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COMBINED GEOPHYSICAL SURVEYS FOR MAPPING ANDESITE PLUGS CONTROLLING GROUNDWATER FLOW

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مسح جيوفيزيقي مشترك لتخريط تداخلات الأنديزيت الطولية المتحكمة في تدفق المياه الجوفية

الخلاصة: تم استخدام عدة طرق جيوفيزيقية (المغناطيسية و الكهرومغناطيسية والتثاقلية و السيزمية) فى ولاية أريزونا بالولايات المتحدة الامريكية لمسح تدخلات الأنديزيت والتى تم تحديد أماكنها عن طريق المسح المغناطيسى الجوى للمنطقة.

و قد أمكن بواسطة المسح المغناطيسى والكهرومغناطيسى الأرضى الحصول على أفضل النتائج عن عمق وموقع تدخلات الأنديزيت حيث كان مدى الامتداد فى الاتجاه الشمالي-الجنوبى هو ٦٠٠ متر تقريباً، وكان العمق إلى قمة أسطوانة الأنديزيت هو ما يقرب من ٣٠٠ متر و لم يصل المسح السيزمى لعمق كاف لتواجد الانديزيت بينما لم يبدو المسح التثاقلى متاثرا بوجود هذا الانديزيت.

ABSTRACT: *Four different geophysical methods were used near Chino Valley, Arizona, USA in order to map a suspected intrusive Andesite, identified as plug 15, which had originally been found using aeromagnetic data already acquired over the area.*

Magnetic, transient electromagnetic, seismic, and gravity surveys were conducted. The magnetic and TEM surveys provided the best indication of the location and depth of the plug. The North-South spatial extent of this plug was estimated to be approximately 600 meters. The depth to the top of the plug was found from the TEM survey to be approximately 300 meters at the center of the survey. The seismic survey did not reach deep enough to find the Andesite anomaly and the gravity survey did not appear to be affected by the plug. Magnetic, TEM, and seismic surveys were also performed at another site located approximately 1.25 km northeast of plug 15. The seismic survey did not reach deep enough and the magnetic survey was too short to provide a depth interpretation. The single TEM sounding indicated a very high resistivity value at this site.

INTRODUCTION

Surface geophysical methods for investigating the composition, structure, and nature of the subsurface have reached a high degree of sophistication in recent years. The impetus for technological improvements has realized that geophysics can aid in addressing societal problems related to the environment and engineering, in addition to the more traditional problems in petroleum and mineral explorations for which many of the methods were initially developed (Reynolds, 1997).

Improvements in both instrument precision and computational efficiency have made electrical, seismic, gravity, magnetic, and other techniques quite successful for delineating the shallow subsurface to a resolution necessary to address engineering and environmental problems (Reynolds, 1997).

The use of geophysics for groundwater studies has been stimulated in part by a desire to reduce the risk of drilling dry holes and also a desire to offset the costs associated with poor groundwater production. Today, the geophysicists also provide useful parameters for hydro-geological modeling of both new groundwater supplies and for the evaluation of existing groundwater aquifers (McNeill 1990).

Because of the inherent ambiguity in earth models obtained from geophysical data, the importance of an integrated approach to geophysical investigation cannot be over-emphasized. All known information regarding the surface and subsurface properties at a site should be used to guide selection of parameter constraints, models, and range of possible interpretations. Also, two or more independent geophysical data sets, which are sensitive to different earth properties and noise factors, can greatly increase the accuracy of an earth model.

Multiple geophysical surveys were conducted in the Verde Valley Watershed near Chino Valley, Arizona, USA. The purpose of the geophysical investigation was to provide additional data for use in the United States Geological Survey (USGS).

This watershed provides water resources to one of the fastest growing rural counties. Resource managers need to thoroughly understand the groundwater system in order to predict how increased demands on water will

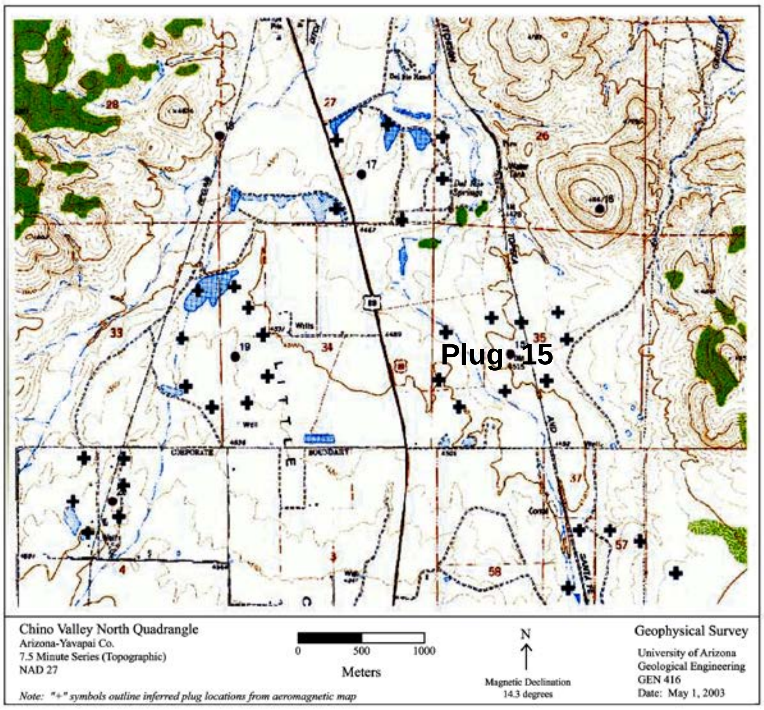

Fig. (1): Location map of Latite-Andesite plugs in the Verde valley watershed region, Arizona, USA.

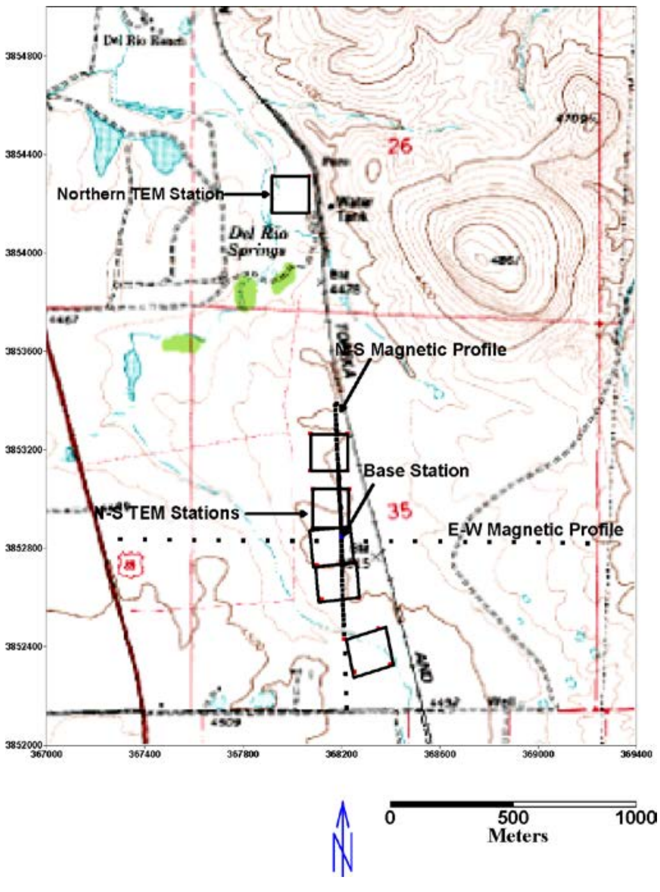

Fig. (2): Location map of the survey area showing the magnetic and electromagnetic profiles

impact this area. Specifically, the geophysical surveys will aid in locating and delineating the extent of the Latite-Andesite plugs that are believed to interrupt the groundwater flow in this region.

Regional aeromagnetic and gravity maps of the area were used to delineate the Latite-Andesite boundaries in study area. Figure 1 shows detailed map of the plugs near the survey site. The "+" symbols represent the boundary of the Latite-Andesite plug inferred from the aeromagnetic map.

GEOPHYSICAL METHODS

Four different geophysical methods were used at the Verde Valley Watershed including magnetic and transient electro-magnetic, in addition to seismic and gravity techniques. The surveys were designed to delineate the Latite-Andesite plugs and to gather more detailed data on their physical characteristics which will be used as constraints in hydrogeological modeling.

The seismic survey did not reach deep enough to find the Andesite anomaly and the gravity survey did not appear to be affected by the plug. Magnetic and TEM surveys provided the best indication of the location and depth of the plug. So, only these two methods will be discussed in details. Figure 2 shows the profiles conducted using the magnetic and TEM methods in the survey area.

Magnetic Survey

The magnetic method is one of the oldest geophysical survey methods. It has been used for many decades in the mineral and petroleum industries for mapping geologic basement trends, faults, and mineral or petroleum prospects. The magnetic method has been used in recent years for various engineering and environmental purposes.

The purpose of the magnetic survey done was to investigate the magnetic characteristics of Latite-Andesite intrusive plugs that are postulated to occur in the area of study.

The location of the magnetic survey was selected, using information through existing aeromagnetic maps. The aeromagnetic maps indicated the general location of a remanent negative anomaly that is interpreted to be a Latite-Andesite plug (Fig. 1). Magnetic ground survey was conducted and centered over the interpreted plug, so that it could be delineated in greater detail. The magnetic survey was composed of four separate magnetic profiles; the first three of which were clustered in the area referred to as plug 15. Line 1 is extended in North-South direction for a total distance of 1215 meters. Line 2 is 36 m west of Line 1 and is also oriented in the North-South direction, with a length of 230 m. Line 3 was perpendicular to Lines 1 and 2 with an approximate East-West orientation and was 1900 m long. Line 4 was located northeast of the first three lines. It was oriented East-West and extended to a length of 235 m.

Two EDA-Omni-IV proton precession magnetometers were used for this investigation. The magnetometer consists of a console unit connected to a sensor mounted on a staff. For this survey, the field station staff height was 4.3 m and the base station one was 0.25 m. One magnetometer was used as a stationary base- station, while the other was moved from location to location recording the total field and vertical gradient along each profile. The difference between simultaneous magnetic total-field readings at the base and field stations was used to remove the earth's magnetic-field changes.

Transient Electromagnetic Survey

In the time-domain electromagnetic (TEM) method, a transmitter emits nearly square-wave current pulses of alternating sign and the transient, or decaying field, is measured when the transmitter is off. With this method, the depth and total conductivity of a buried target are reflected primarily by the magnitude of the secondary field, as well as the rate of decay and spatial extent of the anomalous response (McNeill, 1990, 1994).

The equipment consists of a transmitter-receiver system that can be arranged in different geometries depending upon target of interest and the survey design. The transmitting and receiving antenna loops consist of wire on the ground, with the size depending upon the depth of exploration desired and the size of the target (Fig. 3). The depth of exploration attained in a vertical sounding configuration can vary from few meters to more than 1,000 meters, depending upon transmitter loop size and geometry, available power from the transmitter, and ambient noise levels (Zonge, 1992).

In this field survey, the TEM loops were positioned along a North-South direction for a total distance of 915m from the base station, coincident with the magnetic survey. The dimensions of each transmitter loop, in meters, at six locations were 10 x 10, 20 x 20, and 40 x 40, with the most southern loop located at the base station and the most northern loop located at 915m. The depth of investigation for the 10 x 10 loop was approximately 50 meters; the 20 x 20 loop was approximately 100 meters; the 40 x 40 loop was approximately 130 meters.

The NanoTEM system, which is a fast turnoff and sampling TEM system for shallow measurements (Fig. 3) was used with an in-loop (central loop) configuration of 10m, 20m and 40m loop sides. The in-loop NanoTEM resistivity sounding survey configuration uses the NT-20 transmitter, which is connected to a square loop of wire laid on the ground. The receiver loop is located at the center of the transmitter one and is connected to the GDP-32 receiver through a short length of cable. A 5m-receiver loop side with the 10m-transmitter loop, while a 10m-receiver loop with both the 20m and 40m-transmitter loops were used. The transmitter side length of the loop is approximately equal to 2-3 times the desired depth of exploration. The in-loop TEM sounding method is described in McNeill (1990) and Zonge (1992).

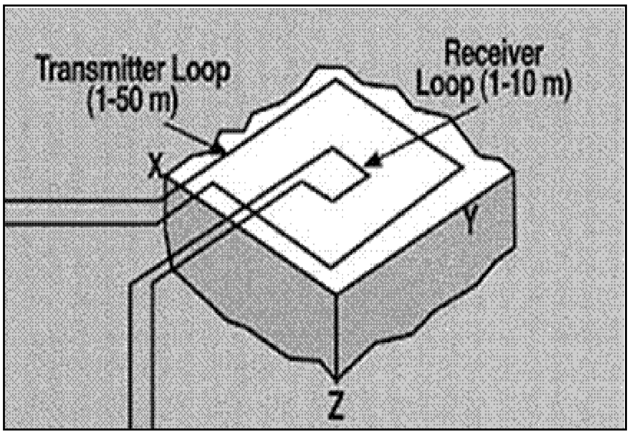

Fig. (3): TEM system setup for shallow measurements.

The data acquired from these loops, along the entire baseline, was ultimately inconclusive, showing no indication of any object that may or may not be the Andesite plug. The higher variations in resistivities recorded are attributed to shallow, unsaturated alluvium.

A second transient electromagnetic survey was conducted at the same site, over the same area. Larger transmitter loops (150 x 150 meter) were used in order to increase the depth of investigation to 700 meters. These larger loops were laid out along the same North-South trending baseline over the locations of the smaller loops used in the previous survey. The exception to this would be the most northern loop, which was moved farther north to a location 1200 meters north of the most southern loop at base station. Transmitter loops were laid out at six locations overall.

For this deeper depth of penetration, the TEM system with 150m-loop sides called ZeroTEM was applied. In this case a multi-turn receiver coil, which is equivalent to an area of 10,000 m^2 and located at the center of the transmitter loop we used. ZeroTEM gives late-time voltage data, which correspond to deeper layers while NanoTEM gives more early-time voltage, which corresponds to shallow layers (Zonge 1992).

RESULTS AND DISCUSSIONS

Magnetic Survey

The difference in the magnetic total-field readings between the base and mobile field stations provided the most useful information in this survey. A vertical gradient measurement was also collected at each station. The vertical gradient indicates the rate of change of the magnetic field in the vertical direction. The gradient measurement is most effective for detecting near-surface metallic sources that could distort the magnetic field. This survey exhibited localized spikes that occurred due to abrupt terrain changes near ephemeral washes. These small, localized spikes were also observed in the total-field data. The "+" symbols represent locations of washes as in figure 4a.

Line 1 of the magnetic survey has a large total-field magnetic anomaly, approximately 250 nT in magnitude (Fig. 4a). It is a negative anomaly and therefore indicates reverse polarity caused by remanent magnetization. The fairly broad curve of the dip in magnetic intensity indicates that the source is located relatively deep in the subsurface. A rough estimate of the lateral extent of the plug ranges from 400-500 m south of the base station to 100-200 m north of the base station. These estimates were based on the steepest gradient observed from the profile. One important point to mention is, since this North-South profile line has not been corrected for the earth's magnetic inclination, i.e. the data have not been reduced to the pole, the shape of the anomaly will be asymmetrical and the lateral length should only be considered as an estimate.

Line 2 (not shown), parallel to Line 1, was not long enough to record the full anomaly. However, it does mimic the trend of Line 1 over the same distance, and verifies that the magnetic readings measured in Line 1 are accurate.

Line 3 is perpendicular to both Lines 1 and 2. The graph of magnetic total-field intensity (Fig. 4b) displays the same negative trend as the North-South lines, but a double anomaly is present. The first of two negative anomalies is approximately 200 nT in magnitude and is located at 320 m west of the base station in Line 3.

However, 380 m east of the base station a larger negative anomaly of 400 nT in magnitude is observed. This anomaly has a much steeper profile gradient compared to the western anomaly and indicates that the Latite-Andesite plug is closer to the surface compared to the western anomaly. The interpretation of this double anomaly is that there are two batholiths or dikes of Latite -Andesite, which intruded separately but relatively close to each other. They may possibly be connected at depth. Centered between the two anomalies may be basin fill, which would account for the positive magnetic

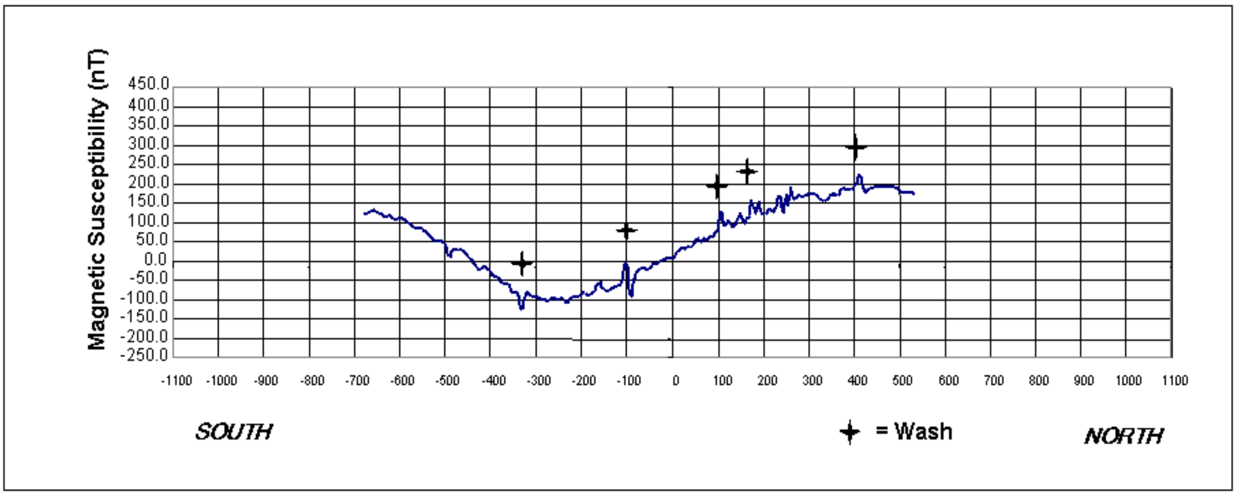

Fig. (4a): Magnetic Line 1 (North-South), Total Field Magnetic Intensity vs. Distance

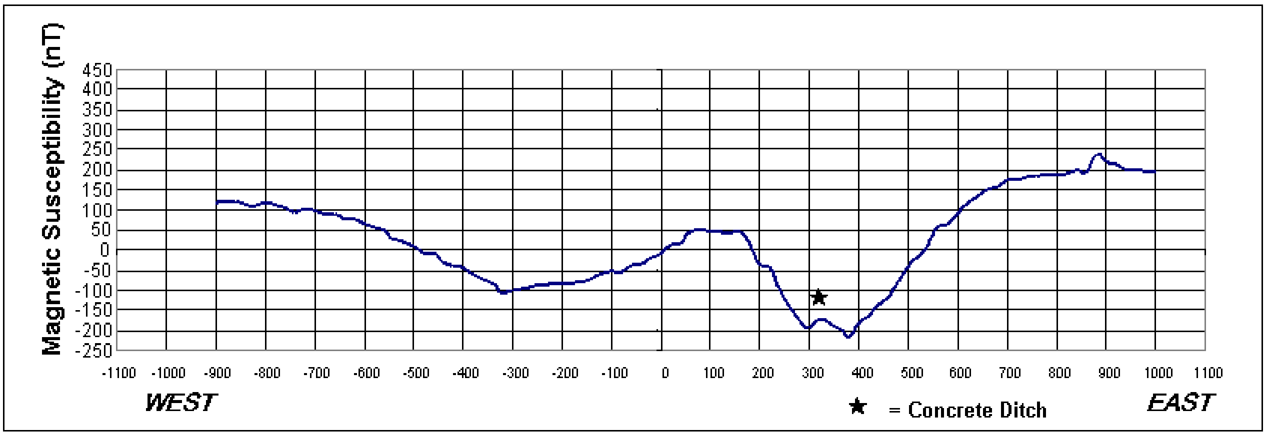

Fig. (4b): Magnetic Line 3 (East-West), Total Field Magnetic Intensity vs. Distance

response detected between them. To the south, both separate magnetic anomalies may unite together based on the pre-existing aeromagnetic map. The size of the double anomaly, shown in Line 3, is estimated to be 1020 m in length with the western edge located at 500 m west of the base station and the eastern edge located at 520 m east of the base station. The boundary of this anomaly was based on the interpretation that both anomalies are part of the same large Latite- Andesite plug inferred from the aeromagnetic maps. The boundary of the anomaly was also determined by the steepest gradient method used for Line 1.

The fourth magnetic profile line was located northeast of the first three lines. A large quantity of scrap metal was observed along the entire profile path and data should, therefore, be interpreted with caution. Large data spikes in the gradient profile illustrate the complexities of the magnetic data due to the amount of scrap metal present. The trend of the magnetic total-field data showed a decrease in intensity towards the East. This profile contains the sharpest gradient of the four lines, which indicates that the source is located at a very shallow depth. This area was believed to have a Latite- Andesite plug outcropping at the surface and this is supported by the output data. The intent of recording this magnetic survey line was to provide a comparison between a surface outcrop magnetic response and a buried Latite- Andesite magnetic response. Since Line 4 did not extend laterally enough to record background levels of magnetic intensity, these data were used to make estimates of depth and edge constraints was not possible.

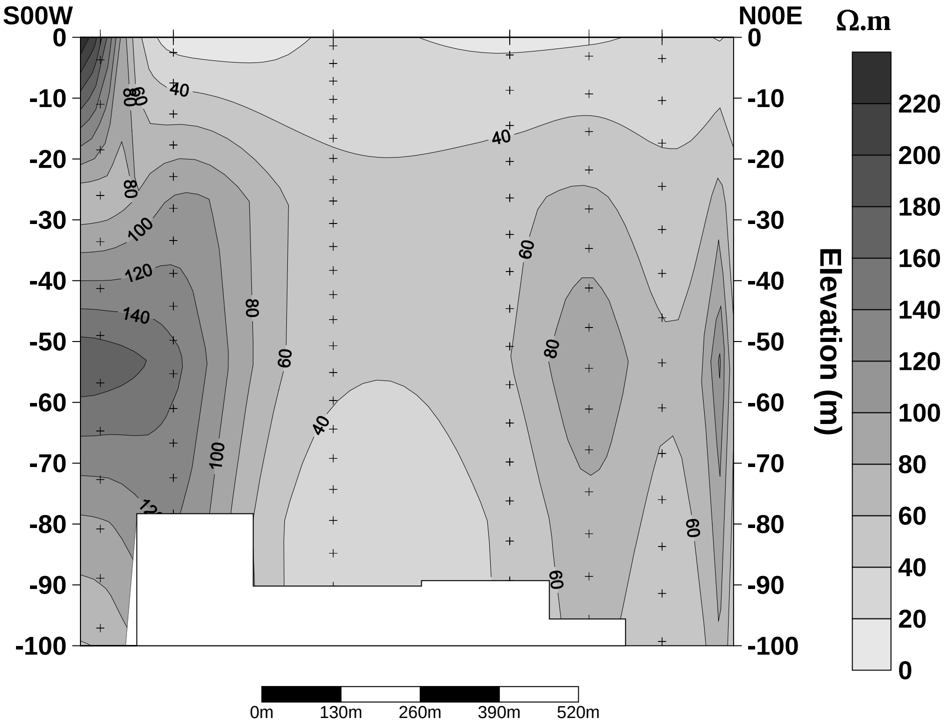

Fig. (5a): Resistivity-depth section for a TEM in-loop configuration (transmitter 40x40m and receiver 10x10m).

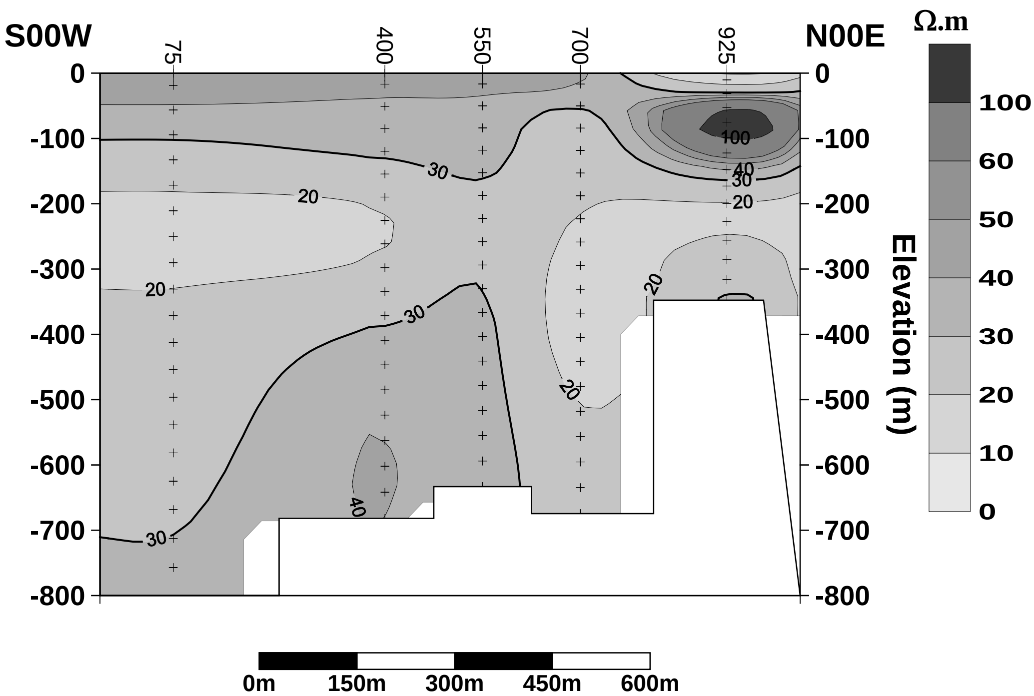

Fig. (5b): Resistivity-depth section for a TEM in-loop configuration (transmitter 150x150m and receiver equivalent area of 10,000 m^2).

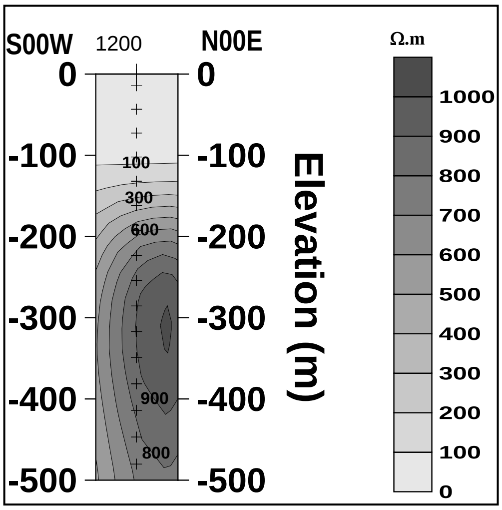

Fig. (5c): Resistivity-depth section for the northern TEM in-loop configuration (transmitter 150x150m and receiver area of 10000 m^2).

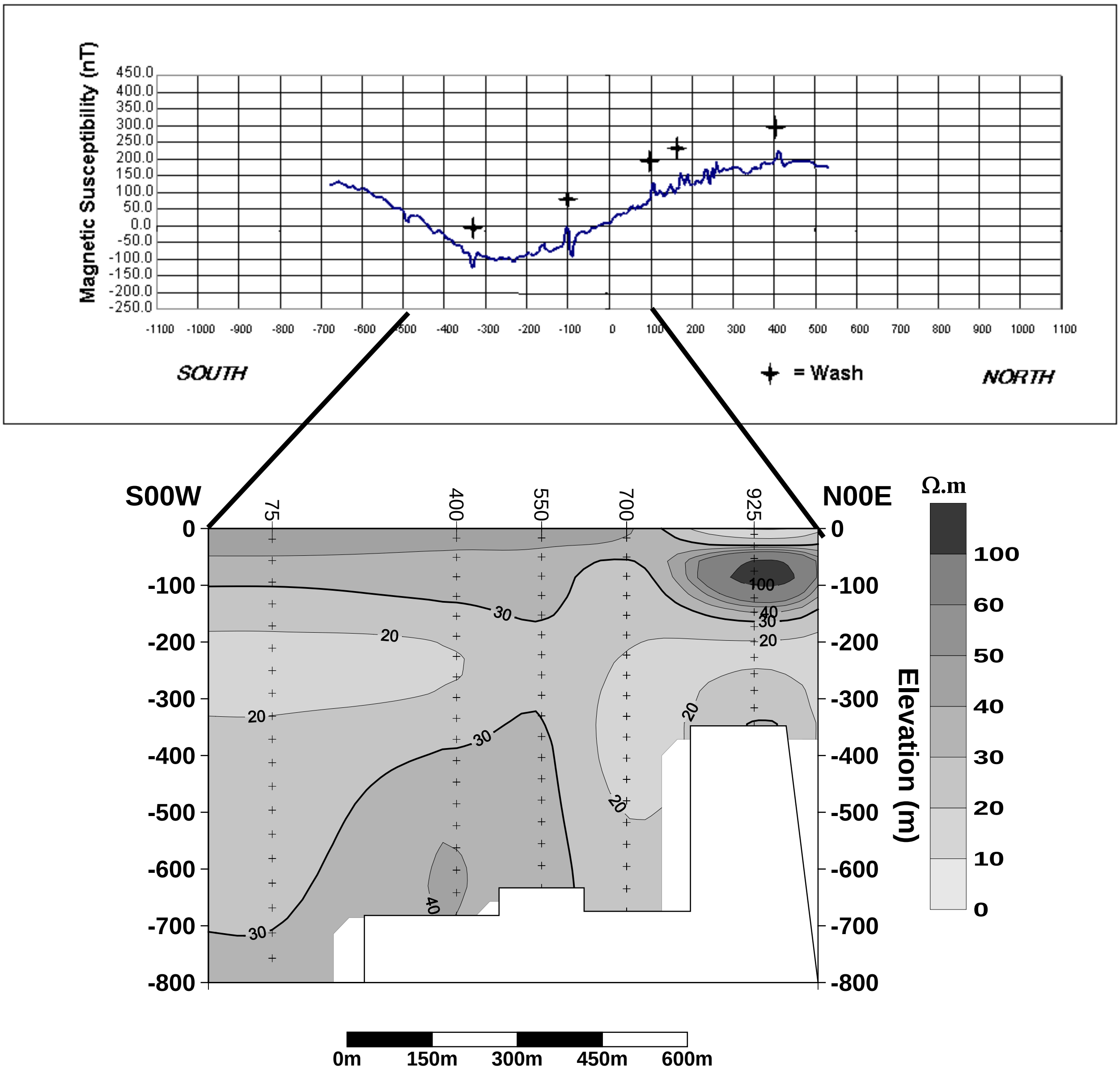

Fig. (6): Magnetic and TEM correlation on North-South line.

Transient Electromagnetic Survey

Since the depths to water table and the Andesite plug at this site were not known at the time of the survey, different loop sizes were experimented.

Measured data was modeled in collaboration with Zonge Engineering using TEM Smooth-model Inversion software (STEMINV), which transforms in-loop TEM soundings to profiles of resistivity versus depth. Another code called MODSECT was used to read Zonge inversion-program model files and to create contours of the inversion-model-section for resistivity versus depth. Final resistivity-depth plots are displayed using the Surfer griddling and contouring program.

Figure 5a shows a resistivity-depth section for a transmitter loop of 40x40m and receiver loop of 10x10m. The typical depth of investigation for this loop is about 100 to120 m for the range of resistivities encountered in this site. The data show basically the vadose zone of the basin-fill deposits above the water table, which is expected to be at a depth of 100m. This plot shows more conductive materials at depth, which means that more saturated sediments below the water table, can be detected.

Figure 5b shows a resistivity-depth section for a transmitter loop of 150x150m and a receiver coil, equivalent to an area of 10,000 m^2. The typical depth of investigation for this loop is about 700-800m for the range of resistivities encountered at this site. The figure shows a roughly convex anomaly with resistivities that vary from 30-40 Ohm.m at a depth of 700+ meters at the most southern location. It begins to rise gradually to a depth of 300 meters at the mid-point of the baseline (550 meters). The anomaly then drops steeply to an undetermined depth beyond that point.

The interpretation of this plot is that the high-resistivity region indicates an Andesite plug at a depth of about 300m and extending to 800m. The plug is surrounded by low-resistivity sedimentary deposits that are fully saturated with water. The resistivity of this plug may be higher than the values of the contours due to the effect of the low resistivity of the upper layers and because of inversion non-uniqueness, which means that more than one resistivity value could fit the same model.

In order to verify this assumption, a single 150m loop was measured at the northern part of the Chino Valley shown in figure 5c. TEM measurements at this site show very high resistivity readings (about 1,000 Ohm.m) close to the surface at about 200m and extending with depth. It seems that the plug is close to the surface at this northern site. It is through that this plug could be similar to the southern one (Fig. 5b).

Since the aeromagnetic survey was the main tool used in locating the original anomaly, the electromagnetic survey was compared to the data found from the magnetic survey. By examining the North-South magnetic line in comparison to the North-South TEM survey (Fig. 6), a rough estimate of the lateral extent of the plug ranges from approximately 100 meters north of the base station to 500 meters north of this base station. This is based on the magnetic field decrease at the same location as an increase in resistivity shown on the TEM line.

CONCLUSION

The postulated Latite-Andesite plug in the Verde River Watershed near Prescott, Arizona, USA is associated with a negative magnetic anomaly. An aeromagnetic survey was initially used in locating the original anomaly. Ground magnetic and electro-magnetic surveys were conducted to delineate the depth and extension of the Latite-Andesite anomalies. By examining the North-South magnetic line in comparison to the North-South TEM survey, a magnetic field decrease was found at the same location where an increase in resistivity on the TEM line. The depth estimated from the TEM survey is approximately 300 meters to the top of the plug at the center of the survey and extending to 800m.

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