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Authors' addresses

D. Kerr *(dkerr@nrcan.gc.ca)*
R. Knight *(rknight@nrcan.gc.ca)*
B. Kjarsgaard *(bkjarsga@nrcan.gc.ca)*
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

P. Budkewitsch *(paul.budkewitsch@ccrs.nrcan.gc.ca)*
Canada Centre for Remote Sensing
588 Booth Street
Ottawa, Ontario K1A 0Y7

D. Bryan *(doug.bryan@diavik.com)*
Diavik Diamond Mines Inc.
Box 2498, 5007-50th Avenue, Yellowknife
Northwest Territories X1A 2P8

Surficial geology, spectral-reflectance characteristics, and their influence on hyperspectral imaging as a drift-prospecting technique for kimberlite in the Diavik diamond mine area, Northwest Territories

D. Kerr, P. Budkewitsch, D. Bryan, R. Knight, B. Kjarsgaard
Terrain Sciences Division, Ottawa

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Abstract: Numerous kimberlite pipes have been discovered in the Lac de Gras area, but detection of new pipes is proving more and more difficult in areas characterized by thick overburden cover and few kimberlite indicator minerals in till. This paper summarizes the surficial geology and provides preliminary analyses of the spectral-reflectance characteristics of kimberlite, till, and bedrock for kimberlite exploration in the Diavik mine area. Proglacial sediments deposited prior to glaciation may protect the kimberlite from glacial erosion and therefore no kimberlitic debris is produced. Field and laboratory spectrophotometer measurements were made of bedrock, till, and kimberlite material to document their reflectance properties. Fourteen samples from till of varied thicknesses were tested and all have relatively similar reflectance characteristics. However, significant differences exist in the spectral-reflectance characteristics of the till and kimberlite material in the 400 to 2500 nm range.

Résumé : De nombreuses pipes de kimberlite ont été découvertes dans la région du Lac de Gras, mais il devient de plus en plus difficile de découvrir de nouvelles pipes dans les régions où les dépôts meubles sont épais et les minéraux indicateurs sont rares. Le présent article résume la géologie de surface et présente les résultats d'analyses préliminaires des propriétés de réflectance spectrale de la kimberlite, du till et du socle rocheux qui aideront la recherche de kimberlite dans la région de la mine Diavik. Les sédiments proglaciares déposés avant la glaciation peuvent protéger la kimberlite contre l'érosion par les glaciers, empêchant ainsi la production de débris kimberlitiques. Des mesures au spectrophotomètre ont été prises sur le terrain et en laboratoire sur des échantillons de socle rocheux, de till et de kimberlite en vue de documenter les propriétés de réflectance des échantillons. Quatorze échantillons de till d'épaisseurs variées ont été analysés et partagent des propriétés de réflectance semblables. Il existe cependant des différences significatives entre le till et la kimberlite dans la bande de 400 à 2500 nm.

INTRODUCTION

This study, part of the GSC's project on 'Understanding the diamondiferous Lac de Gras kimberlite field, Northwest Territories, focuses on fieldwork undertaken in June 2001 on the Diavik Diamond Mines Inc. claims east of Lac de Gras. Canada's first diamond mine, BHP/Billiton's Ekati, and Canada's soon to be second diamond mine, Rio Tinto/Aber Diamonds Corporation Diavik mine, are located here (Fig. 1). Despite the significant number of kimberlite pipes discovered to date in the Slave Province, kimberlite is becoming increasingly difficult to locate by the most commmonly used exploration methods in the Lac de Gras area — indicator-mineral sampling of overburden (primarily till) and airborne and ground geophysical methods. More recently, both airborne and ground hyperspectral surveys have been undertaken as potential exploration methods for a variety of mineral-deposit types in glaciated regions. This project aims to summarize the surficial geology and glacial stratigraphy in order to assess hyperspectral ground surveys as a drift-prospecting technique for kimberlite in an area with varied overburden thickness.

METHODS

Fifteen stations were established across the study area from which a total of fourteen 10 kg till samples were collected for detailed trace-element geochemical analysis on various grain-size fractions. Sites were selected so that thin till with bedrock outcrops (till veneer) and thicker till (till blanket and hummocky till) were sampled. Striae and other ice-flow indicators were recorded wherever possible. Field and laboratory spectrophotometer measurements were made of bedrock, till, and kimberlite material to document their reflectance properties. The new till samples complement the till geochemistry work by Wilkinson et al. (2001), as well as the original 170 regional GSC till samples from this map area that were collected for textural and trace-element geochemical analyses

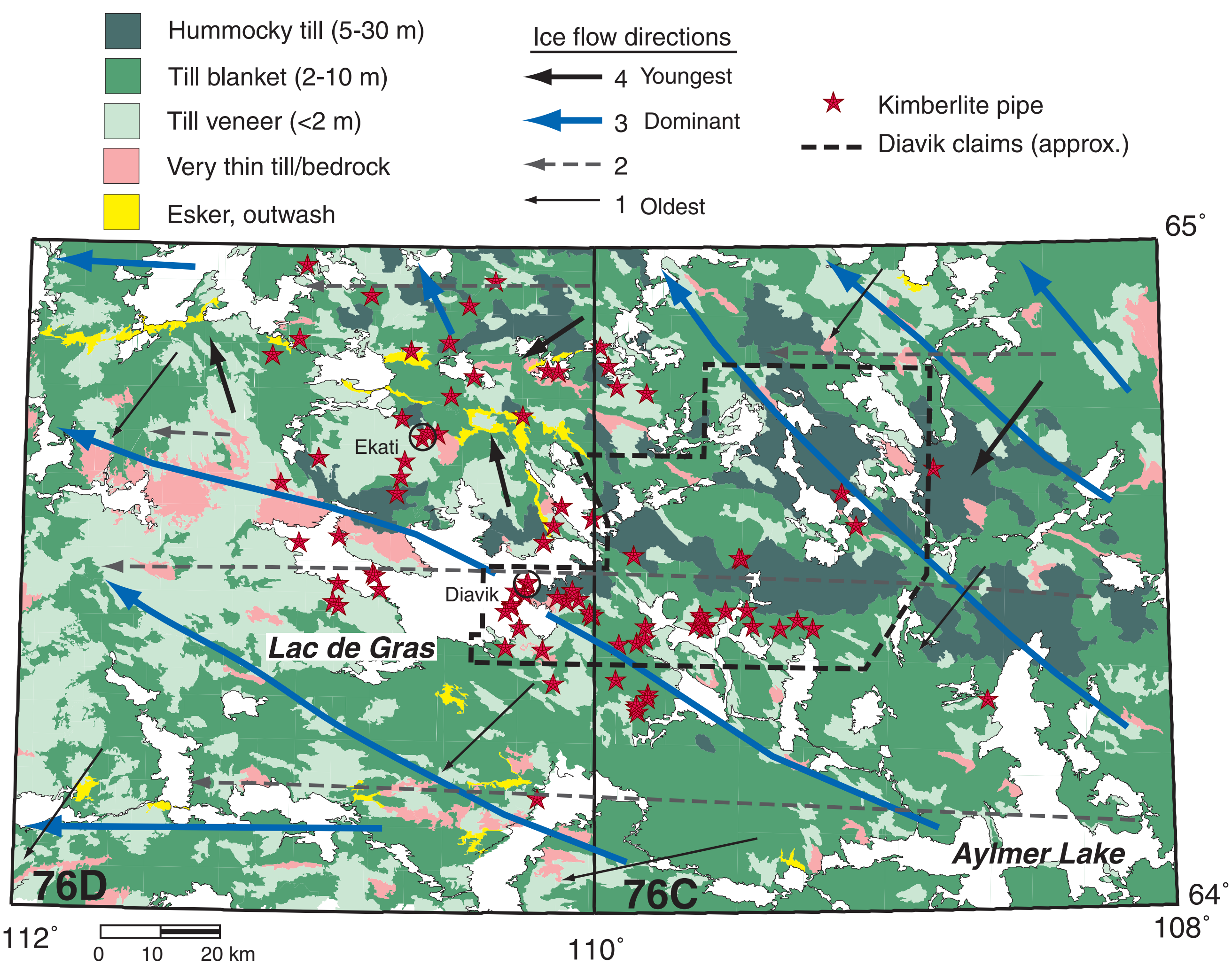

Figure 1. Location map with generalized surficial geology and ice-flow data, Lac de Gras area, Northwest Territories (modified from *Wilkinson et al., 2001).*

(Dredge et al., 1995b). As part of the original study, 55 additional 10 kg samples were collected for heavy-mineral and kimberlite-indicator analyses (Dredge et al., 1995a), and pebble samples were collected to assess ice-flow styles and glacial transport distances.

REGIONAL SETTING

The Diavik claims under investigation as part of this study lie within the northeast quadrant of the Lac de Gras map area (NTS 76 D) and the northwest and central parts of the Aylmer Lake map area (NTS 76 C), Northwest Territories. Elevations range between about 410 m and 480 m. Local relief is low, commonly <10 m in areas of rock and till blanket, although relief >30 m is prevalent in areas of hummocky till and some eskers are over 45 m high. Numerous lakes occupy glacially scoured bedrock basins and smaller water bodies occur in depressions on the till surface. Most drainageways are shallow; streams have not cut into bedrock or the till plain. The area lies north of the treeline, and glacial deposits are covered with low shrubs, alders, and tundra heath vegetation.

BEDROCK GEOLOGY

The study area lies within the central Slave Province of the Canadian Shield. Lord and Barnes (1954) mapped the bedrock and made casual observations on striations and eskers. Bedrock consists of Archean volcanic rocks and greywacke, i.e. mudstone turbiditic sedimentary rocks belonging to the Yellowknife Supergroup (Henderson, 1970; Padgham and Atkinson, 1991). The turbidite has been folded, faulted, metamorphosed to various degrees, and formed into low-grade phyllite and medium-grade porphyroblastic schist. These metasedimentary rocks were intruded by younger, ca. 2.61 Ga diorite-granodiorite and ca. 2.59 Ga biotite and muscovite+biotite monzogranite (Kjarsgaard et al., in press). Proterozoic diabase dyke swarms trending northeast, east, and north-northwest crosscut the area; some dykes are 50 m wide. Numerous Cretaceous to Eocene kimberlite pipes have intruded these older rock types (Armstrong and Chatman, 2001). Bedrock has been subjected to intensive postglacial frost shattering, and large blocks have been frost heaved up to 1 to 2 m.

SURFICIAL MATERIALS

Till, a matrix-supported glacial diamicton, is the most extensive deposit in the area. Only one stratigraphic unit of till has been recognized from mapping and it is attributed to the Wisconsin Glaciation (Dredge et al., 1994). The clast content of till varies from 5% to 40% of the total volume of material, but is generally about 25%. Matrix size varies according to bedrock source and amount of meltwater associated with deposition. Till derived from granitoid rocks has a sandy matrix, whereas that derived from the Yellowknife Supergroup is siltier. Where glacial meltwater was associated with till deposition, the matrix is commonly medium- to coarse-grained sand.

The till sheet has been divided into three subunits, i.e. veneer, blanket, and hummocky till, on the basis of thickness and surface morphology (Fig. 1). Till veneer is generally <2 m thick, contains bedrock exposures, and conforms to the underlying bedrock morphology. It is generally loose and its surface is characterized by high concentrations of cobbles and boulders of local provenance. Till blanket is generally estimated to be 2 to 10 m thick. Till blankets either drape the underlying bedrock, forming gently undulating till plains, or contain low-relief drumlinoid features. Blanket tills are relatively compact and contain fewer boulders than veneers. Hummocky till deposits are >5 m thick and form irregular topography with relief up to 30 m; bedrock forms are totally masked. Hummocky till forms a discontinuous belt about 40 km wide across the central part of the Aylmer Lake map area and at the east end of Lac de Gras (Dredge et al., 1999).

Glaciofluvial deposits are geographically widespread, but of limited extent, and are dominantly in the form of eskers and related kames. Eskers range from small, sinuous ridges a few hundreds of metres long to larger, more linear features up to 45 m high and 15 km or more long. The ridges vary from sandy and flat topped to bouldery and sharp crested. Exposures of bare, washed rock up to 1 km wide commonly flank large esker ridges and connect esker segments, attesting to subglacial meltwater flow activity (Rampton, 2000). Potential Pleistocene drainage channels were noted by Lord and Barnes (1954). Eskers underlie till, cut into till, and lie at the surface above both till and outcrop. Small kames consisting mostly of sand are associated with the esker systems and the washed zones. They range from streamlined forms to irregularly shaped mounds.

Glacial-lake sediments were identified only in a few localities; they were thin, sandy, and not aerially extensive. However, well developed raised beaches were noted on the flanks of some eskers and bedrock outcrops at the east end of Lac de Gras, a few metres above the present-day lake level.

GLACIAL HISTORY

The Diavik claims lie within the central part of the Keewatin sector of the Laurentide Ice Sheet (Dyke and Prest, 1987). At its maximum at 18 000 BP, the northern margin of the Keewatin ice sheet lay north of the Arctic coast and as far west as the Mackenzie Valley. Radiocarbon dates suggest that ice still covered the region about 10 000 BP, but that the ice front had retreated east of Aylmer Lake by 9000 BP.

The striation data indicate an early southwestern regional ice flow, possibly relating to the build-up phase of the last glaciation, as indicated in Figure 1. This was followed by a westward flow tentatively placed during the main part of the Late Wisconsin glaciation. A final shift to a dominant northwestward flow was responsible for the formation of glacial landforms such as drumlins and fluted bedrock observed today (Ward et al., 1995). Major esker ridges and their tributaries trending northwest in the central and northern parts of the area may have developed during the same late-glacial phase. The broad band of hummocky moraine in the central part of the study area, with associated boulder lags, rim ridges, and till plateaus, suggests that part of the ice sheet downwasted. Near Lac du Sauvage, partly flattened wooden twigs in one esker within hummocky drift date to about 8500 BP (Dredge et al., 1996). They suggest that the hummocky belt was a late ice remnant that persisted after other areas were deglaciated.

Evidence for short-lived, isolated glacial lakes that formed during deglaciation occurs in some areas in the form of raised gravelly beaches. Those occurring at the east end of Lac de Gras may relate to temporary ice-dammed lakes that existed between stagnant ice masses.

GLACIAL STRATIGRAPHY AND IMPLICATIONS FOR DRIFT PROSPECTING

Until recently, little was known about overburden stratigraphy in this part of the Slave Province because of a lack of natural exposures along lakes and rivers. It is only with the advent of drilling associated with kimberlite exploration and later geotechnical surveys that our knowledge of the third dimension of the local surficial geology has increased. The typical secrecy related to early mineral exploration in general is another factor that makes it difficult to obtain new and accurate geological data for the public realm. However, with the opening of the first diamond mine in the area, the Ekati mine, and with a second, the Diavik mine, nearing production, more information is becoming available.

In one early case study at Hardy Lake in the northwest corner of NTS 76 C (Aylmer Lake) McKinlay et al. (1997) reported the stratigraphy over a kimberlite pipe (Hardy Lake 02) situated under a lake. This pipe was located through a combination of anomalous kimberlite indicator minerals in till and geophysical surveys. The basal kimberlite was interpreted to have been scoured out by glaciers, then overlain by 2 to 3 m of granitic boulders, 12 to 17 m of till, and a cap of 3 to 5 m of postglacial lake-bottom sediments.

Recent reverse-circulation drilling data from a number of logs on the Diavik claims provide a better indication of overburden thickness associated with specific types of surficial sediments. Kimberlite pipes overlain by till originally mapped as till veneer (Dredge et al., 1996) were in most cases covered by 2 to 5 m of overburden. Surficial materials mapped as till blanket overlying some pipes varied in thickness from 5 m to 34 m. There were no indicative surfaces features, such as the absence of nearby bedrock outcrops, to suggest the unexpected relatively thick package of overburden sediments recorded over some kimberlite pipes. Kimberlite pipes overlain by hummocky till in plains with irregular topography were generally covered by 9 to 12 m of overburden. Three of the kimberlite pipes studied are located in areas covered by glaciofluvial sediments that also show evidence of meltwater-scoured hummocky till and bedrock. Overburden thickness in these areas ranged from 4 to 15 m. One of the most significant thicknesses of surficial sediments recorded over a kimberlite, in an area mapped as till blanket northeast of the Diavik mine, is approximately 42 m. The stratigraphic sequence, from bottom to top, consists of granite intruded by kimberlite, overlain by 4 m of clay, 4 m of sand, and 34 m of till. The basal clay unit may represent a proglacial lake that was gradually infilled with sandy glaciofluvial outwash, recording the advance of the ice during the last glaciation. Till was subsequently deposited during full glacial conditions and during deglaciation.

This particular stratigraphic setting may be responsible in part for the relatively small numbers of kimberlite indicator minerals found in till throughout much of this region. Despite low sampling density of surface till in regional surveys undertaken by the GSC (Kerr et al., 1998), it is clear that few kimberlite indicator minerals (pyropes, Cr diopsides, Mg ilmenite, and chromite) occur in the northern and central region of the Aylmer Lake map area, compared to the Lac de Gras map area. Low kimberlite indicator mineral counts in till in this area have also been reported by Diavik, even though several kimberlite pipes have been discovered, some of which are diamondiferous. Indicator minerals become incorporated in till during glacial erosion of kimberlite. However, if the kimberlite is in a depression that is infilled by sufficiently thick proglacial sediments prior to glaciation, the sediments may protect it from glacial erosion and therefore no kimberlitic debris is produced. Ice would have advanced over the glaciolacustrine and glaciofluvial sediments, depositing till over this protective cap. Variations of erosional and/or depositional activity on this model may account for the occurrence of minor amounts of indicator minerals in till or outwash where overburden is relatively thick.

REMOTE SENSING

Landsat images have been used to identify paleodrainage networks for alluvial diamond exploration (Marshall and Baxter-Brown, 1995), and other work has illustrated the potential for the thermal infrared band on Landsat images to gauge lake-surface temperatures as a proxy for deep lakes, perhaps underlain by eroded kimberlite (Rencz et al., 1996). Kruse and Boardman (1997) recognized the difficulties of prospecting for kimberlite using hyperspectral-imaging systems given poor exposures, but revealed success in mapping minerals associated with kimberlite.

Hyperspectral-imaging technology is a great deal more advanced than multispectral sensors, sampling at much narrower wavelength bands and commonly recording 100 or more spectral bands. The advancement of remote sensing for mapping till deposits in support of drift prospecting has not been fully investigated. The varied glacial stratigraphy and extensive vegetation cover in the region present significant challenges and lead to a need to assess the role of remote sensing for diamond exploration in northern environments. To add some understanding to part of this problem, we present preliminary results on the spectral-reflectance response of bedrock exposures, unweathered and nonweathered kimberlite, and various till samples collected in the Lac de

Gras area. The spectral-reflectance profiles of these materials can be consulted to access the potential for broadband satellite data or narrow-band hyperspectral data for discriminating among these different materials.

SPECTRAL-REFLECTANCE MEASUREMENTS

Ground and laboratory spectral measurements were acquired using a GER3700™ spectroradiometer. This is a portable field instrument and this particular unit has 577 channels sampling within the wavelength range of 400 to 2490 nm. The field measurements were made by nadir viewing of relatively flat and horizontal target surfaces. Details on the method of precise ground-based data collection are described in Secker et al. (2001). Reflectance values presented here are with reference to a Spectralon® panel. Indoor laboratory measurements were made in much the same fashion, with full field-of-view illumination supplied by a BBA incandescent lamp. Data in this paper should be considered preliminary, but do provide reliable results upon which we base our conclusions. The complete set of spectral measurements will be accessible from the CCRS Arctic Spectral Library at a future date.

***Figure 2.** Vegetation-free surface of a muscovite+biotite monzogranite in the Lac de Gras region, Northwest Territories.*

Bedrock

A limited number of bedrock spectral readings were made in situ during the short time available to us in June 2001. Figure 2 shows an example of a typical vegetation-free and glacially polished surface of muscovite+biotite monzogranite. The corresponding spectral-reflectance curve is given in Figure 3.

Till

Fourteen till samples were collected from active or recently active mudboils. Samples (10 kg) were taken from unvegetated till surfaces selected within an otherwise regionally well vegetated zone. The site charactistics are listed in Table 1 and the spectral-reflectance characteristics are plotted as Figure 4. These are laboratory measurements made on the finer matrix portion of the till. Thin layers of sample till were left to air-dry indoors for approximately 200 hours. To achieve representative results, all samples were sieved to remove lithic clasts larger than 6 mm that could potentially bias the spectral response. A minimum of four independent measurements with a field of view approximately 6 cm in diameter were averaged to produce the spectral-reflectance profiles. Common absorption features are observed near 2210 nm, 2320 nm, and to a lesser degree, 2250 nm (Fig. 4), and are similar for all till samples. Some slope differences are observed in the 400 to 1000 nm range. Three spectra exhibit relatively steeper slopes in this region (samples 7052K, 7056K, and 7058K) and are slightly more brownish than the average grey of the till (*see* Table 1). This colour may be due to trace amounts of organic material ((?)tannins), iron oxides, or both. It is of note that no evident differences in the spectral-reflectance profiles have been related to the total till thickness at the sampling location.

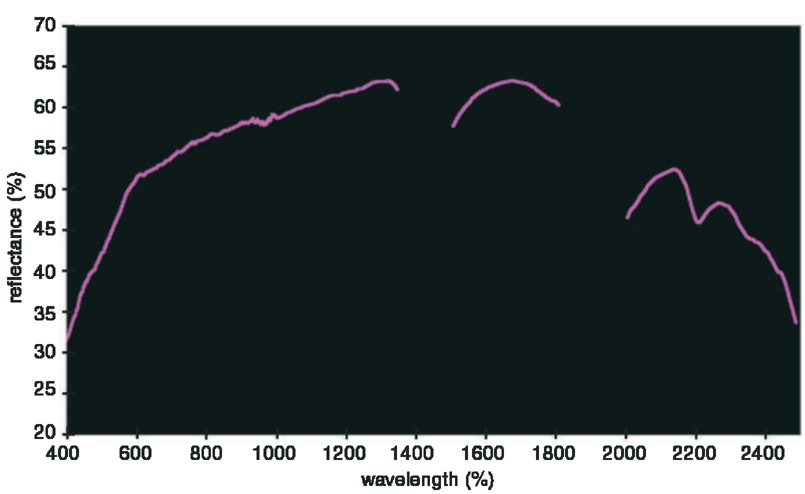

Figure 3.

Spectral-reflectance profile (400–2500 nm) of muscovite+biotite monzogranite. Absorption bands near 1400 nm and 1900 nm due to H_2O and OH are omitted in this plot.

Table 1. Till sample data.

Sample no.	Material	Colour (dry)	Till thickness (m)	UTM easting	UTM northing
7050K	till	grey	<10	604229	7173090
7051K	till	grey	<10	602082	7173507
7052K	till	brownish-grey	<3	599098	7177938
7053K	till	grey	<3	586167	7175537
7054A	kimberlite	grey	>42 depth		
7054K	till	greyish (lighter)	<42	556684	7169277
7056K	till	brownish	<3	535379	7145489
7057K	till	grey	<5	539365	7141656
7058K	till	brownish-grey	<18	555120	7143033
7059K	till	greyish (lighter)	<18	556710	7145983
7060K	till	greyish (lighter)	<3	566159	7148439
7061K	till	grey	<3	565811	7147934
7062K	till	grey	<9	554448	7157557
7063K	till	grey	<3	575576	7180026

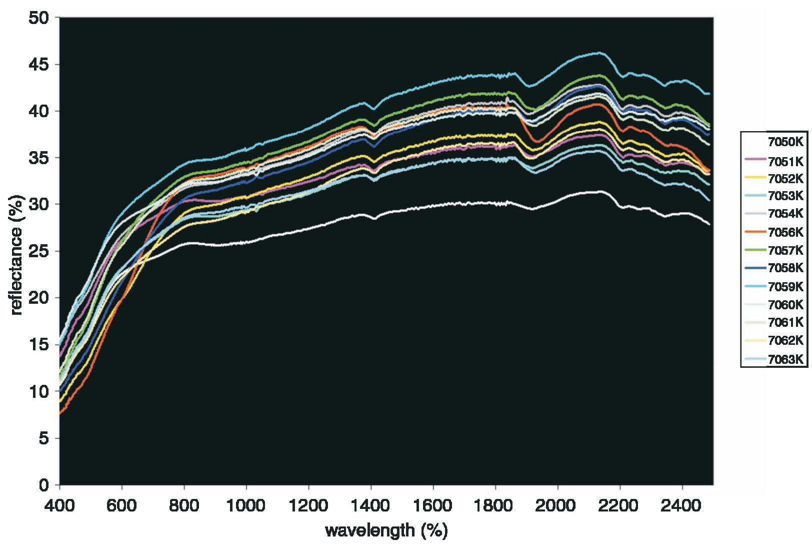

Figure 4.

Spectral-reflectance profiles (400–2500 nm) of Lac de Gras till (dry samples). Absorption bands near 1400 and 1900 nm are due to H_20, OH, and H_2O, respectively.

Kimberlite

Kimberlite outcrops are very rare in the Lac de Gras area. However, kimberlite boulders and pebbles can be observed in glacial till at surface. The presence of kimberlite would not be unambiguously detectable by multispectral data (e.g. Landsat or SPOT), but subpixel concentrations could be identifiable using algorithms designed to take advantage of the numerous bands in hyperspectral-imaging data. This is important, particularly with data from airborne instruments where pixel sizes are usually less than 10 m. The accurate identification of kimberlite depends entirely on distinguishing spectral-absorption features and the spectral contrast between the background (sum of all unwanted) and the target (desired) materials.

Figure 5 illustrates the spectral-reflectance characteristics of a nonweathered kimberlite sample collected near Lac de Gras. The absorption features near 1050 nm (10^{-9}m) agree with the known spectral reflectance of olivine (Clark et al., 1993). Olivine macrocrysts (1–20 mm) constitute 10 to 50 modal per cent of typical Lac de Gras field kimberlite; the olivine is partly to completely preserved. The absorption features in the 2000 to 2500 nm range provide some insight into the secondary minerals including clays, serpentines, and carbonates associated with weathered kimberlite. For many rock-forming minerals, including this assemblage, absorption features in the shortwave infrared wavelength range of 1500 to 1800 nm are typically absent. The weathered kimberlite sample described here is taken from the subsurface, as retrieved from drill core. The spectral profile (Fig. 5) is relatively flat and low in reflectance. A small absorption feature is recognized at 2320 nm and may be related to the presence of weathered olivine (Mg-OH bond) or undetermined clay minerals.

The majority of kimberlite intrusions in the Lac de Gras area are generally recessive-weathering and do not outcrop, putting them out of reach of optical methods of remote sensing. Although kimberlite indicator minerals are sought in surficial deposits, their modal proportion in kimberlite is limited to trace amounts or a few per cent at most. On the other

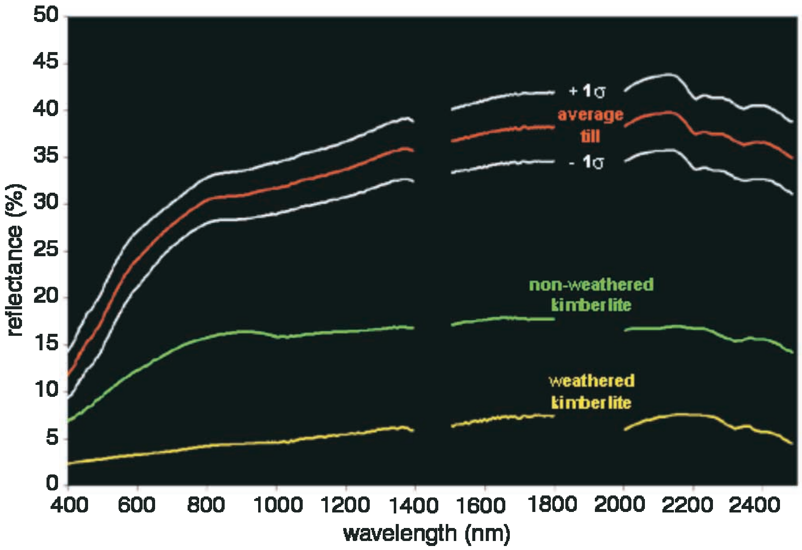

Figure 5.

Spectral-reflectance profiles of weathered kimberlite, nonweathered kimberlite rock, and the average of all glacial till in Figure 4.

hand, the matrix of weathered kimberlite is the bulk of the material and may be present locally in varied quantities within the overlying till. The spectral-reflectance profiles illustrated in Figure 5 exhibit the distinct differences between glacial till and kimberlite (nonweathered and weathered). The likelihood of recognizing a dominant proportion of weathered kimberlite material in till is highest in close proximity to its source. Where till veneers are present, cryoturbation may bring this material to the surface. For these reasons, the spectral-reflectance characteristics of these primary (olivine) and secondary (clay) minerals are key in the evaluation of hyperspectral-imaging technology for identifying kimberlite occurences. Laboratory measurements of actual mixtures of weathered kimberlite and till will enable us to test quantitatively the threshold required to recognize the presence of weathered kimberlite in overlying till using hyperspectral data.

DISCUSSION OF SPECTRAL-REFLECTANCE DATA

The spectral-reflectance characteristics presented here should be considered preliminary. The 2000 to 2500 nm shortwave–infrared portion of the spectral-reflectance profiles appears to host three main absorption features for the till — near 2210, 2320, and 2250 nm, commonly associated with Al-OH, Mg-OH, and Fe-OH hydroxyl bonds, respectively. The monzogranite outcrop exhibits a relatively bright spectral-reflectance profile and a well developed absorption feature near 2210 nm. Weathered kimberlite exhibits a relatively dark and flat spectral response, but weak absorption features near 1050 and 2320 nm correspond well to those of an olivine-rich concentrate and Mg-OH bond. Illite clay may account for a high proportion of the till matrix, whereas weathered kimberlite material typically encountered in drill cores may possibly contain a high proportion of disordered smectite clay. However, mixtures of other minerals clearly exist and complicate the measured spectral reflectances. The mineralogical interpretations of these absorption features will be tested by X-ray diffraction.

Remote-sensing methods are likely to be of use in areas of thin till cover where fragments of nonweathered kimberlite rock may be located. In the case of weathered kimberlite, only a high proportion of this altered material may be identified in mixtures with till because of the low overall reflectance and lack of strong diagnostic absorption bands. With these limitations described, however, it is the extensive tundra vegetation in the Lac de Gras area, which obscures direct observation of surficial deposits, that will limit such remote-sensing investigation. On the other hand, kimerlite is known to occur at or near surface in the high Arctic (e.g. Somerset Island, Brodeur Peninsula), and the use of hyperspectral imaging for direct exploration of kimberlite may be more applicable in these environments.

SUMMARY

As in any drift-prospecting survey, a thorough understanding of the nature and origin of surficial sediments and glacial history is necessary. As demonstrated here, the stratigraphic record should also be an integral part of the study to determine which exploration methods are suitable and to assist in interpreting the results. The presence of proglacial clay and sand capping kimberlite bodies in the Aylmer Lake map area may explain in part the low abundances of indicator minerals in this area, as compared to the Lac de Gras map area. Indicator minerals become incorporated in till during glacial erosion of kimberlite. However, if the kimberlite is in a depression that is infilled by sufficiently thick proglacial sediments prior to glaciation, these sediments may protect it from glacial erosion and therefore no kimberlitic debris is produced. Ice would have advanced over the glaciolacustrine and glaciofluvial sediments, depositing till over this protective cap.

Limited sampling carried out in the Lac de Gras area has shown that the spectral-reflectance characteristics of surface till samples in the 400 to 2500 nm range all exhibit similar features, regardless of the total till thickness. Some slope differences in the visible to near-infrared and broad absorption features observed in some near 900 nm are minor and likely reflect various levels of iron oxides present in the till. Weathered kimberlite material exhibits relatively dark and featureless spectral-reflectance characteristics that are distinct from those of the overlying glacial till. A strong potential exists to distinguish between these two materials when they are exposed at surface. Mixtures of till and weathered kimberlite will prove more difficult to recognize. Continued exploration success in this region will rely on kimberlite exploration models that incorporate various drift-prospecting methods.

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