Preprint - accepted for publication in *The Leading Edge*, July 2000, Vol. 19, No. 7, The Society of Exploration Geophysicists.

Fluid Flow Mapping at a Copper Leaching Operation in Arizona

Norman Carlson and Kenneth Zonge, Zonge Engineering & Research Organization, Inc.,
Tucson, Arizona, USA
George Ring and Martin Rex, BHP Copper, Inc., San Manuel Mining Division,
San Manuel, Arizona, USA

Background. At the San Manuel copper mine in southeastern Arizona, recovery of copper from the oxidized portion of this porphyry mineral resource is being achieved through a large in situ leaching operation using weak sulfuric acid solution. In the past, this activity was coordinated with open pit and underground mining, but in today's economic climate, only the in situ operation continues. The acid solution (20 grams per liter) is injected in wells un-pressurized at varying depths up to several hundred meters, usually at rates of only a few tens-of-gallons per minute. The copper-bearing pregnant leach solution (PLS) is recovered either in nearby recovery wells or in collection areas in the underground workings 350 m to 500 m (1200 to 1600 feet) below the surface. A thorough description of in situ mining in general as well as at San Manuel specifically can be found in Swan and Coyne (1992). Due to the economic efficiency of this mining method, the in situ operation at San Manuel has expanded from two test wells in the mid-1980s to more than 900 wells covering over 650,000 square meters of the open pit mine. Over the past twelve years, geophysical surveys have been useful in both planning and monitoring the expansion of the in situ field.

At this site, the geophysical surveys served economic as well as environmental needs. Economically, tracking and monitoring the leachate is important to ensure against the loss of valuable (copper-bearing) solution. In addition, if the fluid flow is understood, then the most efficient recovery system can be used (recovery well versus underground collection). Environmentally, injecting sulfuric acid into the subsurface doesn't conjure up an attractive image to the public, of course. The ability to provide government entities with geophysical results to support monitoring well information and hydrological models has been important in meeting state government requirements with respect to protection of the local aquifer.

The geophysical method used was the controlled source audio-frequency magnetotellurics (CSAMT), which is a well-established resistivity exploration tool, described in detail by Nabighian (1991) and Van Blaricom (1992). Briefly, this method is an electromagnetic, far-field (plane-wave) resistivity mapping tool that provides very good lateral resolution, greater depth of investigation, and has significant logistical advantages over other methods in difficult environments such as an operating mine. For example, the transmitter equipment and large dipole are fixed throughout the survey, and are located several miles from the mine, unaffected by mine activities. In contrast, for the depths required in this survey, transient electromagnetic (TEM) methods would require large transmitter loops of wire in the mine, which would be difficult and time-consuming to move along and across the pit benches. In the mine, the CSAMT receiver equipment is small and backpack-portable, and wire lengths are small, allowing the crew to work on narrow benches and minimizing their impact on the mining activities. Since CSAMT is a frequency domain method, active notch filters can be used in the receiver to minimize power line noise (60 Hz) and its odd harmonics, which often have amplitudes almost as strong as the 60 Hz noise.

The first CSAMT survey at San Manuel was conducted in 1988 after initial tests of the in situ program were completed and the field was being expanded. Over the course of the last 12 years, nine surveys have been completed. During all of these surveys, an electric-field dipole size (and station spacing) of 30.5 m (100 feet) was used, and transmitted frequencies were from 2 Hz or 4 Hz up to 4096 Hz or 8192 Hz in binary increments. Usually, from one to six stations were read simultaneously, depending on the curvature of the particular bench on which the crew was working.

Interpretation. By strict standards, much of the interpretation of the CSAMT data should be considered somewhat empirical. An open-pit mine, in a geologically complex area such as San Manuel, is obviously a 3-D problem, but there are currently no 3-D inversion models available for CSAMT. The data have been modeled with 1-D and 2-D smooth-model inversion programs, but 3-D effects are certainly evident in the data. As a result, interpretation has been more of an “iterative” process, attempting to correlate geophysical results with hydrologic models, geologic information, and injection/recovery results.

Given this modeling limitation, we have attempted to enhance the interpretation by performing numerous tests and comparisons, including measurements before-and-after well installation, before-and-after mine water injection, and before-and-after acid injection. In one test in 1996, readings were even made after turning off the power to all of the pumps in the entire in situ field, for comparison with data acquired while the pumps were powered and operating. Comparisons also included repetition of measurements using multiple transmitter sites, since the orientation of the mine benches required two transmitter dipole orientations for maximum signal strength.

Figure 1(a) shows the results of one of these tests. The plot shows the data repeatability over time from August, 1998 to November, 1998 on Bench 2640N in cross section form (stations in feet across the top, elevation in feet along the side). As is standard practice, the resistivity data (in ohm-meters) are contoured and colored on a logarithmic scale, though we have highlighted two of the contours for emphasis. No injection of fluids occurred in this area, and we see very good repeatability of the data.

For comparison, Figure 1(b) shows the results on Bench 2460N, approximately 85 m (275 feet) away (horizontally), acquired at the same time as Figure 1(a), with an intermediate set of readings that were acquired in September, 1998. During the time interval between the August 1998 data set and the September, 1998 data set, natural mine water was injected into a single well located approximately 16.7 m (55 feet) off-line between stations 10800 and 10900. There is a weak, but definite decrease in resistivity between August and September. Water injection continued, and by November 1998, a more pronounced decrease in resistivity is evident. The changes seen here are significantly weaker than the changes we have seen resulting from acid injection, as expected, since the acid solution is substantially more conductive than the natural mine water. The injection test itself was run to test fluid flow paths in preparation for a possible expansion of the in situ field in this part of the open pit. The combination of these two tests on Bench 2460N and 2640N provides clear evidence of the ability of the CSAMT method to map even relatively small changes in resistivity in this electrically noisy environment.

Finally, the data in Figure 1(c) show the change in resistivity over time after injection of the acid leaching fluid on Bench 2280S. In this case, a 10:1 decrease in resistivity is evident in the region centered at a depth of approximately 60 m (200 feet) on the eastern 100 m (300 feet) of this line segment where injection was in progress.

Economic Applications. In addition to its use as a general monitoring tool, the CSAMT results have been economically useful in two ways. For example, one area (called Zone 12) was originally planned and drilled as an underground collection zone. After injection was in progress, the CSAMT data showed that fluids were not migrating downward as far or as rapidly as expected, but were accumulating in the upper 100 m to 150 m. Figure 1(c) includes some of the data from this area. As a result, Zone 12 was reconfigured from an underground collection zone to a shallow recovery well zone; several injection wells were converted to recovery, and normal recovery wells were added to the zone, which then began returning the expected fluid amounts. In this case, the geophysical information was instrumental in determining the most efficient recovery system for this zone of the in situ field.

In a second example, the CSAMT data were important simply as a tool in locating an accumulation of fluids in an unexpected area. A strong low-resistivity anomaly developed in the shallow subsurface in an area of the pit adjacent to, but not part of, an injection zone. This low-resistivity feature was drilled, and a saturated region of PLS was found to be the source of the anomaly. Recovery wells were installed in this area and copper was produced from a region that would otherwise not have been developed for several years.

Environmental Applications. The environmental applications are less tangible, but certainly just as important. The geophysical data assist in filling gaps between monitoring wells and provides an image of the subsurface that serves to corroborate the hydrologic models. This ability to produce an image of the subsurface from repeatable data that can be correlated with hydrology and geology has been particularly useful for the environmental firm contracted to prepare the Aquifer Protection Permit for the state of Arizona.

Figure 2 is an example, showing a cross section through the mine of the CSAMT data. On the basis of tests such as those described above, we use the 20 ohm-meter contour as an approximate outline of zones containing PLS. The resulting geophysical picture is consistent with expected behavior of the subsurface fluids. The low-resistivity anomaly associated with the PLS fluids begins on the north beneath the northernmost limit of injection, and plunges to the south paralleling the mine topography. At the bottom of the pit, however, the anomaly extends all the way to the underground collection areas at an elevation of approximately 297 m (975 feet), again completely consistent with the drillhole and subsurface information obtained in the underground workings.

By combining data for the whole area acquired during a relatively short time, a 3-D image can be generated, which is useful in visualizing the fluids in the subsurface. Since the data are interpolated between 1-D or 2-D model results, this is a pseudo 3-D model, but it is still very useful in displaying a large amount of data for non-geophysicists. Figure 3 is an example of such an image, showing the subsurface volume that is less than 20 ohm-meters in resistivity, interpreted as the PLS in place during the 1996 CSAMT survey. In this image, the “funneling” of the fluids into the underground collection area is clearly evident.

Conclusions. Despite the extremely difficult working environment, and the complex, 3-D nature of the geology, we have seen considerable economic value in using the CSAMT method as a monitoring tool in the in situ mining operation at the San Manuel copper mine. Since rigorous 3-D modeling is not yet possible, frequent tests and comparisons have been important in our interpretation of the data, as well as in establishing a “comfort zone” for government oversight of the environmental implications of this type of operation.

Suggestions for further reading. *Electromagnetic Methods in Applied Geophysics, Volume 2, Application, Part B*, edited by M. Nabighian (Society of Exploration Geophysicists, 1991). ***In Situ Recovery of Minerals II*,** edited by S.A. Swan and K.R. Coyne (The Engineering Foundation, 1992). ***Practical Geophysics II for the Exploration Geologist*,** edited by R. Van Blaricom (Northwest Mining Association, 1992).

Acknowledgments: The authors would like to acknowledge the work of Greg Mazur, formerly of BHP Copper’s San Manuel Mining Division and we thank BHP Copper, Inc. for permission to use this data.

Corresponding author: norm@zonge.com

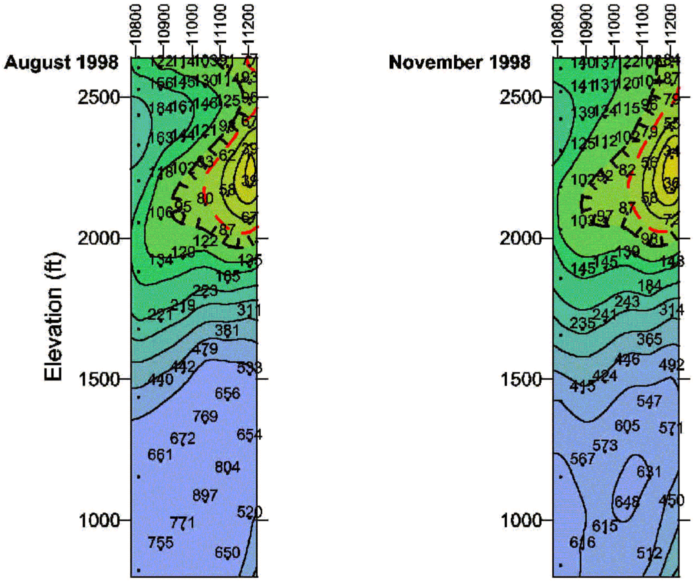

Figure 1(a): Bench 2640N repeatability test (no injection activity)

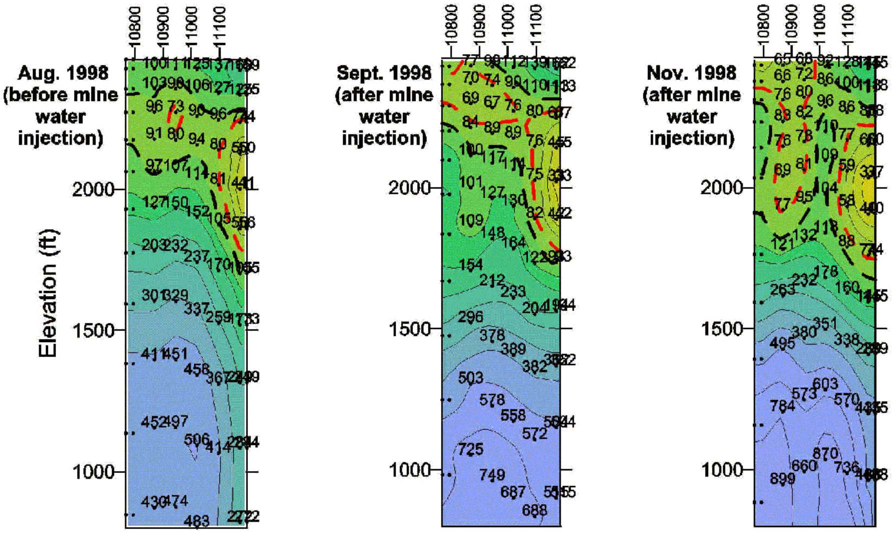

Figure 1(b): Bench 2460N (mine water injection test)

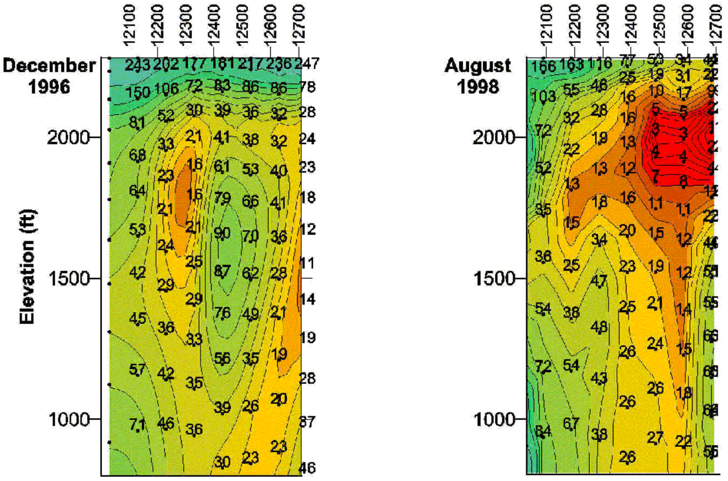

Figure 1(c): Bench 2280S (after acid injection)

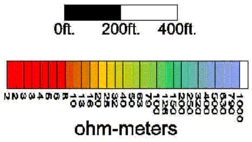

Figure 1(a-c): CSAMT smooth-model inversion results in cross section form.

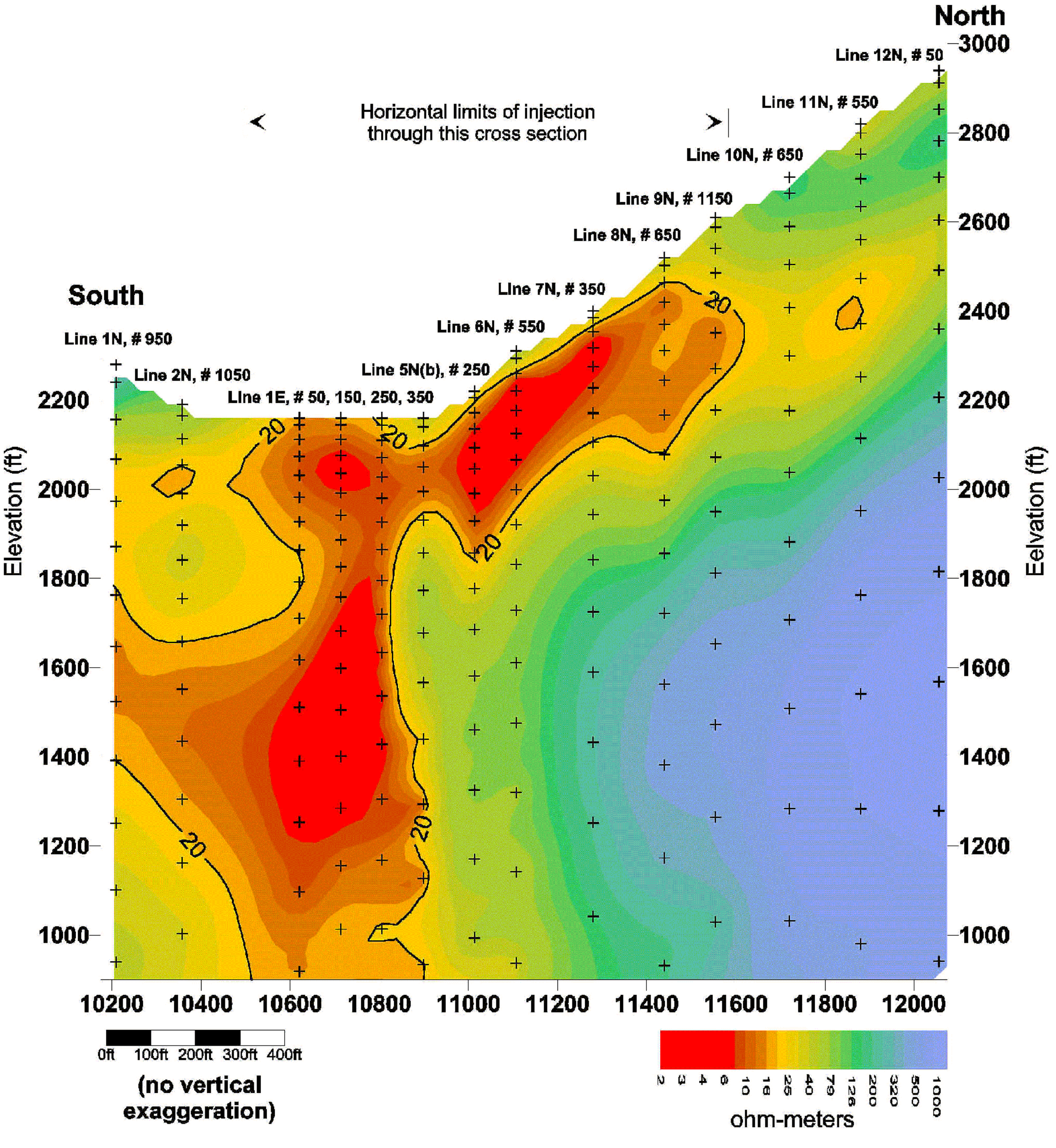

Figure 2: South-north cross section of 1996 CSAMT data through a portion of the open pit mine at San Manuel. The 20 ohm-meter contour is highlighted as the interpreted limit of the fluids in the subsurface.

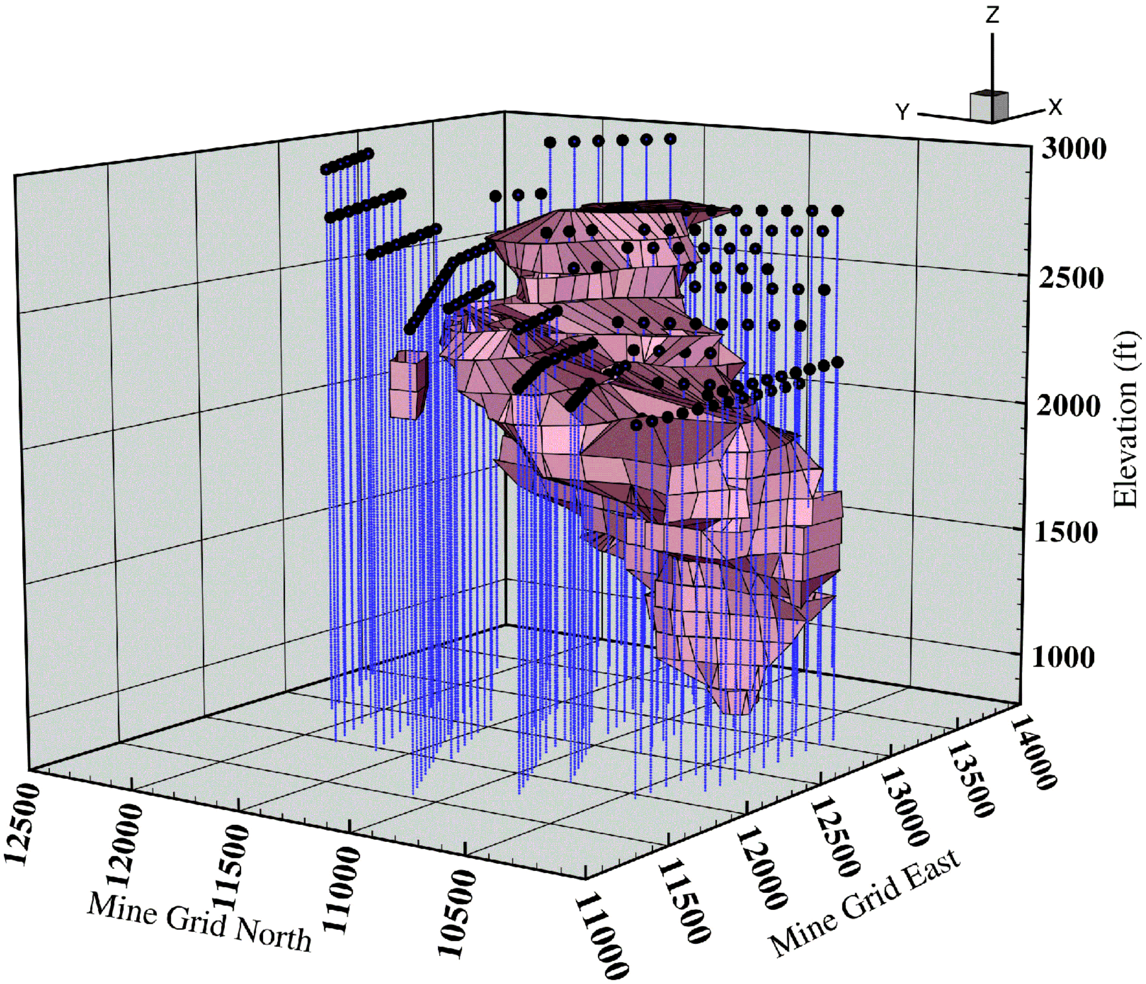

Figure 3: A pseudo 3-D image of the CSAMT smooth-model inversion results, viewed looking northeast. The subsurface area less than 20 ohm-meters in resistivity is enclosed and shaded. The surface locations of the CSAMT stations used to generate this image are shown as black dots, with plumb lines projected to depth.