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Review of Methods for Prediction and Identification of Small Faults

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ABSTRACT

Fault system is the oil and gas reservoir is one of the main control factors of characteristic changes especially, for dense reservoirs, so it is very important for quality reservoir prediction. However, due to the complex relationship and contradiction between the genesis and scale problems of small faults and the characteristics and resolution of seismic response, the seismic detection technology of small fault development zones is one of the current research hotspots. Seismic attribute analysis is one of the effective means for small fault identification and prediction. Various types of seismic attributes can be obtained by doing different mathematical and physical transformations on seismic data, and various different kinds of seismic attributes can be obtained based on seismic data. Different seismic attributes can describe different geological features, and a single seismic attribute has good ability to identify faults, but a single seismic attribute to predict reservoir The single seismic attribute has good ability to identify faults, but the single seismic attribute may have multiple solutions when predicting reservoir parameters. Therefore, by preferring multiple attributes that can reflect the reservoir characteristics in the work area for analysis, multiple solutions can be reduced and the prediction accuracy can be improved, which is very practical in fault prediction.

KEYWORDS

Small Fault Identification; Seismic Properties; Curvature; Coherent Bodies; Ant Bodies; Multi-Attribute Fusion.

1. INTRODUCTION

Faults occur when rock formations are subjected to tectonic stress. In reservoirs, the production, migration, and preservation of oil and gas are significantly influenced by faulting[1]. Major faults also affect the structural orientation of hydrocarbon-bearing blocks. Beneath major faults, smaller faults intricately dissect these blocks, complicating the relationships between oil, gas, and water. This complexity determines the scale of structures and the effectiveness of traps, directly impacting well placement design, field development plans, and, importantly, enhancing production rates in oil fields and ensuring safety in coal mines. Consequently, predicting the development of fault zones has become a focal point in geophysics, carrying both theoretical significance and practical application[2].

Research on seismic attributes such as coherence, edge detection, curvature, and ant tracking has highlighted their excellent capability in identifying fault zones and fracture development zones associated with structural origins[3]. Additionally, analysis of multi-attribute integration techniques, including direct stacking, attribute fusion, and supervised neural network computation, has shown promising practicality in predicting fault development zones[4-5].

2. SEISMIC ATTRIBUTES

Seismic attributes are mathematical transformations of seismic data that reveal geometric, kinematic, dynamic, or statistical characteristics of seismic waves. The presence of subsurface faults causes variations in the lateral rock physics properties of the formations, resulting in changes in seismic wave parameters such as wavelength, frequency, and amplitude, known as seismic responses of small faults. These seismic responses can be reflected in seismic attribute information, with different scales of small faults exhibiting varying seismic responses. Therefore, in recent years, in oil and gas exploration and development, amplitude, frequency, phase seismic attributes, and some analysis techniques such as seismic waveform classification, time-frequency analysis, and along-layer slicing have been widely used to identify and predict the development zones of small faults. Due to the complexity and diversity of small fault formation, seismic attribute analysis techniques are more suitable for inferring the overall outline of fault development zones, while finer analyses of small fault seismic attributes mainly focus on abrupt changes (discontinuities) in seismic reflection waveforms. Techniques such as coherence analysis, edge detection, curvature analysis, and ant tracking analysis are primarily employed for this purpose[6].

2.1. Coherence attribute

Since its proposal in the 1990s, seismic coherence technology has evolved to its fourth-generation algorithm. However, regardless of the specific coherence technique, all aim to highlight spatial discontinuities by leveraging waveform similarities between seismic traces. Conventional coherence algorithms perform direct computations between seismic traces without considering factors such as dip and azimuth angles. Guided coherence, on the other hand, integrates the dip and azimuth angles of the seismic coherency axis at each sampling point along the lines and traces. By using dip control, coherence information can be corrected. After processing along the inclined plane, coherence attributes are guided along the three-dimensional direction, where seismic phases are roughly continuous on this plane. Compared to conventional coherence, guided coherence offers higher resolution and less interference from random noise. Through coherence analysis, the distribution patterns and extensional forms of fault development zones, namely areas of low coherence values, can be clearly identified.The formula is as follows:

$$\sigma^2 = \frac{\sum_{j=t-\frac{L}{2}}^{t+\frac{L}{2}} w_{j-t} \sum_{i=1}^{I} (x_{ij} - \bar{x}_j)^2}{\sum_{j=t-\frac{L}{2}}^{t+\frac{L}{2}} w_{ij} \sum_{i=1}^{I} (x_{ij})^2} \tag{1}$$

where j denotes the variance calculation time; i represents the number of seismic tracks, which is a real number; I represents the number of horizons and faults selected in the calculation of variance, L is the length of the time window at the time of variance calculation

2.2. Curvature attribute

Curvature represents the degree of bending or deformation at a point on a surface. Curvature attributes can describe the curvature features induced by structural deformations such as faults and folds. Seismic curvature attributes have a direct relationship with stress. When the stratum is in anticline, its normal vectors diverge, resulting in positive curvature. When the stratum is in monocline or flat layers, its normal vectors are parallel to each other, resulting in zero curvature. When the stratum is in syncline, its normal vectors converge, resulting in negative curvature.Usually, after seismic horizon interpretation, smoothing is needed. Therefore, the curvature values around discontinuities are similar to anticline or syncline structures, with non-zero curvature values. Generally, the greater the absolute value of curvature, the greater the stress on the rock layers, leading to the development of small faults. Thus, the relationship between curvature attributes and small faults reflects the degree of stress on the strata, which can be used to predict the development of faults based on the magnitude of curvature. Linear anomalies constructed from curvature can predict fault development zones, where the length of curvature anomalies corresponds to the extension length of the structural zone, and the direction of curvature anomalies indicates the trend of the structural zone.There are various types of curvature, such as mean curvature, Gaussian curvature, principal curvature, maximum curvature, maximum positive curvature, and minimum negative curvature. Based on previous experiences, the most effective curvatures for identifying and predicting small faults are usually maximum positive curvature and minimum negative curvature.

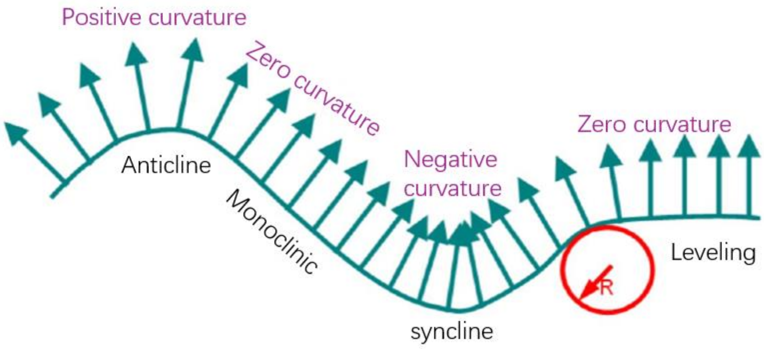

Figure 1: Two-dimensional curvature of the curve

According to the experience of previous researchers, there are some limitations to using horizon curvature attributes for identifying and predicting small faults:

(1)The accuracy and precision of stratum information are limited because stratum information is obtained through a combination of manual interpretation and software-based automatic tracing. Since horizon curvature attributes rely on stratum information, the accuracy of curvature attributes cannot be guaranteed.

(2)The calculation of horizon curvature attributes mainly relies on seismic data's horizon-based construction rather than the original amplitude of seismic data volume. Therefore, it is more susceptible to noise interference. Consequently, appropriate filtering methods need to be selected for preprocessing before obtaining curvature attributes. Otherwise, it can severely distort stratum information, leading to significant errors in fault prediction results.

2.3. Ant tracking technique

The ant tracking technique utilizes the principle of information exchange and path optimization among a group of bionic ants during foraging, where the ants always choose paths with the most information and continuously update this information to eventually find the optimal path. By applying this principle, the technique can highlight seismic discontinuities and enhance fault imaging. Based on literature research and previous experiences, the ant tracking technique is more effective for studying small faults rather than identifying large fault scales. Therefore, it is primarily used for researching small faults.

In seismic data, differences in amplitude, phase, and azimuth within the seismic volume act as pheromones. Ants move forward along potential locations where small faults may develop, utilizing the information exchange among the ant population. As more ants move towards areas of potential fault development, the technique progressively describes the potential fault until it is fully delineated.

The ant tracking technique is typically combined with curvature attributes and implemented using Petrel software. The steps involved are as follows:

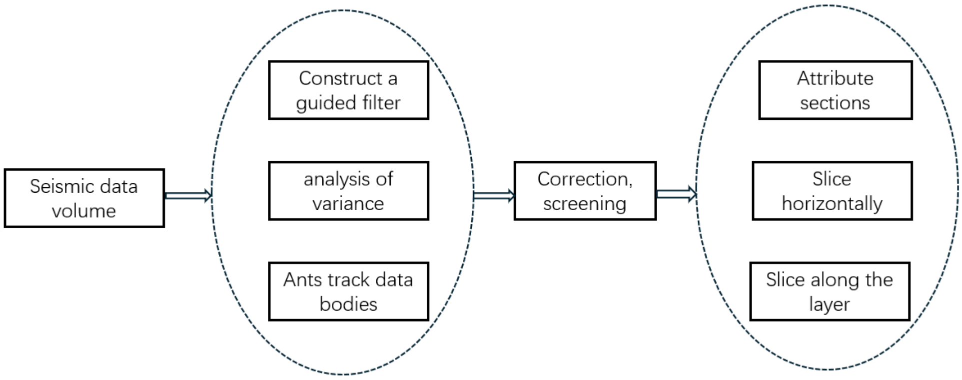

Figure 2: Schematic diagram of ant tracking technology

(1)Use filtering (structure-guided filtering) to smooth the raw seismic data volume and attenuate random noise interference in the seismic data.

(2)Setting ant tracking parameters involves determining the initial boundary range, which influences both computational efficiency and the density of ant distribution. Based on previous experience, when predicting small faults, it's advisable to choose a relatively small initial boundary range, typically between 4 to 5 units. The tracking step size refers to the interval at which each ant conducts its search, and it's crucial for maintaining resolution; typically, a step size of 3 voxels is chosen based on experience. Additionally, orientation control is important since ant tracking is sensitive to traces of low-dip layers.

(3)Extracting curvature attributes and using them, or other polarity data, as the original data body for ant tracking can save runtime and yield more accurate predictions of small faults. Curvature attributes are closely related to the accuracy of small fault predictions, with extensive literature research showing that the most effective attributes are maximum positive curvature and minimum negative curvature.

(4)Using seismic data with stronger discontinuities, along with setting parameters such as fault strike, dip, and other structural information, allows for fault orientation control during tracking. Additionally, setting optimal initial boundaries, ant tracking biases, ant step size, allowed invalid steps, allowed valid step counts, and stopping criteria are crucial conditions for ant tracking. These conditions collectively facilitate the tracking of ant bodies.

3. SEISMIC MULTI-ATTRIBUTE ANALYSIS TECHNIQUE

The seismic attributes used in the study of small faults are numerous, each reflecting different characteristics. These attributes have their own emphasis when describing geological features, resulting in varying application effectiveness. Attributes like dip angle and azimuth can depict fundamental changes in geological structures, while coherence attributes excel in identifying features within faults and channels. Curvature attributes are sensitive to subtle geological variations. Considering the issue of the inherent ambiguity of individual attributes, it is common practice to select multiple attributes that reflect reservoir characteristics in the study area. This approach helps reduce ambiguity and enhance prediction accuracy.

3.1. The principles of seismic attribute optimization

For seismic multi-attribute fusion technology, the quality of attribute extraction will directly affect the accuracy of reservoir prediction and calculation rate in the later stage, and the optimal selection of attributes is very important. The main principles followed in the selection of seismic attributes are as follows:

(1) the set of attributes can effectively classify the samples and ensure that the attributes are relevant to the geological target.

(2) ensure that the preferred attributes are as independent as possible from each other, so as to achieve more diversification and optimization.

(3) Eliminate irrelevant interference and maximize useful information. In general, the extracted attributes should be representative (sensitive), which can highlight their unique sensitive characteristics, and the number of attributes should avoid redundancy, and the number of samples should not be too much.

3.2. Seismic multi-attribute fusion technology

Seismic multi-attribute fusion technology is not merely about stacking attributes; it is an application of seismic imaging. It involves spatial standardization of different attribute images, followed by using specific algorithms to reconstruct pixel codes for creating new images. Before conducting multi-attribute fusion, it is crucial to select attributes representing different characteristics based on optimization principles. Then, mathematical methods are applied to merge different seismic attributes, complementing and enhancing each other. This comprehensive analysis helps address instability and ambiguity issues associated with single-attribute predictions, thereby improving reservoir prediction accuracy and guiding fault identification more effectively.There are various methods for seismic multi-attribute fusion. Early techniques involved color space-based fusion technology, typically representing different information using three primary colors (red, green, blue). In the 21st century, fusion techniques based on mathematical methods and disciplines such as neuroscience have emerged. Each fusion method has its own scope of application and limitations, highlighting the necessity of selecting appropriate attribute methods for prioritized fusion.

4. CONCLUSION

As 3D seismic exploration continues to advance and computational capabilities improve, seismic attribute technology is becoming increasingly mature in fault interpretation. Based on extensive literature research, this article elaborates on the principles and advantages and disadvantages of using seismic data for identifying and predicting small faults. However, single attributes have limitations. Furthermore, the complexity of small fault development results in poor performance when using single attributes alone. Therefore, when interpreting faults, attribute fusion methods are often employed. Multi-attribute fusion technology reduces the ambiguity of single attributes and enhances the ability to identify small faults. This is particularly significant in the study of small fault prediction and will be a key focus in future attribute research.

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