

VISIBLE/INFRARED SPECTROSCOPY (VIRS) OF VOLCANOGENIC MASSIVE SULPHIDE HYDROTHERMAL ALTERATION PRODUCTS, TULKS VOLCANIC BELT, CENTRAL NEWFOUNDLAND: AN ADDITIONAL EXPLORATION TECHNIQUE?

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ABSTRACT

Volcanogenic massive sulphide deposits generally have zoned mineral alteration systems related to the hydrothermal circulation cells that led to their formation. In ideal situations it is possible to use field observations of such alteration to vector toward potential ore horizons. However, in many cases, such reasoning relies on subsequent detailed petrographic and litho-geochemical investigations; but the fine-grained and cryptic nature of much of the alteration may be an obstacle. A relatively new technique that may alleviate such delays is the use of portable reflectance spectrometers that provide visible/infrared spectroscopy (VIRS). This allows field identification of alteration minerals and compositional inferences that may constitute vectors to potential ore horizons.

Visible/infrared spectroscopy methods were applied to two of the volcanogenic massive sulphide deposits in the Tulks Volcanic Belt of central Newfoundland, namely the Daniels Pond and Boomerang deposits. Both deposits have ubiquitous white mica and chlorite alteration, and mineralogical zonation in the field is poorly developed. Identification of such zonation is further hindered by the inherent lack of outcrop in the vicinity of the deposits.

Results from both deposits, and regional rock sample suites, illustrate a distinct shift in the wavelengths of the Al-OH absorption feature in white micas from distal to proximal environments. The Al-OH absorption feature in white micas distal to ore is generally at >2000 nm (i.e., muscovite to phengite composition), whereas the absorption feature shifts to lower wavelengths (<2000 nm) in samples proximal to ore (i.e., paragonite composition). The VIRS data thus record subtle variations in alteration mineral chemistry that would otherwise be difficult to detect, and which may provide a directional indicator (vector) to favourable horizons.

INTRODUCTION

It has long been recognized that ‘fossil’ hydrothermal fluid alteration pathways in submarine volcanic sequences record fluid circulation cells that moved cool recharge waters *via* seawater infiltration down into the Earth’s crust, and then focused them at high-temperature discharge zones. The latter are the locus of sulphide deposition in most volcanogenic massive sulphide (VMS) deposits (*e.g.*, Franklin *et al.*, 2005). It has also long been recognized that systematic mineralogical and litho-geochemical changes in such rocks allow identification of the key parts of such hydrothermal systems. These include large-scale, semi-conformable alteration zones in the vicinity of fluid recharge, and focused discordant alteration ‘pipes’ associated with the high-temperature discharge zones. Several methods have been devised to quantitatively estimate the intensity of alteration

based upon litho-geochemical analyzes; *e.g.*, the Ishikawa alteration index (Ishikawa *et al.*, 1976), which measures the intensity of sericite and chlorite alteration, and the chlorite–carbonate–pyrite alteration index of Large *et al.* (2001). The use of these geochemical vectors, in addition to detailed field mapping, drillcore logging, and petrography have led to a better understanding of VMS systems. In exploration, they allow inferences to be made regarding possible proximities of altered rock assemblages to sulphide deposits.

Although this exploration approach has been well documented and proven, it is harder to apply in areas where regional metamorphic assemblages, commonly consisting of white mica, coexist with alteration minerals related to focussed hydrothermal circulation cells. In these cases, recognition of alteration systems during field mapping is very difficult and the interpretation of zonation within a

hydrothermal system is dependant upon extensive sample collections, followed by detailed petrographical and litho-geochemical analysis, and subsequent data analysis.

Since the 1990s, there has been increasing use of portable reflectance spectrometers that measure absorption spectra in the visible/near infrared/shortwave infrared (VIS-NIR-SWIR) region. The technique, herein abbreviated as VIRS (visible/infrared spectroscopy), is discussed in more detail by Kerr *et al.* (*this volume*). This technique, particularly in the short wavelength infrared (SWIR) region of 1300 to 2500 nm, detects fundamental absorption features related to OH, H₂O, CO₃, NH₄, Al-OH, FeOH, and MgOH molecular bonds (*e.g.*, Thompson *et al.*, 1999). This allows identification of minerals, and definition of compositional variations amongst mineral groups, including hydrous mineral species such as chlorite and white mica, which are important alteration minerals in VMS deposit systems (*e.g.*, Herrmann *et al.*, 2001; Jones *et al.*, 2005). The VIRS method is ideally suited to this study of hydrothermal alteration, in which minerals are commonly fine grained and difficult to identify. Similar studies using SWIR spectrometry, both in Australia (Herrmann *et al.*, 2001) and Canada (Jones *et al.*, 2005), have illustrated that the technique is an effective method to quantify intensity of alteration and trends in mineral compositions resulting in empirical vectors to some types of VMS deposits.

The main secondary minerals in the Tulks Volcanic Belt (TVB) consist of sericite (*i.e.*, fine-grained white mica), pyrite, quartz, carbonate, and minor chlorite in felsic to intermediate pyroclastic rocks, and chlorite, pyrite, carbonate, and epidote alteration in less common mafic rock types (*e.g.*, see Hinchey 2007, 2008, and Hinchey and McNicoll, 2009). These mineral assemblages can result from regional-scale greenschist-facies metamorphism as well as localized hydrothermal circulation cells related to VMS deposits.

This study presents the results and interpretations of VIRS analysis of host rocks and alteration zones associated with two VMS deposits in the TVB, namely the Daniels Pond and Boomerang deposits, and also some data from regional outcrop samples. The main aims of the study were to:

- 1) determine the VIRS spectral characteristics of the white micas associated with each of the deposits, and to ascertain any controls on spectral variations, and
- 2) to compare the VIRS results with litho-geochemical and other data to determine if spectral characteristics can be used as an additional tool for vectoring toward VMS mineralization in the TVB.

GEOLOGICAL SETTING AND VMS DEPOSITS

The following is a brief overview of the geological setting of the TVB and the VMS deposits discussed in this paper. For a more detailed discussion the reader is referred to Hinchey (2007, 2008) and Hinchey and McNicoll (2009).

Regional Geology

The Dunnage Zone of the Newfoundland Appalachians (Figure 1) represents the vestiges of Cambro-Ordovician continental and intra-oceanic arcs, back-arc basins, and ophiolites that formed in the Iapetus Ocean (Kean *et al.*, 1981; Swinden, 1990; Williams, 1995). It is bisected by an extensive fault system (the Red Indian Line) into a western peri-Laurentian segment (Notre Dame and Dashwoods subzones), and an eastern peri-Gondwanan segment (Exploits Subzone). The Red Indian Line separates the Buchans Group, and locally the Red Indian Lake group (Rogers *et al.*, 2005), which formed on the Laurentian side of the Iapetus Ocean, from the Victoria Lake supergroup (VLSG) that formed on the Gondwanan side of the Iapetus Ocean.

Mapping by the Geological Survey of Newfoundland and Labrador (GSNL) in the 1970s and 1980s (*e.g.*, Kean, 1977; Kean *et al.*, 1981; Evans and Kean, 2002 and references therein) indicated that the TVB represents the remnants of one of several bimodal Cambrian to Ordovician volcanic-arc sequences. Together with adjacent volcanic and sedimentary belts of variable tectonic affinities, it belongs to the VLSG (Evans and Kean, 2002).

Local Geology and Mineralization

The TVB covers an area of approximately 65 by 8 km, trending from the northeast- to southwest. It is a bimodal belt dominated by felsic volcanic rocks and variable amounts of mafic volcanic rocks, felsic pyroclastic rocks, and volcanoclastic rocks derived from both felsic and mafic sources. The region also includes intrusive bodies that are generally interpreted to be synvolcanic.

The TVB experienced lower to middle greenschist-facies metamorphism and moderate to strong deformation. The presence of well-developed, bedding-parallel regional foliations, defined by the alignment of chlorite and sericite, commonly obliterates primary textures in the rocks. The stratigraphy typically strikes northeast and dips steeply to the northwest, and the belt is transected by shear zones and faults.

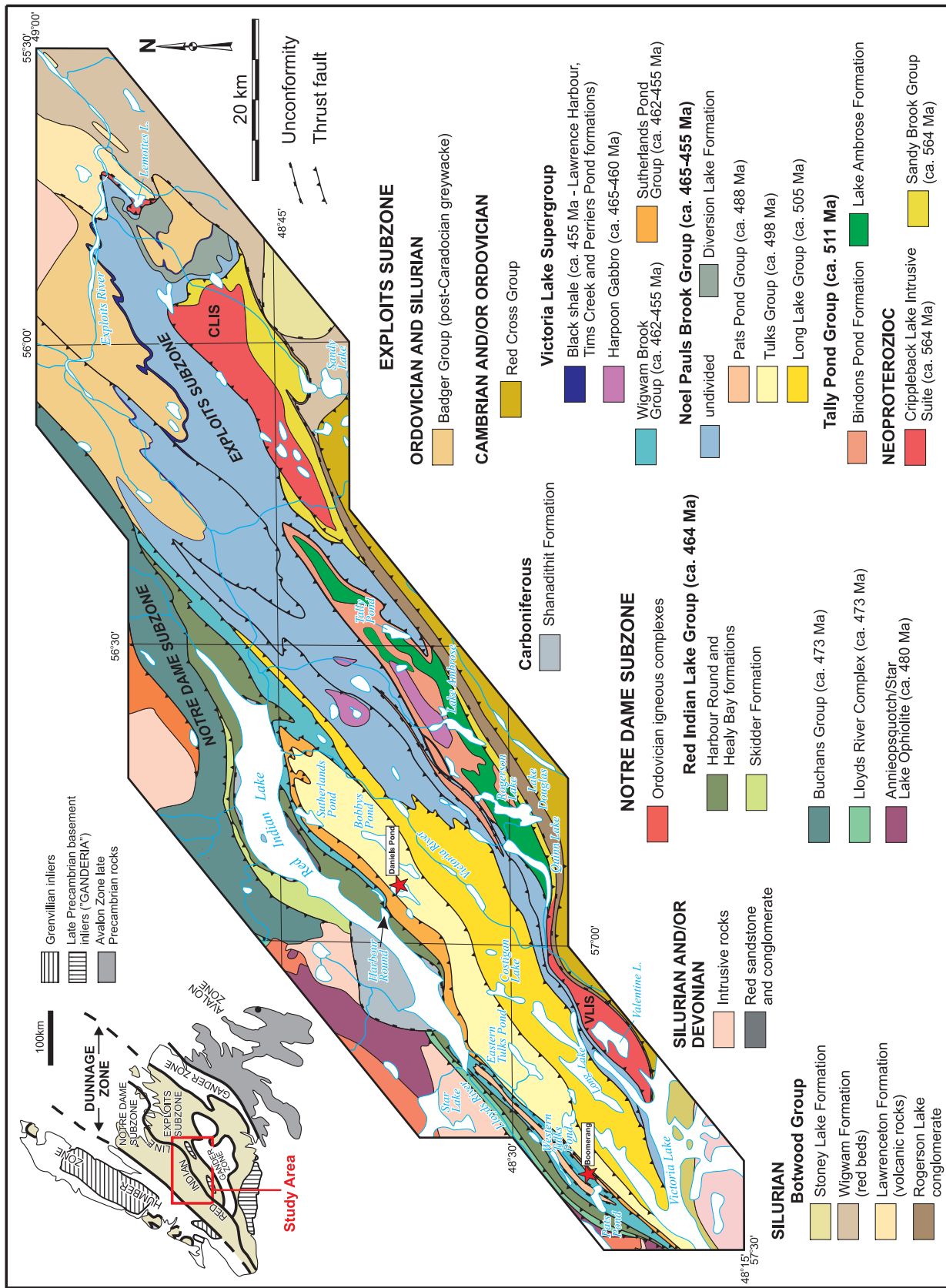


Figure 1. Location and generalized geology of the area surrounding Red Indian Lake, including rocks of the Victoria Lake supergroup. Note the location of the Daniels Pond and Boomerang Lake Intrusive Suites denoted by the red stars. Modified from McNicoll et al., 2008. VLIS - Valentine Lake Intrusive Suite; CLIS - Crippleback Lake Intrusive Suite

There are five main known VMS deposit clusters in the TVB, as well as numerous prospects and zones of alteration. These deposits, from north to south, include the Bobby's Pond, Daniels Pond, Tulks East, Tulks Hill, and the Boomerang deposits. Volcanic massive sulphide mineralization is typically associated with intense sericite–silica–pyrite alteration and lesser chlorite and carbonate alteration, and is interpreted to have formed both in sub-seafloor replacement environments as well as in exhalative environments (*see* Hinchey 2007, 2008 and references therein).

Volcanogenic Massive Sulphide Deposits

Daniels Pond Deposit

The Daniels Pond deposit, with a NI-43-101 compliant indicated resource at a 1.5% Zn cut-off of 1.16 million tonnes grading 4.44% Zn, 2.12% Pb, 0.31% Cu, 87.79 g/t Ag, and 0.60 g/t Au, as well as an additional inferred resource of 0.45 million tonnes with similar grade (Royal Roads Corp., Press Release, March 13, 2008), is located on the southeast side of Red Indian Lake in the vicinity of Harbour Round (Figure 1). It is hosted by a sequence of intermediate tuffs and lapilli tuffs that exhibit sericite–silica–pyrite alteration, with local chlorite–carbonate alteration. Extreme alteration in the vicinity of the deposit makes the identification of the original rock types difficult in the field and in diamond-drill core. The host rocks are steeply dipping, and based on the observed grading of volcanoclastic and epiclastic sequences in drillcore, the sequence is interpreted to be overturned to the northwest. The stratigraphic footwall rocks, now sitting structurally above the ore horizon, consist of extremely altered intermediate to mafic tuffs to lapilli tuffs, and intermediate to mafic amygdaloidal sills. The stratigraphic hangingwall, now sitting structurally below the ore horizon, is composed of volcanoclastic debris flows containing quartz-phyric felsic volcanic clasts, argillite and massive sulphide clasts. The remainder of the hangingwall sequence consists of variably altered intermediate to felsic to intermediate tuffs, lapilli tuffs, and associated volcanoclastic sedimentary rocks.

The intermediate volcanic and volcanoclastic host rocks are intensely altered. Alteration mineral assemblages consist of sericite–silica–carbonate–chlorite–pyrite and local aluminium-rich minerals. Little, if any, of the original minerals are preserved. Occasionally, relict plagioclase crystals (~0.5 mm) are partially preserved, as well as occasional quartz eyes (0.1–0.5 mm). The groundmass is dominated by mixtures of fine-grained (μm scale) sericite and microcrystalline mosaics of quartz.

Massive sulphide mineralization is contained within two lenses, *i.e.*, a pyrite-rich, low-grade lens to the northeast

and a base-metal-rich lens to the southwest. The sulphides are structurally modified and display tectonic banding and recrystallization of sphalerite, chalcopyrite, galena and pyrite. The massive sulphide lenses are confined to a narrow belt of highly strained rocks trending north–south. The base-metal-rich sulphides consist of tectonically banded sphalerite–galena–pyrite±chalcopyrite. The presence of coarse-grained pyrite, which overprints sulphide banding, suggests that the ore has been extensively recrystallized.

Regional-scale alteration is observed in both the hangingwall and footwall distal to the main mineralized horizon. This alteration, considered to be of regional hydrothermal origin, consists of fine-grained sericite as well as rhombohedral carbonate alteration.

Boomerang Deposit

The Boomerang deposit, with a NI-43-101 compliant indicated mineral resource estimate of 1.36 Mt grading 7.09% Zn, 3.00% Pb, 0.51% Cu, 110.43 g/t Ag, and 1.66 g/t Au (Messina Minerals Inc., Press Release, June 21, 2007), is located toward the southern extremity of the TVB, approximately 17.5 km southwest of the southern tip of Red Indian Lake (Figure 1). It is hosted by a series of felsic to intermediate volcanic rocks, coarse-grained volcanoclastic rocks and finer grained sedimentary rocks, cut by bimodal sills and intermediate dykes.

The stratigraphy of the deposit is divided into a hangingwall sequence, the mineralized horizon, and the footwall sequence (Squires *et al.*, 2006; Dearin, 2006). The hangingwall sequence consists of undifferentiated, locally fining-upwards, felsic to intermediate volcanoclastic rocks dominated by quartz ± feldspar crystal-ash tuffs, fine-grained sedimentary rocks (black shales, greywacke and chert), with bimodal, locally amygdaloidal, sills. The felsic to intermediate tuffs that dominate the hangingwall rocks are composed of 0.5–2 mm broken plagioclase crystals (~10–40 vol. %) and <0.5–1 mm quartz crystals (~5–20 vol. %) in a very fine-grained quartz and feldspar matrix. The footwall sequences consist of strongly sericitized felsic volcanic rocks, with local chlorite and carbonate alteration. These tuffaceous rocks are very similar to those in the hangingwall, but exhibit more intense hydrothermal alteration, and typically contain up to 10 vol. % disseminated pyrite and base-metal stringers.

The mineralized horizon of the Boomerang deposit consists of strongly altered fine-grained pyroclastic felsic volcanic rocks, and sedimentary rocks (black shales, chert and argillite), which are intimately associated with the massive sulphide mineralization. The massive sulphides form several lenses within this sequence. It is possible that the sedi-

mentary rocks acted as a physical barrier or ‘cap-rock’ to the mineralized fluids. The sulphides consist of fine- to medium-grained banded and wispy intergrowths of sphalerite (both red and yellow varieties), chalcopyrite, galena, and pyrite. Silicate gangue, dominated by relict quartz crystals, commonly occurs within the massive sulphides. The massive sulphides at Boomerang are interpreted to have formed through sub-seafloor replacement processes (Squires *et al.*, 2005; Hinchey, 2007).

VISIBLE/INFRARED SPECTROSCOPY RESULTS

Samples and Associated Data

The majority of the samples used for this study were collected as part of an earlier metallogenic investigation of VMS deposits in the TVB. Samples were collected from representative drillcore from the main VMS deposits in the belt, as well as from field outcrops in the vicinity of VMS occurrences and throughout the TVB as a whole. Subsequent petrographical and lithochemical investigations were also conducted. Rocks were classified by degree of alteration using petrographic observations as well as commonly employed indexes of alteration, including the Ishikawa alteration index (Ishikawa *et al.*, 1976), and the chlorite–carbonate–pyrite alteration index of Large *et al.*, (2001) (*e.g.*, Hinchey 2007, 2008; Hinchey and McNicoll 2009; and J. Hinchey, unpublished data, 2011).

Spectral Methods and Background

Visible/infrared spectroscopy data were collected from drillcore samples from both VMS deposits; 241 spectra were collected from the Daniels Pond deposit over seven drillholes, and 55 spectra collected from the Boomerang deposit over three drillholes. The spectra from the Daniels Pond deposit were collected at 5-m intervals (with decreased spacing of 2.5 m in the vicinity of the ore horizons) at the DNR core facility in Buchans. The spectra from the Boomerang deposit were acquired from previously collected samples, such that sample locations were not evenly spaced, but rather correspond to lithologic variations down the hole. Additional spectra were collected from a suite of hand samples representing the TVB. All data were acquired with the GSNL Terraspec Field Pro spectrometer. For details on the instrument, and methods of data acquisition and analysis see the article by Kerr *et al.* (*this volume*).

In this study, absorption features in the short-wavelength-infrared region (~1300–2500 nm) characteristic of the white mica minerals are the main topic of interest. Spectra from these altered rocks are invariably dominated by the signature of white micas, although other minerals may be present. Data analysis was carried out using ‘The Spectral

Geologist’ (TSG) program. This program interprets spectra through a comparison of the collected spectra to a reference library of mineral standards, and determines the precise location of the specific absorption features associated with the white micas in the sample.

Infrared absorption features are directly related to the mineral compositions in the sample being analyzed. Absorption is related to the crystal structure of minerals, such that energy at specific wavelengths is transformed into vibrational energy of specific chemical bonds when a sample is irradiated (Thompson *et al.*, 1999). Minerals have specific sets of absorption features that permit their identification and inferences about compositional variation to be made. In this particular study, absorption features in the range of 2200 ± 30 nm were assessed. This feature is related to the Al-OH bond (Post and Noble, 1993), and it allows compositional variation in white micas to be estimated (Figure 2).

Characteristics of White Mica Compositions and Spectral Variations

In this report, ‘white mica’ refers to minerals ranging from potassic species, such as muscovite ($K_2Al_4[Si_6Al_2O_{20}][OH,F]_4$) and illite ($K_{1.5-1.0}Al_4[Si_{6.5-7.0}Al_{1.5-1.0}O_{20}](OH)_4$), to phengite (a muscovite with a Si:Al ratio greater than 3:1 and increased Si with substitution of Mg or Fe for Al in octahedral sites), and sodium-rich paragonite ($Na_2Al_4[Si_6Al_2O_{20}][OH]_4$). The sharp Al-OH absorption feature between 2180 and 2228 nm (Herrmann *et al.*, 2001; Duke and Lewis, 2010) (Figure 2) is the most diagnostic SWIR feature of white micas. The wavelength of this absorption feature is related to the proportions of the major cations in the mica being analyzed, namely octahedral Al, and silica, iron, and magnesium. These cations are exchanged within the structure of mica through the Tschermak substitution ($Si^{iv}(Mg, Fe)^{vi} \leftrightarrow Al^{iv}Al^{vi}$), which leads to composition variation amongst the micas (Duke, 1994). Post and Noble (1993) illustrated that there is an inverse linear correlation between the wavelength of this absorption feature in muscovite and the octahedral Al content of the mineral. High contents of octahedral Al produce short Al-OH wavelengths, whereas lower contents of octahedral Al (associated with increased Si and Fe+Mg) result in longer Al-OH wavelengths. Wavelengths for the white mica minerals observed in this study range from approximately 2189–2197 nm for sodium-bearing micas (paragonite), 2200–2213 nm for ‘normal’ muscovite and illite, and 2215–2222 nm for phengite (Figure 2).

Previous studies have also focused on the variations in the absorption features of white mica as potential exploration techniques in the search of VMS deposits. Herrmann *et al.* (2001) and Jones *et al.* (2005) used SWIR results from

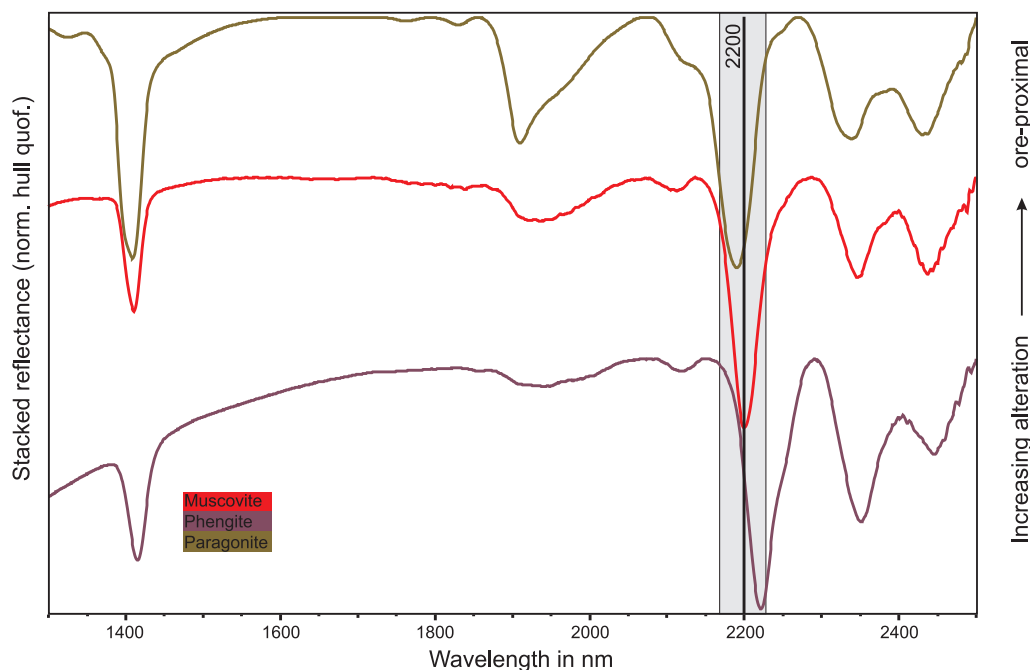


Figure 2. Typical examples of VIRS spectra from white micas in TVB samples. Note the decrease in the wavelength position of the Al-OH absorption feature with increasing alteration and increased proximity to ore horizons, representing shifts from muscovite and phengite compositions toward paragonite compositions. The section of the spectrum shown is from the short-wave length infrared (SWIR) region. Note that the vertical scale is arbitrary and that the stacked spectra are offset for clarity.

VMS deposits in Tasmania–Queensland and Vancouver Island, British Columbia, respectively, to illustrate that subtle shifts in the white mica spectra (usually to lower wavelengths) can be used to define alteration zonation, trends in mineral compositions and to potentially vector, toward some types of VMS deposits.

Daniels Pond

The VIRS data from the Daniels Pond (VMS) deposit illustrate systematic white mica spectral variations between 2180–2228 nm as a function of proximity to known VMS mineralization (Figures 3 and 4). Within the intermediate volcanic rocks, the position of the Al-OH absorption feature wavelength systematically decreased from ≥ 2200 nm (e.g., muscovite to phengite) in the distal samples to < 2200 nm (e.g., paragonite) in those closest to the ore horizon (Figure 3). Directly above and below the VMS horizon, the position of the Al-OH feature wavelength increases; possibly recording Fe or Mg substitution in the mica structure. Distal to the VMS horizon, Al-OH absorption feature wavelengths are locally influenced by rock type, illustrated by the mafic sills in the hangingwall (Figure 4).

In addition to the four mineralized diamond-drill holes analyzed from the deposit (only one is presented in Figure

4), three diamond-drill holes that missed mineralization were also analyzed (results of two drillholes are illustrated in Figure 5). These were located along strike to the northeast and southwest of the deposit, and also ~ 500 m to the west. Two of these drillholes returned consistent white mica Al-OH absorption wavelengths around 2200 nm (e.g., Figure 5a), attributed to normal potassic mica, whereas the drillhole located northeast of the deposit gave similar patterns to the mineralized drillhole illustrated in Figure 4. It should be noted that in the latter diamond-drill hole (DN-32), the lithology from ~ 120 m depth to the end of the hole is inferred to represent an altered intermediate volcanic rock compared to the quartz crystal tuff that dominates the upper portion of the drillhole. However, all rocks are herein interpreted to be synchronous and the VIRS spectra shows a systematic decrease in the wavelength of the Al-OH feature, decreasing to approximately 2192 nm. The last spectra from the bottom of the hole illustrates the characteristic increase in absorption wavelength seen immediately above and below massive sulphides in the other diamond-drill holes (Figures 4 and 5b). As this drillhole occurs directly along strike to the northeast from known mineralization, it could indicate that the favourable horizon is very close.

The Al-OH white mica absorption feature wavelengths have a very slight positive correlation with the Ishikawa alteration index (Ishikawa *et al.*, 1976), and no correlation with the chlorite–carbonate–pyrite alteration index of Large *et al.*, 2001 (Figure 4). In this case, the Ishikawa alteration index decreases with proximity to ore and as such is not a useful vector to mineralization. Hence the VIRS data seem to act as much better vectors to the ore horizon than the typical alteration indexes.

Boomerang

The VIRS data collected from the diamond-drill hole samples at the Boomerang VMS deposit indicated distinctly

lower wavelengths for the Al-OH absorption feature in proximity to VMS ore horizons, but the pattern is not as well developed as at Daniels Pond (*e.g.*, Figures 6 and 7). Spectra distal to ore (*e.g.*, >50 m away) typically have Al-OH absorption features >2210 nm, suggesting phengitic compositions. In contrast, spectra proximal to ore (*e.g.*, <50 m away) have Al-OH absorption features <2200 nm; indicative of paragonitic compositions. The spectra from Boomerang do not show the characteristic local increase in the wavelength of the absorption feature seen at the Daniels Pond deposit, but this could reflect the lower sampling density at Boomerang.

In contrast to the samples from the Daniels Pond deposit, the Boomerang Al-OH white mica absorption feature wavelengths locally have a very slight negative correlation with both the Ishikawa alteration index and the chlorite-carbonate-pyrite alteration index (Figures 6 and 7). In this case, the two alteration indexes increase with proximity to ore, where the white mica Al-OH absorption wavelengths decrease with proximity to ore.

Regional Outcrop Samples

Regional samples collected throughout the TVB were also analyzed by VIRS. These regional samples were grouped based on distance from any of the known five major VMS ore deposits in the TVB (Table 1). As with the dia-

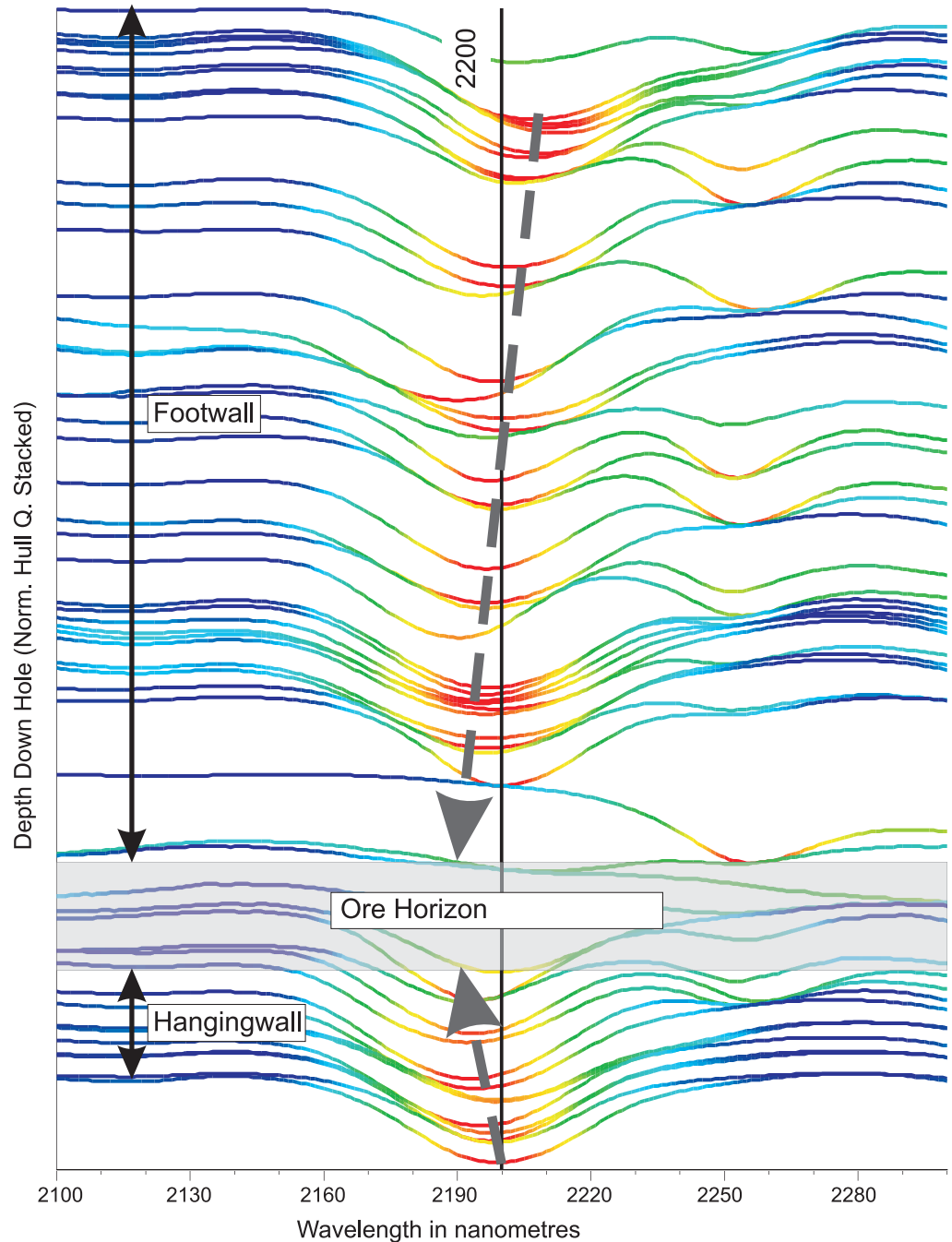


Figure 3. Example of stacked spectral lines illustrating the variations in the position of the Al-OH absorption feature in white micas in areas distal and proximal to the VMS ore horizon at the Daniels Pond (VMS) deposit, TVB. Note the general decrease in wavelength as the ore horizon is approached from the hangingwall and footwall (note that stratigraphy is overturned). As with Figure 2, the vertical scale is arbitrary. Note that compared to the spectra in Figure 2, this represents an expanded view of the spectra in the 2200 ± 30 nm region, and due to the number of spectra being displayed the vertical scaling makes the spectra look less pronounced.

mond drill-core data, there seems to be an association between proximity to mineralization and the wavelength of the Al-OH absorption feature, with lower values in areas

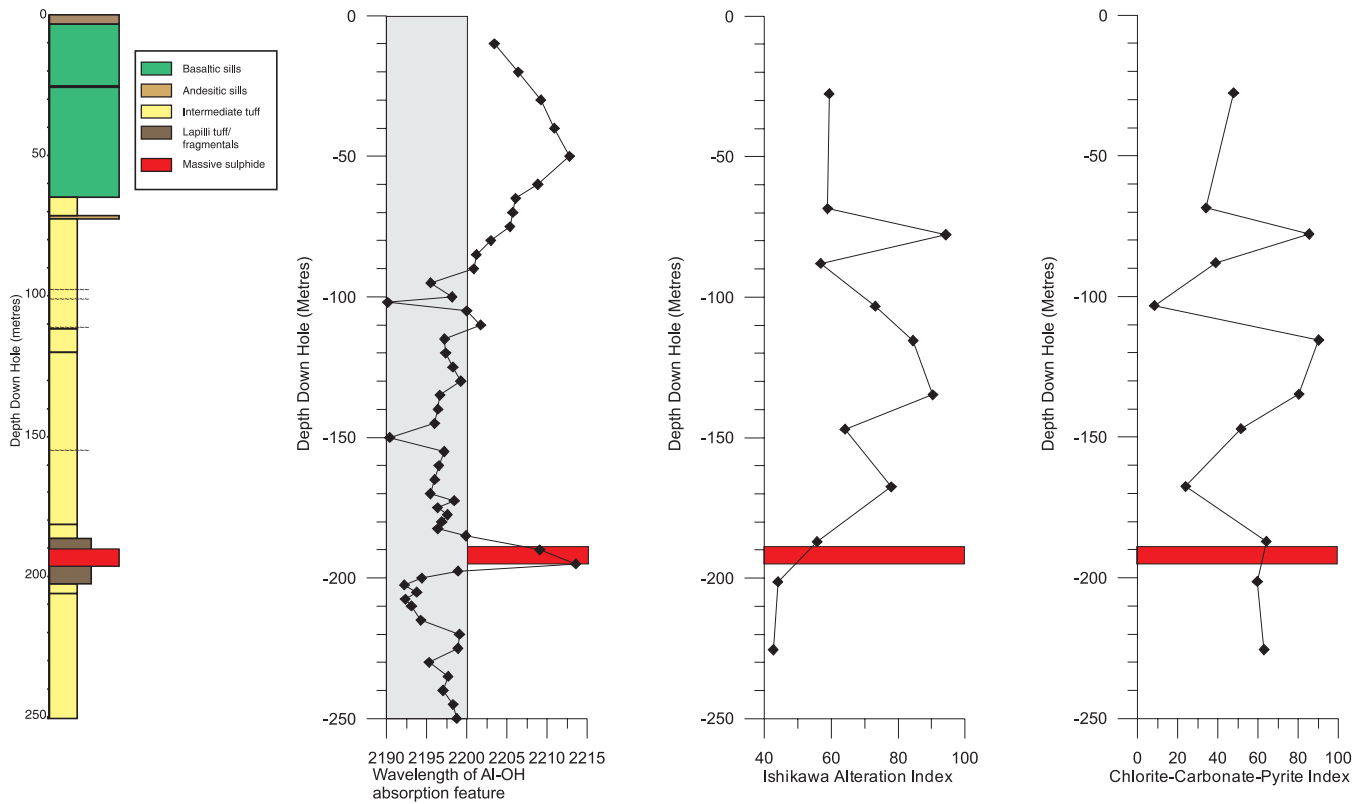


Figure 4. Diamond-drill hole DN-02-02 from the Daniels Pond deposit, TVB. Note the general decrease in the wavelength position of the Al-OH absorption feature as the ore horizon is approached. The increased wavelength in direct proximity to the ore is interpreted to result from isomorphous replacement of octahedral Al by Ba, Mg, Fe and V; related to the mineralized hydrothermal fluids. Note also the very slight positive correlation between the Al-OH wavelength and the Ishikawa and chlorite-carbonate-pyrite alteration indexes, indicating that the latter alteration indexes do not work as a method to vector to the Daniels Pond ore horizon.

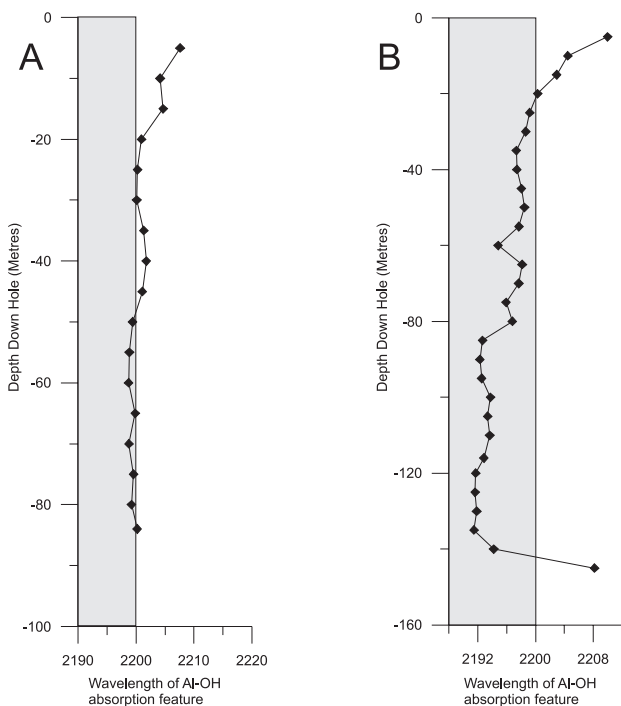


Figure 5. A) Diamond-drill hole DN-29, located well to the west of the Daniels Pond deposit, which did not intersect ore. Notice that the wavelength position of the Al-OH absorption feature does not decrease in contrast to the drill-holes that intersected the ore horizon. B) Diamond-drill hole DN-32, which did not intersect ore and is located along strike to the northeast of the Daniels Pond deposit. This displays similar spectral shifts to drillhole DN-02-02, which intersected mineralization.

proximal to mineralized zones (Table 1). However, the results from each group overlap within their standard deviations, possibly related to the fact that smaller VMS occurrences and showings in the TVB were ignored for the purpose of the groupings, and that the samples are only representative of a two-dimensional view with the third dimension (subsurface) being largely unknown.

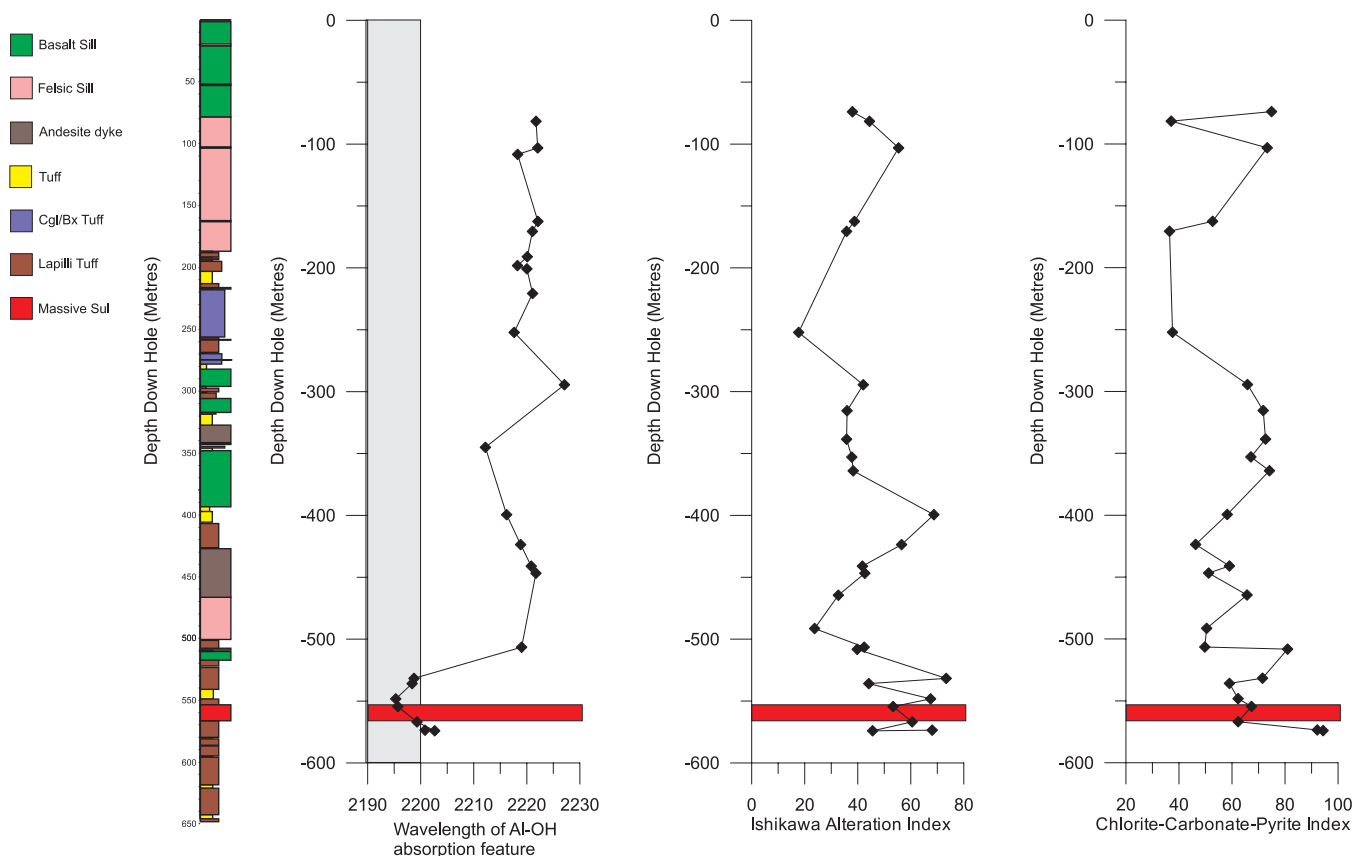


Figure 6. Diamond-drill hole GA-97-05 from the Boomerang deposit. Note the general decrease in the wavelength position of the Al-OH absorption feature as the ore horizon is approached. Also note the very slight negative correlation of the Al-OH wavelength with the Ishikawa and chlorite-carbonate-pyrite alteration indexes. In this case, all three exploration techniques seem to vector toward massive sulphide ore.

DISCUSSION

The common presence of white mica and pyritic alteration throughout the TVB makes field mapping of alteration zones related to VMS mineralization difficult. Detailed analysis of alteration zoning, if possible, commonly depends on petrographic and lithochemical investigations.

In other locations, several previous studies have illustrated the capability of VIRS analyses to document compositional changes in white micas related to Al, Si, Fe and Mg contents of these minerals (Duke, 1994; Herrmann *et al.*, 2001; Jones *et al.*, 2005; Duke and Lewis, 2010). These compositional variations are commonly attributed to various degrees of hydrothermal alteration, and as such could, potentially, be used as vectors toward favourable horizons.

The results of this study suggest that similar compositional variations, and potential vectors towards favourable horizons, may exist at the two VMS deposits studied. At Daniels Pond and at Boomerang, there is a systematic decrease in the wavelength of Al-OH absorption features of

white mica from muscovite and phengite (≥ 2000 nm) in distal samples through to paragonite (< 2000 nm) in those proximal to the ore. This systematic decrease in the wavelength of the Al-OH absorption feature is observed in both the hangingwall and footwall to the ore deposits, suggesting that hydrothermal activity continued during the deposition of the hangingwall rocks. The more abrupt decrease observed in the Boomerang example may be related to the more impermeable sedimentary rocks that locally overlie the deposit, which may have impeded upward fluid flow. The distinct shift of the Al-OH absorption feature to higher wavelengths in the samples directly adjacent to the ore horizons may be related to higher contents of Zn, Ba, Mg, Fe and V than other samples proximal to ore (*e.g.*, Jones *et al.*, 2005). Some of the other spiky patterns observed in the wavelength of the Al-OH absorption features in Figures 4, 6, and 7 are interpreted to be related to the different rock types that were analyzed and their influence on secondary mica compositions. In addition, structural controls on fluid movement, which influence the distribution of alteration minerals, may also lead to such patterns.

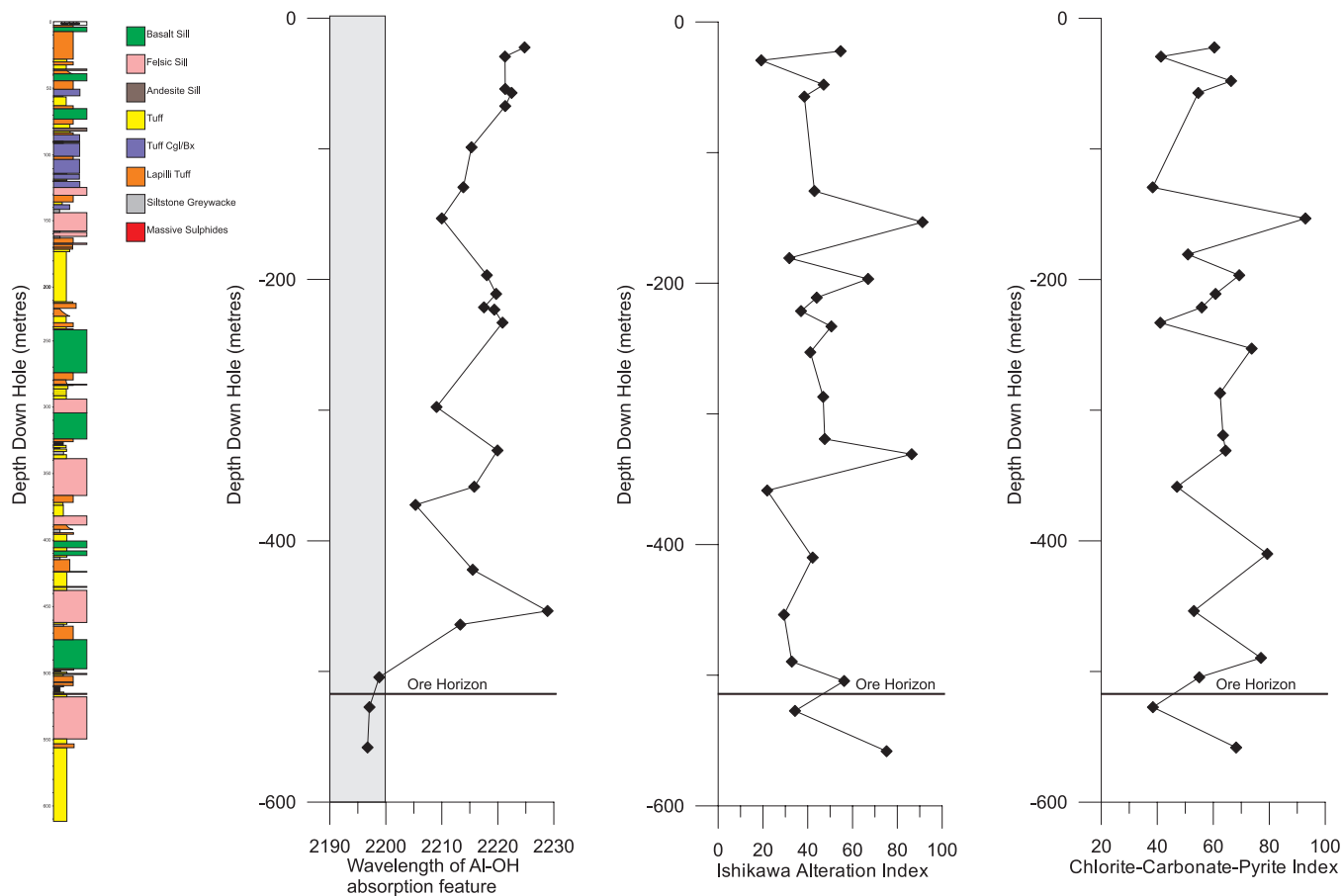


Figure 7. Diamond-drill hole GA-05-021 from the Boomerang deposit. Note the general decrease in the wavelength position of the Al-OH absorption feature as the ore horizon is approached. In this case, there is very little if any correlation with either the Ishikawa or the chlorite–carbonate–pyrite alteration indexes.

Table 1. Average white mica Al-OH wavelengths related to ore proximity

Distance (metres) from any of the 5 main VMS deposits in the TVB	Number of samples with measurable Spectra	Average AIOH feature Wavelength	Standard Deviation
0-400 metres	6	2203.66	5.62
400-800 metres	4	2209.96	6.44
800-2000 metres	15	2213.33	12.32*

* includes three samples from minor VMS occurrences with Al-OH feature wavelengths of 2195, 2198, and 2198.

This study suggests that VIRS investigations of altered rocks could be advantageous for exploration for VMS deposits in central Newfoundland at the prospect scale, especially if such spectral information could be collected in the field. Data of this type cannot replace traditional prospecting and exploration techniques, but it represents another useful tool in the hunt for ore bodies in areas compromised by lack of outcrop and pervasive low-grade metamorphism.

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