LINEAR E-SCAN: A reconnaissance resistivity mapping system that evaluates its own anomalies en route

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ABSTRACT

Single line resistivity traversing is commonly used in geothermal exploration, particularly in rough terrain, but also as a first pass test of more accessible prospective ground. Terrain restrictions often prevent the acquisition of the additional data needed to evaluate a single-line anomaly, which could be reacting to geothermal activity directly below, to the side, or even as far away as several miles, if the anomaly is caused by an intercepted outflow plume.

The initial use of an automated multiple-electrode potential-mapping traverse system:

- increases the effective depth of penetration and the width of the sampled survey route by three- to six-fold, thereby increasing the opportunity to detect anomalies, and
- provides for immediate deployment (in any terrain conditions) of the one or more perpendicular survey lines needed to evaluate a single-line traverse anomaly.

Any potentially important anomaly can therefore be mapped fully, within 4 to 10 days, so that the optimum drill positioning or other follow-up testing can be selected. An anomaly explained by non-economic causes is rejected, perhaps after 1 or 2 days of testing. Once the anomaly is fully defined and classified, the survey traverse resumes.

Introduction.

The automated field instrumentation used for 3-D multi-directional E-SCAN resistivity mapping can also be applied in a single-line traverse operating mode. The advantages of the full 3-D system (any-terrain flexibility and substantial depth of investigation characteristics) are retained in the traverse mode. The fact that the same hardware is used means that at any time, the traverse setup can be expanded to accommodate either a single cross-line, or a full 3-D multi-directional grid setup, to test and evaluate traverse anomalies during a pause in the field traverse.

* E-SCAN and LINEAR E-SCAN are registered trade marks of Premicr Geophysics Inc.

The need to detail single line resistivity anomalies.

Single-line reconnaissance resistivity traversing is commonly used in geothermal exploration to test large areas, in widely spaced traverses across flat ground, in a single traverse encircling the lower flanks of a volcano, and in traverses along available routes through rough terrain or along valley bottoms.

An interpretation problem occurs when an anomaly is detected in single-line data, and terrain or other factors prevents the acquisition of the additional data needed to understand the initial response. Shallow and deep anomalies require different treatment.

Shallow responses (i.e. located near the top of the pseudosection) are simple to interpret in terms of the spatial location of the source of the anomaly: it will be close to the traverse line itself. However, shallow anomalies, both conductive and resistive, can have a profound effect on the observation of deeper responses, often obscuring them entirely (Shore and Clearwater, 1992). The acquisition of additional data that is not affected by the initial near-surface anomaly may be required to effectively test the deeper part of the traverse section.

Deeper responses (more correctly, responses originating farther from the line of electrodes, either laterally or to depth, and appearing on the lower part of the pseudosection) can be caused by one or more sources which can be located beneath, to the left, or to the right of the line, and/or at locations up or down the line.

Without the additional data, a single-line anomaly may remain enigmatic and untested. It may *potentially* indicate a nearby geothermal feature, but can provide no information as to the location, shape, size or other characteristics of the anomaly source to guide drilling or other follow-up investigations. The only technically correct result at this stage might be a circle on a map, indicating the broad area that can host the cause(s), whether geothermal or otherwise, of the single-line resistivity anomaly.

Many questions will remain, and they will be different questions depending on the geologic/topographic setting, and the character of the anomaly. Using Figure 1 for an example, the three anomalies A, B, and C each occur in different exploration settings.

Anomaly C lies in valley sediments, spanning two side valley drainages, both of which have known hot springs in their upper reaches. Is the conductive anomaly mapping one, two, or no outflow plumes? From which valley? Or is the anomaly associated with conductivity originating directly below, at the intersection of some main valley structure with a fault in one or more side valleys? Is the main valley sediment simply deeper here, enriched by ash washed down the drainages from the volcanic complex, and therefore locally conductive but not directly due to geothermal causes? Two or more of these features combined?

The site of anomaly D presents fewer obvious possibilities, but the degree of uncertainty remains just as high. There are no side valley intersections nearby, but that doesn't exclude the possibility of a structural intersection lying below. Thermal fluids rising in structures directly below is a possibility. A simple increase in non-geothermal conductive valley sediments is another.

For anomalies C and D, more resistivity data is needed to resolve the source geometries and provide a clear indication of the next exploration step. (If resistivity data is too hard to get, temperature gradient drilling may be required to confirm the extent of possible geothermal interest in the anomalous area.)

Anomaly A-B is part of a series of anomalies mapped on a dipole-dipole array traverse across the complex about a mile above the lower river elevation. The center anomalies prompted the installation of the sub-parallel line to the west to try to acquire some dimensional perspective on the possible causes of the anomalies. Even with the added line of data, the interpretation remained highly ambiguous,- the anomalies could be explained by no fewer than 11 possible sites for conductive bodies, with one to five bodies involved in any of a hundred possible combinations. Using northwest regional and local geologic trends to help, a model consisting of two parallel conductive zones striking northwest was proposed (Shore, 1981). In fact, the single half-circle conductive zone shown west of the dipole anomalies (Figure 1) is the only conductive feature in the area; it is responsible for the multiple responses on the adjacent dipole-dipole traverse lines.

An automated, multi-electrode potential mapping system.

During the very active period of geothermal exploration in British Columbia from 1975 to 1982, the idea for a remote-controlled, rough terrain, resistivity electrode switching system (E-SCAN) went from concept, to prototypes, to operational system. The need was initially expressed in the extremely rough terrain of the Meager Mountain volcanic complex, and later in the Mt. Cayley geothermal prospect. Both volcanoes are part of the Garibaldi Belt, a northern extension to the High Cascades. Conventional resistivity traversing was being conducted along valley bottoms, and an occasional accessible route across high ground. Extremely steep and dissected terrain kept all but the shallow-penetration 2-point Schlumberger array mapping techniques from testing over 90% of the areas. A deep penetration approach that could be effectively deployed in any type of terrain was clearly desirable.

The initial utilization in rough terrain at Mt. Cayley, BC (Shore, 1983a, 1983b) and Mt. Makushin, Alaska (Shore and Ryder, 1986) proved the ability to operate in extreme terrain and provided the first experience with multi-directional potential field resistivity data sets.

It soon became apparent that, while the acquisition of *any* data in rough terrain was the initial objective, the qualities of the dense, overlapping, multi-directional data set presented exploration advantages in all terrains, especially where complicated near-surface features or subtle, deep targets were involved. The measurement of the absolute values of the potential fields set up by current injection at multiple, successive points was similar in effect to measuring the individual multi-directional data bits in an X-ray CAT-scan: the resolving power of the data set emerges as the data are organized into 3-D map views through the subject matter. Advances in 3-D inversion processing of the multi-directional potential data set (Li and Oldenburg, 1991, 1992) now permit interpretation and 3-D viewing of the geo-electric earth to identify bodies and structure at depths of several miles.

In another development direction, the use of remote-controlled electrode switching for linear traverses was tried in

Figure 1 (facing page) ***Reconnaissance resistivity traverses***

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.

A geothermal system lying beneath the line or to one side within the search envelope of the traverse (see Figures 2, 3) would be detected.

At right, a dipole-dipole resistivity traverse sweeps along a valley-bottom road, while another traverses a higher elevation route across the Mt. Cayley BC geothermal prospect.

The extreme terrain makes it difficult to obtain the additional survey data needed for the interpretation of traverse anomalies. To obtain the second sub-parallel line of data to help define anomalies A and B, wires were lowered down the slope from the upper traverse route to electrode sites, which were then connected to instruments remaining on the upper, traversible route. (The additional dipole-dipole traverse data were still not adequate to unambiguously identify the source of the anomalies, the half-disc area marked "E-SCAN".)

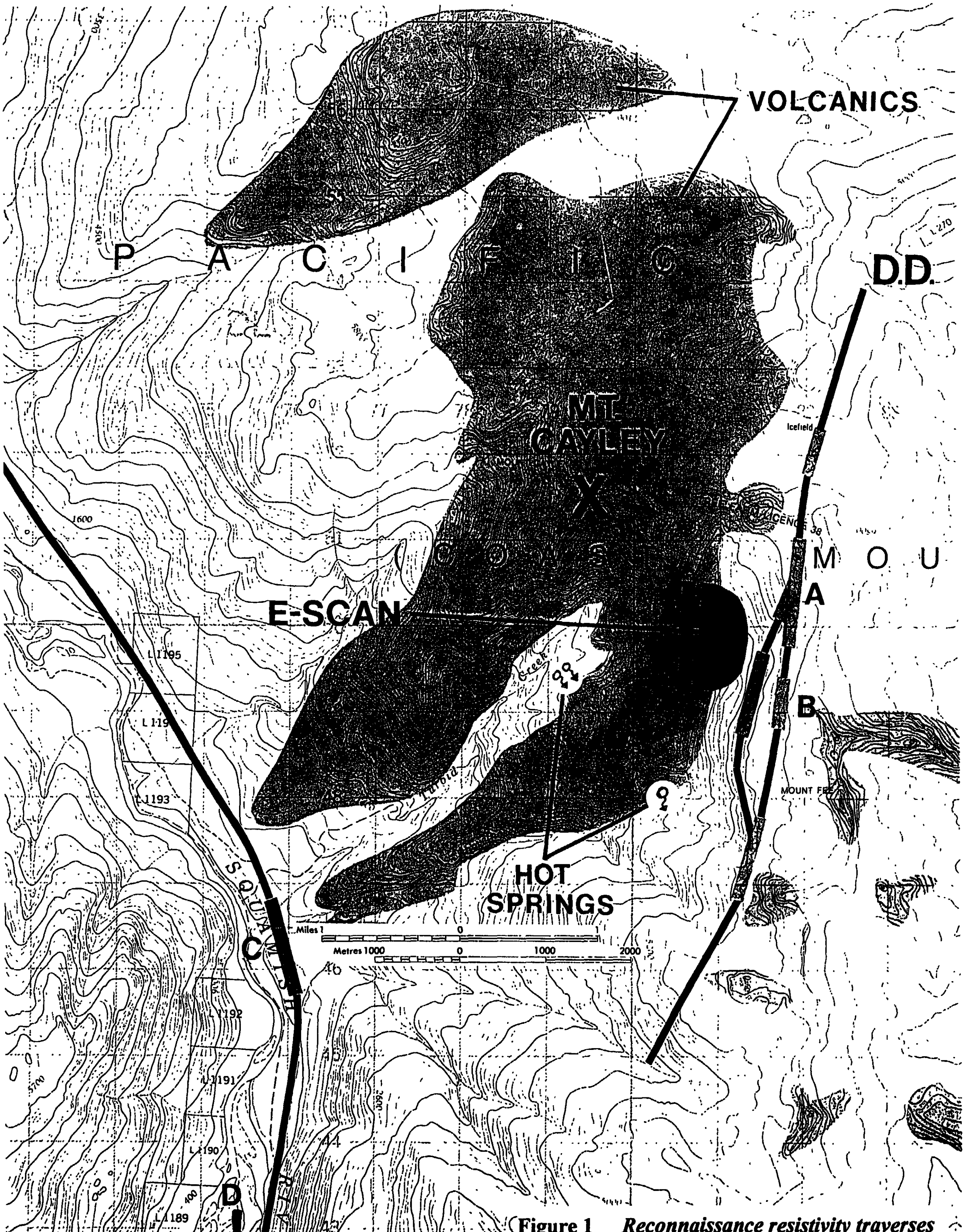

Figure 1 *Reconnaissance resistivity traverses*

the Aiyansh area of BC (Shore, 1985). A 20 km long single traverse was conducted along a graben edge, over fresh lava flows and assorted lithologies, in search of geothermal activity near a 200 year old eruptive center. With automated electrode switching, the traverse mapped both dipoles and absolute potentials over a depth of investigation of >3 km and an effective lateral survey sweep 6 km in width.

The example data set

Although a cross-valley line was used to test an anomaly, the Aiyansh LINEAR E-SCAN survey did not proceed to a full 3-D evaluation, nor was there any prior traverse data for comparison. However, at Mt. Cayley, a rough terrain dipole-dipole traverse generated anomalies which were later resolved by mapping with full 3-D E-SCAN, suggesting that this would be an appropriate case study for comparison of results. Since there was no initial LINEAR E-SCAN traverse done at Mt. Cayley, we have assembled the equivalent results for examination. We have extracted from the all-inclusive multi-directional data set exactly those measurements which were taken between electrode sites that duplicate the initial dipole array traverse, and also the nominally positioned cross-lines illustrated in this paper. These are not synthesized, extrapolated or interpolated data, but the actual electrode-to-electrode measurements which were recorded when the whole area was intensively, multi-directionally mapped. If the reader will grant this re-arrangement only of the actual time sequence of data acquisition, then perhaps we can derive some useful perspective from examining the suggested process of en route anomaly investigation in the most complete manner available.

En route evaluation of anomalies

A few simple rules are applied, to maintain exploration objectivity in the field. When an anomaly is detected, the cross-line is installed across the nominal (plotted) center of the anomaly. If the anomaly source is then understood to be shifted to a different range of possibilities, then the next cross-line(s) should be placed through the center of those possibilities. Since the additional lines can be physically installed virtually anywhere, the follow-up planning can concentrate on objectively evaluating the geophysical and exploration questions, and not on terrain limitations.

The figures are extensively captioned to describe the sequence of steps in the anomaly evaluation process. All pseudosections are plotted at the same scale using a Y axis effective depth (Ze) of Edwards (1977) to allow comparison between pseudosections of different array types.

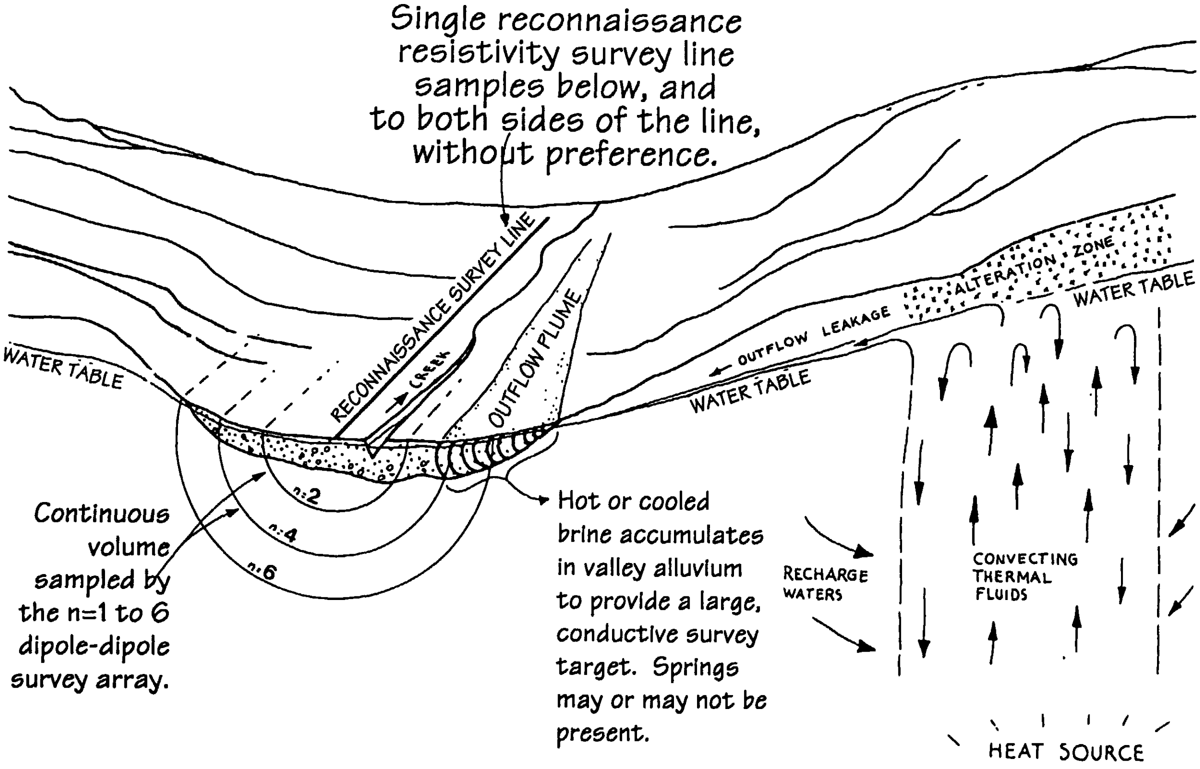

Figure 2 ***Dipole-dipole array resistivity survey.*** The extent of this survey traverse's effective range of measurement (laterally and to depth) is indicated by the n=6 limit. The detection of the conductive outflow plume will be shown as an anomaly in the n=4, 5, and 6 levels of the pseudosection plot. However, there will be no clues in the pseudosection to suggest whether the cause of the observed anomaly lies below, to the left or to the right of the line (or some combination of these). Additional geophysics or geological input is needed.

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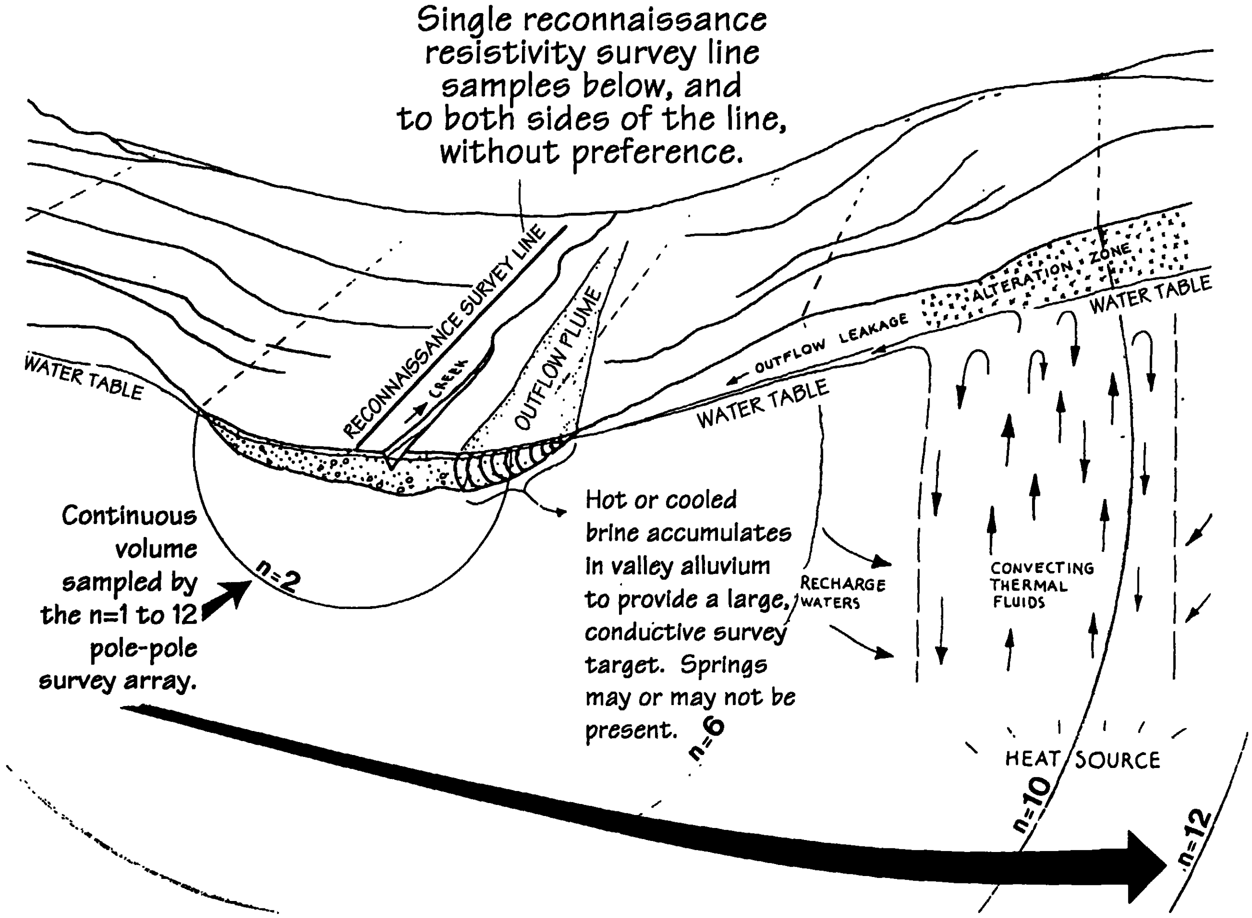


Figure 3 ***Pole-pole array resistivity survey.*** From the same electrode station interval used by the dipole-dipole survey of Figure 2, the pole-pole array survey measures a larger volume, with electrode separations routinely up to n=12. In the absence of a well-developed outflow plume (a rocky valley with no alluvium host, for example), the broader sampling might detect the geothermal system itself.

Having detected an anomaly, interpretation as to which part of the valley to investigate first (left side, right side, or below the line?) remains a problem. Additional geophysics or geological input is required. In this case, the automated survey hardware supports the immediate deployment of a survey line (or lines) *across the valley* to map the anomaly source in three dimensions, before the survey traverse moves on.

Measuring the absolute potentials (pole-pole) instead of gradients (dipole-dipole) provides the high signal needed for large scale mapping: at n=12, the pole-pole array signal level is still five times larger than the dipole-dipole array signal is at n=6 (Figure 2).

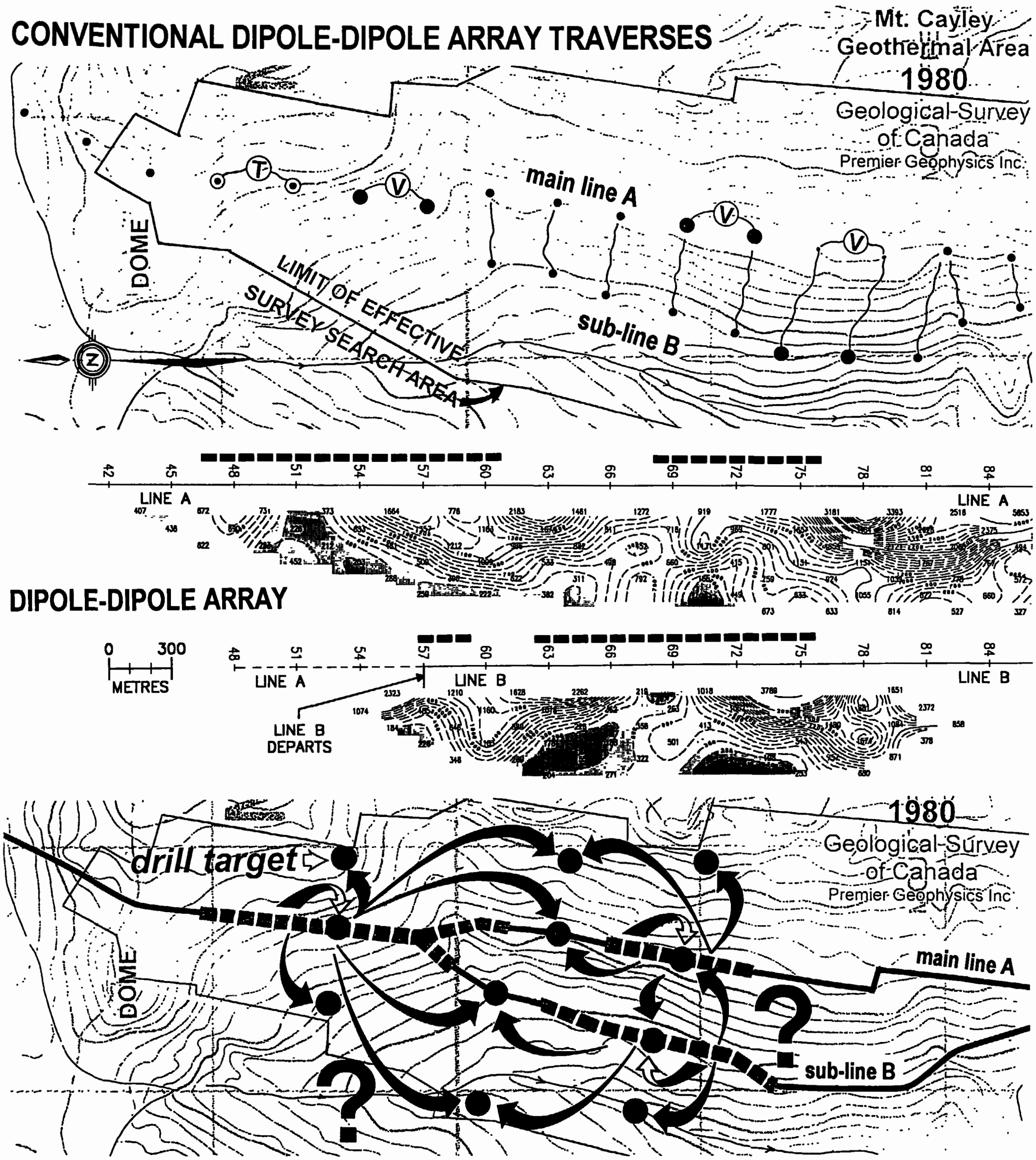


Figure 4 ***Conventional dipole-dipole array resistivity survey.***

Upper: Electrode stations, with a current dipole (T) and several measurement dipoles (V) in place. The V dipole at right shows how the lower line B was measured using wires dropped down the steep slopes to electrode dipole positions below.

Middle: Pseudosections show three conductive anomalies.

Lower:. Within the effective search area, several dozen models involving combinations of one to eight conductive bodies located in eleven different locations (marked by drill target symbols) can reasonably explain the dipole-dipole anomalies. In practical geothermal exploration terms, one could expect to drill 3 or 4 holes before thermal gradient observations could be expected to help in ***a)*** focusing on the legitimate target location(s), and ***b)*** firmly eliminating all other possible targets.

The left and right groups of drill targets represent responses from possible bodies beside and/or under the survey lines. The center four targets acknowledge the fact that the two anomaly groups may be a "double-peaking" response to a single body beneath and/or to one side of the lines.

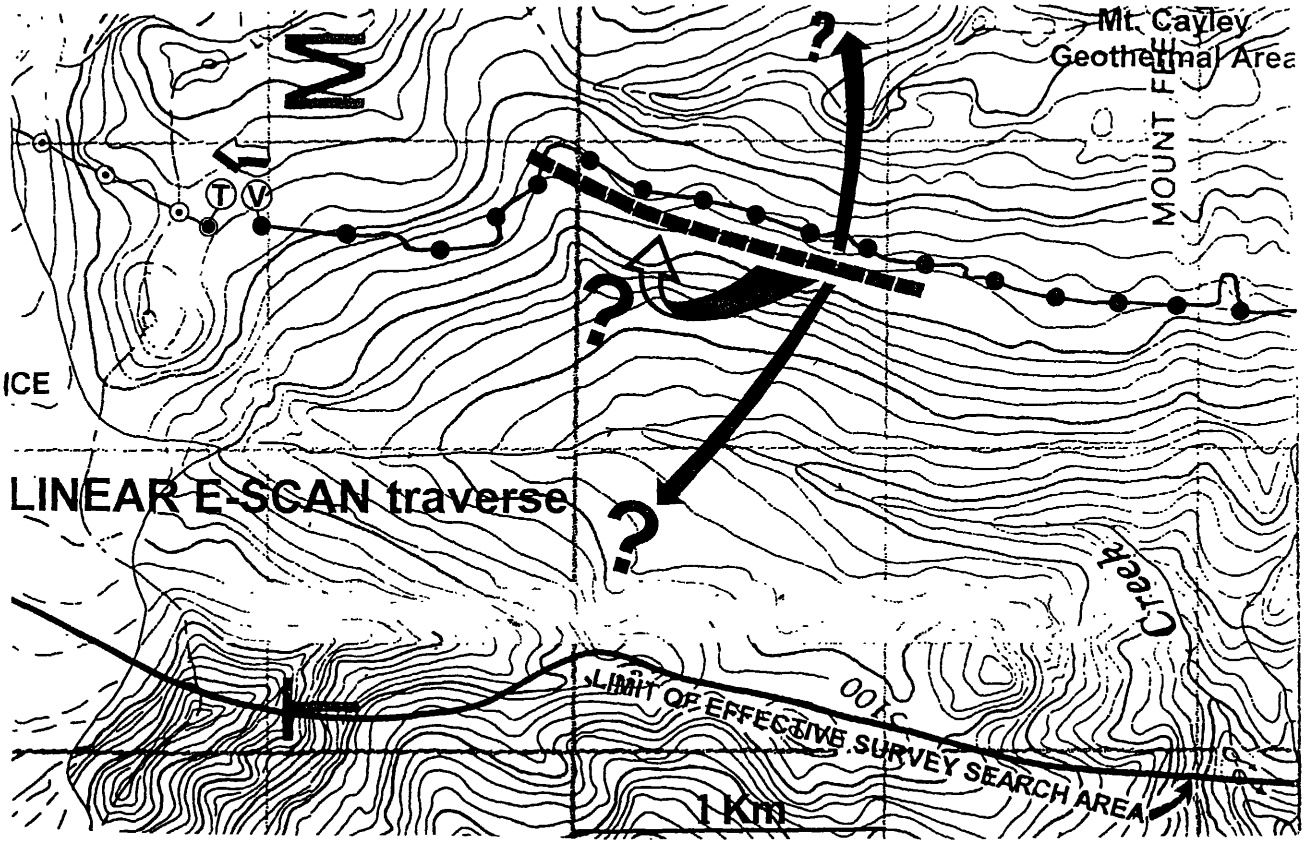
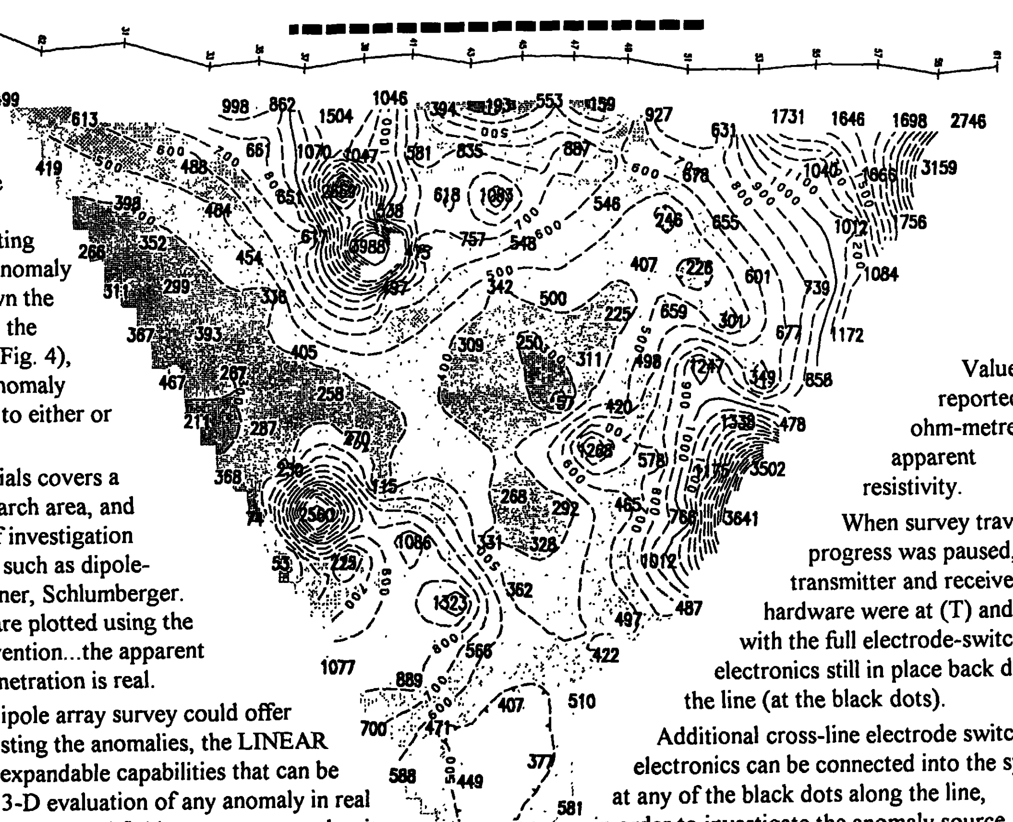


Figure 5
LINEAR E-SCAN:
reconnaissance traverse survey line.



The LINEAR E-SCAN traverse follows the route of the 1980 dipole-dipole array traverse, also detecting a significant conductive anomaly which plots half-way down the pseudosection. As with the dipole-dipole anomalies (Fig. 4), the cause(s) of such an anomaly could lie beneath, and/or to either or both sides of the line.

Mapping absolute potentials covers a wider effective survey search area, and greater effective depth of investigation than any derivative array such as dipole-dipole, pole-dipole, Wenner, Schlumberger. Data in Figures 4 and 5 are plotted using the same Y axis scaling convention...the apparent difference in effective penetration is real.

While the conventional dipole array survey could offer no further options for testing the anomalies, the LINEAR E-SCAN equipment has expandable capabilities that can be drawn on for exhaustive 3-D evaluation of any anomaly in real time, while the equipment, crew and field support are on the site.

Values are reported in ohm-metres apparent resistivity.

When survey traverse progress was paused, the transmitter and receiver hardware were at (T) and (V), with the full electrode-switching electronics still in place back down the line (at the black dots).

Additional cross-line electrode switching electronics can be connected into the system at any of the black dots along the line, in order to investigate the anomaly source.

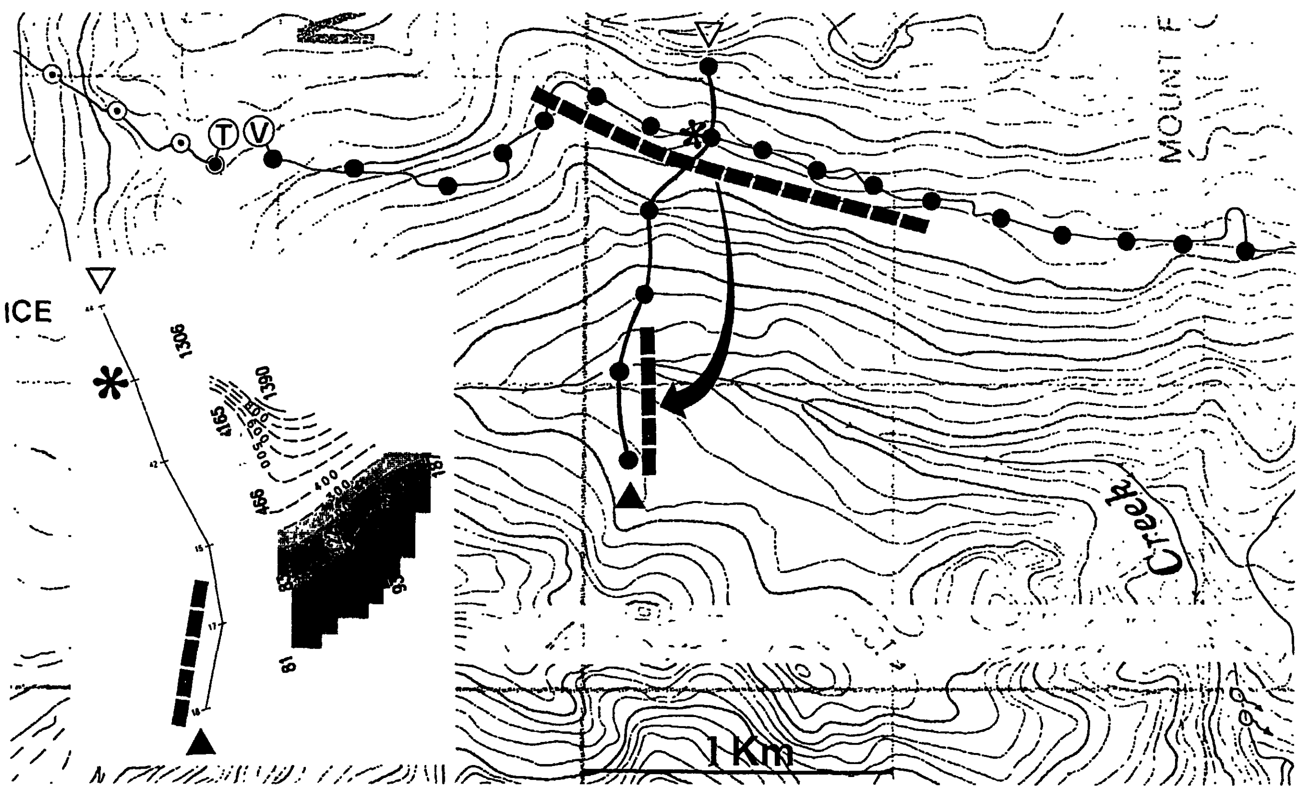


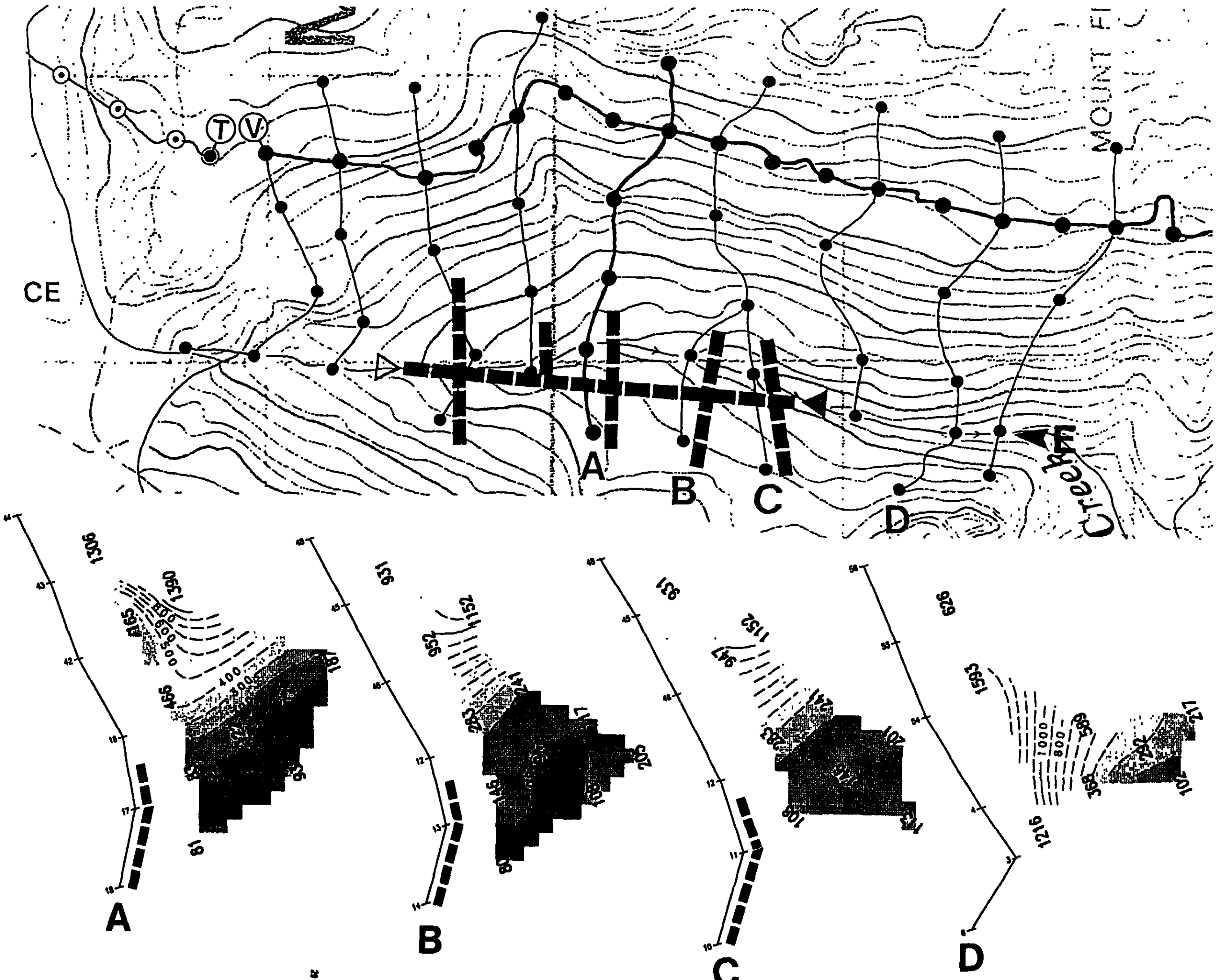
Figure 6 LINEAR E-SCAN *Step 2: a single cross-line tests to the left, right and beneath the traverse line.*

With the traverse instrumentation still at (T) (V), a cross line of remote-operated electrodes is installed, using the easiest route across the center of the anomaly. These new electrodes are wired into the automated acquisition system at (*). Within a day of making the decision to investigate, the traverse anomaly the line has been installed, the potential data have been shot, and the above pole-pole array plot is constructed for review.

An anomalous conductive body lies near surface (and possibly at depth) off the west end of the cross line. Beneath the traverse line (at the *) and eastward, resistive signatures prevail, so these sites (see Figure 5) are eliminated.

However, the signature reported on the cross-line could be caused by shallow, conductive volcanics,- and there is not yet any evidence to indicate deeper resistivity conditions.

A decision must now be made as to whether or not to continue to map out the anomaly, to either resolve a clear and unambiguous drill target, or to confirm that the anomaly is not of interest and should be dropped. The geologic setting is favourable, and the reported resistivities are interesting, at less than 100 ohm-metres in a crystalline rock environment averaging >1000 ohm-metres elsewhere. Therefore, a decision to advance to Step 3 (more cross-lines) would likely be made.



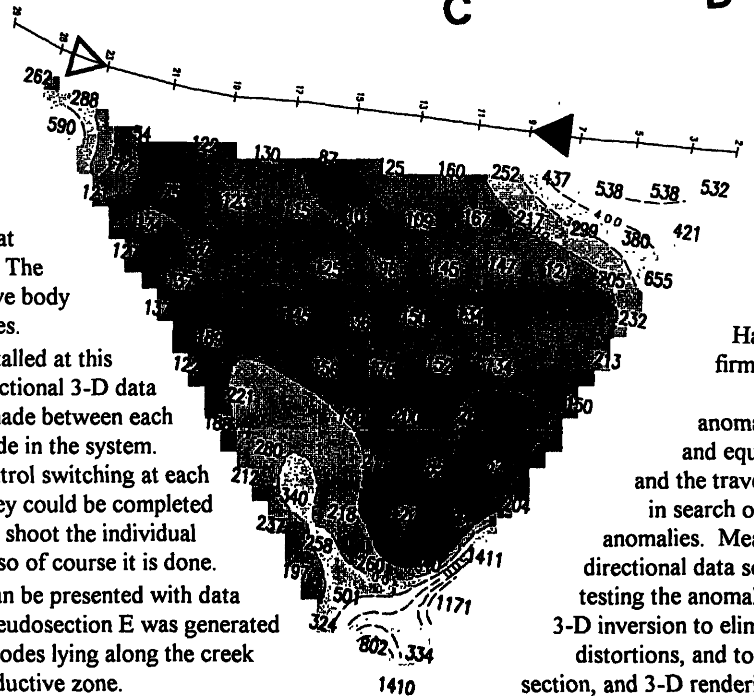


Figure 7
LINEAR E-SCAN
Step 3: multiple cross-lines add 3rd dimension to the resistivity mapping.
The initial cross-line (A) is now flanked by adjacent cross-lines that test to the west edge of the area. The near-surface part of the conductive body is now being defined on three sides.
Note that the instrumentation installed at this stage can acquire a full multi-directional 3-D data set, in which measurements are made between each electrode and every other electrode in the system. Using the automated, remote-control switching at each electrode, the complete 3-D survey could be completed in about the time it would take to shoot the individual parallel cross-lines (4 to 5 days), so of course it is done. With 3-D data, pseudosections can be presented with data from any series of electrodes. Pseudosection E was generated from data shot between the electrodes lying along the creek valley, across the anomalous conductive zone.

Having located and confirmed a single conductive cause for the traverse anomaly, the cross-line wire and equipment are recovered, and the traverse survey is resumed in search of more reconnaissance anomalies. Meanwhile, the full multi-directional data set that was acquired in testing the anomaly can be processed by 3-D inversion to eliminate the near-surface distortions, and to provide detailed plan, section, and 3-D rendering of deeper features.

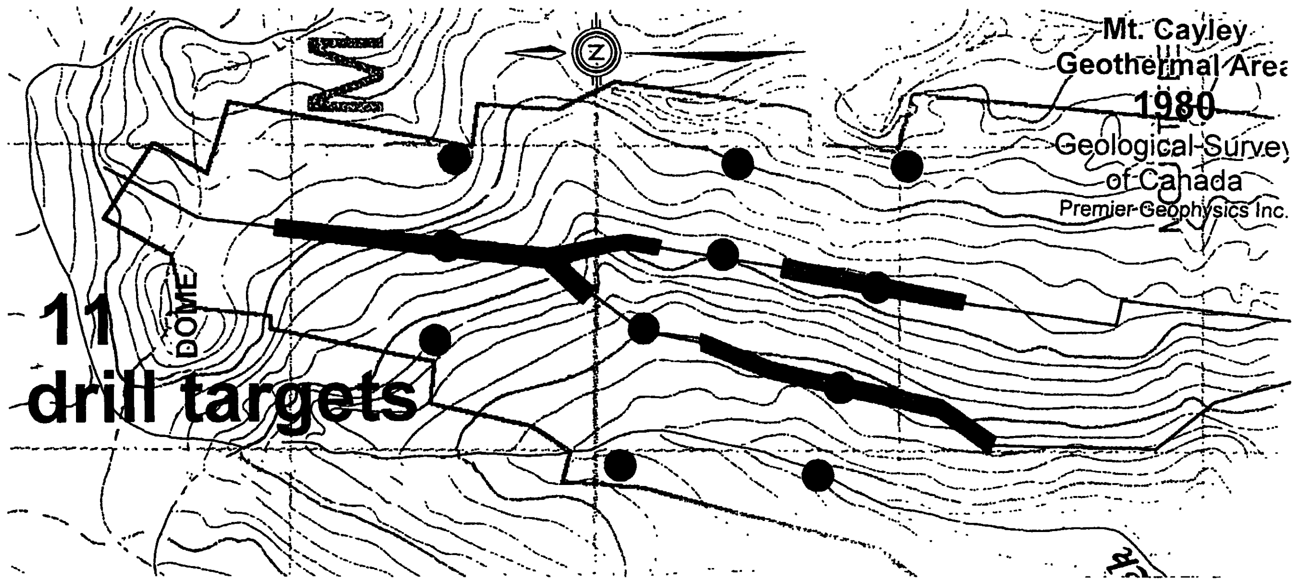


Figure 8 *Comparison of exploration information: the conventional traverse results*

The conventional dipole-dipole traverse was successful in advising of a nearby feature(s) of potential interest, but could not deliver an unambiguous (and correct) definition of the next required step for exploration. Of the 11 possible locations for conductive bodies, 3 or 4 might have to be drill tested to begin to understand, possibly with the assistance of downhole thermal gradient information, that a signature of possible geothermal interest lay to the west, and not under the lines, or to the east.

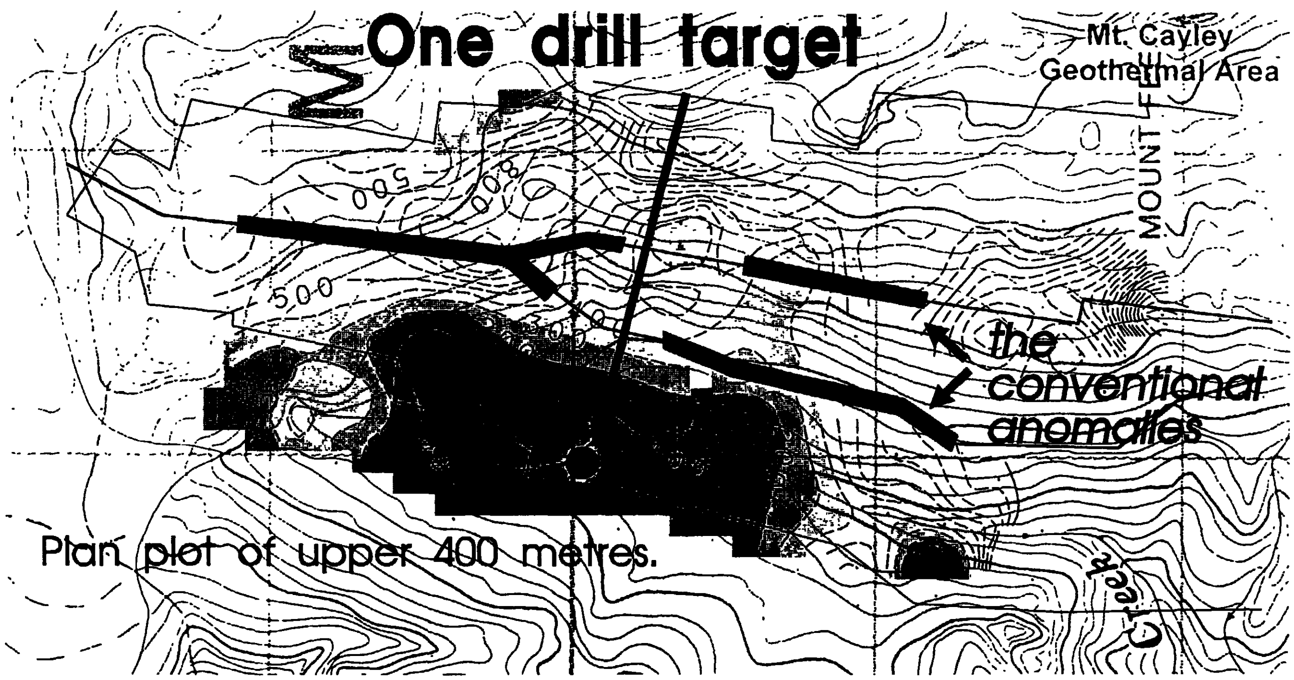


Figure 9 *Comparison of exploration information: the LINEAR E-SCAN (and real-time 3-D follow-up) results*

One drill target characterizes this final plan plot of raw data. The plot shows the contoured resistivity results obtained from the shortest spacing measurements within the multi-directional data set. The plot shows clearly the single explanation for both the LINEAR E-SCAN traverse anomaly, and for the group of three dipole-dipole traverse anomalies (a classic "double-peak" response caused by a single conductor "shorting out" the conventional array dipoles as they pass by.) Also of importance, the plot shows, equally clearly, the *absence* of any significant conductive bodies at each of the other 10 possible locations suggested by the traverse data. All possibilities have been thoroughly tested. Drilling requirements are significantly reduced, and project scheduling is potentially accelerated,. As a result of increased certainty and reduced drilling, the net costs both in overall cash requirements and in environmental disturbance would appear to be reduced substantially.