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CHOOSING APPROPRIATE GEOPHYSICAL EQUIPMENT FOR GEOTHERMAL ENERGY EXPLORATION

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ABSTRACT

Many projects using earth science methodologies apply geophysics as a surface investigation tool for studying buried or concealed geologic features and economic resources. The availability of modern geophysical instrumentation and data interpretation software is often critical to the success of these projects. However, most projects using geophysics lack the resources to evaluate, purchase, maintain, and provide training for geophysical equipment and software. Hence prudent choice of exploration geophysical equipment and software tools is essential.

The purpose of this paper is to provide the reader an in-depth understanding of how geophysics is used to explore for geothermal resources. We first introduce the reader to various systems used to collect geophysical data. We then explain in general terms the capabilities and limitations of geophysical systems. Next, we expound on the various elements involved in planning and then executing investigations using geophysical equipment. Finally, we explain the different aspects of quality control and quality assurance of geophysical systems and present various approaches for demonstrating and documenting findings from use of geophysical systems. The proper selection and application of surface geophysical techniques for achieving quality data cannot be overstated. Obviously, a wide range of available equipment is desirable. Unfortunately, it is difficult to judge the most appropriate instrument for a particular geophysical job. This paper tries to highlight some of the geophysical equipment on the market, their capabilities and weaknesses.

1. INTRODUCTION

Geophysical techniques offer many advantages and they are always part and parcel of the geothermal exploration campaigns. However, geophysical instruments are useful only when they are operated correctly and efficiently. New or potential users want to obtain effective results as rapidly as possible and experienced users are constantly seeking to improve the results of geophysical surveys. In geophysical exploration, the selection of the equipment, personnel, and procedures used to detect and locate anomalies greatly affects the efficiency and effectiveness of the geophysical survey.

1.1 Effectiveness

The degree to which the geophysical process meets or exceeds the needs and requirements of the stakeholders (owner, client, and public). It answers the question, *"How well does the geophysical system perform?"*

1.2 Efficiency

The degree of effectiveness of the process compared to the resources used. Optimizing efficiency leads to customer satisfaction by minimizing time and cost and maximizing value. It answers the question, *"How long does it take and how much does it cost?"*

Geophysical detection and positioning methods range from basic to more complex. The simplest methods utilize handheld instruments that alert the operator to anomalies with a visible or audio signal. The operator records the anomaly location with a pin and flag. More sophisticated devices acquire geophysical data using self-recording instruments. The data is post-processed to identify anomalies for further investigation. The methodology selected should ultimately be the one that will meet the performance objectives for the response action and should be able to detect the items of interest to specified depths. Because there are relatively wide variances in both the capabilities and cost in currently available geophysical investigation technologies and procedures, trade-offs between effectiveness and efficiency may be necessary. These trade-offs should be understood and explicitly incorporated into the decision-making process as necessary.

Before one decides to purchase geophysical equipment one needs to base this on the need, its application and experience from its usage by other people. Further, once one has identified the equipment and its manufacturer it is important to decide on the model, considering its capabilities and if those extra features are worth the extra cost being attached.

In this paper we use the term *geophysical equipment/systems* to define the entire "package" of tools and procedures used for a given project, or used to meet a specific project goal. The term *geophysical equipment/systems,* therefore, can be thought of as the collection of tools and procedures that are finally selected for use from the array of technologies and deployment options available on the market.

2. AVAILABLE GEOPHYSICAL SYSTEMS

Geophysical technologies currently supported fall within the general categories of geoelectrical methods, potential-field methods, and electromagnetic field methods. Part of the geophysicist job is (1) anticipating and sourcing for new and emerging geophysical technologies that his job will need within the next few years, (2) evaluating and recommending purchase of new geophysical equipment and software, (3) maintaining geophysical equipment and laboratories and (4) providing geophysical training and outreach. For example, some of the new and geophysical technologies that have been developed, tested and applied for geothermal energy exploration over the last ten years by the scientific research communities world-wide include: (1) high-resolution aeromagnetic (HRAM) surveys for mapping faults, folds, and lithological variations within near-surface sedimentary units, and for adding new detail to bedrock geologic maps; (2) conventional ground and airborne electromagnetic (EM) and time-domain electromagnetic (TEM) methods for identifying subsurface geology and groundwater conditions through measurements of electrical conductivity over a range of shallow depths (down to 500-700 m); and (3) Magnetotelluric (MT) and audiomagnetotelluric (AMT) sounding for mapping conductivity structure at crustal depths (down to 50 km).

Further, commercial, public-domain and in-house geophysical software packages for general and specific geophysical methodologies are available and these include: (1) the USGS potential-field geophysical software package for the PC, which contains over 300 computer programs and is widely distributed to the public; (2) USGS geophysical software for Unix systems; (3) geoelectrical modelling packages for TEM data and (4) a suite of Windows protected-mode programs for processing and imaging MT data. Many commercial Windows-based geophysical software packages used for gravity and magnetics are also available on the market.

3. METHODOLOGY AND TYPES OF EQUIPMENT IN GEOTHERMAL EXPLORATION

All geophysical systems have inherent strengths and weaknesses. Very seldom will one instrument or system have the best absolute detection rate, the lowest false alarm rate, the highest production rate, and the lowest cost. Hence one needs experience and intuition to get reliable and useful information from manufacturers' manuals to use to select an optimum geophysical system(s). Table 1 lists some geophysical equipment available on the market that has been employed to carry out surface work for geothermal energy exploration. The list is not exhaustive. It should be stressed from the outset that this list is not an advertisement for the corresponding companies but a sampling of what has been used and the author does not in way recommend one type of equipment over its competitor. Rather it serves to bring the point home that a geophysicist faces an enormous task in deciding what equipment to procure for a geothermal exploration project.

TABLE 1: A list of some of the available equipment on the market that can be used for exploration for geothermal energy

Category	Equipment
Gravity	La Coste Gravity Meter Scintrex CG-5 Autograv Worden gravity meter
Magnetics	Geometrics G856 Magnetometer Geometrics G816 Magnetometer Scintrex SM4G (Gradiometer) Scintrex SM4 (Total Field) Magnetometer
Resistivity	Terrameter Geonics EM/16/16R Geonics EM34 Soiltest R-40 Soiltest R-60 Metronics EM Zonge TEM Phoenix MT
Seismology	Reftek Seismographs Geometrics ES3000 Seismograph Geometrics ES-1225 Seismograph Geometrics ES-2415F Seismograph

A geophysical anomaly is defined as geophysical measurement(s) that are distinguishable from nearby background measurements. Quantifiable anomaly characteristics are limited to digital geophysical mapping systems and some analogue systems that provide a digital readout of the instrument's measurements. All other systems offer only the ability to use qualitative characteristics to detect and select anomalies. Geophysical systems produce data that offer several advantages in how a geophysical survey can design criteria for detecting anomalies and analyzing the characteristics of those anomalies to decide whether or not they place the geothermal prospect to that recommended for drilling, using their characteristics as the basis in categorizing between "more likely to be associated with geothermal reservoirs" and "less likely to be associated with geothermal reservoirs". In some cases, it is possible to categorize an anomaly as "Not likely to be geothermal reservoirs". Depending on how an anomaly is categorized, a decision can be made as to whether or not the survey should proceed and drilling that anomaly.

A geothermal resource "detectability" is dependent upon numerous factors, but the general rule is, the larger the resource, the deeper it can be detected. Many factors must be considered when evaluating whether a given geophysical system or technique can detect a given geothermal resource at a specified burial depth. Factors that are specific to geothermal resources that affect how deep they can be detected include their size, surface area, volume, weight, and their 3D orientation with respect to the geophysical sensor when the sensor is passed over them. Factors of the geophysical systems that are relevant to the detection depths of geothermal reservoirs include, the physical size of the instrument's transmitter and receiver coils, the operating power of the transmitter coil, the sensitivity of the receiver(s), the measurement/sampling densities, the speed of the survey platform, the distance of the coils above the ground, and the geologic conditions and environmental conditions at the site. For example in magnetic surveys the relevant factors are the sensitivity of the magnetometer, the measurement/sampling densities, the distance of the sensor(s) above the ground, and the geologic conditions and environmental conditions at the site. Lastly, a factor common to all geophysical surveys, both analogue and digital, is how the criteria for anomaly selections are established. Often a trade-off must be made between the total number of anomalies that can be selected for further investigation and the number of low-amplitude anomalies that can be neglected for now.

The maximum possible depth of geothermal reservoir is an important consideration in the selection of an appropriate detection system. There are many cases where a geothermal reservoir can be deeper than geophysical systems can currently reliably detect. At such locations, it is possible that undetected geothermal reservoir remains deeper than it can be detected or if it is detectable the resolution is compromised and interpretation complex.

Detection and location of geothermal reservoirs primarily depends on the ability of geophysical instruments to distinguish the physical characteristics of these reservoirs from those of the surrounding environment. Since a geothermal resource is made of a heat source, fluid reservoirs, permeable and impermeable rocks, no one methodology is able to detect and locate all the parameters associated with the resource. For example the potential methods are better at locating heat sources while the resistivity technique is sensitive to reservoirs since they contain conductive brine. The best currently available detection systems tend to detect at most two types of anomalies. Several instruments currently under development or improvement are to enhance resolution and increase the depth of penetration.

The strengths and weaknesses of some of the equipments on the market are with respect to data collection, maintenance and replacement of malfunctioning parts. Unfortunately, each instrument has different operational limitations and sensitivities, which depend on the subsurface environment. Therefore, it is recommended to use multiple instruments whose data convert to the same primary performance measures. This should improve the confidence that changes in reservoir conditions are real and not affected by the measuring systems themselves. In our discourse, we focus on the two geophysical detection systems currently available and widely used to detect geothermal reservoirs and heat sources, namely resistivity and gravity. We briefly explain why their use is limited to specific parameters within the surface geothermal investigations arena.

3.1 Resistivity equipment

The objective of resistivity data interpretation is to delineate the resistivity variation with depth assuming that the earth is electrically homogeneous and the resistivity only varies with depth and relate them to hydrogeological and thermal structures associated with geothermal reservoirs. From several of these soundings a 1-D or 2-D model is constructed by use of computer inversion programs. We now discuss two resistivity systems, i.e., TEM and MT.

3.1.1 Transient Electromagnetic (TEM)

Common TEM systems use a Central Loop Array in which a 300m x 300m transmitter wire loop is used. Depending on the anticipated depth of investigation, a larger or smaller loop may be used. A half-duty square wave current is transmitted at frequencies of 16, 8, 4 and 2 Hz, powered by an electric generator (see Figure 1). Output ranges up to 120 volts, 1 amp maximum. The TEM system transmits a low-frequency electromagnetic signal into the earth. This signal causes charged particles to flow, which generates a secondary electromagnetic wave. The system transmits at one of three different frequencies. Logarithmically spaced sampling gates are used with 16 Hz having 25 gates starting at 36.14 μsec to 12.18 msec; 4 Hz with 31 sampling gates starting at 36.14 μsec to 48.42 msec and 2 Hz with 34 gates starting at 84.18 µsec to 96.85 msec. At each repetition rate, several repeated transients are stacked and stored in a memory cache inside the data logger and are later transferred to a Personal Computer (PC) for processing.

The transmitter and the receiver timing are controlled by synchronized high-precision crystal clocks that are in the receiver and the transmitter controller. This is achieved by synchronizing the receiver and the transmitter controller prior to data acquisition to ensure that induced voltage is measured by the receiver only after the transmitter has been turned off. Raw data is read and downloaded from the GDP-16 receiver using a specialised computer program. Averages and standard deviations of repeated transient voltage measurements and late time apparent resistivity as a function of time are further calculated by another software, followed by use of an interpretation program which performs 1-D inversion on the data. This program offers options of fitting the models to either the measured voltage or late time resistivity values. Smoother models are also achieved by use of Occam's (minimum structure) inversion. Apparent conductivity is the weighted average of the conductivity distribution with depth of the ground in the vicinity of the receiver. More complex models can be evaluated through forward modelling. Although results are not as well constrained or detailed as results from electrical resistivity soundings, TEM surveys are far more rapid than electrical resistivity and do not require penetration of the ground surface with an electric current.

The TEM system is most useful as a reconnaissance tool for mapping lateral conductivity variations from the surface to a depth of about 500 to 1000 meters. Such lateral variations may be due to changes in water chemistry (plume of contaminated fluids escaping a landfill), the depth to low-conductivity bedrock, or water-filled voids in the near surface. However, penetration is greatly hampered by the presence of conductive near-surface layers such as saline sediments. The heavy generator and transmitter unit make the system cumbersome especially when carrying it over rough terrains. Geothermal resources are usually located at depths over 1000 m hence investigations of greater depth the TEM needs to used in conjunction with another system such as Magnetotellurics.

FIGURE 1: TEM System in Operation

3.1.2 Magnetotellurics (MT)

An example of a Magnetotelluric system is the MTU-5A, from Phoenix Geophyics-Canada. See Figure 2. The system can be made up of several 5-channel units, one of which is used as a remote reference station for the data acquisition system. This kind of array takes advantage of the fact that electro-magnetic noise from the power line (50 or 60 Hz) and a human activity tends to vary considerably over distance, whereas the natural magnetic signal tends to be the same over large distances; the lower the frequency, the less variation. A 12V battery powers each MT data logger.

MT-5A systems acquire MT data in frequencies ranging from about 400 to 0.0000129 Hz (over a period of about 21.5hrs). The sounding locations are distributed over the prospect area. Since the instruments are synchronized to Co-ordinated Universal Time (UTC) via signals from Global Positioning System (GPS) satellites, low-noise time-series data acquired from the remote reference station is processed in combination with data from the roving field station (that acquired simultaneously) to reduce the effects of local noise and improve the quality and reliability of the survey results.

Time-series data downloaded from the MTU-5A units are viewed using software from the manufacturer. This program allows viewing and printing of graphical representations of the raw time-series data, power spectra derived from the time-series data and coherence between pairs of orthogonal channels

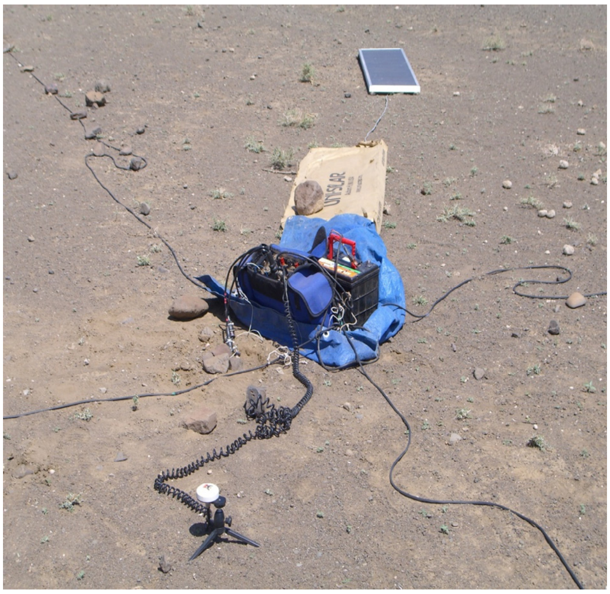
FIGURE 2: An MT Resistivity System

Using another computer program the raw time series data is Fourier transformed. Fourier coefficients are then reprocessed using data from the reference site to filter out noise-affected data and then written to industry-standard EDI format for use with a geophysical interpretation software.

TEM data collected on same locations as the MT sites are also exported to the interpretational program, where their 1-D models are used for static shift corrections on the MT data and then a 1-D inversion of the MT data is performed.

One of the strong points of the MT system is its penetration depth – investigating down to over 50 km, depending on the period the data is allowed to be collected. However, at the near surface its resolution is not as good as that of TEM and hence a combination of the two techniques is advisable. One inherent shortcoming of the MTU system is the porous pots (electrodes) which require more attention than steel pins. They deteriorate to unusable conditions in about 6 months and need to be replaced.

3.2 Gravity Instruments

Volcanic centres, where geothermal activity is found, are indicators of cooling magma or hot rock beneath these areas as shown by the recent volcanic flows, ashes, volcanic domes and abundant hydrothermal activities in the form fumaroles and hot springs. Gravity studies in volcanic areas have effectively demonstrated that this method provides good evidence of shallow subsurface density variations, associated with the structural and magmatic history of a volcano. There is a correlation between gravity highs with centres of recent volcanism, intensive faulting and geothermal activity.

3.2.1 La Coste and Romberg

One of the instruments on the market for gravity measurements is the Lacoste and Romberg gravimeter model G-767. See Figure 3. The equipment is powered by a rechargeable battery that keeps the inside at a constant temperature. A zero length spring suspension is used to attain high sensitivity, with a lever system used to null the meter. The lever system acts on the main spring rather than on a weak "measuring spring", thus reducing hysteresis errors and stabilizing the calibration. Drift is reduced to less than 1.0 mgal per month by thermostating.

The Model G-Gravity Meter has a fine micrometer screw with a 200-mgal range and a range resetting screw which permits the gravity meter to be read anywhere in the world. Using the short-range micrometer screw greatly reduces errors caused by micrometer screw imperfections, which accounts for most of the improvements in accuracy of the Model D Gravity Meter over that of the Model G. A calibration factor is sufficiently accurate and complete to reduce errors to about 0.01 mgal of the complete gravity range. More quoted specifications for model D include: **Accuracy:** Better than 0.01 mgal; **Drift:** Less than 0.5 per month; **Repeatability:** 0.005 mgal; **Power Consumption:** 3 watts at 12VDC.

Reduction of data is done using standard loop misclosure corrections if the algebraic sum of the gravity difference between the stations is not equal to zero. In this case, this sum of the closing error was distributed around the loop using the inverse weighting method. The loop closure errors generally vary from 0.1 to 0.2 g.u. All loops are normally closed in less than 2 hours. Since tides are linear over times and less than this, tidal corrections are assumed to have been included in the drift correction procedures. The maximum tidal corrections are generally found to be 1 g.u.

Data collected by the La Coste & Romberg has to be manually recorded into a notebook. This instrument is sensitive to movement and hence great care needs to be taken during measurement and during transport. Though it is expensive, once it is handled with care it can be operated for several decades, only requiring maintenance by the manufacturer every 10 years or so.

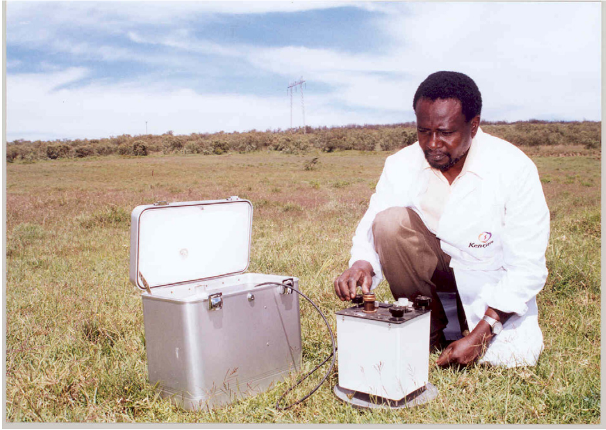

FIGURE 3: A La Coste & Romberg model G-Gravity meter in operation

3.2.2 ScintrexCG-5 Autograv

The Scintrex CG-5 Autograv is the latest advance in gravity instrumentation. See Figure 4. The manufacturer quotes the following specifications:

- Premium Rugged Sensor.
- Superlative noise reduction.
- The lightest of all automated Gravity meters.
- Fast USB & RS-232 data dump.
- Standard 1 microgal resolution.
- Smart long life batteries.
- Stores data internally automatically.
- Flexible data formats.
- Large 1/4 VGA graphics display.
- 27 key alpha numeric keyboard.
- User-accessible automated instrument alignment.
- Online terrain correction.
- Instrument self diagnostic upon power up.

FIGURE 4: A Scintrex CG-5 Autograv in operation

It should be noted that the quoted positive points about the autograv come at a price. The equipment is not cheap.

3.3 Software

Before making the final decision on the purchase of the identified equipment one needs to check with the manufacturer if it is accompanied with software packages acquisition, data transfer and processing or even able to carry out 1D and 2D inversion and modelling. It is also advisable to inquire if the software runs under Windows or Unix operating platforms and if an integrated on-line help system exists to assist the operator; and finally, if it is user friendly in data display, data storage and retrieval.