Multiscale faults and karst caves prediction in deep Ordovician carbonate in Tarim Basin, China

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Summary

Strike-slip fault is well-developed in Tarim basin, faults together with karst caves developed along the faults in deeply buried Ordovician carbonate is main reservoir in this area. Accurate prediction of these faults and karst caves is crucial for petroleum exploration. Different seismic attributes are applied to predict multiscale faults and karst caves, large scale faults (>1/4λ) are identified based on seismic discontinuity, while medium scale faults (>1/100λ and <1/4λ) are detected using maximum curvature attribute. Principal Component Analysis (PCA) and unsupervised clustering are utilized to analyze multiple attributes, to categorize the attributes into distinct classes, allowing for the ranking of fault and the subsequent delineation of fracture lineaments. The karst caves are characterized using the maximum amplitude gradient in horizontal direction (MAGH). The study culminates in the characterization of the fault-controlled karst cave reservoirs within the deep Ordovician carbonates by integrating the prediction results.

Introduction

The Ordovician deep marine carbonates, especially the Yijianfang Formation (O_2yj) and the Yinshan Formation ($O_{1\text{-}2}y$), are the main targets for oil exploration and development in Shunbei area of the Tarim basin.

The multicycle tectonic evolution in this region has led to the development of strike-slip faults in deep marine carbonate formations. These faults not only connect to deep hydrocarbon source rocks of the Cambrian Yuertusi Formation but also serve as permeability corridors for fluid migration. Additionally, epigenic karstification together with underground river karstification and karstification along deep faults has resulted in multistage karst formation.

Fault-controlled karst cave reservoirs are considered the most important reservoir in this area, contributing substantially to oil production (Zhang et al., 2022). Several large oil fields found in recent years are attributed to deep fault-controlled karst reservoirs, making the prediction of faults and karst caves a critical factor in petroleum exploration.

In the Shunbei area, strike-slip faults exhibit different segments due to associated extensional and compressional stresses. These faults can be categorized into three subtypes: transtension, transpression, and pure strike-slip. Transtension faults typically feature wide fault zones and negative flower structures in seismic profiles, while transpressional segments, rock surrounding the fault were squeezed on both sides, from a series of fault anticlines, often presenting positive flower structures. Pure strike-slip faults, which lack vertical displacement, are challenging to detect on seismic data (Figure 1). The fault width and oil production associated with transtensional faults are significantly larger than those with transpressional properties (Lv et al., 2022).

Karst caves observed in the O_2yj and $O_{1\text{-}2}y$ Formations, have lower impedance than the surrounding carbonate rocks due to cave collapse or filling with low-velocity material, large karst caves usually exhibit strong beadlike reflections in seismic data (Figure 2). However, heterogenous like fracture and small caves were observed in karst caves from well drilling and logging, with a scale of a few tens of meters, exceed the resolution of seismic data. The detection of karst caves is crucial for ensuring the success of oil development.

The challenge lies in characterizing faults using different seismic attributes, especially considering that the Ordovician carbonates in the Shunbei area are buried deeper than 7000 meters, and carbonate fault-controlled karst reservoirs are often extremely heterogeneous. large-scale fault can be predicted well through seismic discontinuous attribute like coherence, However, in addition to large-scale faults, medium and small-scale faults and karst caves are also vital

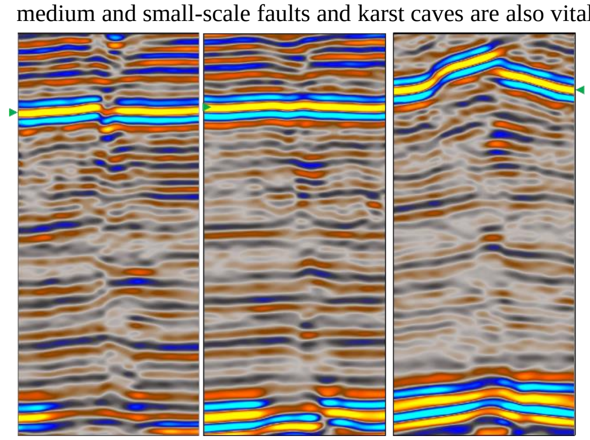

Figure 1: The seismic section across the strike-slip fault reveals different geological structures, including a transtensional segment with a negative flower structure (left), a pure strike-slip without vertical displacement (middle), and a transpressional segment with a positive flower structure (right). The green triangle arrows indicate the top position of the Yijianfang Formation (O_2yj).

for well path planning and drilling operations. This study apply a comprehensive set of seismic analysis methods including seismic discontinuity, maximum curvature, PCA and unsupervised clustering method to predict strike-slip faults, and MAGH were used to detect karst caves.

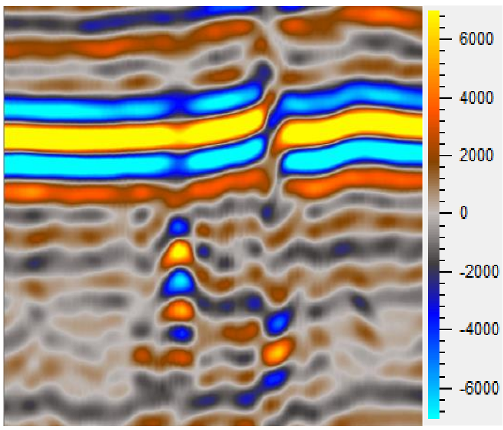

Figure 2: seismic section across fault and karst caves in Yijianfang Formation (O_2yj).

Method

Our approach to fault detection involved a combination of techniques. Initially, we applied structure orientation filter and diffusion filter to reduce noise and enhance the fault (An et al. 2021). We then calculate seismic attributes such as discontinuity, dip and curvature, these attributes are analyzed by PCA method extract principal component information and mitigate the uncertainty associated with individual attributes (Xu et al., 2023). Following this, unsupervised clustering was employed to classify the attributes into several classes representing different scale faults. The clustering result were ranked based on maximum curvature and dip attribute, i.e. large fault has larger value of curvature and dip, meanwhile, small fault has smaller value. A curvature threshold was established from these rankings, and curvatures exceeding this threshold were enhanced to extract fault lineament (Figure 3).

Amplitude gradients were calculated in three dimensions to construct gradient tensor (Chopra and Marfurt 2020), the three eigenvalues of gradient tensor represent amplitude gradient perpendicular to reflectors, maximum and minimum amplitude gradient in horizontal direction, respectively. The MAGH effectively suppress strong flat reflect event and magnify the horizontal contrast which will illustrate the karst caves. The distribution of karst caves within 3D seismic data volume can be discerned. with higher MAGH values indicating a greater contrast between the karst caves and the surrounding rock.

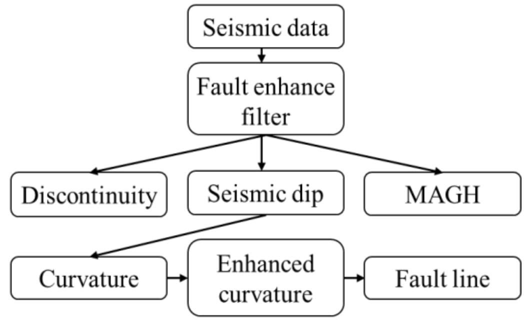

Figure 3: workflow of multiscale faults and karst caves prediction.

Examples

To demonstrate the effectiveness of our methods, we analyzed a 3D post-stack reverse time migration seismic dataset collected in the Shunbei area. The dataset, with a bin size of 25m×25m and a vertical sampling interval of 2ms, provided high-resolution images of the subsurface. Using the methods described above, we detected multiscale faults and karst caves.

Seismic discontinuity clearly delineated large-scale faults, with transtension and transpression segments of strike-slip faults exhibiting significant discontinuities (Figure 4). However, pure strike-slip faults without vertical displacement were challenging to identify on the discontinuity map at the top of the O_2yj Formation. In contrast, the maximum curvature shows more detailed fault information, including small faults outside the principal deformation zone.

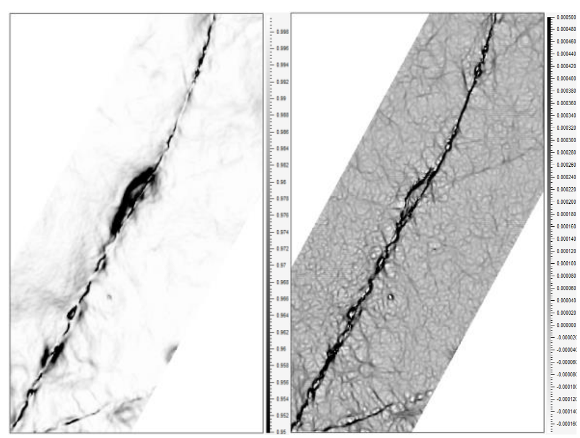

Figure 4: At the top of the Yijianfang Formation (O2yj), the analysis of discontinuity (left) and maximum curvature (right) reveals that the maximum curvature attribute provides more detailed information regarding fault structures.

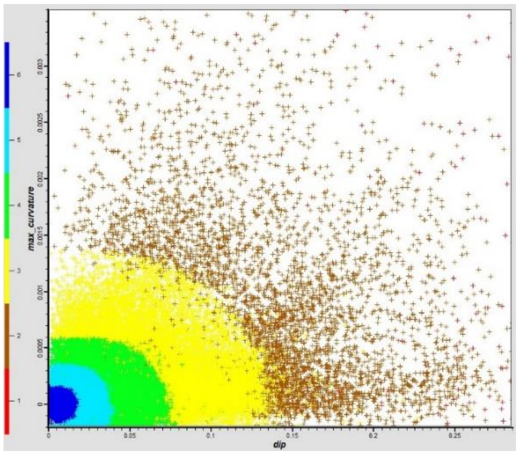

Figure 5: Ranking of unsupervised clustering based on maximum curvature and seismic dip. Large fault has larger value of curvature and dip.

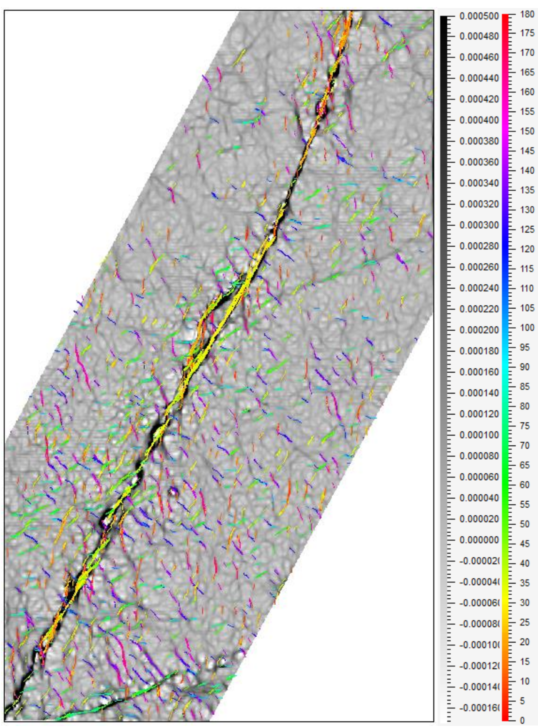

Figure 6: An overlay of multiscale faults is superimposed on the maximum curvature map at the top of the Yijianfang Formation (O_2yj), with the color of the faults representing their azimuth

By applying PCA, unsupervised clustering, and ranking on discontinuity, maximum curvature, and seismic dip attributes, we were able to classify different scales of faults and establish a curvature threshold (Figure 5). Curvatures below 0.0003 can be regard as background rock fracture beyond the seismic resolution, while curvatures greater than 0.0003 were enhanced considered as different scale fault. This enhancement allowed us to extract fault lines from the enhanced curvature attribute and compile them into a comprehensive dataset.

Figure 6 displays an overlay of multiscale faults superimposed on the maximum curvature at the top of O_2yj Formation. Each line represents a distinct fault. These faults exhibit a strong correlation with curvature, revealing more detailed fault information, such as length and direction. Figure 7 displays a seismic section across karst caves and corresponding MAGH result. Karst caves can be extracted from MAGH volume by using a specific threshold. fault-controlled karst cave reservoirs within the deep Ordovician carbonates can be characterized by integrating the prediction results, which is helpful for effective petroleum exploration and reservoir characterization.

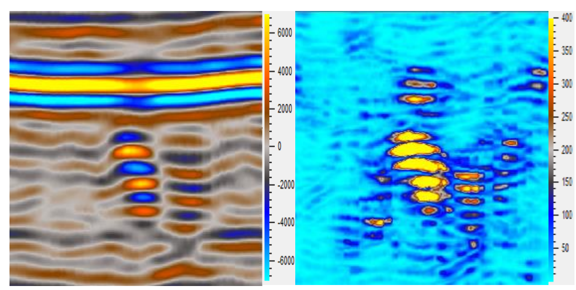

Figure 7: A seismic section through a karst cave (left) is juxtaposed with the corresponding MAGH attribute (right), where higher MAGH values are indicative of the presence of karst caves.

The approach outlined in the paper has been validated through drilling operations in the Shunbei area, with a particular focus on the NE-striking fault zone and the exploration of beadlike strong amplitude anomalies. These anomalies, which are suggestive of potential hydrocarbon reservoirs, are identified through seismic reflection patterns.

The drilling findings indicate that the reservoir encountered is predominantly composed of karst-cave systems. The total reservoir thickness of 64.5 meters in measure depth includes a 16.0-meter weakly gas-bearing layer and a 48.0-meter dry layer. This stratigraphy is indicative of a complex subsurface environment where hydrocarbon accumulation is influenced by the intricate nature of the karst formations.

Figures 8(a)-(d) display the seismic section and attributes along the well path. Two faults are visible along the path, and a karst cave is observed near the measured depth of 7180 meters. The faults, extracted using enhanced curvature, are depicted in Figures 8(e) and (f) from a top view and a southward perspective, respectively. Faults along the well path are consistent with discontinuities and maximum curvature attributes, revealing more fault details. Two main faults are located, and in addition, faults with different azimuths have also been extracted. The faults and karst caves predicted by our approach are consistent with the drilling findings.

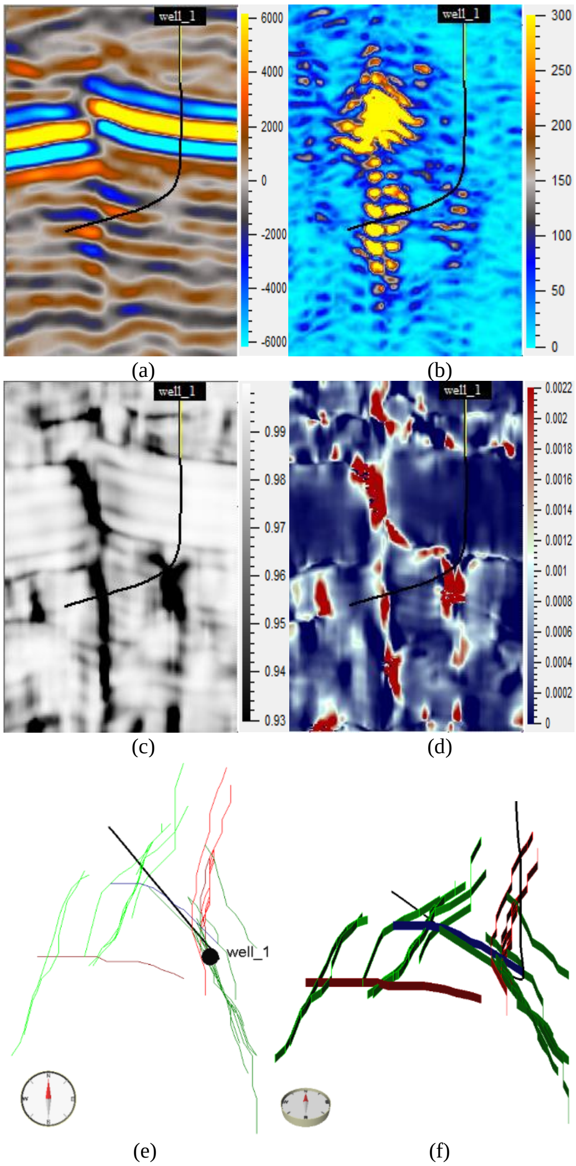

Figure 8: A seismic section through a well in this area (a) is juxtaposed with the corresponding MAGH (b), discontinuity attribute (c) maximum curvature (d), fault line near the well form top view (e) and view from south (f), black solid line indicates the well path.

Karst cave near the measure depth of 7180 meter was fully filled by calcite which interpreted as weakly gas-bearing. The reservoir's characteristics are marked by strong heterogeneity in both horizontal and vertical directions.

Conclusions

In this study, we have applied a comprehensive set of seismic analysis methods to predict strike-slip faults and karst caves within the Shunbei area. The application of PCA, unsupervised clustering, and ranking attributes on discontinuity, maximum curvature, and seismic dip attributes, has been instrumental in enhancing our multiscale faults interpretation by reducing the inherent uncertainty in analyzing individual attributes. We have been able to identify multiscale faults with greater precision. The karst caves can be discerned using MAGH attribute. The fault-controlled karst cave reservoirs within the deep Ordovician carbonates have been characterized through integrating the prediction results. Our findings contribute to a more detailed understanding of the subsurface fracture networks and fault-controlled karst reservoirs, which are essential for effective petroleum exploration and reservoir characterization.