MASW and GPR survey to delineate depth-to-bedrock and crystal cavities for mineral exploration, Hiddenite, North Carolina

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Abstract

MASW and GPR methods were used as exploration techniques to locate potential mineral deposits within a geologic setting of highly deformed metamorphic rocks overlain by lateritic soil horizons. A 24-channel land-streamer system was used to profile overlying lateritic horizons and bedrock up to depths of 100 feet. MASW survey geometry was optimized for depths up to 60 feet and high horizontal resolution. High-powered 100-MHz bi-static antennas were used to collect data along the seismic lines as well as in areas unsuitable for the MASW method.

The two exploration methods provided independently derived constraints to the bedrock depth and structural model. The GPR method was effective in identifying shallow targets in the laterite, determining depth to competent bedrock, and identifying targets within the shallow bedrock zone. The MASW 2-D shear wave velocity \( V_s \) profiles were useful for delineating the laterite/rock interface and identifying anomalies near the top of and within the competent bedrock zones. The data were integrated to develop a bedrock structure map and spatially delineate exploration targets.

Introduction

In July of 2004, HGI was contracted by Esmeralda Exploration to investigate the feasibility of performing a geophysical investigation (primarily GPR) at their property in Hiddenite, North Carolina (Figure 1). The primary goal of the investigation was to test the effectiveness of geophysics to provide depth information for overburden calculations. Secondary considerations were to obtain information on the ore potential of the overburden and bedrock. The site is located in one of three North American locations where emeralds have been found, and is the only one that has produced significant quantities of the gemstones (Wise, 2002). The deposits at Hiddenite occur in quartz veins cutting Precambrian schists and gneisses.

Esmeralda's mine site is adjacent to the actively producing North American Emerald Mine at which a ground penetrating radar investigation had previously led to significant emerald discoveries (Crowson, R., and Delea, D.M., 1998; Wise, 2002). Unlike the producing mine, the client’s site contains an appreciable thickness of lateritic soils that were thought by some to be a deterrent for applying the GPR technique. HGI did not discount the use of GPR, but agreed that seismic methods would be more suitable under the site conditions. The particular technique proposed was a multi-channel active...
surface wave (MASW) survey using the dispersion analysis of Rayleigh-type surface waves to extract a shear wave velocity depth profile.

The objective of the current investigation was therefore to assess the suitability of the surface wave seismic technique to identify bedrock anomalies possibly hosting gemstone-quality minerals and to provide overburden depths at the Esmeralda mine site. The client provided HGI with a topographic image map of the 2.365-acre mine site. This map showed a large excavation in the middle of the property. Based on the limited area available for investigation and information provided verbally by the client, HGI developed a surface wave seismic exploration program. The exploration plan had to be continuously revised in the field due to unexpected access restrictions, on-going review of the data, and requests from the client. An additional complicating factor was the unexpected depth of the bedrock, which resulted in limitations of shot offset distances. The survey geometry was therefore adjusted to generate wavelengths capable of penetrating to rock depths while resolving geologic features within the most promising portions of the mine site.

**Technical Approach**

The initial plan was to perform the seismic surveys as specified and follow them by GPR data collection if time permitted. The rationale for this plan was to use the multidisciplinary survey program to produce data sets yielding complementary constraints on subsurface structure. As such, these data sets can be integrated to produce more comprehensive results. One goal of such an integrated geophysical approach is to determine geologic interpretations consistent with all interpreted data. However, innate differences between geophysical survey types (i.e., differing resolution abilities) and the uncertainty in the interpretation of geophysical data (i.e., imprecise knowledge of the radar velocity profile) sometimes produce inconsistencies in the geological conclusions rendered from the different investigation types. Thus, to minimize the uncertainty present in this investigation, interpretations from individual data sets were iteratively

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Figure 1.: Location of the investigation, Hiddenite, North Carolina.
updated to achieve a more globally consistent geologic section. Overall, the combination of seismic and GPR provide an effective means of bounding study area stratigraphy and establishing reliable structural trends.

In response to the aforementioned limitations, locations for the seismic surveys were determined “on the fly.” The seismic data for each line were reviewed for quality control and as input to determine subsequent seismic survey geometry. Prior to commencing the next seismic line, the raw data from each channel for the current line were reviewed, as was a preliminary dispersion analysis of all the shot gathers for that line. Five seismic lines were completed in this fashion. The five line locations were the only accessible areas of the mine site that could be surveyed using the surface wave method. Other areas could not be surveyed due to excessive topographic relief or the inability to produce a straight-line array of geophones.

GPR traverses were subsequently made along each of the seismic lines and at three additional locations. In this way the GPR method provided a cost-effective way of increasing the spatial distribution of depth points for mapping.

Data Collection

Five seismic lines and eight GPR traverses were completed at the mine site. Approximately 920 feet of seismic and more than 1,000 feet of ground penetrating radar data were collected.

MASW Seismic Survey

The surface wave seismic survey was performed using a Geometrics Geode® 48-channel exploration seismograph. Data were collected along a total of five seismic lines. The basic survey geometry at the mine site consisted of a land-streamer system with 15 or 17 receivers spaced 5 feet apart (Figure 2). The shot-offset distance for each line varied slightly and ranged from 50 to 80 feet. The source/receiver increment was 5 feet.

To acquire surface wave data, HGI used 4.5-Hz OYO geophones/receivers (at ~60% damping) deployed along linear multi-channel geophone arrays. The geophone arrays were attached to our Geometrics Geode® 48-channel exploration seismograph unit via a seismic cable that relays the motion-induced electrical signals from individual sensors to the seismograph. The electrical signals were subsequently recorded in the seismograph unit as SEG-2 Rev 1, 32-bit integer data. Our acquisition software provided a number of Windows-based browsers that permitted the on-site display and evaluation of data quality. Seismic energy was generated primarily with a propelled energy generator (PEG) using a 90-pound hammer (Figure 3) and a Betsy seisgun that, when impacted by a hammer, shot industrial blanks into the ground to create an airwave. The seisgun was used at locations where the PEG could not be set up.
Figure 2.: Land-streamer used for MASW seismic survey.

Figure 3.: Propelled energy generator being mounted on HGI field vehicle.
After deployment of the geophone array and acquisition equipment, on-site testing was undertaken to evaluate background noise levels, to demonstrate the recording of meaningful surface wave data, and to estimate signal-to-noise (S-N) values. This phase of the operation also tested the appropriateness of important acquisition parameters, such as sampling rate and total record length. The quality of the seismic signals was verified in the field at each shot location. For records exhibiting low S-N levels, additional shots were used to additively stack the coherent parts of the signal, which helps mitigate the detrimental effects of random environmental noise.

**GPR Survey**

Ground penetrating radar data were collected using a Geophysical Survey Systems, Inc. (GSSI) SIR System 2 digital ground penetrating radar system. The GPR data were displayed on a color monitor for immediate visual inspection and quality control and simultaneously recorded on the system’s 6-Gbyte hard drive for later processing and interpretation. The GPR system was run in continuous transmitting and receiving mode using a scan rate of 32 scans per second and a recording time of 600 nanoseconds (ns).

The GPR investigation consisted of two components: a) a survey designed to resolve features within the overburden, and b) the identification of bedrock and bedrock anomalies. A 100-MHz bi-static high-powered antenna in continuous data collection mode was selected for the survey (Figure 4). The separation distance of the transmitter and receiver was one meter. The 100-MHz antenna was chosen because it provides the wavelength and signal strength to penetrate the lateritic soils at the site and a resolution capability suitable for geologic features.

![Figure 4. 100 MHz bi-static GPR antenna on lateritic soils.](image-url)
Data Analysis and Synthesis

Following the field data collection, the geophysical data were transferred to a PC at the HGI office. The data were archived, processed, and analyzed using the following proprietary software:

- GPR: GSSI’s RADAN for Windows NT™ with Structural and Stratigraphic Interactive Interpretation Module®
- MASW Analysis: SurfSeis®
- Grid Modeling: Surfer® 8.0
- Graphic Presentations: Surfer® 8.0 AutoCAD® 2000

A depth-to-bedrock map and cross-sectional profiles were created from the integrated database produced from the processed seismic and radar data sets.

**MASW Seismic Survey**

Data reduction and analysis of MASW data were performed using the SurfSeis® program developed by the Kansas Geological Survey (KGS). Initial steps were the consolidation and reformatting of individual shot gathers for each line into a single multi-record file format. The survey geometry was defined for each KGS record. Dispersion curve analysis was then performed for each shot gather in the multi-record file by examining the change in phase velocity vs. frequency using the fundamental mode component of the dispersion data. Non-linear inversion modeling of each dispersion curve was performed and resulted in a 1-D mid-point representation of $V_s$ and $V_p$ depth profiles. Interpolation of the 1-D data using a Kriging algorithm produced a 2-D grid of the $V_s$ data. Color-filled contoured profile plots were then generated from the $V_s$ grid. Figure 5 shows an example profile, and Figure 6 shows a profile containing an anomaly interpreted as a cavity.

Fifty-seven (57) depth points were selected from the 5 MASW profiles for the mine site. Each depth point was assigned a surface elevation from which the corresponding bedrock elevation could be calculated. The surface elevations were taken from the image map provided by the client.
Figure 5.: Example of $V_s$ profile generated from MASW survey.

Figure 6.: Example of $V_s$ profile showing an interpreted bedrock cavity.
**GPR Survey**

The GPR data were processed using high-pass filters, horizontal smoothing, background removal, and gain adjustments. Two-way travel times to the top of GPR reflectors were then picked and entered into an ASCII file according to file number and traverse offset. All generated ASCII files were incorporated into a collective database.

Site- and unit-specific GPR propagation velocities were estimated by integrating migration velocities, estimates based on experience, and calibration with seismic data. GPR travel-time data were then mapped into the depth domain using these velocity estimates. The 100-MHz antenna system had maximum penetration depths of 40 to 50 feet.

The primary use of the radar data was to enhance the spatial coverage of depth points for the bedrock depth model at the mine site. One hundred-four (104) bedrock depth points were obtained from the GPR records from the mine property. As for the seismic data, a surface elevation was assigned to each depth point so that the corresponding bedrock elevation could be calculated. An example of a GPR record collected on exposed rock at the mine site is shown in Figure 7. Dipping of the schistose bedrock is clearly visible.

![GPR record collected at the mine site showing banding and dip of schistose bedrock.](image)

**Data Synthesis**

The 57 MASW and 104 GPR data points were compiled to form an integrated spatial database. These spatial data were also used to construct a best-fit 2-D grid-model using Surfer for Windows®’ kriging algorithm for the top of bedrock. The Kriging analysis was performed using anisotropy parameters to compensate for the non-uniform data distribution. Areas where data were not acquired or were insufficient to analyze surface trends have been blanked in the grid model. A matrix-smoothing function was applied to the grids to emphasize the bedrock surface trends. Surfer® was also used to
create a contour map for the elevation of the top of the bedrock surface (Figure 8), on which potential drilling targets were overlaid.

![Bedrock surface contour map.](image)

**Figure 8:** Bedrock surface contour map.

**Conclusions**

The geophysical study proved the efficacy of the surface wave seismic and GPR techniques for mapping soil and rock characteristics in lateritic terrain. Data from the GPR survey using 100-MHz high-powered bi-static antennas were obtained to depths of more than 50 feet. Surface wave seismic profiles reached depths of more than 90 feet. GPR and MASW seismic techniques identified several targets in both the overburden and bedrock. Within the spatial constraints of the project, an integrated database was created and used to develop a contour map for the top of bedrock at the site.

Figure 8 shows a bedrock valley aligned in the northeast-southwest direction and a less well-developed bedrock valley oriented approximately northwest-southeast. These valleys probably reflect the major fracture or structural fabric trends of the bedrock at the site. The orientation of the bedrock structures in Figure 8 and the concentration of GPR and seismic anomalies support the northeast mineralization trends reported in historical data and noted from visual observation of adjacent mining.

Exploration for emeralds is actively proceeding at the site, using both HGI’s geophysical results and hands-on methods. Information about the current status of work at the site can be found at [http://www.esmeraldausa.com](http://www.esmeraldausa.com).
References


Patterson, J.E., Cook, F.A., 1999, Successful application of ground penetrating radar to gem tourmaline exploration, Canadian Mineralogist, 37, pp.862-863.
