Paper 89

Geophysical strategies for kimberlite exploration in northern Canada

Power, M. [1], Hildes, D. [1]

1. Aurora Geosciences Ltd.

ABSTRACT

Geophysical methods are a critical component of kimberlite exploration programs in northern Canada. Successful projects require the application of complementary techniques selected on the basis of the kimberlite facies likely present in the target area. Because of differential glacial abrasion, kimberlites may be eroded to different levels in a target area. The facies of kimberlite exposed in the scoured top of an eroded pipe will govern the geophysical response. In general, total magnetic field surveys are useful in locating pipes or dykes regardless of the kimberlite facies present. Crater facies kimberlite shows the greatest contrast in physical properties with respect to granitic and gneissic country rock and this facies of kimberlite responds well to electromagnetic surveys. Unfortunately, surficial sediments can generate EM and magnetic field responses which resemble those of crater facies kimberlite. The critical problem in screening these anomalies is to determine whether the associated resistivity low persists to depth. Because the low resistivity material is also less dense than the surrounding rocks, gravity surveys, suitably corrected for the effect of the water column if conducted over lakes, can be a useful screening tool in this situation. Capacitive coupled resistivity (CCR) and seismic refraction surveys are also useful in determining the source geometry. Diatreme facies kimberlite produces more subtle responses than crater facies kimberlite and also generates anomalies easily confused with surficial features. For both crater and diatreme facies kimberlite pipes, ground penetrating radar (GPR) surveys can be used to define their tops and guide subsequent drill testing but are of limited use in conclusively identifying kimberlite in the absence of other methods. Hypabyssal kimberlite is most often found in dykes and sills and can be mapped with total magnetic field and investigated in detail with GPR or seismic reflection surveys.

INTRODUCTION

The application of complementary geophysical techniques has been a key component of diamond exploration programs in northern Canada since the discovery of diamondiferous kimberlite near Lac de Gras in 1991. During the early 1990's, exploration strategies focused almost exclusively on the application of total magnetic field and electromagnetic surveys, using a limited suite of known responses to guide target identification. In the latter part of the decade, drilling success rates declined and subsequently a wider range of techniques were employed to winnow targets from a much larger number of subtle responses, most of which were associated with surficial features. Coincidentally, an appreciation developed that a wide range of geophysical responses were associated with kimberlite intrusions and that this range reflected the depth of erosion. This paper summarizes several successful approaches for employing geophysical techniques in northern diamond exploration.

KIMBERLITE INTRUSIONS

Kimberlite is an alkalic ultramafic rock generated in the upper mantle and rapidly emplaced during explosive volcanic events (Kjaarsgard, 1996). In the Slave Craton and adjacent areas, these erupted in subaerial to shallow subaqueous environments and consequently many of the resulting vent systems are vertical to steeply dipping carrot-shaped bodies, equidimensional in plan and tapering gradually with depth. Kimberlite intrusions tend to occur in clusters or fields, with the large scale distribution possibly controlled by deep seated structural features and local emplacement controlled by shallow zones of weakness such as faults or the margins of diabase dykes.

The features of a typical kimberlite body are shown in Figure 1. Kimberlite volcanoes form distinctive pipes which can be subdivided from top to bottom into crater, diatreme and hypabyssal facies kimberlite. Crater facies kimberlite is a mixture of tuffaceous kimberlite, surrounding country rock and overlying sediments. In much of the Slave Craton, crater facies kimberlite include a significant component of shale and mudstone, sometimes with a significant component of entrained organic material. Large blocks of surrounding country rock (xenoliths) shattered from the volcanic vent margins are present in some pipes. A Crater facies kimberlite is often deeply weathered and serpentinized. Diatreme facies describes an explosive kimberlite breccia composed of fine-grained kimberlite, mantle nodules and angular fragments of the

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surrounding country rocks. Diatreme facies rocks are generally confined to a central breccia pipe and are generally less altered than crater facies rocks. Hypabyssal kimberlite consists of unaltered fine-grained kimberlite with mantle nodules and rare fragments of country rock. Hypabyssal kimberlite bodies include dykes, blind intrusions and the root zones of kimberlite pipes.

In a given kimberlite field all three facies may be present at surface as a result of differential glacial abrasion and quarrying, and because of blind intrusions. The variation in depth of erosion can occur over distances of a few tens of kilometres or less. Kimberlite dykes, sills and blind intrusions can occur proximal to volcanic vents.

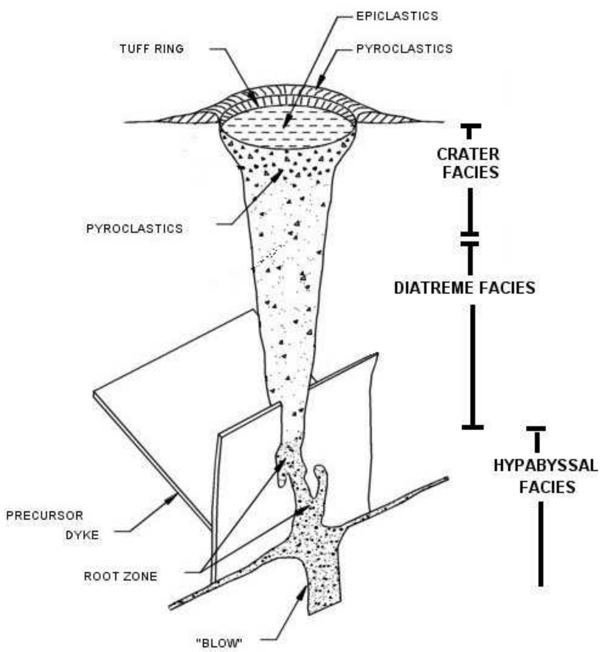


Figure 1: Facies and components of a typical kimberlite pipe with no erosion (modified after Mitchell (1986)).

The range of physical property contrasts between kimberlites and country rocks in the Slave Craton are illustrated in Figure 2. Kimberlites have generally higher magnetic susceptibility than surrounding gneisses and granites and are additionally prone to retain remnant magnetism. As a consequence, magnetic anomalies are commonly associated with kimberlite intrusions although the association can be subtle. Crater facies kimberlites often displays anomalously low magnetic susceptibility relative to surrounding country rocks, reflecting the proportion of entrained non-susceptible sediments. The electrical resistivity, seismic velocity and density of kimberlites increase with depth from crater facies through hypabyssal facies. As a consequence, crater facies display the greatest contrast in physical properties with respect to country rock and is the most readily detectible with geophysical methods. Unfortunately, the low electrical resistivity, density and magnetic susceptibility of a crater facies kimberlite is similar to that of fine grained glaciofluvial sediments common in the shield regions of northern Canada. Discriminating between these sources is a central problem in screening potential crater facies targets. In the Canadian shield environment, diatreme facies kimberlite usually has less physical property contrast with respect to country rock than crater facies kimberlite. As a result, EM and electrical resistivity methods are less diagnostic over these rocks. Hypabyssal kimberlite is almost indistinguishable from granitic or gneissic country rocks on the basis of electrical resistivity and is most readily detected by a contrast in magnetic susceptibility or the presence of remnant magnetism.

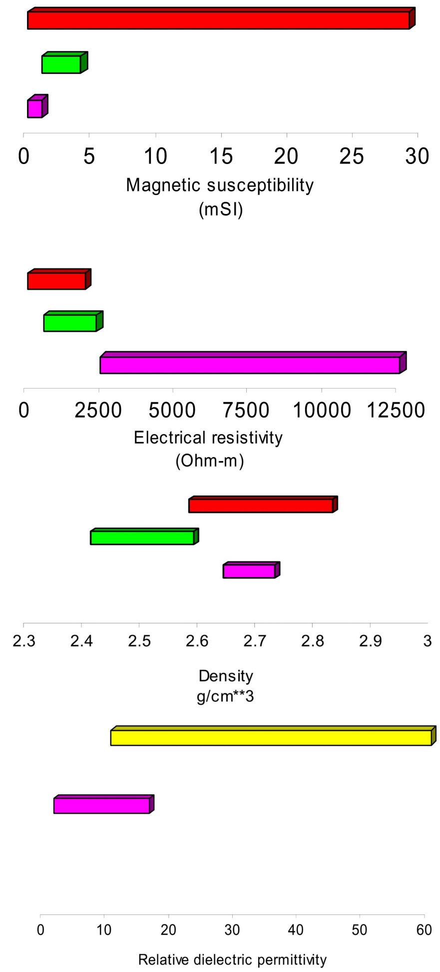


Figure 2: Physical properties of diatreme and hypabyssal facies (red), crater facies (green), undifferentiated kimberlite (yellow) and gneissic / granitic country rock (purple) in the Lac de Gras area (C. Kennedy, personal communication, 2007; Nabighian, 1987).

SOURCE AREA ASSESSMENT

Prospective areas for kimberlite exploration are normally defined by extensive till geochemical surveys to locate characteristic kimberlite indicator minerals and, occasionally, fragments of kimberlite. Once a source area is defined, airborne total magnetic field and electromagnetic surveys, principally helicopter borne (HEM), are routinely used to locate targets within this region. Magnetic signature remains the principal means of detecting and ranking an airborne target. An assessment of the likely depth of erosion in the inferred source area is critical in determining the probable magnetic field signatures.

Typical kimberlite pipe magnetic signatures are shown in Figure 3. The common feature in virtually all kimberlite pipe responses is a roughly equi-dimensional magnetic signature covering a few hectares (the largest known pipe in the three Canadian northern territories covers about 20 ha.) These anomalies are generally associated with structural features such as faults (linear lows) or diabase dykes (magnetic highs). Kimberlite is generally more susceptible than the surrounding rocks and the total field anomalies can directly indicate the location and shape of tephra fans as in Figure 3(a) (amplitude 300 nT) or the location of multiple vents in a larger complex as in Figure 3(b) (amplitude 60 nT). Crater facies kimberlite responses, illustrated in Figures 3(c) and (d) are often expressed as a 60 to 150 nT smooth magnetic low. In some fields (eg. Parry Peninsula area and Victoria Island) kimberlite pipes are

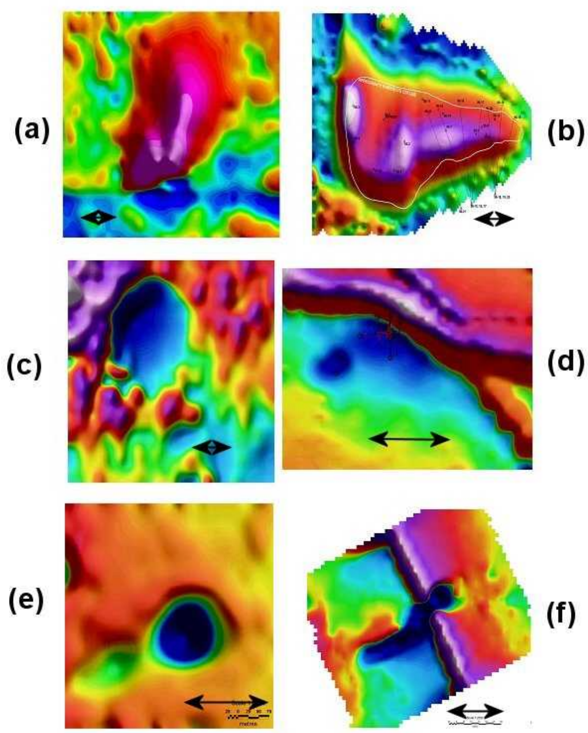


Figure 3: Kimberlite pipe total magnetic field responses, showing a range of possible magnetic signatures. Positive anomalies are shown from a 300 nT high susceptibility crater facies (a) and a 60 nT high susceptibility diatreme and crater facies (b). Subtle negative responses illustrate low susceptibility crater facies in (c) (-60 nT) and (d) (-150 nT). Large negative amplitude anomalies (-300 to -800 nT) from remnant magnetism shown in (e) and (f). The double headed arrow represents 200 metres in each image.

associated with dipolar or strongly negative anomalies reflecting remnant magnetism as shown in Figure 3(e) (amplitude –800 nT) and Figure 3(f) (amplitude –300 nT).

Unfortunately a large variety of features can produce magnetic anomalies similar to those of kimberlite pipes. Magnetic field lows similar to those generated by some crater facies kimberlite targets are created by deep bedrock topographic depressions filled with non-susceptible glaciofluvial sediments. If the clay-rich, they also generate spurious coincident resistivity lows. Fault intersections are often recessive zones of persistent vertical alteration which generate both magnetic and resistivity lows. Boulder trains of magnetically susceptible bedrock can generate tempting elliptical magnetic highs. As a consequence of this, airborne magnetic surveys serve principally as a means of defining a large set of potential targets but are of limited use in screening targets except in areas with non-susceptible country rock where the kimberlites are obvious drill targets. This situation is common in areas covered by non-magnetic carbonates north and west of the exposed Slave Craton.

CRATER & DIATREME FACIES TARGETS

Pipes containing crater facies kimberlite can generate very obvious geophysical targets if present in areas with non-conductive bedrock and only a thin veneer of overburden. In the Lac de Gras area, the majority of crater facies kimberlites produce magnetic lows with coincident HEM apparent half-space resistivity lows (to 10 ohm-m) and discrete conductor responses.

More generally, however, many prospective areas are covered with conductive glaciofluvial sediments which themselves generate a large number of spurious magnetic and resistivity lows. As a result, a key challenge in exploring for crater facies kimberlite is to assess the depth extent of an anomalous source body. Because of the inherent ambiguity in magnetic field inversions, attention focuses on the coincident EM conductor. In assessing potential crater facies kimberlite targets the central question becomes: “Does this conductor persist at depth?”

Both crater facies kimberlite and glaciofluvial sediments are less dense than the surrounding or underlying bedrock. Consequently, gravity surveys can be used to assess the depth extent of these electrical conductors. Gravity methods were employed sporadically for kimberlite exploration in the early 1990’s but came into more general use later in the decade when real time kinematic (RTK) GPS receivers and automated gravimeters were paired and rapid, high precision gravity surveys became possible (Power et. al., 2004)

A unique problem in northern Canada is that many of the potential targets occur under small lakes and the water column in these lakes generates Bouguer lows. Conventional bathymetric corrections employing infinite slab approximations are inappropriate and overcorrect the data. A better solution is to correct the Bouguer anomaly data using a bathymetric model of the lake incorporating the known shore outline and depth measurements at various points on the lake. During winter conditions these measurements are taken by drilling and sounding line or by using an acoustic depth sounder with the sensor placed in a small pool of windshield anti-freeze on the ice surface. This latter approach only works if the water depth is more than about 6 metres and can yield spurious results in deeper water if cracks are present.

Figure 4 illustrates the utility of these surveys using an example from the Torrie Pipe, 45 km northwest of the Ekati Mine. Figure 4(a) shows the final Bouguer data after all conventional corrections (drift, latitude, Bouguer slab, Free air, Bullard-B and terrain effect (to 3 km from any station)). The outline of the kimberlite pipe is shown with a dashed line. The pronounced Bouguer low is coincident with deep water in the lake (30 m). After bathymetric corrections, the Bouguer anomaly is reduced and the low is shifted to the north (Figure 4(b)). During drill testing of this target located a 50 m by 50 m granite xenolith in the southern portion the pipe, coincident with a small magnetic high (Figure 4(c)). The bathymetrically corrected Bouguer anomaly data correctly reflects the presence of this granite xenolith and illustrates the danger of using uncorrected Bouguer anomaly data to drill test anomalies.

Anomalous thicknesses of surficial sediments will also generate Bouger lows. Modeling results and unfortunate experience suggest that a Bouguer anomaly amplitude of at least –0.5 mGal is a suitable threshold for identifying potential drill targets.

Capacitive coupled resistivity (CCR) is a relatively new technique uniquely suited for use in northern Canada. The method employs long wires to inject low frequency alternating current into the ground via capacitive rather than direct (galvanic) contact. A dipole-dipole array is towed in-line and the depth of investigation is proportional to the dipole separation. The method works well in resistive ground and permits rapid coverage either on foot or by towing the system behind a snowmobile. The data can be inverted using conventional DC resistivity modeling techniques provided the ground is resistive (Kuras et. al. 2006).

CCR surveys conducted with multiple dipole separations can be used to investigate the depth extent of HEM conductors. Figure 5 illustrates the results of these surveys over a known kimberlite and over a drill-tested overburden conductor. The CCR data was inverted using the UBC-DCIP resistivity program (DCIP2D 1998) and the inversion sections depict the interpreted distribution of the 2D resistivity with areas beyond the resolution of the survey blanked out.

The inversion results over CT-55 (Figure 5(a)) correctly located the top of this land-based crater facies pipe (intersected at a depth of 35 m) and also indicated that the low resistivity material persists at depth. Over a nearby false target (Figure 5(b)), CCR inversions indicated that the weakly conductive material associated with a magnetic high did not persist at depth to the same extent can be rapidly conducted with a single spread of geophones laid over the target by firing two shots at large off sets from either end of the geophone array. On lake-based targets, the blast points can be located on land. At large shot offsets (>200 m) the highest velocity linear arrival is assumed to arise from bedrock. Reversed profiles are necessary to estimate the true bedrock velocity because of the possibility that the top of the bedrock surface may dip. An example of the results from a seismic refraction survey over the Bay kimberlite pipe is shown in Figure 6. Linear arrivals from water, ice, overburden,

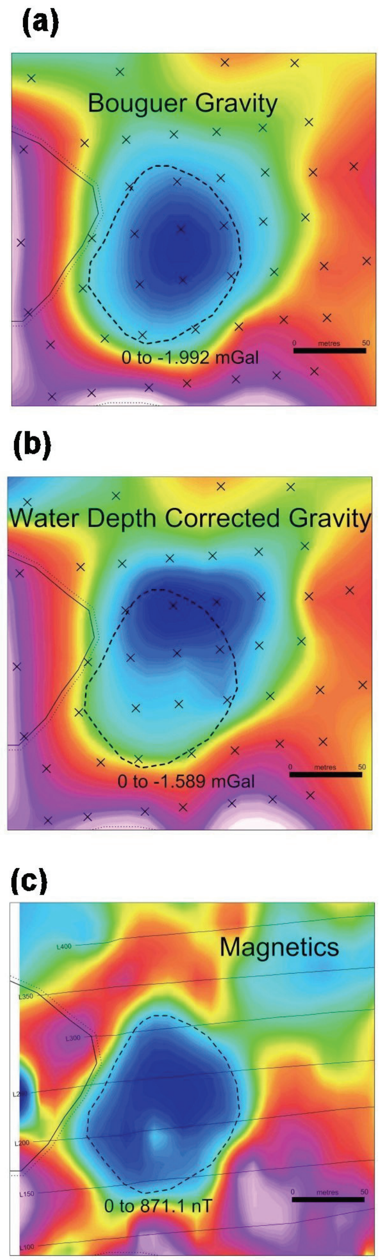


Figure 4: Crater facies kimberlite gravity and magnetic response of the Torrie Pipe showing the effect of a large granitic xenolith in the southern end of the pipe. Panel (a), with no bathymetric correction, does not correctly image the xenolith.

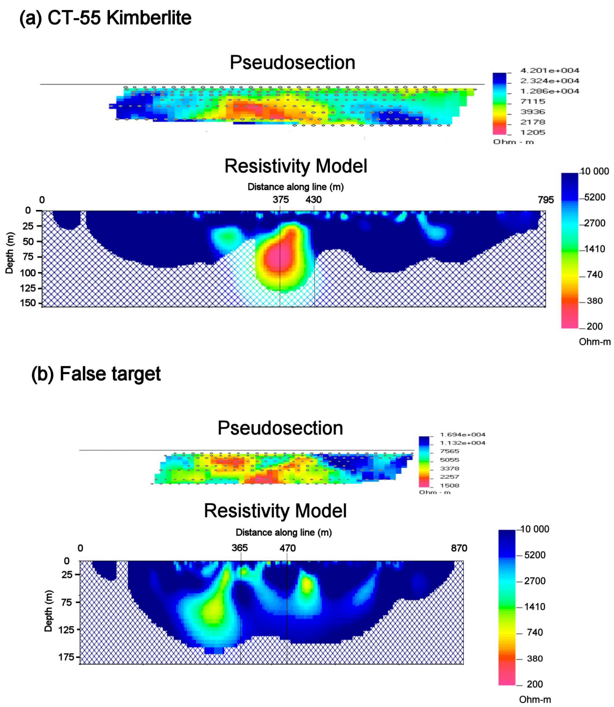


Figure 5: CCR surveys over a land-based kimberlite and over a drill tested barren target.

weathered and fresh kimberlite are identified (events WA, IC, OB, K1 and K2 respectively). The inverse slope of the linear arrival yields the apparent seismic velocity and the average of the reversed profiles is a suitable estimate of the true bedrock seismic velocity. In this instance, fresh diatreme facies kimberlite (K2) with a velocity of 4300 m/s was mapped.

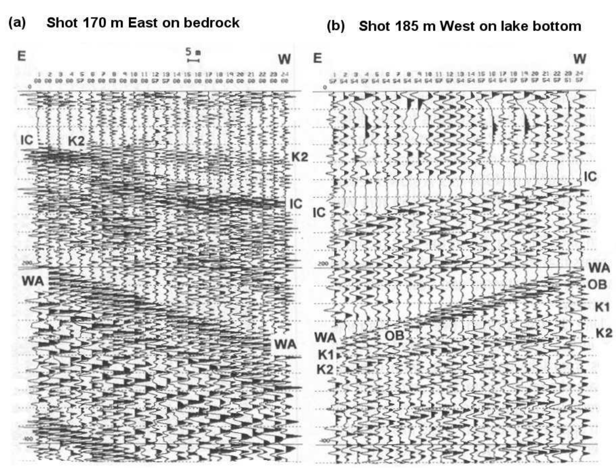


Figure 6: Seismic refraction survey over a kimberlite pipe showing water (WA), ice (IC), overburden (OB), weathered kimberlite (K1) and fresh kimberlite (K2) arrivals.

False seismic targets can be generated by velocity anisotropy in fracture zones. To mitigate this problem, a target is normally tested with a pair of orthogonal seismic profiles; the apparent bedrock seismic velocity on each profile should be that of kimberlite in the case of a valid target. A more serious problem is that there is a velocity overlap between kimberlite and some metasedimentary rocks found in greenstone assemblages. A careful assessment of the likely bedrock seismic velocity – perhaps involving an in-situ measurement – should be made before these surveys are used to screen potential kimberlite targets.

An alternate approach to assessing potential crater facies kimberlite pipes is to look at the character of the top of the conductor. GPR surveys can be useful in this regard although experience has shown that these surveys cannot be used as the sole discriminator in screening airborne targets. Figure 7 shows the response over both lake- and land-based kimberlite pipes. Figure 7(a) illustrates the response over the CL-25 pipe, east of the Snap Lake Mine recorded at 25 MHz. Bedded crater facies kimberlite generates strong, smooth reflections with very high signal attenuation. In contrast, the surrounding fractured granite generates numerous diffraction hyperbolas. Figure (7(b)) illustrates the response over the CT-55 kimberlite at 12.5 MHz. The top of the crater facies kimberlite is clearly evident as a strong reflector at a depth of 37 m beneath a section of boulder till. Experience with GPR over a number of kimberlite pipes has lead the authors to conclude that GPR is most useful for defining the limits of a kimberlite pipe once an initial drill hole has conclusively confirmed the presence of kimberlite. Low frequency surveys (25 / 12.5 MHz) are generally necessary to mitigate scattering by boulders and to achieve maximum depths of investigation.

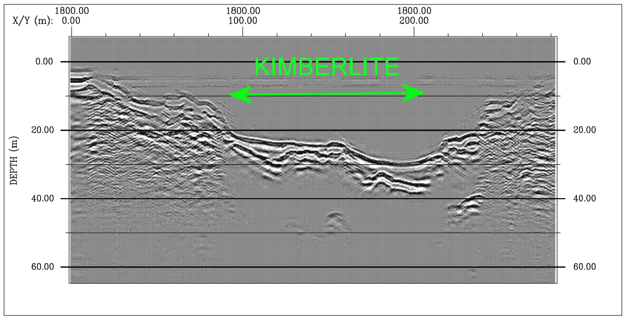
Diatreme facies targets were first recognized in the heavily explored areas near the Ekati and Diavik Mines. In general these generate weaker and more ambiguous resistivity, gravity and seismic responses than crater facies kimberlites. With these targets, detailed till geochemical surveys immediately down-ice from prospective geophysical anomalies is necessary to minimize the number of false targets selected for drilling.

HYPABYSSAL KIMBERLITE

The discovery of the high grade diamondiferous Snap Lake dyke established that hypabyssal facies kimberlite was an overlooked target during the initial phases of the diamond exploration program in northern Canada. Hypabyssal facies kimberlite shows the least contrast in physical properties with respect to surrounding country rocks and occurs in small bodies such as dykes and sills. Both of these factors attenuate the geophysical responses associated with hypabyssal kimberlite bodies. Dykes and sills on the other hand generate wide, persistent indicator mineral trains and a restricted source region can be readily defined with till geochemical surveys.

Total magnetic field surveys have proven to be the only method which can readily locate these targets in a defined source area. GPR surveys have been used successfully to map the lateral extent of some dyke and sill systems.

(a) GPR response over a lake-based pipe



(b) GPR response over a land-based pipe

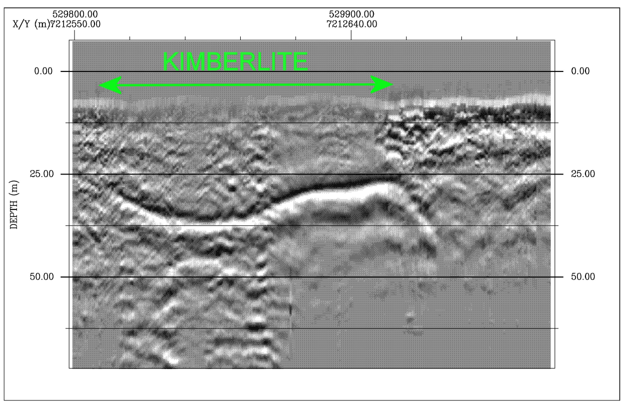


Figure 7: GPR responses showing the strong, smooth reflectivity of bedded crater facies kimberlite.

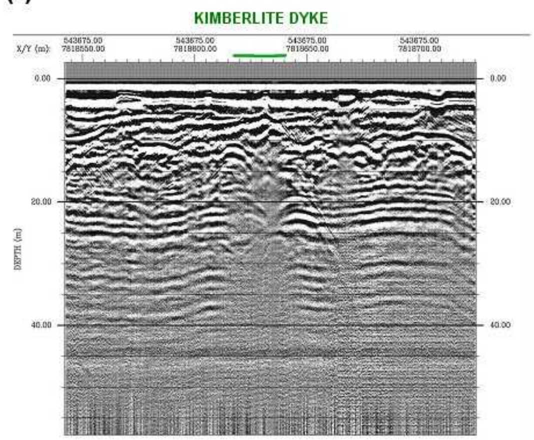
Figure 8 illustrates the response of GPR systems over vertical and moderately dipping kimberlite dykes. Figure 8(a) shows the response over a vertical dyke intruding flat-bedded limestone. The margins of the dyke produce diffraction haloes and the dyke is evident as a break in the horizontal reflections from the limestone bedding planes. Figure 8(b) displays the response of a moderately dipping kimberlite dyke intruding granitic rocks (Mud Lake dyke). Radar reflections originate at the boundary between water-saturated kimberlite and the surrounding granites. Spurious GPR anomalies resembling those expected from kimberlite dykes can be generated by gouge filled fault zones.

Seismic reflection has also been used to map hypabyssal kimberlite. Figure 9 is a reflection section collected over the Snap Lake dyke with a 1024 channel ARAM system, using Vibroseis and dynamite as energy sources. Single phones spaced 4 m apart were used for data collection and shots were spaced 8 m apart. The 1 to 2 m wide dyke is clearly visible as a discrete feature to depths of 1800 m. Fortunately, in this situation the host rock consisted of monolithic granitic gneiss and there were no interfering reflections. Seismic reflection is appropriate for delineation of drill tested economic target given the high cost of the surveys.

CONCLUSIONS

Successful geophysical exploration programs for kimberlite exploration rely on a suite of methods tailored for the facies of kimberlite known or inferred to be present in a defined source area. The selection of appropriate methods and the interpretation of the results has to be guided by sound geological

(a)



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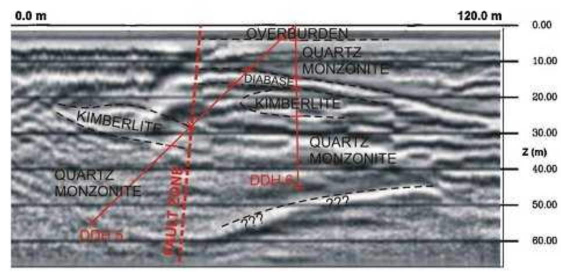

Figure 8: GPR responses over hypabyssal kimberlite dykes.

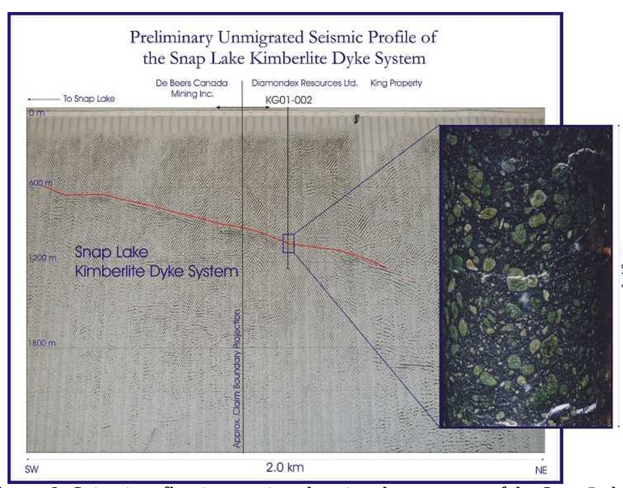

Figure 9: Seismic reflection section showing the response of the Snap Lake hypabyssal dyke.

information including the type of bedrock, the orientation of bedding and of structural features, the presence of complicating features such as faults or alteration zones and the nature and thickness of overburden. An assessment of the depth of glacial erosion likely to be encountered is critical in both selecting the appropriate mix of surveys and in assessing their results.

In all cases, magnetic field surveys are the essential first tool in screening the source areas of kimberlite indicator mineral trains. Resistivity is a useful tool in exploring for both crater facies and diatreme facies kimberlite where coincident total magnetic field anomalies (often lows) and coincident resistivity lows are good indicators of prospective targets. The critical problem in exploring crater facies targets is determining the depth of the associated conductor to discriminate between bona fide crater facies targets and surficial conductors. Gravity, CCR and seismic refraction surveys are useful in this task. GPR surveys can be used to delineate the top of crater facies kimberlite pipes but are not useful in conclusively establishing the presence of kimberlite. Hypabyssal kimberlite is most readily detected with total magnetic field surveys and can be delineated in detail with GPR or seismic reflection surveys if confined to sills or dykes.

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