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STATE OF THE ART IN IP AND COMPLEX RESISTIVITY

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ABSTRACT

Since the crash of copper prices in 1983, little research has been done concerning the source and nature of the induced polarization (IP) response, and until the last several years there has been little interest in disseminated sulfide (porphyry copper) deposits. 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.

Even though there has been a lack of interest in IP and IP research during the past 12 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 a valid IP response and electromagnetic (EM) coupling effects.

INTRODUCTION

The most significant advancements in IP and complex resistivity (or spectral IP) over the past 10 years have not been in theory or practice, but rather in development of sophisticated instrumentation, for both receivers and transmitters, and the development of robust data processing, modeling, and inversion code.

The crash of copper prices in 1983 followed by the steep decline in oil prices in 1985, and the resulting dissolution of the minerals divisions of major oil companies, sharply curtailed all the IP and complex resistivity research work that was in progress at that time.

IP surveys are now being used on a worldwide basis, and will continue to be used effectively whenever disseminated sulfides are the target. Recently IP has been examined for use 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. *Electrical Engineering Times* predicted that by 1982 about 60% of the market would be for instrumentation which contained microprocessors. That percentage was reached well before 1982, and today virtually everything has at least one microprocessor in it, including greeting cards and some children's toys.

What has been one of the largest driving forces to reduce the cost and size of computers and computer controlled instrumentation, aside from the development of high-speed microprocessors (MPUs)? It has been the low cost of memory. In 1975 memory was selling for 50 cents to $1 per byte. Today, 32 megabytes of memory for a desk-top PC sell for about US$150, or about 5 ten-thousandths of a cent per byte, or 5 microdollars per byte. By the time this paper is published, the cost of memory will probably be significantly lower.

Today, the computer industry is still forging ahead at an unprecedented rate. Several years ago computer companies were announcing major new developments about every 18 months: now announcements come every 12 months or less. This rapid activity is a constant challenge to keep up with the industry and to predict what the future holds.

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

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development to run these new devices can take an inordinate amount of time and money.

The original goal 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 geophysicist have a perceived need to gather time-series data (raw, digitized waveforms) in the field and then run the data 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. However, recording all of the time-series waveforms for one day's worth of time-domain or frequency-domain IP data can take more than one gigabyte of data storage.

With this much data being recorded, how can data be rapidly transferred from the field receiver to an office or camp computer?

1. Serial port? No, too slow.
2. Parallel port? Possibly. The new Enhanced Parallel Port (EPP) hardware and software can transfer data at a rate of about 1 megabyte per second (MB/sec).
3. Direct bus connections? Possibly, but extreme care must be taken not to expose the bus to the elements while in the field.
4. Removable hard drives? Again, possibly, but a removable hard disk means that the operator will have to break the environmental seal on the receiver to remove the disk, which could cause any number of headaches.
5. Design network hardware into each receiver system. This is a definite possibility, perhaps using an infrared port for complete isolation.

Whatever the solution, one must be able to move data at a rate close to 1 MB/sec or higher.

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). Most units have 16 bit analog-to-digital converters (ADCs), signal detection levels in the tens of microvolts, or lower, and have limited 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.

What can be done to improve existing instrumentation?

1. Improve signal-to-noise ratio. ADCs with more bits of resolution and low-noise operational amplifiers.
2. Use smarter and faster in-field processing for data quality assessment.
3. Increase data storage capacity.
4. Make the units smaller and lighter. Utilize new types of battery packs.

Following are some of the new devices that will affect future instrumentation and will be used to implement the improvements listed above:

- Sigma-delta analog-to-digital converters. Improve signal-to-noise ratio with 24 bit, 96 kHz conversion rate. Development of these devices is being fueled by the audio industry.
- ASICs (Application Specific Integrated Circuits). Reduces chip count, enlarges available board space, reduces power and permits the engineer to make his own custom circuit design.
- Gigabyte hard disks. Now available in lap-top PCs, so they are small and low power and can be put into portable geophysical receivers.
- Lithium-ion rechargeable batteries. These high energy density batteries are being fueled by the laptop PC market. They are not yet available for general usage, but they will be soon.
- LCD liquid crystal displays. The new ones are small, low cost, low power, have wider temperature ranges, and higher contrast. Some have backlit screens for night operation.
- GPS receivers for positioning and synchronous timing. These are already being used to a limited extent. GPS systems will be an integral part of all geophysical instrumentation in the near future.

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 survey configurations use the dipole-dipole (D-D) and pole-dipole (P-D) arrays for profiling, and gradient arrays for generating plan maps delineating lateral changes.

Electrical resistivity tomography, or ERT, is a developing area in the use of resistivity and IP. Configurations include surface-to-surface, surface-to-downhole, and cross-hole arrays.

Reconnaissance IP (RIP) or vector IP (VIP), developed by Kennecott around 1970, is being resurrected and used extensively for porphyry copper exploration. Arrays include the traditional *wagon wheel* which uses a transmitter bipole of about one km in length, and orthogonal receiver dipoles spaced about 1.5 km away from the center of the transmitter bipole, and oriented at plus and minus 45° about a line drawn from the center of the transmitter bipole to the receiver site. The receiver sites are spaced uniformly around the transmitter, like spokes on a wheel (usually about 8 stations per wheel). Another variation is a broadside array which uses a one- to two-km long transmitter bipole, and a number of orthogonal dipole measuring stations spaced on a one-half to one-km grid off to one side of the transmitter bipole, and extending up to 8 km away from the transmitter site.

Another developing area is the use of IP for 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.

The main reason for developing multi-frequency IP (complex resistivity or spectral IP), was two-fold: first, to be able to remove EM coupling effects from IP data, and second, to try 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. New models will be developed as more work is completed to determine the electrochemical sources for the IP response.

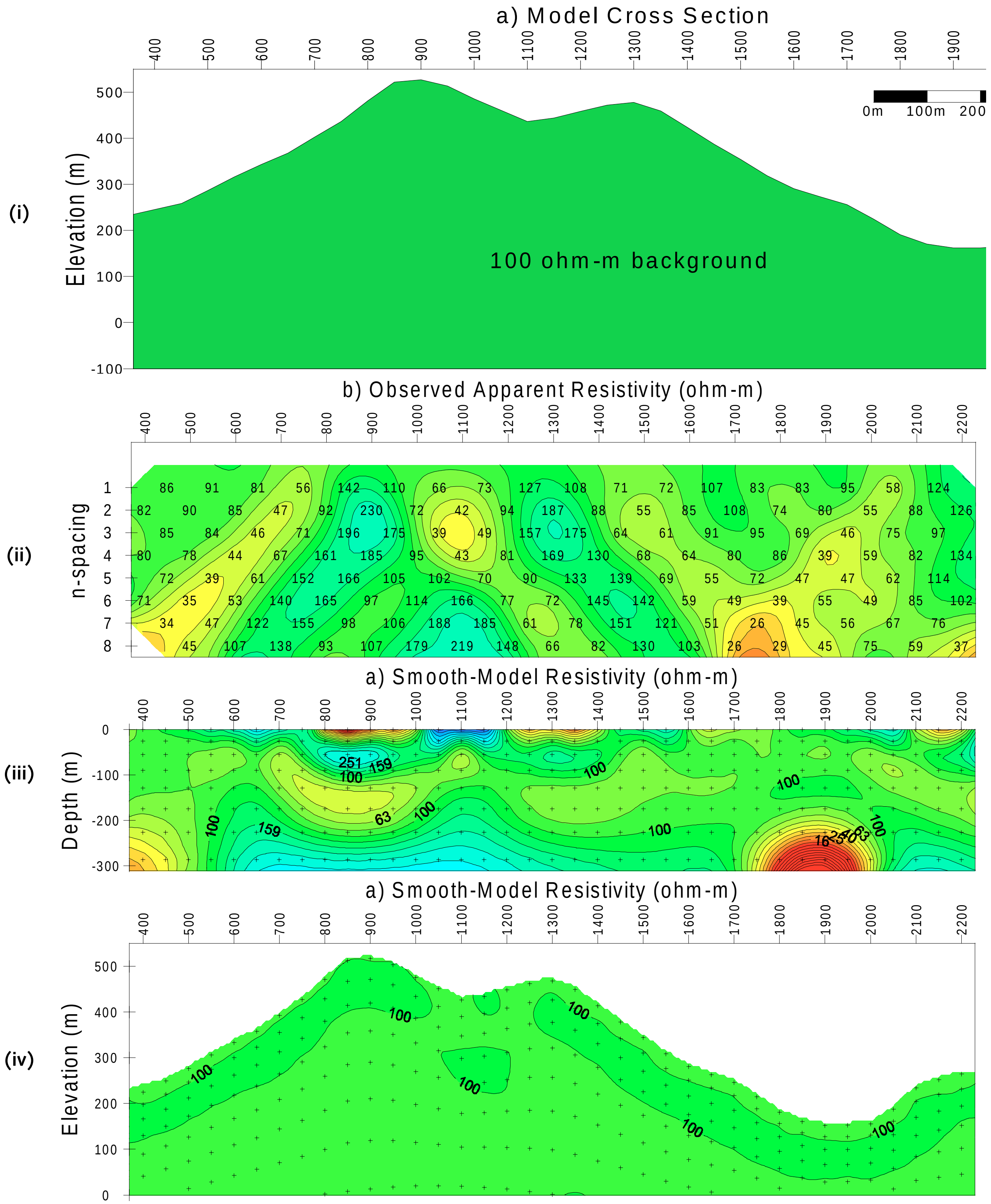

Figure 1: *(i) A 100 ohm-m homogeneous section with topography. Vertical and horizontal scales are equal.* ***(ii)*** *A dipole-dipole pseudosection of resistivity data calculated for the 100 ohm-m model in Figure 1.* ***(iii)*** *Inversion of data from the pseudosection in (ii) without taking topography into account.* ***(iv)*** *The inversion results when topography is used in the inversion of data from (ii).*

NON-TRADITIONAL IP MEASUREMENTS

Recently, considerable interest has been expressed in 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 the 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).

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. There is a lot of information in the EM coupling response being discarded. Likewise, there is useful IP information in the TEM measurements that is presently considered noise. Perhaps a method will be discovered in the near future that will enable the removal and use of this information as a diagnostic tool.

RESISTIVITY AND IP MODELING AND INVERSION

One of the fastest developing areas, with the advent of the Pentium PCs, has been the progress made in 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 development of 2- and 3-D inversion code will be a major factor over the next several years, and this development may be more important than the improvements discussed above for instrumentation. But remember, 3-dimensional modeling and inversion means using instrumentation that can acquire large arrays 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 to understand for project geologists as well as 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. The standard resistivity/IP pseudosection for D-D and P-D arrays will soon be a thing of the past and will be used only 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 ohm-meter 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 ohm-meter 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.

A note of caution: as with all computer generated data, be diligent in determining whether the results are good or bad, since the computer can generate beautiful color sections that are completely worthless.

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 50th anniversary of the "proof of concept" of the IP method in the laboratories of Newmont, and the 49th year since the first IP measurements were made at San Manuel, Arizona. With the next ten years predicted to have more changes and advances than the past ten, the journey for electrical geophysics should be more than interesting.

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