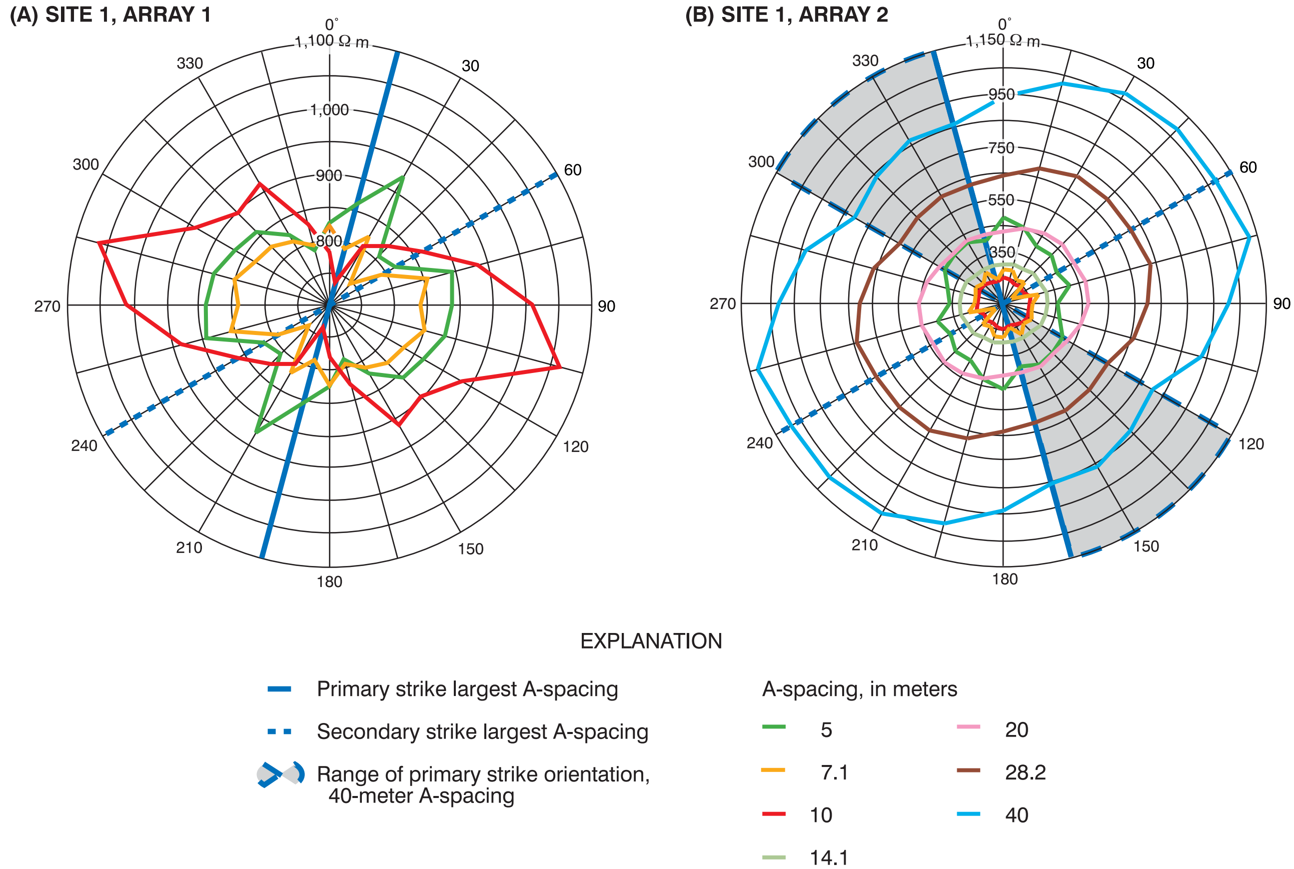

Figure 8. Polar plots showing azimuthal square-array direct-current resistivity at site 1 for arrays 1 and 2, Bedford, N.H. Apparent resistivity in ohm meters (Ω m), is plotted as a function of azimuth, in degrees east of true north; (A) resistivity of square array 1, center at 700 Ω m; (B) resistivity of square array 2, center at 150 Ω m. Site and array locations are shown on figures 1 and 2, respectively.

Electromagnetic (EM and VLF) surveys indicate electrically conductive anomalies that are consistent with the presence of fractured bedrock. 2-D and square-array resistivity surveys, and geologic information corroborate to support the presence of a fractured-bedrock zone. These surveys indicate that lineaments are close to near-vertical conductive features, dipping southeast, identified with geophysical methods. These features may represent fractured-bedrock zones, which likely transmit water. Near-horizontal features in bedrock, interpreted as sheeting fracture zones, were identified with GPR and 2-D resistivity geophysical methods.

Site 2, Windham, New Hampshire

Site 2 on Marblehead Road in Windham, N.H. (fig. 9), is a mostly wooded, valley-wetland setting, and ranges in elevation from about 170 to 210 ft in the area of the surveys. Walsh and Clark (1999) mapped the bedrock geology of this area with a contact between the Berwick Formation, and the Ayer Granodiorite (fig. 9). The bedrock is exposed at the surface on topographic highs at this site. The overburden generally is less than 20 ft thick and is mapped as a till, which is unsorted to poorly sorted clay, silt, sand, pebbles, cobbles and boulders, with some gravel (Larson, 1984). Three mapped lineaments at the site were observed from a LOWALT platform trending 71°, 74°, and 355° (Ferguson and others, 1997), and one with a CIR platform, trending 77° (fig. 9). The 71°, 74°, and 77° trending lineaments were fracture correlated using the 1,000-ft buffer analysis technique (R.B. Moore and others, U.S. Geological Survey, written commun., 2001). Lineament criteria are visible at the site as a swale on line 1, trending 350°, and a shallow elongated valley trending 70°. Fracture data in a 4,000-ft radius of the site have three peak orientations: 310°±9° (100 percent, normalized height), 68°±11° (14 percent, normalized height), and 25°±34°(9 percent, normalized height). Fractures in

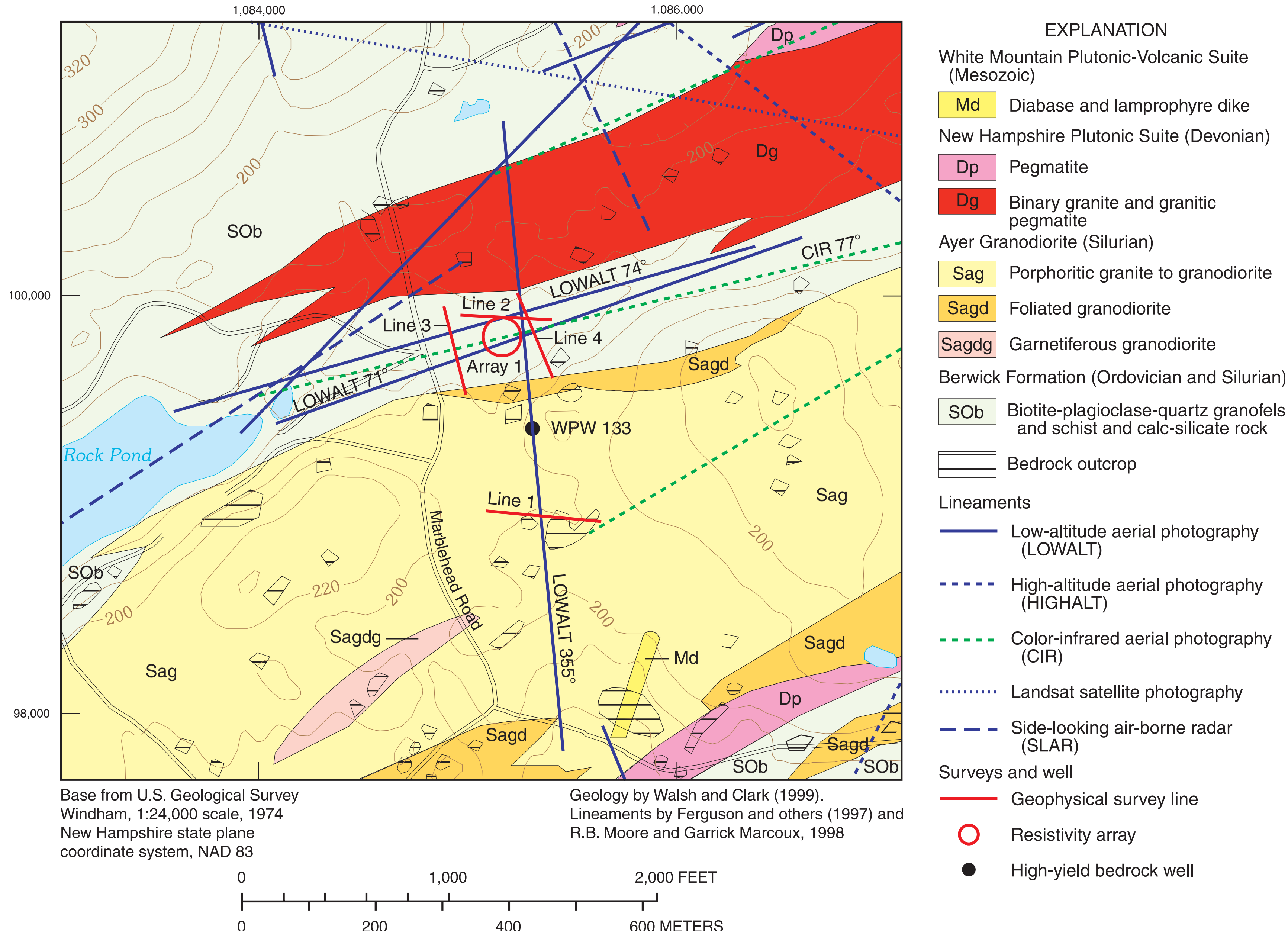

Figure 9. Geophysical survey locations, bedrock geology, and lineaments at site 2, Windham, NH. Site location is shown on figure 1.

an outcrop between line 3 and line 4 have a strike and dip of 70° and 19° dipping to the south, parting along foliation, and have a strike and dip of 67° and 35° dipping to the north.

Well WPW 133 (fig. 9) is drilled to a depth of 300 ft with a reported yield of 100 gal/min. Approximately 7 ft of overburden is present above the bedrock, and the static water level in the well is at 10 ft below landsurface. Probabilities of exceeding a yield of 40 gal/min from a 400-ft-deep well at this site ranged from 8 to 15 percent. A 14-percent probability is calculated for the 98.4-ft (30-m) square cell that well WPW 133 is in (R.B. Moore and others, U.S. Geological Survey, written commun., 2001). Variations in probability at the site most likely are caused by lithologic contacts and topography.

Four geophysical survey lines were located to bisect lineament locations on each side of well WPW 133 (fig. 9). Line 1 extends 570 ft from west to east and is on a trail in the woods to the south of WPW 133. It is on a topographic high with outcrops of the Ayer Granodiorite. Lines 2, 3, and 4 are in an east-west trending (70°) shallow valley. Logs from two monitoring wells reveal that the valley is filled by a 15-20-ft thick sequence of outwash and till. Line 2 extends 440 ft from west to east and is set in the woods, parallel to a monitoring-well access road to the north of well WPW 133. Line 3 is parallel to Marblehead Road, and extends 440 ft from north to south in a wooded area west of well WPW 133. Line 4 is parallel to line 3 in a wooded area to the east of well WPW 133, and extends 440 ft from north to south. An array center was chosen on the basis of availability of flat terrain and the location of anomalies from other techniques. The center of array 1 is at 200 ft along line 2, 90 ft to the south in the center of the valley (fig. 9).

Geophysical Surveys and Interpretation

Seven geophysical surveys were used to characterize site 2. Overburden thickness and physical properties were derived from results of seismic refraction, GPR, EM, and 2-D resistivity surveys. Bedrock characteristics and anomalies that could be caused by bedrock fractures are seen in the seismic refraction, GPR, magnetometer, VLF, EM, 2-D resistivity and square-array resistivity survey results (figs. 11-19).

Seismic-refraction data were collected along line 1 and line 2 and at 90° to each line. These data were examined only with respect to average seismic wave velocity in bedrock along each line, to look at variations in relation to orientation to a suspected fracture zone. Seismic refraction on line 1 was centered at 350 ft. The seismic velocity in the bedrock along line 1 is 11,500 ft/s, whereas the velocity normal to line 1 is 15,000 ft/s. Seismic refraction along line 2 is centered at 213 ft. The seismic velocity in bedrock along line 2 is 11,000 ft/s, and the velocity normal to line 2 is 9,500 ft/s.

GPR data were collected on lines 1, 2, 3, and 4; data from line 1 indicate features below the bedrock surface. A reflector below land surface from 0 to 160 ft along line 1 ends at a bedrock outcrop, which indicates that it is likely caused by the bedrock surface. A bedrock outcrop from 370 to 390 ft indicates that subhorizontal reflectors are below the bedrock surface from 375 to 500 ft along line 1. These reflectors are interpreted to be sheeting fractures (fig. 10).

Magnetometer measurements were made along all four lines at site 2 (figs. 11-14). The average magnetic field measure at this site during the surveys is 71 nT. Line 1 survey results indicate a magnetic low of 51 nT centered at 55 ft (fig. 11a). Data collected along line 4 indicate a magnetic low of 33 nT between 230-280 ft, and another low of 36 nT between 330-340 ft (fig. 14a).

VLF tilt-angle surveys at lines 1, 2, 3, and 4 indicate anomalies. Inflections along line 1 were detected at 70, 100, 140, 370, 405, and 430 ft (fig. 11b). Line 2 tilt-angle measurements have inflection points at 110, 240, 340, 380, and 415 ft (fig. 12b). Line 3 results indicate weak inflection anomalies at 255, 305, and 395 ft (fig. 13b). The VLF data from line 4 has a tilt-angle inflection point at 235 ft (fig. 14b).

EM surveys were collected on all lines at site 2. Along line 1, a VD anomaly at 380 ft indicates a near-vertical conductor (fig. 11c). Results of the VD survey from line 2 indicate a near-vertical conductor anomaly, possibly dipping east, at 180 ft (fig. 12c). Line 3 VD-survey results indicate a vertical conductor anomaly centered at 220 ft (fig. 13c). The results from survey line 4 indicate the bedrock is more conductive in the north than in the south (fig. 14c). The dip of features on lines 1-4 were not readily apparent from the EM data.

2-D resistivity was measured at lines 1, 2, 3, and 4. Models were created to verify interpretations of the data. A near-vertical fracture on line 1 is interpreted at 110 ft and an eastward-dipping fracture is interpreted as intersecting the bedrock surface at 345 ft (fig. 15).

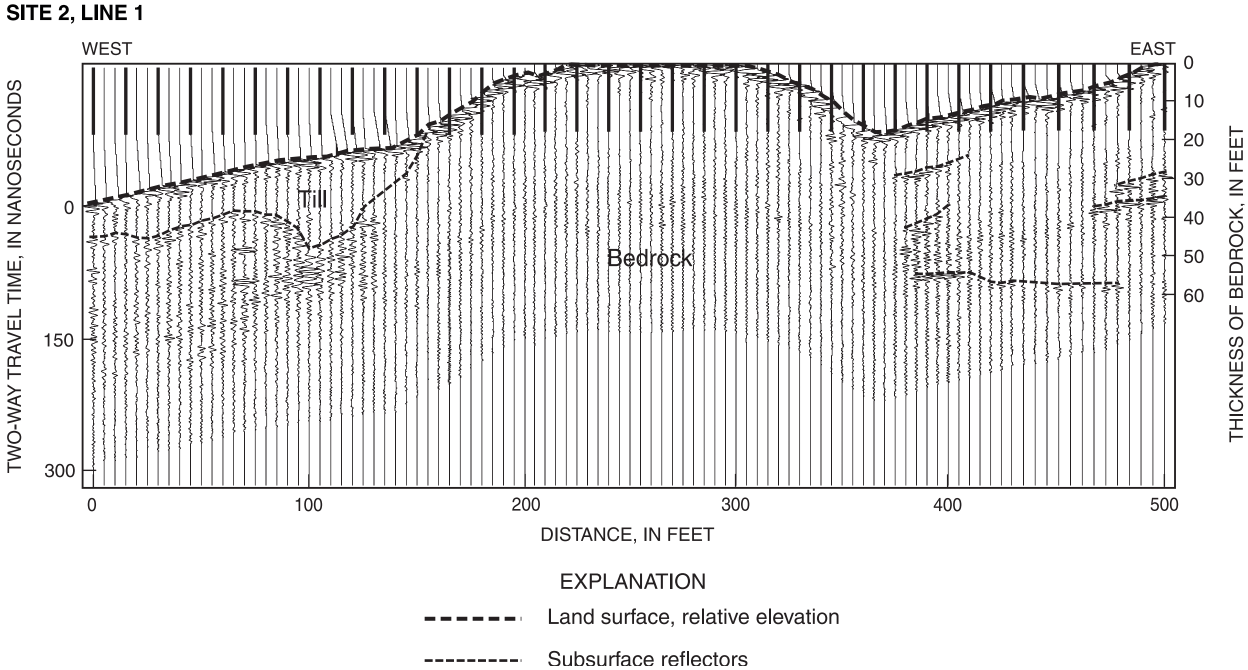

Figure 10. Processed ground-penetrating radar profile at site 2 from line 1, Windham, N.H. Site and line locations are shown on figures 1 and 9, respectively

Near-horizontal conductive features also can be interpreted from the dipole-dipole array at 345-450 ft that were not modeled (fig. 15a). A horizontal conductor at depth from 0 to 440 ft also was interpreted based on the Schlumberger array (fig. 15b). The model, created to check interpretations of the data from line 2 (fig. 16), displays the effect of fractures intersecting from different orientations. Based on the results from lines 3, 4, array 1, and lineament data, a fracture zone with a strike close to the strike of line 2 intersects the line from 190 to 440 ft. A conductive zone striking roughly perpendicular to line 2 intersects the bedrock surface at 110 ft along the line (fig. 16). Interpretations of line 3 indicate a fracture zone dipping to the south, and intersecting the surface of the bedrock at 200 ft (fig. 17). For line 4, a conductive south-dipping feature intersects the bedrock surface at 150 ft along the line (fig. 18).

Square-array resistivity data were collected at array 1. The primary conductive strike determined graphically is 75× with a range of 60× to 105× at the largest A-spacing of 20 m (fig. 19). Increases in resistivity from the 5-m A-spacing through the 20-m A-spacing indicate a two layer model; conductive overburden and resistive bedrock (fig. 19).

Integration of Results

Line 1 at site 2 (fig. 11) has two locations containing anomalies from multiple techniques. 2-D resistivity and VLF anomalies indicative of conductive features in bedrock were found between 100 and 115 ft along the line. EM, VLF, and 2-D resistivity anomalies indicative of conductive features in bedrock are between 350 and 375 ft along line 1, whereas 2-D resistivity data indicate an eastward dip. Near-horizontal fractures begin in the GPR record at 375 ft and extend to at least 500 ft. The seismic-refraction velocity of bedrock parallel to line 1 is approximately 3,500 ft/s slower than the velocity normal to line 1 centered at 350 ft. This decrease in velocity is consis-tent with dominant fracture trends near parallel to the low-altitude lineament (fig. 9), striking roughly towards line 2 and the well.

The line 2 survey is near-parallel to a suspected fracture zone, which bisects line 3 and line 4 intersecting line 2 at 270 ft. Interpretation of the data is difficult because line 2 may cross two bedrock-fracture zones at different orientations. EM and 2-D resistivity anomalies indicative of conductive features in bedrock are roughly normal to the line at 180 ft. 2-D resistivity indicated a possible eastward dip to the

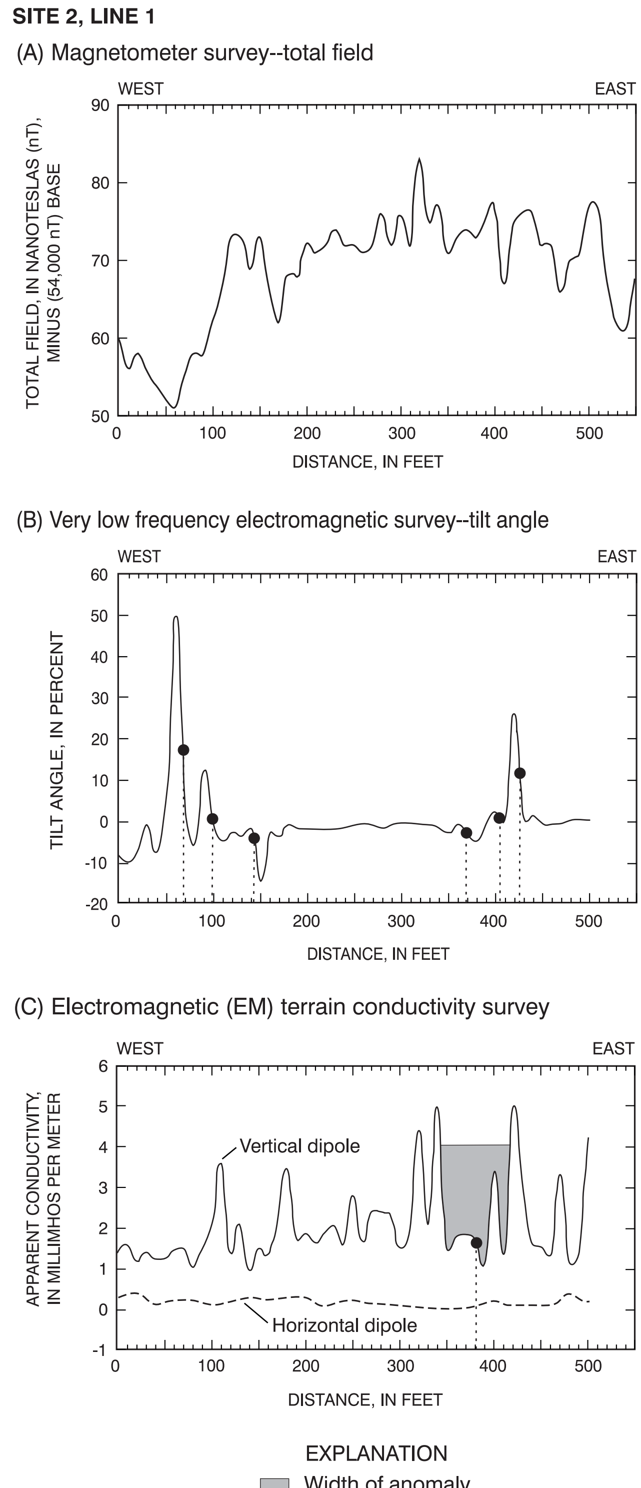

Figure 11. Magnetic and electromagnetic surveys at site 2 from line 1, Windham, N.H. (A) magnetometer survey; (B) very low frequency (VLF) electromagnetic survey; (C) electromagnetic (EM) terrain conductivity survey with a 20-meter (65.6-foot) coil spacing. Site and line locations are shown on figures 1 and 9, respectively.

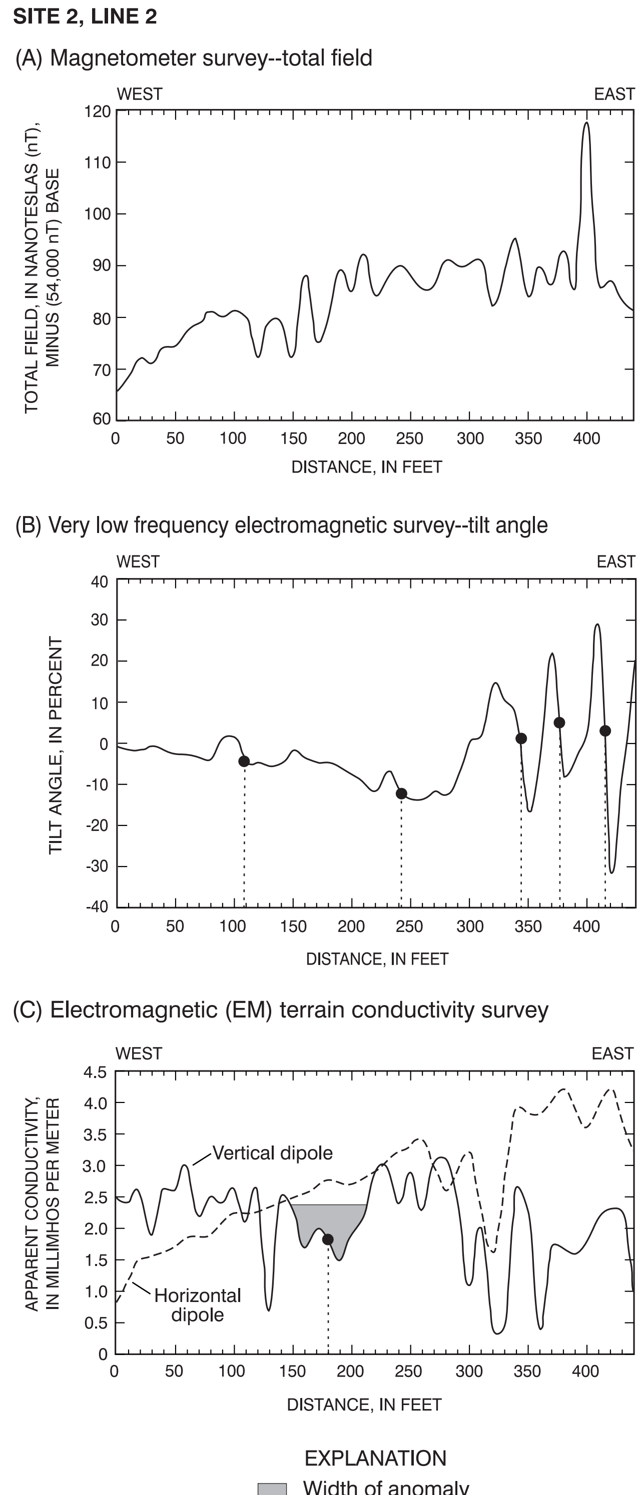

Figure 12. Magnetic and electromagnetic surveys at site 2 from line 2, Windham, N.H. (A) magnetometer survey; (B) very low frequency (VLF) electromagnetic survey; (C) electromagnetic (EM) terrain conductivity survey with a 20-meter (65.6-foot) coil spacing. Site and line locations are shown on figures 1 and 9, respectively.

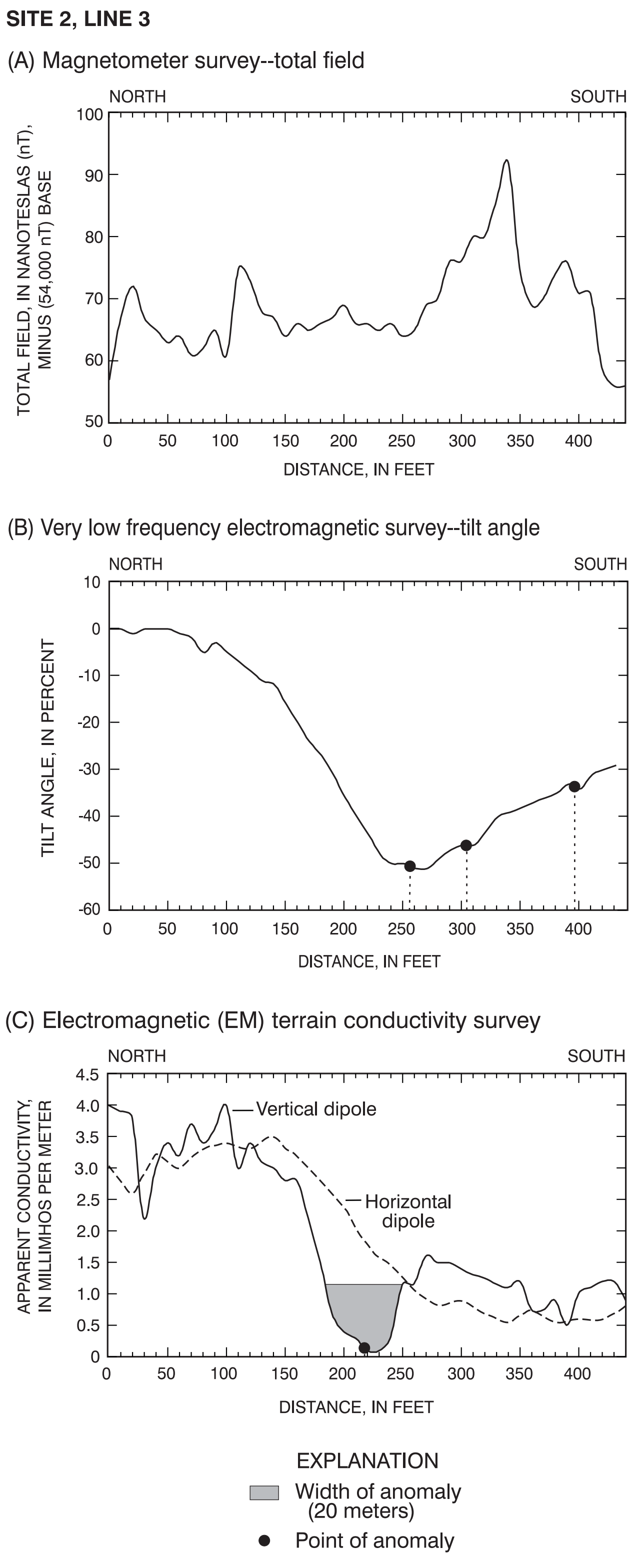

Figure 13. Magnetic and electromagnetic surveys at site 2 from line 3, Windham, N.H. (A) magnetometer survey; (B) very low frequency (VLF) electromagnetic survey; (C) electromagnetic (EM) terrain conductivity survey with a 20-meter (65.6-foot) coil spacing. Site and line locations are shown on figures 1 and 9, respectively.

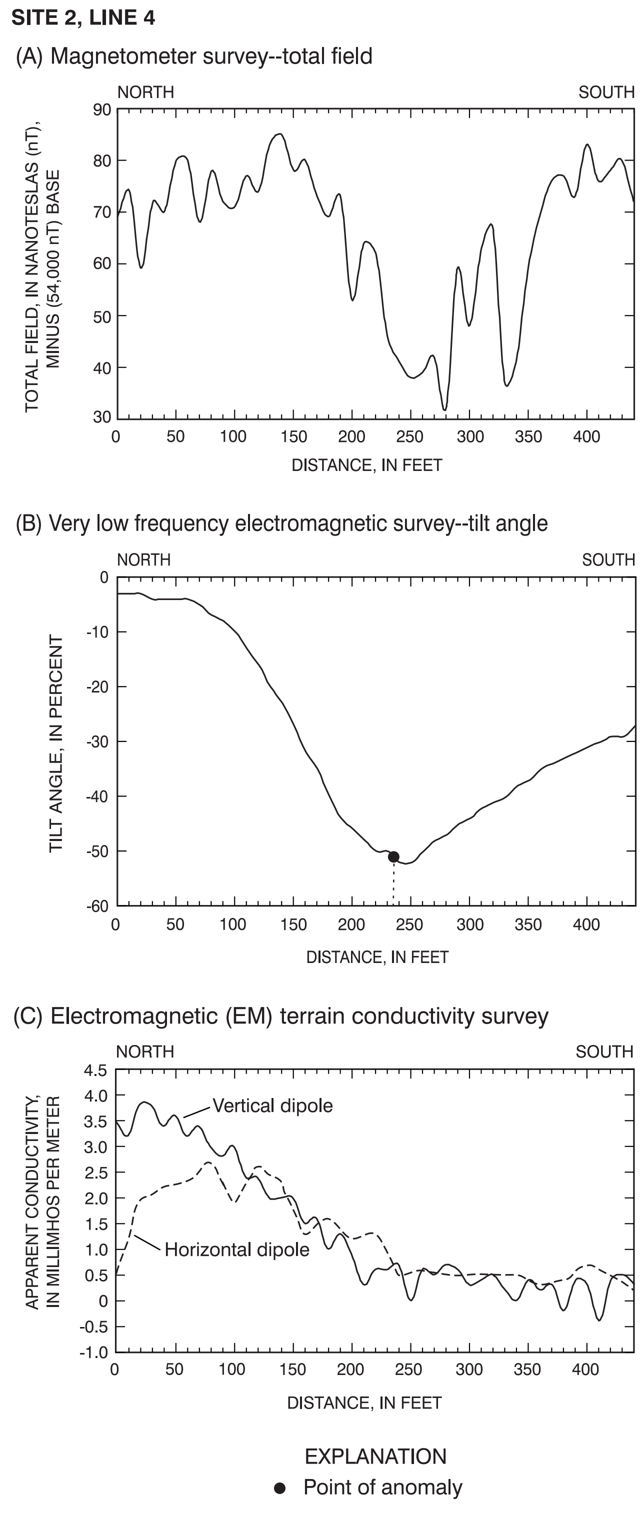

Figure 14. Magnetic and electromagnetic surveys at site 2 from line 4, Windham, N.H. (A) magnetometer survey; (B) very low frequency (VLF) electromagnetic survey; (C) electromagnetic (EM) terrain conductivity survey with a 20-meter (65.6-foot) coil spacing. Site and line locations are shown on figures 1 and 9, respectively.

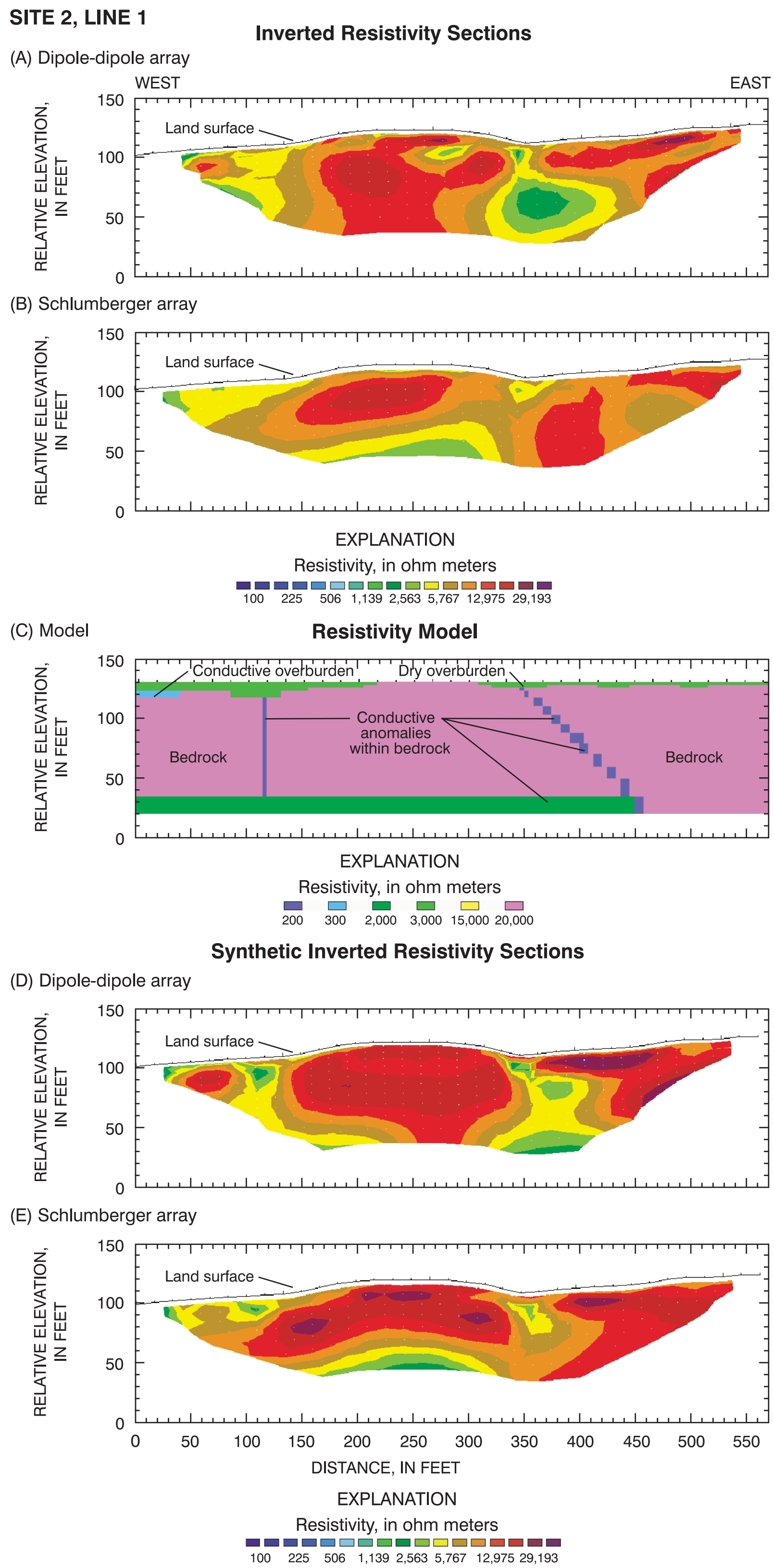

Figure 15. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 2 from line 1, Windham, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 9, respectively.

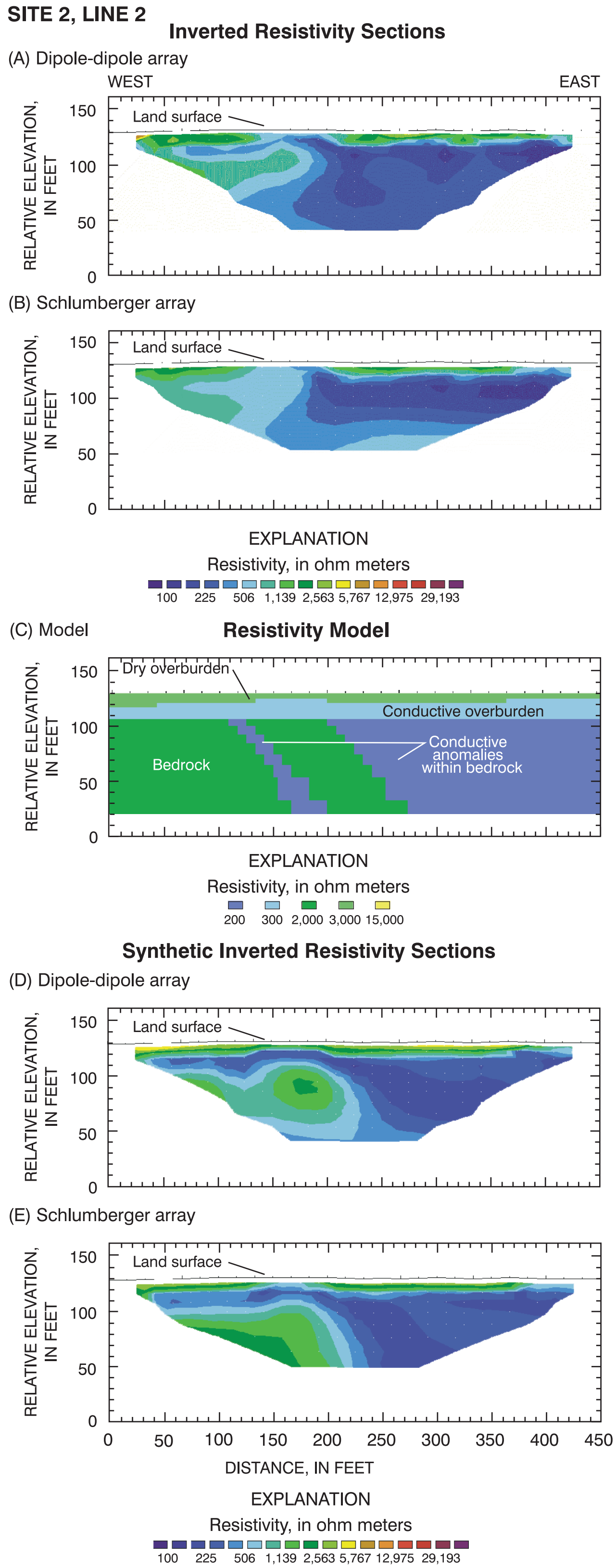

Figure 16. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 2 from line 2, Windham, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 9, respectively.

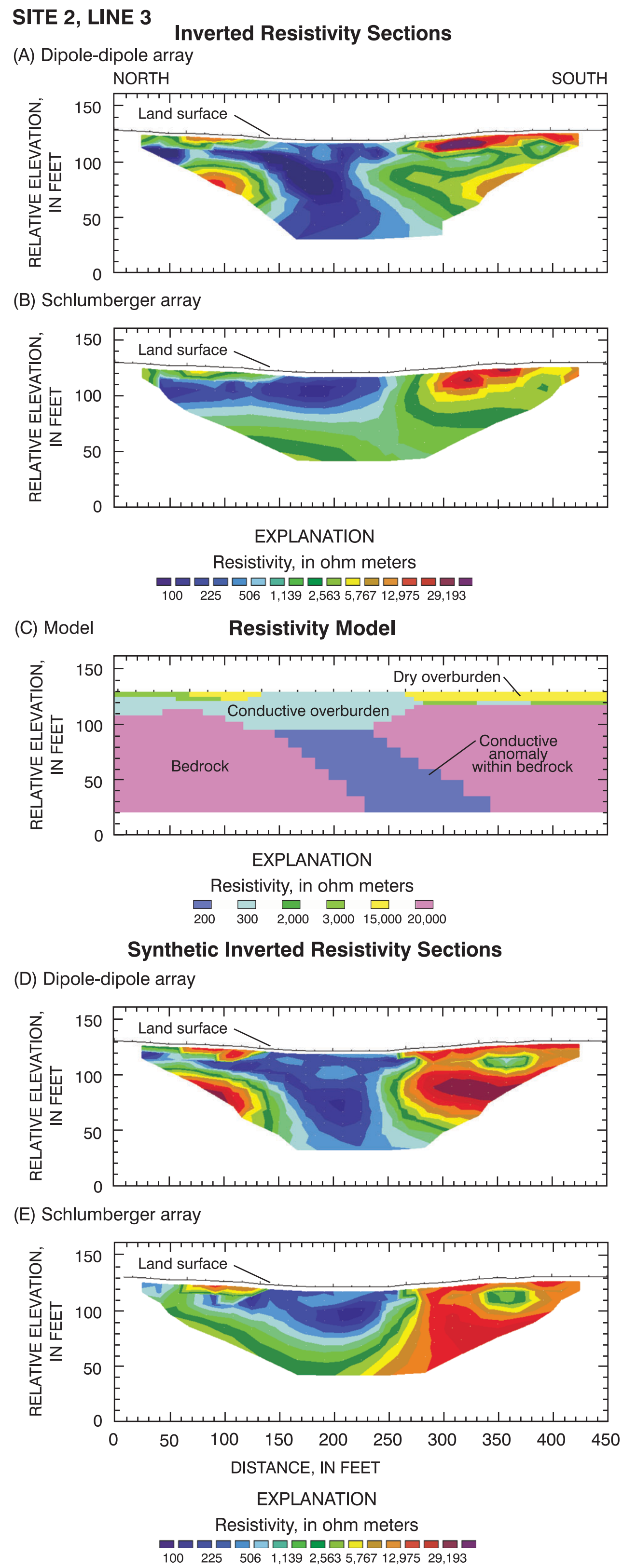

Figure 17. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 2 from line 3, Windham, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 9, respectively.

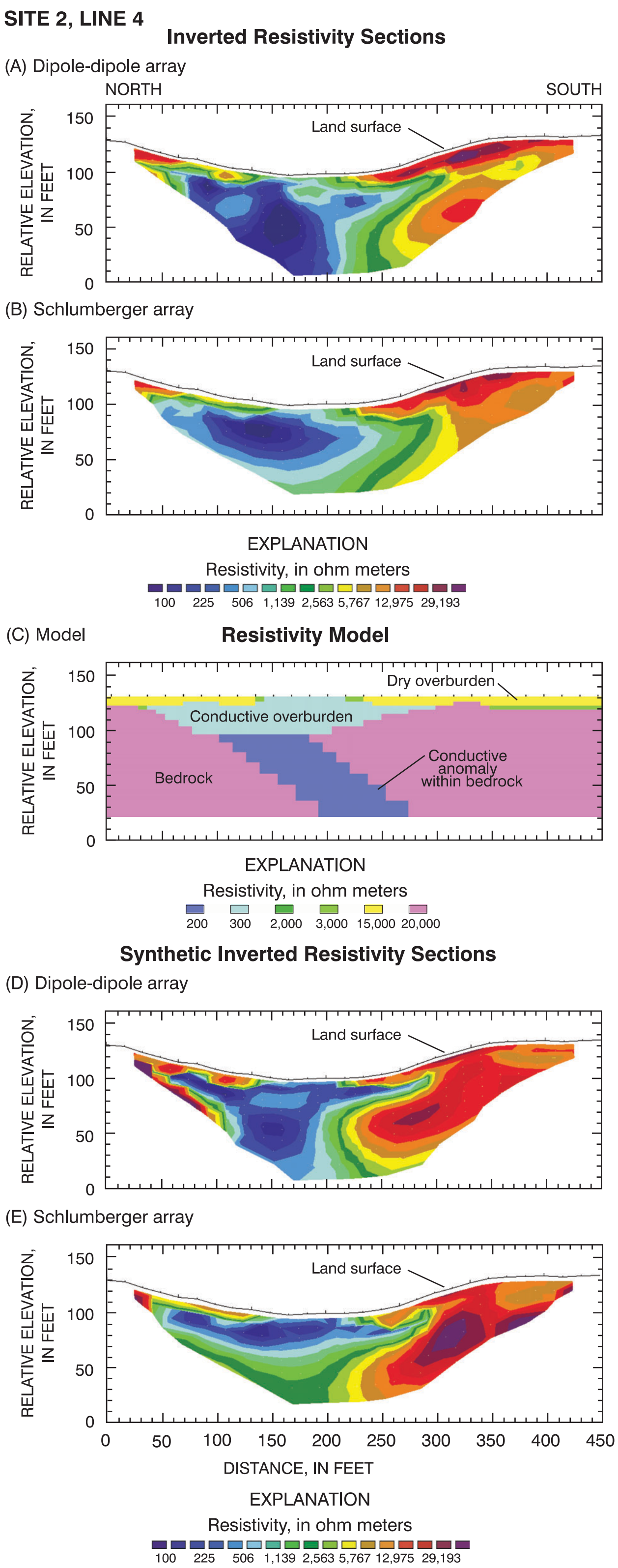

Figure 18. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 2 from line 4, Windham, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 9, respectively.

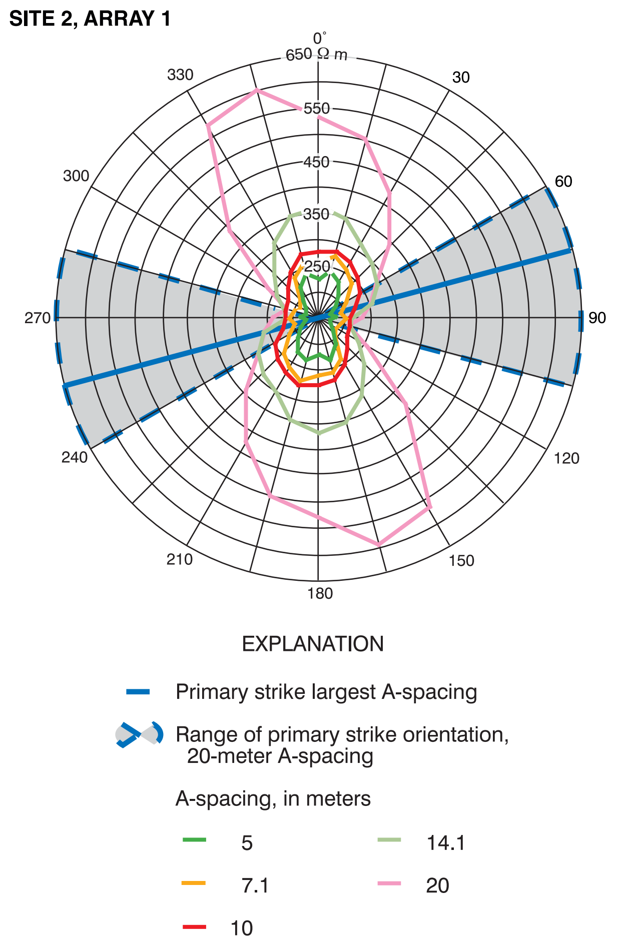

Figure 19. Polar plot showing azimuthal square-array direct-current resistivity at site 2 for array 1, Windham, N.H. Apparent resistivity in ohm meters (Ω m), is plotted as a function of azimuth, in degrees east of true north, and resistivity center is at 150 Ω m. Site and array locations are shown on figures 1 and 9, respectively.

line 2 anomaly. The seismic-refraction velocity of bedrock along line 2 is approximately 1,500 ft/s faster than the velocity normal to line 2, which indicates that the dominant fracture trend is nearly parallel to line 2.

Line 3 has a steeply dipping conductive 2-D resistivity anomaly (fig. 17) that correlates with the location of an EM anomaly indicative of a conductive feature in bedrock (fig. 13b). Line 4 has a steeply dipping conductive 2-D resistivity anomaly (fig. 18) that correlates with the location of a VLF anomaly, indicative of a conductive feature in bedrock (fig. 14). A magnetic low identified along line 4 coincides with the deep, down-dip portion of the 2-D resistivity feature. The anomalies bisecting line 3 and line 4 appear to be the same continuous feature based on the primary conductive strike from the square-array resistivity and the location and orientation of lineaments.