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ELECTRICAL RESISTIVITY SURVEYS OF KARST FEATURES NEAR FORT STANTON, LINCOLN COUNTY, NEW MEXICO

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Abstract.—Beginning in 2002, earth-resistivity measurements using an in-line dipole-dipole array were used to locate existing passages in Fort Stanton Cave and possibly find undiscovered extensions of known passages. Eight resistivity profiles display the effects of known cave passages, and several anomalies that may represent unknown passages or related fractures and bedding-plane separations.

INTRODUCTION

Fort Stanton Cave is an extensive cave system developed in the Permian-age San Andres Formation, with more than 15 km of passages surveyed to the present limits of exploration. The development of this cave system is discussed by Davis and Land (2006).

Beginning in 2002 a series of experimental geophysical measurements were made near Fort Stanton Cave, three km northeast of the historical military post of Fort Stanton (Fig. 1). These surveys were conducted in order to locate possible extensions of known passages and to serve as a guide to future exploration in the cave.

DATA COLLECTION AND ANALYSIS

A resistivity system was constructed using an in-line array of 17 copper-clad steel electrodes. A dipole-dipole electrode arrangement was used to collect the data (Dobrin, 1960; Loke, 1998). Resistivity measurements using a dipole-dipole array were begun in April, 2002. Between 2002 and the present (2006) more than 30 lines were surveyed. Eight of these lines were selected for presentation below.

The resistivity system incorporates a line of metal electrodes driven into the ground. A battery-powered source injects a constant current through two electrodes, and the voltage difference (potential) is measured sequentially between all the other pairs of electrodes. Current is then injected into the next pair of electrodes and the process is repeated for all pairs of the electrodes. The "apparent" resistivity is calculated for each measurement. The apparent resistivity for a given test geometry is influenced by the complete travel path for the measurement and yields a weighted average of resistivity in the volume tested. An optimization process is then applied to the compiled dataset to develop an approximate distribution of the subsurface earth resistivity.

Data were analyzed using the program *Res2Dinv* (Loke, 1998). This program uses a smoothness-constrained least-squares inversion method to provide an estimate of the resistivity distribution of a vertical slice within the earth. The process is fully automated. The results are presented as a profile similar to a geologic cross-section, incorporating land-surface topography.

INTERPRETATION OF RESISTIVITY PROFILES

The two-dimensional model has several limitations when applied to field data in karst areas. First, topographic corrections are applied only along the line. No corrections are made for topographic features adjacent to the line, so valleys adjacent to the line can appear to be resistive zones beneath the line, and hills near the line can disguise resistive zones beneath the line. Second, the resistivity inversion process, in common with most geophysical methods, does not result in a unique solution. An identified resistive anomaly can be caused by discontinuous air-filled voids in areas of subsurface collapse or by small solution passages located close together as by large discrete cave passages. Third, the ability of the technique to resolve a feature varies with electrode spacing. Closely spaced electrodes can detect shallow caves, but will not extend the interpreted profile deeply enough to detect deeper caves. Conversely, widely spaced electrodes can detect deep caves, but only if they are large, while small, shallow cavities may be overlooked. Finally, the interpretation process favors smooth contouring over the abrupt contrasts that cave passages present. Because of this fact, the resistivity values that the model applies to the cave passages depend on the surrounding rocks' resistivity. This is why the model shows indistinct cave boundaries and is why a relative, rather than an absolute, logarithmic scale is used in presenting the computed electrical sections. An example of the effect of a cave passage on the interpretation is shown in Figure 2.

Resistivity data for a passage 7.5 m wide at a depth of from 30 to 40.5 m were generated using the program *Res2Dmod* (Loke, 2002) and then processed using *Res2Dinv.* The cave was represented by a single node with a resistivity of 1,000,000 ohm-m in a uniform matrix with a resistivity of 200 ohm-m. The resulting anomaly is larger than the simulated passage shown by the white rectangle, and the maximum resistivity contrast is less than about 60 ohm-m. What appear to be additional anomalies, with smaller

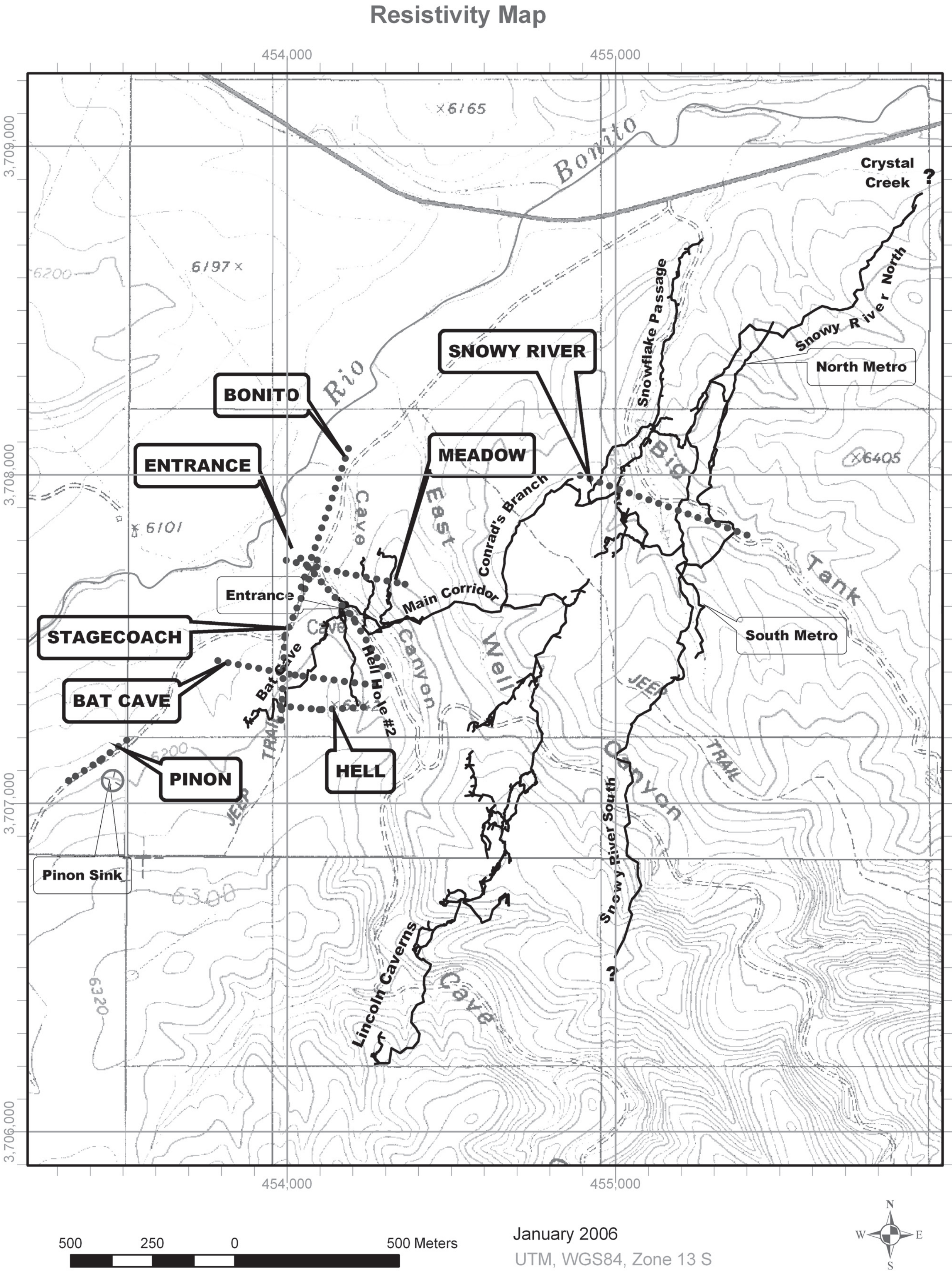

FIGURE 1.—Location of selected resistivity lines near Fort Stanton Cave.

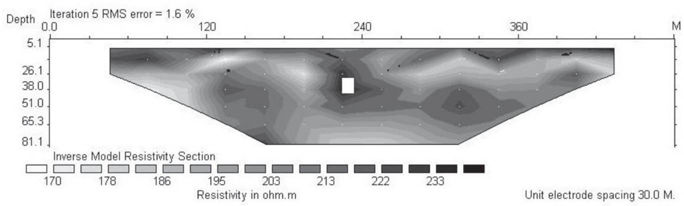

FIGURE 2. Simulated anomaly due to a cave passage 7.5 meters wide and 10.5 meters tall.

resistivity contrast, at 165 and 315 m are artifacts introduced by the combination of forward modeling and inversion.

RESISTIVITY PROFILES

Several profiles were run over known sections of the cave to evaluate the method. The profiles are reproduced in gray scale, and caves are shown in white. Initially, a line with 30 m electrode spacing was run across Bat Cave, a passage trending southwest from the entrance of Fort Stanton Cave. The interpreted profile (Fig. 3) shows a resistive anomaly coincident with, but deeper and broader than, Bat Cave. The anomaly extends east beyond the known extent of Bat Cave towards the 'Hell Hole Number Two' passage. Both passages have rubble and sediment floors extending to an unknown depth (indicated by the stippling in Figure 3) which may contribute to the resistive anomalies appearing deeper than the passage.

A second resistivity line was run near the entrance of the cave. This profile (Fig. 4) shows resistive zones at the entrance sink, at a distance of about 240 m along the line, and the Circle Route part of the Main Corridor (Fig. 1) between about 300 and 360 m. In addition to these known cave passages, the section indicates a possible passage at about 510 to 540 m at a depth of about 35 m, similar to the depth of the rest of the cave in this area. There is also an indication of a possible deep passage at the west end of the line (120 m). Less confidence can be placed in this anomaly because it appears at a bottom corner of the section where, because of the limited number of electrodes, the potential distribution is poorly

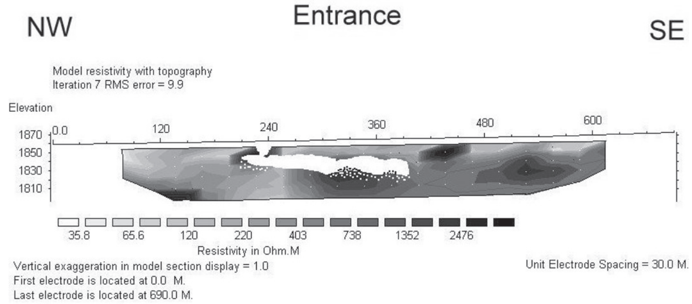

FIGURE 4. Resistivity profile at the Fort Stanton Cave Entrance. See Plate 15 for a color version of this figure.

defined compared to the middle of the section. There is no known connection from Ft. Stanton Cave to these latter features.

An east-west line was run across a meadow north of the cave entrance (Fig. 5). This line crossed two known cave passages, 'Hell of a Thousand Pinches' (H.O.T.P.) and Russell's Crawl. These passages are too small and deep to be resolved with any precision, but the large resistive zone at the east end of the line may be due to the composite effect of the two passages and their associated rubble-filled zones.

Snowy River, a large passage in the easternmost part of the cave, was discovered in September, 2001, (details can be found at: http://www.nm.blm.gov/misc/snowy_river/snowy_river.htm) but exploration and survey of this passage were delayed until July, 2003. During this interval a line was run across the valley south of the discovery site. The profile (Fig. 6) showed a large resistive zone near the middle of the valley, which was assumed to be the southern extension of Snowy River, as well as a deep resistive zone near the east end of the line that was ignored at the time. The cave passage survey in 2003 not only determined that Snowy River had been correctly detected, but the deep anomaly at the east end of the line was explained when the Metro passage was discovered and found to pass under the east end of the line.

Several lines were run across areas where there were no known cave passages. A surprising number of them produced large, shallow anomalies that appear to be isolated features. One of these (the Stagecoach anomaly) underlies a road used for 'old west' stagecoach rides west of the cave entrance (Fig. 7).

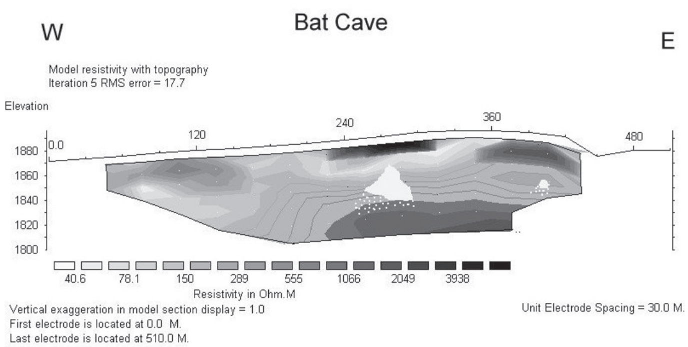

FIGURE 3. Resistivity profile at Bat Cave. See Plate 15 for a color version of tis figure.

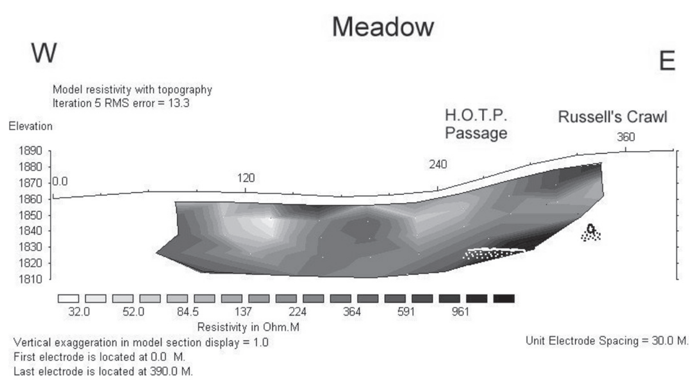

FIGURE 5. Resistivity profile across a meadow north of the Entrance.

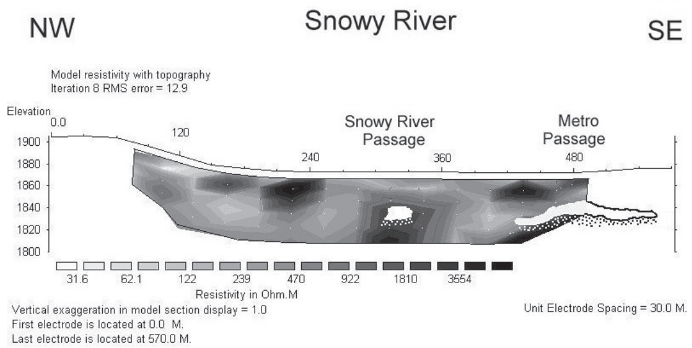

FIGURE 6. Resistivity profile across Snowy River and the Metro. See Plate 15 for a color version of thig figure.

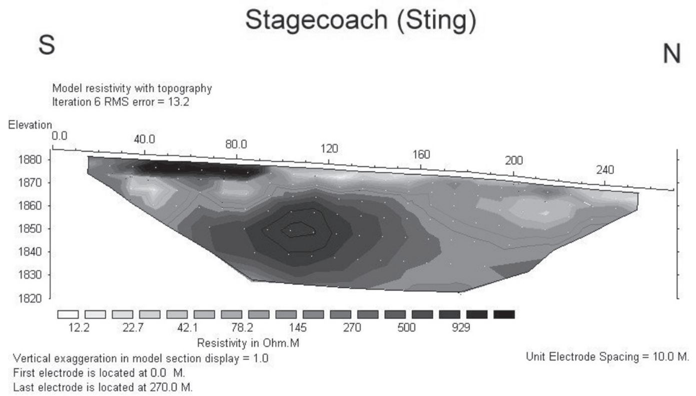

FIGURE 8. Resistivity profile along the Stagecoach Route west of the Entrance using the Sting system. See Plate 15 for a color version of this figure.

The large anomaly at 360m on the Stagecoach line (Fig. 7) has no surface expression and is not near any known cave passage. In August, 2003 a commercial resistivity system (STING/SWIFT, built by Advanced Geosciences, Inc.) consisting of an array of 28 electrodes at 10m spacing was used to collect more detailed data on the anomaly (Fig. 8). The location, size and approximate depth of the anomaly agree between the two profiles. Additional parallel lines about 50m east and west of this line did not indicate any continuation of the feature.

Several lines south of an area between the Bat Cave and Hell Hole Two passages identified scattered resistive zones. The first line, Hell Hole Two Line 1 (Fig. 9), run with the Sting system, shows a large resistive anomaly ('Hell') beneath the center of the profile at a depth of about 20 m with an upward extension that may come within 10 m or less of the surface. The extent and continuity of this anomaly suggest that it could be a large cave passage. There is no surface expression of this feature, as it is beneath a smooth hillside covered with gravelly soil. Adjacent lines 30 m and more to the south showed much smaller anomalies that may not be related to this large feature.

Several lines were run near a large sinkhole about one km southwest of the entrance. One of these shows a large anomaly southwest of the sinkhole (fig. 10), which also appears on a parallel line about 30 m west, but like the lines at the Stagecoach anomaly, additional parallel lines failed to show an extension of this feature.

DISCUSSION AND CONCLUSIONS

The dipole-dipole resistivity method works well in the area of Ft. Stanton Cave. Known passages of sufficient size and proximity to the surface could usually be located, and resistive anomalies on some profiles were later discovered to match known cave passages. The horizontal locations of the passages appear to be accurate within the limitations imposed by the electrode spacing; however, the method is not as well suited to estimate depth. Although some anomalies agree with the passage depths, in some cases the passages are far above or below the anomalies shown on the profiles.

The abundance of smaller, isolated anomalies may be due to factors present while the Fort Stanton Cave system was developing. The cave displays a complex history of ceiling collapse, sediment fills, and partial re-excavation (Roger Baer, 1972, written comm.). This observation agrees with the fact that about half of the presently known cave has been discovered by digging through collapse zones or sediment-filled passages. The complex history of sediments in the cave, revealing several episodes of sediment

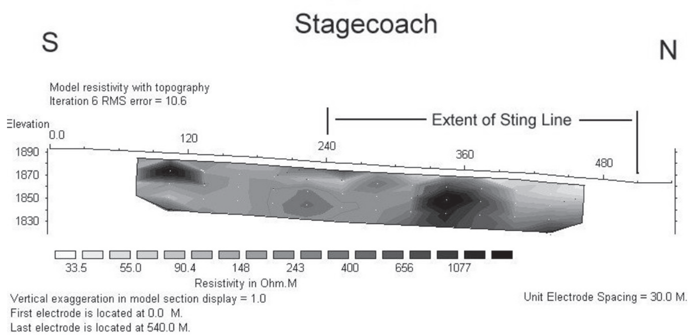

FIGURE 7. Resistivity profile along the Stagecoach Route west of the Entrance.

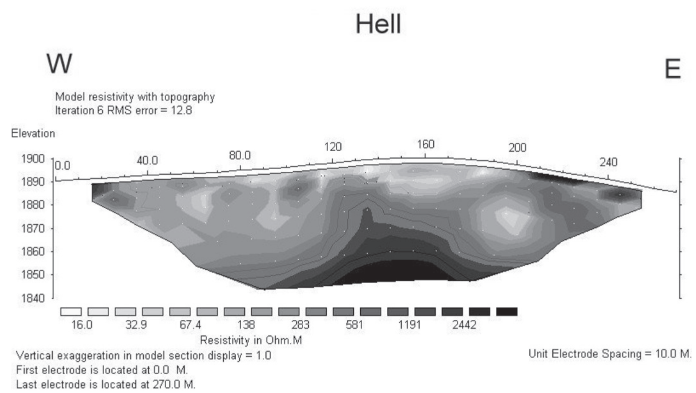

FIGURE 9. Resistivity profile between Bat Cave and Hell Hole Two.

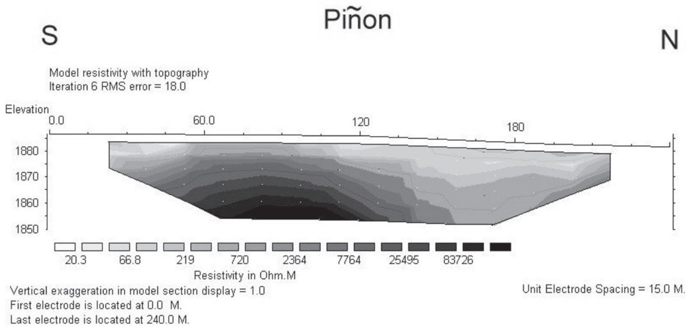

FIGURE 10. Resistivity profile near Piñon Sink.

filling and re-excavation, implies that there are likely to be passages isolated from the known cave by unexcavated sediments. The isolated anomalies might therefore be interpreted as domes caused either by solution or ceiling collapse above passages that have been subsequently filled with sediment washed in from the surface. The anomalies could also be incipient domes in which rock has separated along fracture planes but not yet collapsed, because even a small break in the continuity of the rock, producing a small air gap, can greatly influence the resistivity profile.

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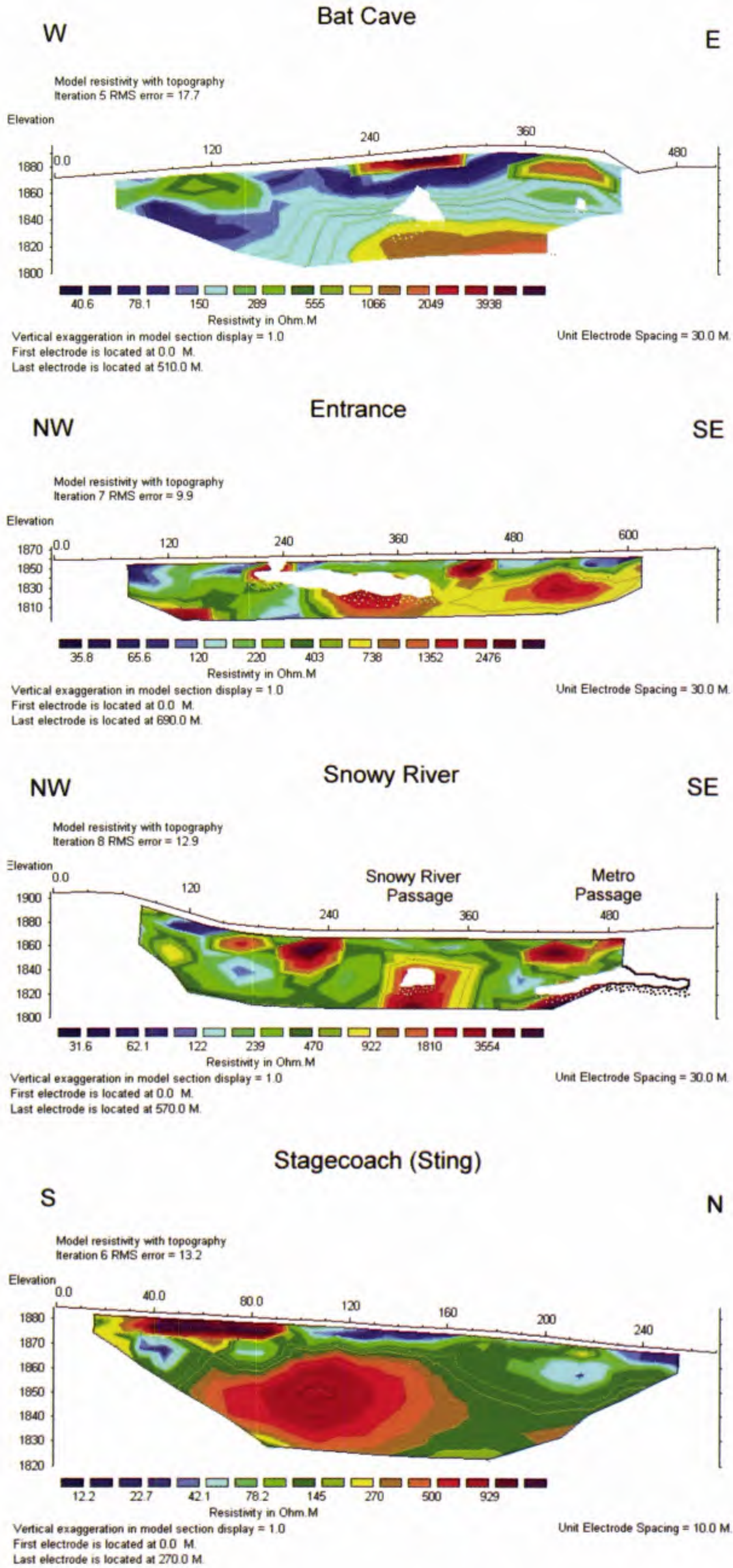

PLATE 15. See paper by McLean and Luke, p. 227, for details on the construction and interpretation of these profiles.