Towards an integrated depth imaging workflow for hardrock seismic data employing full-waveform inversion: case study from the Kylylahti massive sulfide deposit, Finland

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Reflection seismics is emerging as an important asset for mineral exploration in hardrock environments. However, many exploration geologists are not fully convinced yet about the benefits seismics can bring in their projects. This might be due to the unsatisfactory results provided e.g. by applying standard time-domain imaging workflows to characterize complex geological media which is often the case for mineral exploration targets. While pre-stack depth migration (PreSDM) has been a standard approach in the hydrocarbon exploration industry, it has only recently been adopted to imaging hardrock seismic data. One of the major obstacles for its wider adoption is the lack of robust velocity model building tools. Conventional reflection tomography fails if there are no coherent reflections to drive model updates. First-arrival tomography (FAT) has been successfully used in many cases, but its resolution is inherently limited and depth penetration is constrained by small velocity gradients typical for crystalline rocks as well as limited offsets. In recent years, a new technique of velocity model building called full-waveform inversion (FWI) has helped hydrocarbon industry to solve complex imaging challenges, e.g. seeing through gas clouds and resolving shallow velocity heterogeneities. FWI is bringing unprecedented resolution in elastic/anelastic parameter models as compared to ray-based methods.

Here we explore the applicability of FWI as a velocity model building tool for imaging hardrock seismic data using crooked 2D seismic profiles acquired within the COGITO-MIN project at the Kylylahti polymetallic mine site in Finland. Two, approximately 6 km long, lines were acquired with 10 m receiver and 20 m shot spacing using a mix of Vibroseis (4-220 Hz sweep) and dynamite sources. Data are of high quality with clear first breaks visible up to a maximum offset of ~6 km. Time domain imaging included standard DMO stack/post-stack and pre-stack time migration. Coherent reflections were imaged only outside the direct exploration target, i.e. the Kylylahti formation. Subsequent depth-imaging efforts using specialized Kirchhoff PreSDM (coherency migration, Fresnel-volume migration and their combination, CBFVM) demonstrated that even with a constant velocity, significant uplift in image quality is observed as compared with the time domain. Those results were further improved with the velocity models built by FAT.

In the same way as for Kirchhoff PreSDM, FWI was performed in 3D to account for the crookedness of the profiles. We used a time-domain acoustic FWI code developed by the SEISCOPE consortium. Data pre-processing was kept to a minimum and aimed at improving coherency of the early arrivals and flattening of the spectra between 4-30 Hz used in the inversion. Surface waves and shear waves were excluded by a carefully designed mute function. After initial source signature estimation, we decided to exclude dynamite shots as their wavelets were varying much at different locations. We run the inversion using single frequency band, gradually decreasing gradient damping to allow deeper velocity updates. The resulting velocity model shows more details as compared with the starting FAT model and includes some low-velocity zones at depth, which look geologically plausible (lithology change/fault/shear zones). The applicability of this model for depth imaging was subsequently validated by running standard PreSDM, producing better-focused common-image gathers, as well as specialized PreSDM. Specialized Kirchhoff images obtained with the FWI model are better focused at the key reflectors and some new events become visible. The structures revealed in the migrated image also correlate well with features observed in the velocity model itself.