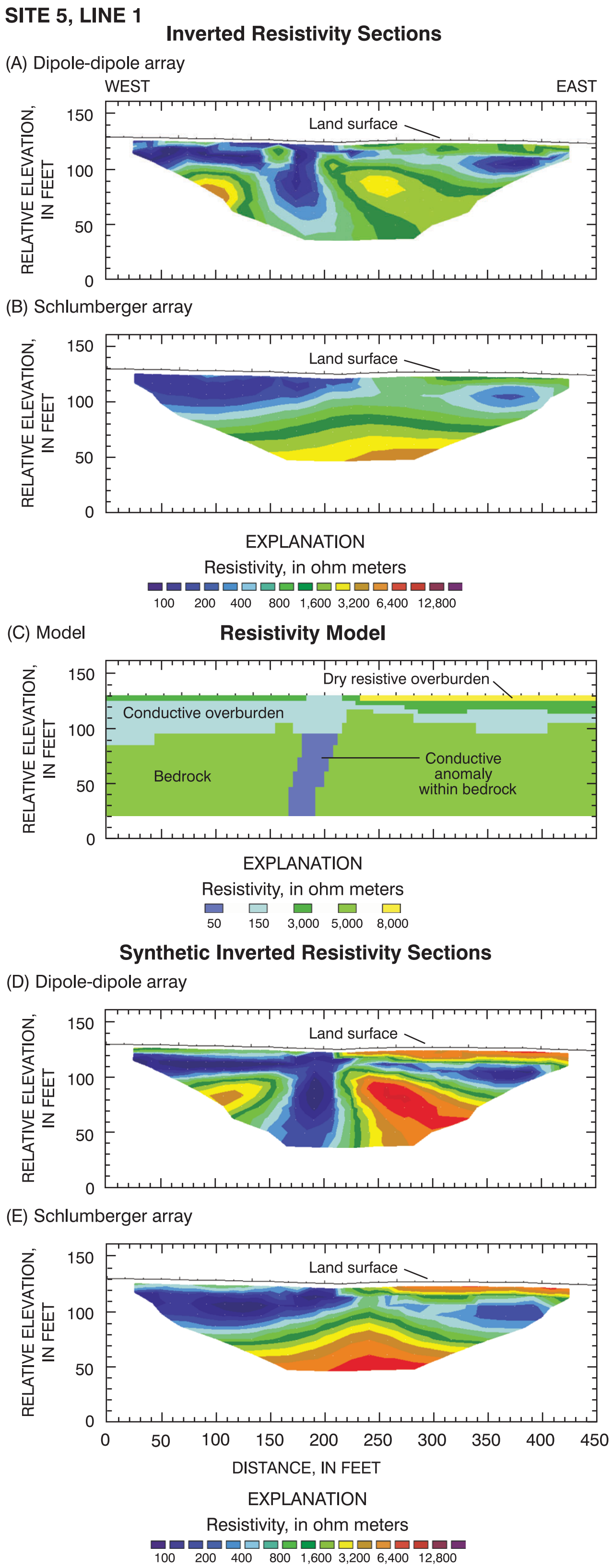

Figure 36. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 5 from line 1, Goffstown, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 33, respectively.

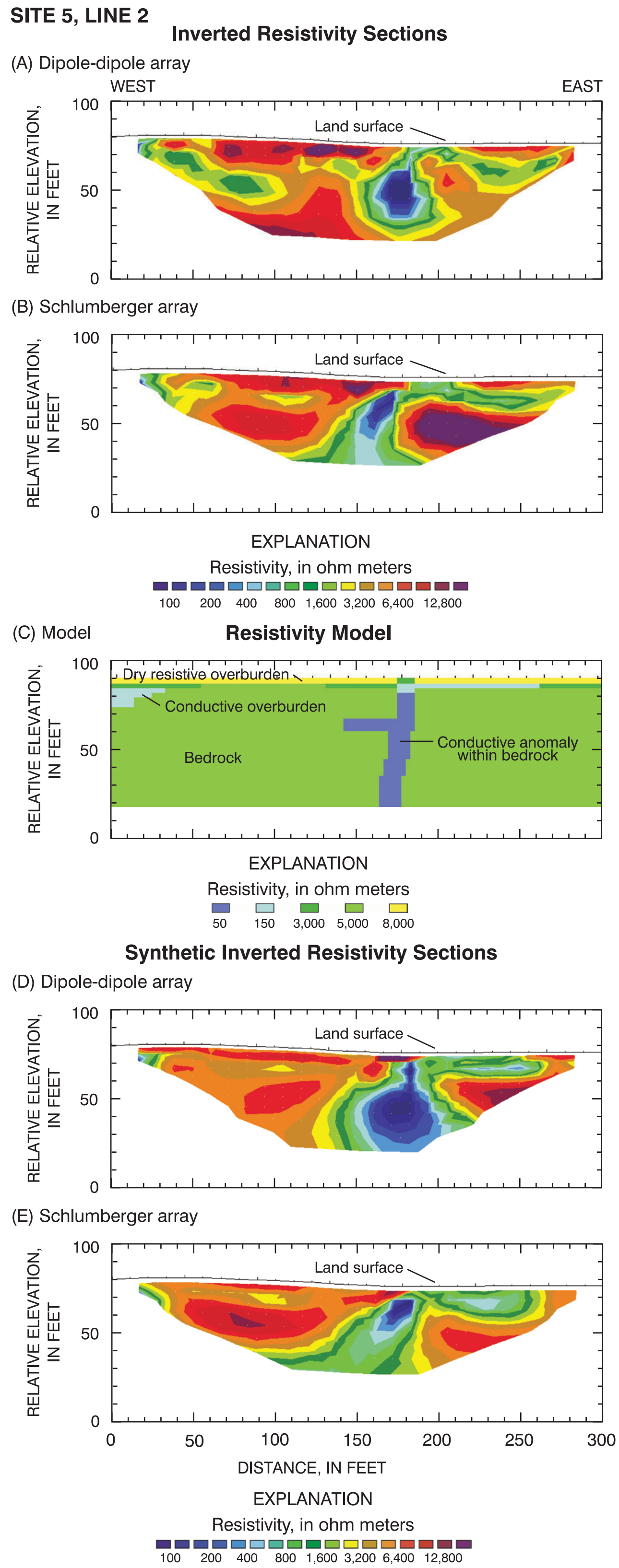

Figure 37. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 5 from line 2, Goffstown, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 33, respectively.

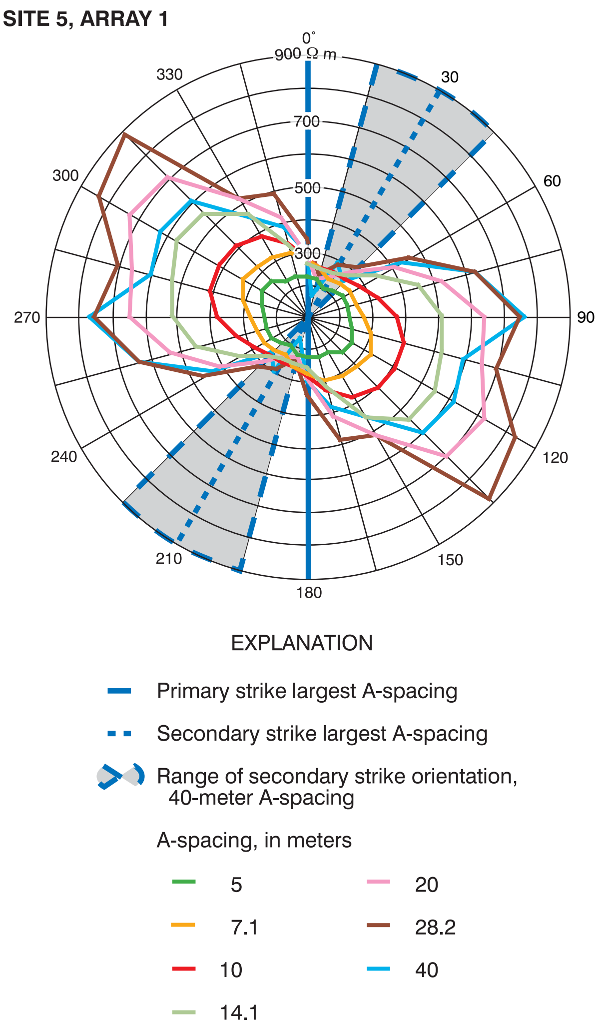

Figure 38. Polar plot showing azimuthal square-array direct-current resistivity at site 5 for array 1, Goffstown, N.H. Apparent resistivity in ohm meters (Ωm), is plotted as a function of azimuth, in degrees east of true north, and resistivity center is at 100 Ωm. Site and array locations are shown on figures 1 and 33, respectively.

geology of this area as the Berwick Formation of the Merrimack Group. Mapped lineaments at the site were observed from LOWALT and HIGHALT platforms (Ferguson and others 1997), trending 44° and 353°, respectively (fig. 40). Fracture data inside a 4,000-ft radius of the site has three peak orientations: 37°±6° (100 percent, normalized height), 294°±7° (67 percent, normalized height), and 278°±4° (50 percent, normalized height). The closest fracture measured in outcrop is more than 3,000 ft away.

Well SAW 207 was drilled to a depth of 533 ft at site 6 (fig. 40) and has a reported yield of 630 gal/min. The depth to bedrock at well SAW 207 is approximately 18 ft. A nearby test well SAW 272 was available for borehole-geophysical surveys. Well SAW 272 was drilled through 17 ft of overburden to a depth of 345 ft in bedrock and has a reported yield of 150 gal/min. Sediment accumulation or rock fragments at the bottom of the well SAW 272 likely account for the borehole tools being unable to reach a depth greater than 335 ft. Three geophysical survey lines bisected lineaments (fig. 40). All of the lines are to the south of the wells in the open field. Line 1 extends 750 ft from northwest to southeast. Line 2 extends 440 ft from northwest to southeast. Line 3 extends 440 ft from west to east. Array 1 was centered between the western ends of lines 2 and 3 (fig. 40).

Geophysical Surveys and Interpretation

Six surface and six borehole geophysical surveys were used to characterize site 6. Overburden thickness and physical properties were derived from GPR, EM, and 2-D resistivity survey results. Seismic-refraction, EM, 2-D resistivity, and square-array resistivity surveys were used to determine bedrock properties. Anomalies that could be caused by bedrock fractures are seen in the VLF, EM, 2-D resistivity and square-array resistivity survey results. Caliper, fluid temperature and resistivity, and EM borehole logs were used to characterize and help identify bedrock fractures measured in the OTV logs.

Seismic-refraction modeling was used to identify a bedrock seismic velocity of 9,800 ft/s parallel to line 1 (K.J. Ellefsen, U.S. Geological Survey, written commun. 1997). This velocity is just

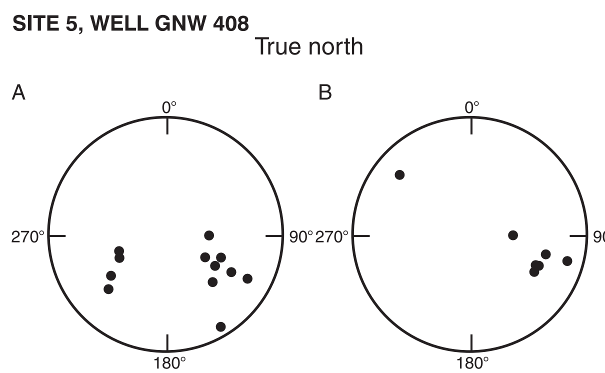

Figure 39. Lower hemisphere equal-area nets from bedrock well GNW 408 at site 5, Goffstown, N.H., showing (A) borehole fractures and (B) borehole contacts and foliation. Site and well locations are shown on figures 1 and 33, respectively.

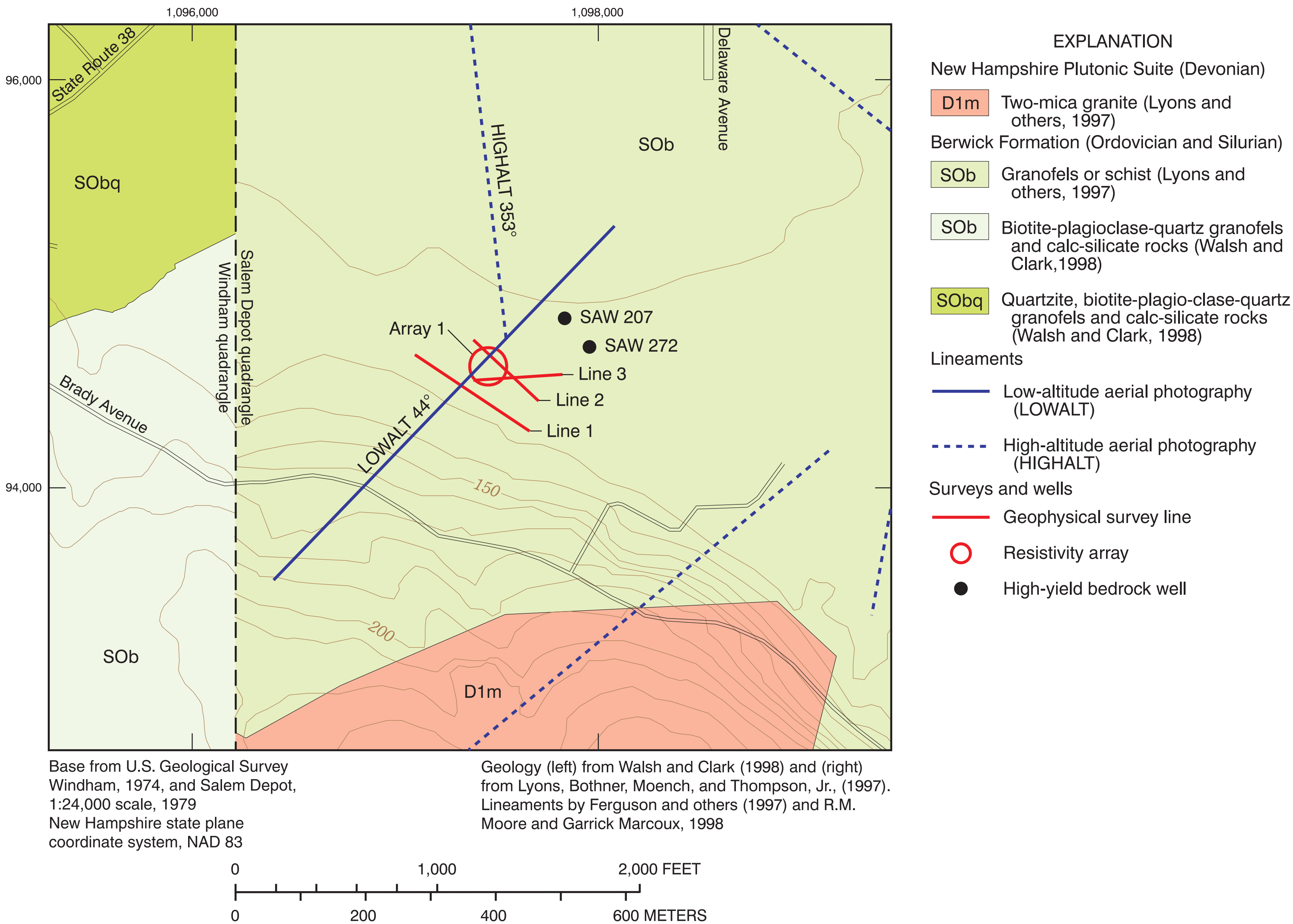

Figure 40. Geophysical survey locations, bedrock geology, and lineaments at site 6, Salem, N.H. Site location is shown on figure 1.

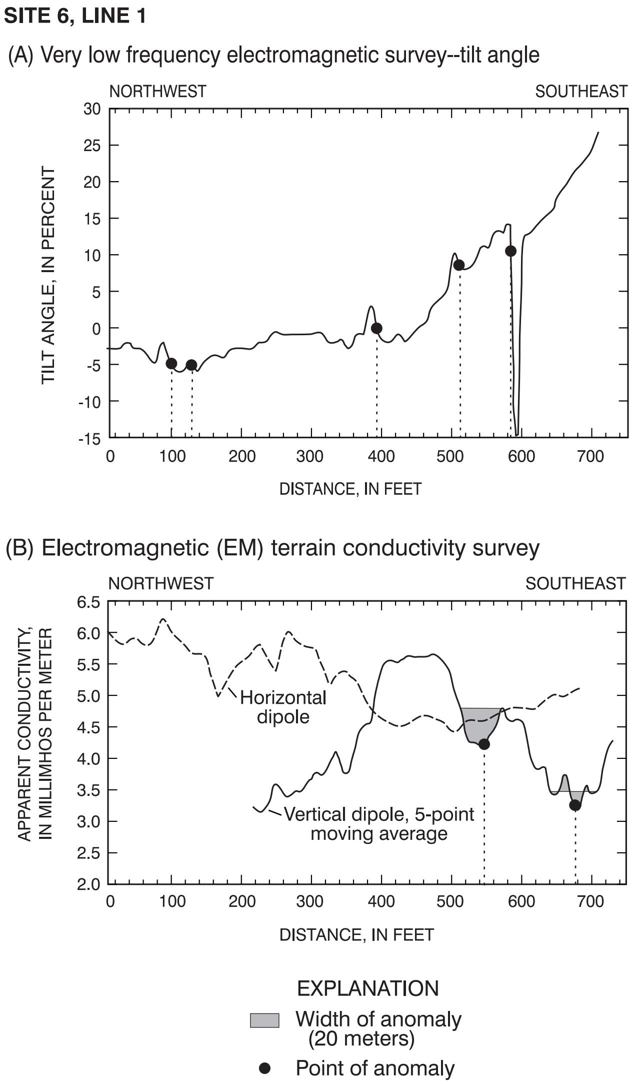

Figure 41. Electromagnetic surveys at site 6 from line 1, Salem, N.H. (A) very low frequency (VLF) electromagnetic survey; (B) electromagnetic (EM) terrain conductivity survey with a 20-meter (65.6-foot) coil spacing. Site and line locations are shown on figures 1 and 40, respectively.

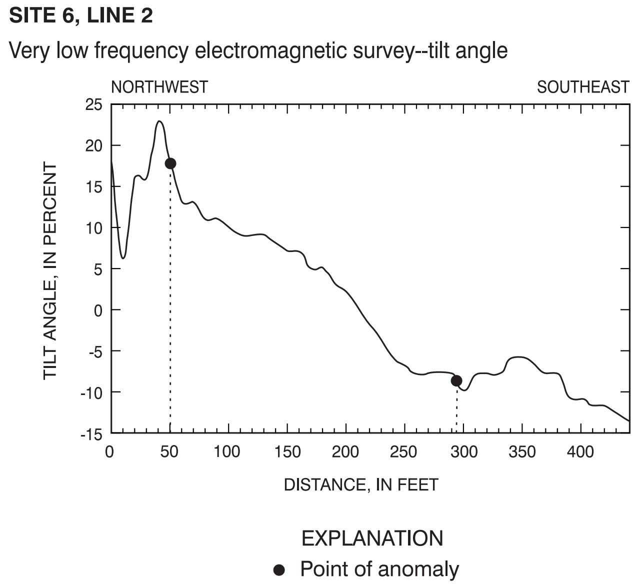

Figure 42. Very low frequency (VLF) electromagnetic survey at site 6 from line 2, Salem, N.H. Site and line locations are shown on figures 1 and 40, respectively.

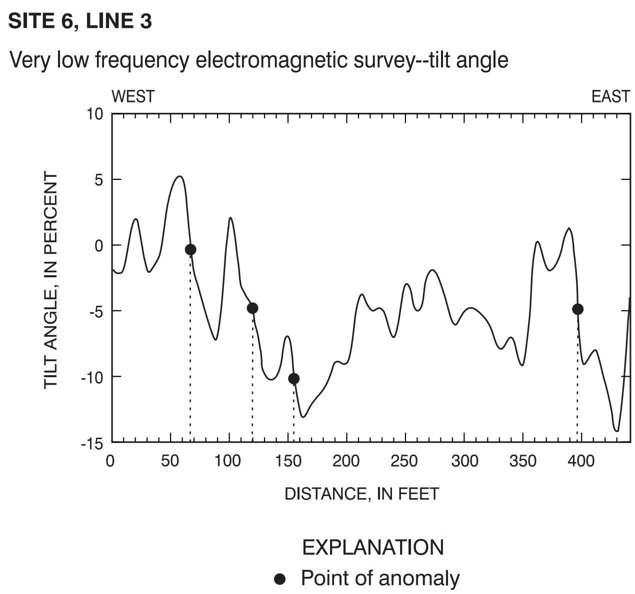

Figure 43. Very low frequency (VLF) electromagnetic survey at site 6 from line 3, Salem, N.H. Site and line locations are shown on figures 1 and 40, respectively.

below the low end of the range of bedrock velocities (10,000 to 20,000 ft/s) typically found in New Hampshire (Medalie and Moore, 1995). A low trough in the bedrock was noted beneath the LOWALT lineament.

GPR was collected on all lines at site 6. Lines 2 and 3 were collected using a continuous profile method, line 1 was collected using the point-survey method. Reflectors were identified in the overburden but the signal was attenuated before reaching bedrock.

VLF tilt-angle surveys were made at all lines (figs. 41-43). Line 1 has inflections at 100, 130, 395, 515, and 580 ft (fig. 41a). Line 2 tilt-angle results indicated inflection anomalies at 50 and 295 ft (fig. 42). Inflection anomalies are at 65, 120, 155, and 395 ft (fig. 43) from the survey of line 3.

EM surveys were collected along line 1 (fig. 41b). Vertical-conductor anomalies with the VD survey results were at 545 and 675 ft.

2-D resistivity surveys were used to characterize lines 1, 2, and 3. Models were created to support interpretations of the data. Resistivity data from line 1, 2, and 3 indicate three resistivity units: thin resistive unsaturated zone, conductive saturated zone, and resistive bedrock. Line 1 also has a fourth resistivity unit interpreted as fractured bedrock. Below the interpreted bedrock surface, at about 270 ft along the line, is a conductive anomaly with an apparent dip to the southeast (fig. 44). Line 2 data indicates a topographic high in the bedrock surface at 230 ft along the line (fig. 45). Anomalies in the bedrock were not identified with survey results from line 2 or 3 (fig. 46), only changes in the elevation of the bedrock surface were identified, with the bedrock being the deepest at the west end of line 3.

Square-array resistivity data were collected at array 1. Surveys were made with A-spacings of 5-20 m. Resistivity data from array 1 has a primary conductive strike of 75° when surveyed with the largest A-spacing (20 m). The secondary strike from array 1 at the 20-m A-spacing is 300° with a range of 285° to 330° (fig. 47).

Caliper, fluid temperature, fluid resistivity, and EM conductivity logs for well SAW 272 were used to identify and confirm fracture zones indicated on the OTV logs (appendix 1C). A cluster of fractures were identified on the lower hemisphere equal area net that have a range of strikes and dips of 201-211° and 46-85°, dipping NW (fig. 48). A group of contacts and foliation trends were identified, which have a range of strikes and dips of 191-229° and 38-78°, dipping NW. Fractures in the group fall within the range of strikes for the group of contacts and foliations. There also were widely scattered fractures and contacts and foliation outside of the identified groups (fig. 48). The largest fracture zone, at 264.5 ft, was identified as transmissive with fluid-temperature and resistivity logs from ambient and pumping borehole conditions. Caliper and EM logs correlate with this fracture zone, which was observed in the OTV log on a contact, with a strike and dip of 240° and 64°.

Integration of Results

2-D resistivity results from line 1 indicate a prominent conductive east-dipping feature in the bedrock at 270 ft; however, results form lines 2 and 3 did not indicate major anomalies. Locations of anomalous results from different surface-geophysical methods could not be correlated at this site. The closest anomalies using VLF and EM were 35 ft apart on line 1 at 545 and 580 ft along the line. Thick, saturated overburden may obscure the VLF and EM survey results at this site.

Conductive strikes from square-array resistivity results that have the same orientation as fractures identified in outcrop, or remotely sensed lineaments, likely are related to fracture zones. The strike of the 20-m A-spacing secondary anomaly from array 1 (300°) has the same orientation as a fracture peak in the mapped geologic data at this site striking 294°±7° (67 percent, normalized height). The LOWALT lineament at the site with an orientation of 44° is just outside the error range for the maximum fracture peak at 37°, with a ±6° error range.

Borehole surveys from well SAW 272 show that the strikes and dips (average, 206° and 60°) of a group of fractures are generally coincident with a group of foliation and contacts (average 214° and 62°). The largest transmissive fracture zone characterized in the borehole data, (at a depth of 264.5 ft), dips towards, and if projected, would intersect well SAW 207 and may contribute to its yield. This fracture, which is coincident with a contact, is within 7.5° of the orientation of the primary strike from the square-array resistivity survey.

Although the locations of anomalies detected by electromagnetic (EM and VLF) surveys do not correlate spacially at site 6, they do indicate fractured bedrock. The lack of agreement between techniques may be caused by thick conductive overburden obscuring bedrock signatures. Because the overburden covering bedrock is thick, the geologic data used at this site may represent more regional rather than site specific conditions. DC-resistivity surveys and arrays and borehole data more clearly indicate fractured bedrock than other geophysical surveys at site 6 in Salem.

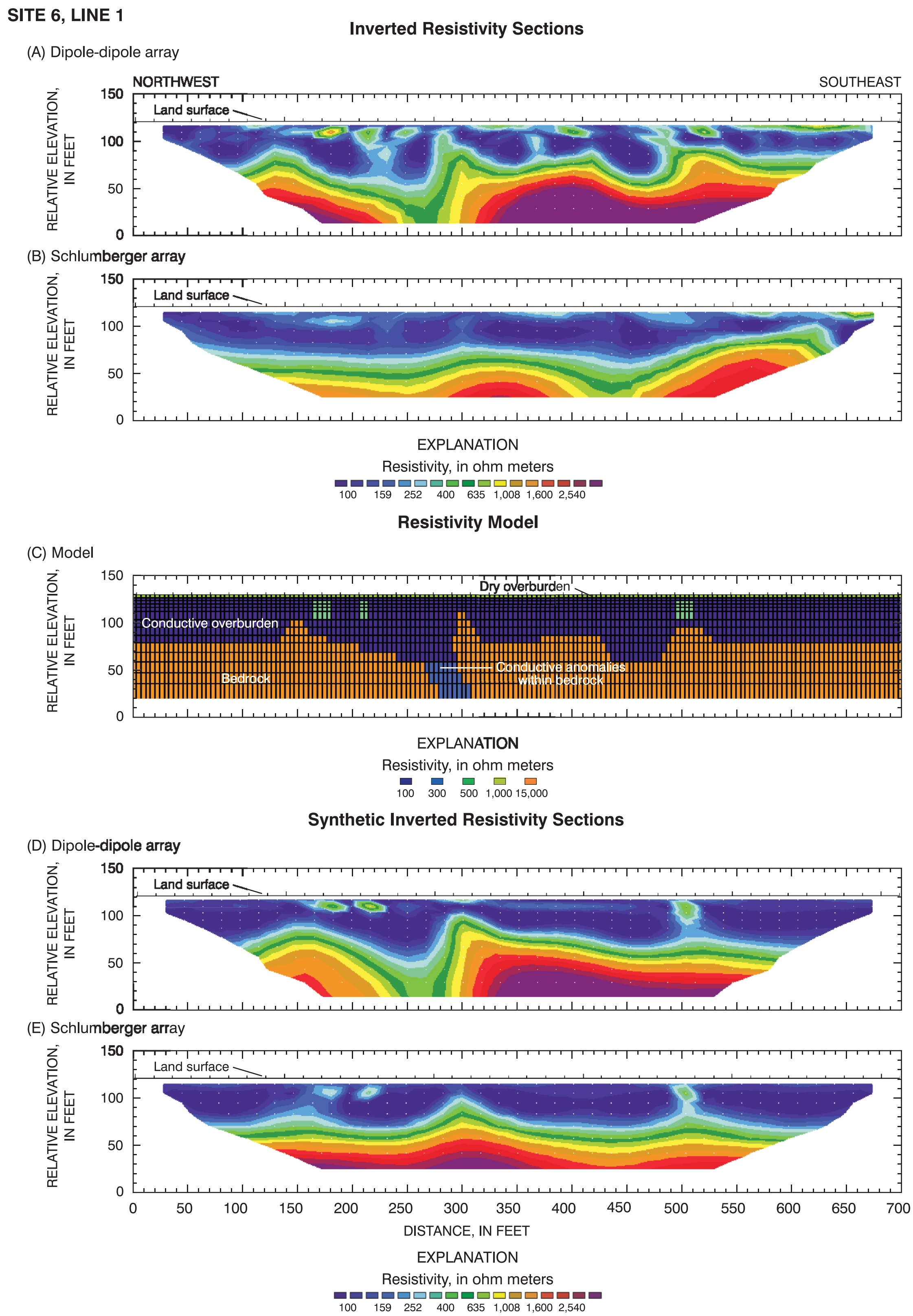

Figure 44. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 6 from line 1, Salem, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 40, respectively.

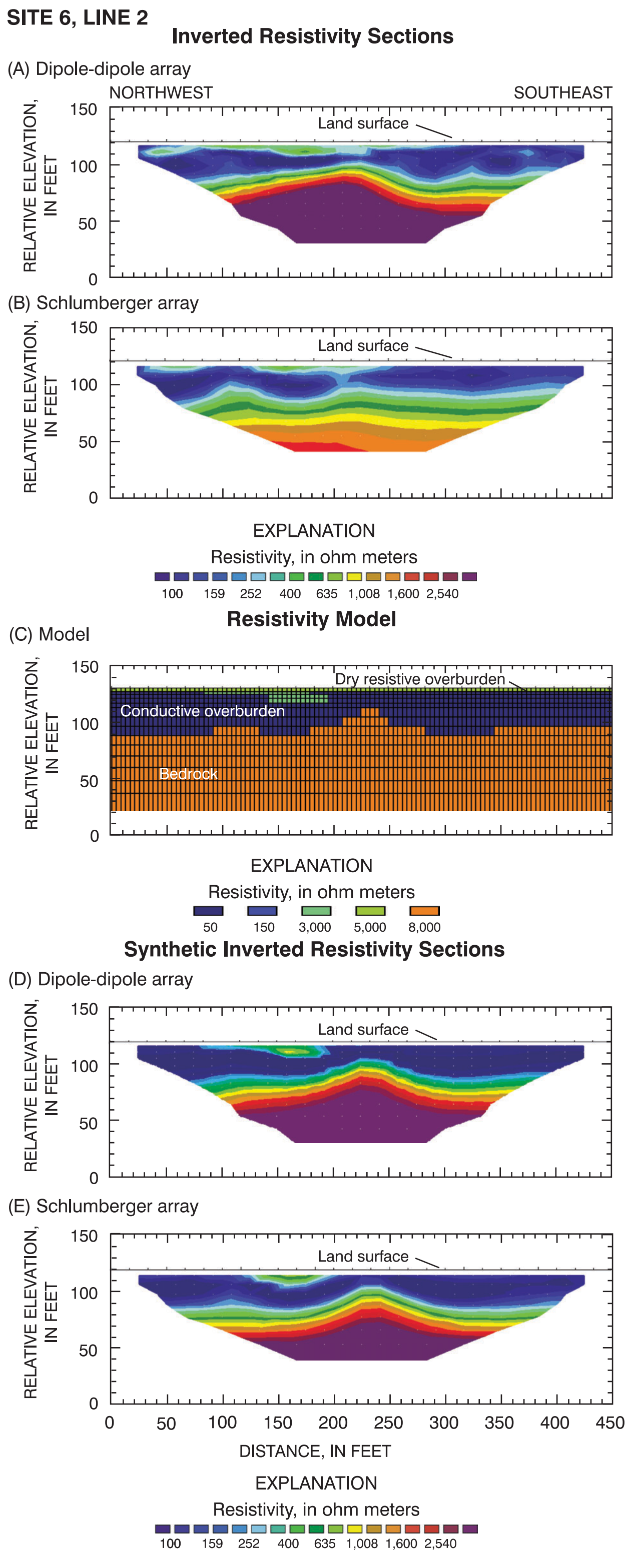

Figure 45. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 6 from line 2, Salem, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 40, respectively.

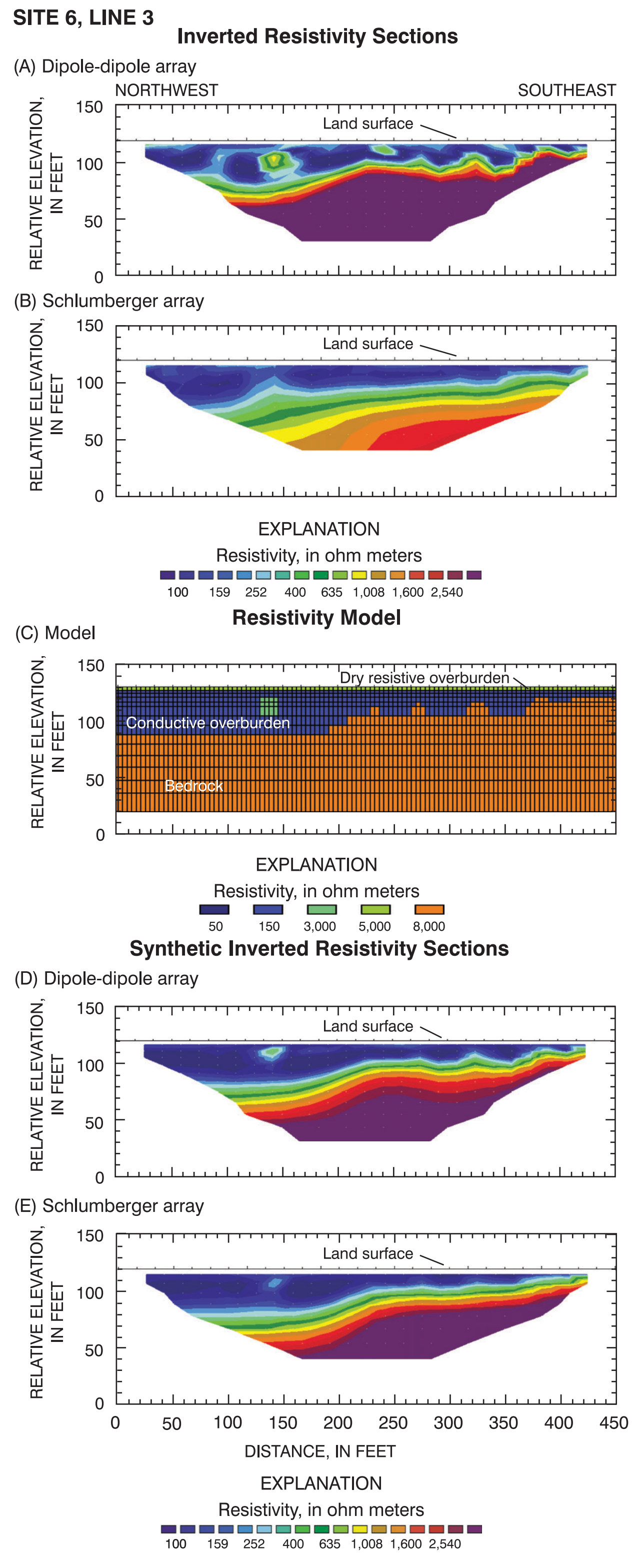

Figure 46. Cross sections showing (A and B) inverted resistivity sections of two-dimensional, direct-current resistivity data at site 6 from line 3, Salem, N.H.; (C) model based on field data from A and B; and (D and E) synthetic resistivity output data from Model C. Site and line locations are shown on figures 1 and 40, respectively.

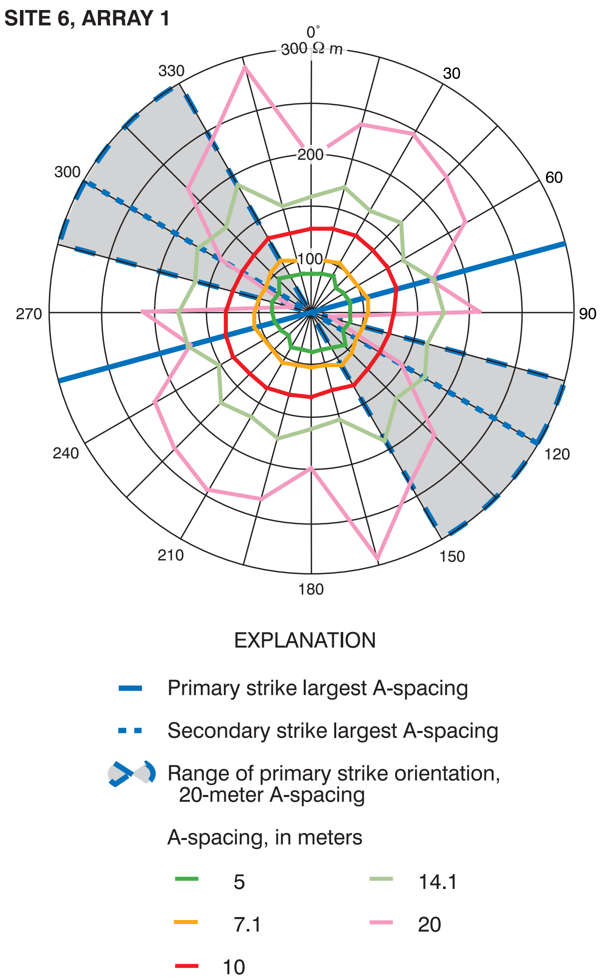

Figure 47. Polar plot showing azimuthal square-array direct-current resistivity at site 6 for array 1, Salem, N.H. Apparent resistivity in ohm meters (Ω m), is plotted as a function of azimuth, in degrees east of true north, and resistivity center is at 50 Ω m. Site and array locations are shown on figures 1 and 40, respectively.

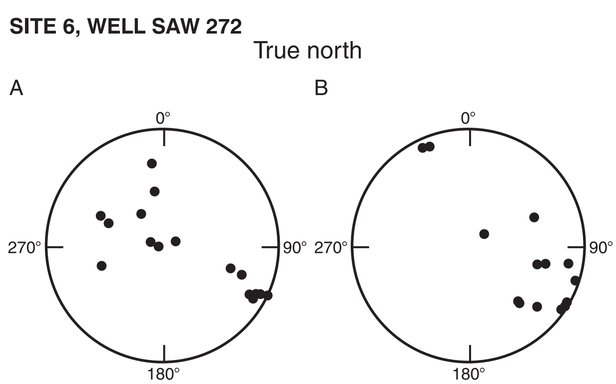

Figure 48. Lower hemisphere equal-area nets from bedrock well SAW 272 at site 6, Salem, N.H., showing (A) borehole fractures and (B) borehole contacts and foliation. Site and well locations are shown on figures 1 and 40, respectively.

SUMMARY AND CONCLUSIONS

Bedrock aquifer ground-water resources in New Hampshire have been assessed statewide by the U.S. Geological Survey, in cooperation with the New Hampshire Department of Environmental Services, to identify areas that are favorable for more intensive investigation. This study identified site-specific anomalies in geophysical-survey results from sites 1, 4, and 5 in the Pinardville 7.5-minute quadrangle, and sites 2, 3, and 6 in the Windham 7.5-minute quadrangle that indicate the location of bedrock-fracture zones that are potentially water bearing.

At four of the sites, geophysical anomalies were closely correlated with geologic-fracture data and lineament locations and orientations. High-yielding bedrock wells at all of the sites indicate highly transmissive fracture zones in those areas. Surface-geophysical methods used in this study were able to identify the locations of fracture zones at these sites.

Seismic-refraction and ground-penetrating radar were used primarily to characterize the overburden, and provided limited bedrock characteristics. At some site locations, velocities of seismic waves through bedrock indicated a dominant fast trend near parallel to a specific fracture orientation. Where seismic wave velocities were slow, measurements often were nearly perpendicular to an interpreted fracture zone. Where overburden was thin or absent, GPR results located near-horizontal bedrock fractures zones that geologic mapping and lineament analysis could not identify. Conductive overburden sediments, particularly till, generally obscured GPR penetration to bedrock.

VLF and EM surveys provide a rapid means to locate conductive features such as water-filled fractures. VLF surveys identified several likely fracture zones, however, these surveys were susceptible to cultural interference and were often difficult to interpret. In addition to providing qualitative information about the thickness and conductivity of the overlying formations, EM surveys identified several fracture zones, and in some cases, their dip direction. The EM surveys can be done relatively quickly and are easy to interpret. Whereas other techniques, for example a lineament analysis, may indicate the surface expression of a fracture zone, geophysical methods sometimes help identify the dip direction of that zone. Dip direction is the next most valuable piece of information required to target a well through a fracture zone.

The collection of various layers of data and inversion processing of 2-D resistivity surveys yielded results that indicate overburden types and saturation, depths to bedrock, and most importantly, depths and dips of fracture zones. Modeling was used to back up interpretations of resistivity data and incorporate known information from well data and surface observations of overburden materials and bedrock outcrop into the analysis. Incorporating multiple pieces of information increased the confidence in 2-D resistivity interpretations. Of the seven surface geophysical methods investigated, analysis of 2-D resistivity surveys provided the most quantitative information on fracture-zone location and dip direction.

The orientation of conductive-geophysical anomalies identified with square-array resistivity showed varying agreement between geologic fracture and lineament data. At some sites, available indicators (outcrop fracture measurements and lineaments) to strikes of features were confirmed, whereas at other sites, they were not. At arrays where conductive-fracture zones were not interpreted, other features could cause the azimuthal-square-array resistivity anomalies if the horizontal layer assumption (bedrock surface and overburden) of the model was violated.

Borehole-geophysical data identified transmissive-fracture zones at the three sites surveyed. Borehole-survey data reinforce interpretations drawn from surface geophysical, geological outcrop, and remote-sensing surveys. Two sites had agreement between orientations of anomalies from surface geophysics, borehole-geophysical-survey feature orientations, and geologic data. At site 6, with no outcrops nearby, a large transmissive-fracture zone located with borehole geophysics was projected towards another high-yielding well that was not accessible for logging.

The various geophysical surveys described in this report illustrate how geophysical methods can be integrated to help define the hydrogeology at different sites in crystalline rock. These survey results were analyzed in conjunction with other data, such as geologic outcrop, well logs, and remotely sensed data to interpret the location of subsurface fracture zones at high-yield well sites.

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