Kimberlite Delineation by Seismic Side-scans from Boreholes

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ABSTRACT
Structural and lithological delineation is seen as an emerging mining application of seismic imaging. The general benefits expected from applying delineation techniques include: reduced economic risk, shorter project timelines, and more accurate resource evaluations. The structural aspect has been documented relatively well in the past decade and consists mainly of mapping faults, fracture zones, and dissolution features, bearing an impact on geo-technical models and designs. Mineral resource delineation by seismic techniques is a comparatively recent addition to the seismic application menu and is seen as a promising technique for the coming decades.

INTRODUCTION
Current resource evaluation projects at kimberlite mines offer relevant examples of various aspects of lithological delineation. The geometry is diverse, from semi-horizontal thin folded and faulted dikes to nearly vertical irregular pipes. Physical properties can also be quite diverse, with contrast inversions relative to the country rock within the same body. The country rock itself can range from very competent to very fractured and weathered.

Critical requirements for accurate resource estimation are being set for the determination of morphology and volume of the kimberlite pipes and dikes, combined with generally shorter timelines and stricter budgetary constraints. Conversely, the variation of shape and physical properties of kimberlites require tens of borehole pierce points to estimate the volume of a kimberlite pipe within 15% variance on estimate. The high cost of drilling brought the need for complementary (rather than alternative) means of mapping the kimberlite–country rock contact. The aim is not to eliminate drilling, a quite impossible proposition, but to make better use of available boreholes and achieve faster and more reliable resource evaluations with an optimised drilling programme.

The first requirement is to provide a spatial resolution on the order of a meter. With seismic velocities in the range 5000–6000 m/s, a frequency band of 500–3000 Hz is needed. A tool with these characteristics is to be deployed in boreholes, in order to reach closer to the imaging target and get a suitable imaging angle relative to it. The borehole tool consists of a piezoelectric source and an inline array of 20–30 hydrophones or 3-component accelerometer receivers placed at 1 m or 2 m intervals. The Vibrometric VIBSIST SPH is a time-distributed swept-impact source [1]. With such sources, the seismic signals are produced as rapid series of impacts, the impact intervals being monotonically varied to achieve a non-repeatable sequence. As the energy is built up from a large number of relatively low-power impacts, the high frequency components of the seismic signal are maintained.

FINNSCH, SOUTH AFRICA

The first high-resolution borehole seismic side scan measurements were conducted in 2003 at De Beers’ Finsch mine in South Africa, [2]. The geology at Finsch produced a seismic response within a range of at least of 150 m, which was the largest expected target distance. Most of the signal energy was found in the 400–2400 Hz frequency band, the resolution being better than 1 m (a quarter of the wavelength of the acoustic signal).

Figure 1 displays a depth-distance profile where the kimberlite–country rock interface appears clearly as a boundary between the ‘flat’ region in the country rock (left) and the ‘lively’ kimberlite response (right). The measurements were done in a borehole drilled from the country rock and intersecting the kimberlite at approximately 110 m depth. The rich kimberlite response is produced by structures within the pipe. The relative lack of response of the country rock is due to its practically intact state, as indicated among others by a very high seismic velocity of nearly 6700 m/s.

The same profile is shown in Figure 2 integrated with the relevant section of the pipe model. This remarkable fit is however also due to several particularities of the Finsch site. Firstly, the clearly different seismic response of the kimberlite and the country rock is unfortunately not something always to be counted on. Generally, a certain amount of detective work is needed to identify the actual boundary amongst several wave fronts backscattered by internal structures in both country rock and pipe. Secondly, the resolution of the seismic result mentioned above is given in terms relative to the method itself (a fraction of the wavelength). It can well happen in practice that the knowledge of the actual borehole position is significantly less accurate than the seismic resolution figure. At Finsch, the pipe model available prior to the seismic surveys had been checked and fairly well proven in the region of the would-be seismic surveys, which provided a solid base to verify the results against. In spite of the limited scope (four boreholes in all for both single-hole and cross-hole side scans), the Finsch mine survey proved to be extremely important as a proof of concept.

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SNAP LAKE, CANADA

High-resolution seismic side-scan surveys were conducted at Snap Lake in 2004, as part of a series of tests for geophysical delineation of a sub-horizontal kimberlite dyke, [3], [5] and [6]. The measurements were carried out in a fan of four sub-horizontal boreholes, slightly less than 100 m long. The layout of the survey is presented in Figure 3. The Snap Lake survey has been particularly interesting because it offered a direct comparison with side-scan radar and with a basic cross-hole tomographic seismic technique [5]. Moreover, such seismic techniques, as described in [5], generally require the site to be silent, a difficult requirement to meet in an active mining environment. The seismic side-scan, [3], was also intended to dispel this prejudice.

The cross-hole tomographic survey produced general conclusions on the possible existence of deeper features, parallel with the target dyke and on the possible folding and gaps in the dikes, without however producing results resolved well enough to be used as a part of a delineation exercise. Both of these observations of principle were confirmed at a detailed scale by the high-resolution side-scans, as shown in Figure 7.

Figure 4 displays a view from SW of the seismic profiles migrated vertically under each hole. The different levels of contrast in Figure 4 are due to semi-transparent rendering, which allows the profile-to-profile continuity of the features to be observed as a means of artifact discrimination. Figure 5 shows the shallow part of the profile in Figure 4, where preliminary interpretations of the 2D profiles were drawn with red and yellow lines and the actual position of the target dyke, determined by subsequent excavation, is depicted by green dots. The corresponding radar side-scan [6] is shown in Figure 6. There are clearly corresponding features between seismic and radar, although the actual target seems to be more reliably imaged by seismics. Indeed another sub-horizontal trend, dipping roughly in the opposite direction than the target dyke, and a third set of steeply inclined features were also identified by side-scan seismics and seem to be present in the radar profiles as well. Another sub-horizontal trend, dipping roughly in the opposite direction than the target dyke, and a third set of steeply inclined features were also identified.

In general, radar and high-resolution seismics tend to produce comparable quality delineation results at very detailed scales, although they map different and not always pairing physical properties. The argument in favor of seismics develops once the investigation scale is increased as shown in Figure 7. Here the profiles are extended downwards. The target dyke imaged at its predicted position is depicted by green dots. It appears indeed that the kimberlite dyke follows a structural trend populated by other reflectors with the same orientation. Five deeper features were identified and mapped to a depth of approximately 100 m.
DIAVIK, CANADA

An extensive programme of seismic investigations for geophysical delineation of sub-vertical kimberlites was conducted at Diavik during years 2004 – 2006. The 2004 & 2005 surveys were carried out in pipes A154N and A154S, followed by pipes A21 and A418 in 2006, in a total of eleven boreholes drilled into the country rock and aiming to intercept the pipes at depth. A typical migrated seismic section is displayed in Figure 8.

After processing, the migrated seismic profiles were integrated with the pipe models, using all available information, to honor geological determinations from boreholes (pierce points). Such a result is presented in Figure 9, where double dot rows suggest possible double solutions. A double event is seen also in Figure 8 and it indicates a double reflection received from slightly different azimuths from the irregular boundary of the pipe. As a
result, updated pipe models were produced, as shown in Figure 10.

Figure 9. Combined seismic interpretations, best case (pink) and worst case (red) scenarios, from four boreholes around pipe A154N, [4], at Diavik Diamond Mine, 2005.

Figure 10. Reshaping of the pipe model based on the interpretations from the seismic side-scans, shown in blue. Initial model on the left and final model on the right.

CONCLUSIONS

The range of the side-scan seismic investigations is estimated at more than 150 m in a working mine conditions, including noise from ongoing mining activities. Using a frequency band of 500–3000 Hz, the intrinsic resolution of the measurements has been better than one meter.

To obtain a real sub-meter accuracy (equal to the intrinsic resolution of the procedure) the velocity must be correctly estimated to +/- 1% across the imaged volume. Piece points at the bottom of the hole and/or in its vicinity did help significantly the velocity calibration. The accuracy of the farther interface of the pipe location depended on the existence of piece points, as the availability of velocity determinations through the pipe was scarce.

Naturally, the simpler the shapes of the targets the less data needed to image them. Ideal structures consisting of planar slates, circular or elliptic cylinders or cones can be described by independent single or cross-hole. Similarly with surface seismics, targets with more complex shapes demand the extension of the survey along a transverse direction, i.e. towards a typical 3D layout.

Adjacent side-scans were used to produce the 3D delineations of the targets. Additional information came from borehole logs and generic geological data on the probable orientations of the targets.

Existing pipe models were used to guide the interpretation. The zone around the model prediction in which the best solution is sought has been +/- 10m distance from the hole and +/- 15° deviation from the assumed local dip.

Borehole high-resolution seismic methods were successful in delineating the kimberlite–country rock contact in all three case histories presented.

If applied routinely, they can provide a cost effective way to increase knowledge of geology and raise confidence in the geological model, reducing risk in resource estimation.

REFERENCES