The Development of New Exploration Technologies at Noranda: Seeing More with Hyperspectral and Deeper with 3-D Seismic

John C. Gingerich, *Director, Research and Technical Innovation, Exploration, Noranda Inc., Toronto*
Larry W. Matthews, *Coordinator Seismic Technology, Noranda Inc., Calgary*
Michael J. Peshko, *Manager Remote Sensing Technology, Noranda Inc., Toronto*

ABSTRACT

Noranda has successfully developed and implemented two leading edge mineral exploration technologies, hyperspectral remote sensing and 3-D seismic surveying. Airborne hyperspectral imaging provides detailed geological and mineral mapping capability at both a regional and project scale facilitating improved selection of prospective terrain and an accelerated exploration cycle. Noranda, in partnership with Falconbridge, has licensed the exclusive use of the Earth Search Sciences Inc. (ESSI) Probe-1 hyperspectral scanners (128 channel, 0.43-2.5 µm spectral range) that are capable of mapping in excess of 3500 km^2 per day at 10m pixel resolution. The technology has been successfully deployed on four continents over a broad range of terrain from desert to boreal forest and the high Arctic.

To augment Exploration's deep search initiatives, Noranda has successfully modified and implemented existing 3-D seismic technology to assist targeting massive sulphides located at depths ranging from 500m to 2000m. In the fall of 1998 and early 1999, Noranda completed an 18 km^2, 3-D seismic program in Eastern Canada by successfully drill testing acoustic impedance anomalies locating massive sulphides at depths in excess of 1100m.

INTRODUCTION

The unrelenting drive to increase reserves at lower cost and higher frequency is not unique to Noranda. In emerging terrains and/or remote areas, exploration timelines are long and the cost and risks are high. These prospective areas are typically defined in tens of thousands of square kilometers and it can cost $100's to $1,000's per square kilometer to collect sufficient traditional exploration data (geophysics, geology, geochemistry) to make effective exploration decisions.

Noranda had recognized the potential benefits of hyperspectral imaging in the late 1980's, however, no suitable systems or production processing software were available. In the early 1990's Noranda participated in the development and testing of available instrumentation (e.g. Geoscan, GERIS) in anticipation of a low-cost, effective commercial system. The promise of this technology was to provide detailed geologic and mineral information of the earth's surface that would ultimately lead to a better selection of projects and an accelerated exploration cycle.

Noranda's recognition of the potential competitive advantages prompted a detailed analysis of the technology risk and cost:benefit of available business opportunities. In 1997 Noranda and Falconbridge entered into an agreement with Earth Search Sciences Inc. (ESSI) to gain access to a high quality imaging spectrometer (Probe-1) that had the required specifications. The key challenges were to develop effective survey (instrumentation, logistics, etc.) and processing methodology and establish clear mineral applications in a broad range of environments (Chilean deserts to Canadian Arctic). With the support of senior management, Noranda was able to work with ESSI and world experts (e.g. Canadian Space Agency, Canadian Center for Remote Sensing, Remote Measurement Services) to solve issues encountered and realize the benefits of hyperspectral surveying.

With considerable infrastructure investment and well-established potential in regions such as Kidd, Horne and Brunswick, Noranda entered into "Deep Search" technology evaluation in the early 1990's. Seismic technology appeared to hold promise and unlike hyperspectral technology, there was a well developed service industry, advanced processing capability available and well-understood survey applications.

Research into the application of seismic methods for base metal mineral exploration began in 1993 as a collaborative program headed by the Geologic Survey of Canada (GSC) and included Inco and Falconbridge (Milkereit et al., 1991; Milkereit et al., 1996). Noranda initiated an independent program in 1995. Recognizing the potential synergy between Noranda Exploration (Norex, NME, Noranda Inc.) and sister company Canadian Hunter Exploration Limited (CHEL), a collaborative relationship was implemented to optimize the modification of existing oil and gas 3-D seismic technology for this purpose. After the completion of the initial 1996 3-D program at Matagami (Adam et al., 1996; Adam et al., 1997), Noranda continued the advancement of reflection seismic technology while maintaining a close working relationship with the GSC and Memorial University.

In the fall of 1998, Noranda completed their second 3-D seismic survey on the Halfmile Lake property, located in northern New Brunswick. Subsequent drill testing during the spring of 1999 of an acoustic impedance anomaly at a depth of ~1200m, intersected a significant accumulation of sub-economic massive sulphides. This marks the first reported time 3-D seismic technology has been successfully used as an exploration tool for the direct detection of massive sulphides. Noranda's ability to successfully implement seismic programs derives from its systematic approach to pre-survey assessment with a commitment to undertake the necessary fundamental steps. Specifically, the success is a result of: 1) the measurement of physical properties, 2) the utilization of best-in-class technology, 3) the adherence to universally accepted seismic program protocols and 4) the development of integrated interpretation tools. Noranda's implementation of 3-D seismic technology provides a unique, cost-effective targeting or sterilization capability that will facilitate deep-search exploration in mature mining districts where the cost of this technology is a cost effective alternative to deep stratigraphic drilling.

HYPERSPECTRAL TECHNOLOGY

Mineral exploration using spectral remote sensing techniques is well recognized and accepted in the mining industry. Traditional remote sensing is based on the Landsat Thematic Mapper (TM) that has been in use for over 20 years. Although the mining industry has enjoyed considerable success from Landsat TM data for mineral exploration, the number of channels and the broad bandwidths (100-200 nm) limits the sensor for mineral applications. The coarse spectral resolution of the data serves only to detect mineral groups and prevents reliable discrimination of other features with similar spectral characteristics (e.g., clay and carbonates minerals with absorption features in the 2.20 µm and 2.30-2.35 µm range respectively). The recent commercialization of airborne hyperspectral remote sensing systems, with its ability to accurately map individual minerals, marks the beginning of a new era in geological mapping and mineral exploration.

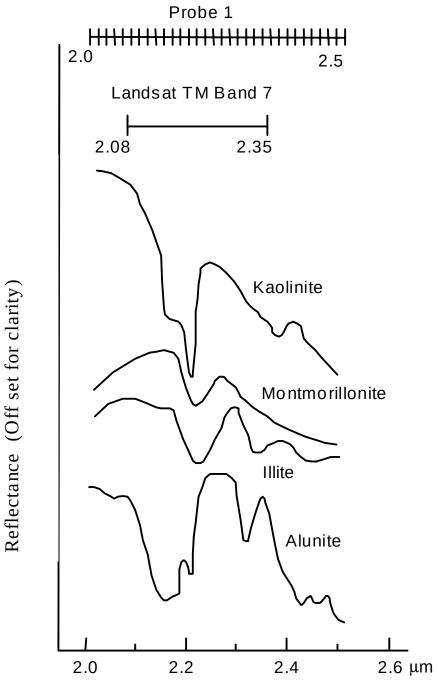

Figure 1. Laboratory spectra of four alteration minerals and the band positions of Landsat TM and Probe-1 in the SWIR region. The spectral resolution of Probe-1 allows for the differentiation of individual mineral spectral (modified from Sabins, 1997, p380).

It has been well documented that reflectance and emission spectroscopy (the measurement of light as a function of wavelength) of minerals is sensitive to specific chemical bonds caused by electronic and vibrational processes between elements (Hunt, 1977; Hunt and Ashley, 1979). As a result, individual minerals may be fingerprinted by their spectral responses or signatures allowing for direct identification of different minerals and rock types (Figure 1). Hyperspectral imaging is the integration of optical remote sensing and traditional spectroscopic technologies and refers to the collection of individual reflectance spectra (measurements of 10s to 100s of contiguous spectral channels) for each pixel element across an image. With the improvements in spectral fidelity and the ability to image smaller areas on the ground, hyperspectral imaging represents a shift from qualitative to quantitative analysis. Airborne hyperspectral scanners are capable of mapping individual minerals, including kaolinite, muscovite, alunite, pyrophyllite, chlorite and calcite at spatial resolutions of 10m or less. The combined improvement of spectral and spatial resolutions greatly increases the probability of accurate geological interpretation by providing explorationists with detailed geological and mineral distribution maps.

The Hyperspectral Opportunity

Noranda recognized in the late 1980's that recent advancements in remote sensing technology held the promise of providing low-cost, detailed mineral/geology maps. Historically, the development of hyperspectral technology has been driven ostensibly by military and other government agencies who developed systems that were either too expensive, propriety or unsuitable for mineral exploration (e.g. AVIRIS, HYDICE, MIVI, CASI). Effective mineral exploration applications require a system that can acquire spectral information in the Short Wave Infrared (SWIR) region (2.0 - 2.5 µm) where clay and carbonate minerals and alunite have distinctive spectral features as well as in the visible and near infrared regions (0.40 - 1.0 µm) where iron oxides (ferric iron) have distinctive spectral characteristics. A number of commercial hyperspectral imaging systems were developed over last 10 years (e.g. GERIS, Geoscan), but concerns about instrument stability (calibration, signal to noise, etc.) and relatively high costs resulted in only limited use by the mineral industry. Borstad and Associates with the backing of Placer, Cominco, and Barrick initiated the commercialization of the Canadian Centre for Remote Sensing's Short Wave Full Spectrum Imager (SFSI, 1.2 - 2.4 µm). However the limited spectral range of the sensor and development issues made it unattractive to Noranda at that time.

In 1997 Noranda and Falconbridge jointly entered into an exclusive license agreement with Earth Search Sciences Inc. (ESSI) for the use of their Probe-1 hyperspectral system. The Probe-1 is a 128-channel "whiskbroom style" imaging spectrometer covering a spectral range between 0.43 and 2.5 µm. The instrument was built by Integrated Spectronics Pty. Ltd. In order to minimize geometric distortions in the recorded imagery, the Probe-1 is mounted on a compact 3-axis, gyro-stabilized mount. Geo-location of nadir pixels is assisted by the recording of aircraft GPS positional data and tagging each scan line with a time that is referenced to the UTC time interrupts from the GPS receiver.

Challenges to Operational Surveying

A series of instrument/application validation tests (Australia, Canada, USA) were undertaken jointly with ESSI to investigate Probe-1 survey performance and to identify the challenges to produce quality information in a production environment. The main issues identified were the development of production-oriented survey methodologies and data processing/management practices to handle the flood of new data to meet exploration demands. The combination of high spatial and spectral resolutions generates an enormous volume of data. In a typical production survey, the Probe-1 collects approximately 5-6 Gbytes of hyperspectral data per day. Hyperspectral data cannot be effectively analyzed using the traditional methods designed for the Landsat TM and new concepts have evolved to exploit this flood of data (e.g. Boardman, 1993; Boardman and Kruse, 1994). Continued improvements in computer hardware and in the development of innovative algorithms for processing and analysis have made it possible to effectively analyse and interpret hyperspectral data. However, a suitable commercial "turn-key" solution did not exist and a time- and cost-effective processing stream had to be developed.

Noranda and Falconbridge have collaborated with a number of external groups (Canadian Centre for Remote Sensing, Canadian Space Agency, Remote Measurement Services, ABB Bomen, Ball Aerospace, University of Alberta, AIG, and others) to examine and develop new processing solutions to optimize the data processing stream and final mineral map output. Noranda ultimately developed an acquisition and processing protocol that provided the necessary on-site and down-stream capabilities in order to respond to the time frames of a competitive exploration environment (Figure 2). This was achieved by focusing directly on extracting the optimal geological information for specific exploration opportunities. Once survey logistics have been arranged (e.g. survey area, aircraft, support), a limited on-site data processing station is setup in order to ensure data quality standards and provide preliminary map products for quick evaluation of the effectiveness of the survey. Although commercial software exists that provides effective data analysis, no off-the-shelf software tools are available to handle the pre-processing of hyperspectral data and a certain amount of internal development was required. The most important step is the incorporation of hyperspectral mineral maps into an exploration program by integrating additional geological data and deposit models.

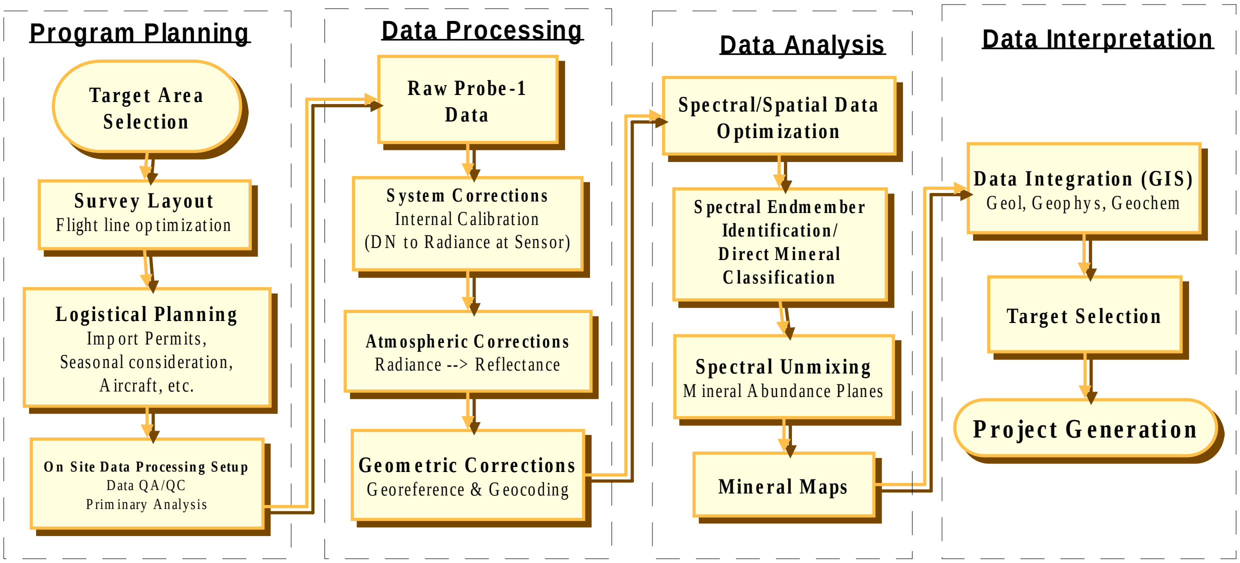

Figure 2. Flow chart of typical hyperspectral data stream for operational surveying.

The high dimensionality of hyperspectral data along with the natural complexity of mineralogical relationships on the ground (sub-pixel mixing) presents exploration geologists with a considerable amount of new geological information to integrate into their exploration programs. In some cases where the exploration model is well defined, it may be a relatively straight forward process to go from raw data to exploration targeting. In areas where the exploration/geological model may be less defined, the application of hyperspectral imaging needs to be developed in a way to advance an exploration program. This requires an understanding of both the science of hyperspectral imaging and the geological model within an exploration context. This know-how along with advances in hardware and software has made it possible for hyperspectral technology to be routinely delivered at a reasonable cost.

Hyperspectral Imaging as a New Geological Tool

Hyperspectral imaging provides a new and accurate source of geological information. Traditional exploration techniques (EM, Magnetics, Landsat, etc.) are undertaken to "assist" the identification of geology, alteration and mineralization by mapping physical property attributes (e.g. conductivity, magnetic susceptibility, and density) that are not necessarily unique to the exploration target. These indirect methods are used to infer targets that are referred to as "anomalies". "Anomalies" have little meaning in the language of hyperspectral exploration technology that has the ability to map mineral abundance over large areas (e.g. the surface abundance of iron oxides) rather than identifying anomalies with inferred geologic attributes. While the quantitative aspects provide clear target vectors to the geologic model, it must be remembered that some form of exposure is required. Figure 3 is an example of Probe-1 data that has been processed to show a selection of target minerals on a grey-scale image highlighting a large alteration system. What may before have been defined as an "anomaly" is now clearly resolved in more definitive geological and mineralogical terms.

The hyperspectral mineral maps are in themselves not a direct discovery tool and in all but few instances do not detect the economic mineral sought. The maps provide accurate spatial and compositional information to the key parameters (geology, mineralogy) associated with the target deposit model (alunite, jarosite, etc.). Therefore, hyperspectral mineral maps may be difficult to interpret in areas where little is known about the geology or deposit model and key mineralogical relationships may go unnoticed. Conversely, a geologist with an understanding of the area's geological processes would be able to exploit hyperspectral mineral maps to interpret mineralogical relationships with confidence, and relate them to the geological problem at issue. To fully exploit the technology a highly skilled and experienced geologic staff on the ground is a necessity.

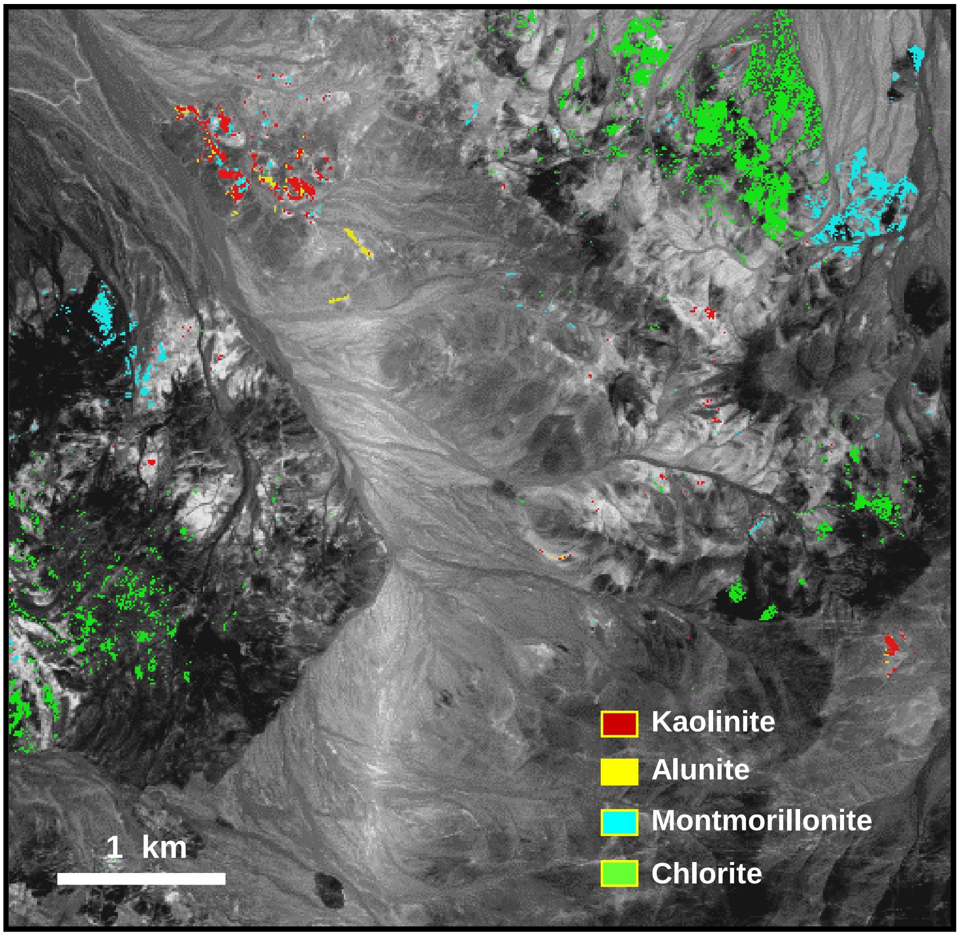

Figure 3. Probe-1 hyperspectral image mapping a suite of alteration minerals in northern Chile.

Noranda has successfully deployed the technology in a broad range of environments (Arctic, Canadian Shield-Boreal Forest, desert regions in northern Chile) and in each environment was able to define exposed geology, alteration and mineralization (gossans). Costs for these programs are highly influenced by location (Mob/Demob), weather and access to suitable aircraft; however, under the right conditions it is possible to acquire in excess of 3500 km^2 /per day at 10 m pixels which greatly reduces unit costs for gathering exploration data. The technology has the unique advantage of mapping large regions (e.g. Chile-Peru porphyry belt 75km x 1000 km) at 10m centres within months at a detail unachievable through traditional methods (mapping, geochemistry). This advanced level of geologic information improves project/target selection, improves the rate discovery and ultimately lowers the cost of exploration.

As more systems become available (e.g. Texaco/GER system?, Anglo?) hyperspectral technology will become a standard tool within the exploration industry. With the advent of satellite systems it will become more broadly used than Landsat. Those first able to identify the primary targets and advance the geologic concepts will be the ultimate winners. Noranda has established a significant position to ensure it remains a leader in the highly competitive search for new mineral deposits.

3-D SEISMIC TECHNOLOGY

Seismic technology has been deployed for 75 years in the Petroleum Industry and has evolved as the primary (exclusive) exploration, targeting tool. Nearly US$4B is spent annually in seismic surveying in the Petroleum Industry, an amount almost twice the current world's entire mineral exploration budget. Outside of Noranda and Anglo (Campbell et al., 1984; Campbell, 1990; Durrheim et al., 1991; Pretorius et al., 1987; Pretorius et al., 1997) there are few significant, ongoing seismic programs in the Mineral Industry.

Noranda's initial involvement in seismic technology began in the early 1990's with the participation in a collaborative program (Falconbridge and Inco) conceived by the GSC Seismic Group. Eaton et al. (1997) postulated that seismic technologies had advanced to the point where surveying in crystalline rocks would not only provide stratigraphic and structural information, but would provide additional targeting information from the scattering wave response of massive sulphide ore bodies at depth.

Researchers had periodically investigated seismic applications in the Mineral Industry. However, with only limited, sporadic success and high cost, a mineral seismic survey industry never evolved. Compared to the Petroleum Industry, there are a number of issues that make 3-D seismic surveying difficult and challenging. These include:

- As a general rule the Signal:Noise (S/N) ratio is significantly lower than generally experienced in the Oil & Gas Industry. Questions remained as to instrumentation capability that could provide the necessary data quality.
- The near surface weathering statics are severe and geophone coupling is challenging.
- Overall the Mineral Industry simply lacked the necessary physical property data to make informed decisions.
- Given the complex nature of the wavefield, stronger interpretation (3-D data integration, imaging and modelling) tools were required.
- The recorded wavefield is complex and massive sulphide targets potentially manifest themselves as secondary scattering sources (typically noise). New approaches to data processing were required.
- Could a cost-effective methodology be developed to reliably evaluate prospective geology between depths 500 to 2000 m?

Matagami, Quebec

Matagami was the initial proving ground for seismic technology for Noranda. Both Falconbridge and Inco undertook their testing in the Sudbury basin. The first seismic acquisition occurred in 1995 when a 2-D line was recorded in order to establish the field parameters necessary to conduct the larger 3-D survey in April 1996. The 20km^2 3-D seismic survey covered an area that included the Bell Allard ore deposit. While the massive sulphide was detected, the hosting stratigraphy is complex and produced significant reflectivity (Adam et al., 1996). Results from this work were encouraging. Many of the technical issues appeared to be solvable; however, the complex signatures left a lingering doubt as to the effectiveness of using seismic as a targeting tool. To help resolve these uncertainties a 3-D GOCAD exploration model using the seismic and available borehole geological control was developed to better interpret the recorded wavefield.

The seismic program continued with physical property and template 2-D studies local to existing infrastructure (Geco, Halfmile, Heath Steele, Bathurst, Gaspe, Sturgeon Lake and Duck Pond). As our understanding of the technical and site issues advanced, a protocol evolved that provided a road map to successful implementation of seismic technology. This methodology consists of the following steps: (a) rock property measurements, (b) borehole logging and core rock property measurements, (c) forward stratigraphic and structural modelling, (d) 2-D field parameter testing and templating, and (e) 3-D survey acquisition for drill locations and area sterilization. Each of these steps has a jumping off point and are conducted in sequence as each carries information vital to the success of the following phase.

Halfmile Lake, New Brunswick

Memorial University had undertaken a template seismic acquisition program over the Halfmile Lake deposit in 1993. The 2-D survey was unfortunately unable to detect the deposit. In 1995 Noranda resurveyed the deposit using state-of-the-art equipment and proved conclusively that direct detection of sulphides in this area was possible (Salisbury et al., 1997). A follow-up 2-D line was acquired in the fall of 1996 along the Otterbrook Road. This line helped to establish optimum field acquisition parameters and also identified new amplitude anomalies (Figure 4). As a consequence of the complex structural history of the area, it was possible that the anomalies were originating from out of the plane of the 2-D seismic line.

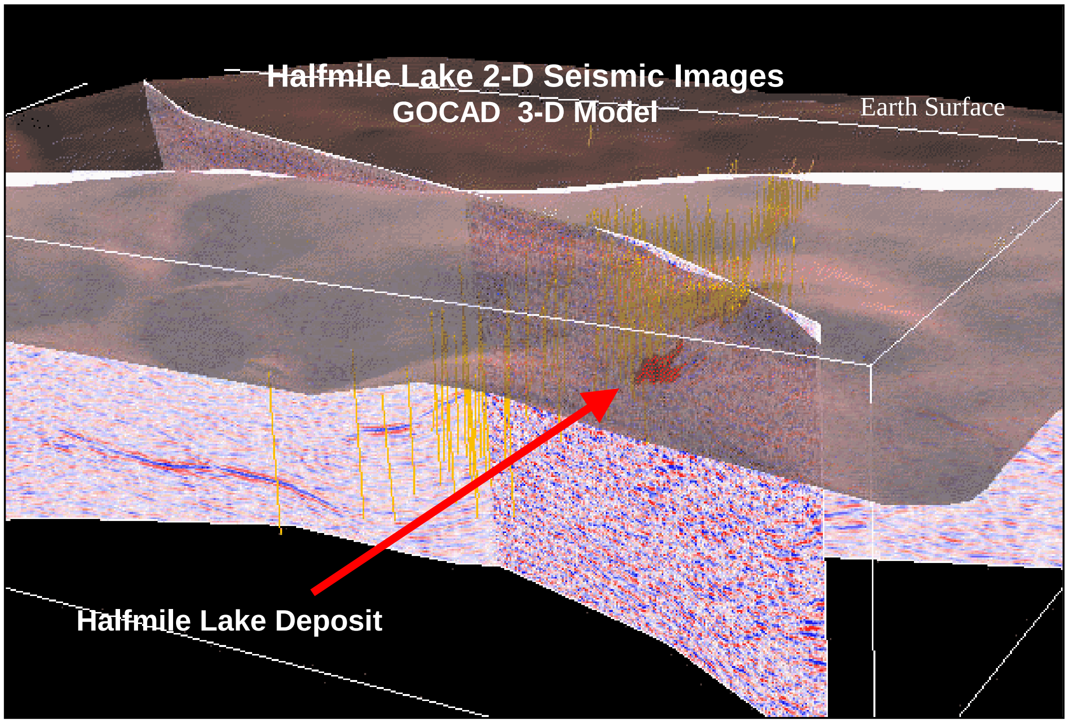

Figure 4. **3-D image illustrating 2-D seismic profiles, the Halfmile Lake deposit and the outline of the proposed 3-D seismic experiment.**

In order to spatially locate and determine the off-line extent of these lead anomalies, as well as any others that may be present in the area, an 18-km^2 3-D survey was acquired in September 1998. Significant acoustic impedance anomalies were defined, one down-dip of the mine series (~1000m) and the other considerably deeper at ~1600m. The geometry of the acoustic impedance anomalies could never have been determined from 2-D data alone. Figure 4 provides a 3-D representation of the acoustic impedance relative to the Halfmile Lake deposit. Both targets were drill tested. The deeper anomaly was produced by a broad structural/deformation zone of significant velocity anisotropy within a massive

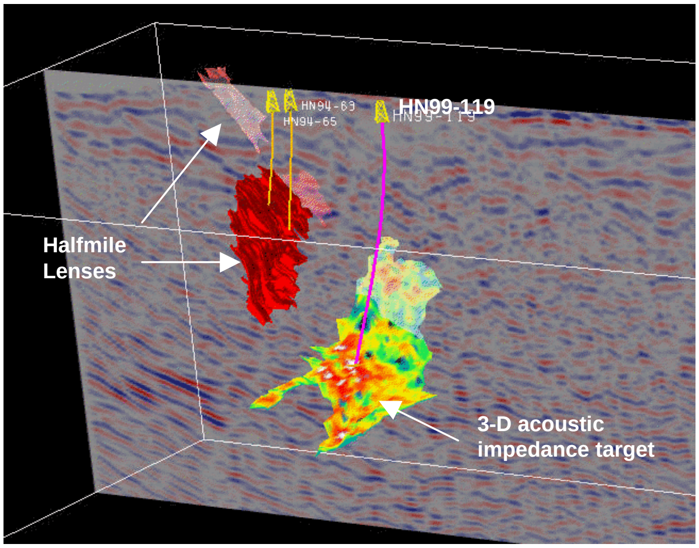

Figure 5. **2-D profile extracted from 3-D volume with colour coded amplitude acoustic impedance target**

sequence of porphyry. Hole HN99-119 (Figure 5), targeted on the other amplitude anomaly, intersected 50m of sub-economic massive sulphides containing 4.5m @ 10.61% Zn, 1.41% Pb, 0.22% Cu, 14.58 gpt Ag. With the 3-D data volume it was possible to accurately map the geometry of the acoustic impedance target and not only provide an initial drill target location but also provide additional detail on size and thickness (as indicated by drilling) to help assess economic importance early in the drill program.

The success at Halfmile confirms the role that seismic surveys can play to improve targeting beyond 500m depth. Given the high cost (estimated \$50,000 km^2) to implement a 3-D survey, it is not intended to be a ubiquitous tool for deep search problems in developed Mining Camps. However, in the right environments 3-D seismic surveying can provide a cost-effective alternative to deep systematic grid drilling.

Noranda's ability to implement seismic programs derives from its commitment to undertake the necessary fundamentals including the measurement of physical properties, the utilization of best-in-class technology, the adherence to universally accepted seismic program protocols and the development of integrated interpretation tools. Noranda's 3-D modelling/imaging technology, borehole logging program and physical rock property analysis, along with the selected test programs, has provided a unique understanding of the potential application of seismic to massive sulphide mineral exploration.

Conclusions

The demonstrated capability of the Probe-1 airborne hyperspectral system and emergence of additional new hyperspectral imaging systems (airborne and satellite) has marked the beginning of a revolution in geological mapping and mineral exploration. Geologists now have the ability to collect systematic information on geology, alteration and mineralization at an accuracy and scale (1 to 10m pixels) unachievable through alternative approaches (e.g. mapping, regional geochemistry). This wealth of information will place new demands on geologists to develop improved exploration models to fully exploit the direct and indirect targeting information.

The application of hyperspectral imaging is expected to improve target selection in emerging geologic terrain, which should ultimately lead to new discoveries and lower cost (Noranda estimates are 1/10 the costs of alternative methods). In the more mature exploration environments, detailed mineral information will improve targeting with better maps on the distribution and concentration of alteration and mineralization (clays, Fe-oxides, etc.). At both the regional and project scale, accurate quantitative evaluations will result in better programs at an overall lower discovery cost.

With recently published material on the use of seismic reflection technology around the world, as well as Noranda's own experiences, it is more convincing than ever that seismic technology can play a meaningful, albeit limited role, in base metal exploration. The efforts over the past couple of years have established surface-reflection seismic as a tool that can record acoustic-impedance information from depths well below the established remote sensing limits (e.g. magnetics, EM). Field acquisition schemes currently employed do not achieve a good image above 400 meters, where other techniques are better suited and more cost effective. The wavefields gathered carry significant stratigraphic information in areas such as Matagami (Adam et al. 1996). In others they appear to offer the possibility of a direct sulphide detection tool as demonstrated at Halfmile Lake. As we move forward, it will be necessary to judiciously apply this technology to the most prospective terrain where alternative approaches fail to provide the same time and cost benefits. We are now able to re-examine the historically productive mining camps of Canada and elsewhere, where exploration has waned for lack of targeting capability in search of the next Horne.

It is important to note that these developments could only have taken place with strong support from Noranda senior management. Both these programs moved forward during one of the worst downturns in the exploration industry in 25 years. While each program has identifiable risk, the potential benefits, if successful, are substantial. Noranda's commitment to technological excellence and growth has resulted in the development of two technologies that provide "new capability for discovery" of near surface deposits in the emerging nations of the world and the Kidd/Horne-type deposits that have gone undetected within the world class mining camps of Canada.

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