Automatic extraction of horizons through faults

Introduction

Accurate seismic data interpretation can get more accurate reservoir prediction results. As the basis of seismic interpretation, horizon interpretation plays an important role in exploration. In recent years, with the improvement of exploration difficulty, the quality of data collected is not good. It puts forward higher requirements for horizon interpretation methods. The traditional method of automatic horizon extraction is mainly based on the local slope of seismic data, selecting a specific seed point, and accumulating recursively according to the local slope. However, because the slope of discontinuous reflection such as fault and noise can’t be accurately obtained, this method can only be used for seismic data with continuous and simple structure. And the extraction error will accumulate with the distance, resulting in the horizon far away from the seed point can’t be accurately extracted.

Wu and Fomel (2018) used structural tensor to estimate the linearity and local slope of seismic data. Linearity can reflect the continuity of seismic reflection. The linearity is used as the weight to control the influence proportion of slope at fault and guide the horizon extraction. At the same time, DTW (Dynamic Time Warping) algorithm is used to directly correlate the seismic traces on both sides of the fault. According to the principle of consistent phase, the horizon passing through the fault can return to the correct position. Structure tensor is an algorithm based on image domain, which calculates the linearity and local slope by calculating the internal relationship between the pixels in the image. The algorithm has poor noise resistance and stability, and is easily affected by aliasing (Jiang, 2018).

To solve this problem, this paper studies an automatic horizon extraction algorithm under fault control. First, the local slope is obtained by plane wave destruction. The prediction step is selected to construct the prediction, and a prediction data volume is obtained. The non-stationary similarity algorithm is used to calculate the similarity between the original data and the prediction data volume, which is used as the weight (Liu et al., 2014). The weight obtained by this method has higher resolution to faults. Then, based on the slope and phase, the horizon extraction equation is constructed. The slope determines the overall trend of the horizon curve, and the phase describes the details of the horizon curve. In the least square system, the initial horizon curve is solved iteratively to get the final horizon curve. The method is applied to synthetic data and field data, and the results show that it can accurately extract cross fault horizon. It is also robust to noise.

Slope estimation

Slope estimation can be divided into local slope estimation and similar slope (Li and Liu, 2021) estimation. The local slope reflects the dip information of the event and determines the overall trend of the horizon curve. The similar slope reflects the phase information of seismic wave and depicts the details of horizon curve.

In my research, plane wave destruction is used to estimate the local slope (Fomel, 2002). Plane wave destruction is mainly based on the local plane wave differential equation to solve the slope. The local plane wave differential equation can be expressed as

\[ \frac{\partial P(t,x)}{\partial x} + \sigma \frac{\partial P(t,x)}{\partial t} = 0 \]  

(1)

Where \( P(t,x) \) is the wave field of plane wave, \( t \) and \( x \) represent time and offset, \( \sigma \) is the seismic reflection slope, which represents the first derivative of time to offset. The essence of plane wave destruction is that there is a connection between a certain seismic trace and its adjacent seismic traces. The information of the current seismic trace can be predicted by the adjacent traces. The plane wave differential equation can be solved by the finite difference method after \( Z \) transformation of time and space. The local slope is usually obtained by \( Z \)-transform domain five-point central difference filter.

The overall trend of the horizon curve has been determined by the local slope, and the details of the horizon curve need to be described to reflect the discontinuous reflection characteristics such as fault
and noise. At this time, we need to introduce the phase information, and get the similar slope by directly establishing the relationship between seismic traces. The similar slope can be obtained by DTW. DTW can dynamically program two signals to get the best match between them. As shown in Figure 1. For the two series with different lengths in Figure 1 (a), DTW can automatically warp them to make the two series as consistent as possible. The result of warping is shown in Figure 1 (b).

![Figure 1](image)

**Figure 1** (a) Before dynamic time warping. (b) After dynamic time warping.

When solving the DTW algorithm, it can be decomposed into a series of subproblems. By dealing with these subproblems, the final solution is obtained (Hale, 2013). In seismic data, for two seismic signals \( f[i] \) and \( g[i] \), the function of DTW algorithm is to calculate the time difference series \( u[i] \)

\[
f[i] = g[i + u[i]], i = 0, 1, 2, \ldots, n - 1
\]

In a seismic profile, we can correlate all time samples of any two seismic traces by DTW, and get the time difference series. Using the time difference series, the similar slope \( \theta \) can be expressed as

\[
\theta = \frac{\Delta t(x)}{\Delta x}
\]

Where, \( u \) is the time difference sequence calculated by DTW algorithm. \( \Delta x \) is the interval between two seismic traces. \( \Delta t(x) \) is the time interval between two seismic traces on the horizon curve.

**Automatic horizon extraction under fault control**

In the horizon extraction, if we want to extract the discontinuity event well, it is necessary to characterize the fault. The accuracy of fault detection will directly affect the accuracy of horizon extraction in discontinuous reflection. In this study, nonstationary similarity technology is used for fault detection. Firstly, the plane wave destruction filter is used to construct the prediction data volume. Then the non-stationary similarity between the original data and the prediction data volume is calculated. By using the method of shaping regularization instead of localization to smooth the seismic data in space, the time windows at different positions can be adjusted adaptively. Using this method to characterize the non-stationary seismic signal, the results can show the local characteristics of the signal very accurately (Liu et al., 2014). And the similarity can represent the difference between the two signals. By combining the similarity attributes with the non-stationary features of seismic data, the similarity indexes based on different features of the data can be obtained. This index can provide a good method for fault detection, so as to better guide the horizon extraction work.

Based on the idea that the slope of seismic horizon curve is equal to the pre-estimated local reflection slope, a horizon extraction equation can be established (Wu and Fomel, 2018)

\[
\begin{bmatrix}
W\frac{\partial t(x)}{\partial x} \\
\lambda W\frac{\Delta t(x)}{\Delta x} \\
\mu \frac{\partial^2 t(x)}{\Delta x^2}
\end{bmatrix}
\approx
\begin{bmatrix}
W\sigma \\
\lambda \omega \theta \\
0
\end{bmatrix}
\]

Where, \( w \) is the weight of nonstationary similarity calculation. \( t(x) \) is the horizon curve. \( x \) is the track number. \( \sigma \) is the local slope. \( \lambda \) and \( \mu \) represent a small constant, which is used to balance the equation. \( \theta \) is the similar slope. Firstly, one or more control points on the same horizon are selected, and the initial horizon curve is calculated by using the selected control points. When the number of selected control points is one, the initial horizon curve is a straight line passing through the control point. When the number of control points is multiple, the initial horizon curve is obtained by interpolation based on the
information of all control points. Based on the established equation of horizon extraction, the method of matrix solution is used to update the initial horizon curve iteratively. The least square solution of the equation can be obtained, which is the final horizon curve.

Application of synthetic example

In order to verify the effectiveness of the proposed algorithm, a synthetic data is used to test, as shown in Figure 2 (a). The model is part of the synthetic data constructed by Claerbout (2006). It is a sinusoidal synthetic seismic image containing faults.

![Figure 2](image)

Figure 2 (a) Synthetic data from Claerbout. (b) Horizon extraction results.

The method described above is used for automatic horizon extraction, and the results are shown in Figure 2 (b). It can be seen that the horizon curve can be accurately extracted when only one control point is selected. In the lower left corner of the seismic section, the horizon curve is very precise for fault description. At the same time, for the upper right corner of the section, this method can effectively eliminate the influence of boundary effect and has higher stability. The horizon far away from the control point can also be accurately fitted.

In order to verify the anti-noise performance of the algorithm, random noise with signal-to-noise ratio of 3 is added to the above data, as shown in Figure 3 (a). Automatically extract the horizon from the noisy data, and the result is shown in Figure 3 (b). It can be seen that the extracted horizon is well matched with the real horizon, the fault position is clear, and the horizon is still accurate far away from the control point.

![Figure 3](image)

Figure 3 (a) Noisy data. (b) Horizon extraction results.

Application of field example

The above model has theoretically verified the effectiveness of the algorithm for fault fine characterization. The noise data test also proves that the method has anti-noise performance. In order to further prove the applicability of the proposed method, it is applied to field seismic data. The field seismic data selected is a subset of the Parihaka seismic data obtained off the coast of New Zealand (New Zealand Petroleum & minerals, 2014). It can be obtained from SEG open data repository. The
seismic profile contains complex geological structure, including multi generation fault and meandering channel system, as shown in Figure 4 (a).

![Figure 4](image)

Figure 4 (a) Marine data. (b) Horizon extraction results.

The horizon extraction result of the marine data is shown in Figure 4 (b). It can be seen that when there is only one control point, the whole horizon fits well. The horizon near the fault can be clearly displayed, and the channel information can also be reflected, which further verifies the effectiveness of the proposed method.

Conclusions

This paper improves a method of horizon fitting based on slope information under fault control. This method is more accurate and stable for cross fault seismic data horizon extraction. Firstly, the plane wave destruction is used to obtain the horizon dip information and determine the overall trend of the horizon curve. According to the dip information, structural prediction is made. The non-stationary similarity coefficient between the original data and the prediction data volume is calculated and used as the weight parameter to control the influence proportion of the slope at the fault. Then the similarity between different traces of the original data is calculated, and the similarity slope is obtained. The phase information is used to further depict the details of horizon curve. Finally, the control point is selected as the starting point of horizon extraction. Guided by the dip and phase information, the iterative solution is carried out under the least square system to realize the automatic horizon extraction. The effectiveness of the method is proved by the detection of synthesis and field data. The noise test shows that the method has the ability of anti-noise. However, the accuracy of the algorithm is questionable for the event that can’t be identified manually.

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References

Li, J.L. and Liu, G.C. [2021] Automatic horizon extraction method of seismic data based on plane wave similarity. 82nd EAGE Conference and Exhibition.