Abstract

A multidisciplinary geophysical study was performed at Naval Air Station, Brunswick, Maine. The goal of the study was to provide a better understanding of the possible migration pathways of the contaminants in bedrock fractures and deeper stratigraphic zones whose geometries might be controlled by bedrock morphology. The scope of work consisted of mapping the bedrock surface, identifying and locating fracture zones, and mapping the continuity and extent of key stratigraphic horizons. Seismic refraction and reflection, GPR, and resistivity were used to meet the study goals.

Geophysical data were combined with existing borehole and cone penetrometer information to produce an integrated database that was used to create models of the bedrock and key stratigraphic surfaces. Both raw data and model-slice profiles were prepared to illustrate the morphology of the surfaces and identify possible bedrock fractures.

The results of the study included delineation of the post-glacial bedrock valley terrain, identification of glacial depositional features, and suggestion of a pattern for fracture corridors in the study area. Low-velocity zones identified in the refraction surveys and fractures interpreted from the resistivity profiles correlated well with some previously identified regional and local lineaments.

Introduction

The Eastern Plume at Naval Air Station (NAS) Brunswick, Brunswick, Maine, has been attributed to past solvent disposal practices producing groundwater contamination from chlorinated volatile organic compounds (VOCs). The former Fire Department Training Area (Site 11) is one of three primary source areas for the plume. Training activities at this site covering almost 4 decades resulted in significant introduction of VOCs into the groundwater. The area is known to provide recharge to shallow and deep overburden aquifers and may also provide recharge to the bedrock aquifer. A plume of the VOC-impacted groundwater extends in the deep overburden aquifer along the eastern boundary of the base, which is on the United States Environmental Protection Agency’s (US EPA) National Priorities List.

In September 2003, Gannett Fleming (GF), an EPA subcontractor, contracted Hager GeoScience, Inc. (HGI) to perform a geophysical investigation in support of the ongoing environmental investigation at the NAS. The primary objectives were to map the bedrock surface, ground-truth photo-lineaments, and identify other possible fracture zones that might serve as contaminant pathways. Secondary objectives included mapping key stratigraphic horizons, specifically the Presumpscot Clay, interpreted as the natural barrier to both vertical and lateral migration of the plume.
Technical Approach

The geophysical study at the NAS Site was designed to acquire a distribution of data suitable for mapping the spatial extent of the Presumpscot Clay and bedrock topography/fracture zones. A multidisciplinary approach using geophysical methods of seismic refraction and reflection, ground penetrating radar, and resistivity were used to meet these objectives.

HGI’s investigation was analogous to reconnaissance-stage efforts of subsurface characterizations, similar to what may be conducted to characterize geologic controls for resource deposits. Substituting contaminants for resources, it follows that this type of study is important as an upstream effort in contaminant studies useful for locating future probe and well sites. In the current situation, it could be used to re-evaluate the contaminant migration models already developed.

The strategy underpinning the exploration program and access for the traverse locations were developed by GF. In some instances, HGI assisted in program revisions and clearing new survey lines. In light of a short and inflexible field schedule, HGI’s goal was to provide sufficient resources and equipment to perform as many simultaneous surveys as possible.

Although HGI’s major objective was to investigate bedrock characteristics, substantial emphasis was placed on also obtaining shallow stratigraphic information. Therefore, in some areas survey geometries for seismic refraction, resistivity, and GPR were adjusted for shallow investigations.

A revised approach to remedy specific and unanticipated background noise interference was not possible. In addition to the anticipated air traffic, most of the survey day contained constant noise interference from an airplane engine test facility several orders of magnitude higher than the signals from most end and off-end seismic shots. The approach for this problem was to wait for breaks in the noise, or “shoot through the noise” and stack several shots when possible. The frequency spectrum of the interference was broad and within the seismic signal band, thereby reducing the effectiveness of filtering techniques.

Sources of metallic interference unearthed shortly before fieldwork was scheduled to begin required that two resistivity lines be removed from the program and GPR lines substituted. By using mid- and low- frequency radar systems, HGI could perform shallow and deep investigations in many areas not included in the original resistivity program, thereby increasing the spatial resolution for the data interpolation.

In addition to providing the limited standard data from each seismic and resistivity survey section, increasing the spatial resolution of the data distribution by using GPR and existing well data allowed us to model the stratigraphic target horizons using gridding algorithms suitable for defining surface trends available from the point data. Stretching the scope of work initially agreed to, HGI compiled various bedrock and sediment data considered to have a high confidence level in both data values and location. These data were integrated with the geophysical data points to create a compilation of about 1000 data points for the top of bedrock, Clay, and Transition Unit separating an Upper and Lower Sand.

Survey control was a major issue. Considerable effort was made to accurately locate the data points in the Maine state planar coordinate system. GF provided GPS coordinates and elevation for selective points along HGI’s geophysical survey lines. HGI then calculated the easting, northing, and elevation for each interpreted depth point based on the measured points. Figure 1 shows the combined borehole, probe, and geophysical data points used for this study.
The multidisciplinary survey program produced three distinct data sets that yielded complementary constraints on subsurface structure. As such, these data sets required integration before affording more comprehensive results. Overall, the combination of borehole constraints and seismic, GPR and resistivity data provided an effective means of bounding study area stratigraphy and establishing reliable stratigraphic trends.
Data Acquisition

Geophysical data were acquired along 16 GPR lines, 8 seismic refraction lines, 4 resistivity lines, and one seismic reflection line. The locations of the geophysical survey lines are plotted on Figure 1.

GPR Survey

GPR data were collected using Geophysical Survey Systems, Inc. SIR System 2 and 2000 digital ground penetrating radar systems. The GPR data were displayed on a color monitor for immediate visual inspection and quality control and simultaneously recorded on the system’s hard drive for later processing and interpretation. Depths to discontinuous interfaces were recovered from the recorded travel-time data using radar propagation velocities estimated through calibration with borehole logs and from material specific velocity tables.

The GPR investigation consisted of two components: a) a survey designed to resolve stratigraphy to the top of the Presumpscot Clay, and b) a survey to identify deeper and significant stratigraphic features, including bedrock. After testing various antenna frequencies and setups, a 100-MHz bi-static antenna in survey wheel data collection mode and Multiple Low Frequency (MLF) bi-static antenna system in both survey wheel and point modes were selected.

MLF data were used to derive deeper stratigraphic information, while the 100-MHz data were used to constrain Transition and Clay unit boundaries. MLF data were collected using discrete, stacked measurements at 2-foot intervals and continuous acquisition regulated by a calibrated survey wheel. Stacking signals in the point collection mode increased the signal-to-noise ratio and produced much cleaner records than the survey wheel mode. Surveys using the 100-MHz antenna system were conducted exclusively in the survey wheel collection mode. In all modes, transmission rates were either 32 or 64 scans per second. The time acquisition windows for MLF and 100-MHz data collection ranged from 400 ns to 1500 ns.

Resistivity Survey

The resistivity survey geometry was designed to optimize the depth of investigation while maintaining the ability to resolve shallow stratigraphy. The survey was performed using a Swift SuperSting® resistivity unit with an acquisition array up to 56 electrodes.

An electrode test was conducted prior to each survey to determine the electrode coupling with the soil. To improve the electrical contact between survey electrodes and resistive sandy ground, sandy soil around the base of the electrode was dampened with salt water or other electrolytic solutions. A second battery pack was also added to boost the transmitted energy in areas of poor coupling.

Four resistivity profiles were acquired, one oriented south-north and the other three west-east. The survey electrodes and instrumentation for three of the lines were configured for a dipole-dipole array, which represented a trade-off in resolution between lateral and depth dimensions. A Wenner array was used for the fourth line in order to satisfy the need for horizontal resolution over an area of shallow bedrock. Because the survey could not be re-scheduled, this line was completed immediately following an extended period of ground-saturating rain, which limited the lateral and vertical extent of the data.

Seismic Refraction Survey

The seismic refraction survey was performed using a Geometrics Geode® 48-channel exploration seismograph. Data were collected along eight seismic refraction lines. The geophone spacing ranged from 5 to 20 feet, depending on the vertical and horizontal resolution requirements at
each line location. Variable spacing was used within a line to address variable resolution requirements.

Refraction data were acquired as SEG-2 Rev 1, 32-bit integer data using 14-Hz Mark Products geophones deployed along linear 48-channel geophone arrays. Seismic energy was generated with a Betsy seisgun or hammer blows on an aluminum plate.

Site-specific testing was undertaken to evaluate background noise levels, demonstrate the recording of meaningful refraction data, and estimate signal-to-noise (S-N) values. This phase of the operation also tested the appropriateness of important acquisition parameters, such as sampling rate (~0.125-0.25 ms), the need for acquisition and real-time monitoring frequency filters, and total record duration (~0.2-0.5 s).

A minimum of 7 shot points were used for each refraction line, including off-end (up to 200 feet), end, quarter, and mid-spread shots. The quality of the seismic signals was verified in the field at each shot location. Shots were stacked as necessary to increase S-N levels, thereby helping mitigate the detrimental effects of random environmental noise. Shot locations were also mirrored to enable examination of the reciprocity of refractor travel times.

Seismic Reflection Survey

Reflection data were collected along only one line (SRL-7), where it was chosen as the preferred method for imaging the slope of deep bedrock. The linear distance available for surveying the deep bedrock surface at an angle approximately perpendicular to its slope was inadequate for seismic refraction and resistivity.

The seismic reflection data were collected using the Geometrics Geode® 48-channel exploration seismograph using 100-Hz Mark Products geophones. Data were collected at 49 shots, each measured by 24 receivers spaced 5 feet apart. Using the common offset CDP method and the 24-channel shot array, we achieved 12-fold coverage for as much of the line as possible.

A number of walkaway test shots were taken at offsets of 30, 50, 70, and 90 feet. Significant surface wave and airwave noise was observed to contaminate the near offset shots, leading to the selection of 70 feet as a suitable source-geophone offset. Each seismic trace had a total recording time of 250 ms and was sampled at 0.5 ms, which allowed for signals of up to 1000 Hz to be accurately represented. Data were collected in a common offset configuration, with a shot-point-nearest-receiver distance of 70 feet, and an overall shot array length of 115 feet.

Data Reduction and Analysis

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®
- Resistivity: Res2DINV V.3.4®
- Seismic Refraction: SIPT2 iterative ray tracing
- Seismic Reflection: Linear Radon Transform
- Grid Modeling: Surfer® 8.0
- Graphic Presentations: Surfer® 8.0, AutoCAD® 2000

The map plates, profiles, and radargrams were created from processing of the multidisciplinary data sets and the integrated database.

GPR Survey

Significant pre-processing of GPR data was required to reduce the detrimental effects of noise associated with radio frequency signals and reflections from surface structures and buried debris. High-
pass and spatial filters, horizontal smoothing, background removal, gain adjustments, and wavelet deconvolution were performed as essential processing steps. Two-way travel times to the tops 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 using onsite borehole log constraints, migration techniques, and experience at similar sites. GPR travel-time data were then mapped into the depth domain using these velocity estimates. Maximum penetration depths were 40-50 feet for the 100-MHz and 106 feet for the MLF antenna system.

Data from approximately 8200 linear feet of GPR traverses were included in the database. GPR lines 1, 8, 16, 17, and 12B (a very short segment) were not used because they contained sufficient interference from power lines and other sources to render the data inconclusive.

The radar data were primarily used to enhance the spatial coverage of depth points for modeling stratigraphy and bedrock. Figure 2 shows examples of the significant features observed in the GPR records, including dipping bedrock and stratigraphy.

**Figure 2**: A portion of the record for GPR Line 12c showing east-dipping sands and bedrock, as well as clay pinching out against the bedrock (near bedrock “notch”).

**Resistivity Survey**

Resistivity data were downloaded from the SuperSting® unit to a PC for processing with Res2DINV® modeling software. Data analysis was restricted to data points showing less than a 5% fluctuation between successive readings. Strong outliers were also eliminated to generate smoother models. Final models were characterized by a 15-30% root mean square (R.M.S.) error, indicating limited resolution of shorter wavelength structure. Modeling results were imported into Surfer® for Windows for final contouring and graphical presentation. A maximum depth of 150 feet was achieved along three of the four resistivity lines.

A total of 3476 linear feet of resistivity data were collected and used for this study. The profiles proved to be specifically useful for identifying possible bedrock fractures and generally useful for obtaining relative depths of bedrock and stratigraphic layers. Figure 3 shows good examples of possible bedrock fractures represented by anomalous conductive zones along the bedrock horizon.
Seismic Refraction Survey

Seismic refraction data were analyzed using Rimrock Geophysics’ SIPT2® V. 4. Modeled results were correlated with available known constraints, such as stratigraphy encountered in neighboring boreholes. Model velocities were correlated with average velocities of the expected media types, and the correlation of model structure with other geophysical data.

Velocity information was used to semi-quantitatively elucidate the presence and degree of fracturing/jointing in bedrock by examining the velocity profiles for locations exhibiting prominent and localized low-velocity zones (LVZs). These zones were traced on a line-by-line basis to help establish the orientation and extent of fracture/joint systems. Such constraints served as an independent confirmation of, and improved resolution over, the results obtained from regional fracture trace studies.

Seismic profiles generated during data analysis illustrated the general bedrock valley and specific depressions indicative of eroded fractures that correlate well with measured low bedrock velocities. An interesting aspect of the bedrock velocity data is the occurrence on a regional scale of lower bedrock velocities in the western side of the bedrock valley. Seismic lines 1 through 3 also illustrate the thinning Clay and Transition Unit sediments at the west side of the bedrock valley. Figure 4 shows the seismic refraction profile for Seismic lines 1 and 2.
Seismic Reflection Survey

The SRL-7 data were converted to the SEPlib format to enable use of linear Radon Transform, a more advanced signal processing technique than that offered by the KGS Winseis software.

After application of a refraction mute to eliminate the first arrivals, a bandpass filter with corners at 40 and 250 Hz was applied to the data to increase the relative strength of the prime observed reflector.

Additional processing included application of the linear Radon Transform, additional processing, and finally conversion of the stacked section from time to depth using a uniform velocity of $V_{int}= 2750$ ft/s. The analysis of refractions and the geologic cross section developed from nearby well log data were used to constrain subsurface velocities.

The seismic reflection data show one prominent reflector, a westward-dipping layer with topographic relief of approximately 40 feet (Figure 5). Based on the cross-sectional model, this reflector is interpreted as the top of bedrock.

A significant amplitude and phase anomaly is present on the interpreted bedrock section for 30 feet between distances of 140 and 190 feet. The discontinuous reflections in this region are consistent with a localized fracture system or faulting with a minor amount of block offset. Raw data records indicate that the cause of the disruption may be nearly vertical.
Data Synthesis

Data from the geophysical surveys and boreholes were compiled to form an integrated database of approximately 1000 data points: 669 from seismic, 250 from GPR, 81 from resistivity, 39 from bedrock wells, and 44 from clay wells. These data were used to construct a best-fit 2-D grid model using Surfer® for Windows’ kriging algorithm for the top of bedrock, Presumpscot Clay, and Transition Unit. Kriging algorithms incorporating anisotropy parameters were used to create the grids. Areas where data were not acquired or were insufficient to analyze surface trends have been blanked in the grid model. Final contour maps were then produced with Surfer® for Windows. A matrix smoothing function was also applied to the grids to emphasize the surface trends. Contour maps representing the mapped horizons were created from the grids. Isopach maps of the Presumpscot Clay and Transition Unit were created from the grids using grid math functions. Slices through the grid models were used to construct depth profiles of the interpreted stratigraphy.

Structure contour maps of the bedrock and clay surfaces and the bedrock surface map (Figure 6) clearly show the bedrock valley and valley-controlled drainage system sloping to the north.
Figure 6.: Bedrock surface map showing bedrock valley with north-trending drainage path.

Isopach maps of the Clay and Transition Unit show the thickness of these units as controlled by this system. Of particular interest are the zones of thin clay shown as filled color contours in Figure 7.
Figure 7: Isopach contour map of the Presumpscot Clay. This map identifies, in shades of red, the areas where the clay thickness is 5 feet or less.

Figure 8 is a composite map integrating the structural data interpreted from resistivity and seismic data with the bedrock surface structure map and lineaments. It includes location plots of lineaments, wells, as well as the locations of possible bedrock fracture corridors. There is good correlation of the eastern north-south lineaments and the local lineaments. Based on this compilation, possible fracture corridors trend north-south and east-west. Based on the position of the western north-south interpreted fracture, the east-dipping bedrock slope may be the fault plane.
Conclusions

The geophysical investigations and stratigraphic modeling show the geological constraints on migration of the Eastern Plume at Naval Air Station, Brunswick:

- A north-sloping drainage pattern in the Presumpscot Clay, and, to a lesser extent, Transition Unit surfaces within a bedrock valley sloping in the same direction.
• East-dipping stratigraphy in the Transition Unit and overlying undifferentiated sand unit.
• Structural corridors in bedrock in the north-south and east-west directions.

Further, the isopach map for the Presumpscot Clay developed from our investigations (Figure 6) indicates that the clay thickness is quite variable over the study area and is less than 5 feet thick at some locations.

The data produced by this study was subsequently used to site a new extraction well screened in the fractured bedrock.

References

Thompson, W.B., Borns, H.W., Jr., 1985, Surficial geological map of Maine, Maine Geological Survey.

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