Abstract

The Earth's subsurface exhibits heterogeneity at multiple scales. Constraining the heterogeneity is critical to enhance our understanding of the geological conditions. Compared to borehole-based approaches that are limited to the vertical dimension, surface-based geophysical measurements, especially ground penetrating radar (GPR) and seismics, allow to effectively reveal the laterally correlated features of subsurface. GPR and seismics are based on the propagation of electromagnetic and seismic waves, respectively, which have strong mathematical analogies. The two methods both have good potential to constrain heterogeneity. In this thesis, four novel quantitative interpretation techniques are proposed, with three for exploring the radar wave velocity or correlation structure of the shallow subsurface using GPR, and one for characterizing sub-vertical structures in crystalline environment using seismics. For the shallow subsurface, detailed knowledge of dielectric properties, e.g., radar wave velocity, is of particular interest because it provides a fine-scale image to describe the heterogeneity. Nonetheless, high-resolution velocity estimation through common-offset GPR reflection measurement is currently not possible without complementary borehole information. Regarding the subsurface velocity distribution as the superimposition of a smoothly varying background velocity field and a small-scale velocity fluctuation field, the first study of this thesis develops an approach utilizing diffraction components to infer the background velocity field and reflection components to invert the velocity perturbation field. The results from synthetic and field data tests show the effectiveness of this method. A distinguishing feature of this method is that it does not require any borehole calibration or conditioning information, which is rather attractive for common-offset GPR reflection surveys. The step of background velocity model estimation is important because a local bias in the inferred model can largely affect the result. To improve the performance of diffraction-based velocity analysis, a second study presents a weighting strategy based on a local semblance focusing measure. The designed weight function varies in accordance with the sensitivity of a diffraction curve to changes in migration velocity. Synthetic and field data tests show that the method can increase the resolution of the semblance spectra, which correspondingly reduces the uncertainties in diffraction velocity analysis. An alternative way to characterize complex shallow subsurface with GPR data is to estimate the geostatistical properties related to the heterogeneity. To estimate the geostatistical parameters efficiently, a third study proposes a supervised-learning scheme. The convolutional neural network is trained on a vast database of 2D autocorrelation images obtained from convolution-based modeling of synthetic GPR data for a comprehensive range of stochastic subsurface velocity models. Results from synthetic and field data tests confirm the viability of using a trained network to estimate the structural aspect ratio of the subsurface heterogeneity. The estimation is still robust in the presence of high noise levels. In the last study of this thesis, the seismic data from Ivrea-Verbano Zone are taken as an example to test the ability of using diffracted wavefields and a geostatistical view to interpret the steeply dipping structures in crystalline environment. Synthetic seismic reflection data for sub-vertically structured canonical models of crustal heterogeneity are employed to corroborate the viability of the proposed techniques. From the field seismic data, the continuity and dominant dip angle of subvertical structures in the probed region are assessed. This work provides interesting insights and potentially new perspectives regarding the seismic reflection surveys in crystalline terranes. Ultimately, the technical advances in this thesis have the potential to improve our understanding of complex subsurface environments.

Though the current applications are limited to 2D cases, the extensions of the four proposed methods to 3D are conceptually straightforward.