Imaging an Orebody Ahead of Mining Using Borehole Radar at the Snap Lake Diamond Mine, Northwest Territories, Canada

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ABSTRACT

Borehole radar is a proven geophysical technology that can be used to map an orebody ahead of mining. This paper will present a case study, where borehole radar is being used within the mining cycle to map out orebody blocks, both as a strategic and tactical tool. Refined equipment and procedures now enables a slimline borehole radar tool to be deployed on the end of drill rods, making it easier and faster to deploy in an underground mine with minimal impact on the mining process.

Boreholes are drilled in advance of mining; cover holes to ensure the competence of the hanging wall and geology holes to determine the location and grade of ore are two such examples. All of these boreholes can be entered using a borehole radar tool to map geology and structure ahead. The radar data can provide images of the orebody as well as help detect potential water bearing structures that could impact on safety at a mining face.

INTRODUCTION

The Snap Lake mine near Yellowknife in the Northwest Territories of Canada (Figure 1) exploits a shallowly dipping diamondiferous dyke. On an exploration scale the dyke was found to be uniformly dipping; however, on a mining scale it was found to be more complex. The orebodies' emplacement is thought to have been controlled by a set of pre-existing low angle fractures. As a consequence the dyke is not a uniform sheet but a series of ramps, jogs and bifurcations. This complex structure meant that traditional mapping methods from drilling alone would not enable the detail needed to map the dyke accurately for mining. Borehole radar (BHR) was proposed as a technology that could provide a means to map the dyke directly ahead of production with a resolution of 1 m.

The first BHR surveys conducted over three test panels in 2004 and 2005 (Smith *et al,* 2007) proved the concept of imaging the three dimensional shape of the orebody over the test panel areas, and established the feasibility for continuing with the evaluation and development of the technique. These tests proved that:

- the propagation conditions in the granite host favours the high resolution imaging needed to a range of approximately 75 m from the drill hole; and
- the geological structures at a scale of greater than 1 m can be accurately mapped, providing mine planners with the information required to ensure on-time evaluation of geological risk and a smooth flow of ore to the plant.

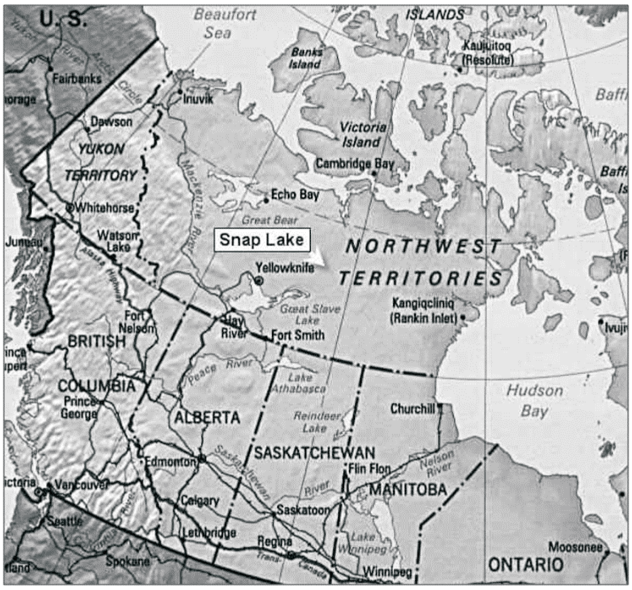

FIG 1 - Map of Canada showing the location of the Snap Lake mine near Yellowknife in Northwest Territories.

Since the test surveys, BHR has been used extensively at Snap Lake mine. Early surveys were carried out after the drill rigs had been removed, using pulleys anchored at the ends of horizontal boreholes. A number of these holes were over 600 m long. Pulley installation and operation was tolerably laborious, but the effort limited early BHR surveys to boreholes in good condition.

Present day BHR surveys at Snap Lake – and a number of mines in the Bushveld – are nearly all carried out while the drill rig is on site, using the drill string as a radar transport vehicle. The torpedo-like radars are either pumped down the string and out through the rotary bit; or they are tripped downhole on dielectric spacer rods, screwed onto the string in place of the bit. Driller deployed pump-down borehole radar surveys are now run in all of the underground boreholes that are drilled at Snap Lake. The information retrieved has made a significant contribution both to mid/long term mine planning; and (on shorter time scales and ranges) to effective operational decision making at the face.

GEOLOGY AND MINING BACKGROUND

The orebody is a shallow dipping (-15°) diamondiferous kimberlite dyke that intruded into a series of Archean granite-gneiss and metavolcanic rocks. The dominant type of kimberlite is a macrocrystic hypabyssal kimberlite, abbreviated as HK (Smith *et al*, 2007). Locally a number of subordinate units, such as veined hypabyssal kimberlite and kimberlitic breccias are identified (Mogg, 2003). The average thickness of the dyke is 2.8 m.

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Figure 2 (adapted from McCullam, 2006) illustrates the morphology of the dyke. Its emplacement is thought to be controlled by a set of pre-existing low angle fractures. The ramps, jogs and bifurcations illustrated in Figure 2 occur at a 1 m to 5 m scale, which has implications for mining, but is difficult to map or predict with traditional drilling methods alone.

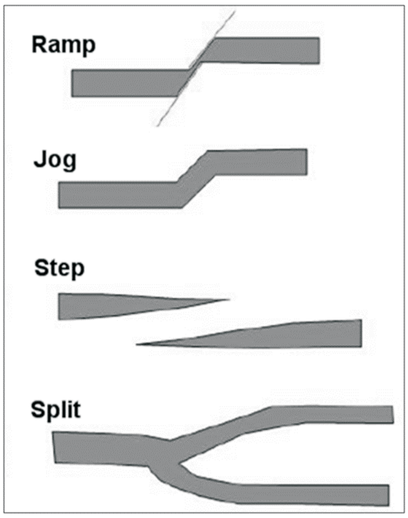

FIG 2 - Schematic and nomenclature of structural features of the dyke (after McCullam, 2006).

The modified room and pillar underground mining method used at Snap Lake is illustrated in Figure 3. It is crucial for consistent production that short-term mine planners have high resolution information about the topography of the dyke ahead to enable them to make on-time adjustments and to productively move resources around the mine.

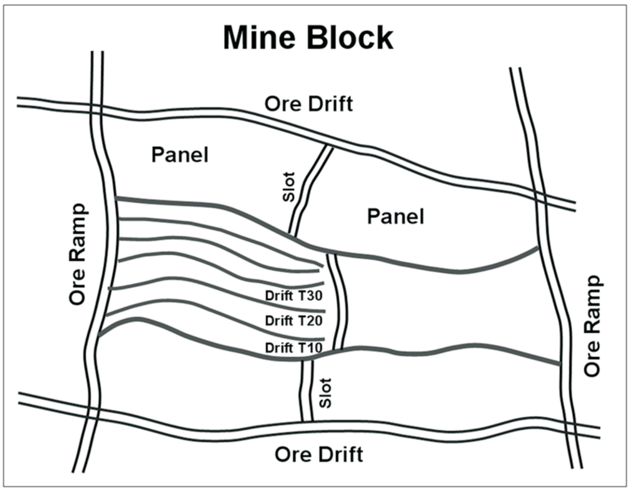

FIG 3 - Schematic mine plan layout showing the relationship between mine block and mine panels.

USING BOREHOLE RADAR FOR IN-MINE MAPPING OF PLANAR OREBODIES

Borehole Radar (BHR) is an electromagnetic subsurface imaging technique designed for imaging or detecting discontinuities in resistive hard rock formations. BHR is deployed in drill holes for both geotechnical and exploration for a fraction of the cost of drilling the hole. BHR works best when the tool is deployed in a resistive host rock and used to image a conductive orebody. Reflections are normally caused by sharp changes in the electrical properties of the rock and can yield information on geological change, faults/fractures, voids, dykes, orebody geometry, etc. On the other hand, conductive or highly fractured rock formations increase the attenuation (scattering) of electromagnetic energy making BHR less effective.

Instrumentation

A BHR tool consists of a transmitter and receiver, which can be combined in the one antenna, resulting in a radar transceiver probe or as two separate ~1.6 m long transmitting and receiving antennas in two separate probes, usually separated by a 2 m fibre optic spacer. Both antenna configurations have their advantages and disadvantages; however, due to logistical and space constraints in underground hard rock mining, usually 'single stick' transceiver probes are used. The current BHR design has come a long way in the last couple of years. Improving from probes that were connected by fibre optics to a digital acquisition system at the borehole collar (Vogt, 2006) to self-controlled radar transceivers with onboard memory (Bray *et al,* 2007) enabling surveying to be conducted on the drill rods directly after the boreholes are drilled, in the same manner that borehole deviation surveys are conducted. Single stick transceivers, which were rolled out progressively from 2004 onwards, now enable BHR to be surveyed in all underground boreholes, where previously broken ground and difficulties with end of hole pulley deployment methods hindered success.

The slimline BHR tool has been designed specifically for underground mining. Its ~28 mm core diameter enables it to be sheathed in a variety of housings – typically 32 mm and 43 mm outer diameter – to run for four hours to depths of well over 2 km, and to fit into exploratory geological or cover drill holes with diameters of 48 mm or less, while it records a radar trace at one or two second intervals into an on-board flash memory. The BHR tool is broadband, with a bandwidth that depends on the borehole's environment, but stretches typically from 20 MHz to 80 MHz. The transmitter power and receiver sensitivity give it a range in most hard rock environments of at least 30 m from the borehole, and up to 80 m in some rock types. The dielectric properties of the host rock determine the range that BHR can achieve. Hard resistive host rocks such as granite and basalt provide good platforms for BHR; however, softer rocks such as sandstone have limited range.

Slimline BHR tools are omnidirectional. Reflection data is recorded from signals received from 360° surrounding the boreholes. While a lot of research is being conducted in directional radar technology, it is difficult to fit an efficient directional radar antenna in a probe that will fit in underground mining drill holes, eg less than 48 mm diameter.

Borehole radar survey design

Establishing a good relationship between the borehole design and layout, and the layout options open to the mine geologist or engineer is absolutely critical in successful radar implementation. Valuable radar reconnaissance data can be secured from isolated 'boreholes of opportunity', BHR profiles of individual ~150 m long single underground cover holes can make an immediate contribution to mine safety. In optimising the extraction of thin reef or vein style panels, BHR surveys are usually conducted as a series of fans, or more regularly spaced reflection surveys. However, the borehole design depends greatly on the type of orebody, the geological discontinuities associated with it and the available site access for drilling. Here we will concentrate on the design and interpretation of a BHR survey for a typical thin reef or vein style deposit.

Survey design is conditioned by limitations of site access and possible parallel layering due to bedding or joint planes within the host rock. A good design starting point is to view the borehole radar's 'world view' of a stratified deposit. Consider, in

Figure 4a, the descent of a BHR down an inclined borehole that passes through two parallel interfaces, called here a hanging wall interface and the dyke plane. Passage through each plane in turn generates an inverted 'V' pattern in the time-section of a trace gather shown in Figure 4b. Echoes from nadir line and side-swipe (or off-axis) diffractors appear on the radar time section as inverted hyperbolas.

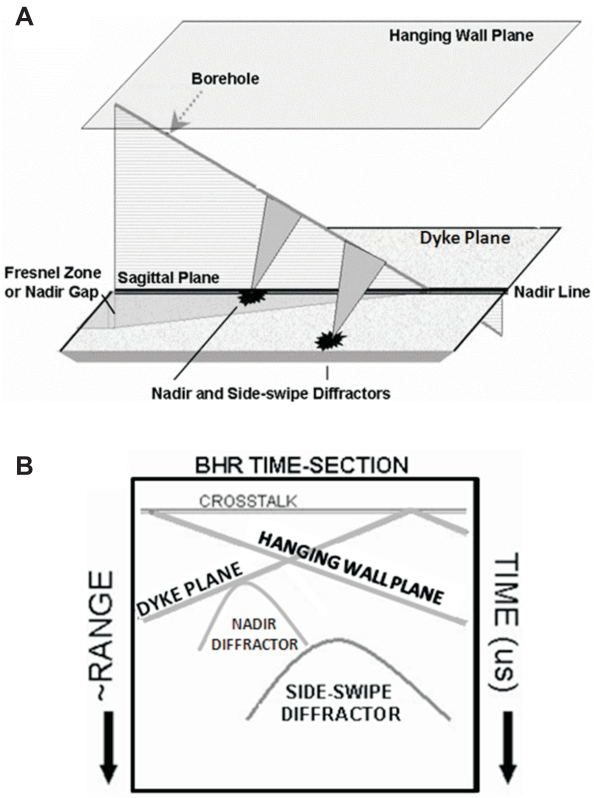

FIG 4 - (A) Example borehole radar layout, (B) resulting borehole radar time section.

BHR time sections are often dominated by specular reflections from areas on the planes that straddle so-called nadir lines. Nadir lines are the loci of reflection points on a reflecting plane. The normals to the surface at these points collectively define the so-called sagittal plane.

BOREHOLE RADAR AT SNAP LAKE MINE

The dielectric properties of the dominant granitic host, hosting roughly 80 per cent of the orebody, are very good and offer high translucence to VHF wave propagation (est Q ≥ 35). A typical range of 75 m is achieved with the 'single-stick' BHR with a bandwidth of 10 - 125 MHz. All BHR data acquisition at Snap Lake is performed with GeoMole BHR instruments.

Survey design

Mining development at Snap Lake diamond mine is all on-dyke dictating the location of drill hole collars for BHR surveys. Many boreholes are drilled at a low angle ~12° to the dyke. They slowly climb up into the hanging wall enabling BHR to image the nadir line along the dyke below the drill hole. The line often tracks an intended line of mine development. BHR is deployed both in specifically drilled holes as well as other holes drilled for geotechnical, geology or as mining cover holes. Provided that the holes don't climb too steeply to enable specular reflections of the dyke below, almost any hole can be used for BHR surveying to image the Snap Lake dyke, and most boreholes are.

Figure 5a shows the locations of boreholes surveyed with BHR at Snap Lake mine before July 2008. The near-straight borehole trajectories are overlain on the mining development. Note the twists and turns of the mining development as it attempts to follow the rugged dyke. All development shown in Figure 5a is on dyke except for a straight conveyor drift in the footwall, which crosses the figure from the bottom left to top right.

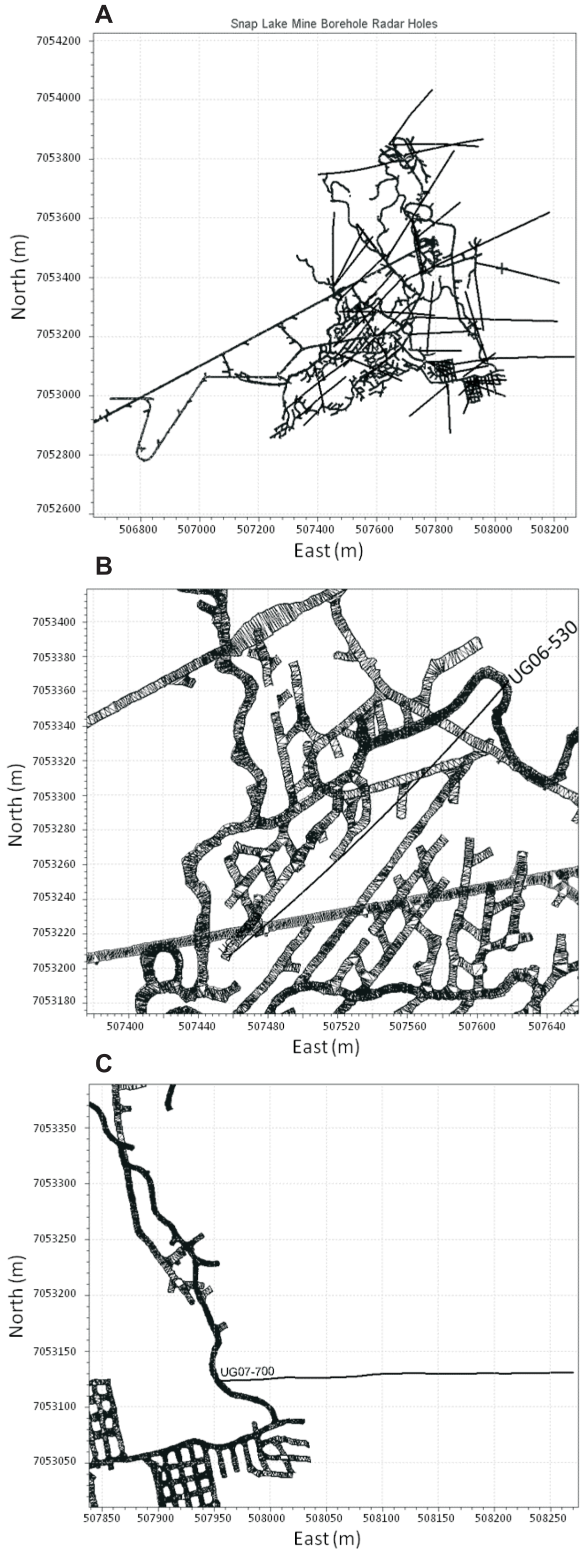

FIG 5 - (A) Plan view of Snap Lake development with Borehole Radar boreholes; (B) zoom in of UG06-530 borehole location; (C) zoom in of UG07-700 borehole location.

Boreholes are drilled for coverage with BHR over future mining blocks. Boreholes are also drilled in a short term or tactical sense in complex geological areas to find the dyke when a jog or ramp is encountered during mining. Due to the structural complexity of the dyke, it is not always possible to ensure full coverage of the dyke with BHR before mining commences, especially in areas of advance development. Tactical applications of BHR provides the miners with short range information directly ahead of their development face. Holes UG06-530 and UG07-700 are good examples of how BHR is being used at Snap Lake mine. Their locations are shown in Figure 5b and 5c respectively.

Borehole radar results and interpretation

The examples shown here illustrate how BHR is being used in the mining sequence to assist with both tactical geological mapping in unexpected geologically complex areas and long term mine planning. Figure 5 shows the locations of boreholes UG06-530 and UG07-700 which have their borehole radar results examined here in more detail.

UG06-530 borehole radar results

Borehole UG06-530 is a prime example of how BHR can be used tactically to delineate jogs and ramps that are causing problems in advance of mining. During development across the block, a steep ramp in the dyke was encountered. Mining development attempted to follow the ramp but became difficult as the dyke's dip increased causing development to be halted. BHR data from the area was then reviewed for any information on the dyke's geometry.

Review of the data revealed that borehole UG06-530 crossed over the area of concern. The data was combined with geological data from wall mapping and a good correlation between the BHR interpreted location of the dyke and the actual mapped location of the dyke in the greater area was found. A detailed interpretation of the BHR was then made and the location of the dyke ramp in the halted mining heading was found. The mine technical team was then able to create a plan to mine through this area without any additional stoppage of production in the heading.

The BHR data for UG06-530 is shown in Figure 6. The data has had a broad band-pass filter and automatic gain control applied. The horizontal axis shows distance down the borehole in metres and the vertical axis shows radial range from the borehole in metres. Note the clear reflection from the dyke moving across the section.

The migrated BHR data for borehole UG06-530 is shown in Figure 7. The image shows symmetry about the drill hole due to the omnidirectional nature of the GeoMole BHR tool. Note in the figure the interpretation of the two dykes above and below the borehole.

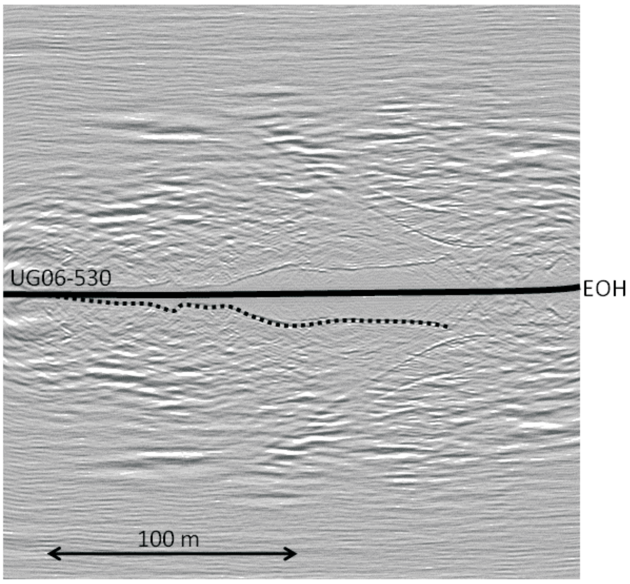

FIG 7 - UG06-530 migrated sagittal plane showing the interpreted dyke as a dotted line. Note the jogs and ramps in the data. The migrated data is symmetrical about the borehole due to the non-directional nature of the radar system.

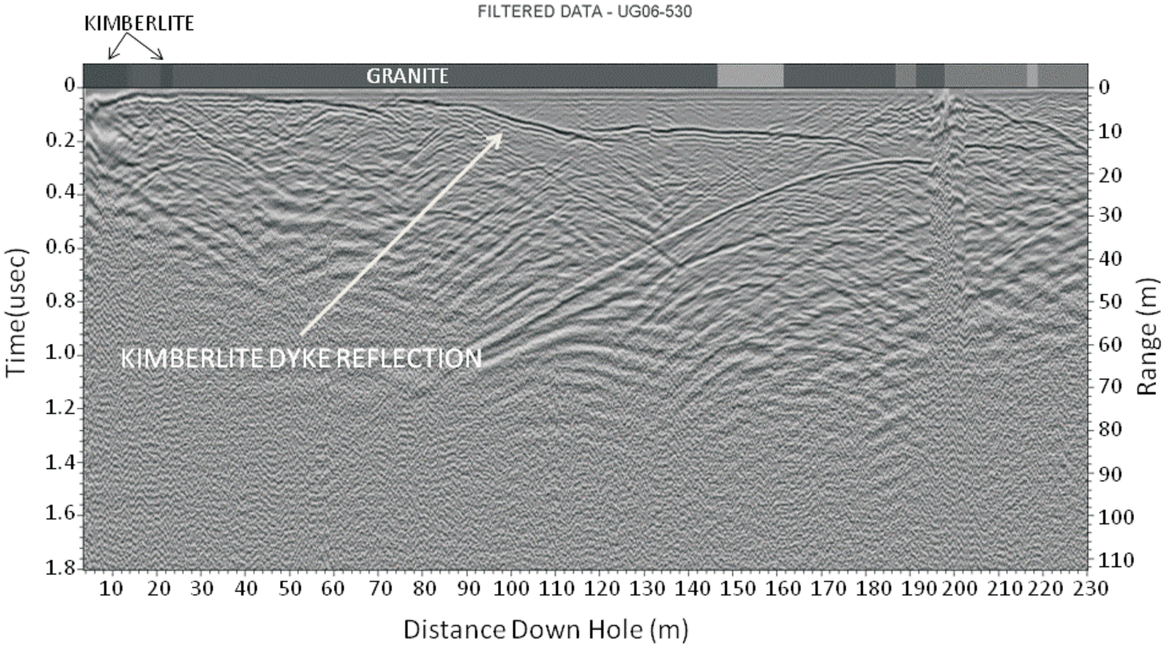

FIG 6 - UG06-530 borehole radar time-section. Distance downhole is shown on the horizontal axis. Radial range from the borehole is shown on the vertical axis. The geological log for the hole is overlain at the top of the section.

UG07-700 borehole radar results

The BHR results for borehole UG07-700 illustrate how BHR can be used for mine planning. A 'tear' in the dyke was interpreted from surface drilling, but it was difficult and expensive to determine the extent of the 'tear' from drilling alone. A probe hole was drilled, and then surveyed with BHR, across the tear area with the intention of picking up the dyke with an intersection point on the other side of this 'area of non-conformity'.

The drill hole intersected a second dyke at about 300 m downhole. The BHR survey had great success in delineating the extent of the two dykes in the area. Follow-up drilling has confirmed the BHR results and additional BHR surveys have assisted with the modelling of the area where it was found that the 'area of non-conformity' was actually a 'hole' not a 'tear'.

The BHR data for UG07-700 is shown in Figure 8. The data has had a broadband-pass filter and automatic gain control applied. The horizontal axis shows distance down the borehole in metres and the vertical axis shows radial range from the borehole in metres. Note the clear reflection from the two dykes cross-cutting the section. The first reflection seen moving away from the hole as the radar descends is the dyke currently being mined. The second reflection seen moving towards the borehole as the radar descends is the second dyke – sitting below the main dyke in this area.

The migrated BHR data for borehole UG07-700 is shown in Figure 9. The image shows symmetry about the drill hole due to the omnidirectional nature of the GeoMole BHR tool. Note in the figure the interpretation of the two dykes above and below the borehole.

SUMMARY AND CONCLUSIONS

The work presented in this paper demonstrates that using BHR can dramatically contribute to lowering the mine operating costs. By strategically conducting BHR surveys both prior to, and within the mining cycle, geological knowledge about the orebody is improved. Information from BHR surveys enable short-term mine planners to make informed decisions that can improve production and reduce downtime from unexpected complex geology.

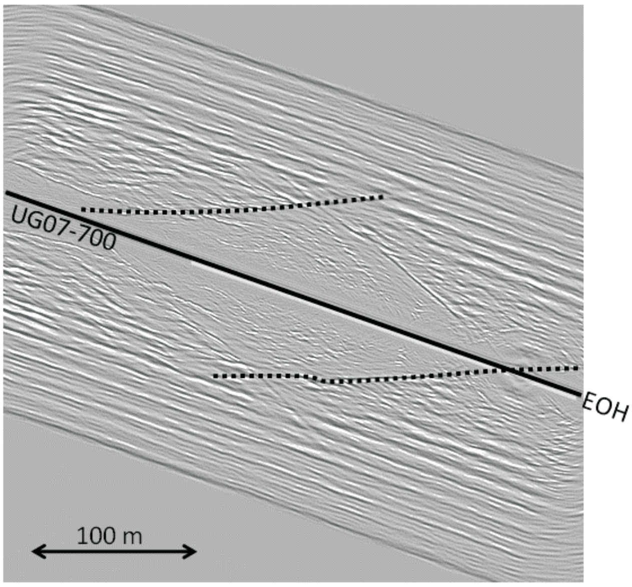

FIG 9 - UG07-700 migrated sagittal plane showing the interpreted upper and lower dykes as dotted lines. The migrated data is symmetrical about the borehole due to the non-directional nature of the radar system.

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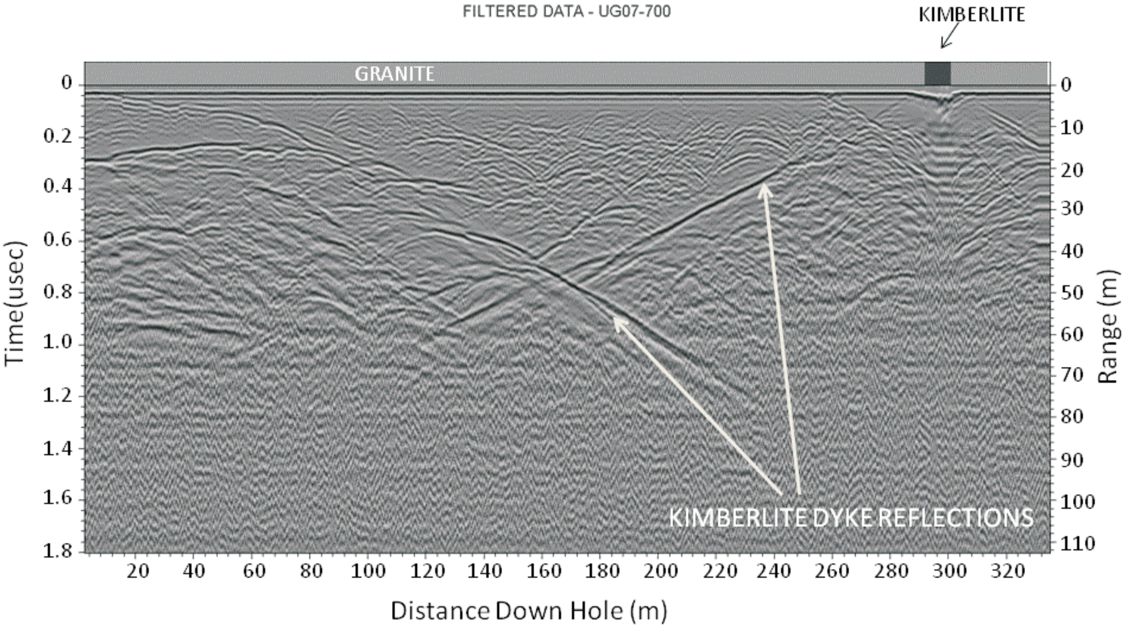

FIG 8 - UG07-700 borehole radar time-section. Distance downhole is shown on the horizontal axis. Radial range from the borehole is shown on the vertical axis. The geological log for the hole is overlain at the top of the section.

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