ELECTRICAL IMAGING,
An Old Technology Effectively Modernized

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Introduction

Electrical imaging represents a re-emergence of an old technology. The technology has been hampered by high cost compared to other methods. However, through advances in field equipment design capability, and the development of computer algorithms necessary to effectively and accurately reduce and present the geophysical data, electrical imaging is now cost competitive with more commonly used geophysical techniques. The new and future applications of this technique for the efficient development of groundwater resources will change the way groundwater aquifers are exploited and managed.

Choice Geophysical Methods

The use of electrical resistivity measurements has been a favorite tool of geophysicists for over 200 years because of the wide range of resistivities values found in nature. Resistivities in various geologic settings can be found ranging from less than 1 ohmmeter for ore bodies to over 10,000 ohmmeters for precambrian gneisses. This represents a greater dynamic range for this technique than most other commonly used methods as shown in Table 1 (data from Jakoski, 1950 and Carmichael, 1989).

Table 1

Method	**General Minimum**	**General Maximum**	**Units**	**Range** (orders of magnitude)
Seismic	200	7,000	Feet/second	1
Resistivity	0.1	10,000	Ohmmeters	5
Gravity	0.8	8.2	Grams/cubic cm	1
Magnetic Succeptibility	5	500,000	Unitless	5

Only magnetic succeptibility has an equal range, and magnetic succeptability is not normally evaluated in field investigations. Despite its range, however, the resistivity method has not been effectively exploited to make use of the available wide variations in this property. There are several historical limitations that have inhibited a more broad use of this method.

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Historical Electrical Methods

The utility of resistivity techniques has not received widespread attention in recent years because of its excessive costs in data collection, interpretation and presentation relative to other, more popular geophysical methods. Collecting resistivity data requires putting an electrical current into the ground (measured in amps) and measuring the potential (voltage). With these two values, an apparent resistivity of the subsurface can be established. The classic applications of resistivity techniques are discussed in several documents, which the reader can examine in detail (Van Nostrand, and Cook, 1966), but are summarized herein.

The most popular techniques of data collection require the use of four electrodes, which are moved for each measurement. When one person is employed monitoring the current and potential values, two people are employed moving the electrodes. Therefore, data collection typically requires a three-person crew. A good crew is capable of performing a measurement every 4 to 5 minutes.

When the spacing between electrodes is maintained constant and the locations are moved across the ground surface, a profile of apparent resistivity values across an area can be developed. When the spacing between electrodes is varied around a central location, a sounding of apparent resistivities is developed. By spreading the electrodes further apart for each measurement, the resistivity method measures deeper into the subsurface.

Both profiling and sounding methods measure apparent resistivity. This is a measurement that encompasses the entire volume of subsurface being effected by the measurement. The resistance, which can be related to geology in the subsurface, is typically established by modeling various geological features (depth, thickness, resistance). This inversion process is used to re-create the setting that caused the measured apparent resistivity. For sounding data, the apparent resistivity was compared to "type curves" to develop an interpretation of the layers in the subsurface. In the 1980s modern computer methods were being applied to the model problem.

Historic Limitations

Historically, the steps that went into developing resistivity results and the limitations inherent in the method were poorly understood outside of the geophysical community. Because of the apparent complexity of the technique (and variability of interpretation), resistivity results were at times compared to "black magic" by those who did not understand the methods employed.

Profiling methods measure the lateral variation in apparent resistivity, but do not easily provide insight into true actual resistivities. Profiling has generally been replaced in near surface investigations with electrical conductivity surveys, which are collected in a much more rapid fashion.

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Sounding methods, which have not been replaced by electromagnetic conductivity, develop a vertical picture of the subsurface, which geophysicists model or invert to develop an interpretation of subsurface resistivity. A technically weak spot for geophysicists performing resistivity surveys has historically been limited success in the integration of sounding and profiling techniques. Computer programs, which attempted to merge the two methods, were slow and hampered by the computer technology of the day.

Improvements

Hardware

In 1981, Barker published a paper (Barker, 1981) suggesting that a multi-electrode cable could be used to measure resistivities using electrode offsets, which reduced known deficiencies of the Wenner resistivity array. The use of a multi-electrode cable allowed multiple electrodes to be placed into the ground before any measurements were performed. This could be done with one or two people, which resulted in smaller data collection crew size.

Bison commercially presented the multi-electrode Bison Offset Sounding System (BOSS), which implemented Barker's ideas. With the BOSS, many electrodes were placed into the ground and a manual switch selected various electrode combinations. The BOSS collected data faster than most other resistivity data collection methods, but suffered from data quality difficulties. The approach also provided an integration of sounding and profiling methods.

Full automation of resistivity data collection came from Advanced Geosciences Inc. (AGI) of Austin, Texas. In 1994, AGI presented a programmable microprocessor controlled switching system (SWIFT) with data collection memory built into a resistivity meter (STING). Using an electronic switching system instead of a multi-core cable, the Sting/Swift system overcame several of the limitations of the BOSS System. The Sting/Swift equipment accelerated data collection from five minutes per measurement to to four measurements per minute. By performing multiple measurements within this time window, a mathematical evaluation of the measurement quality can be provided.

Software

In the 1970s, programs written in Basic were available to invert resistivity soundings. An experienced geophysicist was needed to define the resistivity answer for the model to start with, so the algorithms could refine the human conclusions. By 1990, the state of the industry had evolved to the place where the inversion programs could be used with minimal human initialization. All that was needed was a kernel function. Generally, computers were not used to present profiling information.

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In 1996 (Loke and Barker, 1996), a rapid least squares data inversion method was introduced. Starting with a homogeneous earth model during the first iteration, a partial derivative calculation contrasts the earth model with the field data. The homogeneous earth model reduces the need for an experienced person to establish a starting point. Subsequent iterations estimate partial derivatives of the model. This mathematical manipulation reduces the use of computer time and memory space by eight to twelve times as compared to the traditional least-squares method of modeling. The result is a two dimensional earth profile built from mathematically modeled resistivities.

Improving the efficiency of the computer programs, at a time when computer hardware was becoming more efficient, resulted in an exremely powerful tool for the inversion of electrical imaging data. Several commercial software companies are using the basic mathematical technique to provide high quality products to the geophysical industry.

IMPACT

Delineation of fractures

When the Sting/Swift equipment is applied to mapping fault locations to position high yield wells, the EI method has been successful by delineating subsurface boundaries and bedrock fractures, which are groundwater flow pathways. The method has proven itself cost effective in data gathering and interpretation and in providing increased understanding of subsurface features. The following examples show some of the successful applications of EI.

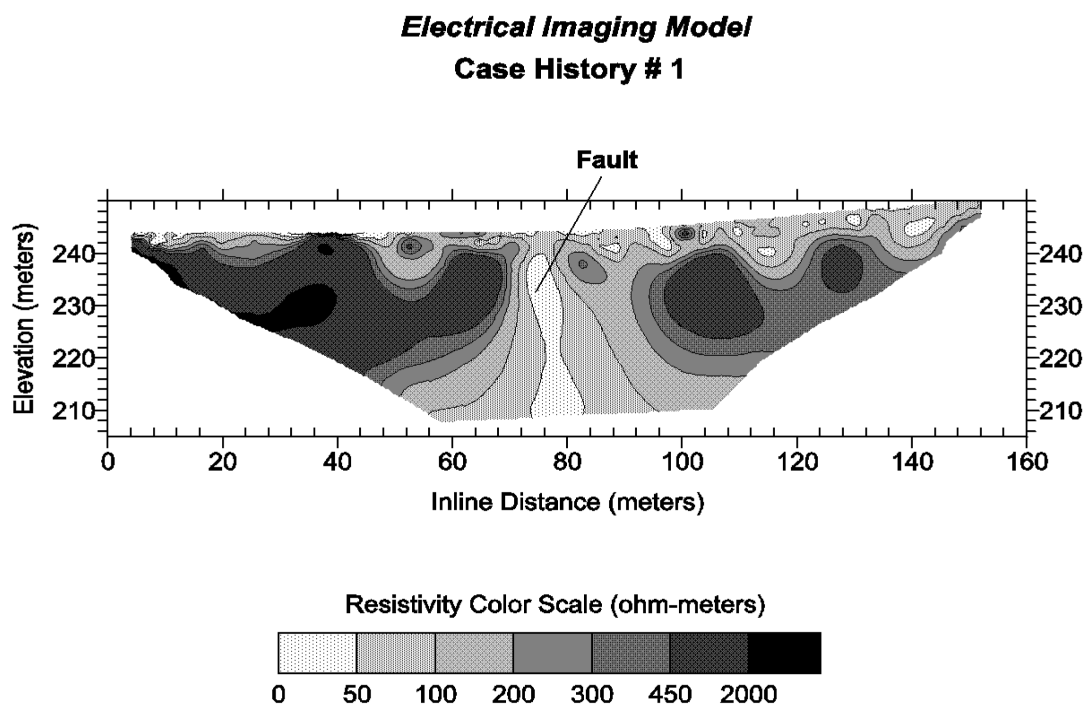

Figure 1 – Electrical stratigraphy model showing a bedrock fault .

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Example #1

An industrial client near Shady Grove, Pennsylvania, was performing a groundwater investigation. A geologic fault with a north-south orientation had been mapped by the Pennsylvania Topographic and Geologic Survey (Root, 1968) between the carbonate Shady Grove and the Zullinger Formations. This fault contact was mapped coincident with a topographic change (higher elevation to the east) and an unusual V-shaped water table configuration suggesting preferential groundwater flow to the south. EI was used to help select well locations along the fault where preferential groundwater flow was expected. The EI survey was conducted in a direction perpendicular to the mapped fault for the purpose of determining how the suspected fault would be revealed and to site wells. Data from four EI traverses were collected at a spacing of 6 meters between electrodes. This resulted in the collection of 1,320 total meters of data at the site.

A fracture or fault would be expected to have a low resistivity relative to the predominant matrix due to higher moisture content of weathered materials. The resulting EI profile (Figure 1) clearly indicates the location of a resistivity low depicted by light gray. Wells drilled subsequent to the EI survey demonstrated the presence of the fault and resulted in abnormally high yields relative to other wells in the area.

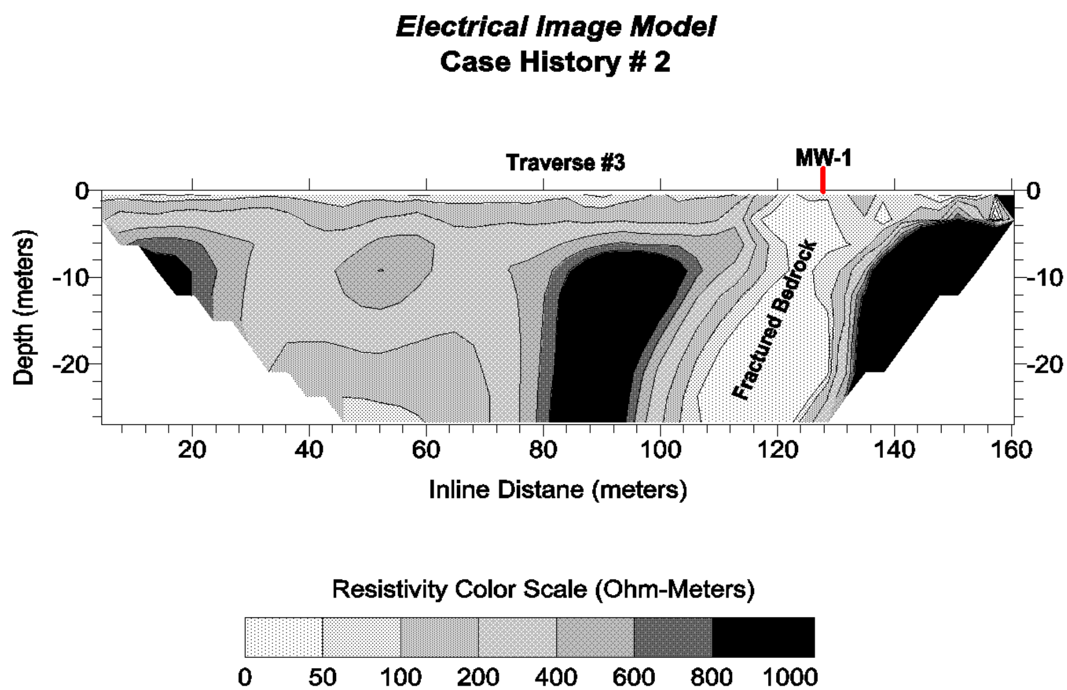

Figure 2 – EI Model for Limestone Bedrock Fractures and Solution Features.

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Example #2

At a petroleum tank farm, groundwater flow occurs primarily through conduits in the solution-prone limestone bedrock. The investigation was performed to evaluate the location and distribution of subsurface migration pathways expressed as linear tonal patterns (fracture traces) on aerial photographs. The purpose of the work was to define migration pathways of hydrocarbon in the soil and groundwater for remedial design. As such, the location and trend of bedrock fractures were critical to placing monitoring wells where they would accurately characterize groundwater flow for designing a remedial approach.

Groundwater quality at the tank farm had been impacted by hydrocarbons. Weathered gasoline was present in the groundwater in a 105 by 150 meters plume centered near a monitoring well (MW-1). The historically highest detected dissolved hydrocarbon concentrations had occurred at wells MW-1.

The specific EI investigation included measurement and analysis of four parallel traverses oriented across the path of groundwater containing hydrocarbons. The reason for exploring this area was to pinpoint the location of fractures that provide groundwater flow conduits. The four profiles resulted in approximately 685 linear meters of surveyed section to a depth of approximate 15 meters.

The electrostratigraphy model from processing Traverse 3 is presented on Figure 2. Areas of high resistivity (greater than 800 ohmmeters) were interpreted as competent limestone. Areas of moderate resistivity (200 to 800 ohmmeters) were interpreted as less competent (partially fractured and/or solutioned) limestone. Zones with lower resistivity (between 50-200 ohmmeters) were interpreted as areas of soil, fractured limestone, and/or solutioned limestone. However, these areas may also be interpreted as soil where low resistivities occur near the ground surface. Finally, areas where resistivity was less than 50 ohmmeters were interpreted to represent potential soils, very fractured rock, or mud filled voids.

Data evaluation at Traverse 3 suggested shallow bedrock beyond 110 meters inline distance. Resistivity readings suggest that approximately 2 to 3 meters of soil cover is present from 0 to 110 meters inline distance. Three nearly vertical zones of competent limestone were interpreted along the traverse. A large zone of fractured limestone was suggested between 105 and 125 meters inline distance, near well MW-1. Within this fractured limestone, a low resistivity was measured at 15 meters below grade level. This zone could be interpreted as very fractured limestone and/or a mud-filled void in the bedrock.

There appeared to be a good correlation between the surface expression of fracture traces identified from air photographs and the interpreted EI sections. The conceptual hydrogeologic model based on the fracture trace analysis and the EI survey results were utilized in the design of a groundwater remediation approach for the site.

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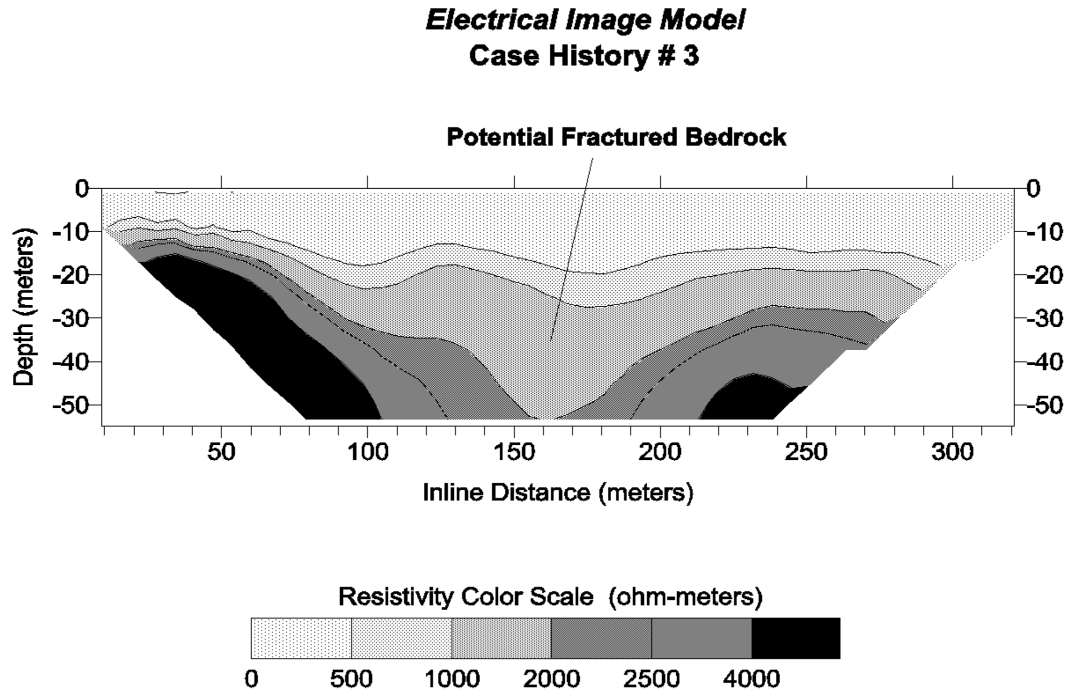

Figure 3 – Electrical Stratigraphy Model for Example # 3.

Example #3

This case history presents the results of a geophysical investigation conducted by SAIC in July 1998 in Waverly, Iowa. The work was performed to support an investigation to site a municipal water supply well for the city of Waverly.

In the Waverly area, groundwater flow occurs primarily through fractures in the limestone bedrock. As such, the location and trend of bedrock fractures are critical in placing water supply wells to obtain the highest sustainable yields. Photo lineaments (fracture traces) were observed on aerial photographs, suggesting fracture bedrock zones beneath the areas. An EI survey was performed to characterize the bedrock under the photo lineaments.

Four EI traverses were conducted so that they transected the photo lineaments. Data were gathered utilizing a spacing of 6 meters between electrodes. This resulted in the collection of 1,320 total meters of data at the site.

The best fracture target was identified on Traverse 1 (Figure 3), which shows a low resistivity zone at depth at an inline distance of 162 meters. The resistivity lows correlate well with the observed photo lineaments and are interpreted as fractured bedrock

Based on the EI and the photo lineaments, the best drilling location was selected. A test well was drilled in September 1998, which encountered a large fractured bedrock zone. A short-term pumping test suggested a yield of approximately 2000 gallons per minute. A permanent water supply well is planned for the spring of 1999 in that location.

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Summary

The examples presented within this paper show the application of EI to the identification, confirmation and mapping of bedrock fractures. The same kinds of information can be developed for lithologic information. The EI method has been proven an effective tool for evaluating the subsurface on many sites. In particular, EI appears to be a solution to pinpointing well sites on fracture locations. EI measures the earth resistivity in detail, along a profile, in a fraction of the time required by the older resistivity method familiar to some. In addition to improvements in data gathering, computer interpretation of the raw (apparent resistivity) data enables inversion to true resistivity, which increases the correlation to lithology.

As discussed previously, the identified electric boundaries separating layers of different resistivities may or may not coincide with boundaries separating layers of different lithologic composition. This may result in the electrostratigraphy varying from the gross geologic stratigraphy. Therefore, caution should be exercised when reviewing geoelectrical cross sections. If these limitations are taken into account in planning, implementing, and interpreting a survey, EI can continue to be a cost-effective tool for fractured rock characterization.

New advances in EI will allow for three-dimensional surveys and cross-borehole surveys, which will make this technique even more successful for fracture characterization. In areas where very complex subsurface features are present, three-dimensional survey data collection techniques and data inversion software have recently been developed. Also, the resolution of electrical surveys carried out with electrodes on the ground surface decreases exponentially with depth. One method to obtain reasonably good resolution at depth is by making measurements with the electrodes in boreholes. New downhole cables have recently been developed to allow for downhole data collection. These techniques will allow for the use of EI for a much wider range of applications to obtain susburface information.

Today, many companies provide “silicon” products for use in the geophysical industry. Few of these companies, were around in 1980. With the advances in silicon products of these and similar companies and the continued improvements in data collection techniques, algorithms and personal computers, resistivity can again reassume its position as a leading geophysical tool. Resistivity, in the form of electrical imaging, should be considered a new, cost competitive, geophysical technology for the twenty first century.

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Mr. Hoover has over 30 year's geophysical experience, and is currently employed by Dawood Engineering. Mr. Hoovers' experience ranges from environmental and engineering applications to near surface problems, exploration for oil and gas production, to research and development for a major oil company. Technical responsibilities have included all aspects of the geophysical industry, ranging from data acquisition, processing, data interpretation, and reporting. Surface Geophysical experience includes seismic reflection and refraction, resistivity, electrical imaging (EI) electromagnetic (including EM-31, EM-34, EM-61 and VLF), magnetometer and gradiometer, gravity, ground penetrating radar (GPR) and a variety of utility locating tools. Borehole geophysical experience includes the use of resistance, resistivity, SP, gamma, neutron, caliper, temperature, sonic, density, dipmeter, and televiewer data and equipment.

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