Introduction

For the past few years, sub-azimuth stack seismic data have been selected and used for fault description, reservoir prediction and fluid detection and this work has made significant progress in the field of seismic data interpretation. But, in most instances, the constant azimuth can’t parallel (or perpendicular) all the fracture strikes. So, how to find the azimuth parallel (or perpendicular) all the fracture strikes and extract the data corresponding to this azimuth is the key. A great deal of previous theoretical research proves that the properties of the P-wave changes regularly with the changing of the angle between the propagation direction of seismic wave and the strike of fractures. Sena (1991), Grechka Vladimir & Ilya Tsvankin (1998) and Ruger (1998) all propose that in anisotropic media, the P-wave velocity, reflection coefficient, etc. change periodically with azimuth. Hao Shouling and Zhao Qun (2004), Qi Yu, et al. (2009) conducted physical models study on the azimuthal anisotropy of P-wave being propagated in high-velocity HTI media and achieved the following conclusion: The amplitude of the top and the bottom of the HTI media decreases with the increase of the angle between the line and the fracture strike; the reflection time of the bottom surface of the fracture medium increases with the increase of the angle. In this paper, according to seismic wave propagation properties in fracture media, a method that the fault-sensitive and reservoir-sensitive dominant azimuth seismic data are adaptively extracted point by point on the basis of the azimuth-preserved migration processing of the “Wide-azimuth, broadband and high-density (WBH)” data is proposed. The dominant azimuth seismic data is applied to the reservoir research and has improved reservoir prediction accuracy.

Method and/or Theory

The definition of Dominant Azimuth

It can be inferred from the previous physical model study results that the top of the HTI media, the azimuth corresponding to the strong amplitude of the event of gather is parallel the fractures strikes, the dominant azimuth of the reservoir prediction; and the azimuth corresponding to the weak amplitude is perpendicular the fractures strikes, the dominant azimuth of the faults. And the bottom of the HTI media, azimuth corresponding to the convex apex of the event is parallel the fractures strikes, the dominant azimuth of the reservoir prediction; and the azimuth corresponding to the concave apex of the event is the dominant azimuth of the faults. Thus, the following 4 Dominant Azimuths are defined (figure 1):

- **The Minimum Time Azimuth ($\theta_{AZmin}$)**: The azimuth corresponding to the convex apex of the event of Azimuthal Gather (Figure 1a) is the dominant azimuth of the reservoir at the bottom of the HTI medium;
- **The Maximum Time Azimuth ($\theta_{AZmax}$)**: The azimuth corresponding to the concave apex of the event of Azimuthal Gather (Figure 1b) is the dominant azimuth of the fault at the bottom of the HTI medium;
- **The Strongest Amplitude Azimuth ($\theta_{AZmax}$)**: The azimuth corresponding to the strongest amplitude of the event of Azimuthal Gather (Figure 1c) is the dominant azimuth of the reservoir on the top and (or) bottom of the HTI medium;
- **The Weakest Amplitude Azimuth ($\theta_{AZmin}$)**: The azimuth corresponding to the weakest amplitude of the event of Azimuthal Gather (Figure 1d) is the dominant azimuth of the fault on the top and at the bottom of the HTI medium.

![Figure 1: Definition of Dominant Azimuth.](image-url)
Method and Algorithm

An effective approach for seismic data regularization has been presented by Wang Xia, et al. (2017). The data regularized in offset-azimuth domain can be denoted by $D(x, y, t, l, \theta)$, where $(x, y)$: the coordinate, $t$: time, $l$: offset, $\theta$: azimuth.

Firstly, an equal-azimuth stack is applied to $D(x, y, t, l, \theta)$:

$$G_{\theta}(x, y, t, \theta) = \int D(x, y, t, l, \theta) dl$$  

(1)

And then, a full-azimuth stack is applied to $G_{\theta}(x, y, t, \theta)$:

$$S(x, y, t) = \int_{0}^{\theta_{\text{max}}} G(x, y, t, \theta) d\theta$$  

(2)

Then, we define the cross-correlation matrix between $G_{\theta}(x, y, t, \theta)$ and $S(x, y, t)$:

$$R[S, G_{\theta}] = \{ \rho(x, y, t, \theta, \Delta t) \}$$  

(3)

Where, $\rho(x, y, t, \theta, \Delta t)$ is calculated by cross-correlation formula:

$$\rho(x, y, t, \theta, \Delta t) = \frac{\sum (TrS(x, y, t + \Delta t) - TrS(x, y, t + \Delta t) \cdot (TrG_{\theta}(x, y, t) - TrG_{\theta}(x, y, t))}{\left(\sum (TrS(x, y, t + \Delta t) - TrS(x, y, t + \Delta t) \cdot (TrG_{\theta}(x, y, t) - TrG_{\theta}(x, y, t))\right)^{2}}$$  

(4)

Where, $TrS(x, y, t)$ and $TrG_{\theta}(x, y, t)$ are the traces of $S(x, y, t)$ and $G(x, y, t, \theta)$. $\Delta t$: the cross-correlation time delays,

Moreover, the Minimum time $\Delta t_{\text{min}}$ of $G_{\theta}(x, y, t, \theta)$ and the corresponding azimuth $\theta_{\Delta t_{\text{min}}}$ can be determined by:

$$\Delta t_{\text{min}}(x, y, t) = \min_{\theta} \Delta t(x, y, t) = \arg \rho(x, y, t, \theta, \Delta t)$$  

(5)

$$\theta_{\Delta t_{\text{min}}}(x, y, t) = \arg \rho(x, y, t, \theta, \Delta t_{\text{min}})$$  

(6)

Similarly, the maximum time $\Delta t_{\text{max}}$ of and the corresponding azimuth $\theta_{\Delta t_{\text{max}}}$ get from following:

$$\Delta t_{\text{max}}(x, y, t) = \max_{\theta} \Delta t(x, y, t) = \arg \rho(x, y, t, \theta, \Delta t)$$  

(7)

$$\theta_{\Delta t_{\text{max}}}(x, y, t) = \arg \rho(x, y, t, \theta, \Delta t_{\text{max}})$$  

(8)

At the same time, we use $\theta_{\Delta t_{\text{max}}}$ and $\theta_{\Delta t_{\text{min}}}$ to record the azimuths corresponded to the strongest and the weakest amplitude in data $G_{\theta}(x, y, t, \theta)$, so we have:

$$\theta_{\Delta t_{\text{max}}}(x, y, t) = \arg \max_{\theta} G_{\theta}(x, y, t, \theta)$$  

(9)

$$\theta_{\Delta t_{\text{min}}}(x, y, t) = \arg \min_{\theta} G_{\theta}(x, y, t, \theta)$$  

(10)

Finally, 4 Dominant Azimuth Gathers corresponding to 4 Dominant Azimuth based on the formulas 6, 8, 9 and 10 are extracted from $D(x, y, t, l, \theta)$:

$$G_{i, \Delta t_{\text{min}}}(x, y, t, l, \theta_{\Delta t_{\text{min}}}) = D(x, y, t, l, \theta_{\Delta t_{\text{min}}})$$  

(11)

$$G_{i, \Delta t_{\text{max}}}(x, y, t, l, \theta_{\Delta t_{\text{max}}}) = D(x, y, t, l, \theta_{\Delta t_{\text{max}}})$$  

(12)

$$G_{i, \Delta t_{\text{max}}}(x, y, t, l, \theta_{\Delta t_{\text{min}}}) = D(x, y, t, l, \theta_{\Delta t_{\text{max}}})$$  

(13)

$$G_{i, \Delta t_{\text{min}}}(x, y, t, l, \theta_{\Delta t_{\text{max}}}) = D(x, y, t, l, \theta_{\Delta t_{\text{min}}})$$  

(14)

And the 4 Dominant Azimuth Data Volumes are yielded by using the following formula:

$$D_{\Delta t_{\text{min}}T_{0}} = \int G_{i, \Delta t_{\text{min}}T_{0}}(x, y, t, l) dl$$  

(15)

$$D_{\Delta t_{\text{max}}T_{0}} = \int G_{i, \Delta t_{\text{max}}T_{0}}(x, y, t, l) dl$$  

(16)

$$D_{\Delta t_{\text{max}}A} = \int G_{i, \Delta t_{\text{max}}A}(x, y, t, l) dl$$  

(17)

$$D_{\Delta t_{\text{min}}A} = \int G_{i, \Delta t_{\text{min}}A}(x, y, t, l) dl$$  

(18)

Some examples are given in Figure 2. The Minimum time (Figure 2b) is the reservoir prediction dominant azimuth data. The Maximum Time (Figure 2a) is the fault-sensitive dominant azimuth data.
The faults indicated by the green arrows in Figure 2a is sharper at the Maximum Time azimuth data than that in the Figure 2c.

**Figure 2** dominant azimuth data volume sections.

**Example**

The study area is located in the Jiayi fault zone in the western half of the northern part of Tanlu Fault Zone. And the target formation is Carboniferous-Permian metamorphic rocks and granites basement and the overlaid Shuangyang Formation I in Paleogene (E2S1). There are extreme development of fractures and the complicated fracture relationship. Controlled by the early basement faults and paleo-geomorphology, the basal conglomerate in the E2S1, a good reservoir, is deposited into the groove area, thin in thickness and its lateral variation lacks regularity; and since it directly contacts with the bedrock, the seismic reflection from its top surface can’t be separated from that of the bedrock; the bedrock faults have a great influence on seismic waves. Reservoir prediction faces significant challenges. In 2017, the Wide-azimuth Broadband High-density acquisition was implemented in the area. It can be seen from the OVG (Offset vector gather) data that the amplitude and reflection time of the event of the large offset (or large reflection angle) data show obvious periodic changes with the azimuth, indicating the fractures characteristics (Figure 3).

**Figure 3: The OVG data**

Figure 4 is the result of hydrocarbon detection applying the the full-azimuth stack data, sub-azimuth stack data (the 25°-75° sub-azimuth stack data parallel to the primary structural trend) and the reservoir dominant azimuth data, Well O1 is an industrial oil flow well, showing as a dry hole in the hydrocarbon detection of the full stack (Figure 4a) and the sub-azimuth stack data (Figure 4b) parallel to the strike of the structure in the target layer, which is misfit the real drilling result; while high oil content can be seen in the hydrocarbon detection of the dominant azimuth (the Strongest Amplitude) data (Figure 4c), which is consistent with the real drilling result. The four industrial gas wells are indicated by pink dots on the lower right side of the plane. In the view of the prediction results, the hydrocarbon detection results of the full-azimuth stack data (Figure 4a) and the sub-azimuth stack data (Figure 4b) have a lower coincidence rate than the dominant azimuth data hydrocarbon detection results (Figure 4c) with the real drilling.

**Conclusions**

The adaptive extraction method of dominant azimuth seismic data fully exploits the advantages of the “Wide-azimuth Broadband High-density” seismic data, effectively utilizes the azimuth information of the azimuth-preserved migration data, realizes the avoidance of non-predicted target information,
highlights the predicted target information and deeply developed the potential value of seismic data. It is a new method formed based on the theory of P-wave propagation in HTI media. When the seismic wave propagation direction is perpendicular to the fracture strike, the fracture has greater interference to the seismic wave, but the influence of reservoir or fluid anomaly to the P-wave is not obvious, which is not conducive to the identification. When the seismic wave propagation direction is parallel to the fracture strike, the interference of the fracture to the seismic wave is smaller, which is more conducive to prediction of reservoirs and fluids.

![Figure 4](image)

**Figure 4**: Basal conglomerate hydrocarbon detection planes: a. the full-stack data, b. the sub-azimuth stack data and c. the maximum energy data (Legends: ● Industrial gas well; ○ Industrial oil well; ○ Slight oil content; ○ Water zone)

References


