Seismic wave simulation of a complex foothill belt

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Abstract
Foothill belts ‘dual-complexity’ of the surface and underground structures hinders an accurate seismic imaging of complex geological structures. In this paper, the propagation law of the seismic wavefield in the foothill belt is studied through seismic forward modelling and its influences on the seismic data acquisition and imaging. A foothill belt with typical ‘dual-complexity’ characteristics is investigated. Single-shot records and their imaging effects simulated with different absorption coefficients and different near-surface structure models are analysed. The results suggest that strong surface waves and their scattered noise generated by the complex near surface in the foothill belt are the main reasons for the low signal-to-noise ratio and difficulties in the imaging process of seismic data. The viscoelastic-medium modelling method effectively suppresses the surface waves and their scattered noise, which improves the seismic data quality and imaging in the foothill belt, and thus is a suitable forward modelling method for the foothill belts.

Keywords: foothill belt, complex near surface, forward modelling, viscoelastic medium, surface wave

1. Introduction
Foothill belts generally refer to the transition zones of mountains and basins with considerably changing structures (Jing et al. 2011; Di et al. 2012). They have high-quality source rocks, high-quality reservoirs and well-developed oil or gas migration pathways and are one of the areas with the richest oil and gas resources and largest distributions of large oil and gas fields in the world (Liu et al. 2013). They include the Alberta foothill belts in Canada, North America (Yan & Lines 2001), the eastern Cordilla foothill belt in Colombia, South America (Charles & Richard 2009), the Carpathian foothill belt in Romania, Europe and the Zagros foothill belt in Iran, Middle East. Foothill belts are also widely distributed in China, in Tian Mountain, Kunlun Mountain, Qilian Mountain, Helan Mountain, Longmen Mountain, Qinling Mountain, Dabashan Mountain, etc. The joint parts of orogenic belts and cratons have widely developed anticlines and thrust blocks (Song & Yu 2012; Yang et al. 2012), which are favourable areas for the formation of large and super-large oil and gas reservoirs.

Owing to the specific position of the zone of transition from the basin to the mountain range, most of the foothill belts are characterised by ‘dual-complexity’ characteristics including complex near-surface structures and complex underground structures. The underground structure is complex with large-dip-angle strata and development of thrust faults. Regarding the complex surface conditions, large height differences exist in mountains, valleys and other terrains. Strata with different ages and different lithologies are outcropped, with various weathering conditions, largely changing lithology and high heterogeneity (Su et al. 2009; Cao et al. 2013). This leads to bad conditions for field seismic acquisition, low consistency of signal excitation and recording, and strong scatterings of various types of signal. In addition, the target layers of foothill
belts are mostly marine sedimentary strata with small differences in interlayer wave impedance and low energies of effective signals. Therefore, methods to acquire high-quality seismic records in seismic data acquisition (Jaime et al. 2009), obtain high-quality imaging sections in seismic data processing and obtain accurate structures in seismic data interpretation are required for seismic analyses in foothill belts.

To obtain high-quality imaging results, the seismic analyses in foothill belts worldwide mainly involve two key parts, a target-oriented high-quality acquisition technology to improve the quality of seismic data (Hansruedi et al. 2010) and target-oriented prestack depth migration (PSDM) including velocity modelling and other imaging technologies to improve the imaging quality (Zhu & Lines 1998; Liu et al. 2014, 2016). These technologies are effective in foothill belts with relatively simple near-surface structures and underground structures, but it is still difficult to fundamentally overcome the problems for foothill belts with ‘dual-complexity’ characteristics.

An approach to fundamentally overcome the problem in foothill belts for oil and gas exploration is to study the propagation law of seismic waves by forward modelling (Abdulaziz et al. 1999; Grech et al. 2001; Jonás & Mrina 2007, 2009; Denli & Huang 2010) and to develop corresponding seismic data acquisition, processing and interpretation technologies, which has attracted considerable interest in recent years, such as the SEAM II 3D complex foothill belt model (Oristaglio 2013, 2016). However, the complex near-surface structures in foothill belts also lead to new challenges for forward modelling. Therefore, a prerequisite for an effective forward modelling of the foothill belts is to reasonably design a model that can reflect the characteristics of the near-surface structures in foothill belts and determine the forward simulation method suitable for foothill belts.

In this study, a foothill belt with typical complex near-surface and underground structures is selected as the target area. The reason hindering an effective imaging of PSDM with true velocity based on the existing elastic-wave forward modelling is analysed. The signal-to-noise ratio (SNR) of the data obtained by the elastic-wave simulation method is too low to fit for the forward modelling of the foothill belt, which can be improved by a viscoelastic-medium forward modelling method with appropriate medium absorption properties. Therefore, the viscoelastic-medium forward modelling method is suitable for foothill belts with complex near-surface characteristics. By simulation and imaging analyses of the near-surface models with different absorption coefficients, it is demonstrated that the effective suppression of surface waves and their scattered noise is an effective approach to improve the seismic data quality of the foothill belt.

2. Challenges of forward modelling in complex foothill belts

The Zhenba area is located at the boundary of the Sichuan, Shaanxi and Chongqing provinces in South China, in the hinterland of the fault fold zone in Dabashan platform, and basin–mountain coupling area, which is a typical foothill belt with ‘dual-complexity’ characteristics. The complexity of the near surface is characterised by a severe topographic relief (maximum elevation difference larger than 1200 m), variable lithology and steep occurrence. The underground structure is mainly composed of a giant thrust napped fold belt. It is characterised by mainly a fault-related fold, imbricate structure and fault triangle belt. The ‘dual-complexity’ characteristics lead to a very low SNR of the seismic data recorded in this area and unsatisfactory imaging effect (figure 1).

To study the main reasons for the low SNR of the seismic data in the target area, a three-dimensional (3D) model with complex near-surface and complex underground structures is designed according to the geological, seismic and surveying data in the target area (figure 2a). Notably, not only does the surface of the model have a large topographic relief (with a maximum elevation difference of approximately 800 m), but also a layer of mantle rock exists at the near surface with a thickness of approximately 10–30 m and compressional wave velocity ($V_p$) of 1000–1800 m s$^{-1}$. The elastic-wave forward simulation method is used to simulate the 3D model. Figure 2b shows the vertical component of a near offset single-shot record, where it is difficult to identify effective signals, which indicates that its SNR is very low. $V_p$ of the model is used for PSDM for the simulated vertical component, but the imaging accuracy of the structures and faults is low (figure 2c). The PSDM of the elastic-wave simulation data even with the true velocity model cannot be used for an accurate imaging, which indicates that the elastic-wave forward simulation method is not suitable for the analysis of the wavefield characteristics of complex foothill belt models.

To determine the factors leading to the inaccuracy by the elastic-wave simulation, the ‘dual-complexity’ model (figure 2a) is decomposed into two models, a complex near-surface/simple underground structure model with a low-velocity and subweathered zone in the surface and complex near-surface/complex structure model without low-velocity and subweathered zone in the surface. The former model retains the complex surface of the original model, while the underground structure is simplified into a two-layer horizontal layered medium model. Figure 3a shows a section of its $V_p$ model. In the latter case, the complex underground structure of the original model is retained, while the complex near-surface mantle rock layer in the original model is removed. Figure 3b shows a section of its $V_p$ model. In the wave field simulation, the elastic-wave operator of high-order finite difference of the elastic-wave equation is used, and the vacuum
Filling method is used for the topographic surface. Both models are simulated with the same 3D elastic-wave forward modelling method, and then the PSDM is carried out with the corresponding model velocity; the results are shown in figure 3 parts c and d, respectively. The comparison of the imaging results of the simulated data of the two models shows that, for the complex near-surface model with a low-velocity and subweathered zone, the imaging effect of the PSDM with true velocity is not satisfactory even with a simple underground structure. On the contrary, without the low-velocity and subweathered zone in the near surface, the PSDM with true velocity is ideal even with an extremely complex underground structure. Thus, the low-velocity and subweathered zone in the near surface is the main reason for the challenges of forward modelling and imaging in the complex foothill belt.
To further analyse the influence of the near-surface low-deceleration zone (LDZ) on seismic data noise, 3D horizontal layered medium models with and without an LDZ are designed. The thickness of the low-velocity zone is 20 m, while $V_p = 1217$ m s$^{-1}$. The 3D elastic-wave forward modelling method is used for the simulation. A wave field snapshot at 100 ms and surface wave field slice at 120 ms are recorded, as shown in figure 4. Without the near-surface low-velocity zone, the wave field is simple, in the wave front snapshot or surface wave field slice. Besides the reflected P-wave of the two underground interfaces, the converted wave of the first interface, i.e. the second wave between the first stratum interface and surface, is observed. When the model contains the near-surface low-velocity layer, because of the large reflection coefficients of both top and bottom interfaces of the low-velocity zone, the seismic signal largely oscillates, thus generating strong surface waves. Strong scattering would be generated when the strong surface wave propagates along the low-velocity zone in the near surface with a rugged topography (figure 5). The surface waves and

Figure 2. (a) 3D $V_p$ model. (b) Simulation record with the elastic-wave method. (c) PSDM profile with the true velocity.
Figure 2. continued

Figure 3. Simplified model of that in figure 2a and comparison of the corresponding PSDM profile with the true-velocity vertical component obtained by the elastic-wave simulation. (a) Complex near-surface/simple structure model with low-velocity zones. (b) Complex near-surface/complex structure model without low-velocity zone. (c, d) PSDM sections with true velocities obtained by the elastic-wave simulations of the models in a, b, respectively.
their scattered noise largely reduce the SNR of the seismic data.

3. Viscoelastic forward modelling

This analysis shows that strong surface waves and their scattering noise generated by the thin LDZ near the surface are the main reasons for the low SNR of the data simulated by elastic-wave modelling (figure 2). Therefore, for a complex foothill belt model with an ultralow-velocity-deceleration zone, the viscoelastic forward modelling method with medium absorption should be used (Yadari et al. 2008). The real underground medium is closer to a viscoelastic medium. However, the energy absorption effects of different underground media are different. The mantle rock layer is basically the stratum with the highest attenuation of seismic wave energy. Because the surface wave energy mainly propagates along the near-surface mantle rock layer or weathering layer, the attenuation is fastest. The deep reflection signal mainly propagates in the underground medium except for the roundtrip in the near-surface mantle layer; the signal attenuation is relatively slow. Therefore, considering the absorption and attenuation effect of the medium on the signal energy, we can use the attenuation difference attributed to the different propagation paths of the surface wave and body wave to relatively suppress the surface waves and emphasise the body wave energy, and then reduce the near-surface scattering noise (Christina & Gerard 2004) and
improve the SNR. In the specific implementation process, as the absorption and attenuation coefficients of the stratum cannot be completely assessed in the target area and generally the absorption of seismic energy by the strata below the near surface is lower than that in the near surface, we only consider the P-wave attenuation at a certain depth in the near surface without considering the shear wave attenuation.

Using this method, we consider the absorption of the P-wave in a depth range of 100 m below the surface of the model shown in figure 2a. The absorption coefficient is fixed at 10. Figure 6 compares single-shot records with $Q_p$ (P-wave
Figure 6. Single-shot record comparison of the vertical component of the model shown in figure 2a. (a) Elastic-wave modelling. (b) Viscoelastic (attenuation depth = 100 m, $Q_p = 10$) wave modelling.
absorption coefficient) = 10 and without considering the absorption. Without considering the medium absorption, the effective signal almost cannot be observed in the single-shot record and the scattering noise is very high. When the absorption of the medium is considered, the reflected signal of the underground interface is observed and the scattering noises of the surface wave are largely reduced. Considering the lack of near-surface absorption data in the target area, we use the comparative analysis of simulation records and actual data to estimate the near-surface absorption. We consider only the P-wave absorption and not the S-wave absorption. Therefore, the estimated P-wave absorption may be considerably higher than the actual value. The depth of the near-surface absorbing layer can be determined according to the dispersion–depth characteristics of the surface wave and simulation comparison. The determination of the attenuation

Figure 7. Comparison of the true-velocity RTM results for different near-surface P-wave absorption coefficients ($Q_p$). (a) Without absorption. (b) Attenuation depth = 100 m, $Q_p$ = 50. (c) Attenuation depth = 100 m, $Q_p$ = 15.
needs to be combined with near-surface sampling and testing, micro seismic data and other data.

Figure 7 compares the true-velocity reverse-time migration (RTM) imaging results of the model in figure 2a obtained with elastic-wave modelling without considering absorption and with viscoelastic-medium modelling with $Q_p$ of 50 and 15 in the depth range of 100 m. The imaging results in figure 7 show that, when the absorption of the medium is not considered, the scattering noise attributed to the near surface dominates in the profile and that the deep effective reflection is not observed. When the absorption of the near surface is considered (low absorption; $Q_p = 50$), the scattering noise in the near surface is slightly reduced but is still sufficiently high, and some of the weak deep reflection signal can be observed in the high-noise background. When the near-surface absorption is very high ($Q_p = 15$), the near-surface scattering noise is largely reduced with a very fast attenuation and the deep reflection signal is largely enhanced. The absorption and attenuation of the near-surface medium of the model affect the SNR of the simulation data.

We discussed (figure 7) the influences of the absorption and attenuation of the near-surface media on the imaging results of the simulated data. This effect of suppression of the surface waves and their scattering noise by setting the absorption coefficient of the media also shows that the provision of a reasonable suppression of the surface waves and their scattering noise is one of the key approaches for imaging of low-SNR seismic data in the foothill belt. Therefore, the suppression of surface waves and their scattered noise should be considered in the imaging of seismic data in a foothill belt.

4. Examples of modelling

To further verify the actual effect of the viscoelastic-medium simulation, we redesign the 3D model of the target area. First, a 3D structural model is designed using 3D seismic interpretation results. Second, when the mantle rock layer and weathering layer near the surface of the target area are very thin, it is difficult to establish the near-surface model by seismic data. Thus, the near-surface structural model is established by interpolation of micro logging data of 36 wells. Third, using a multi-data fusion method, the 3D underground structural model is merged with the near-surface structure model and a 3D complex piedmont zone model of the target area is constructed by combining the surface elevation of the target area. The model has not only a complex underground structure with well-developed overthrust faults, but also considerable changes in surface elevation with a maximum elevation difference of 800 m. A layer of mantle rock exists near the surface of the model, with a thickness of approximately 10–30 m and P-wave velocity of 1000–1800 m s$^{-1}$. The P-wave absorption and attenuation of the medium are considered within 200 m below the surface. As shown in figure 8, $Q_p$ is fixed at 10 while the absorption of the S-wave is not considered in this model.

The viscoelastic-medium simulation method is used to record a swathe of 3D simulation data for the model shown in figure 8, and then RTM is directly performed with the
Figure 8. 3D model of the complex foothill belt in the target area. (a) 3D $V_p$ model with the near-surface low-velocity zone. (b) Partial enlargement of the near-surface low-velocity-zone $V_p$ profile. (c) Partial enlargement of the shallow part of the profile with $Q_p = 10$. 
true-velocity model without modification processing of the simulated data. Figure 9 compares the RTM profile and velocity profile corresponding to the model. Figure 9a shows that, although the shallow information is not clear due to the influence of the near-surface noise, the reflection signals in the middle and deep layers are very clear and maintain a high consistency with the model, which completely avoids the type of noise in the section shown in figure 2. Thus, the viscoelastic-medium simulation method can be used for the foothill belt with ‘dual-complexity’ characteristics.

5. Conclusions

In this study, the forward modelling of a complex foothill belt with a complex near-surface structure and imaging of its simulated data were studied. The conclusions of this study can be summarised as follows.

(1) The strong surface waves and their scattering noise generated by the LDZ near the surface of the foothill belt were the main reasons hindering the forward
modelling. Thus, elastic-wave forward modelling is not suitable for complex foothill belts.

(2) Viscoelastic-medium forward modelling could effectively suppress near-surface waves and their scattering noise. Thus, it can be applied to complex near surfaces and used to improve the imaging qualities of the seismic data in foothill belts.

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Conflict of interest statement

None declared.

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