SEISMIC CHARACTERIZATION OF THE KARST BEDROCK SURFACE IN THE SOUTHEAST INDUSTRIAL AREA AT ANNISTON ARMY DEPOT, ALABAMA[1]

M.D. Thompson, S.F. Miller, M.A. Glennon, J.M. Cooper, Argonne Nat'l Lab., Argonne, IL.
W.A. Mandell, U.S. Army Environmental Center, Aberdeen, MD.

ABSTRACT

Environmental concerns at the Southeast Industrial Area (SIA) of Anniston Army Depot (ANAD) have been the impetus for geotechnical investigations over the last 20 years. These previous investigations have all failed in one respect, to map the bedrock topography of the underlying Knox Group dolomites. The bedrock surface is an important target: a) lows points provide a greater column of overburden in which to trap contaminants; b) bedrock pinnacles may act as rapid access points into the karst conduit systems; and c) hydraulically transmissive zones are often found within the weathered portion (epikarst) of the bedrock. The approach taken by Argonne was to construct a bedrock surface map integrating existing borehole data with selective seismic-refraction profiling. Initial inspection revealed that depth-to-bedrock measurements based solely on auger refusal were not acceptable in many cases because refusal occurred on top of either large boulders or chert horizons.

Seismic refraction profiling within the SIA required overcoming several technical challenges. First, numerous sumps, fans, and blowers produced strong background noise, as did the constant vehicular traffic and sporadic railroad activity. Secondly, construction design for the SIA was not conducive to seismic profiling as compacted gravel-fill, reinforced concrete, and asphalt paving comprised the ground surface. One solution was simple brute force with upwards of 30 stacks using a weight-drop source to overcome the background din. Other solutions included collecting data during off-hour periods, mounting geophones in gravel, grassy, and asphalt areas adjacent to the major roadways, and paying careful attention to where the shot point was located to avoid impacting on the hardened concrete surfaces. In the latter case, the concrete roadbed acts as a wave-guide, primarily transmitting the seismic energy horizontally and obscuring the underlying geology.

Seismic profiling and analysis of borehole data indicate that at least 4 major bedrock depressions, averaging 20-to-30 m in local relief, occur along the southeast and northeast boundaries. Drilling records indicate more frequent occurrences of clay-filled cavities and fractured and weathered rock along the southeast boundary, suggesting a causal relationship for the location of the bedrock lows. Eight confirmatory boreholes were used to ground truth the seismic models. Four of these boreholes confirmed the presence of the bedrock lows, with one low located where previous investigations had indicated shallower bedrock. The ability to acquire seismic data in an active industrial area where utility lines and sewer systems preclude using electrical or electromagnetic methods helps ANAD to intelligently guide drilling, regulatory, and remediation strategies.

[1]This work has been authored by a contractor of the U.S. Government under contract No. W-31-109-ENG-38. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

Background

Numerous environmental investigations have been conducted at ANAD over the last 20 years, and yet the hydrogeologic system remains poorly understood due to the complexity of the local geologic structure. Argonne National Laboratory (ANL) conducted seismic refraction profiling to map structural features associated with the bedrock and to locate potential zones for groundwater migration. Approximately 2.8 mi (4.5 km) of seismic refraction data have been collected in the Southeast Industrial Area of ANAD (Figure 1). Additionally, eight investigative borings were sited adjacent to the seismic profiles in order to characterize the overburden and bedrock, and to verify or constrain the geophysical models.

Site Description and Geology

ANAD is located in Calhoun County and lies within the Alabama sector of the Appalachian Valley and Ridge Province (Figure 1) (Adams et al. 1926). Cambrian to Pennsylvanian-age strata are exposed in long narrow belts of the northeast-trending ridges and valleys. The sedimentary column in this region has been tilted and thrust-faulted into a series of disharmonic sheets. Most of the thrust faults dip to the southeast, and northwest-directed transport has resulted in the imbricate stacking of large thrust sheets. Local-scale (less than several miles in length) geologic structures range from complex folds and fracture systems near the terminus of a thrust fault, to broader folds within the central regions of the thrust sheets (Osborne 1993).

ANAD is located in the Coosa Valley, which is 20 mi (32 km) wide and trends northeast to southwest for approximately 100 mi (162 km). Bedrock consists of Cambrian to Ordovician-age clastic and carbonate rocks composed of sandstones, shales (mudstones), cherty limestones, dolomites, and quartzites (Osborne and Szabo 1984). The carbonate bedrock is overlain by a dolomite-derived residuum that consists of residual clays with chert fragments and rock boulders. The principal structural feature in the ANAD area is the Jacksonville Fault, which is traced immediately adjacent and nearly parallel to the southern boundary of the SIA (Figure 1). Osborne and Szabo (1984) argued that the Jacksonville Fault dies out near the town of Bynum, southwest of ANAD. However, a more recent geologic investigation southwest of ANAD extends the trace of the Jacksonville Fault further SW towards the Jackson Shoals area near the Talladega Speedway (Osborne 1993).

Hydrogeology

In all areas of ANAD, the piezometric surface of shallow bedrock aquifers occurs within the residuum (SAIC 1996). Hydrogeologic data indicate that the residuum serves as a confining (or semiconfining) layer, with transmissivities increasing downward. The weathered zone is extremely heterogeneous, resulting in highly variable permeabilities. In many cases, the shallow groundwater system is not isolated and leakage of perched water occurs between the residuum and the underlying bedrock. The unweathered dolomites of the Conasauga and Shady Dolomite are the most transmissive sequences in Calhoun County, Alabama (Moser and DeJarnette 1992). Large quantities of water can be obtained from the Knox Group where water-filled solution features are encountered.

Geophysical Methods

Seismic Refraction

Refraction profiling was used to map the top of the dolomitic bedrock in an attempt to outline overburden and epikarst hydrogeologic features. Profile locations were chosen to fill in areas where borehole information was limited and/or where structural and stratigraphic information was paramount. Sixteen seismic refraction profiles, covering approximately 2.8 mi (4.5 km), were collected at ANAD, and are indexed by the name of the closest street, where possible, or by profile number (Figure 1).

The refraction method depends on an increase in seismic wave velocity with depth, which is the case at ANAD where higher-velocity dolomitic rock underlies lower-velocity alluvium and residuum. Exceptions occur where residual rock layers are present within the overburden and where fractured intervals exist at depth below the bedrock surface. In the first case, the refraction method may map the residual layer as top-of-rock. Fractured intervals in the second case will most likely be invisible to the refraction survey.

The seismic data were recorded using 24- and 48-channel seismographs, with geophones spaced at intervals of 2 and 5 m. A Bison elastic wave generator (EWG; 500 lb weight drop) was used as the primary energy source, and a 16 lb sledgehammer was used in areas that could not be accessed by the EWG. Both lower-frequency (~15 Hz) and higher-frequency (40 Hz) geophones were used. The lower-frequency geophones proved most useful in the dry, sandy-to-gravelly areas adjacent to roadways. Higher-frequency geophones, however, aided in attenuating the noise and background hum associated with activities at the base. All profiles employed reverse-spread shooting, with one shot point located near the center of the geophone spread, one at each end, and two or more at distant offsets from the ends of each spread. Longer profiles were constructed from adjacent and/or overlapping receiver spreads.

The first arrival time-picks were processed using the SIPT2 refraction package sold by RIMROCK Inc. (1992). SIPT takes advantage of reverse-spread geometry and far-offset shot points of the survey to compute depths to interfaces below each geophone. In general, a three-layer solution was required to model the refraction data with individual layers interpreted as: Layer-1, dry unconsolidated fill and/or Quaternary sediment; Layer-2, wet or dry unconsolidated sediment or residuum; and Layer-3, either competent or weathered dolomitic bedrock. The range of velocities modeled for the interpreted bedrock (Layer-3) of 9,800 to 17,000 ft/s is consistent with published seismic velocities (9,000-21,000 ft/s) for hard limestone or dolomite (Waters 1981), and with downhole-velocity results obtained during this study. Seismic velocities used to model the overburden sediment are consistent with those obtained by Technos (1985).

Figure 2 illustrates two of the major impediments to performing seismic surveying within the industrial area; interference from activities on base and road-bed guided-waves. Shot record SP-04 shows low-frequency (15-30 Hz) noise contaminating the record. This type of interference is typical within the industrial area as sumps, pumps, and blower-motors turn on and off at irregular intervals. Post-collection filtering, shot-stacking, and using higher-frequency geophones helps reduce these interfering signals. On shot record SP-104, two arrival events are identified. The first is an early, linear, high-frequency, and high-velocity event that is interpreted to be the result of seismic energy being guided by the hardened concrete roadway. These guided-wave events typically die off after 60 m or so. The second event is probably generated by subsurface geologic horizons. A subsequent shot point collected approximately 2.5 m perpendicular to SP-104, and located off the shoulder of the road, showed a marked reduction in the guided-wave and corresponding enhancement of the geologic events.

Figure 3 shows three shot records collected along profile RFR-2, which is adjacent to and northeast of the SIA (see Figure 1). Of interest is that the EWG source was able to generate an identifiable signal out to distances upwards of 750 ft, and that 3 distinct refraction events are observed on the record.

Borehole Geophysics

Vertical seismic profiling was conducted in seven boreholes in order to constrain the refraction models. A three-component geophone was clamped using a side-wall locking device at intervals of 2.5 and 5 ft (0.75-1.5 m) within the borehole. A sledgehammer struck a steel plate at a distance of 5 feet (1.5 m) from the borehole, and the time it took for the energy to travel to the receiver was recorded. Reference geophones were used at the surface to ensure a consistant shot-timing. A range in velocity of 1,600-7,000 ft/s (500-2,134 m/s) was calculated for overburden sediments, and 8,500-20,000 ft/s (2,286-6,096 m/s) for bedrock zones. The overburden sediments generally contain a 1-3 m thick unsaturated, low-velocity zone near the ground surface. These physical measurements are consistent with velocities derived from refraction modeling.

The locations of the eight confirmatory borings are shown in the left panel of Figure 4. Depths to bedrock are also shown as well as an example geophysical log for Boring G1. The depth to bedrock is extremely variable. For example, borings G4 and G5 (northeast) are approximately 300 ft apart and yet show a change of approximately 100 ft in bedrock topography. The question mark adjacent to the Boring G5 depth estimate is used because the boring encountered no consistently thick (>15 ft) dolomite interval. Boring G4 was drilled to ~55 ft in depth and encountered competent dolostone from 27 ft to the bottom of the hole.

The velocity-profile for Boring G1 (Figure 4) illustrates the use of velocity logging for refining the the top-of-bedrock. In this case, the driller's record is less certain in the placement as poor recovery (<20%) occurred in the "clay-with-rock layers" zone between 530 and 550 ft in elevation. The velocity profile increases in velocity within this zone from approximately 6500 to 13,000 ft/s, and maintains high-velocities (>10,00 ft/s) below the zone. Top-of-rock can most likely be placed at approximately 543 ft, rather than the 530 ft indicated on the lithologic column.

Geophysical Profiles

Example models constructed for ANAD are shown in Figure 5 with the locations of boreholes adjacent to each profile drawn as solid-black vertical lines, and the depth to bedrock encountered in that borehole as a solid-black horizontal line. The upper model in Figure 5 corresponds to profile RFR-3 (located along the southeast boundary line), and the lower model corresponds to RFR-8 (SWMU-12) profile located in the southwest part of the SIA.

The interpreted bedrock surface on the southeast boundary profile exhibits local relief of up to 100 feet across the profile. A bedrock high located near the 1,500 ft profile mark rises to within 40 ft of the ground surface (~590 ft msl), whereas the surface of the bedrock to the southwest occurs at an elevation of approximately 486 feet. Northeast of the interpreted bedrock high, the overburden-bedrock interface maintains a relatively flat surface that averages between 550 and 570 ft in elevation. This surface is broken near profile position 3500 by an interpreted bedrock depression, and on the northeast end by a bedrock high. The discrepancy in bedrock elevation obtained from boring G6 is explained as a modeling limitation. Here the refraction algorithm cannot reliably calculate the depth in sharply defined depressions, resulting in an underestimation of the depth. For borehole G2, two horizontal bars are used to indicate where drilling encountered thicker zones (>10 ft) of competent dolomite. An approximately 15 ft thick clayey zone is sandwiched between these dolomite horizons. It appears that the refraction model is picking the lower dolomite horizon as the top-of-bedrock, which suggests that the upper dolomite interval is a laterally restricted floating block.

Along profile RFR-8 (lower model, Figure 5), depth to bedrock varies from approximately 80 ft near borehole G7, to approximately 24 ft near well 95EWLF-5. In both cases, the modeled bedrock depth is in close agreement with the borehole depth, although boring G7 indicates a bedrock surface approximately 12 ft deeper. One explanation for this discrepancy is that the refraction algorithm cannot adequately model the steeply dipping slope to the west, resulting in an undershoot for the depth-to-bedrock estimation. Boring G8 was drilled in 1999 to a depth of 400 ft and verifies the steep slope of the refraction model.

Discussion

One of the principal objectives of the geophysics program at ANAD has been to define the top of the bedrock surface under the SIA, which here is defined as the top of competent rock. This target is important because the hydraulically-transmissive weathered zone would occur above this horizon. Boreholes that do not penetrate to this level would then miss potential zones for groundwater migration. This objective is met by creating a contoured map of the top-of-bedrock surface, constructed from both seismic and borehole information. Boreholes used were restricted to those that cored into dolomitic rock; bedrock depths estimated on the basis of auger refusal were not incorporated into the model.

A color-contoured map of the bedrock surface constructed from borehole and seismic data is shown in Figure 6a. The highest bedrock elevations occur in the upland areas north of the SIA. A shallow ridge trends southward from this bedrock with the flanks sloping gently to the southwest and east-southeast, and dipping more steeply at the ridge's terminus into a bedrock depression due south.

Four bedrock lows, averaging 100 ft in local relief, are present in a narrow belt along the east and southeast boundary of the SIA. The northernmost low is on the northeast boundary, where boring G5 was drilled and did not encounter competent rock until a depth of 130 ft. The second low is near 7th Street East and Roosevelt Drive, the third low is between 2nd Street East and 3rd Street East along Roosevelt Drive, and the fourth is south of the intersection of Roosevelt Drive and 1st Street East. The 4th low is critical because previous auger-drilling efforts indicated a much shallower bedrock surface than is currently shown.

The bedrock depressions formed by these lows are tentatively interpreted to have formed as the result of dissolution of rock that was heavily fractured during the faulting event of the Jacksonville Thrust. This interpretation is consistent with drilling records that show more numerous clay-filled cavities and fractured/weathered rock along the SIA's southeast boundary. Examination of the seismic-velocity of the bedrock surface (Figure 6b) also supports zones of weaker rock in this region

Conclusions

Refraction profiling in the Southeast Industrial Area (SIA) of Anniston Army Depot (ANAD), Alabama, proved successful in delineating the top of bedrock surface, and locating potential points for contaminant migration and/or pooling. Most of the SIA is underlain by a relatively flat bedrock surface, although at least four major bedrock depressions occur along the southeast and northeast boundaries. The bedrock lows are inferred to have resulted from dissolution of heavily fractured and weathered bedrock, which itself was crushed during thrusting along the Jacksonville Fault. The fact that the bedrock lows occur near the borders of the site could make them a focal point for migration of shallow groundwater offsite.

References

1. Adams, G.I., Butts, C., Stephenson, L.W., and Cooke, C.W., 1926, Geology of Alabama, Special Report 14, Geological Survey of Alabama, 312 p..
2. Moser, P.H, and DeJarnette, S.S., 1992, Ground-Water Availability in Calhoun County, Alabama, Special Map 228, Geological Survey of Alabama, 115 p..
3. Osborne, W.E, and Szabo, M.W., 1984, Stratigraphy and Structure of the Jacksonville Fault, Calhoun County, Alabama, Circular 117, Geological Survey of Alabama, 30 p.
4. Osborne, W.E., 1993, Geology of the Eastabooga Quadrangle, Quadrangle Series Map 11, Geological Survey of Alabama.
5. RIMROCK Geophysics, 1992, SIPT2 Refraction Processing Software, Version 3.2, Boulder, Colorado.
6. Science Applications International Corporation, 1996, Anniston Army Depot Southeast Industrial Area Phase 2 Remedial Investigation Preliminary Draft Report, Mclean, VA.
7. Technos Inc., 1985, Investigation of Possible Paleochannels at the Anniston Army Depot, Anniston, Alabama; Report for Environmental Science and Engineering, Inc., Gainsville, Florida, and the U.S. Army Toxic and Hazardous Materials Agency, Aberdeen Proving Ground, Maryland; Technos Project No. 85-138; 39 pp.
8. Waters, K.H, 1981, Reflection Seismology, A Tool for Energy Resource Exploration, John Wiley and Sons, New York, 453 p.

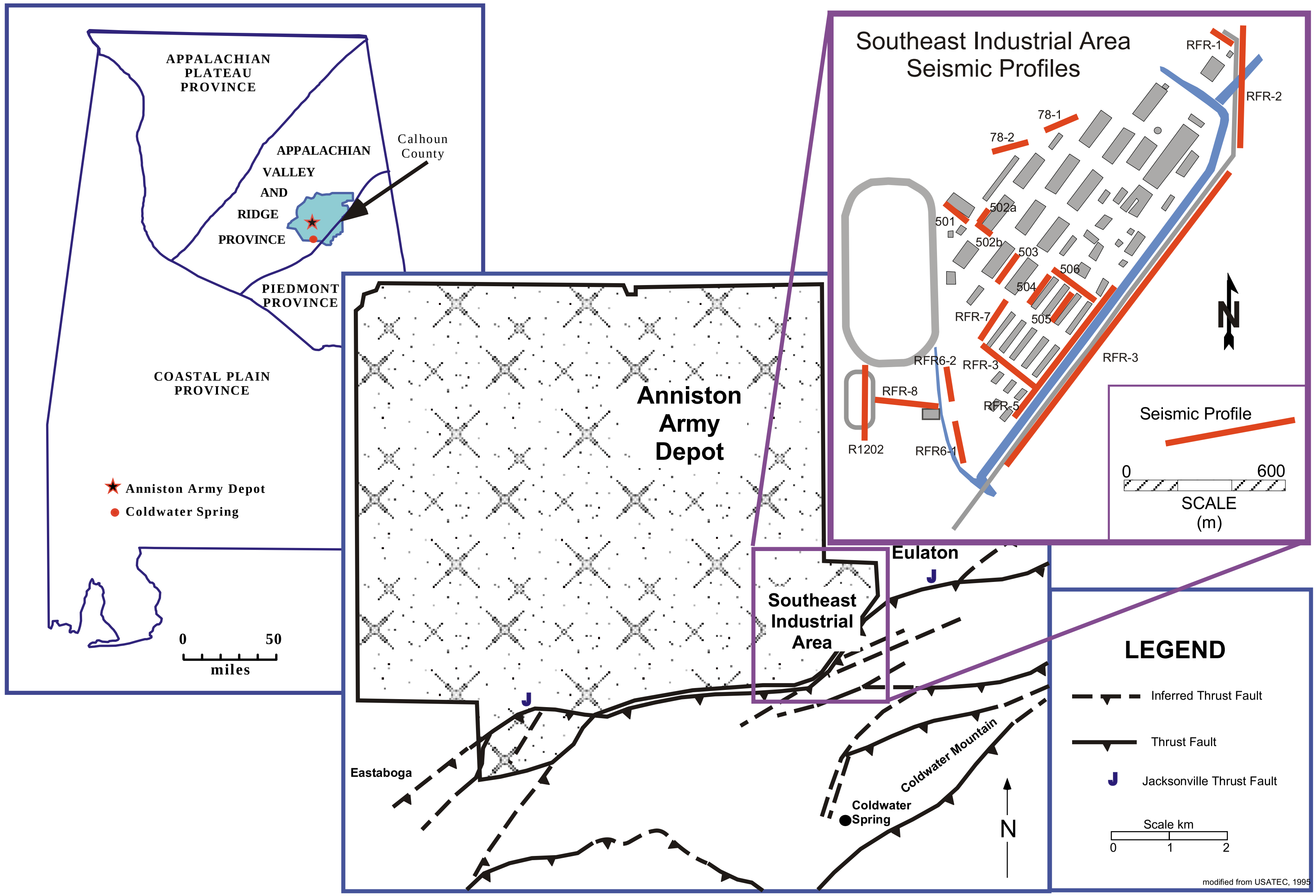

Figure 1. Location map for Anniston Army Depot, Southeast Industrial Area, and seismic-refraction profiles.

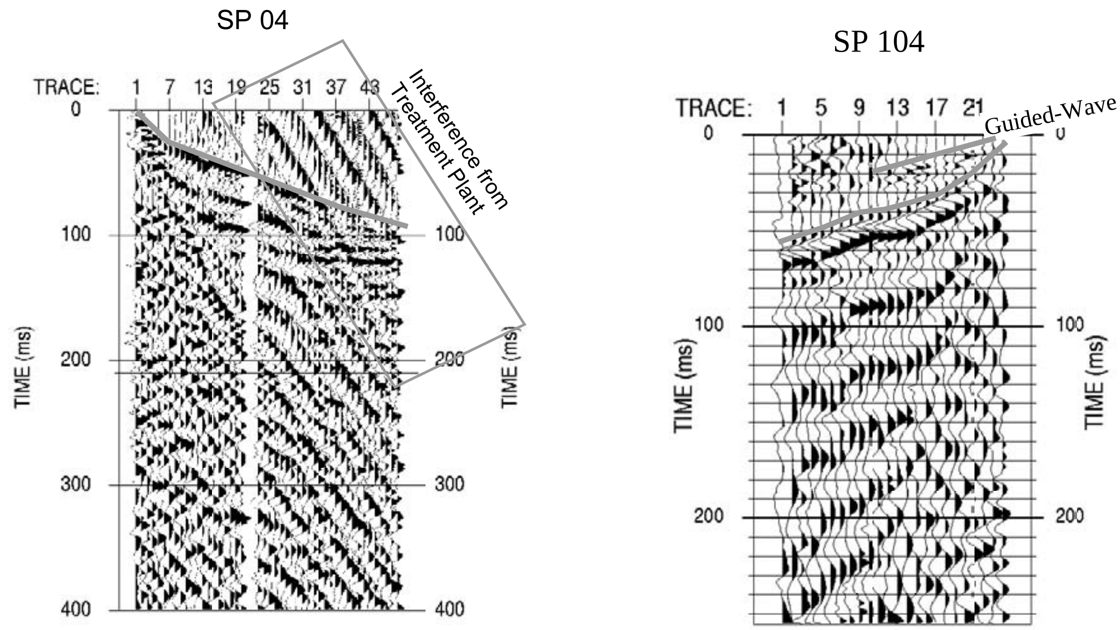

Figure 2. Example shot data collected within the SIA. Interference from active pumps is shown on record SP 04, and a probable road-bed (guided-wave) event is shown for SP 104.

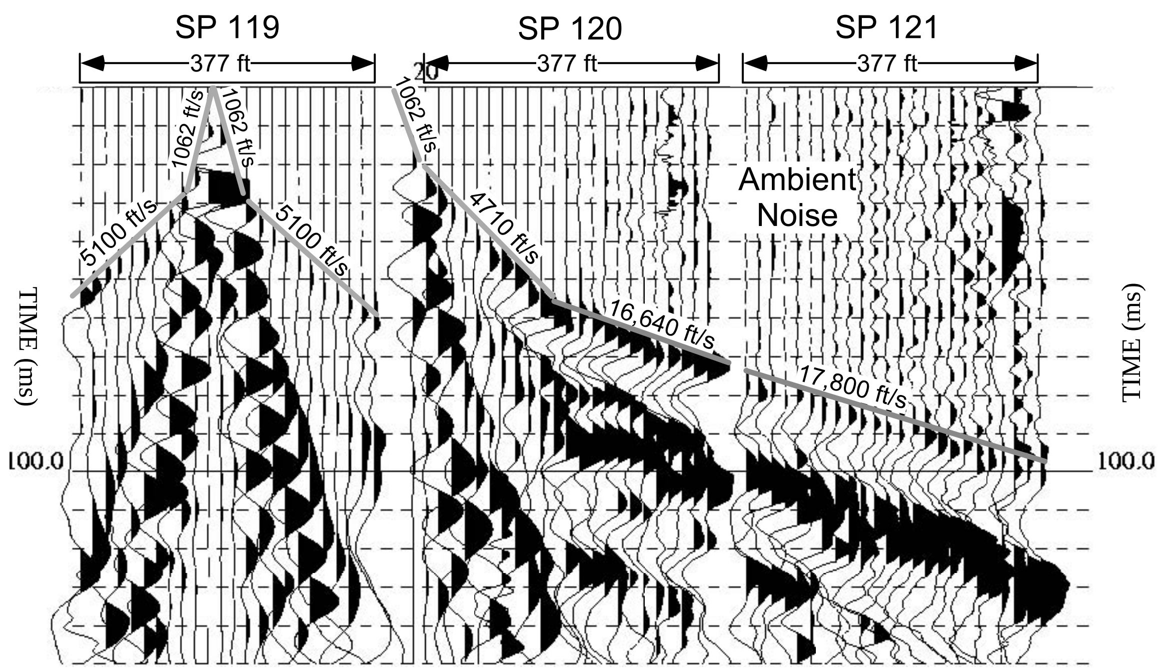

Figure 3. Example Shot Records from Refraction Line RFR-2 (Left panel is a center shot, middle panel is an off-end shot, and right panel is a far off-end shot. Also shown are the apparent velocities obtained from the first-arrivals.

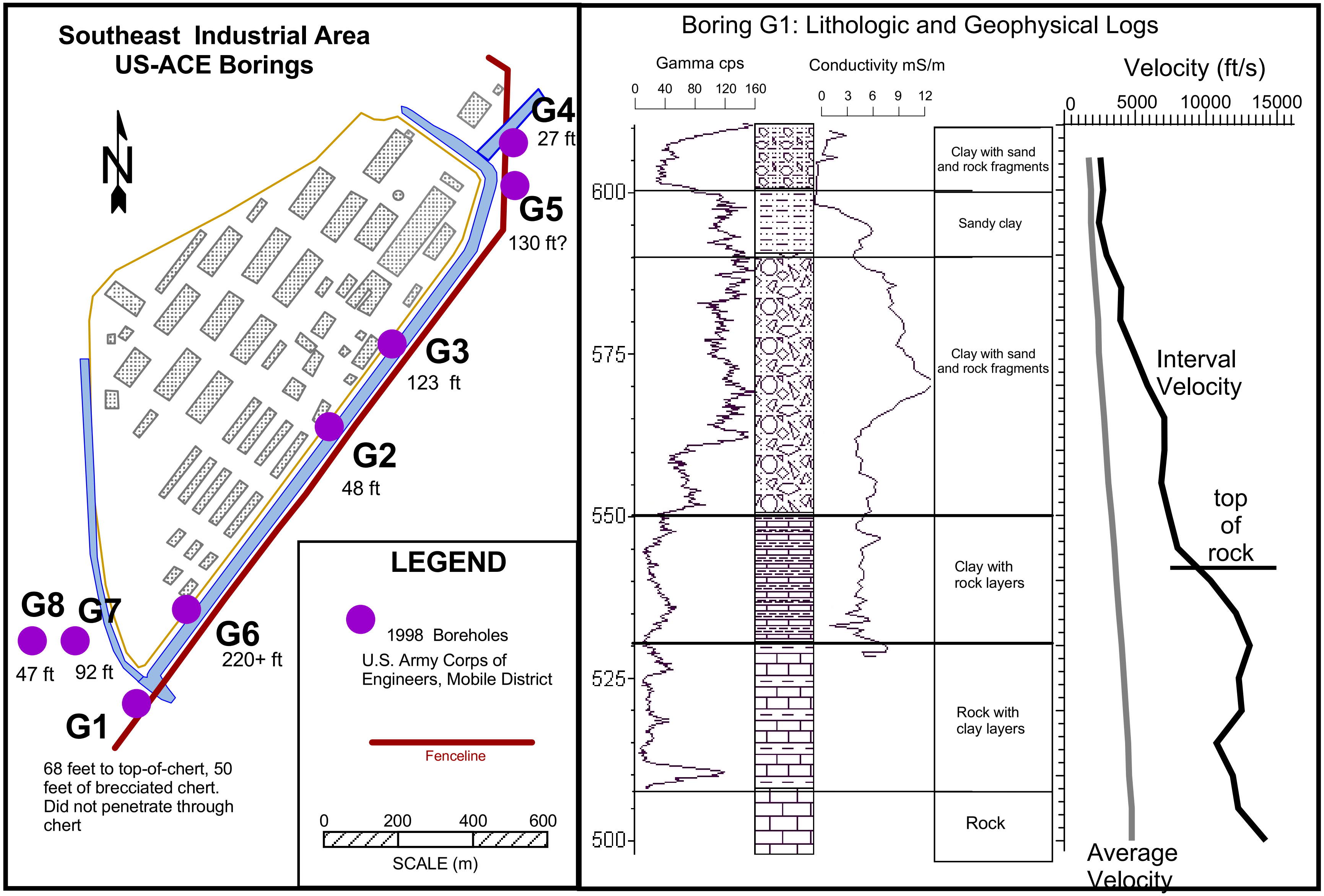

Figure 4. Location of borings and example geophysical and lithological profiles for Boring G1. The boring designator and depth to top-of-rock encountered during drilling are noted in the left panel. The variations in depth are interpreted to be caused by the karstic nature of the underlying rock.

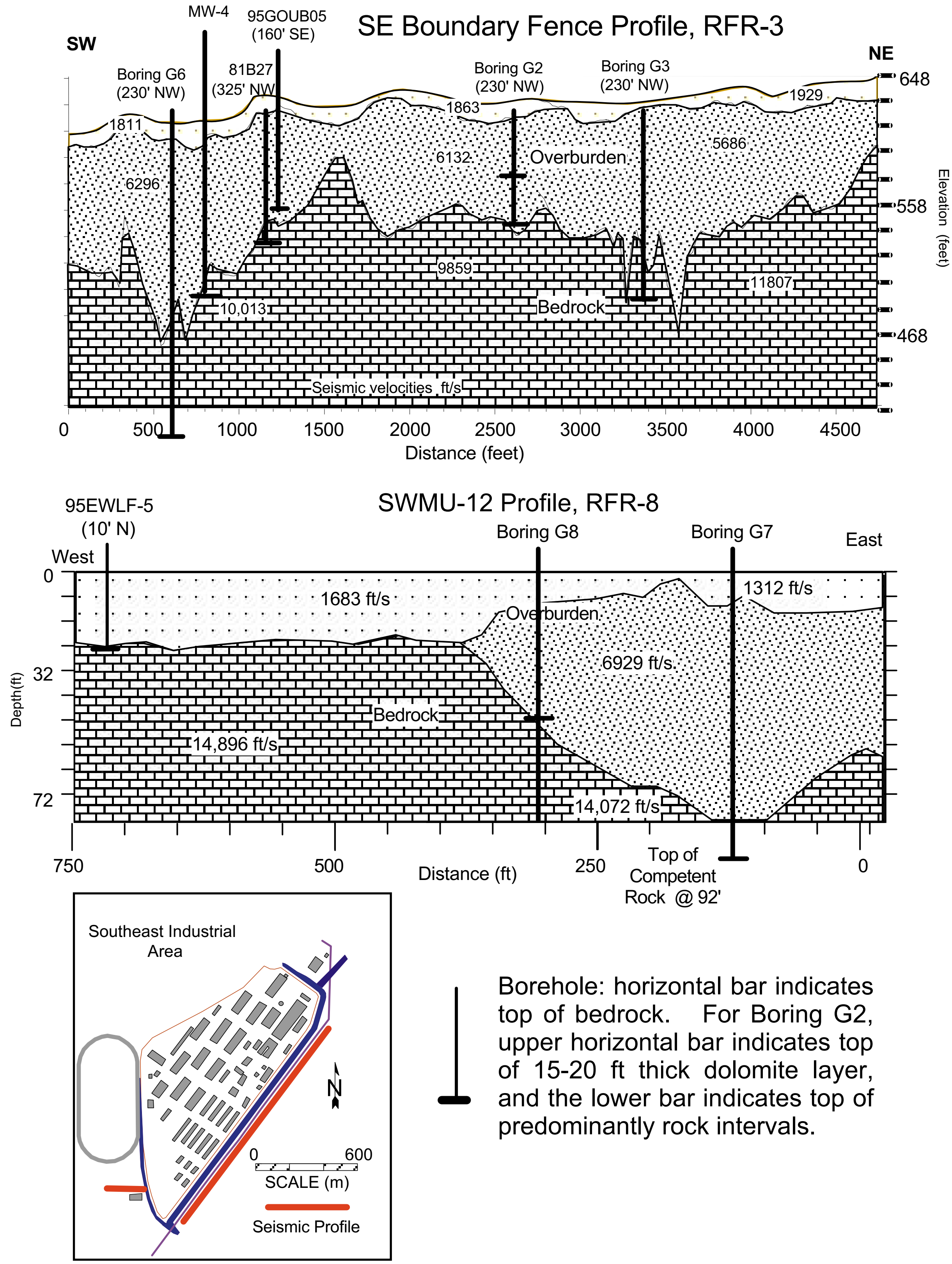

Figure 5. Example refraction models and profile locator map

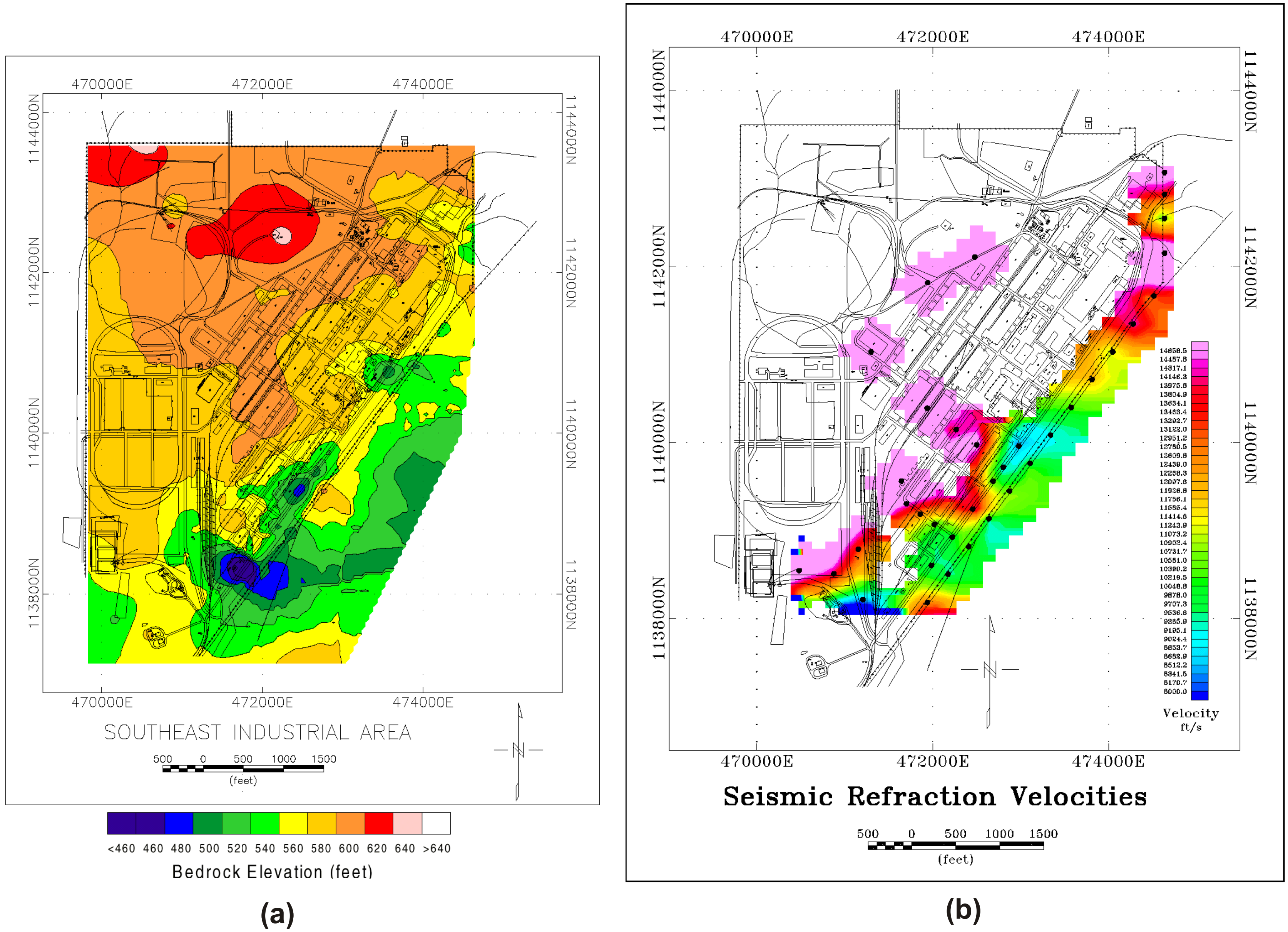

Figure 6. Elevation (a) and velocity (b) of the bedrock surface underlying the SIA. Topographic and velocity lows occur in a narrow band, and are interpreted to be related to the Jacksonville Fault Zone.