The effect of strong near surface scattering on the quality of seismic imaging
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Summary

In land seismic exploration, the scattering generated by small-scale heterogeneities in the shallow layer can cause strong noise in seismic data, resulting in serious problems in the depth image. By introducing random velocity models to simulate velocity fluctuations in the near-surface layer, and using the point spreading function to characterize the image quality, we examined how the surface scattering can affect the migration image. The results revealed that lacking of intermediate scaled velocity information in the shallow part of the migration velocity model can cause phase or travel time errors in the extrapolated source and receiver wavefields, making them fail to focus. This is the primary reason causing deteriorated image quality in regions with strong near-surface scattering. By investigating the effect of velocity fluctuations of different scales to wavefield focusing, we found velocity fluctuations of 200-500 m scale are vital to provide correct phase and travel times. If this part of the information can be obtained and built into the migration velocity, the subsurface image quality can be largely improved. Adopting the high-precision near-surface velocity model building technique, it is possible to create the near-surface migration velocity with the required accuracy. The current study can be the basis for further numerical investigations and the field experiment.

Introduction

Wave equation based prestack reverse time migration (RTM) plays an important role in oil and gas exploration, and have gained wide applications in seismic data processing. However, in land exploration, particularly in certain regions in western China and Middle East, there are often highly complicated small-scale low-velocity structures, e.g., mountainous, loess, desert, existed in the near-surface layer. The sizes of scatters are usually from a few meters to a few hundred meters, and their burial depths usually are less than 1 km. Although generally attributed as “small-scale”, they can be further divided into different categories. For convenience, we roughly separate them into 3 sub categories and will refer them as: small (sub 100 m), intermediate (100-300 m) and large (300-500 m and above). Strong scatterings and heavy attenuations generated in this layer can cause serious problems in seismic data acquisition and migration imaging. However, scatters of different sizes affect the results through different mechanisms. Figure 1 shows a typical shot record in a region with strong shallow scatterings in western China, where deep reflections are almost completely buried in the noise.

For decades, researchers tested various techniques, e.g., long survey lines, wide-line profiling and high density geophone arrays (Tang et al., 2014; Wu et al., 2012), to avoid or suppress the effect of strong near surface scatterings. Although achieved limited successes in certain regions (Ning et al., 2014), the problems have not been satisfactorily solved in most of these regions. In this paper, we investigate the mechanisms how small-scale heterogeneities with different sizes affect the image quality and search for possible approaches that may overcome the impact of shallow inhomogeneous layers on imaging.

The simulation of shallow scattering

Chen et al. (2016) introduced a random layer to simulate the near surface scattering and study its influence on the image quality. We adopt the similar method here. The highly complex small-scale heterogeneous layer is treated as a random medium characterized by a few statistical parameters, including the random spectra, correlation lengths, and root-mean-square (rms) velocity perturbations (Frankel and Clayton, 1986; Xie 2013).

To investigate how migration velocity models with different accuracies of small-scale structures in the shallow layer can...
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affect the image quality, a simple two-layer velocity model is used. The model scale is 10 km x 5 km. The upper layer is a 400 m thick random layer, in which the background velocity is 2000 m/s, the rms velocity perturbation is 10%, and the vertical and horizontal correlation length is 200 m. The lower layer is a homogeneous medium with a velocity of 3500 m/s. To generate migration velocity models with different accuracies, the above velocity model is smoothed using a two-dimensional Gaussian filter

\[ W(x, z) = \exp \left[ -\left( \frac{x^2 + z^2}{\sigma^2} \right) \right], \]

where \( x \) and \( z \) are horizontal and vertical coordinates, \( \sigma \) is the characteristic scale. By applying successive filters with \( \sigma = 30, \ 50, \ 100, \ 200, \ 300 \) and \( 500 \) m on the velocity model, the corresponding models with different accuracies are shown in Fig. 2.

To further observe the differences between these models, we calculate the spatial wavenumber spectrum of the surface random model and express it in double logarithmic coordinates in Fig. 3a, where the abscissa is the wavenumber and the ordinate is the normalized spectral amplitude. Different curves show wavenumber spectra after filtering with different smoothing functions. Fig. 3b shows the velocity along the horizontal direction at the depth of 200 m in models filtered with different smoothing functions, where the ordinate is the velocity and the abscissa is the distance. We see that the unfiltered random velocity layer has the highest velocity perturbations and the richest high wavenumber components. As the smooth radius increases, the random spectrum shrinks towards the low wavenumber, and the velocity models, compared to the original one, gradually lose their accuracy from small to large scale heterogeneities in the near-surface layer.

**Influence of velocity model errors of different scales on the point spreading function**

The imaging near location \( x \) can be expressed as the convolution of the point spreading function (PSF) at the point with the model velocity perturbation. (Gelius, et al., 2002; Xie et al., 2005b; Lecomte, 2008; Cao, 2013; Chen and Xie, 2015; Yan and Xie, 2016; He et al., 2016).

\[ I(x) = R(x) * m(x) \]

(2)

Where \( I(x) \) is the migration image, \( m(x) \) is the model velocity perturbation, \( R(x) \) is the PSF, and "*" denotes the spatial convolution. When the velocity perturbation is a scattering point, i.e., \( m(x) = \delta(x) \),

\[ I(x) = R(x) \]

(3)

where \( \delta(x) \) is a Dirac delta function. The PSF can be regarded as the image acquired by a given acquisition system for a point scatter. As a generalized image, the PSF contains all the information about imaging resolution and imaging defects, and it can also be regarded as the imaging resolution function. We can analyze the effect of model errors on subsurface imaging by studying the influence of shallow velocity model errors on the resolution function.

In order to calculate the PSF, we use a velocity model shown in Fig. 2 and implant a point scatter with 10% velocity perturbation at (5000 m, 3000 m). The acquisition system is composed of 101 surface shots and each shot has 501 surface receivers, all shots are located between distances 2500 m and 7500 m. The shot interval is 50 m, and the receiver interval is 10 m. The source time function is a 16 Hz Ricker wavelet and the recording time is 4 s.
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The original velocity model with a random near surface (shown in Fig. 2a) is used to generate the synthetic data, which is then used to calculate PSFs in models with different accuracies. The PSFs illustrated in Figs 4a-4h are corresponding to velocity models in Figs. 2a-2h, respectively. Figure 4a is calculated in the true velocity model. Even with strong scattering, the PSF is well focused and unbiased. With the increase of smoothing radius from 30 m to 100 m, the near surface models gradually lose the small-scale information. The correspondent PSFs shown in Figs. 4b-4d are slightly affected but still well focused. When the smoothing radius increases to 300 m or 500 m, the near-surface layer starts to lose middle to large scale velocity perturbations; PSFs are seriously affected; and artifacts are developed (Figs. 4f-4g). If we do not have any information on the velocity perturbations in the near surface layer, the PSF has to be calculated using the constant background velocity, and the result is shown in Fig. 4h. The focusing is severely deteriorated and their centroids are deviated from the correct location.

We further analyze effects of shallow velocity errors on the amplitude and phase spectra of the PSFs in the wavenumber domain. Illustrated in Fig. 5 and Fig. 6 are amplitude and phase spectra calculated in models with different near surface accuracies. The amplitude spectra are normalized to unity and the phase spectra are normalized to $-\pi/2 \sim \pi/2$. Panels (a) to (h) are arranged corresponding to those in Fig. 4. Figs. 5a and 6a use the true velocity model as the migration velocity model. The amplitude spectrum has more high-wavenumber contents, indicating their highest spatial resolution. With the near surface layer gradually loses the information of velocity perturbations from small- to large-scale, the amplitude spectra gradually shrink to low-wavenumber and the PSF loses the resolution capability (from Fig. 5b to 5g). In Figs. 6b-6g, the error of the phase spectrum increases with the decrease of the accuracy of shallow velocity model. This damages the zero phase image condition, making the coherent interfernece difficult. When the phase error approaches $\pm \pi/2$, constructive interference becomes impossible and the superposition does not contribute to the imaging.

Influence of model velocity errors of different scales on the depth image

To investigate the effect of near surface scattering on seismic image, we construct a velocity model that includes both shallow random velocity layer and deep reflectors, as shown in Fig. 7. The model size, the shallow random layer, and the acquisition system are the same as those used in Fig. 2, but the lower part of the model include four reflectors. From the above analysis on the PSFs, if intermediate to large scale velocity fluctuation in the shallow layer can be obtained and built into the migration velocity model, the image quality can be greatly improved. To verify this in the image process and estimate the range of velocity model scales that the image senses the most, we use the velocity models in Figs. 7a-7h as the migration velocity model for RTM imaging, and the corresponding results are shown in Figs. 8a-8h.
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Figure 7: Similar to those shown in Fig. 2, except the lower parts are replaced by a layered structure.

Figure 8: Depth images calculated using velocity models shown in Fig. 7. Details refer to text.

As mentioned above, the shallow heterogeneous layer affects the image quality through two ways: causing the wavefield phase errors and generating scattering waves that affect the signal-to-noise ratios. Figure 8a is the image calculated by using the true model as the migration velocity. Although the strong scattering noise generated in the shallow part affects the image quality, the deep reflectors are properly imaged. On the other hand, if there is no detailed information regarding the heterogeneity in the shallow layer, the image is calculated using the background velocity of 2000 m/s, and result is shown in Fig. 8h. In practice, although it is difficult to construct a fine velocity model as in Fig. 7a, it is possible to improve the image quality by adding some intermediate to large scale perturbations into the migration model. For this purpose, we use models 7a to 7h as the migration model for seismic imaging. The results are shown in Fig. 8, where from 8a to 8h, the models gradually losing heterogeneities from small to the large scale, until a constant background. With the increase of near-surface velocity errors, the corresponding image quality gradually deteriorated. When the smoothing scale is less than 100 m, the imaging is still acceptable. However, for the smoothing scale 300 m or larger, the deep reflectors disappeared and the image quickly becomes unacceptable. In the above numerical tests, the sizes of scatters vary from several meters to several hundred meters. If we can build a migration velocity model which includes heterogeneities with scales of 200 m or larger, the image quality can be improved significantly. By combining techniques such as the near-surface high-precision velocity model building (Wang and Chen, 2016), topography static correction, wave equation based static correction, it is possible to obtain a near surface velocity model that can meet the requirement.

Conclusions

In land seismic exploration, small-scale near-surface heterogeneities formed by mountain areas, Gobi desert, weathering layers, etc., are widely existed. Strong scatterings caused by these heterogeneities seriously affect the quality of the depth image. Their major negative effects include: i) the very small-scale scatters generate scattering noises, which strongly attenuate primary reflections and add noises. ii) The lack of intermediate to large scale information in the migration velocity model causes phase errors which prevent the extrapolated wavefield from proper focusing. Our investigations reveal that if we can determine velocity information at these scales and build them into the migration velocity model, the subsurface imaging can be improved. Under the range of parameters numerically tested in this study, if the velocity perturbations of 200 to 500 m scale can be obtained within the depth range of 200-400 m, phase errors can be largely removed and the image quality can be significantly improved. It is possible to obtain velocity models with such accuracy at shallow depth using the current data acquisition density for imaging purposes and the corresponding near-surface velocity inversion technique. While the scattering noise generated by very small scatters can be suppressed by stacking and filtering, etc. The current numerical experiments are conducted under the 2D constant density acoustic model with no free surface. The shallow velocity model is simulated by the exponential random velocity model with 10% rms velocity perturbation and a correlation length of 200 m. Further studies may be extended to more realistic situations.
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