Pre-stack Depth Migration based on VTI Media in Common Shot Domain

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Abstract. With the increasing complexity of seismic exploration targets, the basic imaging theory based on the basic assumption of simple isotropic media cannot meet the actual needs of oil and gas exploration at this stage. Therefore, the study of imaging methods in anisotropic media is of great significance to the exploration of various underground structures and mineral exploitation. In this paper, the SSF continuation operator for VTI anisotropic medium is derived and the one-way prestack depth migration with VTI media in common shot domain is realized. The VTI-HESS model is verified by calculation. Compared with prestack depth migration of various isotropic media, it can be seen that prestack depth migration of VTI media has better imaging effect because of considering anisotropic parameters, which is closer to the actual imaging effect of exploration data.

1. Introduction
In recent years, migration imaging methods in the field of seismic exploration have developed more and more rapidly. Various new migration methods and theories emerge in endlessly, and many excellent results have been achieved. However, there are some shortcomings in the current migration imaging methods, such as Kirchhoff migration, which is difficult to apply to strong lateral velocity variation media.

Wave equation prestack depth migration technology has developed from isotropic media to anisotropic media, and some imaging results have been obtained by predecessors, but there are still many defects. Therefore, starting from isotropic medium migration method and based on the acoustic wave equation of isotropic medium, this paper deduces the SSF wave field continuation operator suitable for common-shot domain migration, and programs to realize prestack depth migration imaging of single-pass wave in common-shot domain. On this basis, the SSF wave field continuation operator suitable for VTI media is derived by adding the influence factor of anisotropic parameters, and prestack depth migration imaging of VTI media is realized. The validity and accuracy of the method are verified by VTI-HESS model.

2. Basic Principle of One-way Wave Continuation in VTI Medium
The general operation step of one-way wave migration imaging in common-shot domain is to extend and image each single-shot record separately, then superimpose all the imaging results of the whole imaging area on the same spatial position points, and finally obtain the results of the imaging area.
2.1. Isotropic Medium Operator

Wave field continuation is the core of wave equation migration imaging. Firstly, the wave field continuation formulas in F-K domain in horizontally layered media are derived by using the two-dimensional acoustic wave equation in isotropic media.

\[
\bar{P}(k_x, z + \Delta z; \omega) = \bar{P}(k_x, z; \omega)e^{\pm ik_x \Delta z}, k_z = \sqrt{\omega^2 s_0^2 - k_x^2} \tag{1}
\]

\(\bar{P}(k_x, z; \omega)\) is the two-dimensional Fourier transform of wave field \(P(x, z; t)\) to \(x\), \(t\), and \(t\) is travel time, \(k_x\) and \(k_z\) are horizontal and vertical wave numbers respectively.

But formula (1) is only applicable when the transverse velocity is uniform. When the transverse velocity of the medium is not uniform, it is dealt with by split-step Fourier method. Firstly, the medium is decomposed into two parts: background field and disturbance field. Background field is a horizontal layered medium. The background velocity field can be calculated directly by using formula (1), and the disturbance velocity field can be time-shifted. Combining with the phase shift calculation of background field, the final SSF one-way wave continuation operator can be obtained.

\[
\bar{P}_0(k_x, z + \Delta z; \omega) = \bar{P}(k_x, z; \omega)e^{\pm ik_x \Delta z} \tag{2}
\]

\[
P(x, z + \Delta z; \omega) = \bar{P}_0(x, z + \Delta z; \omega)e^{\pm i\omega \Delta s(x, z) \Delta z} \tag{3}
\]

Formulas (2) and (3) constitute the SSF wave field continuation operator for prestack depth migration imaging of one-way wave in common-shot domain.

2.2. VTI Medium Operator

The common shot SSF prestack depth migration imaging is based on the assumption of isotropic media. In actual strata, the subsurface medium is usually inhomogeneous medium. Based on SSF wave field continuation imaging of isotropic medium, prestack depth migration imaging of VTI medium is discussed in this section. Similar to isotropic media, SSF wave field continuation imaging in VTI media decomposes the velocity field into background field and disturbance field. However, because the propagation velocity of the continuation operator is the phase velocity varying with the angle, and the anisotropic parameters need to be considered, the stability of the continuation operator is reduced, and the computational complexity is greatly increased, which makes the wave field continuation process of VTI media more complex.

In the case of VTI medium, the background field includes not only the background slowness \(s_0(z)\), but also the background anisotropic parameters \(\varepsilon_0(z)\) and \(\delta_0(z)\). The disturbance field also includes not only the slow disturbance \(\Delta s\), but also the anisotropic parameter disturbance \(\Delta \varepsilon\) and \(\Delta \delta\). At the same time, the vertical wavenumber fraction \(k_z\) is also decomposed into background wavenumber \(k_{z0}\) and perturbation wavenumber \(k_r\) in the case of VTI medium.

\[
k_z(x, z, k_x) = k_{z0}(z, k_x) + k_r(x, z, k_x) \tag{4}
\]

And \(k_{z0} = \pm \frac{\omega}{V_0} \sqrt{\frac{\omega^2 - [1 + 2\varepsilon_0(z)] V_0^2 k_x^2}{(\omega^2 - 2 [\varepsilon_0(z) - \delta_0(z)] V_0^2 k_x^2) V_0^2 k_x^2}} \tag{5}\)

In VTI medium, the transverse velocity field changes little, so the low-order compensation of slow disturbance can be considered only, and the transverse anisotropic disturbance compensation can be omitted to obtain the vertical wavenumber \(k_r\).

\[
k_r(x, z, k_x) = k_{z0}(x, z, k_x) = \pm \omega \Delta s(x, z) \tag{6}
\]
In formula (7), \( V_0 = \min(V_{p0}) \). Formulas (5) and (6) are SSF expressions of vertical wave numbers in VTI media. In the process of continuation, it is similar to the operation of various isotropic media. First, phase shift calculation is carried out in the frequency-space domain, and then time-shift correction is carried out in the frequency-space domain for the phase-shifted wave field.

\[
P(x, z + \Delta z; \omega) = F_x^{-1} \left\{ e^{i k z_0(x) \Delta z} F_x \left\{ e^{i \omega \Delta x(x) \Delta z} p(x, z; \omega) \right\} \right\}
\]  

Formula (7) is the SSF wave field continuation operator in VTI medium. Among them, \( P(x, z + \Delta z; \omega) \) is the post-continuation wave field, \( \Delta z \) is the continuation step, and the value of \( k_{z \omega} \) is calculated according to formula (5).

3. Model Test

In order to verify the adaptability of SSF prestack depth migration imaging method in VTI medium to complex models, it is applied to HESS model. Figure 1a, b and c are P-wave velocity (\( V_{p0} \)) model, anisotropic parameter E and anisotropic parameter delta distribution of HESS model, respectively. Model length \( x = 72320 \text{ft} \), depth \( z = 29980 \text{ft} \), mesh spacing 20\text{ft}. The model has a minimum P-wave velocity of 5000\text{ft/s} and a maximum of 14800\text{ft/s}. The anisotropic parameters are 0.0~0.3 and 0.0~0.2. The recordings are obtained by finite difference forward modeling. There are 280 guns. The first gun's abscissa \( X = 0 \text{ft} \), the gun spacing 200\text{ft}, the single gun's 400 channels receiving, the channel spacing 40\text{ft}, the sampling interval 12\text{ms}, the sampling length 7980\text{ms}, the extension step 100\text{ft} and the extension depth 29800\text{ft} in the migration imaging process. Figure 2a is the result of split-step Fourier prestack depth migration imaging in isotropic media, and Figure 2b is the result of split-step Fourier prestack depth migration imaging in VTI media.

![Figure 1a. HESS P-wave Velocity Model](image-url)
Figure 1b. Anisotropic Parameters $\varepsilon$ of HESS Model

Figure 1c. Anisotropic Parameters $\delta$ of HESS Model
As can be seen from Figure 2, both algorithms can image the model correctly, and the interface of each layer has imaging response. Compared with the isotropic medium migration, the VTI medium migration results are much clearer and the noise is much lower in the same imaging area. For example, in region I, the diffraction arc of VTI prestack depth migration is obviously more convergent than that of isotropic prestack depth migration, and in region II, the imaging result of rock interface in Figure 2b is clearer than that in Figure 2a, which shows that the anisotropic parameter operator can be added to migration imaging to better identify the anisotropic parameter variation of underground media. Finally, compared with the imaging effect in area III, it can be found that the prestack depth migration imaging result in VTI medium is clearer and more continuous than that in isotropic medium.
4. Conclusion
With the increasing demand for accuracy in seismic exploration, wave equation migration imaging has become one of the best migration methods, which has high imaging quality that other methods do not have. In this paper, the prestack depth migration method of SSF single-pass wave in isotropic medium and VTI medium gun domain is studied. It is shown that the final result of wave equation migration imaging is determined by many key technology nodes. Because VTI medium migration adds anisotropic parameters to the whole algorithm flow, it is more similar to real seismic exploration data than isotropic medium migration method, so it can achieve better imaging effect. VTI medium migration considering anisotropic parameter information also provides reliable imaging basis for subsequent seismic data processing and interpretation. Therefore, in the actual production process, migration imaging technology considering anisotropic media parameter information is one of the technologies that can effectively improve the accuracy of seismic exploration imaging.

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