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Kevitsa Ni-Cu-PGE deposit, North Finland – A seismic case study

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SUMMARY

A 3D seismic survey was designed, acquired and processed by HiSeis Pty. Ltd. in 2010 at the Kevitsa Ni-Cu-PGE deposit. The objectives of the survey were the definition of sub-vertical structures (knowledge of which could assist in the design and characterization of the slopes of the proposed open pit), and mapping out the general structural setting of the mafic intrusive.

The 2010 processing of the Kevitsa 3D seismic data was accelerated to meet engineering design deadlines. Although this phase of work was restricted to processing sequences that were not amplitude consistent and to the post stack migration algorithm, never-the-less the resultant product achieved good resolution of the complex structural setting.

The dataset was re-processed in 2014 with the goal of preserving relative signal amplitudes, in order that the volume could be inverted into an acoustic impedance cube. Another reason for re-processing was to improve imaging in shallow depth, by improving the static solution and velocity model used for imaging. Both of these processes are considered to be crucial steps in hard rock seismic data processing. Considerable improvement was achieved through the application of a pre-stack time migration (PSTM) algorithm. Conventional 3D deep-move out corrections (DMO), followed by a post-stack migration algorithm proved to be insufficient to handle the lateral changes of velocities. Consequently, pre-stack time imaging was attempted to aid in handling the highly complex velocity field. The goal was to derive a velocity model appropriate to the geologic environment in order to place events in their correct positions, to properly focus the energy, to avoid introduction of false structures and to flatten the image gathers.

The Kevitsa 3D seismic dataset is considered as being of high quality and as the data volume contains a statistically significant number of log measurements, it is deemed suitable for the seismic inversion.

INTRODUCTION

A design was completed for a 3D seismic survey at the Kevitsa deposit with the objective to image and map steep structures which would impact on the design of the proposed open pit mine. The design incorporated high definition, high resolution and high fold coverage to accomplish this objective. An orthogonal geometry was employed and nine rectangular patches were used to provide a high and uniform fold over the ore bodies under investigation. The survey was shot between February and April 2010, in challenging and changing weather conditions, which included temperatures ranging from -40^0 centigrade (freezing) to +8^0 centigrade (melting). The complex acquisition plan presented numerous data processing challenges requiring the development, testing and implementation of novel processing strategies which have proven to be highly effective.

The survey was completed in a two month period. It required approximately 3 000 shot points; the shot point spacing was 45m, shot line spacing 80m, geophone spacing 15 m and geophone line spacing 70m. Two types of seismic sources were used – Vibsist, and (in areas of difficult access) explosive sources. The survey map and fold coverage plot are illustrated in Figure 1.

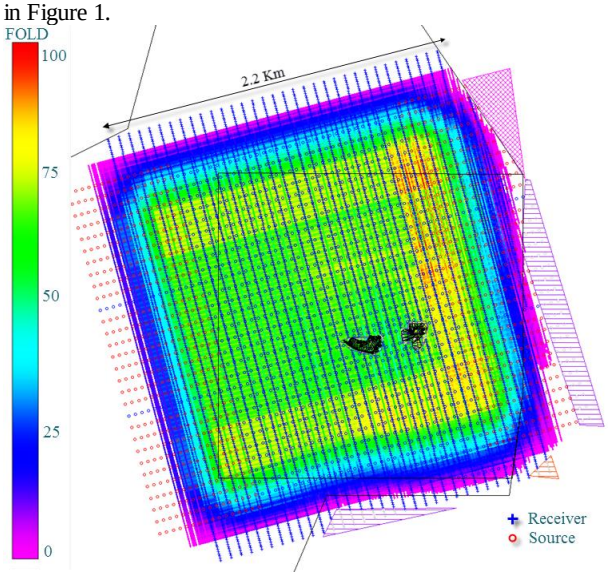

Figure 1. Kevitsa 3D survey design, showing fold coverage.

METHOD AND RESULTS

Following a tedious but successful task of data decoding, the 2010 processing of 3D reflection data was accomplished through several stages.

A first crude 3D cube did not have static corrections applied. In the second stage, all static and dynamic corrections were properly computed with maximised fold coverage. This was done by selecting 10x10m bin size. The importance of deriving accurate refraction static corrections to obtain high-quality seismic section has long been recognized. This procedure was necessary to eliminate variable time delays through the regolith, and is critical for achieving effective imaging. A map of seismic estimated depth of regolith was generated as a bi-product (Figure 2).

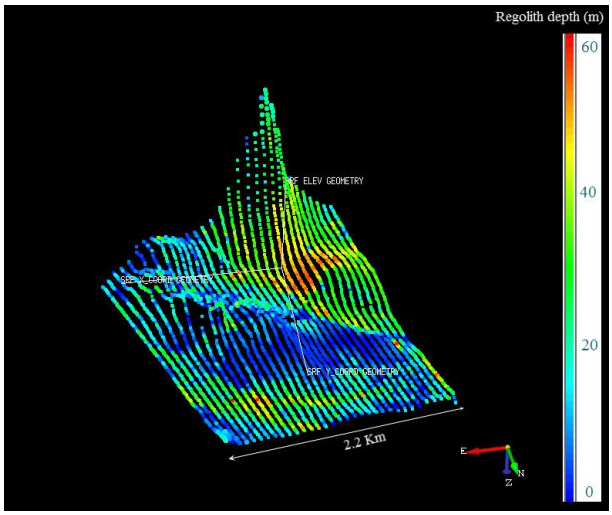

Figure 2. Estimated regolith depth, a 3D prospective.

This estimated depth is relative and typically greater than the true depth of regolith; the result never-the-less resembles the actual variations of regolith topography. The central tenet of this stage of the processing was to work with the highest possible signal-to-noise (S/N) ratio in order to be able to select the best velocity models and also to maximise the suppression of source generated noise (Williams et. al., 2010).

In this 2010 processing there was no goal of preserving relative amplitudes, and thus AGC was used for amplitude recovery and noise normalisation. The imaging stage of processing at that time included 3D DMO correction (considered as a crucial step in hard rock seismic data processing), followed by a post-stack migration algorithm. The results of the 2010 processing are illustrated in Figure 3.

In 2014 the dataset was re-processed. The motivation for reprocessing was to preserve relative amplitudes, so that the volume could be inverted into an acoustic impedance cube. Another reason for reprocessing was to improve imaging at shallow depths by refining the static solution and velocity model used for the imaging. The amplitude consistent processing included: trace editing, spherical divergence, the application of surface consistent amplitude recovery and deconvolution. The imagining technique was Kirchhoff pre-stack time migration. Due to low fold coverage at shallow depths, the static correction had to be further refined. Excellent results were obtained by application of LMO (Linear Move-out) statics

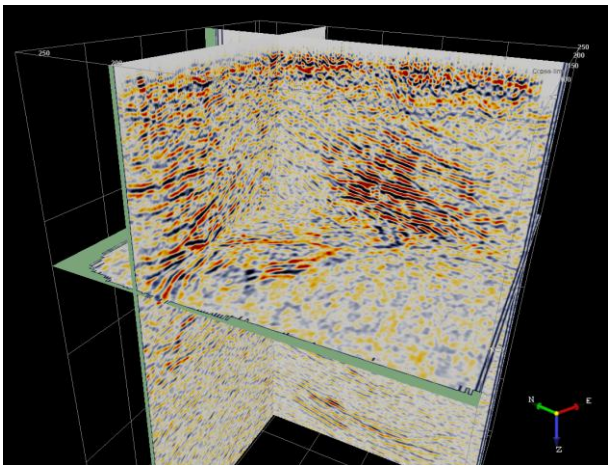

Figure 3. Kevitsa 3D volume in depth, post-stack migration (2010)

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This approach to refraction statics is based on the fact that both the refracted and reflected waves pass through the weathering layer with very similar travel paths. For example, if there is a velocity contrast of 1/3 between the weathering and sub-weathering, the refracted ray path through the weathering is just 6 percent longer than a vertical ray path. The reflected ray path lies between these. Given this situation, static corrections calculated to remove the effect of the variations in weathering on the refraction travel times approximate those required for the reflections. For our method, we calculate the corrections using a commercial surface-consistent residual static correction program. The difference is that the correction is calculated on refracted rather than reflected events. The method calculates both shot and receiver static corrections (Hatherly et al., 1994). This high resolution static solution improved the overall reflectivity of the volume.

Initially, the velocity field used for migration was obtained from CDP gathers after DMO correction had been applied. Given the high velocities and geological complexity of the hard rock environment, errors in velocity estimates result in inadequate migration.

It became apparent that a conventional DMO correction followed by post-stack migration was insufficient to handle the lateral changes in velocity field. Therefore, pre-stack time migration was attempted to aid in handling the complex velocity field. The goal of pre-stack time migration is to derive a velocity model appropriate to the geologic setting and the migration algorithm in use. The measure of the success of the model building and migration process is the ability to satisfy the needs of the algorithm, to place events at the proper position, to properly focus the energy, to avoid introduction of a false structure and to flatten the image gathers. The final PSTM velocity field, converted to interval velocity in depth is illustrated in Figure 4.

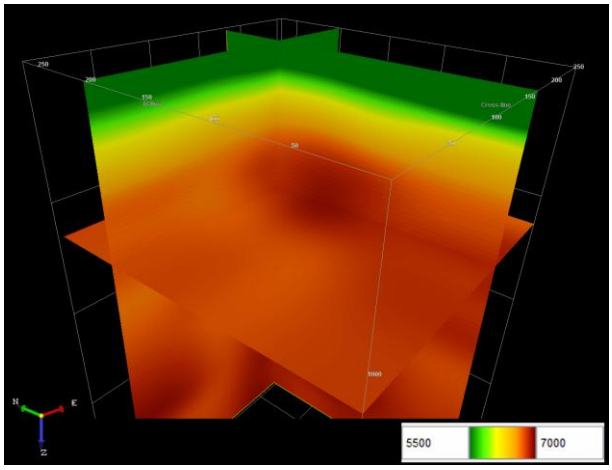

Figure 4. Interval velocity field in depth, obtained from image gathers.

The basic steps in the 3D pre-stack time migration workflow are illustrated below, Figure 5:

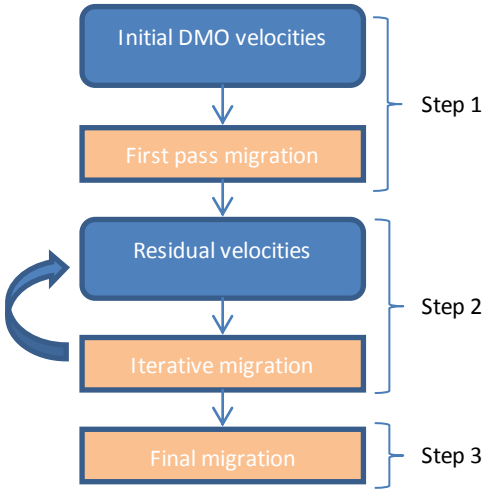

Figure 5. Isotropic pre-stack time migration algorithm

- Step 1: Initial velocity preparation and 1st pass of pre-stack time migration;
- Step 2: Residual velocity model modification, using subsequent iterations of pre-stack time migration;
- Step 3: Final migration;

Step 1 involves the building of the initial stacking velocity model followed by a first iteration of pre-stack time migration. The initial model was built through the use of the RMS velocity model from DMO corrected gathers. The imaging was done on pre-processed CDP gathers, without DMO correction. Typically, many of the reflection events in the image gathers produced by the first pass of migration are not properly imaged. This suggests errors in the initial velocity model, which will require updates to properly image the gathers.

Step 2 uses one or more iterations of residual velocity analysis on image gathers. The residual velocity error, or move out, is determined by analysis of the gathers. This analysis proposes changes to the original velocity model that will more precisely image the gathers. Once the velocity model is updated it is once more used in the pre-stack time migration to produce revised image gathers. These gathers are once again analysed and, if additional correction is required, the velocity updating process is repeated.

Upon achieving a satisfactory imaging of the gathers, one performs Step 3; the pre-stack time migration of the full project using the final velocity model. After the final migration, several post-migration processes may be applied to the data. These include filtering, scaling and calibration of the volume to tie at known well markers.

Outstanding results were achieved using the velocity model from image gathers in the final migration. The pre-stack migration algorithm has produced the best imaging results to date, even in hard rock environments. The final step in the seismic data processing was to use the information from well logs to convert the seismic volumes from two-way travel time to depth. The results of final re-processed section are illustrated in Figure 6.

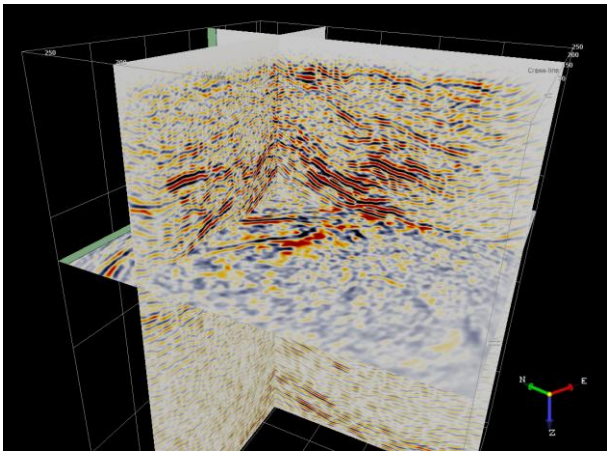

Figure 6. Kevitsa 3D volume in depth, PSTM (2014)

Now, we can convert our whole section back from its seismic "reflection coefficients" into the detailed acoustic impedances (or even velocities) present in our well data. This process is known as inversion or, perhaps more correctly, seismic inversion.

The degree of correlation between the seismic reflections and the log-derived synthetic seismograms critically affects the reliability of seismic inversions. The success of any well-tie depends on many factors such as S/N ratio, image accuracy, relative amplitude preservation, log quality, etc. (Harrison and Urosevic, 2012). Several acoustic inversion (AI) schemes were tested; the sparse-spike unconstrained inversion proved to be the most reliable (Figure 7).

The idea for future work would be to utilise available logs, VSP and geological information to produce a fully constrained AI cube. Considering that seismic velocity in hard rock settings is a monotonic function in space and time the established relationship between acoustic impedance (AI, which is a product of velocity and bulk density) and density can be used to map regions with anomalies, if any. Results could be used to help constrain gravity data inversion; conversely gravity inverted data could be verified against seismic information. The procedure described is rarely considered in hard rock seismic exploration.

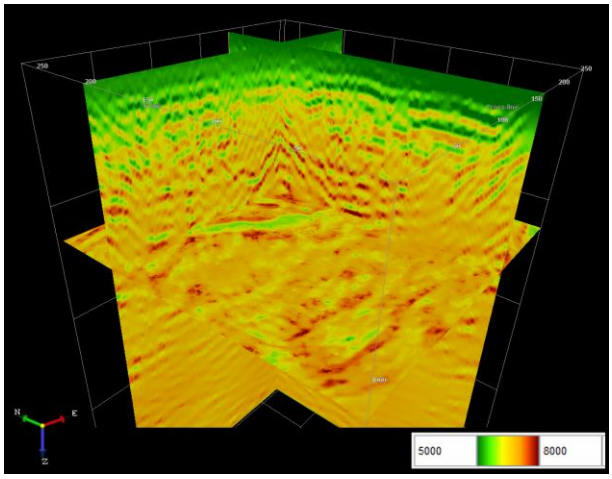

Figure 7. Sparse-spike inversion of Kevitsa 3D volume.

CONCLUSIONS

The 3D seismic survey was acquired over the Kevitsa mineralisation with the objective of mapping steeply inclined structures and associated structures which might critically impact on the design of the open pit. Good processing results were achieved after considerable effort had been put into data decoding. Further refinement of the results was accomplished through full 3D pre-stack imaging. The Kevitsa deposit has complex geology resulting in a laterally variant velocity field. The final velocity field was obtained from image gathers after several iterations of pre-stack migration and velocity updates. This iterative velocity analysis of migrated CDP gathers remains a great straight of pre-stack imaging, even in a hard rock environment.

The main concept behind future work on the data would be to utilise the pre-stack depth imaging method (PSDM). Depth imaging could be constrained by a significant number of high quality physical property measurements in drill-logs deemed suitable for the proposed task. Another recommendation for future work is to use seismic acoustic impedance for improved rock characterisation. For this purpose a fully constrained model based inversion will be required.

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