- 50 YEARS -

STATE OF THE ART
IN IP AND
COMPLEX RESISTIVITY

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ABSTRACT

The use of resistivity and spontaneous potential by the Schlumberger brothers is documented at least as early as 1900 – over 100 years ago! Conrad Schlumberger received a patent on the IP technique in 1912. However, it was almost forty years before Newmont renewed interest in its use and application. From that time (the late 1940's) activity flourished for roughly forty years in both theory and practice, mainly in the search for disseminated sulfides; more specifically porphyries. However, with the crash of copper prices in 1983, interest in disseminated sulfide (porphyry copper) deposits declined dramatically with a concurrent drop in research concerning the source and nature of the induced polarization (IP) response. The precipitous decline in oil prices in 1985 further reduced interest in IP, which was being used as one of the non-seismic alternatives in hydrocarbon exploration. Only in the last few years has interest been renewed.

Despite this general lack of interest in the use of IP and IP research during the past 15 years, the development of instrumentation applicable to resistivity and IP surveys has continued at a fast pace, capitalizing on the development of powerful, high speed, low cost microprocessors. These new microprocessors also fueled the development of robust data processing routines and 2- and 3-D modeling and inversion programs.

Today research continues on the effects of hydrocarbons and other groundwater contaminants on the IP response. IP is used extensively in the search for precious metals by mapping areas hosting disseminated sulfides

that may occur in conjunction with precious metals. Interest has been renewed in porphyry deposits in third-world countries, and complex resistivity (CR) or spectral IP is being used in attempts to discern the source of IP responses and to discriminate between valid metallic IP responses and electromagnetic (EM) coupling effects. Most recently IP has been found to be a cost-effective method in environmental surveys.

INTRODUCTION

The use of resistivity and spontaneous potential by the Schlumberger brothers is documented at least as early as 1900 – over 100 years ago! Conrad Schlumberger received a patent on the IP technique in 1912. However, it was almost forty years before Newmont Mining Corporation as a result of discussions with Radio Frequency Laboratories, of Boonton, N. J., in 1946 renewed interest in its use and application. Interestingly, two Russians published a paper on IP in Geofizika in 1948. Under Arthur Brant's direction his Newmont group, which included many of the acknowledged giants of the industry such as Seigel, Wait, and Collett to name just a few, pursued the theory and application of the technique in the field and laboratory. These and others were part of a joint venture with Phelps Dodge Corporation known as the Mingus Mountain Mining Company that carried out exploration and research in the United Verde Mine area at Jerome Arizona from 1949-1951. From that time activity flourished for over 30 years in both theory and practice. Bleil at Michigan State College, Madden and Marshall at M.I.T, Fraser and Ward at Berkeley, Hallof at McPhar and Patterson at Huntec were also early contributors. Sumi may have been one of the first to investigate mineral discrimination via the time domain waveform in the early sixties. Millett of Phelps Dodge published the first readily usable EM coupling calculations. Later, Van Voorhis et al, at Kennecott, developed the first EM de-coupling algorithms and Zonge introduced the concept of complex resistivity. Pelton presented arguments for using the Cole-Cole model as a basis for IP inversion. The list goes on and on and undoubtedly we have made major omissions.

However, with the crash of copper prices in 1983, interest in disseminated sulfide (porphyry copper) deposits declined dramatically with a concurrent drop in research concerning the source and nature of the induced polarization (IP) response. The precipitous decline in oil prices in 1985 further reduced interest in IP, which was being used as one of the non-seismic alternatives in hydrocarbon exploration. Only in the last few years has interest been renewed.

The most significant advancements in IP and complex resistivity (or spectral IP) in the recent past have not been in theory or practice, but rather in development of sophisticated instrumentation, for both receivers and transmitters, and robust data processing, modeling, and inversion code. However, there is considerable interest in MT ISA Mines MIMDAS type equipment that utilizes expanded arrays, multiple receivers and long sample times.

IP surveys are carried out worldwide, and will continue to be used effectively whenever disseminated sulfides are the target. IP is now utilized in environmental applications. The IP response of buried waste dumps can be very strong - in excess of 100 milliseconds. Research is in progress to discern the effects of hydrocarbons and other contaminants on the cation exchange capacity of clays, and the resultant changes in IP response.

REVIEW OF INSTRUMENTATION

In 1975 there were no analytical instruments being manufactured with internal microprocessors. At that time *Electrical Engineering Times* predicted that by 1982 about 60% of the market would be for instrumentation that contained microprocessors. That percentage was reached well before 1982, and today virtually everything has at least one microprocessor in it, including greeting cards and children's toys.

One of the major driving forces in reducing the cost and size of computers and computer-controlled instrumentation, aside from the development of high-speed microprocessors (MPUs) has been the low cost of memory which has dropped by a factor of $3x10^6$ since 1975. Memory was then selling for 50 cents to US$1.00 per byte. Today, the cost is about $0.15 per megabyte and hard disk drives are selling for US$1.00 per gigabyte.

Today, the computer industry continues to forge ahead at an unprecedented rate. Several years ago computer companies were announcing major new products and lower prices about every 12 months; now they seem to be coming every 6 months or less. This rapid activity presents a constant challenge to keep up with the industry and to predict what the future holds. It is both a curse and a blessing to manufacturers, at least in the mining geophysical realm, where units are measured in tens rather than thousands per annum.

IP INSTRUMENTATION AND DATA HANDLING

We can now build complex, computer-controlled instruments in which the cost of memory is insignificant, and integrated circuits are relatively cheap. But the actual design of printed circuit boards and the software development to run these new devices can take an inordinate amount of time and money.

One of the original goals of using MPU control for geophysical receivers was to get most, if not all, of the data processing done in the field. Now, more and more geophysicists have a perceived need to gather time-series data (raw, digitized waveforms) in the field and then run it through robust post-processing routines, especially in electrically noisy areas. Field data are being acquired in culturally contaminated areas and also by non-geophysicists, so real-time processing with the option to use post processing makes sense. Recording all of the time-series waveforms for one day's data can take up to 50 megabytes or more of data storage. Hard disk drives do not operate over the temperature range encountered in the field, but thanks to the introduction of the flash disk and other solid-state disks this does not present a problem. Flash disks up to one gigabyte are now available. This large amount of recorded data can be rapidly transferred from the field receiver to an office or camp computer via network hardware in the receiver system. New LAN's can move data at a rate of 100 MB/sec.

IMPROVEMENTS IN FUTURE INSTRUMENTATION

IP instruments fall into two categories - single purpose (e.g., IP and resistivity only) and multi-purpose (able to measure resistivity, IP and frequency and time domain EM as a minimum). Several units on the market have 24 bit analog-to-digital converters (ADCs), most have signal detection levels in the tens of microvolts, or lower, and virtually unlimited data storage. Multi-purpose receivers that will make measurements to 10 kHz or above are still relatively power hungry. Power hungry implies large battery packs, which mean more weight, which mean unhappy field crews. Economics is going to continue to be a determining factor in the decision of just how much sophistication is practical on any particular project.

What can be done or is being done to improve existing instrumentation?

1) **Improve signal-to-noise ratio.** ADCs with more bits of resolution and low-noise operational amplifiers. Time series data collection and post acquisition filtering

2) **Smarter and faster in-field (out of the office) processing for data quality assessment.** This requires accessibility to the data "in-field" and the use of high powered PC's

3) **Smaller and lighter units.** Utilize new types of batteries and packs. Also lightweight equipment packaging. There is increased interest in the use of PC's and off-shelf components to make electrical measurements.

IP AS IT IS BEING USED TODAY

Historically, the main reason for running an IP or CR survey has been to detect the response of disseminated sulfides and to map structural variations with resistivity. The same reasoning holds true today. The most popular arrays remain dipole-dipole (D-D), and pole-dipole (P-D) arrays for profiling, and gradient arrays for generating plan maps delineating lateral changes.

The main reason for Zonge developing multi-frequency IP (complex resistivity or spectral IP) was two-fold; to remove EM coupling effects from IP data, and to identify the source of the IP response. EM coupling removal has been successfully achieved and work continues in analyzing the IP response for mineral discrimination. The Cole-Cole representation has gained popularity as the model to determine time constants for the separation of responses due to clays, graphite and metallic-luster (sulfide) minerals. Electrochemical models have been developed which utilize parameters associated with the generation of IP responses such as: Warburg impedance, double layer capacitance, charge transfer resistance, etc. New models will be developed as more work is completed to determine the electrochemical sources for the IP response.

Reconnaissance IP (RIP) or vector IP (VIP), developed by Kennecott around 1970, has been resurrected and is used extensively for regional porphyry exploration.

The effects of IP on transient or time-domain EM (TEM) measurements (Hohman and Newman, 1990) are unwanted and methods are being devised to eliminate these effects. This situation is similar to the removal of EM coupling from IP data. A lot of information in the EM coupling response is being discarded. Likewise, there is useful IP information in the TEM measurements that is presently not utilized. Perhaps methods will be discovered that in the near future will enable the removal and use of this information as a diagnostic tool.

Electrical resistivity tomography (ERT) and electrical impedance tomography (EIT) are developing areas in the use of resistivity and IP. Configurations include surface-to-surface, surface-to-downhole, and cross-hole arrays.

NON-TRADITIONAL IP MEASUREMENTS

There has long been a desire to focus more vertically than is possible with conventional IP arrays. Recently, considerable interest has "focused" on obtaining IP information from controlled source audio-frequency magnetotelluric (CSAMT) measurements (Carlson et al, 1994), and natural source magnetotelluric (MT) measurements (Morrison and Gasperikova, 1996). It appears that one of the easiest ways to get IP information from CSAMT data is to use a synchronous system (receiver and transmitter synchronized together) and measure the phase of the lowest frequency used, say 0.125 Hz. One can consider this as an offset gradient array, which appears to work quite well in areas where ground resistivity is moderate to high (above 20 ohm-meters). Because of the inherently low signal levels, data quality, particularly in measurement of second order effects, presents additional challenges. Long sample times, infield processing and QC procedures may provide a solution.

Another developing area is the use of IP in ocean floor exploration for both mineral and environmental concerns. The USGS (Wynn, 1997) has been successfully experimenting with towed arrays in searching for titanium and other heavy-metals-rich sand deposits.

Zonge has been using a "ZETA " (Zonge Electrical Tomography Acquisition) time domain resistivity/IP system, which uses up to 30 electrodes or more with relatively short dipoles to rapidly obtain high quality data in environmental surveys (2500 or more stations per day) at low cost. More recently they have developed a frequency domain (CR) "ZETA" system for M.I.T. that has broadband capability. In the past, time domain has been used as a way around the inherent frequency domain EM coupling problems. This system appears to solve that problem.

RESISTIVITY AND IP MODELING AND INVERSION

One of the fastest developing areas, with the advent of the Pentium PCs, has been 2- and 3-D forward and inverse modeling. Finally, computers have enough speed and memory capacity to make complex 2- and 3-D modeling both time and cost efficient.

The further development of 2- and 3-D inversion code will be a major factor over the next several years, and this may be more important than improvements discussed previously for instrumentation. But remember, 3-dimensional modeling and inversion mean using instrumentation that can acquire large volumes of data and this acquisition must be economical enough for general use. Again the circle returns to developments in instrumentation.

Improvements in modeling and inversion will make interpretation more accurate and easier for geophysicists trying to explain the data to a project geologist. Some practitioners still interpret pantleg effects (inverted V-shaped anomalies due to measurement geometry) as real features and place drill holes on them. However, the standard resistivity/IP pseudosection for D-D and P-D arrays will soon be a thing of the past and will be used primarily for assessing data quality and as a step prior to data inversion.

Topography has probably played a larger role in the distortion of dipole-dipole and pole-dipole resistivity and IP data than previously realized. For example, Figure 1 shows a 100 ohmmeter homogeneous section with topography. Figure 2 is a pseudosection of dipole-dipole resistivity data acquired over the model in Figure 1. Figure 3 is the inversion of this data assuming a flat earth. Notice there is no correlation between this section and the 100 ohmmeter model section. Figure 4 shows the inversion results when topography is used in the inversion routine. These data plots are from MacInnes and Zonge, 1996.

Figure 5 shows inversion model data from a very rugged area in Papua, New Guinea. Data at depth are limited and topography was not considered in the processing. Correlation between observed and calculated data is excellent, and a strong conductive source is indicated at about 19660 along line at a depth of 225 to 300+ meters.

Figure 6 contains the same observed data but the inversion was carried out taking topography into account. Again correlation of the observed and calculated data is excellent; however, the derived model is significantly different from Figure 5. The conductive source is now clearly centered at about 19840, a distance of 200 meters perpendicularly from the nearest surface approach. This is a known ore deposit whose location is documented.

A note of caution, even when topography is available: we must be diligent in determining whether results make good geologic sense, as the computer can generate beautiful, mathematically correct, color sections that do not accurately reflect geology or mineralization.

SUMMARY

The next few years will be exciting from the standpoint of new equipment development and progress in 2- and 3-D inversion software. It may not be too long, however, before most instruments in electrical geophysics will be basically the same and the major differences will be in the software.

This year is the 56th anniversary of the "proof of concept" of the IP method in the laboratories of Newmont, and the 55th year since the first IP measurements were made at San Manuel, Arizona. With the future predicted to have more changes and advances than the past, the journey for electrical geophysics should be more than interesting.

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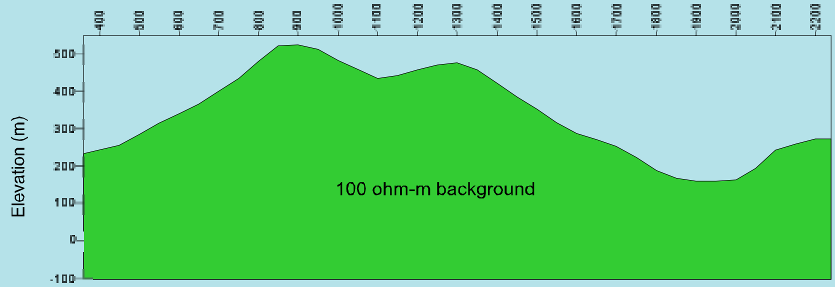


Figure 1: 100 ohm-m homogeneous section with topography.

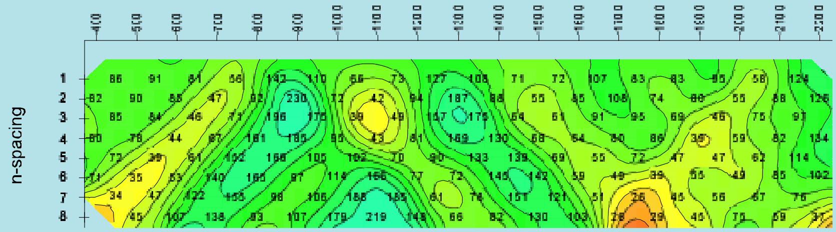


Figure 2: Dipole-Dipole pseudosection of resistivity data calculated for the 100 ohm-m model in Figure 1.

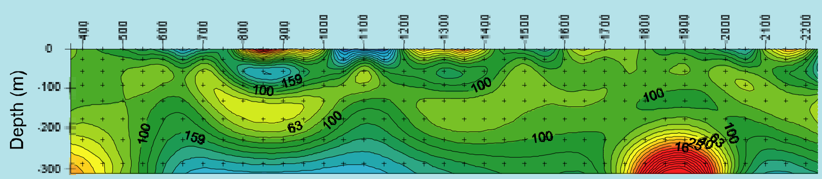


Figure 3: Inversion of data from the pseudosection in Figure 2, without topography.

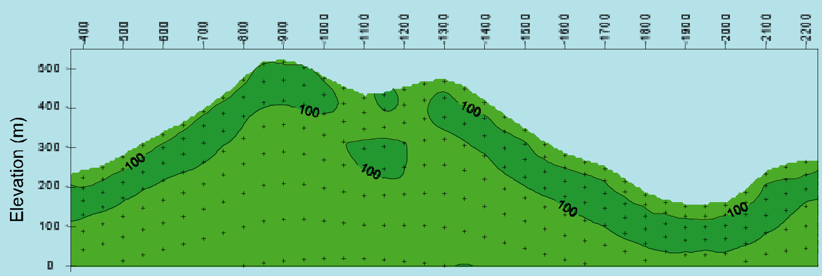
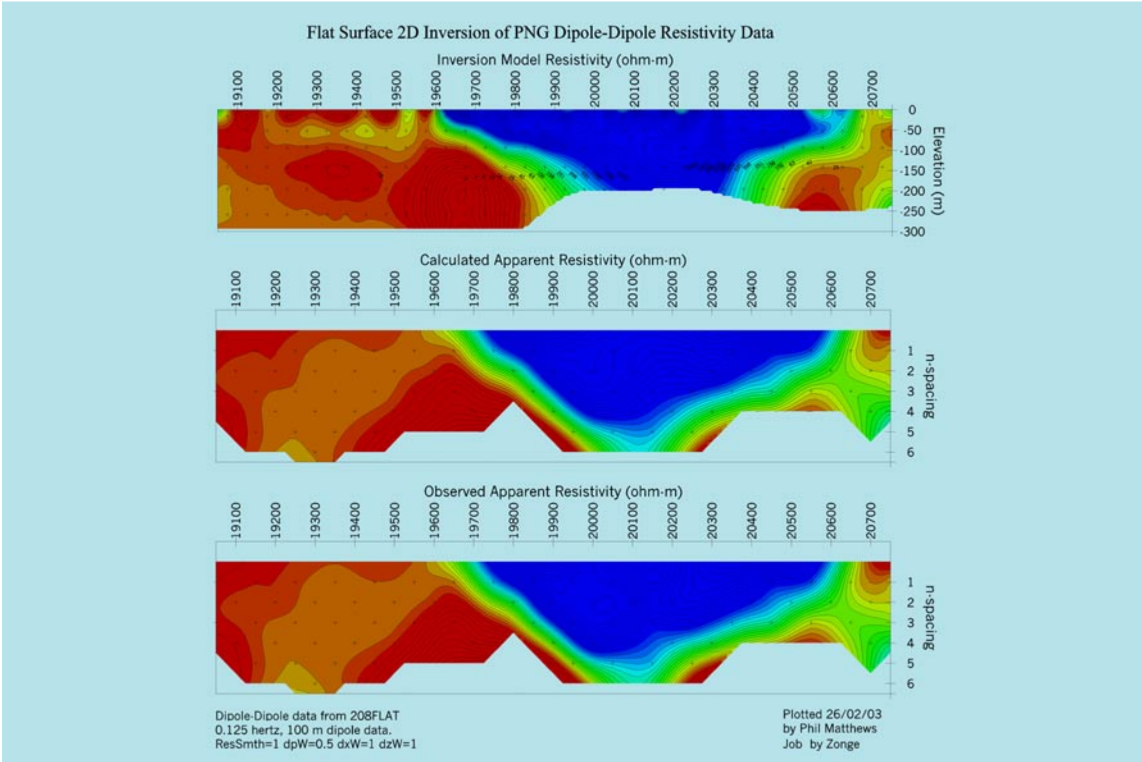
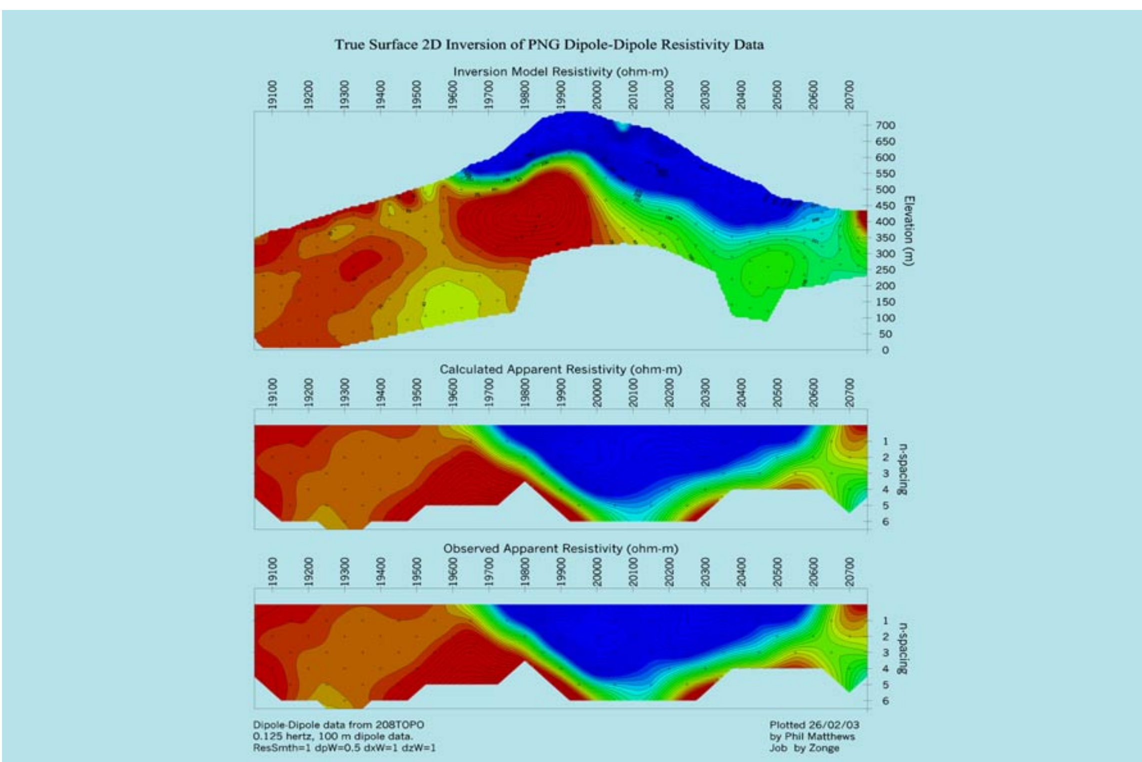


Figure 4: Inversion of data from the pseudosection in Figure 2, with topography.


Flat Surface 2D Inversion of PNG Dipole-Dipole Resistivity Data
Inversion Model Resistivity (ohm-m)
Elevation (m)
Calculated Apparent Resistivity (ohm-m)
n-spacing
Observed Apparent Resistivity (ohm-m)
n-spacing
Dipole-Dipole data from 208FLAT
0.125 hertz, 100 m dipole data.
ResSmth=1 dpW=0.5 dxW=1 dzW=1
Plotted 26/02/03
by Phil Matthews
Job by Zonge


True Surface 2D Inversion of PNG Dipole-Dipole Resistivity Data
Inversion Model Resistivity (ohm-m)
Elevation (m)
Calculated Apparent Resistivity (ohm-m)
n-spacing
Observed Apparent Resistivity (ohm-m)
n-spacing
Dipole-Dipole data from 208TOPO
0.125 hertz, 100 m dipole data.
ResSmth=1 dpW=0.5 dxW=1 dzW=1
Plotted 26/02/03
by Phil Matthews
Job by Zonge