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RESEARCH ARTICLE

Methods and applications of 3-D wave equation common-azimuth prestack migration

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Abstract To tackle the difficulties of a 3-D full volume prestack migration based on the double-square-root (DSR) one-way wave equation in practical applications, the common-azimuth migration approach is first discussed using dual-domain wave propagators under the theoretical frame of crossline common-offset migration. Through coordinate transforming, a common-azimuth prestack tau migration technology that recursively continues the source and receiver wavefields and picks up the migrated results in the two-way vertical traveltime (tau) direction is developed. The migrations of synthetic data sets of SEG/EAGE salt model prove that our common-azimuth migration approaches are effective in both depth and tau domains. Two real data examples show the advantages of wave-theory based prestack migration methods in accuracy and imaging resolution over the conventional Kirchhoff integral methods.

Keywords wave equation, double-square-root, common-azimuth, prestack migration, buried hill, complex fault

1 Introduction

To obtain a more reliable image of complex structures in strong-contrast heterogeneous media, the advanced prestack depth migration technologies should be used to replace the conventional poststack migration methods in seismic imaging processing. Ray-based Kirchhoff migration is the most commonly used method for 3-D prestack depth migration due to its advantages such as efficiency in computation, target-oriented ability and flexibility in handling prestack data geometries. The wave-equation migration based on wavefield continuation algorithms, however, is a more accurate and robust alternative in the presence of multi-pathing and other complex wave phenomena such as caustic. In the past ten years, great progress has been made in studies on wave-theory based prestack depth migration (Stoffa, 1990; Wu and Huang, 1992; Ristow and Ruhl, 1994; Huang et al., 1999; Cheng et al., 2001; Li et al., 2003). With the support of advanced technologies related to PC-cluster systems and parallel computation, wave equation prestack depth migration has become an important imaging tool, and has been successfully applied to imaging the complex structures below salt bodies or in buried hills (Vaillant et al., 2000; Jin and Li, 2002).

The wave equation prestack depth migration technologies based on one-way wave propagators are mainly applied to migrating real 3-D seismic data due to its lower cost compared with reverse-time migration based on two-way wave propagators. They include shot-record migration (and synthetic areal-shot migration) based on the single-square-root (SSR) one-way wave equations, and shot-geophone migration based on the double-square-root (DSR) one-way wave equation. In the shot-record prestack depth migration, downgoing and upgoing wavefields are independently downward continued, and then migration sections are produced by using zero-time imaging condition. To ensure enough imaging aperture, many dummy traces should be padded on both sides of the two wavefields before downward continuation, and thus incurring a great deal of extra computation costs. In a whole, shot-record migration is very time-consuming, and its cost increases linearly with the shot number. To tackle these problems, synthetic areal-shot or delayed-shot migration technologies based on the theory of plane-wave decomposition are studied (Berkhout, 1992; Chen et al., 2004; Zhang et al., 2004). However, these alterative methods do not work as expected when the azimuth angles of 3-D prestack data are distributed in a narrow range or the crossline offset axis is sparsely sampled. On the contrary, shot-geophone (or "sinking survey") migration methods based on the DSR one-way wave equation are computationally efficient and with no limitation of imaging aperture. However, in practical applications, 3-D full-volume DSR wave equation migration is also confronted

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with some difficulties. On the one hand, its high computational dimension requires too many computer resources to be satisfied under current technological conditions, because the whole wavefields are downward continued simultaneously. On the other hand, imaging the prestack data with very low fold in crossline direction using DSR equation 3-D full volume migration will introduce many artifacts and contaminate the real geological structures (Biondi and Palacharla, 1996; Cheng et al., 2003a). Although common-offset (vector) migration (Deregowski and Rocca, 1981), offset plane-wave migration (Mosher et al., 1998) and cross-line common-offset migration (Cheng et al., 2003b) based on the DSR one-way wave equation have tackled the above problems of 3-D full volume migration to some extent, their implementations fail to include reasonable phase corrections in media with strong lateral velocity variations. At present, the common-azimuth migration is the most practical and efficient wave-theory based 3-D prestack depth migration technology because it overcomes difficulties that other migration approaches always encounter, although it was originally proposed to migrate the narrow azimuth prestack data (Boindi and Palacharla, 1996; Vaillant et al., 2000; Jin and Li, 2002; Cheng et al., 2003b; Bevc et al., 2005).

In this paper, under the theoretical frame of crossline common-offset migration, an amplitude-preserving common-azimuth prestack migration approach based on the dual-domain wave propagators is discussed. Numerical examples are shown to prove the validity of common-azimuth migration both in depth domain and two-way vertical traveltime (tau) domain.

2 Double-square-root one-way wave equation 3-D full volume migration operator

According to Cheng et al. (2003a), sinking survey of 3-D seismic data in heterogeneous media can be simulated with the following DSR one-way wave equation in midpoint-offset coordinates

$$\begin{cases} \dfrac{\partial u(\omega,\mathbf{m},\mathbf{h};z)}{\partial z} = -\mathrm{i}\omega s_0\left(\Gamma_\mathbf{s}+\Gamma_\mathbf{g}\right)u(\omega,\mathbf{m},\mathbf{h};z) \\ \dfrac{\partial u(\omega,\mathbf{m},\mathbf{h};z)}{\partial z} = -\mathrm{i}\omega\left(\dfrac{\Delta s_\mathbf{s}}{\Gamma_\mathbf{s}}+\dfrac{\Delta s_\mathbf{g}}{\Gamma_\mathbf{g}}\right)u(\omega,\mathbf{m},\mathbf{h};z) \end{cases} \tag{1a}$$

with the two square-root operators $\Gamma_\mathbf{s}$ and $\Gamma_\mathbf{g}$ satisfying

$$\Gamma_\mathbf{s} = \sqrt{1+\frac{1}{4\omega^2 s_0^2}\left[\left(\frac{\partial}{\partial m_x}-\frac{\partial}{\partial h_x}\right)^2+\left(\frac{\partial}{\partial m_y}-\frac{\partial}{\partial h_y}\right)^2\right]}$$

$$\Gamma_\mathbf{g} = \sqrt{1+\frac{1}{4\omega^2 s_0^2}\left[\left(\frac{\partial}{\partial m_x}+\frac{\partial}{\partial h_x}\right)^2+\left(\frac{\partial}{\partial m_y}+\frac{\partial}{\partial h_y}\right)^2\right]} \tag{1b}$$

where $u(\omega,\mathbf{m},\mathbf{h},z)$ is the 3-D prestack seismic wavefields, which is expressed as a function of midpoint location $\mathbf{m} = (m_x,m_y)$, offset vector $\mathbf{h} = (h_x,h_y)$, depth z, and the circular frequency ω. The slowness perturbation $\Delta s_\mathbf{s}$ at the source location and $\Delta s_\mathbf{g}$ at the receiver location can be written as

$$\Delta s_\mathbf{s}(z) = s_\mathbf{s}(z) - s_0(z),\ \Delta s_\mathbf{g}(z) = s_\mathbf{g}(z) - s_0(z) \tag{2}$$

where $s_0(z)$ represents the reference slowness in the background media; $s_\mathbf{s}$ and $s_\mathbf{g}$ correspond to the slowness at the source and receiver location respectively. The first equation in Eq. (1a) delineates the wave propagation in the background media, and the second delineates the scattering effect related to the lateral slowness perturbations. During wavefields continuation, split-step Fourier, Fourier finite-difference, local Born or Rytov approximation or generalized screen propagators can be applied to solving Eq. (1a) (Popovici, 1996; Jin and Wu, 1999).

According to Cheng et al. (2003a), DSR one-way wave equation prestack depth migration utilizes the zero-time zero-offset imaging condition (Yilmaz, 1979; Claerbout, 1985), namely

$$\begin{aligned} I(\mathbf{m},z) &= u(t=0,\mathbf{m},\mathbf{h}=0;z) \\ &= FT_\mathbf{m}^{-1}\left\{\int d\omega \int dk_{h_x} \int dk_{h_y}\left[W\cdot u\left(\omega,\mathbf{k_m},k_{h_x},k_{h_y};z=0\right)\right]\right\} \end{aligned} \tag{3}$$

where $I(\mathbf{m}, z)$ represents the imaging value, and W represents the wave propagator derived from Eq. (1), and $\mathbf{k_m}$ corresponds to the midpoint wavenumber vector, and k_{h_x} and k_{h_y} correspond to the two components of offset wavenumber vector, and $FT_\mathbf{m}^{-1}$ represents a 2-D inverse Fourier transform over $\mathbf{m}$.

Equations (1a), (1b) and (3) are the basic equations of 3-D full volume shot-geophone migration. Obviously, the algorithm involves 4-D computation, namely operating in (m_x,m_y,h_x,h_y) space for a single frequency component. Such high computational dimensionality presents a great challenge to current computer systems. The frequent 4-D Fourier transforms and inverse transforms over **m** and **h** in the algorithm consumes a great deal of computer time. Furthermore, artifacts will occur when it is applied to the migration of 3-D seismic data in which the crossline offsets are sparsely sampled. These problems usually hamper the practical application of 3-D full volume DSR-based prestack migration (Biondi and Palacharla, 1996; Cheng et al., 2003a). Recent studies (Biondi and Chenmingui, 1994; Biondi and Palacharla, 1996) proved that common-azimuth migration of prestack data after azimuth moveout (AMO) correction is an effective way to tackle these problems. In the next section of this paper, a common-azimuth depth migration operator was derived in a new way. Then, a common-azimuth prestack tau migration approach that can tackle lateral velocity variations was developed.

3 Common-azimuth migration operator in depth domain

The data after Fourier transform along the cross-line offset axis become

$$u\left(\omega,\mathbf{k}_{\mathbf{m}},k_{h_x},k_{h_y};z\right)=\int dh_y e^{-\mathrm{i}k_{h_y}h_y}u\left(\omega,\mathbf{k}_{\mathbf{m}},k_{h_x},h_y;z\right) \quad (4)$$

Inserting Eq. (4) into the imaging condition (3) yields

$$I(\mathbf{m},z)=FT_{\mathbf{m}}^{-1}\left\{\int dh_y\int d\omega\int dk_{h_x}\int dk_{h_y}\left[W\cdot e^{-\mathrm{i}k_{h_y}h_y}u\left(\omega,\mathbf{k}_{\mathbf{m}},k_{h_x},h_y;z=0\right)\right]\right\} \quad (5)$$

where the integral across h_y could be considered as stacking the migration results of the subsets of the seismic data corresponding to a given crossline offset component. Without the stacking step, the migration for individual crossline common-offset gathers ($h_y \equiv h_{y_0}$) becomes

$$I_{\mathrm{CLCO}}(\mathbf{m},z)=FT_{\mathbf{m}}^{-1}\left\{\int d\omega\int dk_{h_x}\int dk_{h_y}\left[W\cdot e^{-\mathrm{i}k_{h_y}h_y}u\left(\omega,\mathbf{k}_{\mathbf{m}},k_{h_x},h_y;z=0\right)\right]\right\} \quad (6)$$

To enhance the run-time efficiency, the integral across k_{h_y} in Eq. (6) can be analytically approximated with the stationary phase method. This is the crossline common-offset migration proposed by Cheng et al. (2003b). Obviously, its implementation involves 3-D computation, namely operating in (m_x,m_y,h_x) space for a single frequency component. It partially tackles the problems that hamper the practical application of 3-D full volume DSR wave equation prestack migration. However, it can only be applied in media without lateral velocity variations, or in smoothly varied media.

When the crossline offset becomes zero (i.e. $h_y=0$), the subsets correspond to common-azimuth data in which the source-receiver pairs are co-azimuth. Thus, Eq. (6) becomes the common-azimuth migration operator (Biondi and Palacharla, 1996).

$$I_{\mathrm{CA}}(\mathbf{m},z)=FT_{\mathbf{m}}^{-1}\left\{\int d\omega\int dk_{h_x}\int dk_{h_y}\left[W\cdot u\left(\omega,\mathbf{k}_{\mathbf{m}},k_{h_x};z=0\right)\right]\right\} \quad (7)$$

The integral across k_{h_y} in Eq. (7) can also be analytically approximated with the stationary phase method.

To tackle lateral velocity variations in complex media, the dual domain one-way wave propagators is applied to continue the source and receiver wavefields. For example, under the small-angle approximation, namely assume $\Gamma_{\mathbf{s}}\approx 1$ and $\Gamma_{\mathbf{g}}\approx 1$ in Eq. (1b), the common-azimuth prestack depth migration operator based on the DSR split-step wave propagator is obtained.

$$\begin{aligned}I_{\mathrm{CA}}(\mathbf{m},z+\Delta z)&=FT_{\mathbf{m}}^{-1}\left\{\int d\omega\int dk_{h_x}\left[A\cdot e^{\mathrm{i}\left(\frac{\pi}{4}-\Delta z\hat{k}_z\right)}\right.\right.\\&\left.\left.\cdot FT_{\mathbf{m},h_x}\left(u(\omega,\mathbf{m},h_x;z)\cdot e^{-\mathrm{i}\omega\Delta z\left(\Delta s_{\mathbf{s}}+\Delta s_{\mathbf{g}}\right)}\right)\right]\right\}\end{aligned} \quad (8)$$

where the vertical wavenumber $\hat{k}_z$ satisfies

$$\begin{aligned}\hat{k}_z&=\hat{k}_{z_s}+\hat{k}_{z_g}\\\hat{k}_{z_s}&=\sqrt{s_0^2\omega^2-\left(\frac{k_{m_x}-k_{h_x}}{2}\right)^2-\left(\frac{k_{m_y}-\hat{k}_{h_y}}{2}\right)^2}\\\hat{k}_{z_g}&=\sqrt{s_0^2\omega^2-\left(\frac{k_{m_x}+k_{h_x}}{2}\right)^2-\left(\frac{k_{m_y}+\hat{k}_{h_y}}{2}\right)^2}\end{aligned} \quad (9)$$

where $\hat{k}_{h_y}$ is the stationary path for the common-azimuth wave propagator, the weight factor A includes terms produced by the stationary approximation and the WKBJ approximation to the amplitude of the wavefields.

It can be seen that the phase correction related to the lateral velocity perturbations and amplitude correction related to the vertical velocity variations are implemented in the process of recursive wavefields continuation. To improve its wide-angle accuracy in media with strong lateral velocity variations, the multiple reference slowness logic of the PSPI method can be introduced into the split-step migration algorithm (Kessinger, 1992). To avoid the instability and make accurate phase correction for wide-angle waves simultaneously, the offset-domain Fourier finite-difference propagators can also be used (Jin and Li, 2002; Sun et al., 2005).

4 Common-azimuth migration operator in tau domain

If the source and receiver wavefields continue downward along the two-way vertical time axis instead of depth axis, the tau domain migration sections are obtained (Cheng et al., 2006). To derive the DSR wave propagators in the two-way vertical time (tau) domain, a coordinate transform is applied.

$$\tau(z)=2\int_0^z s_0(\eta)d\eta \quad (10)$$

Equation (10) means that

$$dz=\frac{d\tau}{2s_0(\tau)} \quad (11)$$

where s_0 is the reference slowness which varies vertically only.

After inserting Eq. (11) into Eq. (8), the common-azimuth prestack migration operator in tau domain is obtained as

$$I_{\mathrm{CA}}(\mathbf{m},\tau+\Delta\tau) = FT_{\mathbf{m}}^{-1}\left\{\int d\omega \int dk_{h_x}\left[A\cdot e^{\mathrm{i}\left(\frac{\pi}{4}-\frac{\Delta\tau\cdot\hat{k}_z}{2s_0}\right)} \cdot FT_{\mathbf{m},h_x}\left(u(\omega,\mathbf{m},h_x;\tau)e^{-\mathrm{i}\frac{\omega\Delta\tau}{2s_0}(\Delta s_{\mathrm{s}}+\Delta s_{\mathrm{g}})}\right)\right]\right\} \tag{12}$$

where Δs_{s} and Δs_{g} are their equivalents in $x-\tau$ space. The zero-azimuth 3-D seismic data in time domain can be migrated using this operator.

Almost all of the traditional time imaging methods are theoretically inaccurate in media with lateral velocity variations because they are derived on the basis of the assumption that the media are laterally homogenous. Similar to its depth domain counterpart, common-azimuth prestack tau migration should work in laterally heterogeneous media due to the phase correction related to the lateral slowness perturbations. It is the distinct advantage over classic prestack time migration.

In addition, tau migration sections can be transformed to depth domain by using a time-to-depth conversion expressed by Eq. (10). To tie wells accurately, the reference slowness $s_0(\tau)$ can be calibrated with the vertical velocity information from well data (such as check shot surveys, vertical seismic profiles, sonic logs, etc.).

5 Azimuth moveout correction of 3-D prestack seismic data

In fact, most of the 3-D seismic data do not have many traces with nonzero azimuth angle. Generally, many sources and receivers are not distributed on the regular recording surface. Therefore, it is necessary to carry out AMO correction on the 3-D prestack data before common-azimuth migration. The AMO correction is a special kind of data regularization. In the first real data example of this paper, the 3-D prestack data are regularized through a successive application of dip moveout (DMO) and inverse DMO (Canning and Gardner, 1992; Xin et al., 2002). In the second real data example, a simple method, namely a successive application of normal moveout (NMO) and inverse NMO, is used to obtain zero-azimuth prestack data.

6 Examples

6.1 Migration of SEG/EAGE 3-D salt model C3N data sets

First, algorithms of common-azimuth prestack depth migration and tau migration are tested on the SEG/EAGE 3-D Sslt model C3N synthetic data. Figure 1(a) and (b) correspond to the depth domain interval velocity and depth migration section of inline 285. Figure 1(c) and (d) correspond to the tau domain interval velocity and tau migration section of the same line. Slices of interval velocity and migration results at depth of 1 200 m are shown in Fig. 1(e) and (f). In comparison, slices of interval velocity and migration results at two-way vertical time of 1.24 s are shown in Fig. 1(g) and (h). Common-azimuth prestack depth migration and tau migration both represent the faults and the salt body very well. Some structures below the salt body are shown in these migrated sections. It is also found that the structures shown in depth and tau space are very similar but differently scaled on the vertical axis.

6.2 Migration of complex structures in buried hill

In this example, the common-azimuth prestack depth migration results are compared with those obtained by using Kirchhoff prestack depth migration. The azimuth angles of the 3-D prestack seismic data are mainly within 30°. The AMO corrections are implemented by using successive application of DMO and inverse DMO. The same velocity model is used in both depth migration cases. Compared with the migrated sections (Fig. 2), it is found that more details of the geological structures in and around the buried hill are shown after DSR one-way wave equation common-azimuth prestack depth migration.

6.3 Migration of seismic data from complex fault belt

This section illustrates the application of common-azimuth prestack tau migration to a land data set from the complex fault belt of Zhongyuan Oilfield in Central China. Figure 3(a) and (b) show the in-line (ILINE_NO = 100) and cross-line (CDP = 706) images from the widely used Kirchhoff prestack time migration algorithm. The seismic interpreters insist that the migration results below 1.6 s need to be improved further. The prestack seismic data and the RMS velocity used in Kirchhoff migration are provided to test our prestack tau migration algorithm. First, an interval velocity model in $x-\tau$ space is separated from the RMS velocity field, and the seismic data are regularized by using a partial stacking flow composed of 3-D NMO using azimuth-independent stack velocity, offsetting regularization and inversing NMO in the inline direction. Then, common-azimuth prestack tau migration using split-step DSR propagator is applied to the regularized data sets. Figure 3(c) and (d) show that the tau migration results correspond to the same in-line and cross-line locations of the top plot (a) and (b), respectively. It can be seen that the imaging resolution is enhanced and more details of the geological structures are well delineated after tau migration. Although about one fourth of the seismic traces within the 3-D prestack data sets have azimuth angles above 30°, prestack imaging algorithm is based on

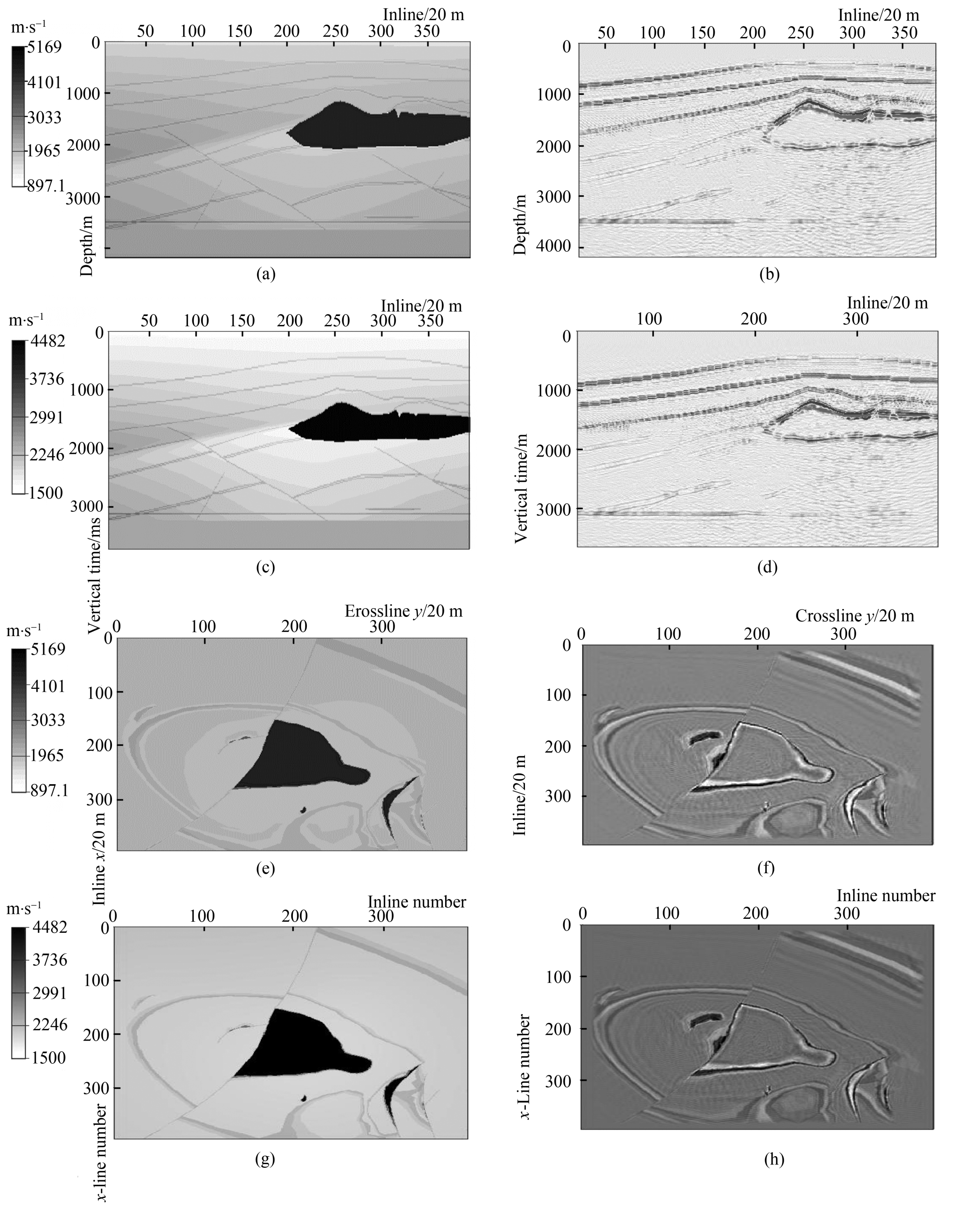

Fig. 1 3-D migration of SEG/EAGE salt model C3N data sets
(a) Depth domain interval velocity and (b) common-azimuth prestack depth migration of inline 285; (c) tau domain interval velocity and (d) common-azimuth prestack tau migration of inline 285; (e) depth slices of interval velocity and (f) common-azimuth prestack depth migration at depth of 1 200 m; (g) time slices of interval velocity and (h) common-azimuth prestack tau migration at two-way vertical time of 1.24 s

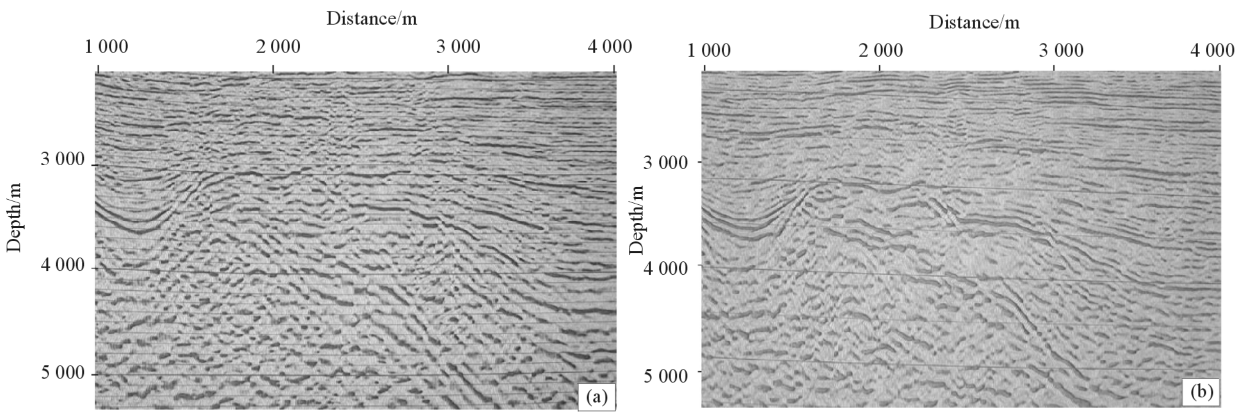

Fig. 2 3-D prestack depth migration of seismic data related to a buried hill
(a) Kirchhoff prestack depth migration; (b) common azimuth prestack depth migration

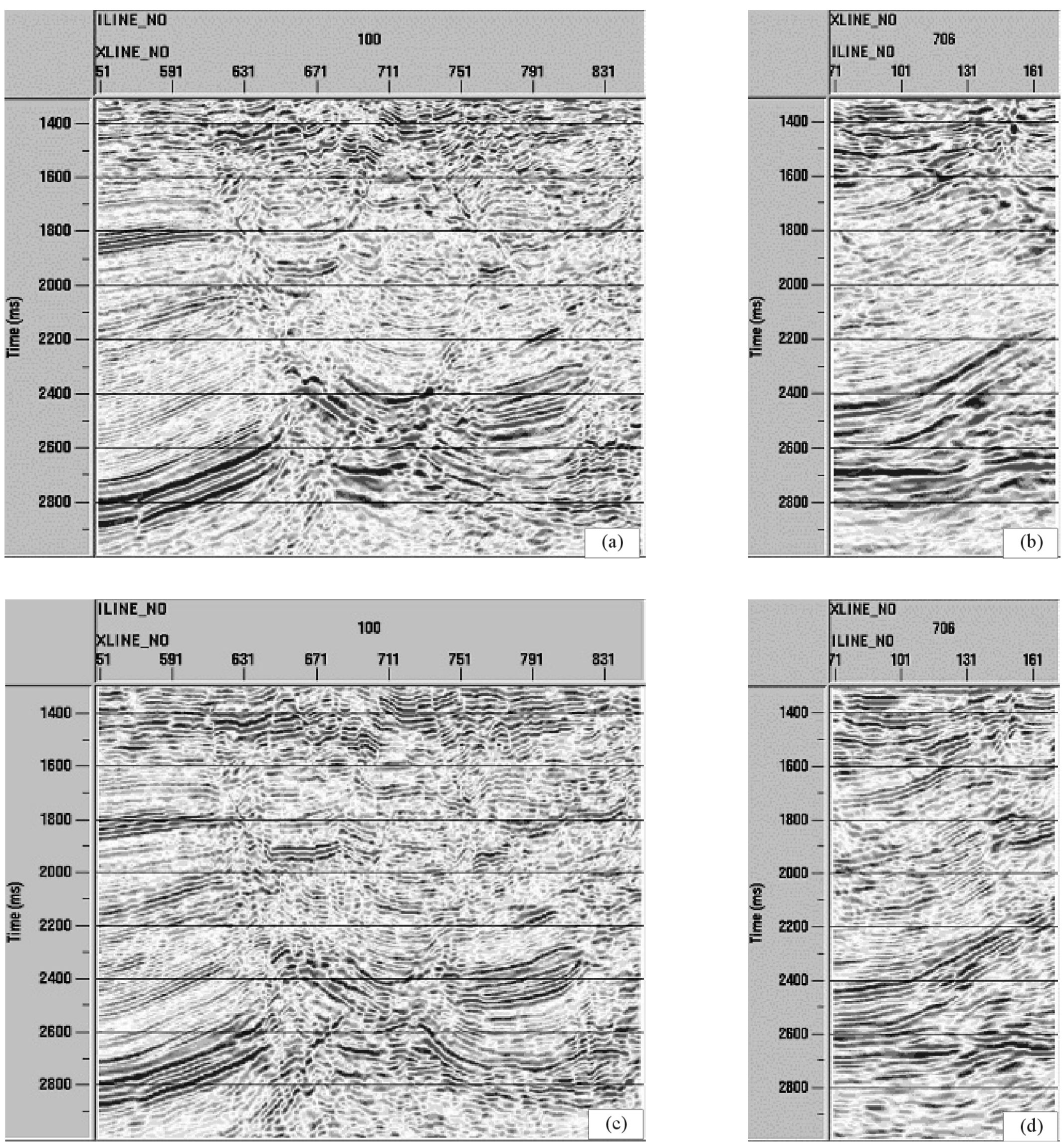

Fig. 3 3-D migration of seismic data from complex fault belt
(a) Inline 100 (b) and crossline 706 sections of Kirchhoff prestack time migration; (a) inline 100 (b) and crossline 706 sections of common-azimuth prestack tau migration

azimuth move-out correction and common-azimuth prestack migration demonstrates its advantages over traditional Kirchhoff prestack time migration.

Parallel algorithms of common-azimuth migration are used in the migration of regularized data sets on the PC-cluster platform. In terms of the computational costs, common-azimuth prestack migration based on DSR one-way wave equation is very efficient compared with anti-aliasing Kirchhoff prestack migration.

7 Discussion and conclusion

As a special kind of crossline common-offset migration based on DSR one-way wave equation, common-azimuth migration effectively breaks away from the dilemma that 3-D full volume prestack migration encounters in practical applications. Unlike traditional Kirchhoff migration, wave-theory based common-azimuth prestack depth migration and tau migration can reasonably tackle complex wave phenomena such as multipathing, caustic and interference, etc. Moreover, their implementations include phase corrections related to lateral velocity variations and amplitude corrections based on WKBJ approximation. In nature, tau migration in this paper is a new approach of prestack depth migration operated in two-way vertical time domain. Compared with conventional prestack time migration, it is more accurate in media with moderate or strong lateral velocity variations. In terms of accuracy and efficiency, common-azimuth prestack migration, based on DSR wave propagator, is very competent for imaging the complicated structures related to buried hills, complex faults, salt and reef, etc. Although the flow of "AMO corrections plus common-azimuth migration" is theoretically suitable for migrating the narrow azimuth seismic data, its distinct advantages are shown in the two real data examples.

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