# GPR AS A COST EFFECTIVE BEDROCK MAPPING TOOL FOR LARGE AREAS

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## Abstract

Hager GeoScience, Inc. conducted a geophysical investigation at the site of a former manufacturing plant in Massachusetts at which contamination had been detected in fractured bedrock. The area of interest covered approximately 48 acres of mixed-use and residential neighborhoods, including a park and cemetery. There was concern about the location and movement of contaminants off the site toward a nearby river. The client had already installed a number of bedrock wells around the contaminant source in order to track the migration direction of the contaminants, as well as an air sparging system to treat contaminated groundwater at the source. After noting anomalous data during pumping of bedrock recovery wells, the client hired HGI to help determine the best locations for additional deep rock pumping wells, as well as to track groundwater (and thus contaminant) movement off the site. HGI's investigation integrated GPR and seismic refraction surveys with data from geologic and aeromagnetic maps, outcrop data, and fracture trace analysis.

The study area is located along the northeast margin of the Narragansett Basin. Geological research prior to starting the geophysical fieldwork identified a network of lineaments/fractures, predominantly trending northwest. The geophysical surveys were designed to relate the lineaments to possible fractures, as well as to map the stratigraphy and bedrock surface to determine the direction of groundwater flow. To this end, approximately 3,000 linear feet of seismic refraction data and 10,000 linear feet of GPR data were collected, mostly along roads and sidewalks.

The seismic refraction survey established the correlation between lineaments and possible bedrock fractures on the basis of low seismic velocities. Sufficient GPR data were collected to produce a bedrock contour map that helped resolve the apparent contradictions between predicted and actual hydraulic gradients under pumping conditions, as well as give the client additional pumping well locations.

# Introduction

Hager GeoScience, Inc. (HGI) conducted a subsurface geological and geophysical investigation of a former manufacturing plant at a site in Massachusetts, in order to define the configuration of the bedrock surface and identify bedrock fractures that could influence the direction of groundwater flow.

A three-phase plan of investigation was proposed and approved by the client:

<u>Phase 1 - Lineament/Fracture Study:</u> A review of readily available topographic, aeromagnetic, geologic, photographic, and other information to determine the bedrock structure of the study area.

Phase 2 - Ground Penetrating Radar Survey: A GPR survey to locate bedrock valleys and fractures.

<u>Phase 3 – Seismic Refraction Survey:</u> A seismic refraction survey at the locations of bedrock valleys or lineaments identified by the Phase 1 and 2 investigations. The purpose of the seismic survey would be to provide information on low velocity zones, help calibrate the GPR data, and provide additional information about bedrock depths.

Phase 1 work consisted of review of information from U.S. Geological Survey high-altitude photographs and topographic, aeromagnetic, and surficial geologic maps for the quadrangle in which the

site was located. This review was followed by GPR field data collection. The Phase 3 seismic refraction survey proceeded only after analysis and integration of information from the first two phases had been completed.

The investigation evaluated an area of approximately 48 acres. Approximately 10,000 linear feet of GPR and 3,000 lineal feet of seismic refraction data were collected.

The data collected from each phase was compiled onto a base plan digitized from City Assessor's maps provided by the client (no AutoCAD base plan was available). The data were interpreted to produce a drawing showing the location of possible bedrock fractures overlain on a contour map of the bedrock surface.

# **Technical Approach**

#### Phase 1 – Lineament/Fracture Study

The first step in characterizing the bedrock within the study area was to define the geologic setting. Background geologic research was performed using in-house and local library sources. All readily available published and unpublished materials were reviewed to assist in defining the geology of the study area, including surficial geologic maps, aeromagnetic maps, Massachusetts State Geologic Map and Report, and USGS Open File Reports.

This research effort was supplemented by mapping of outcrops in and near the survey area, and with a fracture trace analysis using topographic maps and aerial photographs obtained from the USGS. Four black & white photographs on a 20-inch format and four infrared photographs on a 9-inch format were studied as single photos and stereo pairs. These photographs were used to trace lineaments within and in the vicinity of the study area that might be surface expressions of bedrock fractures (Figure 1).

#### Phase 2 – GPR Survey

The information from the background research, fracture trace analysis, and borehole information supplied by the client were used to interpret a structural framework of the area and provide a basis on which to design a confirmatory geophysical survey.

The GPR survey was performed using a GSSI SIR2 ground penetrating radar system to map the configuration of the bedrock surface and locate possible fracture zones. Due to difficult soil conditions, a Multiple Low Frequency (MLF) bistatic antenna system was used. The system was configured to operate at a frequency of 40 MHz to optimize subsurface resolution between depths of 10 and 40 feet. The MLF system was configured to collect data continuously by mounting it on a wooden skid, which the operator pulled behind him while carrying the electronics in a harness. This setup allowed data to be collected continuously along sidewalks and roadways where access might otherwise have been difficult. Distances along each traverse were determined using a survey wheel attached to the rear of the skid.

Using vertical survey data supplied by the client, elevations of the competent bedrock surface were calculated from depths of bedrock reflectors interpreted from radar records using GSSI's RADAN software. The depths were calculated from two-way travel time of radar energy to the bedrock reflector based on soil-velocity calibration at the site. Bedrock depth information was recorded at specific locations along the traverses, as shown on Figure 2. The depth values and eastings and nothings for each location were manually entered into an Excel spreadsheet. Depths were subsequently converted to elevations and contoured using Surfer for Windows software.





## Phase 3 – Seismic Refraction Survey

Results from the Phase 1 and Phase 2 investigations were used to design a seismic refraction survey that would effectively encircle the source of contamination, thereby identifying potential water bearing fractures. The seismic refraction survey was designed to investigate lineaments (Phase 1) and bedrock valleys (Phase 2) located in the vicinity of the site, since these features mark possible bedrock fractures along which contaminated groundwater could flow from the site. Locations of seismic lines are shown in Figure 2.



Figure 2. Location of GPR depth calculation points and seismic refraction lines.

An ABEM Terraloc Mark VI digital 24-channel seismograph was used to perform the survey. Geophone spacing was 10 and 20 feet, and 5 shot points were used along each spread (mid-point, end-points, and as offsets from the endpoints). A 60-pound weight drop striking a steel plate was used to create the seismic energy for each shot point. The seismic data were analyzed using the Crossover-Distance and SIPT2 iterative ray tracing methods, allowing information about bedrock depths, low-velocity zones, and, to a limited degree, soil characteristics to be obtained. Areas of low bedrock velocities were identified as possible fracture zones.

# **Study Results**

#### Phase 1 – Lineament/Fracture Study

Figure 1 shows that the predominant orientation of bedrock lineaments and valleys in the study area is to the northwest. The lineaments represent the Carboniferous basin-margin fracture system and extensional fractures developed during Jurassic and Triassic plate rifting events in the northeastern United States. Associated with the basin-margin or "border" fault in this area are the northwest-trending fractures that define fault blocks displaced vertically by gravity, with a north-to-south rotation. The effect of this movement is north-northwest dipping strata within these fault blocks. Mesozoic rifting event reactivated the Carboniferous tectonic features and added additional fractures to the existing system.

Post-Triassic erosion of the northwest fracture system has been significantly enhanced by glacial erosion during the Pleistocene Period. The glacially eroded northwest-trending bedrock valleys were buried by glacial sediments and are now important features controlling both unconfined groundwater flow and surface drainage where unaffected by human development.

The orientation of bedrock cleavage is east-northeast. Northeast-trending lineaments are also present to a lesser degree. These lineaments are also related to the basin margin faulting and most likely represent the hinges or boundaries of gravity fault blocks. They may have developed as new fractures during the rifting event or were initiated from the reactivation of older Paleozoic or Precambrian faults. Low-angle shallow fractures related to near-surface stress release are prevalent as well.

#### Phase 2 – GPR Survey

The GPR records for most of the surveyed areas were good and provided clear indications of competent bedrock surfaces. In areas where several feet of weathered rock are present, a distinct bedrock reflector was difficult to identify without processing the raw data. Where the bedrock surface is less than 5 feet deep, the bedrock reflectors are too shallow to be resolved by the 40 MHz antenna and were not recorded.

### Phase 3 – Seismic Refraction Survey

The seismic refraction survey identified low-velocity zones along all of the surveyed lines. These zones are interpreted as expressions of the northwest-trending fracture system. However, they may also be the result of the intersection of multiple fractures, or deeply and differentially weathered bedrock. Figure 3 shows seismic velocity cross sections for two of the seismic refraction lines and the corresponding bedrock velocities.

## Conclusions

#### Interpretation of Bedrock

Information from all phases of the investigation was integrated into an interpretation of the bedrock surface configuration and fracture system. Figure 4 presents the interpreted configuration of the bedrock surface as an elevation contour map.

The bedrock surface configuration shown in Figure 4 reflects the regional bedrock structure as modified by glacial erosion during the Pleistocene Period over 10,00 years ago. A series of bedrock highs forms a ridge oriented east-northeast at the north side of the study area; this ridge defines the groundwater divide for unconfined groundwater flow. Similarly, a north-south-trending bedrock ridge forms a divide on the west side of the study area. South and east of these divides, the bedrock surface

generally dips to the southeast. A northwest-southeast-oriented bedrock ridge separates and defines two bedrock valleys.



# Figure 3. Seismic refraction cross sections showing low bedrock velocity zones along two seismic lines.

# Local Groundwater Flow Patterns

From the integrated geological and geophysical study, HGI concluded that groundwater flow in the unconsolidated sediments and upper bedrock zone groundwater flow should be unconfined and toward the east and southeast, following the bedrock surface configuration shown in Figure 4 where unaffected by human development. Groundwater flow direction through bedrock fractures would be closely tied to that of the unconfined flow, i.e., toward the southeast, which would be consistent with the regional bedrock slope, the fracture-controlled bedrock valleys, and surface drainage.

The interbedded impermeable and permeable sedimentary units forming the aquitard and aquifer, respectively, would define groundwater flow within the unfractured lower bedrock zone, in which artesian conditions exist. The direction of flow within this system would be controlled by the orientation of the sedimentary beds as affected by faulting, probably in the opposite direction to that in the upper bedrock system. These differences in movement of ground water and associated contaminants, along with the locations of existing bedrock wells relative to the bedrock highs and lows interpreted from the GPR and seismic data, explain the apparently anomalous behavior of these wells during pumping and were used as the basis for recommending the most promising locations of additional recovery wells.



Figure 4. Bedrock contour map of study area.