Application of Point-by-Point Vector Synthesis in Walkaway VSP Logging Data Processing

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Abstract. At present, it is necessary to use Walkaway VSP logging imaging data to drill horizontal shale gas wells in exploration areas lacking three-dimensional seismic data. Walkaway VSP logging imaging profile can delineate the formation structure around wells, obtain detailed information of dip, inclination and fault around wells, and guide the trajectory design of horizontal wells. But VSP logging is richer and more complex than conventional seismic data. The precondition of up-going wave imaging is to separate up-going P-wave or converted S-wave from complex wave field. Nowadays, most vector synthesis techniques can not completely separate up-going P-wave from up-going converted wave, which affects the accuracy of final imaging results. In order to achieve the best wave field separation effect of VSP logging data, the point-by-point vector synthesis technique is adopted. Firstly, the directional rotation synthesis of horizontal components is carried out according to the maximum energy criterion. Then the rotational synthesis of horizontal and vertical components uses ray tracing based on velocity model to estimate the polarization angle of time-varying upward reflected P-wave or converted wave. The method of "velocity fine-tuning scanning" is applied to search for the best synthesis angle, and the point-by-point vector synthesis is carried out by calculating the time-varying polarization angle. Finally, the best separation effect data are selected as the final vector synthesis result. This technique solves the problem that conventional vector synthesis cannot completely separate up-going P-wave from up-going converted S-wave. Upward P-waves acquired after separation has clear characteristics, more continuous phase axis and good fidelity processing effect, which lays a solid foundation for fine imaging of target formation in the study area and has become an indispensable key supporting technology for optimizing the trajectory of horizontal wells in shale gas development in Sichuan Basin.

1. Introduction
Vertical seismic profile (VSP) is a kind of borehole seismic observation technology. Compared with ground earthquakes, VSP data have high signal-to-noise ratio, high resolution and obvious kinematic and dynamic characteristics of waves [1]. VSP technology provides the most direct correspondence between underground stratum structure and ground survey parameters. This technology can provide precise time-depth conversion and velocity model for processing and interpretation of surface seismic data, improve the accuracy of surface seismic imaging, and solve the imaging problem of small structures near wellbore that surface seismic technology cannot solve. VSP technology realizes high resolution imaging of strata around wellbore, makes lithologic characteristics research and reservoir evaluation results more reliable, thus providing reliable location and depth of drilling target geology.
body, and avoiding target missing in drilling. However, VSP logging data are more abundant and complex than conventional seismic data, and downward direct wave, downward multiple wave, downward converted wave, upward reflection wave, upward converted wave and upward multiple wave can usually be observed. In order to achieve fine imaging and accurately depict the details of formation structure, it is necessary to separate up-going P-wave or converted S-wave from the complex wave field of VSP logging, so as to ensure the final imaging accuracy. In order to separate the wave field more reliably, cleanly and objectively, it is necessary to synthesize the three-component data of Walkaway VSP by vector rotation. Vector rotation synthesis of Walkaway VSP three-component wave field is usually achieved by projecting the observed wave field to the polarization direction of a particular waveform. However, at present, most vector synthesis techniques only rotate the same seismic trace at a fixed angle, often fail to achieve ideal synthesis results. In order to achieve the best wave-field separation effect of VSP logging data, a method of using ray tracing to estimate the polarization angle of up-going wave and point-by-point vector synthesis based on velocity fine-tuning scanning is developed. Combined with multi-channel filtering technology, the up-going P-wave or converted S-wave with clean wave field are finally obtained, which lays a solid foundation for high-precision imaging of VSP logging data. This technology plays an important supporting role in the optimization design of horizontal well trajectory for deep shale gas development in Sichuan Province.

2. Technical principle

2.1. Principle introduction
Vector wavefield rotation synthesis mainly achieves wave field separation by projecting the observed wavefield to the polarization direction of a particular wavefield (e.g. direct P-wave, up-going P-wave and converted wave). The polarization directions of these specific waves are different when they reach the receiver at different observation times. Estimation of polarization angle of up-going P-wave field and converted wave field at different time is the difficulty of this technique. The technology includes three parts: directional rotation synthesis of horizontal component, point-by-point vector synthesis of horizontal component and vertical component, and subsequent multi-channel filtering wave field separation. The horizontal component directional rotation synthesis uses a single direction for the whole channel synthesis, and does not need to be processed at each sampling point. Horizontal and vertical components are synthesized by point-by-point vector synthesis, which is based on the time-varying polarization angle. The final wave field separation uses the sequence from strong to weak to separate the required wave fields one by one.

2.2. Directional rotation synthesis of horizontal components
The observation direction of horizontal component in Walkaway VSP well is not necessarily in the ray plane of shooting point and receiving point, so it is necessary to synthesize horizontal component by directional rotation. According to Fig. 1, it is assumed that the projection of the ray plane in the horizontal direction is in the direction of Hp, which is at an angle of \( \theta_1 \) with the direction of the horizontal component X.

![Figure 1. Horizontal component redirection diagram (top view)]
Then, the directional rotation synthesis of horizontal components of $X$ and $Y$ components can be expressed as

$$
\begin{cases}
    r = x \cos \theta_i + y \sin \theta_i \\
    t = x \sin \theta_i - y \cos \theta_i
\end{cases}
$$

(1)

In the above formula, $X$ and $Y$ represent the two horizontal components measured by VSP, and $r$ and $t$ represent the two components polarized in the plane of $H_p$ and in the plane perpendicular to $H_p$ respectively after directional rotation. The key of formula (1) is to obtain the polarization angle $\theta_1$. Because the polarization direction of P-wave is the same as its propagation direction, the polarization angle $\theta_1$ can be estimated according to the maximum energy near the first arrival of P-wave. The calculation formula is as follows:

$$
\theta_1 = \frac{1}{2} \arctan \left( \frac{\sum_{i=1}^{N} x_i y_i}{\sum_{i=1}^{N} (x_i^2 - y_i^2)} \right)
$$

(2)

In the formula (2), $X_i$ and $Y_i$ represent the sampling values of two horizontal components within a time window including the first arrival of P-wave, and $N$ represents the sampling points in that time window.

2.3. Point-by-point vector synthesis of horizontal and vertical components

Figure 2 shows a schematic diagram of up-going wave propagation direction.$\theta_2$ represents the polarization angle of the up-going wave to the receiving point (the angle between the wave propagation direction and the vertical direction).

![Figure 2. Schematic diagram of up-going wave propagation direction of VSP](image)

If $\theta_2$ is known, the horizontal component and the vertical component can be projected into the coordinate system of the propagation direction, so that the up-going P-wave and S-wave can be rotated into two new components. The calculation formula is as follows:

$$
\begin{cases}
    R = z \cos \theta_2 + r \cos \theta_1 \\
    T = z \sin \theta_2 - r \cos \theta_1
\end{cases}
$$

(3)

In the above expressions, $R$ and $T$ represent two components of polarization in the direction of up-going P-wave propagation and perpendicular to the direction of up-going P-wave propagation, $Z$ represents the vertical component measured by VSP, and $r$ represents the horizontal component of polarization in the ray plane after horizontal directional rotation. For the same receiving point, the up-going waves received at different times come from the reflective interface of different depths. The
direction of propagation of these up-going waves to the receiving point is different, that is, the polarization direction is different. Therefore, in order to synthesize the required wave onto the same component record, it is necessary to synthesize the horizontal and vertical components point by point with time-varying vector rotation [2]. Therefore, the determination of polarization angle $\theta_2$ is very important.

Assuming that the velocity model is known, ray tracing can be carried out and the angle of $\theta_2$ can be calculated according to the ray path. However, velocity models can only be estimated by various methods, such as direct wave estimation based on zero offset VSP, but absolute true values cannot be obtained. Therefore, the angle of $\theta_2$ calculated from ray tracing results also has a large error. In this case, in order to obtain better rotation effect, a rotation synthesis technology based on "velocity fine-tuning scanning" is proposed. That is to say, in a certain range of velocity values, several groups of velocity parameters are divided into equal intervals to calculate the corresponding $\theta_2$ angles, and then the corresponding rotation synthesis results are calculated. Finally, the group of data with the best separation effect is selected as the final result. This step improves the effect of vector synthesis. Through the above rotational synthesis steps, the up-going P-wave and the up-going converted shear wave with similar apparent velocities can be separated into different components. However, there are still down-going and other interference waves. Because the apparent velocities of these waves are quite different from those of up-going P-wave and converted wave (the direction of apparent velocity is opposite), they can be filtered out successively by traditional multi-channel filter or median filter, and finally the separated up-going P-wave and converted wave fields can be obtained.

3. Application Effect of Point-by-Point Vector Synthesis Technology

3.1. Directional rotation synthesis of horizontal components

Fig. 3 is the original X and Y horizontal component records of two shots in Walkaway VSP logging of a well in Sichuan Basin. It can be seen that the horizontal component records are chaotic and the continuity of the up-going and down-going traveling wave coaxial is poor, which indicates that the down-hole geophone has no orientation in the acquisition process, and the direction of its X and Y components is randomly distributed. According to the maximum energy criterion, the two horizontal components are rotated to the horizontal plane and perpendicular to the ray plane, and two new components are synthesized, which are recorded as $r$ and $t$ components respectively (Fig. 4). After directional rotation synthesis, we can see clearly and continuously down-going and up-going traveling waveform events in the horizontal component records of $r$ and $t$. 

![Figure 3](image-url)
3.2. The point-by-point vector synthesis of horizontal and vertical components

Before point-by-point vector synthesis, the records of the vertical component are shown in figure 5, and the records of the horizontal component are shown in figure 4 (a). In order to compare the application effects, the traditional vector rotation synthesis method was first tested, and the results were shown in figure 6. The traditional method is to determine the polarization angle of P-wave based on the first arrival of direct wave, and then rotate the whole seismic trace with the same polarization angle. From the synthetic results, the up-going P-wave and the up-going converted S-wave obtained by traditional methods still exist in both radial and tangential components, which are not completely separated, indicating that the separation effect is not good. However, from the implementation effect, the target function of this traditional method has been achieved, because in the two records after the traditional vector rotation synthesis, the energy near the first arrival is obviously a strong one and a weak one, which is the goal of this method. This shows that the poor separation effect of the traditional vector rotation synthesis method for P-wave and converted S-wave is the defect of the method itself. It is not caused by improper handling of parameters. The main reason is that the traditional method uses the same polarization angle to synthesize the whole seismic trace.
Figure 6. Radial R and tangential T component recording after vector composition by traditional method

Figure 7 shows the result of synthesis using point-by-point vector synthesis technique. After point-by-point time-varying vector synthesis, the radial R component is mainly composed of up-going P-wave and down-going converted S-wave, while the tangential T component is dominated by down-going P-wave and up-going converted S-wave. It can be seen that the up-going P-wave and the up-going converted S-wave are synthesized into two components respectively, and no longer mix and exist in one component at the same time. Point-by-point time-varying vector synthesis has achieved better results than the traditional vector rotation synthesis method, which is well prepared for the next wave field separation.

Figure 8 shows the radial R component recordings synthesized by point-by-point vectors, in which the up-going wave is mainly reflected P-wave and the down-going wave is mainly the interference wave. Yellow line indicates the direction of down-going P-wave coaxiality to be removed, blue line indicates the direction of down-going converted S-wave coaxiality to be removed, and the red line indicates the direction of up-going P-wave coaxiality to be extracted. Using two-step median filter, down-going P-wave and down-going converted S-wave can be removed separately, and the useful up-going P-wave records can be obtained. Generally, the up-going P-wave group obtained by median filtering technology has clear characteristics, more continuous coaxial, good fidelity processing effect, and is more conducive to later imaging [3].
4. Conclusions

(1) The imaging effect of VSP logging depends on the separation accuracy of up-going P-wave and up-going converted S-wave. If P-wave and S-wave are not completely separated, the accuracy of subsequent imaging results will be affected. Point-by-point vector synthesis technology uses ray tracing to estimate the polarization angle of up-going P-wave and velocity fine-tuning scanning method to synthesize. It solves the problem that conventional vector synthesis cannot completely separate the up-going P-wave from the up-going converted S-wave. The up-going P-wave group obtained by this technology has clear characteristics, more continuous coaxial, and good fidelity processing effect. This technology has laid a solid foundation for fine imaging of target formation in the study area, and has become an indispensable key supporting technology for optimizing the trajectory of horizontal wells in shale gas development in Sichuan Basin. Point-by-point vector synthesis technology has been widely used in Chang Ning, Yong Chuan and Mo Xi blocks of Sichuan Province, with good application effect and broad application prospects.

(2) Point-by-point vector synthesis method and the most commonly used Walkaway VSP logging imaging methods (including VSP-CDP conversion imaging method, Kirchhoff VSP migration method, etc.) are sensitive to velocity model. The accuracy of velocity model will ultimately affect the imaging results, and how to build a high-precision velocity model with anisotropy needs further study. It is suggested that the research on the method of "joint anisotropic velocity model establishment between VSP data and surface seismic data" should be further strengthened in the future.

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