REGIONAL CRUSTAL STRUCTURE BENEATH THE CARLIN TREND, NEVADA BASED ON DEEP ELECTRICAL GEOPHYSICAL MEASUREMENTS

By Brian D. Rodriguez

ABSTRACT

Gold deposits along the Carlin trend in northern Nevada are interpreted to have been controlled by deep regional fault systems. Magnetotelluric data along a regional southwest to northeast profile have revealed deeply-penetrating resistivity structures beneath the Carlin and Battle Mountain-Eureka mineral trends which appear consistent with tectonic breaks in the crust and which possibly serve as channels for hydrothermal fluids. The resistivity model shows a high crustal resistivity (1,000 ohm-m) beneath the Carlin trend, a feature that is characteristic of intrusive complexes. Southwest of the Carlin trend, a high-angle, southwest dipping, low resistivity (5-30 ohm-m) zone may be interpreted as a crustal-dimension fault, possibly extending to 15 to 20 kilometers depth. Crustal resistivity across the eastern part of the Battle Mountain-Eureka trend (2,000 ohm-m) is also characteristic of igneous bodies or intruded rocks. The western edge of this crustal high resistivity also corresponds to the Northern Nevada Rift. Southwest of this high resistivity body, a high-angle, northeast dipping low resistivity (10-30 ohm-m) zone may be interpreted as a crustal-dimension fault, probably extending to about 10 kilometers depth.

INTRODUCTION

Genesis of gold deposits along the Carlin trend in northern Nevada is not fully understood and subject to conflicting models (e.g. Arehart and others, 1993; Illchik and Barton, 1997; Radtke, 1985; Shawe, 1991; Sillitoe and Bonham, 1990). These deposits, and other deposits along the subparallel Battle Mountain-Eureka mineral belt, are interpreted to have been controlled by deep regional fault systems. These structures controlled emplacement of magmas generated in the lower crust or upper mantle, and channeled magmatic-derived hydrothermal fluids or heated meteoric waters that transported and deposited the gold ores. To investigate crustal processes that may have contributed to the genesis of gold deposits along the Carlin trend, a regional southwest to northeast profile of magnetotelluric (MT) soundings was acquired in 1996 (line MT-MT', fig. 1). Two-dimensional modeling of the MT profile was used to derive the resistivity structure and investigate its implication on possible heat or magma sources and possible tectonic controls on the linear distribution of mineral deposits.

MAGNETOTELLURIC METHOD

The magnetotelluric method is a passive surface geophysical technique, which uses the earth's natural electromagnetic fields to investigate the resistivity structure of the subsurface. The resistivity of geologic units is largely dependent upon their fluid content, porosity, fracturing, temperature, and conductive mineral content (Keller and Frischknecht, 1966). Saline fluids within the pore spaces and fracture openings can reduce resistivities in a resistive rock matrix. Also, resistivity can be lowered by the presence of conductive clay minerals, graphitic carbon, and metallic mineralization. It is common for altered volcanic rocks to contain authigenic minerals that have resistivities ten times lower than those of the surrounding rocks (Nelson and Anderson, 1992). Increased temperatures cause higher ionic mobility and mineral activation energy, reducing rock resistivities significantly. Unaltered, unfractured igneous rocks are normally very resistive (typically 1,000 ohm-m or greater), whereas faults will show low resistivity (less than 100 ohm-m) when they are comprised of rocks fractured enough to have hosted fluid transport and consequent mineralogical alteration. Carbonate rocks are moderately to highly resistive (hundreds to thousands of ohm-m) dependent upon their fluid content, porosity, fracturing, and impurities. Marine shales, mudstones, and clay-rich alluvium are normally very conductive (a few ohm-m to tens of ohm-m). Metamorphic rocks (non-graphitic) are moderately to highly resistive (hundreds to thousands of ohm-m). Tables of electrical resistivity for a variety of rocks, minerals and geological environments may be found in Keller (1987) and Palacky (1987).

The MT method (Vozoff, 1991) allows us to probe the crust from depths of tens of meters to depths of tens of

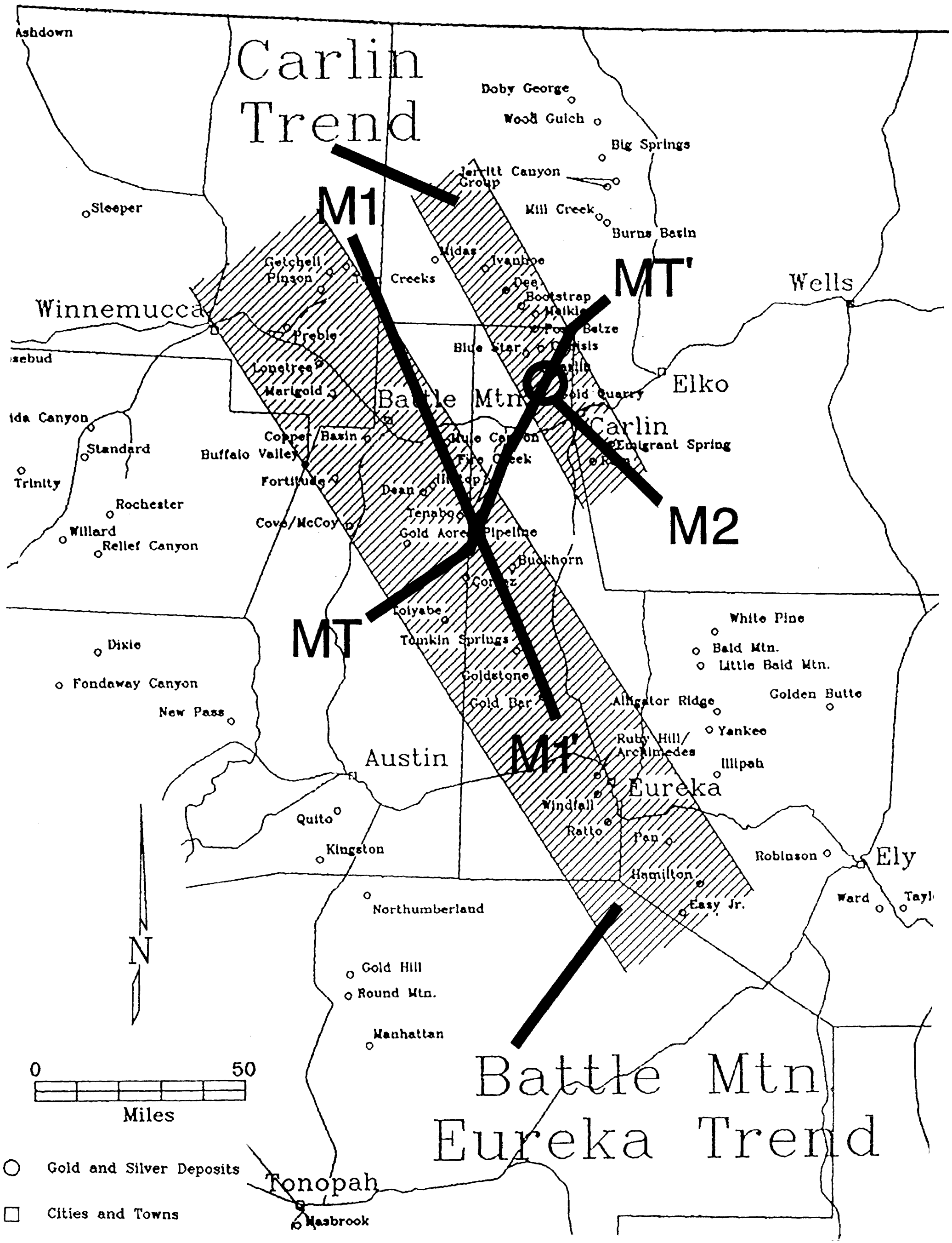

Figure 1. Magnetotelluric transect (MT-MT') acquired in 1996 across the Carlin trend and Battle Mountains-

kilometers by measuring natural variations of the Earth's magnetic and electric field due to world-wide lightning activity at frequencies of 10,000 Hz to 1 Hz and geomagnetic micropulsation at frequencies of 1 Hz to 0.0001 Hz. The natural electric and magnetic fields propagate vertically in the earth because the very large resistivity contrast between the air and the earth causes a vertical refraction of both fields transmitted into the earth (Vozoff, 1972). Using a computer-based data-acquisition and processing system, the natural electric and magnetic fields are recorded in two orthogonal, horizontal directions (the vertical magnetic field is sometimes recorded as well). The resulting time-series signals are used to derive earth tensor apparent resistivities and phases. Generally, a rotated coordinate system that corresponds to apparent resistivity measured along electrical strike (called the transverse electric, TE direction) and normal to strike (called the transverse magnetic, TM direction) is used. The MT method is well suited for studying complicated geological environments because the electric and magnetic relations are sensitive to vertical and horizontal variations in resistivity. The method is capable of establishing whether the electromagnetic fields are responding to subsurface rock bodies of effectively 1-, 2-, or 3-dimensions.

MAGNETOTELLURIC SURVEY

Twenty-seven MT soundings were located along profile MT-MT' (fig. 1) with spacing that varied from 1.5 to 12.4 kilometers. The profile orientation is oblique to the trends of the mineral belts in the center of the profile in order to take advantage of other MT data (Grauch and others, this volume) and to optimize station locations for proximity to roads. This logistical arrangement was required by the U.S. Geological Survey truck-mounted MT system, and by the need to avoid electrical noise, such as power lines. Frequencies sampled ranged from 300 to 0.004 Hz using single station recordings of both orthogonal horizontal components of the electric and magnetic fields. Sampling these frequencies in the Carlin trend area allowed us to probe the crust from depths of hundreds of meters to depths of tens of kilometers.

MAGNETOTELLURIC MODEL

Wannamaker (1983) has found that MT responses in the northern Basin and Range are fundamentally 3-D in nature. However, because 3-D modeling is prohibitively time-consuming, 2-D modeling was used to construct the schematic cross-section of resistivity (fig. 2) along profile MT-MT' (fig. 1).

The MT data were modeled with a 2-D inversion algorithm (Smith and Booker, 1991) called rapid relaxation inverse (RRI). The RRI method provides a rapid means of 2-D modeling and uses a minimum-structure criterion (Smith and Booker, 1988), which substantially reduces unnecessary structural elements in the final solution. The final inversion model generally fit the TM data (misfit 4%) better than the TE data (misfit 12%). The gross structure of the model came from fitting the TM data. Wannamaker and others, (1984) have shown in 3-D MT modeling that approximating 3-D structure beneath a centrally located profile with 2-D modeling is best achieved when fitting the TM curve even at the expense of fitting the TE curve. However, because TM data are quite insensitive to the depth extent of a subsurface body (Eberhart-Phillips and others, 1995), the depths to the base of the bodies in the model are not well constrained. Clarifying the limits of the models with further 2-D and 3-D MT analysis is needed.

DISCUSSION

The resistivity model (fig. 2) shows a high crustal resistivity (1,000 ohm-m) beneath the Carlin trend, characteristic of igneous bodies. Exposures of Cretaceous quartz monzonite near MT station 18, Tertiary granodiorite about one mile southeast of station 16, widespread recrystallized carbonates in these areas (Evans, 1980), and a broad magnetic high (M2 in fig. 2) support the presence of a large, concealed, composite pluton (Grauch, 1996). Southwest of the Carlin trend, a high-angle, southwest dipping, low resistivity (5-30 ohm-m) zone may be interpreted as a crustal-dimension fault, possibly extending to 15 to 20 kilometers depth. This zone may represent a crustal conduit for fluids. This zone would have to contain hot fluids, or clay minerals from hydrothermal alteration in fractures, or even conductive sulfide or graphitic minerals from contact metamorphism to maintain such a low resistivity that extends so deep in the crust. The low resistivity (5-30 ohm-m) zone beneath the northeastern Carlin trend and to the northeast are probably comprised of approximately 5 km of alluvial fill (Jachens and others, 1996) and carbonaceous rocks. Beneath the eastern Carlin trend, and to the northeast end of the MT profile (stations 21 to 27) the change to 1,000 ohm-m at 12 km depth could be the base of the sedimentary section on top of crystalline basement rocks. The moderately resistive (30-100 ohm-m) rocks northeast of the Carlin trend and ubiquitously southwest probably correspond to carbonates in the near surface where local outcrops exist (stations 2, 3, 4, 12, 13, 14, 15, 19, 26, and 27) and other unknown volcanic and/or clastic sedimentary rocks at depth. The low resistivity (5 ohm-m) zone beneath stations 10 and 11 correlates with a known geothermal resource area (Beowawe KGRA near the center of MT profile, fig. 2).

Crustal resistivity across the eastern part of the Battle Mountain-Eureka trend (2,000 ohm-m, between stations 7 and 10, fig. 2) is also characteristic of igneous bodies or intruded rocks. The western edge of this crustal high resistivity also corresponds to the Northern Nevada Rift (M1 in fig. 2, see fig. 1 in Grauch and others, this volume). Southwest of this high resistivity body, a high-angle, northeast dipping low resistivity (10-30 ohm-m) zone may be interpreted as a crustal-dimension fault, probably extending to about 10 kilometers depth. A similar conductive feature is seen across a MT profile about 10-km south (see fig. 3 in Grauch and others this volume). The low resistivity (5 ohm-m) zone embedded at the top of this inferred fault is probably comprised of approximately 5 km of alluvial fill (Jachens and others, 1996) and possibly clay-rich or carbonaceous rocks, similar in size and resistivity to the valley fill northeast of the Carlin trend. At the southwest end of the MT profile, a southwest dipping, low resistivity (10-30 ohm-m) zone beneath stations 1 and 2 probably is valley fill.

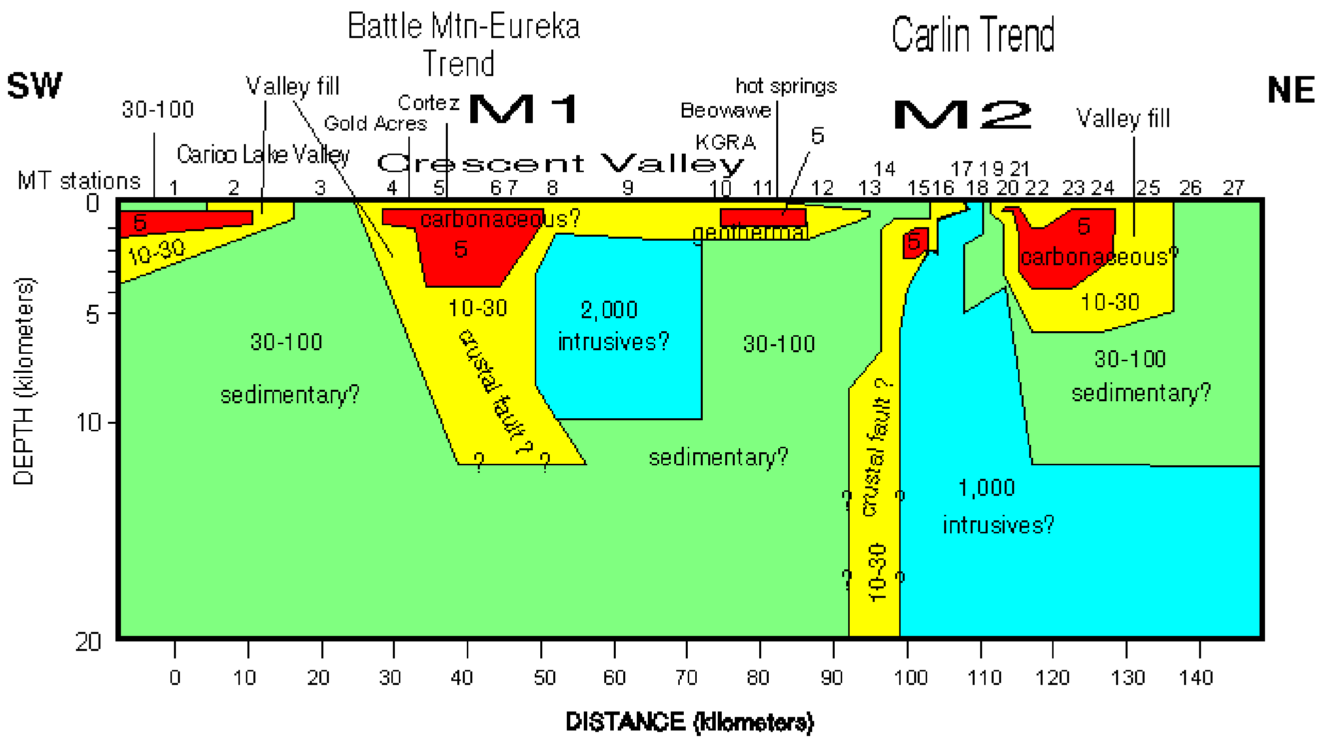

Figure 2. Two-dimensional resitivity model of crustal structure for the magnetotelluric transect (MT-MT' on figure 1) that was acquired in 1996 acros the Carlin trend and Battle Mountain-Eureka mineral belt in northeastern Nevada. M1 is an anomalous linear magnetic high (Northern Nevada Rift) and M2 is a broad magnetic high anomaly (see figure 1). Numbers assigned to interpreted bodies are modeled resistivity in ohm-meters. Vertical exaggeration is approximately four. The bend in the profile (MT-MT' on figure) between MT stations 7 and 10 cause features in the resistivity model to appear wider than they really are because they are projected obliquely with respect to the rest of the profile.

SUMMARY

Strengthening the suggestion of Shawe (1991), the MT data have revealed deeply-penetrating resistivity structures beneath the Carlin and Battle Mountain-Eureka trends which appear consistent with tectonic breaks in the crust and which possibly serve as channels for hydrothermal fluids. In order to confirm whether these crustal structures continue to conform with the location of the linear arrays of gold deposits, new MT data should be added along parallel profiles across adjacent parts and even near the apparent terminations of the gold trends.

REFERENCES CITED

Arehart, G. B., Foland, K. A., Naeser, C. W., and Kesler, S. E., 1993, $^{40}Ar/^{39}Ar$, K/Ar, and fission track geochronology of sediment-hosted disseminated gold deposits at Post-Betze, Carlin Trend, northeastern Nevada: Economic Geology, v. 88, p. 622-646.

Doebrich, J. L., Wotruba, P. R., Theodore, T. G., McGibbon, D. H., and Felder, R. P., 1995, Field guide for geology and ore deposits of the Battle Mountain mining district, Humboldt and Lander counties, Nevada, in Geology and ore deposits of the American Cordillera symposium: Geological Society of Nevada, U.S. Geological Survey, and Sociedad Geológica de Chile, 121 p.

Eberhart-Phillips, D., Stanley, W. D., Rodriguez, B. D., and Lutter, W. J., 1995, Surface seismic and electrical methods to detect fluids related to faulting: Journal of Geophysical Research, v. 100, no. B7, p. 12,919-12,936.

Evans, J. G., 1980, Geology of the Rodeo Creek NE and Welches Canyon quadrangles, Eureka county, Nevada: U.S. Geological Survey Bulletin 1473, 81p.

Grauch, V. J. S., 1996, Magnetically interpreted, granitoid plutonic bodies, *in* Singer, D. A., ed., An analysis of Nevada's metal-bearing mineral resources: Nevada Bureau of Mines and Geology Open-File Report 96-2, p. 7-1 to 7-16.

Grauch, V.J.S., Klein, D.P., and Rodriguez, Brian, (this volume), Progress on understanding the crustal structure near the Battle Mountain-Eurealca mineral trend from geophysical constraints, *in* Tosdal, R.M., ed., Contributions to the gold metallogeny of northern Nevada: U.S. Geological Survey Open-File Report.

Ilchik, R. P. and Barton, M. D., 1997, An amagmatic origin of Carlin-type gold deposits: Economic Geology, v. 92, no. 3, p. 269-288.

Jachens, R. C., Moring, B. C., and Schruben, P. G., 1996, Thickness of Cenozoic deposits and the isostatic residual gravity over basement for Nevada, *in* Singer, D. A., An analysis of Nevada's metal-bearing mineral resources: Nevada Bureau of Mines and Geology Open-File Report 96-2, p. 2-1 through 2-10, 1 plate, scale 1:1,000,000.

Keller, G. V. and Frischknecht, F. C., 1966, Electrical methods in geophysical prospecting: Pergamon Press, New York, 517 p.

Keller, G. V., 1987, Rock and mineral properties, *in* M. N. Nabighian, ed., Electromagnetic Methods in Applied Geophysics Theory: Tulsa, Oklahoma, Society of Exploration Geophysicists, v. 1, p. 13-51.

Nelson, P. H. and Anderson, L. A., 1992, Physical properties of ash flow tuff from Yucca Mountain, Nevada: Journal of Geophysical Research, v. 97, no. B5, p. 6823-6841.

Palacky, G. J., 1987, Resistivity characteristics of geologic targets, in Electromagnetic Methods, *in* M. N. Nabighian, ed., Applied Geophysics-Theory: Tulsa, Oklahoma, Society of Exploration Geophysicists, v. 1, p. 53-129.

Radtke, A. S., 1985, Geology of the Carlin gold deposit, Nevada: U. S. Geological Survey Professional Paper 1267, 124 p.

Shawe, D. R., 1991, Structurally controlled gold trends imply large gold resources in Nevada, *in* Raines, G. L., Lisle, R. E., Schafe, R. W., Wilkinson, W. H., eds., Geology and ore deposits of the Great Basin, Symposium Proceedings: Geological Society of Nevada, Reno, v. 1, p. 199-212.

Sillitoe, R. H. and Bonham, H. F., 1990, Sediment-hosted gold deposits; distal products of magmatic-hydrothermal systems: Geology, v. 18, no. 2, p. 157-161.

Smith, J. T., and Booker, J. R., 1988, Magnetotelluric inversion for minimum structure: Geophysics, v. 53, p. 1565-1576.

___ 1991, Rapid inversion of two- and three-dimensional magnetotelluric data: Journal of Geophysical Research, v. 96, p. 3905-3922.

Vozoff, K., 1972, The magnetotelluric method in the exploration of sedimentary basins: Geophysics, v. 37, p. 98-141.

____ 1991, The magnetotelluric method, *in* M. N. Nabighian, ed., Electromagnetic methods in applied geophysics: Tulsa, Oklahoma, Society of Exploration Geophysicists, v. 2, part B, p. 641-711.

Wannamaker, P. E., 1983, Resistivity structure of the northern Basin and Range: Geothermal Resources Council, Special Report No. 13, p. 345-361.

Wannamaker, P. E., Hohmann, G. W. and Ward, S.H., 1984, Magnetotelluric responses of three-dimensional bodies in layered earths: Geophysics, v. 49, no. 9, p. 1517-1533.