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Hidden anomalies: Small near-surface resistivity variations can completely mask large, deeper anomalies

Greg A. Shore and R. Peter Clearwater

Premier Geophysics Inc. 3 - 11520 Voyageur Way, Richmond, BC. Canada V6X 3E1

ABSTRACT

Recently completed research into the three-dimensional interpretation of complex, multi-body geo-electric regimes (realistic earth conditions) has quantified the extent to which irregular (3-D) near-surface resistivity variation masks or distorts the signal from the larger, deeper-probing array separations of a resistivity survey traverse. The observed effects are much greater than previously anticipated. The signatures from large, buried conductive bodies can be completely obscured by much smaller near-surface features.

In pseudosections manifesting surface-influenced diagonal patterns, the apparent absence of other or "deeper" signatures of interest could influence a premature rejection of an exploration area. The research shows that the only conclusion warranted by such data is: "Surface features present; deeper information uninterpretable. Additional geophysical or other data must be acquired to test this area at depth."

These findings should influence strategies for future exploration, to emphasize the importance of obtaining additional data wherever the effects of near-surface features are recognized. Reconnaissance and other resistivity data from previously-explored areas should also be reviewed for untested opportunities, where the misunderstanding of surface-distorted pseudosections may have led to premature withdrawal from an exploration area.

Introduction

Reconnaissance resistivity traverses are widely used in geothermal exploration, both in rough terrain where only a single valley-bottom traverse may be possible, and in more accessible ground, where an exploration strategy may be served by widely-spaced reconnaissance traverses. Single-line traverses are often successful where well-developed, conductive outflow plumes or extensive clay alteration caps can be expected to indicate the presence of a nearby geothermal system.

Figure 1 shows a typical Pacific Northwest geothermal environment (Meager Creek, BC) which was initially explored with valley-bottom dipole-dipole resistivity traverses encircling a central volcanic complex. One anomaly marked the outflow plume of the South Meager geothermal system (M on the map).

Using a resistivity traverse to identify the upstream limit of the anomaly, explorationists were thus able to identify the point at which the plume entered the valley bottom alluvium. From there, a more detailed search of both sides of the valley eventually identified the source of the plume, a geothermal system lying within the north slopes of the valley.

Figure 2 illustrates how single-line traverses sweep an area. Any anomalous volume of rock lying within the survey array's search radius (the half-cylinder to the sides and to depth) will likely appear as an anomaly on the pseudosection data plot.

Conductive bodies are easier to detect than resistive ones, since a conductive body lying anywhere within the survey array's sampled volume can cause an anomaly. By contrast, a resistive body can lie undetected within the search volume, revealing itself in raw data only when the electrodes are placed in direct contact to force current to flow through the body. Resistive bodies are more likely to require high density data and computer-assisted interpretation. Many geothermal features of reconnaissance exploration interest (outflow plumes, alteration zones) tend to be conductive in nature. Geothermal systems themselves are often anomalously conductive (due to increased fracturing or permeability, saline fluids, elevated temperatures, and alteration clays) but are sometimes resistive or mixed in response, due to dry steam zones and other factors.

Difficulty in interpretation occurs when conductive earth materials are encountered at or near a survey electrode position. Injecting current into an irregular (3-D) conductive body such as an outflow plume has the effect of turning that body into one big electrode, with current flowing from its outer surface into the surrounding rock. The resultant electric field is irregular and unpredictable. Instead of a smooth, uniform field against which we can identify (and roughly quantify) the anomalous signatures of bodies encountered at depth, we have a distorted field of unknown qualities against which normal deep body signatures are likely to be unrecognizable on visual inspection.

Computer-operated data inversion routines must first attempt to quantify the near-surface features, so that their effects in shaping the deep-traveling field can be computed, and discounted. Any anomaly that remains thereafter derives from deep bodies. Inversions, however, require considerably more raw field data than is contained in a single traverse line.

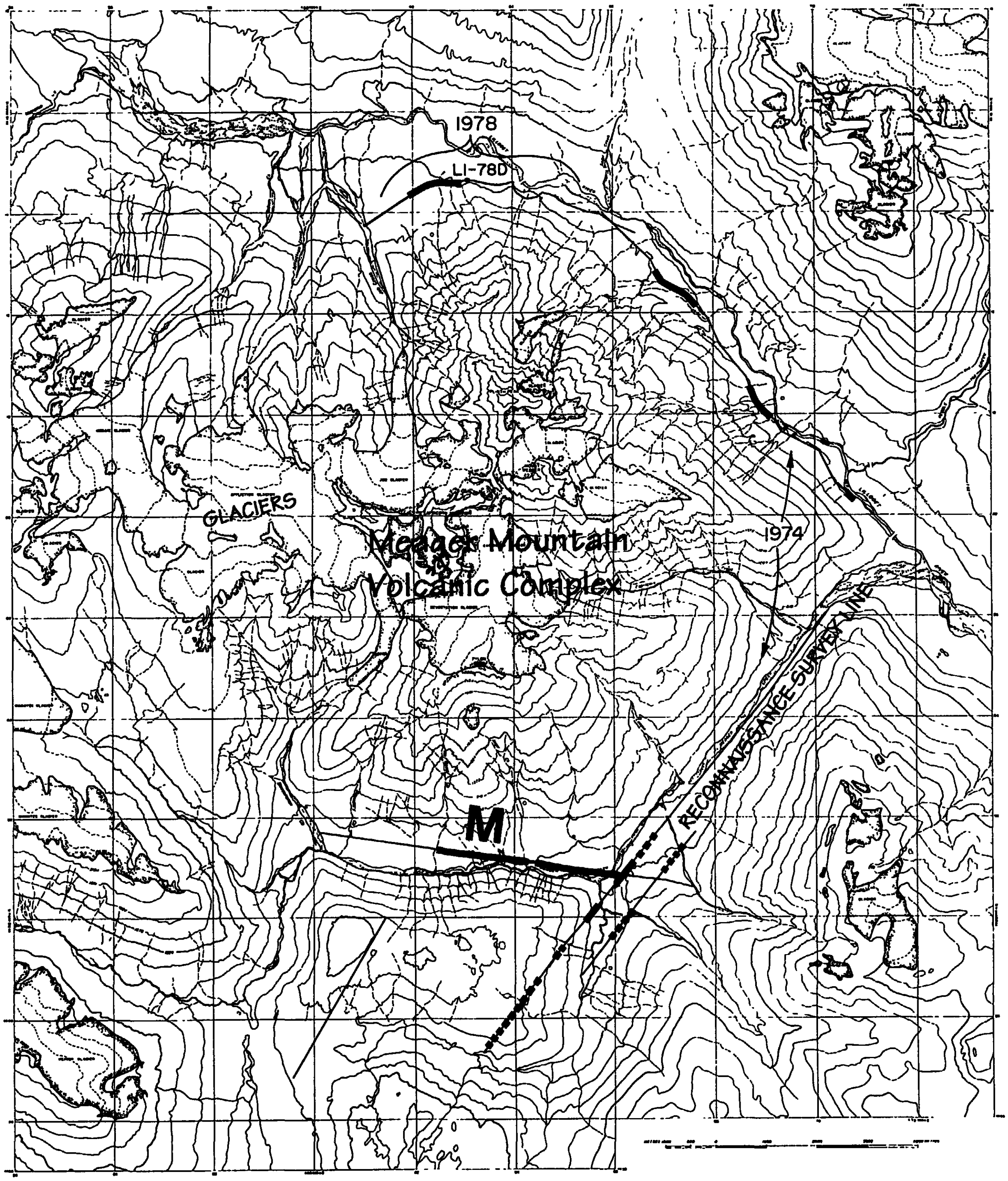

Figure 1 ***Resistivity traversing in large prospect areas.***

DIPOLE-DIPOLE ARRAY
▬ DEFINITE RESISTIVITY ANOMALY
■■■■ POSSIBLE RESISTIVITY ANOMALY

Single line resistivity traverses are used for two reasons:

1. they work... the typically conductive nature of geothermal alteration and outflow plumes allows the effective initial testing of broad areas with one or more large-spacing traverses.

2. limited options... terrain may physically limit the accessible survey routes to single lines along valleys, from which the lateral search capability of the traverse samples a broad area.

The map shows the locations of valley-bottom dipole-dipole survey traverses applied in 1974 and 1978 at Meager Creek, BC, to search for evidence of alteration or geothermal outflow plumes in the otherwise resistive valley debris and bedrock. Several conductive anomalies were found, the largest of which marks the outflow plume of the Meager Creek geothermal system (at M).

Each square on the map is 2 kilometres on a side.

As a result of recent 3-D inversion research using very dense, multi-directional potential field data (Li and Oldenburg,, 1991, 1992), the detailed electrical signatures of geologically realistic earth models[1] can be generated. This permits viewing of the survey results (for various survey arrays such as dipole-dipole, pole-dipole, pole-pole, Wenner, Schlumberger) that would be obtained by a traverse passing across or near any part of the modeled 3D regime, at any angle or array spacing. The model and pseudosections of Figure 3 are derived from the forward modeling and inversion of a complex 5-prism model that features shallow-lying prisms overlying large, buried bodies. Dipole-dipole and pole-pole array "field" results are presented for one traverse route across the model.

In evaluating the responses, both pole-pole and dipole-dipole array pseudosections were generated (110 of each array type, in 4 sets viewed at varying orientations across the model). Sequences of pseudo-depth plan views were created. The apparent resistivity data were also studied as 3-D solid rendered images. In no case could the presence of the two deeper bodies be inferred from the dramatically distorted "field" data set. Figure 3 shows two pseudosections that are typical of the hundreds of viewing perspectives: there is no suggestion of the presence of either buried body. All views were dominated by the flared distortions of the surface bodies, and the cone-shaped "ghost" anomalies beneath them.

We conclude that the observed masking effect of shallow bodies is much greater than generally (intuitively) anticipated. The signatures from large, buried conductive bodies can be completely obscured by much smaller near-surface features.

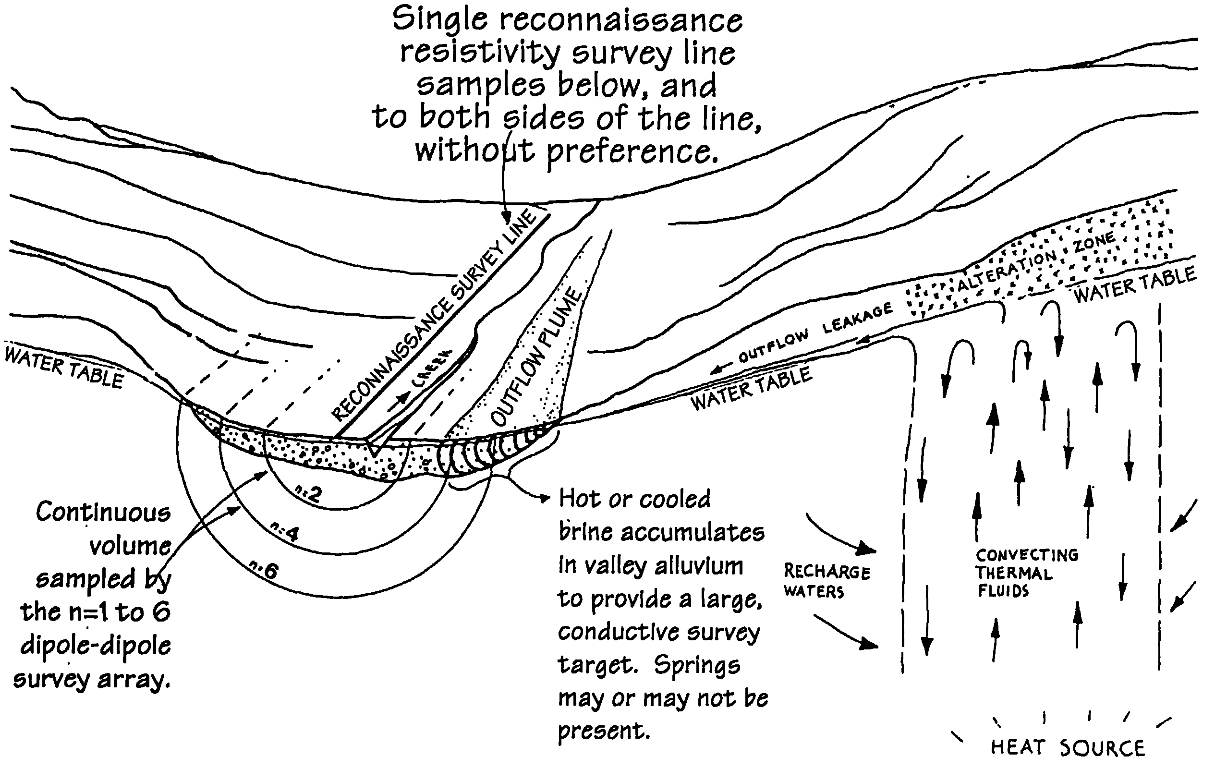

Figure 2 ***A single-line reconnaissance resistivity survey along a valley bottom.***

The signature of the conductive outflow plume in this example will appear in the n=4, 5 and 6 levels of the pseudo-section data plot. Similarly, a large, buried conductive body lying beneath the traverse line (within the sampled volume) would cause an anomalous signature. If there are no sources of near-surface distortion present, either anomaly would be recognized as a feature that warrants additional evaluation.

According to recent 3-D inversion research, a small volume of anomalous (conductive or resistive) earth lying near one or more of the traverse electrodes will generate complex distortion patterns that can completely mask the signatures of other, larger bodies of potential exploration significance. Survey results from traverse sections that exhibit surface-caused diagonal distortion patterns should be treated as incomplete or inconclusive,- the area remains effectively unexplored, both laterally and at depth.

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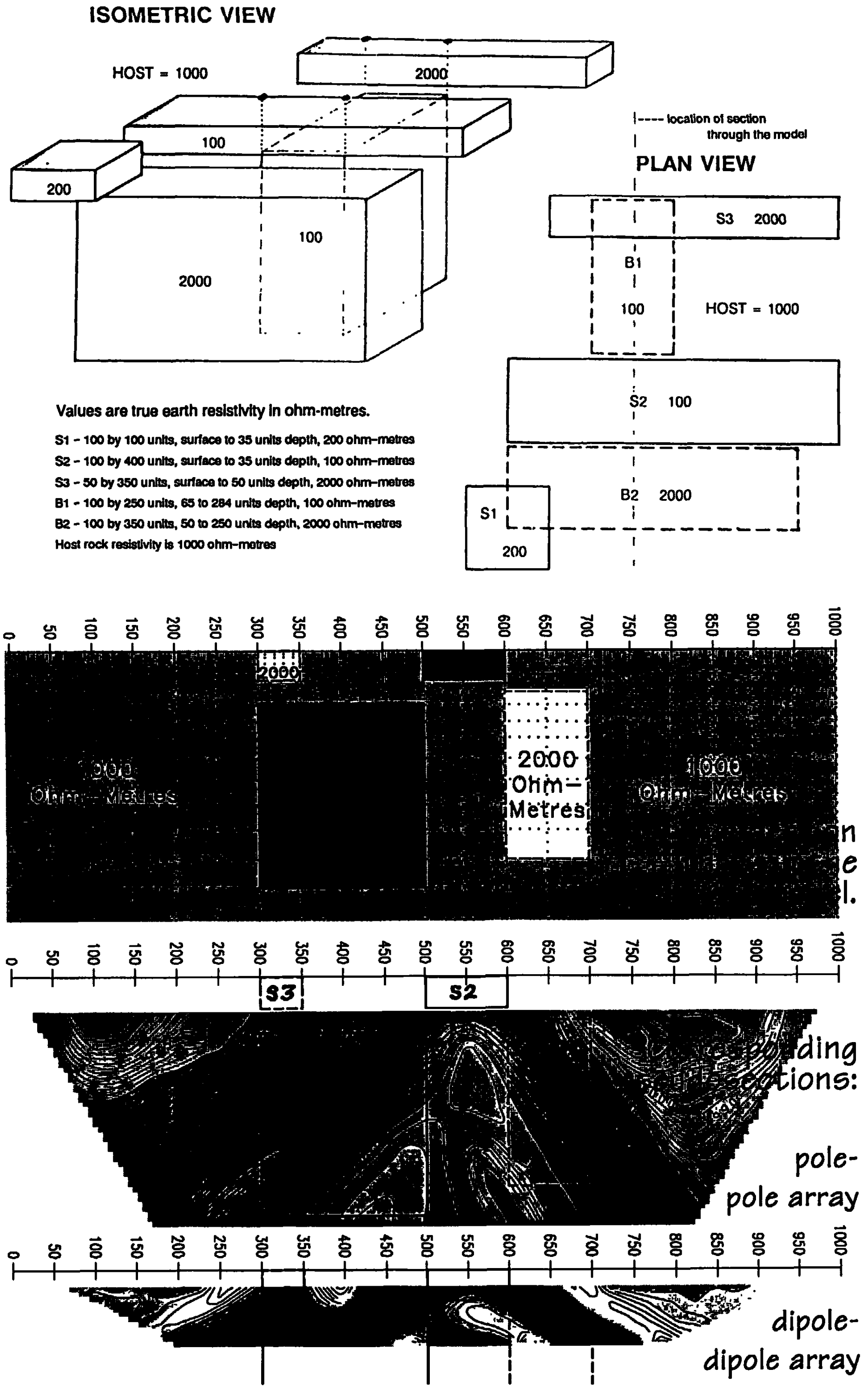
[1] 3-D earth models on the order of 500,000 elements (a mesh of 100 by 100 by 50 elements)

Figure 3 ***3-D model results: near-surface distortions***



Values are true earth resistivity in ohm-metres.

S1 - 100 by 100 units, surface to 35 units depth, 200 ohm-metres
S2 - 100 by 400 units, surface to 35 units depth, 100 ohm-metres
S3 - 50 by 350 units, surface to 50 units depth, 2000 ohm-metres
B1 - 100 by 250 units, 65 to 284 units depth, 100 ohm-metres
B2 - 100 by 350 units, 50 to 250 units depth, 2000 ohm-metres
Host rock resistivity is 1000 ohm-metres

Figure 3 (facing page) 3-D model results: effects of near-surface distortions

In the computed "field data" pseudosections generated from the 5-prism earth model at right, the distortion patterns from the small, near-surface features completely mask the signatures of the larger buried bodies. (The pseudosections are plotted to the Ze convention suggested by Edwards, 1977)

The model background resistivity (host rock) is set at 1000 ohm-metres, perhaps typical of many crystalline environments of the Pacific Northwest. (To change perspective to a southwest environment, a multiple can be applied to all resistivities in the figure, e.g. the resistivities and apparent resistivities of 2000, 1000, 200, and 100 ohm-metres can be restated as 200, 100, 20, and 10 ohm-metres to better reflect some southwest US conditions. The patterns and relative results remain the same. Field workers will remind us that the main difference is that ten times the injected current will be needed to maintain the measured signal at the same levels as in the more resistive model.)

While a buried resistive body (B2, 2000 ohm-metres) is difficult to detect under ideal conditions, the observation that there is absolutely no signature for the 100 ohm-metre buried *conductive* body (B1) surprised most workers involved in the research. Intuitively, it seems likely that such a large, anomalous conductor should impress some recognizable signature over the near-surface effects. The 3-D model results indicate otherwise in every one of the 220 pseudosections (in 4 viewing angles) that were examined.

Geologically, the shallow conductive prism S2 could represent an outflow plume, conductive sediments, weathered or clay-altered rocks, or a number of other common features. The resistive feature S3 is typical of a siliceous unit, an esker, dry gravels, or a fresh volcanic flow lying across the area.

The conductive prism S2 produces strong conductive flares that extend downward at an angle from every edge (two edges being shown here) in both pseudosections. What was called a "pantslegs" anomaly in 2-D feature evaluations is a seen to be a "skirt" in 3-D views. The second component of the shallow prism's typical 3-D pattern is a ghost anomaly directly below, of opposite sense to the prism itself. Regardless of what actual conductive or resistive features may exist below the shallow prism, the ghost signature tends to overwhelm it.

Resistive feature S3 adheres to the expected pattern: a flaring resistive skirt of resistive values is present, with an opposite sense (conductive) cone-shaped ghost anomaly located directly beneath.

The distortion signatures mix to make the distortion pattern more complicated. The conductive flare of S2 merges with the conductive ghost under S3, and also cuts off S3's resistive flare, leaving a circular high that might not be recognized as a flare without the presence of the undistorted flare on the other flank. (Field data patterns can overlap and become complex; clearly formed flaring patterns are not always available to warn of near-surface distortion.)

To establish even a possible 2-D earth interpretation, a minimum of a series of parallel pseudosections showing repetitive patterns is needed. With only one (or even two) traverse pseudosections, no such assumption can be safely made. Single-line pseudosection data, with surface distortions present, are absolutely uninterpretable.

The interpreter must determine the causes of patterns seen in the pseudosection, i.e. try to find the *true earth section,* using only the field pseudosection data. When diagonal flaring or other surface distortion patterns appear in a traverse pseudosection, the only correct conclusion can be: "*this area has not been effectively tested with resistivity, laterally or to depth, due to near-surface sources of distortion... Additional or alternate testing is required*".

Implications for exploration strategy

The most important implication is the possibility that an effectively untested section of traverse ground could be written off on the basis of misunderstanding surface-distorted results.

If resistivity mapping has been considered to be of importance in a geothermal program, then presumably every potential anomaly is of importance. If an area is particularly variable in its near-surface characteristics, a large percentage of traverse data could be compromised by distortion.

As with any regional data sets, a process of interpretation and integration of results with other data is applied to prioritize targets for further follow-up work. The results of our research state that surface-distorted resistivity pseudosections, whether or not they *appear* to deliver any interesting anomalies or features at depth, are not interpretable data and therefore should not influence interpretation or subsequent decisions. They should not be presented as exploration data at all, but rather as gaps in survey results, where the objective of sub-surface exploration has been interpreted as having been defeated entirely by near-surface conditions.

The price potentially paid for ignoring the untested possibilities of a surface-distorted part of a pseudosection can be very high. For example, near-surface distortion features could mask entirely the signature of a linear, sheet-like conductive geothermal system aligned along a valley-bottom fault, directly beneath the survey traverse. (Consider the masking of the buried conductive body of Figure 3.) The resistivity traverse may be the only substantial *deep-probing* test applied in that area, especially if it is rough terrain.

How can we guard against prematurely writing off such an area? Only by considering every surface-distorted traverse response area as "untested", and finding a way to evaluate the area with other approaches designed to overcome or avoid the surface problem. In a worst case where adjacent resistivity data can not be obtained, or do not eliminate the problem, consideration must be given to other techniques, such as a slim-hole drill test to determine if there is a thermal anomaly associated with the area.

The magnitude or strength of the surface-distortion anomaly is not a measure of the extent of its masking of deeper bodies. A shallow anomaly displaying only a modest magnitude still has potentially overwhelming masking power. The shallow feature is affecting the distribution of the injected current near its source, where its current density is greatest, and the effects on the pattern of current as it flows outward are the most extreme. On the other hand, the effects on the current field of distant or deep features are comparatively slight,- even large bodies influence only a comparatively small proportion of the total current field, generating a more locally influential anomaly that is easily lost in the presence of diagonals or ghosts from even modest surface-anomaly distortion.

It is ironic that the same near-surface features (such as an outflow plume or hot-spring swamp) that might first warn us of nearby geothermal resources may also be the cause of masking effects that interfere with detection of the deeper resource itself. As Figure 3 shows, the effects are not limited to conductive features; the fresh resistive flow rocks common to many geothermal areas can also effectively mask deeper responses.

What to do about the problem.

Inform, discuss, plan ahead, and allow a budget to watch for and acquire the detail data wherever distortion compromises the original traverse data. But by all means get the necessary raw data, or consider the traverse incomplete. No amount of advanced computer processing, inversions, or forward models can narrow down the almost infinite number of possible interpretations embodied in the data of a distorted single-traverse pseudosection. Competent, well-positioned field data represent the best possibility for resolution of the problem.

Awareness of the sensitivity of traverse data to near-surface features, and of the inherent uninterpretability of surface-distorted single-traverse resistivity data, is the first step. The evaluation of the single-traverse pseudosection of Figure 4 is appropriately cynical: despite the many numbers and the competent looking contours[2], there truly is nothing that can be learned about the earth deep under this line, and there is definitely no basis for positioning a drill. There is a near-surface conductor, period.

The most important next step may be in budgeting the extra time and funds for investigation of surface-compromised areas, perhaps even planning the means to investigate anomalies in real time, while the crew is on site and the costs are lowest. For contracted survey crews, build in contract options that allow a few weeks extension at your discretion, for anomaly evaluation, and then insist on real-time data feedback, if possible, so that you or your geophysicist can implement the plan. Insist that your crew bring extra supplies on site; the cost is nominal, and follow-up flexibility (and economics) depends on it. The dipole crew that has brought a few thousand feet of extra wire and some spare electrodes to the job site is prepared to get inexpensive, critical extra detail even in rough ground, should the need arise.

An attempt should be made to acquire the needed extra resistivity data by any means possible. The crew can almost always run a sub-parallel line through the approximate anomaly area, even if they have to struggle to install it on some hostile valley slope. The hardware can be moved along the original traverse line, using wires and electrodes located off to one side, up the hill elsewhere, to effectively survey a parallel line. The data from the slightly displaced electrodes represent the measurement of essentially the same sampled volume (Figure 2), but with the electrodes physically moved to locations where the near-surface may more uniform, causing less distortion. A type of automated resistivity traverse hardware is available (Shore and Clearwater, 1992) that provides for additional resistivity measurements to be made in real time, in most terrain conditions, whenever surface-distortion is recognized in traverse data.

All of this does not guarantee an interpretable result, but it is worthwhile to exhaust the immediate options, while available at lowest cost, in the hope that some usable information is developed. Where an important prospect area remains effectively unexplored after best efforts with conventional equipment, it may be appropriate to consider utilizing more advanced tools: the market has for a decade offered multi-directional, any-terrain data acquisition equipment, and lately full 3-D acquisition and inverse modeling services for multi-directional data (Premier, 1992). This system can in most cases eliminate the surface-distortion problems, and provide an unambiguous 3-D analysis of deep electrical features and boundaries even in complex, surface-compromised terrain.

Existing reconnaissance traverse data sets

The review of existing data sets to identify circumstances where uninteresting surface-distorted pseudosection traverse data were written off could yield opportunities for re-evaluation with current technology and perspectives. If a property was worth investing in traverse surveying once, it may still be worth acquiring effective exploration data in the (surface-distorted) coverage gaps that were left behind first time around.

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[2] Pseudosections can look even more irresistibly authoritative when they are computer contoured and colored. If they are single-traverse data and there is near-surface distortion, they remain almost totally compromised.

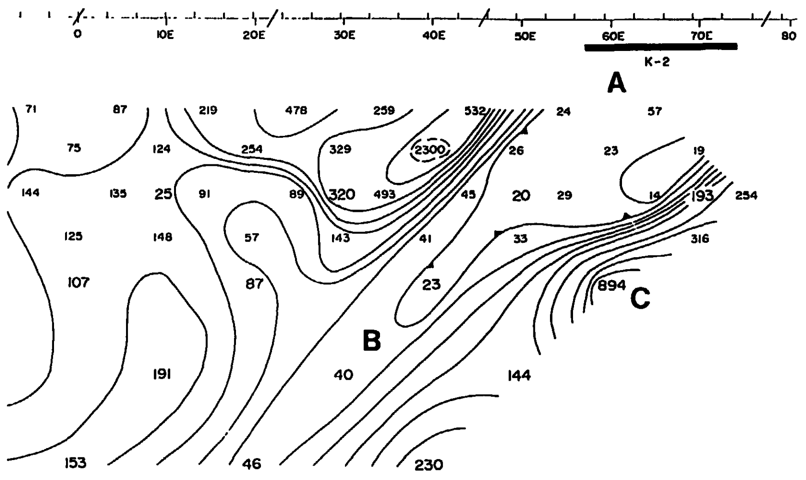

Figure 4 ***What does this single-line pseudosection tell us? ...not much.***

This dipole-dipole array pseudosection crosses a near-surface conductive body at anomaly K-2. While the 1000 foot and 2000 foot survey dipole lengths provide theoretical sampling to over 3000 feet, the strong diagonal extending down from the shallow anomaly K-2 warns us that we probably have useful data only for the very near surface,perhaps for less depth than is usually implied by the upper row of pseudosection numbers. Most of the pseudosection data are overwhelmed by near-surface effects,- distorted beyond interpretation.

From our knowledge of 2-D and 3-D shallow-body responses, we can infer that some very conductive material lies at or near surface in area A, but we can conclude nothing more about the right-hand two-thirds of the pseudosection.

The strong diagonal (B) does not imply a sloping, conductive feature at depth, but neither does it preclude the possibility that a sloping conductive or resistive feature (or any other type and shape of feature) actually does exist right there. The high apparent resistivities below K-2 (at C) conform to the expected resistive ghost expression below the shallow conductor. Any type and number of features could be located here, their signature masked by the shallow distortion pattern. For example, the data can not be used to rule out a sheet-like vertical conductor,- perhaps a fault-controlled active geothermal system resident in the valley bottom. The shallow conductor has effectively cloaked all deeper data with its own overwhelming signature.

The anomaly above is actually caused by the hot-brine outflow plume of a geothermal system (Meager Creek south) flowing in alluvium along a steep-sided valley floor several miles from the system itself, in a different valley. The traverse line data pick up the plume as the traverse crosses the valley at a right angle. Because the survey traverse is near a major system, but in a different, structurally-significant, relatively untested valley, exploration interest is high. It is important not to conclude that the area "has been effectively surveyed, with the known plume detected, and nothing of apparent interest at depth". Inadequate as it may sound, the correct exploration position is: "near-surface conductive plume distortions have defeated this attempt to map the deep valley conditions...try something else."

Data must be collected to satisfy the requirements of some interpretation approach (2-D or 3-D) which can positively identify and eliminate the effects of the near-surface features, and reveal the true geo-electric conditions beneath.

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