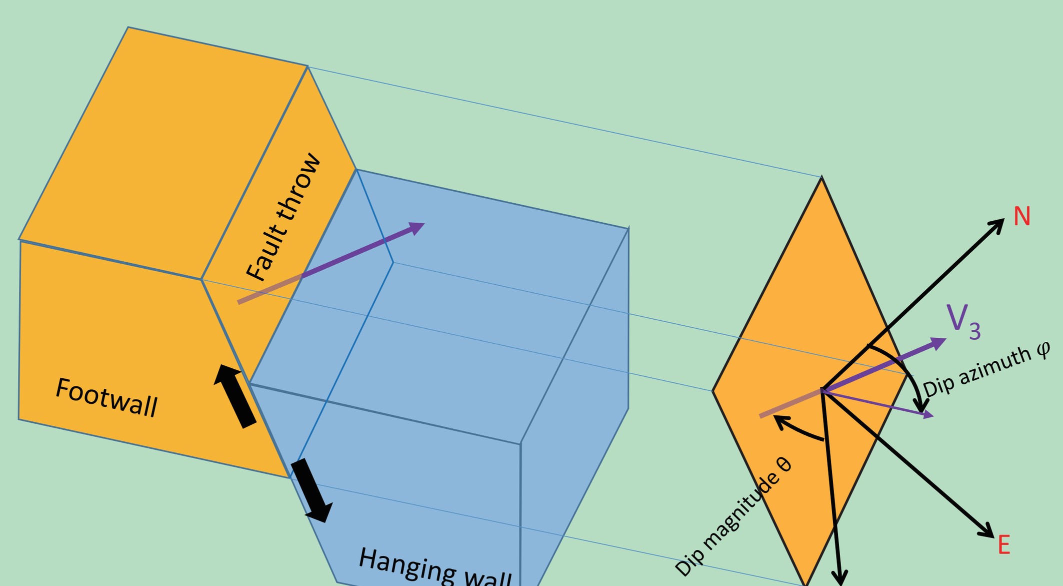
Objectives

- The geometry of the polygonal fault system in cross-section view and in map view
- The characteristics of the faults including the throw and the nucleation points
- The orientation of the polygonal fault system and the relationship to the tectonic background
- Possible genetic mechanism for the polygonal fault system in this area

Method (Fault Enhancement and Skeletonization)



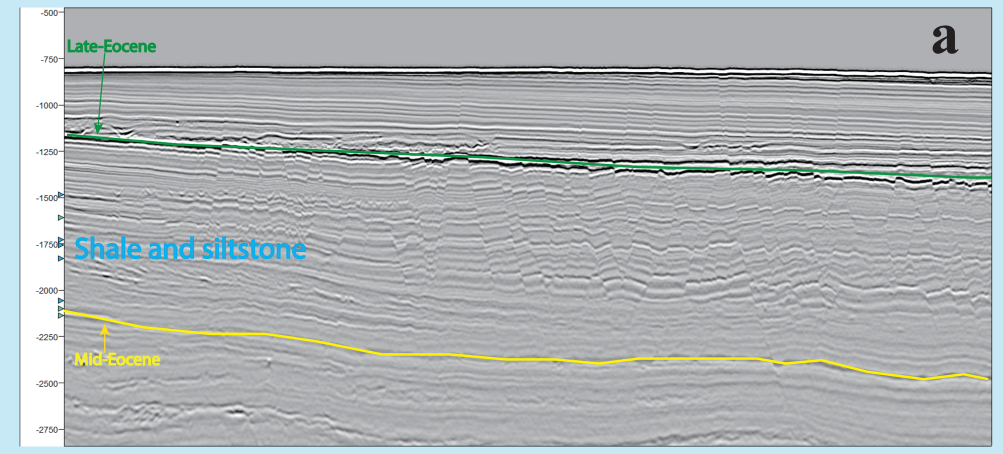
This workflow illustrates the steps used in the directional skeletonization method. The interpreter begins with post-stack data conditioning by applying structure-oriented filtering on seismic amplitude data. After filtering, a coherence or other edge-detection attribute is computed. A directional Laplacian of a Gaussian (LoG) filter produces volume estimates of the probability, dip magnitude, and dip azimuth of locally planar events (eg. Figure below). These events are then skeletonized to produce sharper images. (Jie et al., 2016)

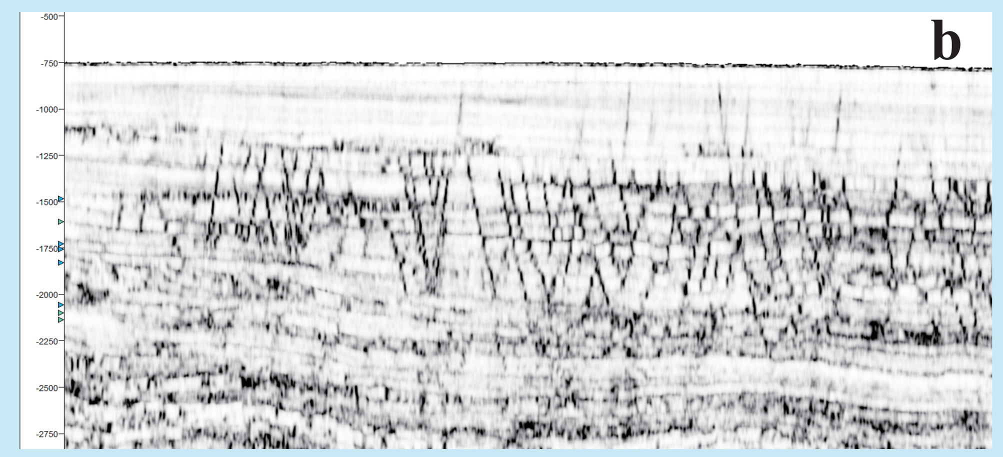


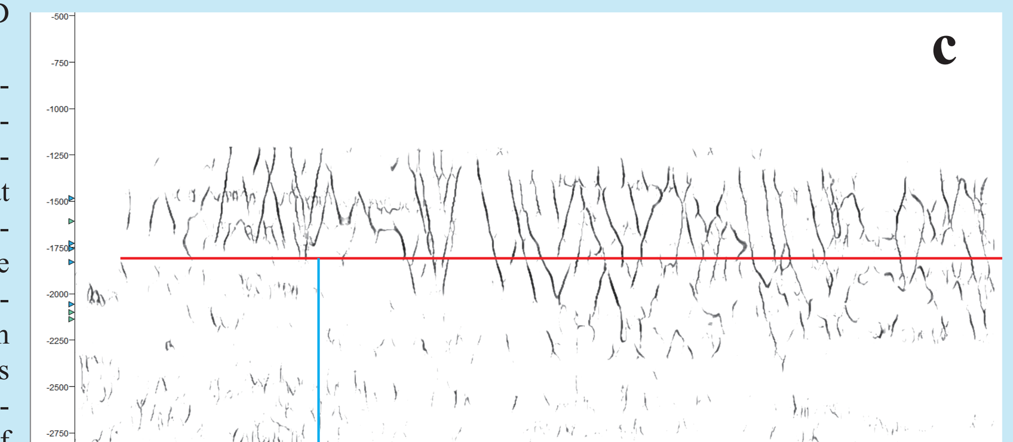
A normal fault defined by the eigenvector V3 perpendicular to the fault plane. The projection of V3 on the horizontal plane defines the fault dip azimuth φ, and the angle between V3 and the z-axis defines the fault dip magnitude.

Results and Analysis

Cross-section







(a) Cross-section view of the seismic amplitude along crossline 2340. The comparison between the variance (b) and the fault skeletonization result (c) of the same cross-section as Fig. a.

Using the well Pakaha-1 tied with the 2D seismic survey which goes through the 3D survey, the sequence boundaries bounding the stratigraphy of the polygonal fault system can be interpreted as Lutetian (Mid-Eocene) and Priabonian (Late-Eocene). The lithology bounding the system is shale and siltstone.

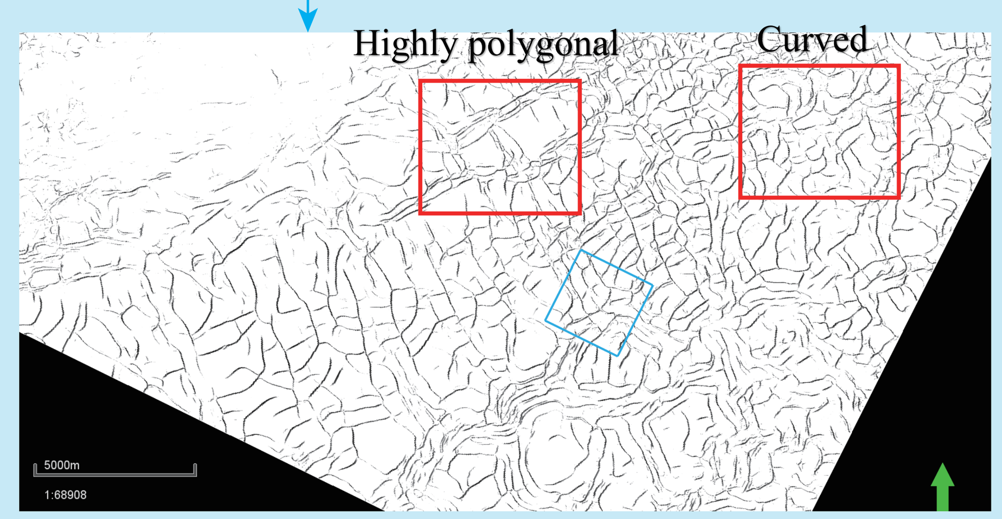
In cross-section (Fig. a), faults are planar normal faults. The displacement on single fault ranges from few ms to tens of ms in TWT. Although the variety of the dip direction, the dip angle is consistent among all the faults. In addition, the rotation and folding of the hanging wall beddings can be observed.

It is obvious that the layer hosting the polygonal faults experienced a volume reduction. Cartwright et al. (2003) attribute the extensional strain to this volumetric contraction, and he added that there was no good physical explanation for the volumetric shrinkage of the fully saturated sediments in a fully sub aqueous environment.

Compared to the traditional coherence map, the skeletonized fault map eliminates the "stair effect" (Fig. b) and present the fault planes more continuously (Fig. c). The skeletonized fault map is later used to produce the 3D fault map and the rose diagram of the fault system.

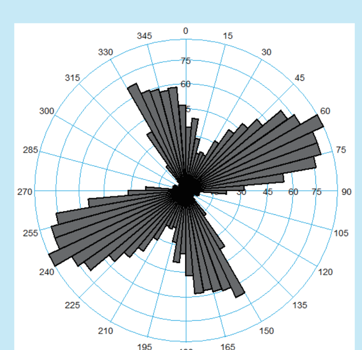
Compared to Central North Sea (Lonergan & Cartwright, 1999) and South China Sea (Chen et al., 2011) polygonal fault systems which developed in multiple stratigraphic tiers, the polygonal fault system in the Great South Basin has only one tier. The reason for the development of multiple tiers of polygonal fault systems might be the variation in the grain size, mud chemistry or compaction rate. The cross-section of the polygonal fault system in this study is representing a relatively homogeneous composition and compaction rate of the fine-grained sediments which can also be supported by the observation of the homogeneous dip angle of all the faults.

Map view

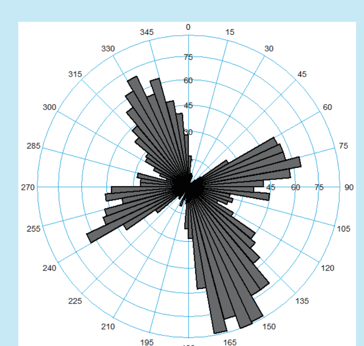


On the map view of the skeletonized fault map, the faults in the polygonal fault system are in a complex network, and the fault length ranges from few hundred meters to thousands of meters. The plan form patterns of the fault system are characterized by a variety from curved to highly polygonal or even rectangular (red boxes). Most intersections of the faults are orthogonal or nearly orthogonal. Although in some cases the strikes of two faults are not perpendicular to each other, the fault traces tend to curve in order to form the orthogonal intersection. The blue box is showing the location where the 3D structural model is produced.

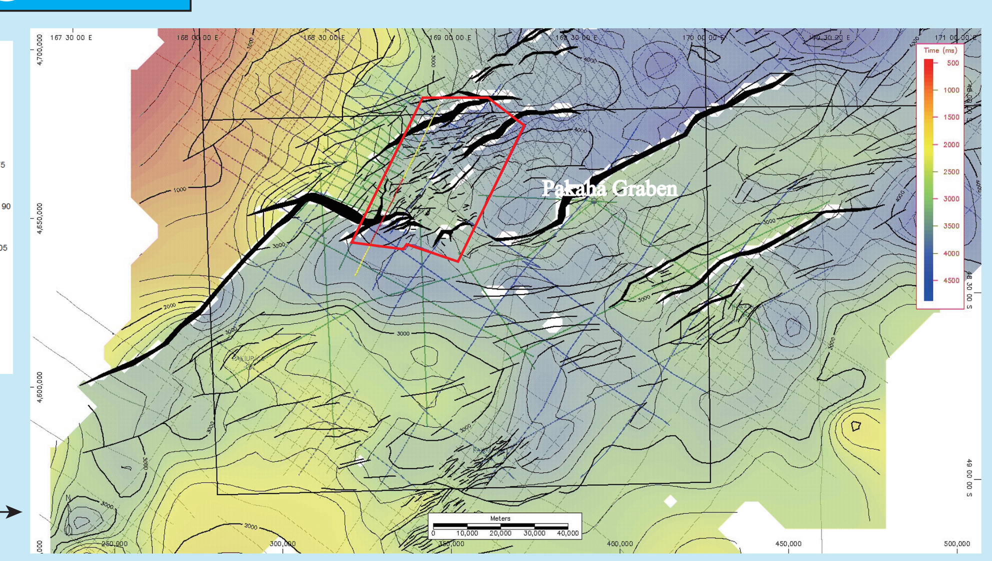
Relationship to Tectonic Background



Strike



Dip Direction

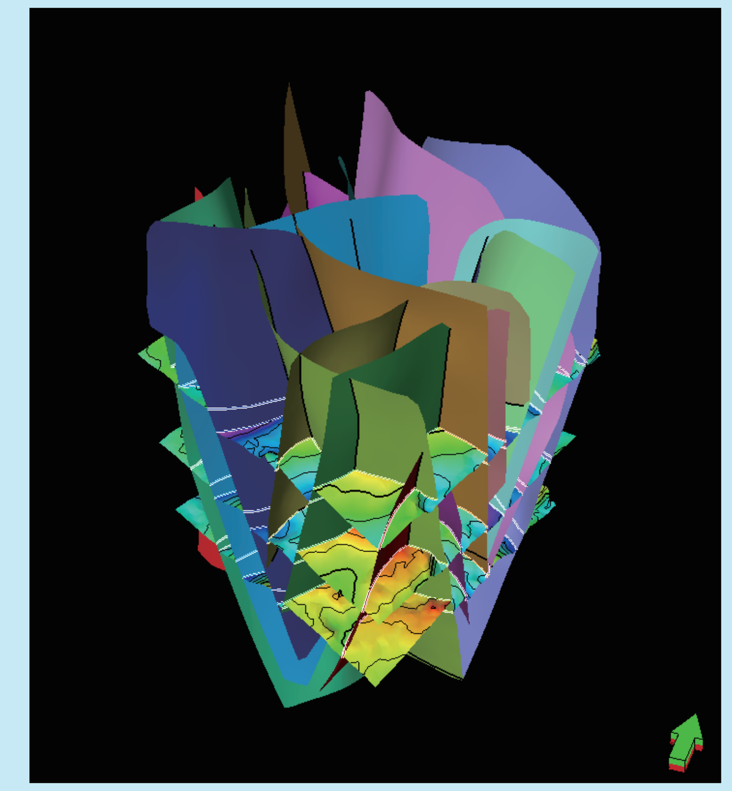


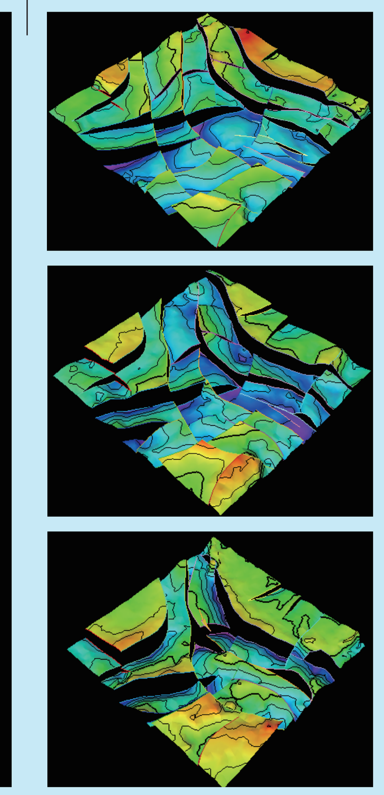
Santonian (Late Cretaceous) sequence boundary TWT structure map

The polygonal fault systems in South China Sea (Sun et al. 2010) and Central North Sea (Lonergan and Cartwright, 1999) show no preferred trend in the orientation of the faults, and the tectonic controls on the formation of the faults are eliminated. However, in this study area, the rose diagrams of the strike and the dip direction of the normal faults in the polygonal fault system show outstanding orientation preference at 60 and 150 degrees. These two preferred orientations represent that they are tectonic related.

The TWT structure map of the Santonian sequence boundary shows the major NE-SW trending normal fault system that defines horst, graben and half graben structures which controlled the Late Cretaceous and Early Tertiary sedimentary evolution (ExxonMobil Exploration Company, 2010). The location of the 3D seismic survey (red polygon) is within the transfer zone between two major normal faults which are located at the Southwest and the East of the Pakaha Graben. The fault orientations within the transfer zone show distinct turning of the fault strikes. Two major orientation of the fault in the transfer zone are NE and SE which are compatible with the preferred orientation of the polygonal faults recorded in the rose diagram. Although there is no evidence showing direct tectonic controls on the formation of the fault system, the influence and the connection is obvious. This observation is illuminating because it shows the possible connection between the tectonic background and the orientation or even the pattern of the faults in the polygonal fault system.

3D Structural Model





(a) 3D structural model of the polygonal faults of selected area with maor faults and three major horizons shown; (b) Three interpreted horizons that are located at different depths in (a). (the color bar is independent for each horizon)

A 3D structure model within a 1250m*1250m box is built (Fig. a). It is a complex fault system in which 22 major faults and 3 horizons are mapped based on the 3D seismic amplitude map. In 3D view, fault planes are not completely planar but the dip is constant along the dip direction. Intersected fault planes are perpendicular to each other, which is consistent with the map view observation of the fault skeletonization map. Some faults are truncated by other faults, while some penetrate through.

On the interpreted horizons (Fig. b), the hanging wall bed dropping along the faults are shown by colder colors. The throw along the faults can be represented by the gap between the hanging wall and footwall on each horizon. In this particular model, the center part is the deepest and the hanging wall of multiple normal faults.

Along the fault length, the throw decreases laterally towards each end. Comparing three marker horizons, it is apparent that the fault throw gradually increases from the top horizon to the bottom one. Based on the observation of the cross-section, the maximum displacement which represents the initial fault nucleation is close to the basal tip. The displacement diminishes on the top and bottom tip of the fault.

Discussion (Genetic Mechanisms)

Models	Density inversion	Syneresis	Gravitational loading
Concept	The density inversion of a clay unit and overburden sediments leads to folding and fracturing of the sediments until the equilibrium density gradient is reached by dewatering	Syneresis is by definition a spontaneous contraction of colloidal materials without evaporation	The concept of the gravitational loading is that normal gravitational loading of certain types of sediments can lead to failure without the need to invoke additional stresses or overpressure
Weakness	The density inversion model is hard to be viewed as a universal mechanism because of lack of folding in many cases	The physical process is poorly understood and the known examples are at a much smaller scale compared to the basin sized polygonal fault systems	The problem of this model is that it requires anomalously low value of internal friction which is not observed from the natural cases

The formation of the polygonal faults has been attributed to four main mechanisms: density inversion, syneresis and gravitational loading as shown in the table above. The observations on the cross-section of the polygonal fault system share some similar characteristics with a polygonal fault system in South Australia interpreted by Watterson et al. (2000). This system is interpreted to be attributed to density inversion model. Some of the hanging wall beddings are folded. Moreover, different from some of the polygonal fault systems which have the highest fault displacement in the center, the maximum displacement along the fault in this study is close to the lower tip. In this case, the density inversion model can provide a good explanation for the fault nucleating in the bottom section which could be the contact between the dewatered soft sediments and overburden sediments, although the density inversion model cannot be a universal explanation for the genesis of the polygonal fault systems. However, syneresis cannot be ruled out completely because this process could be helping the dewatering of the lower sediments.

Conclusion

- This study applies an advanced fault enhancement and skeletonization method to the 3D seismic data of the Great South Basin to map the geometry of the polygonal faults.
- The lithology of the stratigraphy bounding the polygonal fault system in this study is shale and siltstone.
- The faults in the polygonal fault system have two preferred orientations which are compatible with the orientations of the major normal faulting bounding the system.
- Along the fault length, the throw decreases towards the ends. The maximum displacement along the fault dip, which is representing the nucleation point of the fault, is near the base tip of the fault.
- The density inversion model is favored for the genetic mechanism for the polygonal fault system.

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