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E-SCAN, Advanced Resource Evaluation Systems

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Introduction to the

E-SCAN

Multidirectional Electrical Mapping System

A possible candidate
for increasing
the geologic and geotechnical understanding
of the Yucca Mountain
nuclear waste repository site.

October 28, 1990

Premier Geophysics Inc.
Vancouver, B.C.
Reno, Nevada

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Stage 3B: Optional extension of Stage 3, 3A over entire Crater Flat area

Proportional increases in data coverage and plots of Stages 3 and 3A above.
5 x 15 or 22 plan view pseudodepth plots (15 or 22 each of NW, N, NE, E, and "all" orientations of data.)
Pseudosections facing NW, N, NE, and E.
2-D, 3-D inversion/imaging of features.

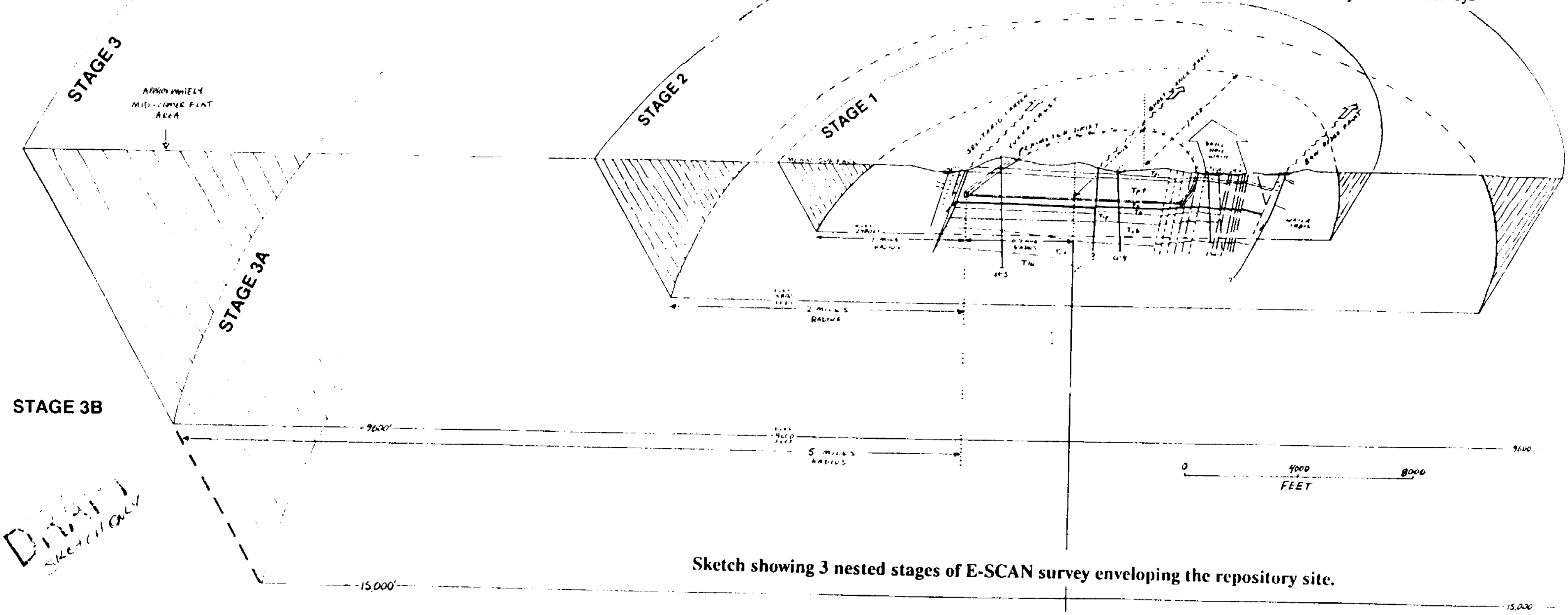
Stage 1 Options:

on all measurements:

- Induced Polarization data

using the E-SCAN grid already in place:

- Mise-a-la-masse surveys or downhole-source surveys
- Rotary Gradient surveys



Sketch showing 3 nested stages of E-SCAN survey enveloping the repository site.

Stage 3A: Optional extension to -15,000'

75,000 measurements to NDIC = 15,000' using the existing 800'-1600' square grid
Additional 5 x 7 plan view pseudodepth plots (7 each of NW, N, NE, E, and "all" orientations of data.)
Pseudosections extended to NDIC 15,000'
2-D, 3-D inversion/imaging of features.

Stage 3: Sub-regional geologic setting

155,000 measurements to NDIC = 9600'
800'-1600' square grid, 155 square miles
5 x 15 plan view pseudodepth plots (15 each of NW, N, NE, E, and "all" orientations of data.)
2200 line miles of pseudosections facing NW, N, NE, and E.
2-D, 3-D inversion/imaging of features.

Stage 2: Larger scale repository area resolution

107,000 measurements to NDIC = 4800'
400'-800' square grid, 26 square miles
5 x 15 plan view pseudodepth plots (15 each of NW, N, NE, E, and "all" orientations of data.)
900 line miles of pseudosections facing NW, N, NE, and E.
2-D, 3-D inversion/imaging of features.

Stage 1: Immediate repository area

224,000 measurements to NDIC = 2400'
200'-400' square grid, 14 square miles
5 x 15 plan view pseudodepth plots (15 each of NW, N, NE, E, and "all" orientations of data.)
1000 line miles of pseudosections facing NW, N, NE, and E.
2-D, 3-D inversion/imaging of features.

Table of contents.

1. SCOPE OF THIS DOCUMENT:

This is general information abour E-SCAN, provided in response to a request for same. It is not a proposal, nor does it purport the be a technically complete presentation of the E-SCAN method and its applications and uses. The information herein has been selected for its perceived relevance to the Yucca Mountain project, and is scientifically correct and objective in its content. Questions regarding claims or assertions made herein, or about possible applications, should be directed to Premier at the earliest conception in order to take advantage of over 15 years of accumulated research and field expertise (much of it unpublished or proprietary) in this particular area of expertise.

The sole purpose of this document is help people involved in the Yucca Mountain project to determine whether or not to look closer at the E-SCAN method.

One encouraging point can be kept in mind: due to the comprehensive, very dense, multidirectional data set, E-SCAN actually simplifies the understanding and utilization of geoelectric data, in much the same way as the CAT-scan actually simplifies the task of sensitive or detailed 3-D X-RAY diagnostics. The CAT-SCAN is a highly automated version of plain old X-RAYs; E-SCAN is the corresponding version of plain old electrical resistivity. The resolving power and interpretability of both techniques is not unexpected when the magnitude and distribution of the respective raw data sets are considered.

It is my belief and indeed my experience that the more a client or user delves into E-SCAN, the greater the realization of just how much vexing assumption and ambiguity has been stripped away from electrical mapping process, just how simple and logical the process becomes, as a result of (simply) increasing measured geoelectric data density by a hundredfold.

> Note: no plots or documentation of modeling techniques or results is presented here. This would be presented at a more advanced stage of discussion of E-SCAN, and would involve slide projection and video equipment.

2. BACKGROUND: PREMIER AND E-SCAN.

E-SCAN was developed by Premier Geophysics Inc. of Vancouver, B.C. starting in 1976, initially for deep geothermal mapping, in extremely rough mountain terrain. Prototype development was achieved over a period of 6 years at a cost of over $3 million dollars, paid by Premier, with valuable financial and test application support from the Geological Survey of Canada, British Columbia Hydro and Power Authority, and the Ministry of Energy, Mines, and Petroleum Resources. The first commercial surveys were undertaken in 1982 and 1983 for the GSC; the first US application was in 1984 on Unalaska Island, Alaska for the Alaska Power Authority. The system and its interpretation software have evolved since 1984 through continued research and development, including a 3-D inversion research program ongoing at the University of B.C. Premier Geophysics Inc. handles Canadian and overseas operations of E-SCAN; US operations are handled by Nevada-incorporated Premier Service Company Inc., out of Reno. At present, there are no other E-SCAN-like systems or users known to Premier.

3. HOW IT WORKS:

E-SCAN automates and eliminates the task of dragging measurement dipoles up and down lines, as undertaken in conventional dipole-dipole or other electrical surveys. To do this, a large area of survey ground is wired up in advance with measurement electrodes, which are daisy-chained together through a computer controlled network of wire and switching devices. Several hundred electrodes are operational at once.

As current is introduced to the ground, the signal generated is measured at each point on the E-SCAN grid in succession, at up to 1000 times the sampling rate of a dragged-dipole conventional survey. Since all electrodes are instantly accessible to the fixed receiver, measurements can be made not just along lines, but across lines in every direction, generating a dense multidirectional data set. Short, medium and extra-long array separation measurements do not need separate surveys with different dipole wire lengths; electronic scanning of the network achieves this range of measurements automatically. E-SCAN maps 600 to 1500 complete, stacked, averaged measurements per day, even in very rough terrain.

Figure 1 illustrates some layouts of E-SCAN grids, showing some of the computerized switchboxes which are the "distributed intelligence" of the E-SCAN network.

4. PROCESSING THE DATA:

Like the CAT-SCAN, E-SCAN's data set is logged to computer disc for later assembly in whatever viewer perspectives may be demanded. The data can be sorted into sets of pseudosections across the property, oriented in any direction chosen by the viewer. Four orientations (facing northeast, north, northwest, and east) are produced as standard. Plan view pseudodepth plots are also generated, usually at 12 to 15 levels (12-15 plots of increasing electrode separation), which provide a good initial sense of the 3-D characteristics of the property.

The pseudosections and pseudodepth plots are subsets of the raw data set, contoured, but not filtered, interpolated or otherwise processed. On many projects, most of the important exploration information can be recognized and interpreted from these plots (usually 150 to 300 apparent resistivity plots per property, and the same amount again for each of IP and metal factor, if measured).

Rather than overwhelming the investigator, the quite massive E-SCAN data set makes life simpler. For example when a faint linear feature is seen in some plan overview plots, the worker can go directly to the set of pseudosections (and unidirectional pseudodepth plots) oriented in the appropriate direction to evaluate and challenge the feature's existence and characteristics. The data set first offers subtle hints (or blatant indications) of electrical features, and then provides the means to logically proceed with tests and evaluations using a number of overlapping perspectives and approaches.

In unidirectional or less dense conventional survey data sets, many of these logical operations, and therefore their conclusions, are not available. Modeling in that case must proceed with these conclusions replaced by assumptions, with corresponding ambiguity of result.

For potentially complex and/or subtle-featured properties (and where a definitive absence of a feature or response may be an important finding, such as at Yucca Mountain), a range of 1-D, 2-D and 3-D forward and inverse programs have been developed for E-SCAN data sets. The 3-D direct inversion uses an unprecedented 10,000 E-SCAN potentials, to resolve 1,000,000 variables in a 100 by 100 by 100 element model earth. These modeling tools, combined with the superior noise-averaging and big-picture perspective provided by E-SCAN, represent a very large step forward in the ability to definitively map subtle but geologically significant electrical features within the earth.

5. A YUCCA MOUNTAIN STRATEGY: THREE 3-D STAGES, PLUS TRANSECT.

Seven sketches follow this text, showing in plan and section view the three 3-D Stages described below. "NDIC" is explained in an appended section.

5.1 STAGE 1: IMMEDIATE REPOSITORY AREA:

224,000 resistivity measurements
(IP optional)
14 square miles
NDIC 150' to 2400'

In Stage 1, intensive multidirectional mapping is applied to the area above and for 1400 feet below the proposed repository horizon, and for a mile outward in all directions from the perimeter drift. Current is injected into the ground at every point on a 200' square grid, while measurements are made at E-SCAN potential electrodes placed at 400' grid intervals (a "200-400" survey). The surface grid is 14 square miles in area. 224,000 separate apparent resistivity measurements are made, at every orientation, at Nominal Depths of Investigation (NDIC) of 150' to 2400'.

Fifteen plan view pseudodepth plots will provide the initial overview of resistivity distribution, variation with depth, structures, boundaries and linear features of single or multiple orientations, and images of the effects of geologic processes on the host rock regime, effects such as subtle hydrothermal alteration imprints across various rock types.

A total of one thousand line miles of apparent resistivity pseudosections will be generated in four viewing orientations, allowing evaluation of linear features of any orientation.

Evidence of past or present active geothermal activity within 2400 feet of surface would be mapped. Hydrothermal alteration images (alteration clays as a conductive zone; silicification as a resistive zoning) would be mapped. Faults bearing an electrical signature would be mapped.

The water table should be recognized, and be interpretable at its absolute depth using inversion.

From the plan and pseudosection data, areas obviously two-dimensional can be subjected to E-SCAN 2-D forward or inverse modeling, using the data subset oriented "just right" across (and in the middle of) the feature of interest. Obvious or suspected fault zones will be candidates for modeling.

Full 3-D imaging will be undertaken at coarse scale to show the entire repository area, to about 2400 feet below surface, with presently known and E-SCAN mapped structure and zoning viewable by rotating, tilting and manipulating the color model images on a screen.

Higher resolution 3-D images can be done for specific features or parts of the repository area, to examine what the "simplest-model" approach of the 3-D system proposes. A 3-D model of 1 million variables (a cube 100 by 100 by 100 elements) is generated from 10,000 or more E-SCAN data.

Several options can be contemplated for Stage 1 survey:

5.1.1 Option 1: Induced Polarization (IP):

IP measurements can be taken by extending the stacking to double or triple the number of pulses normally required for resistivity alone. This has a cost increase effect as the survey progress is slowed, but involves no other complications unless the use of porous electrodes for IP is mandated. IP would be measured at Stage 1 depths only; at greater depths the information returned would likely be unreliable.

IP may provide useful information about both alteration and economic mineralization potential. It may also be an important and sensitive component of any data set that is envisaged as an "electrical environment baseline" to be compared to future mapping results. Review and discussion of E-SCAN IP case material with the Yucca Mountain scientific authorities would help assess the potential value of including IP at Yucca.

5.1.2 Option 2: Self-Potential (SP).

A detailed SP map can be generated from the 224,000 recorded data as a processing option. The information is recorded along with the resistivity data in any case. SP may be diagnostic, to some degree, of the groundwater regime, and may be useful as baseline data for future comparison.

5.1.3 Option 3: Mise-a-la-masse surveys:

If boreholes are accessible, current electrodes can be lowered into the holes and energized at various levels. With the E-SCAN grid in place at surface, complete "mise-a-la-masse" surveys can be conducted in a matter of an hour per survey (as opposed to a normal week or so per survey). These data can be evaluated as potential fields in the normal mise-a-la-masse manner. The data would also be included with the surface data for use with the 3-D modeling program, which accepts any combination of surface and underground electrode locations. Mise-a-la-masse may yield enhanced insights into structure and rock fabric through the repository level, and within the water table zone in particular.

5.1.4 Option 4: Rotary Gradient surveys.

In Stage 1, a Rotary Gradient survey can be done. As with mise-a-la-masse, the entire electrode grid is scanned and the potentials are logged in response to current injected by a pair of electrodes straddling the survey area, several miles distant. This is a conventional Gradient Array survey, done with E-SCAN in an hour instead of two weeks. The potential benefit of a gradient array survey is an uncluttered mapping of the response from deep conductive/resistive zones.

In some areas near-surface resistivity variation distorts the symmetry of the current being injected, masking subtle response patterns. The gradient array introduces a uniform flow of current through the area between the distant current electrodes, the field relatively unaffected by near-surface conductivity variation. The signal (potential field) cuts the surface virtually perpendicularly, and is thus also unaffected by near-surface variation, while marking the subsurface current flow pattern with considerable resolution.

By shooting a complete survey using each of four electrode pairs in four orientations around the grid, a "Rotary Gradient" survey is accomplished. Comparison of the response at various orientations yields additional information and resolution of deep lineaments. This survey is not essential, but could prove informative at low cost if the opportunity arose to employ it.

An interesting unpublished Rotary Gradient case exists and would be available for presentation at some time.

5.2 STAGE 2: LARGER SCALE REPOSITORY AREA

107,000 resistivity measurements
26 square miles
NDIC 300' to 4800'

In Stage 2, multidirectional mapping is applied above and for 3800 feet below the proposed repository horizon, and for two miles outward in all directions from the perimeter drift. Current is injected into the ground at every point on a 400' square grid, while measurements are made at E-SCAN potential electrodes placed at 800' grid intervals (a "400-800" survey). The surface grid is 26 square miles in area. 107,000 separate apparent resistivity measurements are made, at every orientation, at Nominal Depths of Investigation (NDIC) of 300' to 4800'.

Fifteen plan view pseudodepth plots will provide the initial overview of resistivity distribution, variation with depth, structures, boundaries and linear features of single or multiple orientations, and images of the effects of geologic processes on the host rock regime, effects such as subtle hydrothermal alteration imprints across various rock types.

A total of nine hundred line miles of apparent resistivity pseudosections will be generated in four viewing orientations, allowing evaluation of linear features of any orientation. Where pseudosections pass through the Stage 1 volume, the more detailed Stage 1 data will be merged into the pseudosections.

The features mapped will be the same ones suggested for Stage 1, with the area of investigation now twice as deep and extending outward an extra mile. Resolution of features will be diminished from Stage 1 levels due to the larger array spacings.

A repeat of the downhole current injection might not add useful information. Running the Rotary Gradient survey again at this scale could be very useful in investigating deep structure. These issues would be properly addressed after Stage 1 mise-a-la-masse and rotary gradient results were reviewed.

Stage 2 data also provide the adjacent and distant background levels for the 3-D inversion of the detailed 200' data set, thus improving the model's reliability at its edges.

5.3 STAGE 3: SUB-REGIONAL GEOLOGIC SETTING

155,000 resistivity measurements
155 square miles
NDIC 600' to 9600'
Optional penetration to NDIC 15000'

In Stage 3, the multidirectional mapping provides the broad sub-regional picture which E-SCAN case histories so consistently suggest is necessary for understanding any near-surface regime. Penetrating nominally two or three miles under the repository, still with very high densities of measurement, the large scale E-SCAN allows mapping of electrically-marked deep structural features, intrusive bodies and geothermal/hydrothermal systems which extend into the survey envelope. Potentially significant deep structures approaching the repository area from five miles out in any direction(s) may be mapped.

The Crater Flat area would have its eastern portion included in a five mile radius; the survey could be extended over all of Crater Flat, so that a 3-D inversion could be applied and the structure modeled.

Fifteen plan view pseudodepth plots (22 if NDIC = 15000' is selected) will provide the initial overview of resistivity distribution, variation with depth, structures, boundaries and linear features of single or multiple orientations, and images of the effects of geologic processes on the host rock regime, effects such as subtle hydrothermal alteration imprints across various rock types.

A total of 2,200 line miles of apparent resistivity pseudosections will be generated in four viewing orientations, allowing evaluation of linear features of any orientation.

Stage 3 data also provide the adjacent and distant background resistivity levels for the 3-D inversion of the combined Stage 1 and Stage 2 data set, thus improving the model's reliability at its edges. By the time Stage 3 data themselves are modeled, we should know enough about the regional electric regime to reasonably estimate adjacent and far resistivity levels for a satisfactory model.

5.4 DEEP REGIONAL TRANSECT: E-SCAN'S CONTRIBUTION

E-SCAN in its LINEAR mode provides several-mile penetration across any terrain.

The deep penetrating MT methods require two things:

1. A reasonably one-dimensional area to set up on, to ensure minimal near-surface distortion to deep data.

2. A map of near-surface (upper several thousand feet is worthwhile) resistivities that can be merged with the deeper data to allow accurate interpretation of earth resistivities in the MT system's deeper data range.

A LINEAR E-SCAN traverse can provide both the pre-evaluation of sites for MT setup, and the continuous profile of the upper mile or two of resistivity.

Done after the fact, the E-SCAN profile is still useful for interpretation, and the addition of a short cross-line at each MT site would provide important information as to the MT site resistivity variations (if any) that might suggest a local correction factor for the MT data.

LINEAR E-SCAN also has options such as two- or three-electrode wide traverses, where the profile has the added lateral information provided by the parallel profile(s) 1000 feet away. Like 3-D E-SCAN, LINEAR uses no dragged wire, and runs up, over and through extreme terrain with little difficulty, allowing investigators to insist on the geologically desirable transect route, rather than a route dictated by operational limitations.

6. CONCLUDING REMARKS

I hope that this introduction will stimulate discussion and consideration of E-SCAN for the Yucca Mountain area. May I once again emphasize that this document, large as it is, is technically superficial and not appropriate as a basis for technical critique of the method. If a geophysical consultant is asked to comment on this material, may I respectfully suggest that a list of questions, rather than conclusions, would be the appropriate form of report at this stage.

I am always available for consultation on the technical aspects of E-SCAN; my style of support is to always back technical points in question with a) references to reports and scientific literature, and b) case history demonstration of how the aspect of interest actually performs in real data field cases. As a point of interest, my insistence upon gathering a broad base of case history material before publishing widely on E-SCAN explains the lack of extensive published literature at this time, but also provides the source of hands-on answers to many theoretical and technical questions, for anyone who asks.

Greg A. Shore

Premier Geophysics Inc.

October 28, 1990

E-SCAN Resistivity Survey: unparameterized exploration and mapping

"Perhaps the most significant thing that can be said about E-SCAN is that it is not parameterized: not tuned or applied with any specific target, shape, depth, or orientation in mind.

If one's objective is to firmly establish volumes of the earth in which every electrically mappable feature is mapped and therefore can be tested and understood, or perhaps more importantly to Yucca Mountain, to confirm areas containing a definitive absence of such features, then parameterized surveys must by definition be run again and again, until all possible combinations of test parameters have been obtained, and interpretation and modeling can begin with some confidence.

Unparameterized E-SCAN, it can be argued, will objectively map everything, intensively and yet sensitively, in it's single survey pass data set."

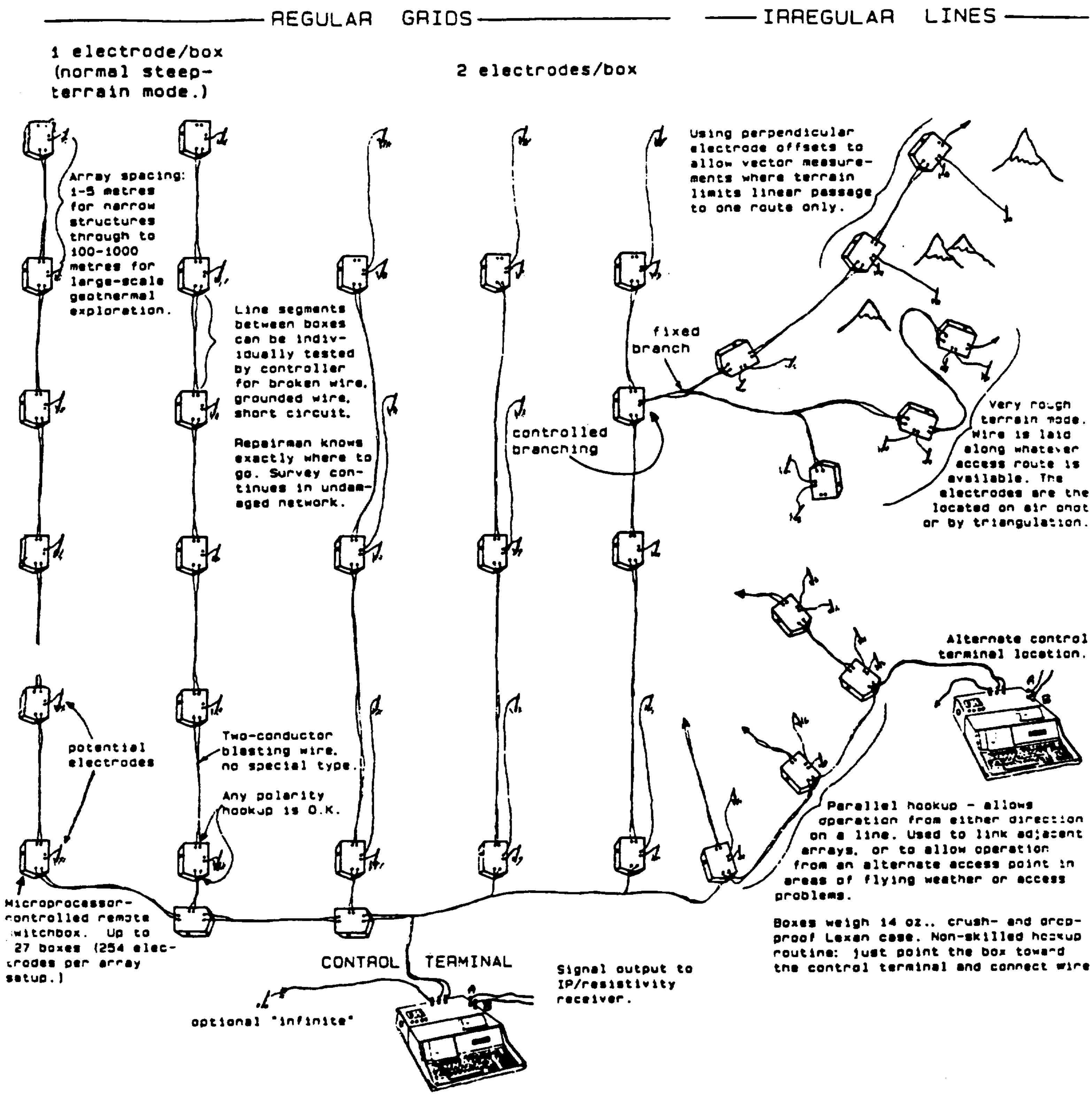
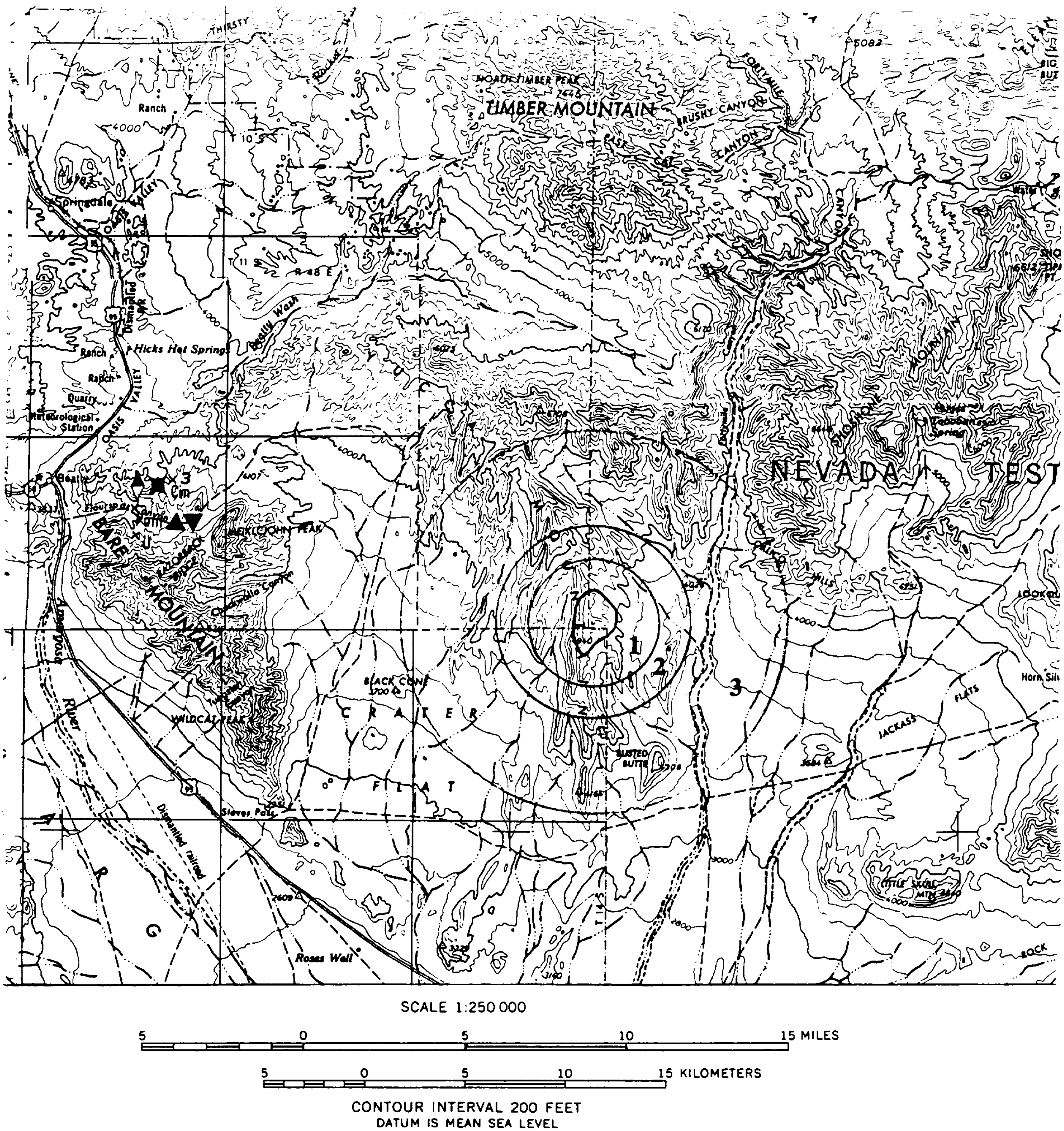


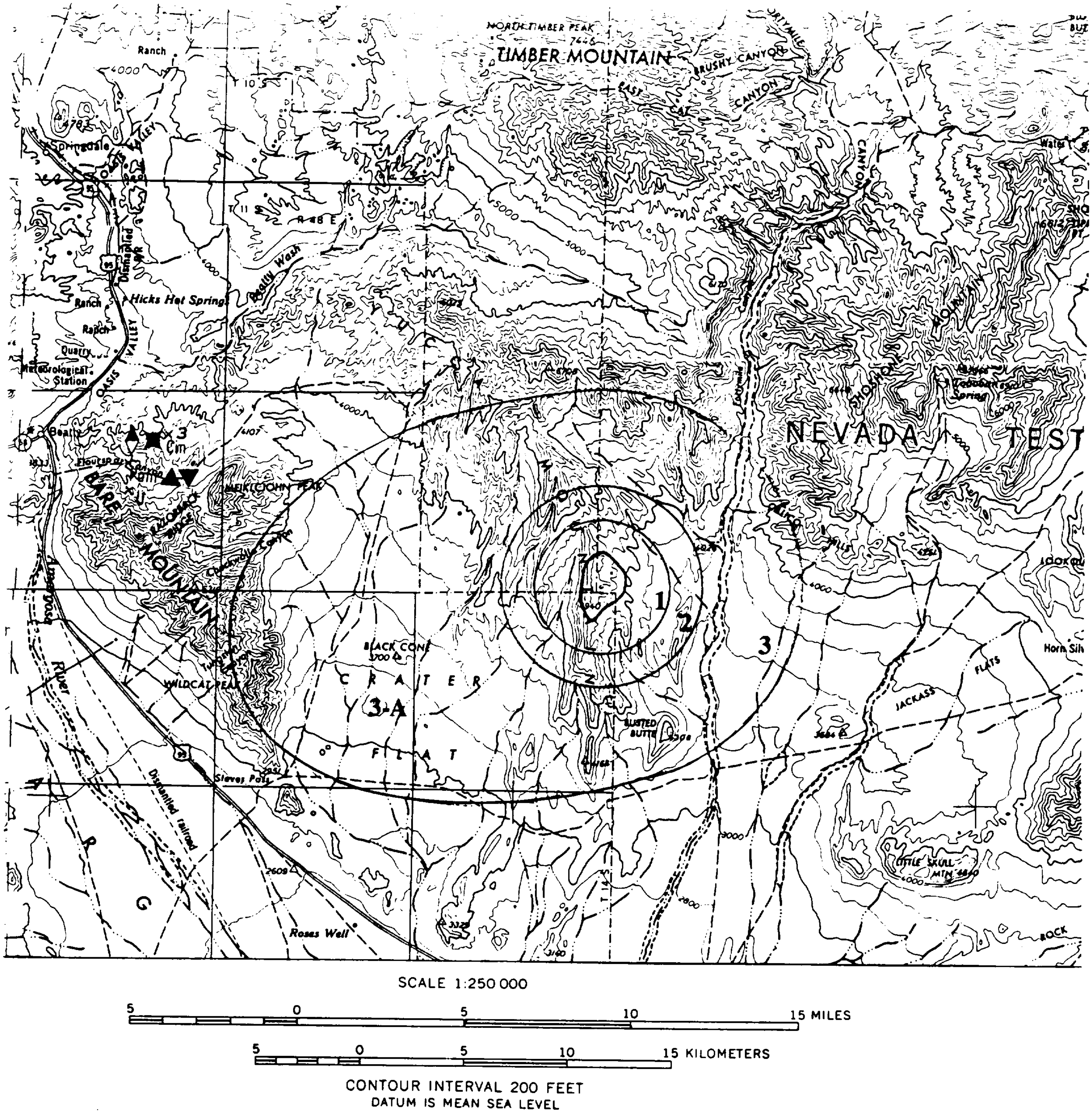
Figure 1 The E-SCAN field hardware system consists of over 120 two-channel microprocessor operated switching boxes, which are in bi-directional digital communication with the central controller. On demand, any two of the up to 250 pre-wired potential electrodes can be instantaneously connected to the controller for a measurement.

500 to 1500 multidirectional shallow, mid-range and deep measurements are made per day, building in one survey pass a data set which is the equivalent of having operated fifteen to twenty different conventional surveys at various orientations and spacings. No wires are dragged back and forth, so marked stations, not cut lines, are all that is required for grid control.

Extreme terrain, lakes, cliffs, and cultural installations are serious impediments for traverse-type surveys. E-SCAN can survey these areas completely and with little delay, laying wire to the required electrode stations from whatever route is convenient and safe.



Plan view of the locations of Stage 1, 2, and 3 E-SCAN Survey Areas.



Plan view of the locations of Stage 1, 2, and 3 E-SCAN Survey Areas, showing extension of 3-A over Crater Flat.

Stage 3B: Optional extension of Stage 3, 3A over entire Crater Flat area

Proportional increases in data coverage and plots of Stages 3 and 3A above.
5 x 15 or 22 plan view pseudodepth plots (15 or 22 each of NW, N, NE, E, and "all" orientations of data.)
Pseudosections facing NW, N, NE, and E.
2-D, 3-D inversion/imaging of features.

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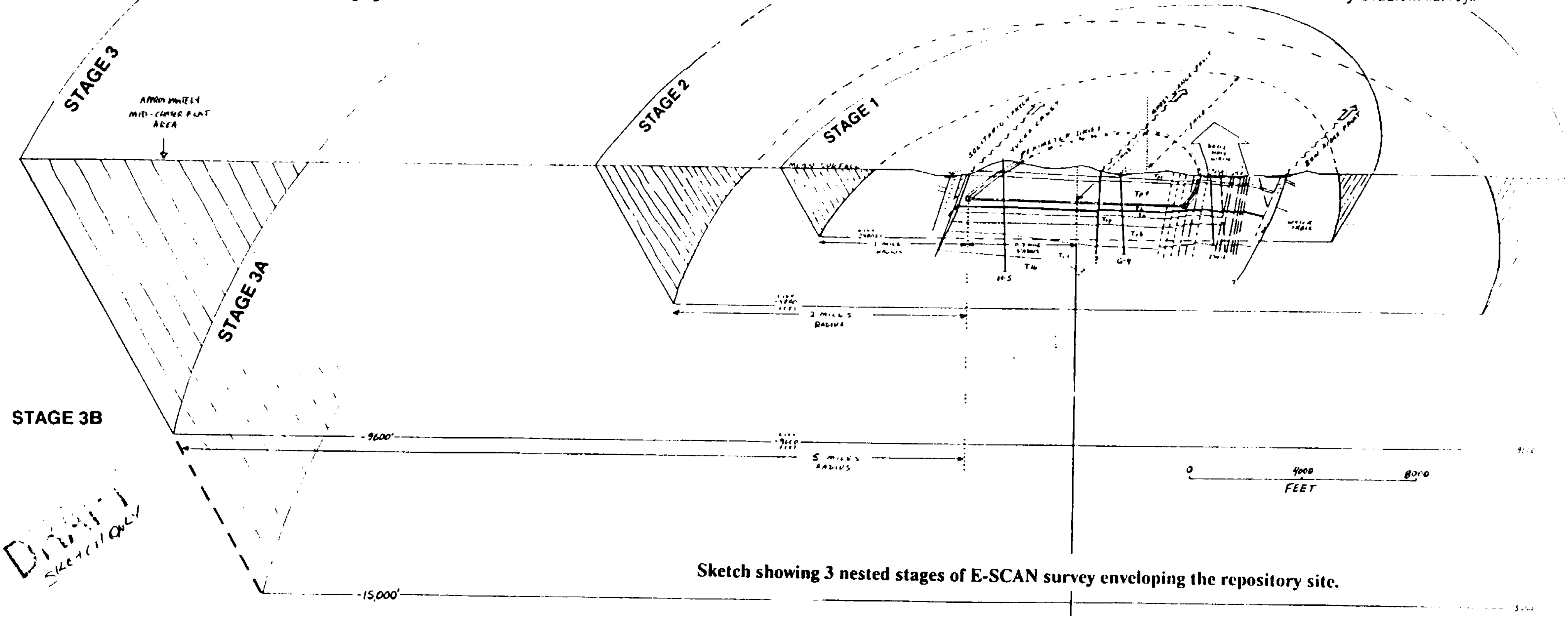

Sketch showing 3 nested stages of E-SCAN survey enveloping the repository site.

Stage 3A: Optional extension to -15,000'

75,000 measurements to NDIC = 15,000' using the existing 800'-1600' square grid
Additional 5 x 7 plan view pseudodepth plots (7 each of NW, N, NE, E, and "all" orientations of data.)
Pseudosections extended to NDIC 15,000'
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Stage 3: Sub-regional geologic setting

155,000 measurements to NDIC = 9600'
800'-1600' square grid, 155 square miles
5 x 15 plan view pseudodepth plots (15 each of NW, N, NE, E, and "all" orientations of data.)
2200 line miles of pseudosections facing NW, N, NE, and E.
2-D, 3-D inversion/imaging of features.

Stage 2: Larger scale repository area resolution

107,000 measurements to NDIC = 4800'
400'-800' square grid, 26 square miles
5 x 15 plan view pseudodepth plots (15 each of NW, N, NE, E, and "all" orientations of data.)
900 line miles of pseudosections facing NW, N, NE, and E.
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Stage 1: Immediate repository area

224,000 measurements to NDIC = 2400'
200'-400' square grid, 14 square miles
5 x 15 plan view pseudodepth plots (15 each of NW, N, NE, E, and "all" orientations of data.)
1000 line miles of pseudosections facing NW, N, NE, and E.
2-D, 3-D inversion/imaging of features.

Note: NDIC

NDIC is the Nominal Depth of Investigation Characteristic, a nominal plotting point for the data generated by a given electrode array assumed to be operating in a uniform earth.

The NDIC is the mean of the mid-portion of the curve indicating the contribution of signal with depth, a curve which extends deeper by some function as electrode arrays are expanded. A measurement of a given NDIC is therefore obviously derived from signal contributed by the earth conditions above and below this point. The signal distribution is distorted in a non-uniform earth, particularly a 3-D situation, requiring interpretation from surface downward and outward to determine the actual geometry of deeper features. This is much the same process as removing the effects of shallow layers in seismic, allowing correct positioning of deeper breaks. The NDIC is therefore truly nominal, but with the above caveat in mind, it is an essential plotting convention if one is to compare theoretical performance of different arrays and eventually to view merged pseudosections and pseudoplan plots of mixed array data.

Premier plots E-SCAN data at the Ze of Edwards (Geophysics, Vol. 42, No. 5), which is for sketch purposes the same as the better-known NDIC for most arrays. (Ze is the median, NDIC is the mean, of the same curve area). The Ze provides a slightly better fit when plotting several arrays on the same pseudosection, e.g. pole-dipole and pole-pole.

Reference to depth or depth of investigation throughout this presentation on raw data (apparent resistivity) acquisition and viewing means Ze or NDIC, unless discussion is about modeled or interpreted results, where the term true resistivity is emphasized.

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Stage 3B: Optional extension of Stage 3, 3A over entire Crater Flat area

Proportional increases in data coverage and plots of Stages 3 and 3A above.
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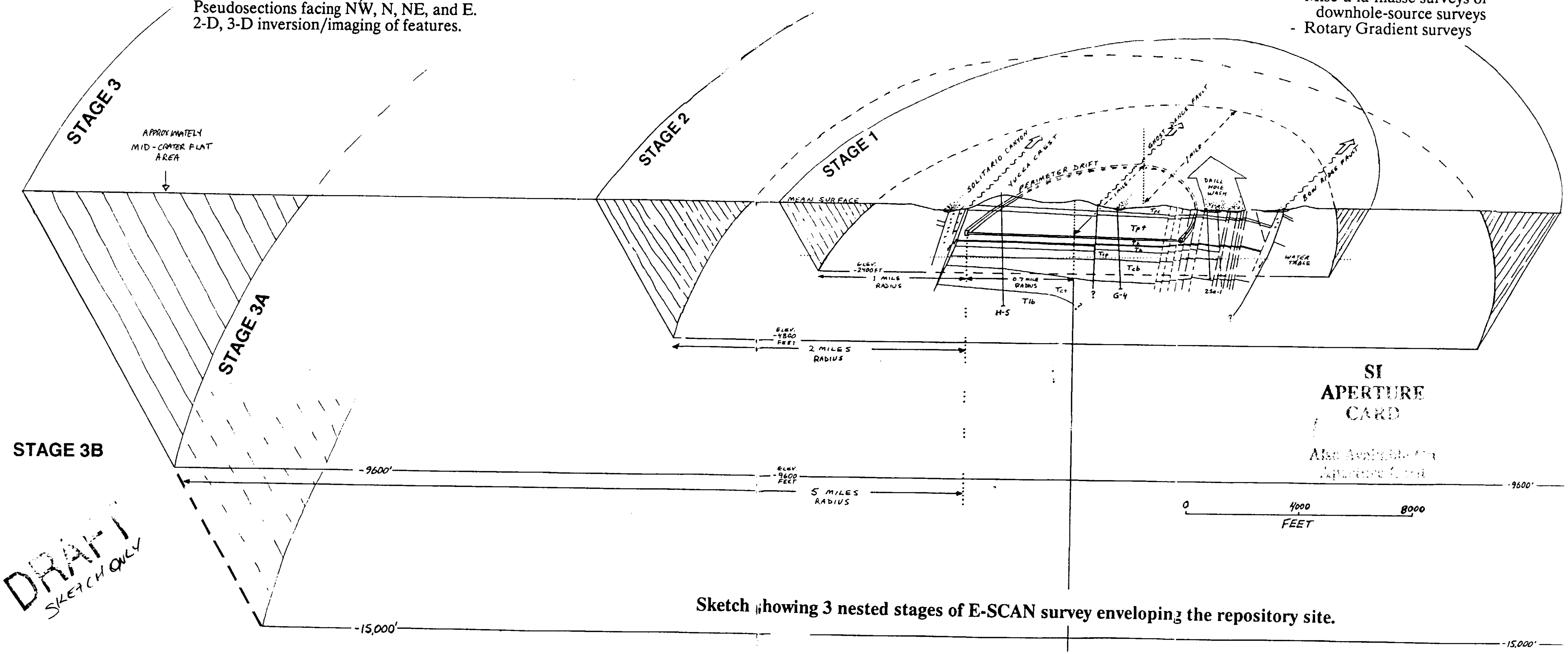

Sketch showing 3 nested stages of E-SCAN survey enveloping the repository site.

Stage 3A: Optional extension to -15,000'

75,000 measurements to NDIC = 15,000' using the existing 800'-1600' square grid
Additional 5 x 7 plan view pseudodepth plots (7 each of NW, N, NE, E, and "all" orientations of data.)
Pseudosections extended to NDIC 15,000'
2-D, 3-D inversion/imaging of features.

Stage 3: Sub-regional geologic setting

155,000 measurements to NDIC = 9600'
800'-1600' square grid, 155 square miles
5 x 15 plan view pseudodepth plots (15 each of NW, N, NE, E, and "all" orientations of data.)
2200 line miles of pseudosections facing NW, N, NE, and E.
2-D, 3-D inversion/imaging of features.

Stage 2: Larger scale repository area resolution

107,000 measurements to NDIC = 4800'
400'-800' square grid, 26 square miles
5 x 15 plan view pseudodepth plots (15 each of NW, N, NE, E, and "all" orientations of data.)
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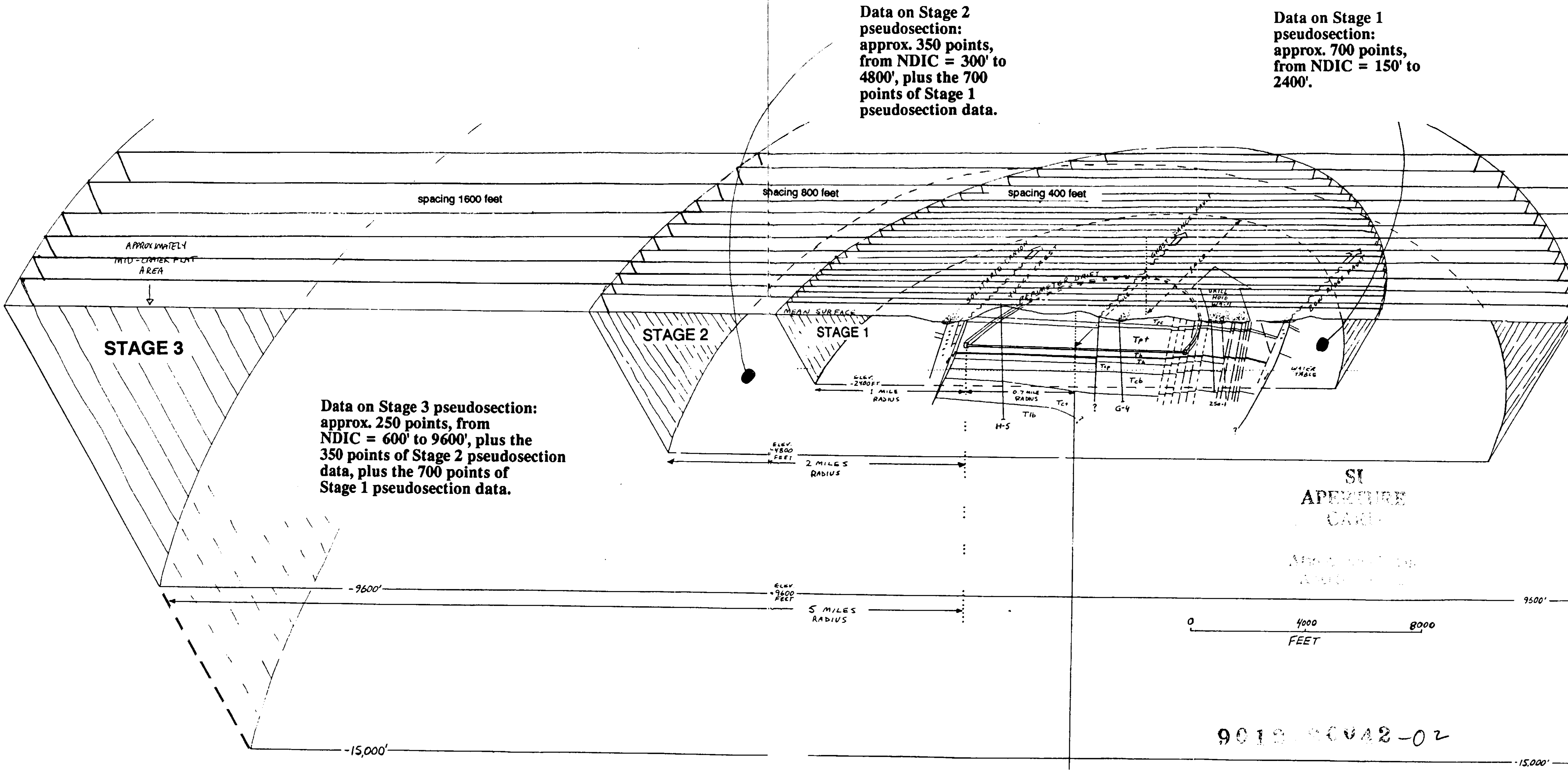


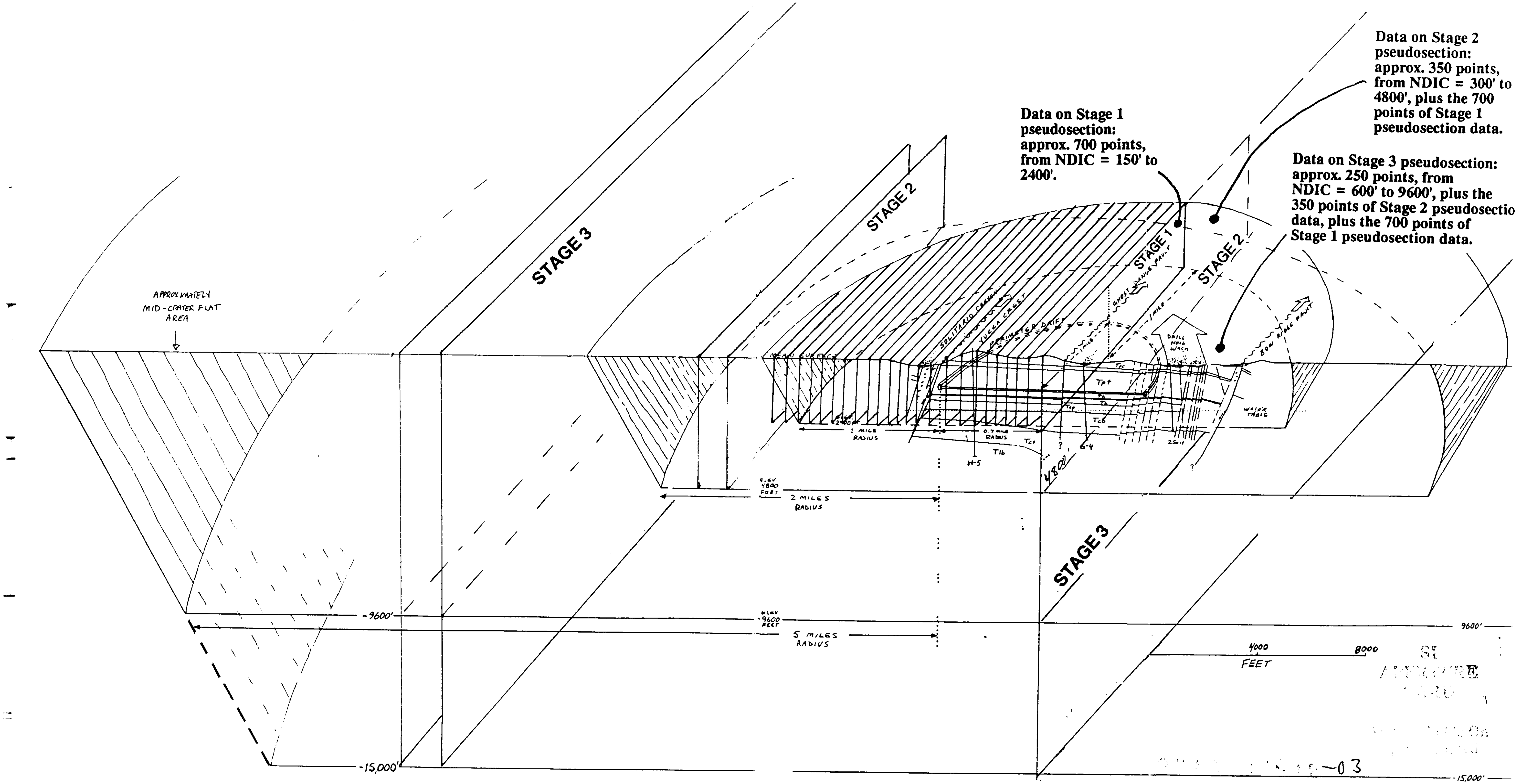
DRAFT SKETCH ONLY

Sketch of Approximate Location and Density of Pseudosections Facing NORTH.

Stage 1 pseudosections are spaced 400' apart; Stage 2 - 800' apart; Stage 3 - 1600'

East-west (north-facing) pseudosections are optimally oriented for viewing and quantifying linear structures and boundaries crossing the pseudosections at a perpendicular angle, i.e. features running north-south. Structure or boundaries running north-south, or parallel to the pseudosections, may show as irregular distortions to the data, or show no response at all. When north-south features have been determined to be truly 2-D, then data from the north-facing pseudosections will be selected to feed 2-D forward and inverse modeling routines. Objective, pre-modeling confirmation of the structural orientation, positive confirmation a lack of 3-D interference, and ability to select optimally oriented (perpendicular) data diminishes or eliminates guesswork and assumptions, thus assuring meaningful model results.

RAW DATA VIEWING PERSPECTIVES



Sketch of Approximate Location and Density of Pseudosections Facing EAST.

Stage 1 pseudosections are spaced 400' apart; Stage 2 - 800' apart; Stage 3 - 1600'

North-south (east-facing) pseudosections are optimally oriented for viewing and quantifying linear structures and boundaries crossing the pseudosections at a perpendicular angle, i.e. features running east-west. Structure or boundaries running north-south, or parallel to the pseudosections, may show as irregular distortions to the data, or show no response at all. When east-west features have been determined to be truly 2-D, then data from the east-facing pseudosections will be selected to feed 2-D forward and inverse modeling routines. Objective, pre-modeling confirmation of the structural orientation, positive confirmation a lack of 3-D interference, and ability to select optimally oriented (perpendicular) data diminishes or eliminates guesswork and assumptions, thus assuring meaningful model results.

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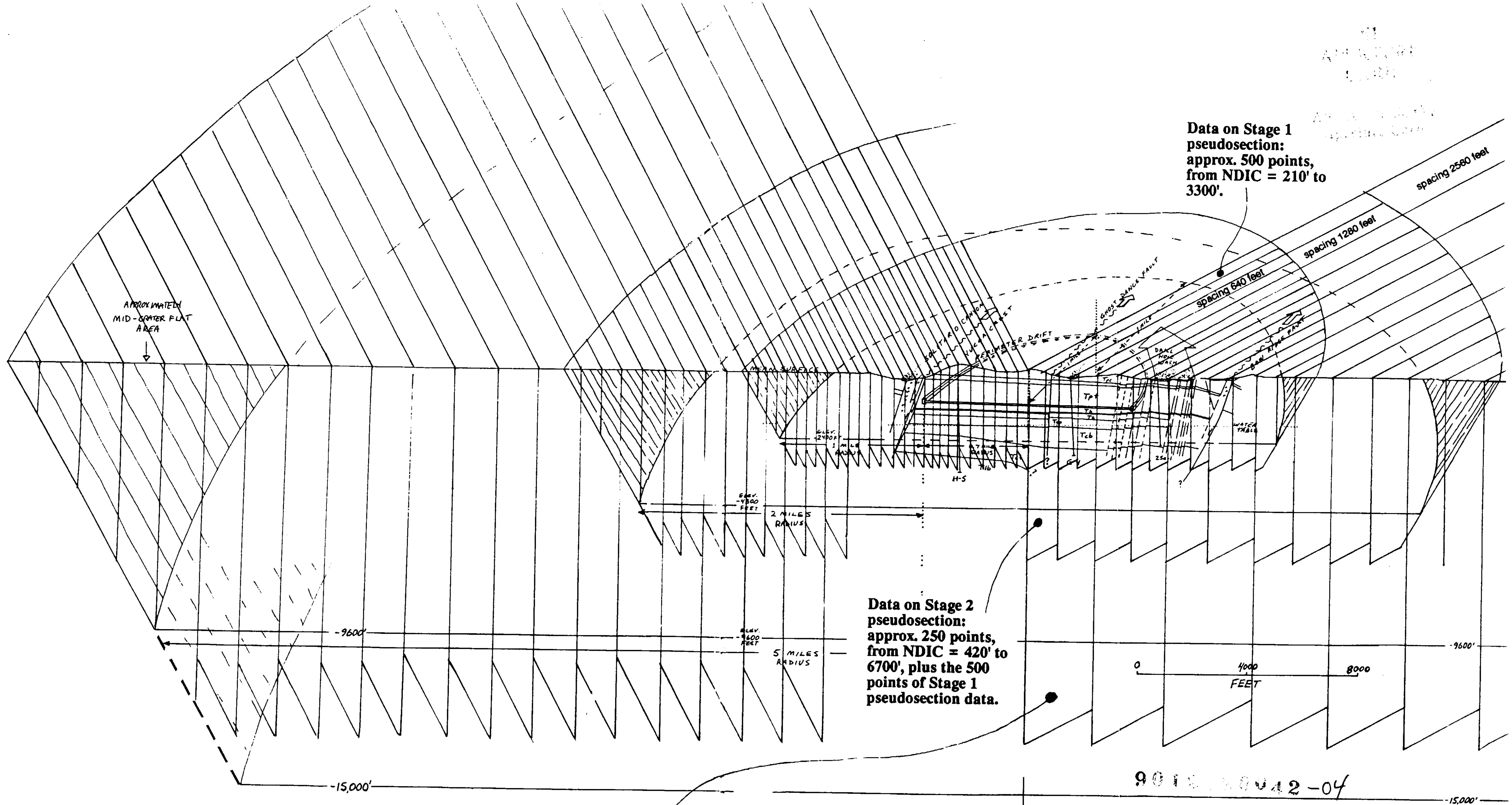

Data on Stage 3 pseudosection: approx. 150 points, from NDIC = 850' to 13000', plus the 250 points of Stage 2 pseudosection data, plus the 500 points of Stage 1 pseudosection data.

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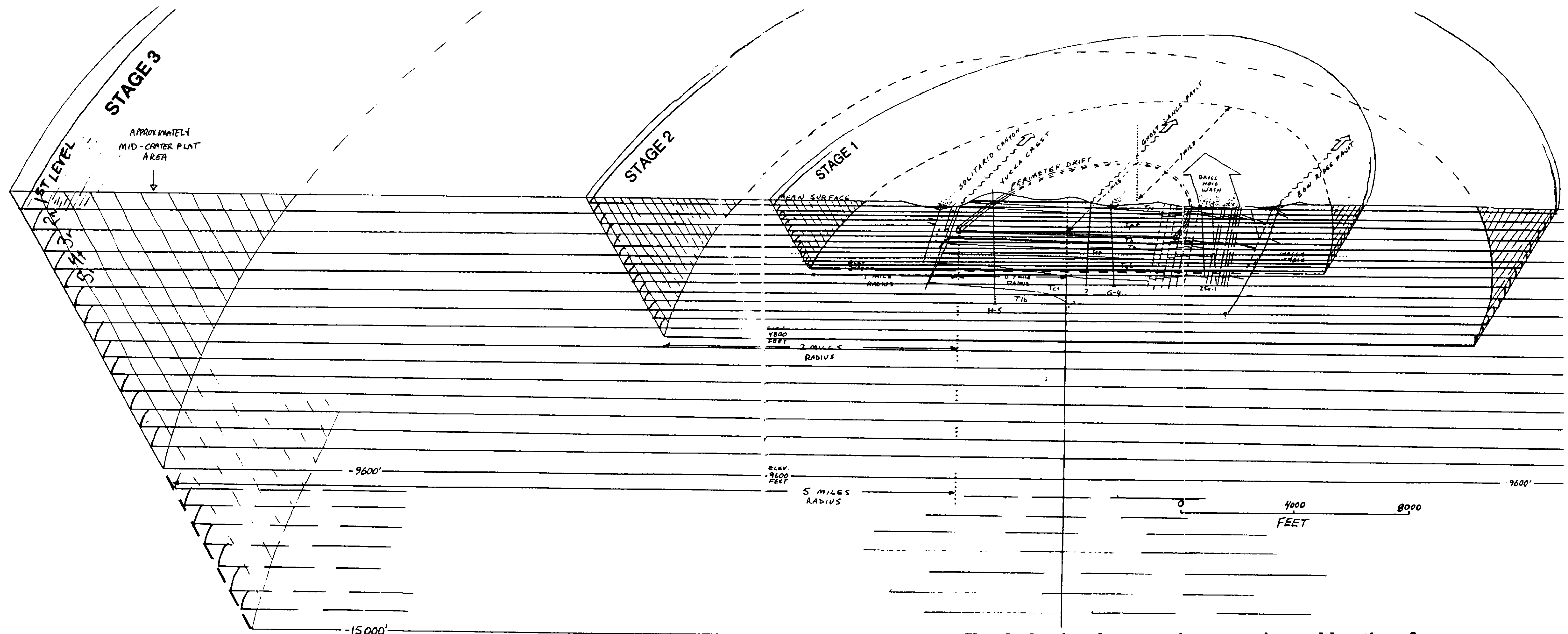
Sketch of Approximate Location and Density of the Grid-diagonal Pseudosections Facing NORTHWEST and NORTHEAST.

Stage 1 pseudosections are spaced 640' apart; Stage 2 - 1280' apart; Stage 3 - 2560'

This sketch shows both the northeast-facing and northwest-facing diagonal pseudosections, which make up two more complete sets of pseudosections in a standard E-SCAN processing package. As with the north-facing and east-facing pseudosections, the diagonal pseudosections are optimally oriented for viewing and quantifying linear structures and boundaries crossing the pseudosections at a perpendicular angle. Because they cross the grid diagonally, the electrode separations (and therefore the nominal depth of investigation NDIC) are all increased by 1.4 times the square grid spacing.



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Sketch showing the approximate spacing and location of pseudodepth plan plots through the survey areas.

Each pseudodepth plan plot contains several thousand data measured at a common array separation, gridded and contoured for comparison with plots positioned above and below. These plan view plots afford the first general 3-D sense of the major electrically-signed structures, trends, boundaries, and zoning. The appropriately oriented pseudosection sets are utilized first to cross-check and challenge these plan-indicated features, and then to provide the detailed characterization of each of the confirmed 2-D linear boundaries or structures, in preparation for modeling. These pseudodepth plots are not true levels, but are the plan view equivalent of pseudosections.

If Stage 3 is extended to -15,000' (22 levels), there will be 38 levels in total, with the closest vertical spacing occurring through the Stage 1 repository detail area.

-05

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The Robertson Case History

A brief review of a project
similar in intent
to that suggested for the
Yucca Mountain area:

**"Map anything and everything,
at every orientation, shallow and deep,
subtle, strong and intermediate,
and then let the data themselves
indicate what is there."**

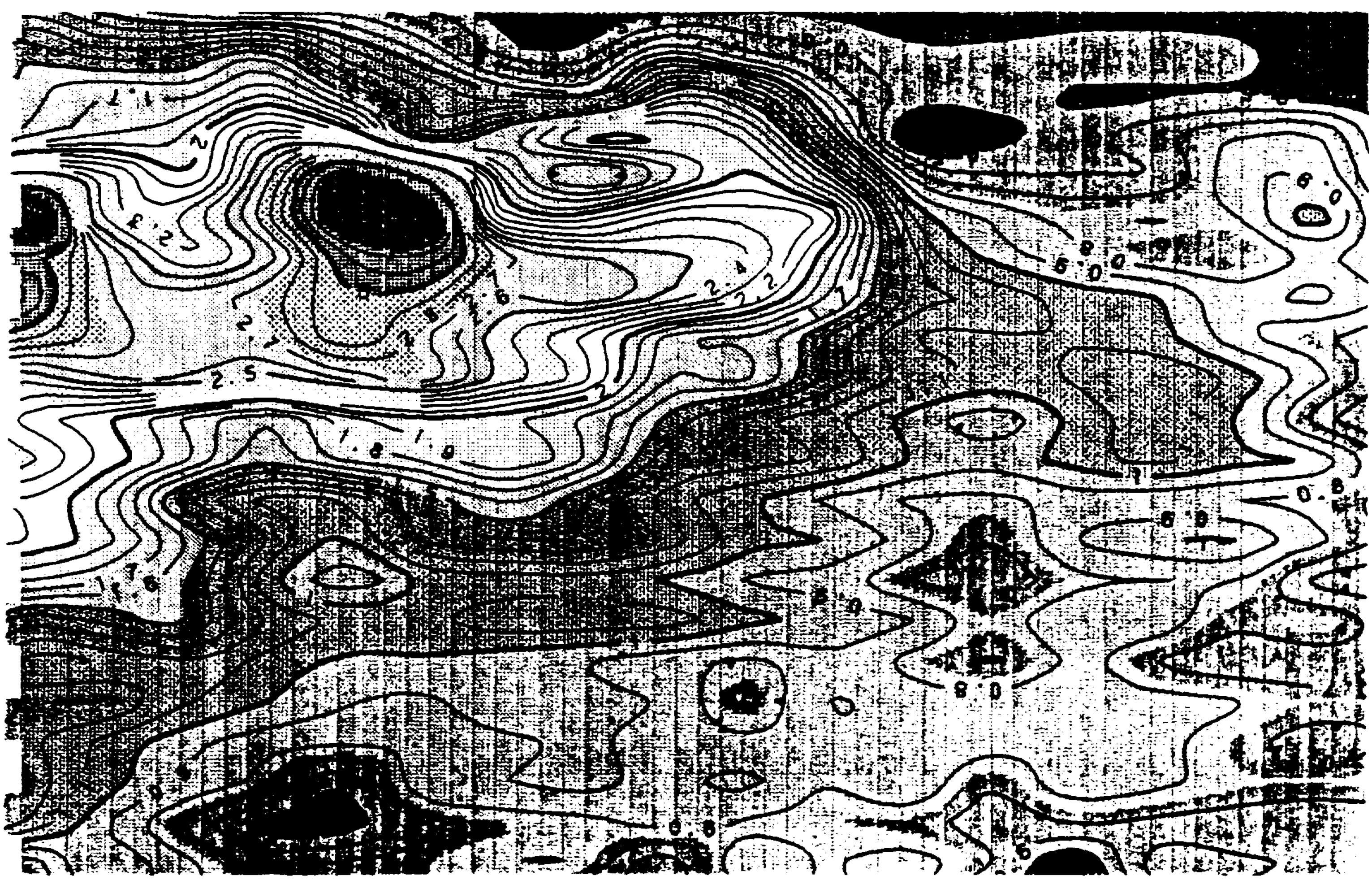
Large scale hydrothermal/epithermal gold exploration:

The Robertson Project, Crescent Valley, Nevada

E–SCAN CASE HISTORY SERIES # 8701.1c

Premier Geophysics Inc.

Vancouver, British Columbia, Canada



Large scale hydrothermal/epithermal gold exploration:

The Robertson Project, Crescent Valley, Nevada

E-SCAN CASE HISTORY SERIES # 8701.1c

Abstract

In 1987, an E-SCAN multidirectional IP and resistivity survey was conducted over Coral Gold's Robertson property, in Crescent Valley, Nevada. The unparameterized survey generated images of two distinctly different, deep-rooted geologic systems within the four square mile property.

The resistivity and IP mapped a major hydrothermal system with a resistive core unit one mile across and at least 1500 feet in vertical extent, surrounded by alteration and sulphide zoning. This pattern provided a template against which to plot known gold occurrences, thereby establishing an empirically-derived "gold signature" exploration zone. Two thousand feet wide, this annular zone encircles the core between the highest IP and highest resistivity zones.

This case illustrates the value of subtle, high resolution lateral and vertical electrical mapping in situations where the gold values do not correspond directly with peak geophysical responses or "bull's eyes".

From the same survey results, a resistive "mushroom" signature is imaged two miles from the hydrothermal system. This mushroom, with a broad, high resistivity cap and resistive stem extending downward for at least a thousand feet below, is similar in size and signature to silicic epithermal gold orebodies mapped elsewhere by E-SCAN (Cinola deposit, Hasbrouck Peak deposit). Unlike the adjacent concentric-zoned hydrothermal system, this is a simple bull's-eye drill target.

1. Technical introduction to multidirectional IP and resistivity

Introduction:

E-SCAN is an automated induced polarization and resistivity survey system which employs a large network of pre-wired electrodes to obtain a dense, deep-probing, multidirectional data set. The survey results are standard IP and resistivity values.

With the exception of specifying a grid spacing (large for broad resolution exploration like epithermal or porphyry exploration, close spacings for highgrade vein structure mapping) the method requires no initial parameterization. In practical terms this means that the user is not required to judge in advance what may be the "best" survey line

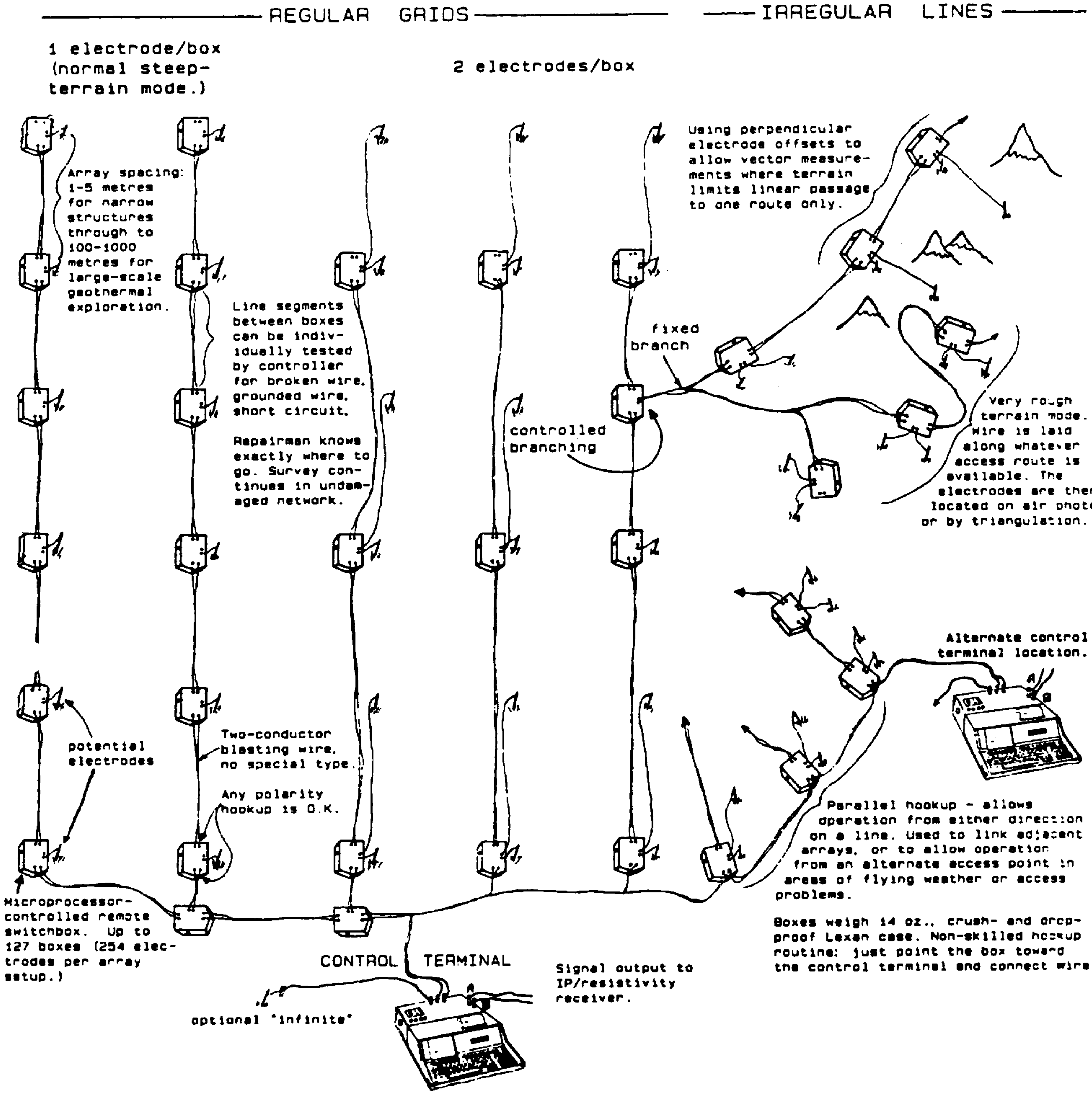


Figure 1 The E-SCAN field hardware system consists of over 120 two-channel microprocessor operated switching boxes, which are in bi-directional digital communication with the central controller. On demand, any two of the up to 250 pre-wired potential electrodes can be instantaneously connected to the controller for a measurement.

500 to 1500 multidirectional shallow, mid-range and deep measurements are made per day, building in one survey pass a data set which is the equivalent of having operated fifteen to twenty different conventional surveys at various orientations and spacings. No wires are dragged back and forth, so marked stations, not cut lines, are all that is required for grid control.

Extreme terrain, lakes, cliffs, and cultural installations are serious impediments for traverse-type surveys. E-SCAN can survey these areas completely and with little delay, laying wire to the required electrode stations from whatever route is convenient and safe.

orientation, or to predict at which depth the "target" will lie.

Since the E-SCAN survey will map electrical features or zones in a broad range of orientation, depth or subtlety of response, the data provided are more objective than those of any single-orientation dipole survey.

The case history which follows illustrates some of the qualities of the multidirectional data set.

Hardware and operational synopsis:

E-SCAN uses over 120 computerized remote switching devices, daisy-chained together with simple blasting wire, to pre-wire a grid of potential electrodes covering an area of exploration interest. Conventional IP and resistivity measurements are made from a fixed receiver, using the switching network to access remote electrodes for sequential measurements (Figure 1).

Conventional IP/resistivity dipole survey crews may spend 50% of the field time moving dipole wires (up to 90% in rough terrain). E-SCAN switches among up to 250 pre-wired electrode stations in milliseconds, permitting 500 to 1500 measurements per day, even in rough terrain, with very little crew movement.

The data set.

The data set is comprised of very dense, multidirectional and multiseparation measurements. The data are sorted and plotted in contoured plan views in a sequence of increasingly deeper plots, at up to 15 pseudodepth levels.

The data set is also "sectioned" to provide pseudosection sets oriented to resolve linear features identified in the plan data maps. Four sets of pseudosections, each rotated 45 degrees from the other, are plotted, to provide optimum viewing and testing for structure or boundaries of every orientation.

A two stage interpretation approach

The standard interpretation approach is to initially study the raw, unfiltered data set through the sequence of plan plots, and the four sets of pseudosections. Indications of structure, linears, boundaries, zoning of values, variation with depth, and any other features which are seen are compiled on summary plan maps to produce an initial, objective 3-D sense of the property's electrical characteristics.

This initial stage of interpretation is repeated at three levels:

1. examination and compilation of features in the upper third of the pseudosections (of all four orientations) and in the shallower three or four contoured plan views. This depth range focuses on overburden aspects, and the direct imaging of features or zones in the ideal economic levels, i.e. close to surface.

2. examination and compilation of features in the middle part of the pseudosections, and in the middle 3 to 6 contoured plan views of the data. This maps mid-depth features in the 500 to 1000 foot depth range and also maps the downward characteristics of shallower zones.

3. examination and compilation of very deep zones and structure in the lower third of the

pseudosections, and in the lower 3 to 6 contoured plan views of the data, representing depths of one thousand to several thousand feet. This maps the continuation of overlying features to depth and tests for deep under-pinning structure which may be the principal control of the mineralization above.

With all of the individual zoning and structural features indentified, the whole data set can now be looked at from an overview perspective. We can consider the implications of deep structural features and adjacent zoning on each of the individual zones. It is now possible to indentify large-scale patterns of structure or alteration which may span two or more of the individual features.

A prioritized list emerges, ranging from recognizeable patterns which in the past have indicated ore possibilities, through to unique but conventionally "unexciting" electrical response zones about which little is known.

The density of the E-SCAN data set allows mapping and recognition of subtle zoning. An example of the importance of this resolution might go like this:

An "uninteresting" zone of background IP reponse, and a resistivity signature just 20% lower than its neighbours (but higher than other resistivity lows on the property) looks like more background, maybe deeper overburden or something.

However, if a deep high resistivity zone appears to be positioned directly beneath this modest low, we could speculate that the low is due to alteration. If that proves to be the case, then we have a signature, **"modest low centered over a deep high may equal alteration over silicification"**, to be looked for elsewhere in the property data.

Given this ability to evaluate the full-depth 3-D context of each of these individual zones of response, no "uninteresting" zone is truly uninteresting until the full investigation is over.

As implied above, the second phase of interpretation involves integration of the objective IP/resistivity mapping results with other property information, such as geologic mapping, drill results, geochemistry, and other geophysics.

If there is no such additional information (such as in a fresh pediment cover play), then the E-SCAN patterns will be the primary drill-targeting information. In place of general pattern drilling, a minimal, precisely targeted drill program can be undertaken to directly test the E-SCAN responses.

Better late than never: stage three interpretation opportunities

A third stage interpretation opportunity can occur at any time. Changes in demand for metals or advances in exploration models and experience can suggest re-evaluation of earlier E-SCAN data for new purposes. Some of our early E-SCAN geothermal survey coverage is relevant today for mapping for low grade porphyry or epithermal gold.

An example of this comes from the Robertson case history: A resistive feature (the "western resistivity feature") was mapped in 1987 some distance from the main focus of the Robertson Project work. In 1989, this feature was recognized as being similar in pattern (and in absolute values) to E-SCAN signatures more recently mapped over two confirmed epithermal gold deposits. The similarity sparked a re-evaluation of the potential significance of this feature, with drilling recommendations resulting.

2. Property geology, survey design and data coverage

Property and geology

The Robertson Project is located in the southern part of the Battle Mountain gold belt, on the west side of Crescent Valley, Nevada. The property extends south toward the Gold Acres mine; the Cortez mine is opposite, across the valley to the east. Familiar names associated with the property are Altenburg Hill, and the ghost town of Tenabo.

The property straddles the edge of the valley, with outcropping hills to the west, and pediment to the east. The extent of historic interest in this property is indicated in Figure 2, which shows hundreds of pits, shafts and workings dating back many decades. The E-SCAN survey area, three miles long across the top and two miles wide down the middle, is outlined.

The dominant rocks in the survey area are pelitic sediments of Silurian and Ordovician ages. A mile-wide Tertiary granodiorite porphyry outcrop has been mapped by the USGS (Figure 3), with an altered, silicic halo surrounding it.

Survey objectives

At about the time of the E-SCAN survey, property owner Coral Gold Inc. was at an advanced stage in identifying the first two zones of economically mineable heap-leach ore. Coral Gold geologists were successfully applying a new mapping and sampling program in combination with a re-interpretation of previous drilling and sampling results.

Project geologists had identified two objectives for immediate and longer-term investigation:

a. the location of heap-leachable oxide ores for immediate production, and,

b. the investigation of potential high-grade ores still within sulphides or in deep structures.

The E-SCAN survey therefore had several objectives:

a. map the character and extent of sulphide mineralization;

b. map deep structures of any type, and,

c. map the character of the granodiorite exposure at depth.

Survey parameters

A grid spacing of 400 feet by 400 feet was chosen. There are no other parameters involved in specifying an E-SCAN survey, since the measurements are inherently multidirectional, and the pre-wired system automatically provides for depth of investigation considerably beyond normal economic survey depths.

Measurement of induced polarization is optional; it was selected in view of the interest in sulphides on this property. 785 disposable copper copper-sulphate porous pot electrodesw were used.

At a 400 foot spacing, this quite typical E-SCAN survey would provide 10 plan view pseudodepth plots between the shallowest nominal depth of investigation (NDIC) of 300 feet, and the deepest, at greater than 1500 feet.

It would also provide sets of pseudosections facing north and facing west across the property, and two diagonal sets facing northwest and facing northeast, all showing data at NDIC of 300 to 1500 feet.

The 400 foot grid survey was intended to map the large scale geologic picture. However, the high density of multidirectional, overlapping data affords resolution of linear features and boundaries considerably better than the normally expected one-half of the grid spacing.

Survey data and computation

The survey generated about 20,000 stacked and noise-averaged potential field measurements, which were then computed as pole-pole array apparent resistivity measurements. These data are approximately equally divided among all orientations and depths. An equal number of corresponding induced polarization values were also computed. (No dipole-dipole or pole-dipole results were computed, although the means to do so remains in the original computer-stored potential field data records.)

The pole-pole data were sorted and plotted in ten plan pseudodepth plots; four summary resistivity plots are presented in Figures 4, 5, 6, and 7, each plot combining two or three of the ten working data plots (for presentation purposes). Two IP plots corresponding with the two shallower resistivity plots are also presented in Figures 8 and 9.

The results shown in this paper are exclusively raw data, as measured in the field. The high density and multidirectional character of the raw data set are illustrated in the IP and apparent resistivity data plots at two selected pseudodepths, in Figures 10 and 11.

All contour routines inherently average adjacent values; nonetheless, with all available filters turned off, some of the detailed character of the original data set remains visible. For example, the "wavy contours" in Figure 7 indicate an anisotropic response due to data alternately measured across and alongside a conductive/resistive linear boundary.

Over two hundred line miles of apparent resistivity pseudosections were constructed, using the pole-pole data, in sets facing west, northwest, north, and northeast (Figure 12). Similar sets of IP pseudosections were also constructed. A small sample of these pseudosections is used to display some specific structure discussed in the Interpretation section.

3. Interpretation: the major hydrothermal system

A hydrothermal system model

Of the several geophysical features imaged by the data, the most immediately significant is the large IP and resistivity system which dominates most of the survey area.

The summary geophysical picture (Figures 13 and 14) is that of a very deep-seated resistive unit almost two miles across, and extending well below the maximum nominal depth of investigation (NDIC) of 1500 feet. The resistive unit is surrounded by a zone of high induced polarization response (also deeply-extending), forming a half-mile wide outermost annulus.

The concentric resistivity and IP pattern would suggest to many geologists a classic hydrothermal system, with resistive core due either to intrusives, silicification, or both, and the annular IP response being part of the zoned hydrothermal mineralization suite surrounding the core.

In this case, the USGS identification of the granodiorite porphyry exposure and surrounding silicic alteration provides support for this general model, and detailed mapping and drill results agree.

Drilling to over 700 feet confirmed 5% to 7% sulphides, no graphite, in the high IP areas (coloured red, orange and yellow), 1% sulphides in the flanks of the IP high (coloured green), and no sulphides in the low IP response areas (coloured blue) of Figures 8 and 9.

Hydrothermal fluids may have migrated outward from the central core (Figures 15 and 16), cooling and precipitating silica as they traveled through vertically confined layers in the surrounding sediments.

Some distance from the core zone, the fluids began to precipitate minor sulphides with the silica, and eventually dropped the last of the silica. The edge of the resistivity high marks the end of silica deposition. Gold was precipitated with the sulphides in this overlapping silica-sulphide zone.

Two possibilities are offered for the ring of intense sulphides which form the outer mineralization shell. In one, the vertically constrained, outward migrating hydrothermal fluids encountered intense fracturing and faulting (possibly related to the emplacement of the core of the system). Suddenly released to flow vertically as well as laterally, the fluids dispersed, cooled quickly, and precipitated the fine-grained sulphides in quantity.

A second model allows the lateral fluid movement, but adds another phase of mineralization, with fluid release into the ring of fractures from deep below. These fluids rise, cool, and precipitate sulphides. This phase would be comprised of low-silica fluids, as little silica is found in the high-sulphide fracture areas. (This is analogous to porphyry deposition).

Gold may have been carried by any phase; it is known to have been present, and was precipitated, in the outward flowing silicic fluid phase. Both of the presently-mined oxide ore bodies lie within this zone.

Incorporating drill results

While E-SCAN data has confirmed a few standard geophysical patterns recognizable as higher-probability gold features, there are no signatures directly confirming gold deposition itself. Furthermore, gold deposition can occur at almost any phase of a hydrothermal system depending on a range of variables such as solution and rock chemistries, temperatures, pressures etc. The significant local signature(s) marking gold occurrence must be established for every individual geologic setting and property.

When promising oxide ore assays and other drill and sampling results were plotted, they all lay in an arc encircling the granodiorite exposure. This area corresponds with the geophysically indicated overlap area where sulphides are just beginning to be precipitated, and silicification is still present (Figure 15 and 16).

Thus, a detailed IP/resistivity pattern of concentric mineralization was matched with empirical knowledge of just where the ore-grade oxides are known to occur, to identify the local oxide ore context and signature.

The black-outlined exploration priority zone (Figure 14) is the local significant signature for oxide ore. It is divided into 17 sub-areas of unique geophysical response, each representing potentially different conditions which may be more or less favourable to gold deposition.

The Gold Pan and Gold Quartz areas have seen limited production in the past. New production has started in areas 4 and 3 (extending down Triplet Gulch), confirming those sub-area signatures as ore-markers.

Mapping oxides from underneath

Successful direct mapping of oxides is not usually possible with geophysics, because the oxidized sulphide ore often looks just like any other oxidized rock or valley debris, neither particularly conductive nor resistive, and has no sulphides to cause an IP response. With sufficient power (signal strength) and resolution, IP can be used to map any remaining sulphides at depth beneath the oxides.

The IP responses at Robertson show just such a situation. Where little or no IP response is seen at 300 to 450 feet NDIC, at 600 to 900 feet the presence of deep 1% sulphides is indicated (the green IP zones marked C and D in Figures 8 and 9). It can be deduced that there may be oxidized sulphide mineralization lying above these deep sulphides.

The sulphide zone (E) appears to be downfaulted across a north-south fault (G) and continues east under valley cover at an estimated 500 to 700 feet greater depth. Another fault at the east edge of the grid displaces the sulphide trend 1000 feet south, to (B), where it again continues east under cover.

Investigation of this deep sulphide linear into the valley obviously requires an extension of the survey. If the intention is to test for oxides, in this case those oxides specifically overlying the inside edge of the high sulphide zone, resolution of such offsets is important.

Deep, highgrade potential

The subsurface geology of the massive resistive zone under the exposure of granodiorite remains somewhat of an enigma. Only shallow drilling in the peripheral areas of the granodiorite has been undertaken to date, while oxide ore development has had priority.

A total absence of airborne magnetic response over the feature increases interest. Intrusives within two to five miles of the survey area all demonstrate airmag signatures, including the intrusive at Gold Acres. This could be one of those cases where there is no magnetite alteration or no primary magnetic minerals associated with the intrusive; otherwise, we are required to find a model to explain the large volume of resistive material mapped to depths probably exceeding 2000 feet.

It has been suggested that the granodiorite may be a sill, or may have been rafted in as a slab (the area is extensively thrust-faulted), in either case forming a cap on a geothermal cell. The deep resistivities would be caused by silicification of the cooled-down system.

If the feature is an intrusive such as a granitic plug, the fluid regime might have risen along the flanks, in emplacement faulting, thermal shock fractures and alteration zones.

The deep resistivity results (Figures 6 and 7) imply two higher resistivity vertical features extending to depth, which could be granodiorite feeders, or highly silicified breccia pipes or feeder structures, with bonanza potential. Deep drilling into, and adjacent to, the higher resistivity centers within the main unit would be required to help resolve the economic potential of this area.

4. Interpretation: structural mapping.

The structure mapped by E-SCAN (the broader dark lines of Figure 14) is consistent with the USGS mapped structure (north-south and northwest-oriented, thin lines) and extends it under the covered areas. Not seen in the earlier mapping, and therefore unexpected, is the east-west structure, perpendicular to the range-front, extending out into the valley.

The plan maps of the data (Figures 4 to 9) provide the first objective indication of possible structures and their orientations. Such indications are further evaluated by selecting the appropriate set of perpendicular pseudosections (Figure 12 and 17), to image each suggested structure along its length.

The following example illustrates the technique by which most of the mapped structure was derived. The technique uses the full E-SCAN data set: plan maps, and pseudosections of every orientation.

The north-south fault (G) noted earlier on both IP plots corresponds with the edge of more resistive rocks in the shallow resistivity plan map (Figure 4). Any one of these linears is sufficient reason to review the area's pseudosections for confirming evidence of structure or boundaries.

The fault has been plotted in the corresponding position on the north facing pseudosections (Figure 17), where its position is confirmed as it divides the uniform conductive western regime from its deeper-lying eastward continuation. The location of the fault is also confirmed in the west-facing pseudosections, again lying at the obvious break between western and eastern regimes.

At the eastern end of the west-facing pseudosections the sulphide-bearing conductor appears to be offset about 1000 feet southward (to B) by another north-south fault. This was initially indicated in the IP plan map in Figure 9. Note the ability to work at depth very close to the edge of the property. This ability is a function both of the inherent deep penetration of pole-pole array, and of the 3-D character of the multidirectional E-SCAN data set which allows cross-referencing of survey-edge structural inferences to confirm or deny plausibility.

5. Interpretation: an epithermal mineralization system?

Centered in the western square mile of the Robertson survey area is a resistive "mushroom" shaped feature. Viewed in the shallowest of the resistivity plan plots (Figure 4), this 2500 foot wide zone is the most resistive feature within the survey area.

Figure 18 presents the IP and resistivity plan view results over this specific area. The data at middle and deep levels indicate a vertical resistive plumbing signature extending deep below the broad surface expression.

The indicated "mushroom" shape, with resistive cap and resistive stem, is similar in pattern and in absolute values to the resistivity signature of two intensely silicified epithermal orebodies: the Cinola deposit on Graham Island, B.C. (Figure 19), and the Hasbrouck Peak deposit (Figure 20), near Tonopah, Nevada. The Robertson feature shares the same resistivity pattern with both of these deposits.

While Cinola has some near-surface IP response due to sulphides and clays, Hasbrouck presents an IP low, indicating complete exclusion of sulphides and clays from the silicified zone. Robertson has the Hasbrouck IP signature, a negligible IP response both in the cap and in the deep structure below.

Given pattern precedents like Cinola, Hasbrouck, and other E-SCAN epithermal survey results, this feature claims an immediate drilling priority, to establish:

a. whether it is an epithermal feature (it could be a sill with intrusive pipe below), and,

b. whether there is gold associated, either in the broad cap, or in the vertical structure.

At time of writing, this structure has not been drilled, the possible significance of the signature only recently having been noted by the author in the course of reviewing subsequent E-SCAN survey results.

6. Concluding remarks.

The survey objectives were to map the character and extent of sulphide mineralization, map deep structures of any type, and map the character of the granodiorite exposure at depth.

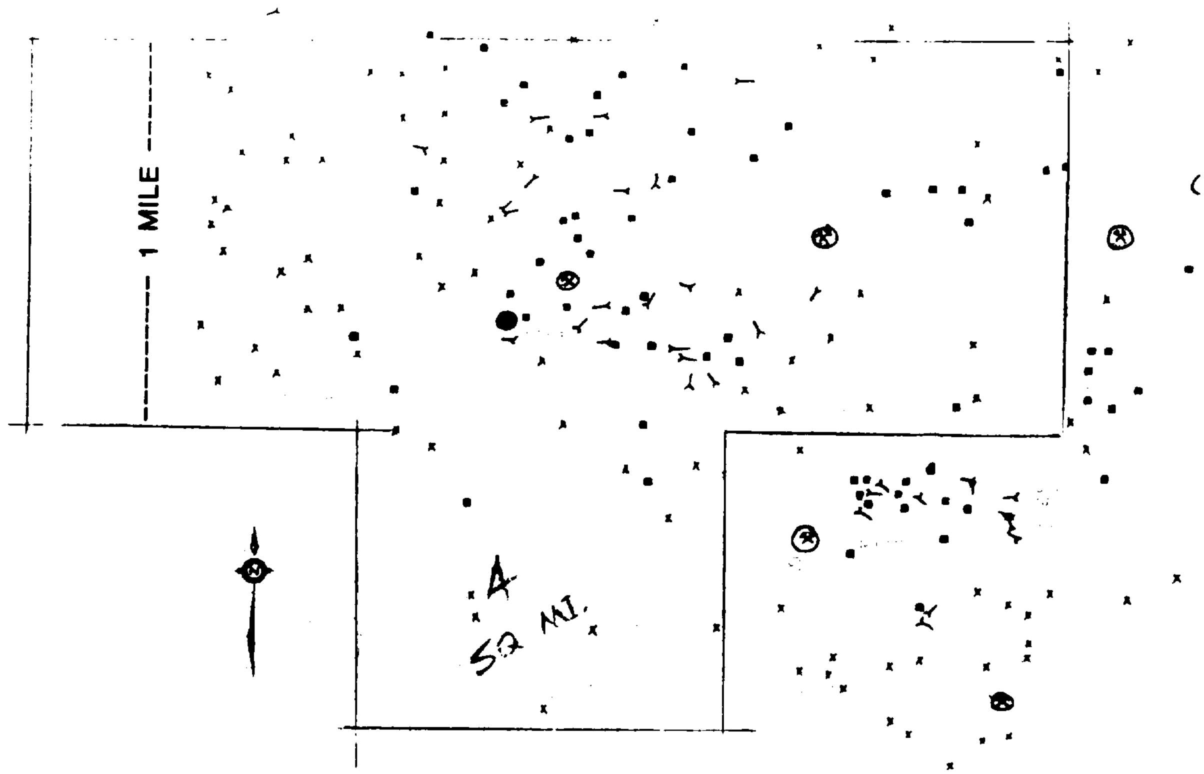
Since the survey was not limited by specific parameterization, but rather mapped the property edge-to-edge with every possible orientation and spacing of measurement, it is no surprise that an integrated geophysical definition of the points of initial interest (the sulphides, the granodiorite, and deep structure) was forthcoming. The survey produced a map of concentric hydrothermal mineralization zoning from which current exploration success could be projected into new areas of similar IP/resistivity signature and therefore similar positioning within the hydrothermal system.

As evidence both of the generality of the all-parameters approach, and of the benefits of the approach in mapping unexpected features, the identification of an epithermal "mushroom" pattern in the western part of the resistivity plots is an example. Unlike the large volume, strongly resistive unit mapped under the granodiorite exposure, this feature requires more subtle resolution to define the deeply-extending, narrow pipe-like feature. To do this, the thousands of multidirectional data measured through that area have provided sufficient noise-averaging and statistical certainty to permit a firm interpretation. All of the necessary raw data were already there on computer disc, ready to resolve whatever feature might come up.

Intensive all-parameter mapping with E-SCAN means that regardless of what an explorationist may expect to find in a property, thorough testing will be undertaken for any features, strong or subtle, in any orientation, which may not or can not be reasonably anticipated. It is the view of the author that this capability is a major step toward realizing the true objective of exploration geophysics: to make explorationists aware of all geologic possibilities, not just hunt for anomalies.

Greg A. Shore

November 1989



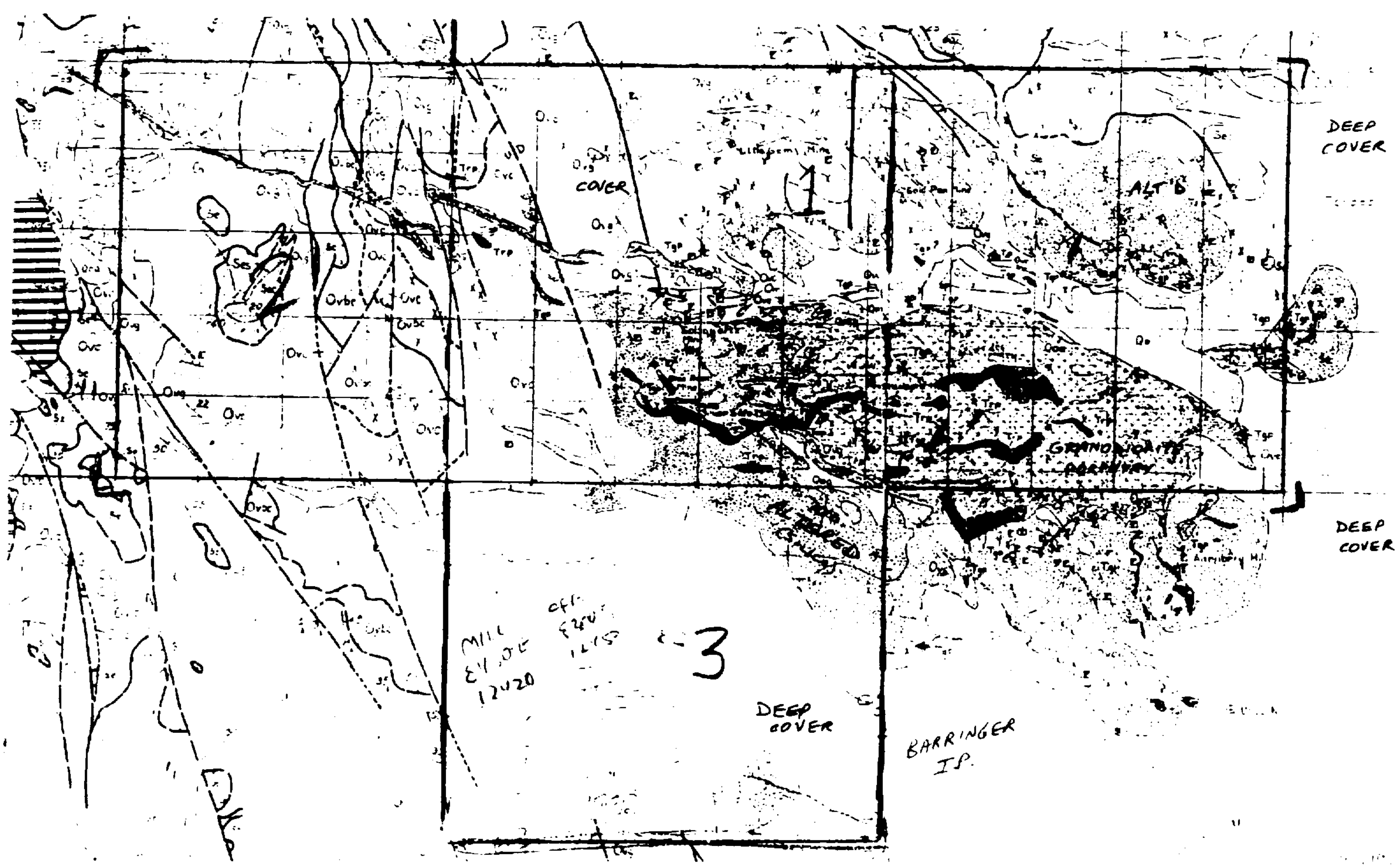
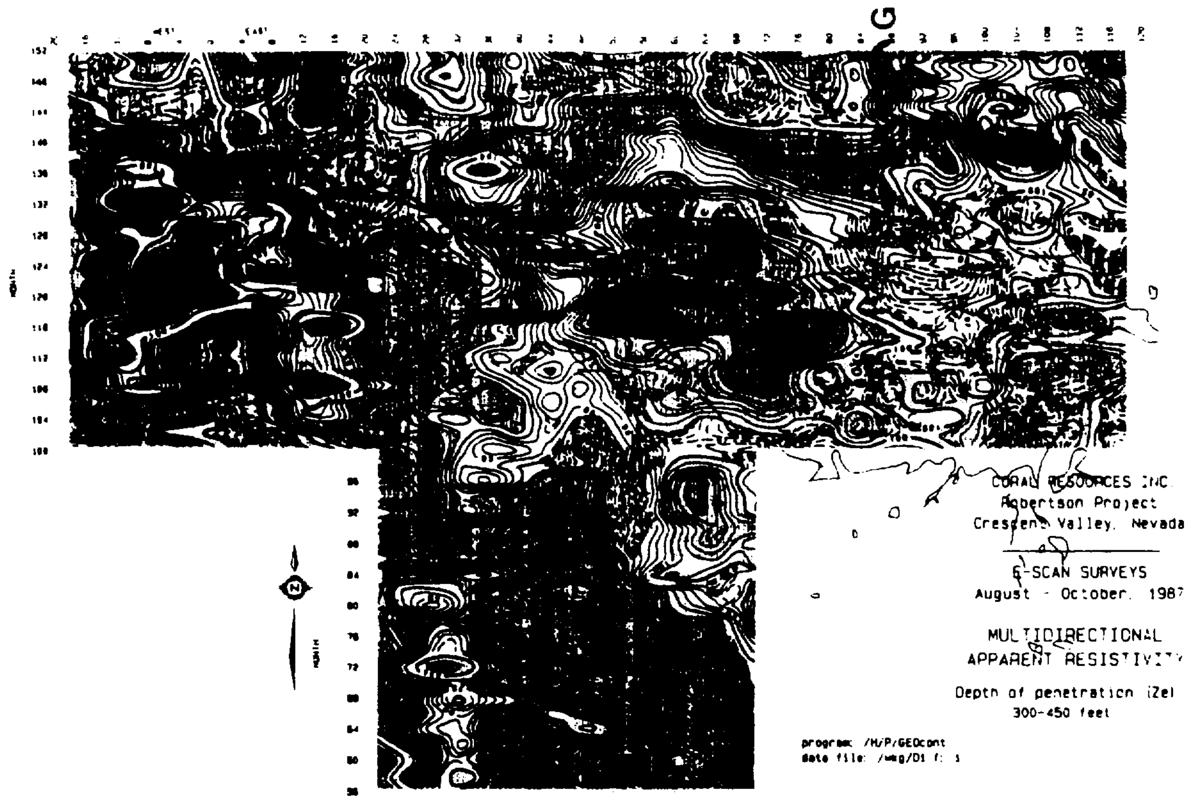


Figure 2, upper: Hundreds of pits, shafts, adits and trenches (above) are evidence of decades of search for the key to the gold mineralization regime on Coral Gold's Robertson Project, at Crescent Valley, Nevada.

Figure 3, lower: The USGS mapped an exposure of granodiorite porphyry in the sediments, surrounded by silicic alteration (green), hinting at what E-SCAN might find. The four square mile survey area covered by E-SCAN is outlined.



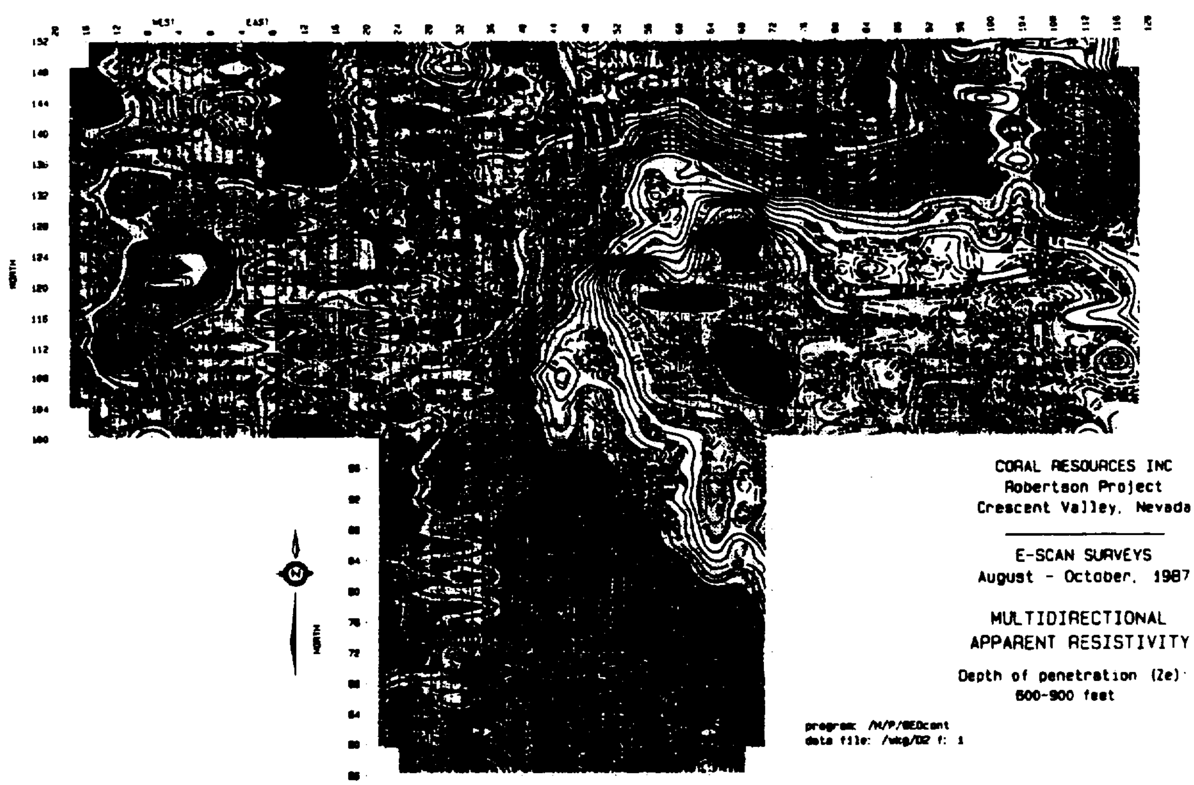
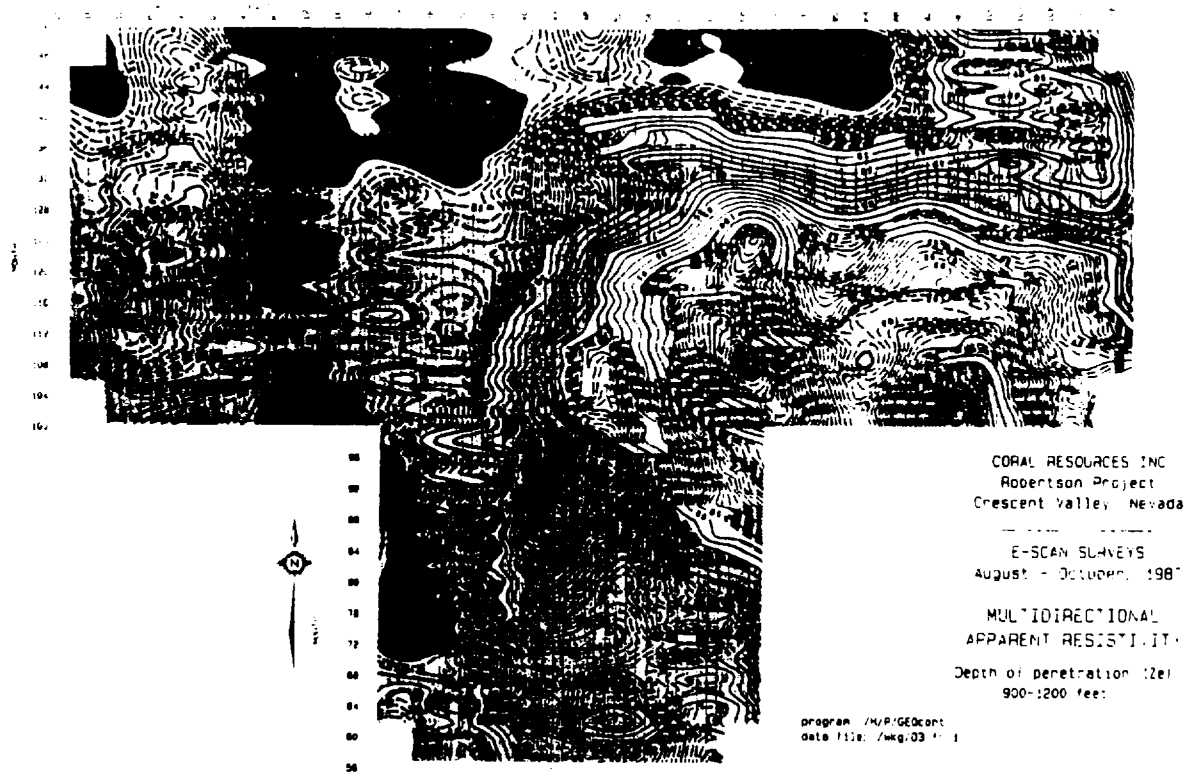


Figure 4, upper: The apparent resistivity map at 300 to 350 feet NDIC shows almost half the grid occupied by resistive rocks of 70 to 150 ohm-metres (yellow, orange), with a smaller, more resistive feature in the western square mile. The blue values are 15 to 30 ohm-metres.

Figure 5, lower: In a deeper plot, at 600 to 900 feet NDIC, the north part of the larger resistive area is weakening, but most of it remains unchanged. The western feature is diminished but still present. Some very conductive deep units (black, <10 ohm-metres) are appearing.



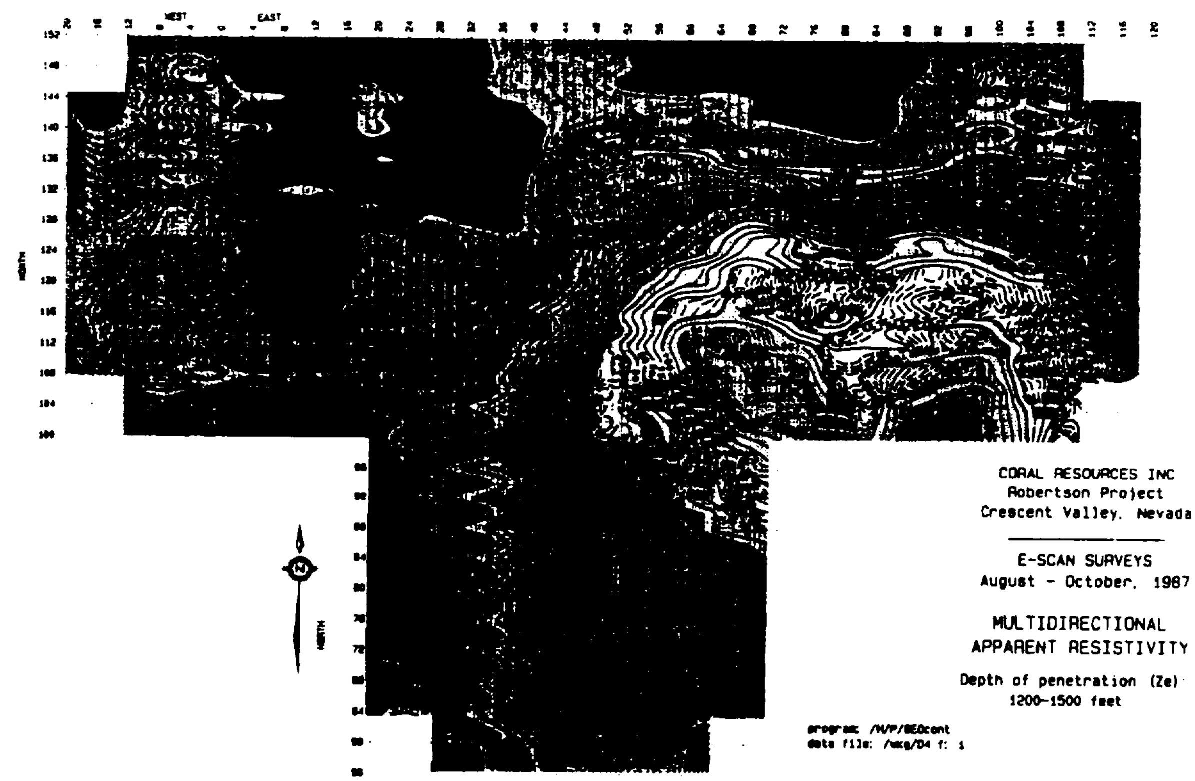


Figure 6, upper: The apparent resistivity map at 900 to 1200 feet NDIC. The main resistive unit remains undiminished; the north part has almost disappeared.

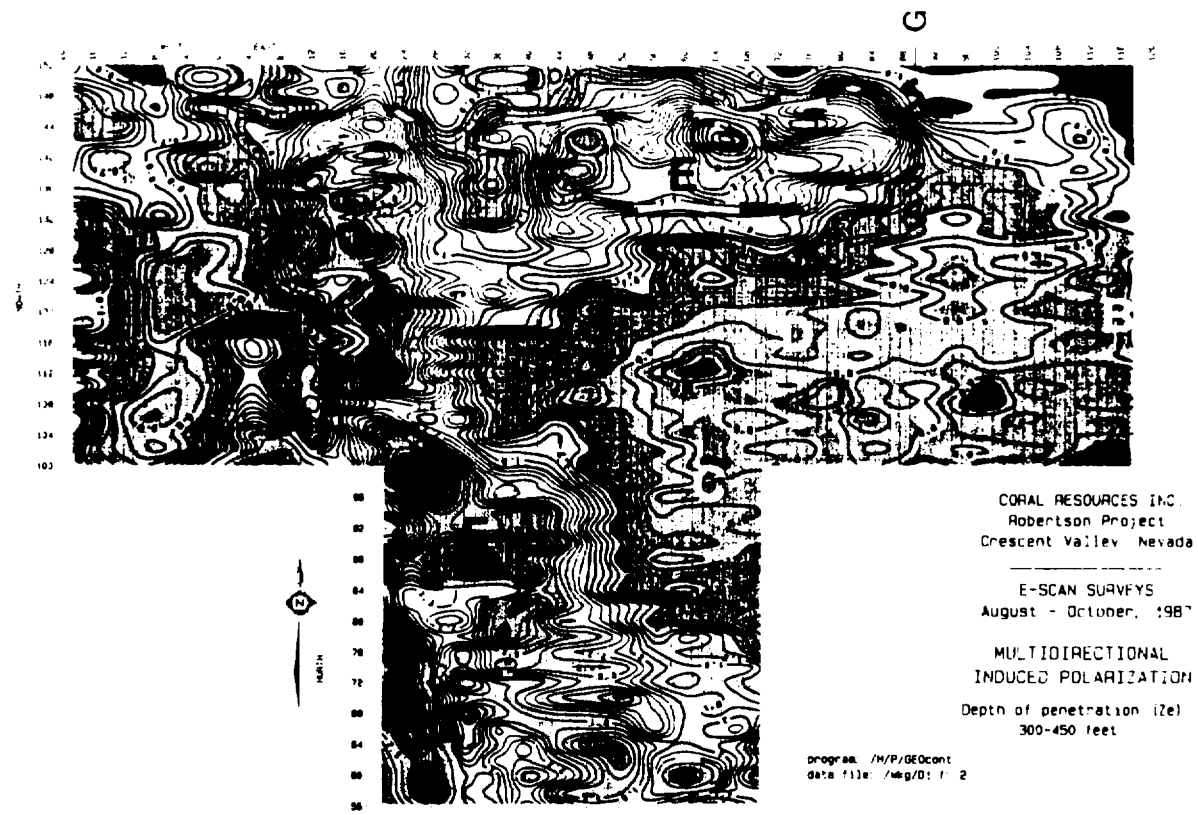
Very conductive deep units (black) take on a north-south linearity parallel to the rangefront, implying deep structural control.

The western resistivity feature retains a resistive signature at depth, indicating vertical, resistive plumbing beneath the broad resistive cap.

Figure 7, lower: At 1200 to 1500 feet NDIC, the western resistive feature has all of the hallmarks of a silicic epithermal mushroom, following closely the E-SCAN pattern displayed by the Cinola deposit in B.C. and by the Hasbrouck Peak deposit, Nevada.

The deep conductors are more prominent; they appear to be as low as 2-3 ohm-metres true resistivity.

The main resistive unit is still undiminished, implying continuity through 2000 to 2500 feet.



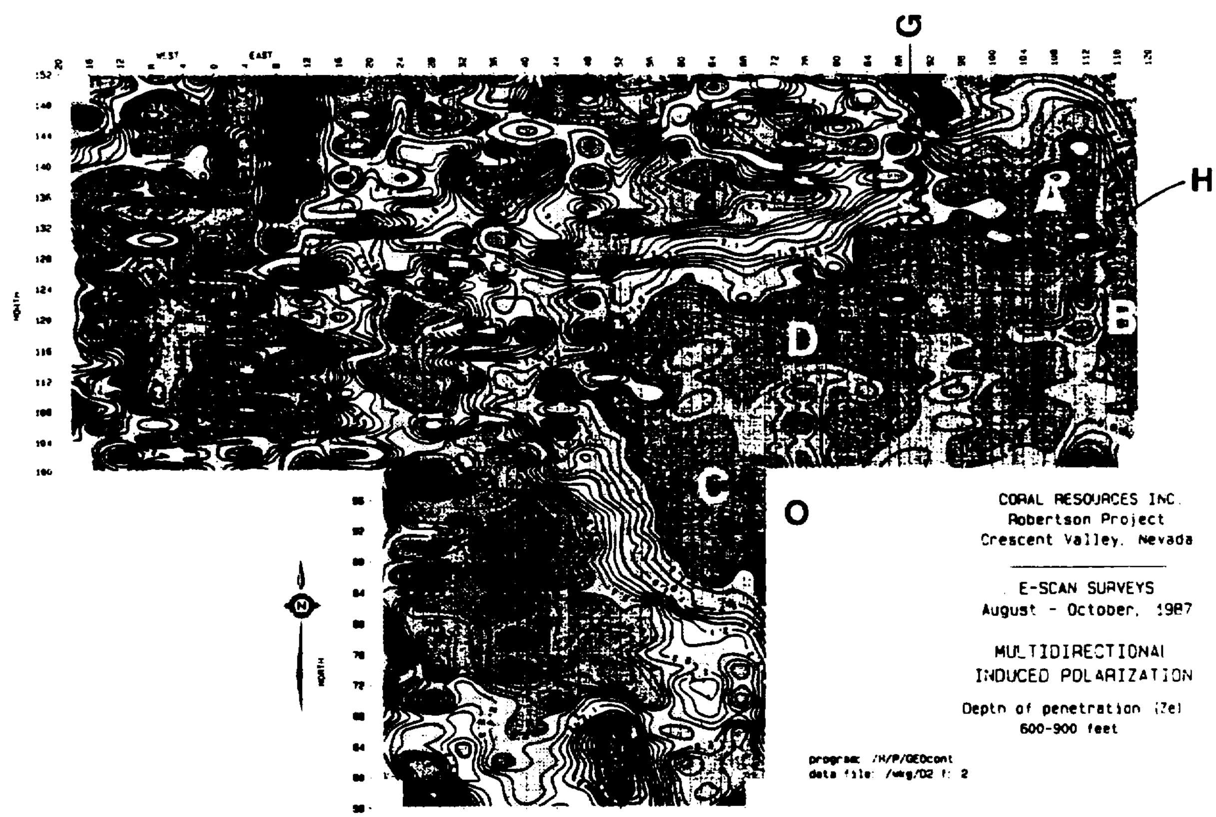
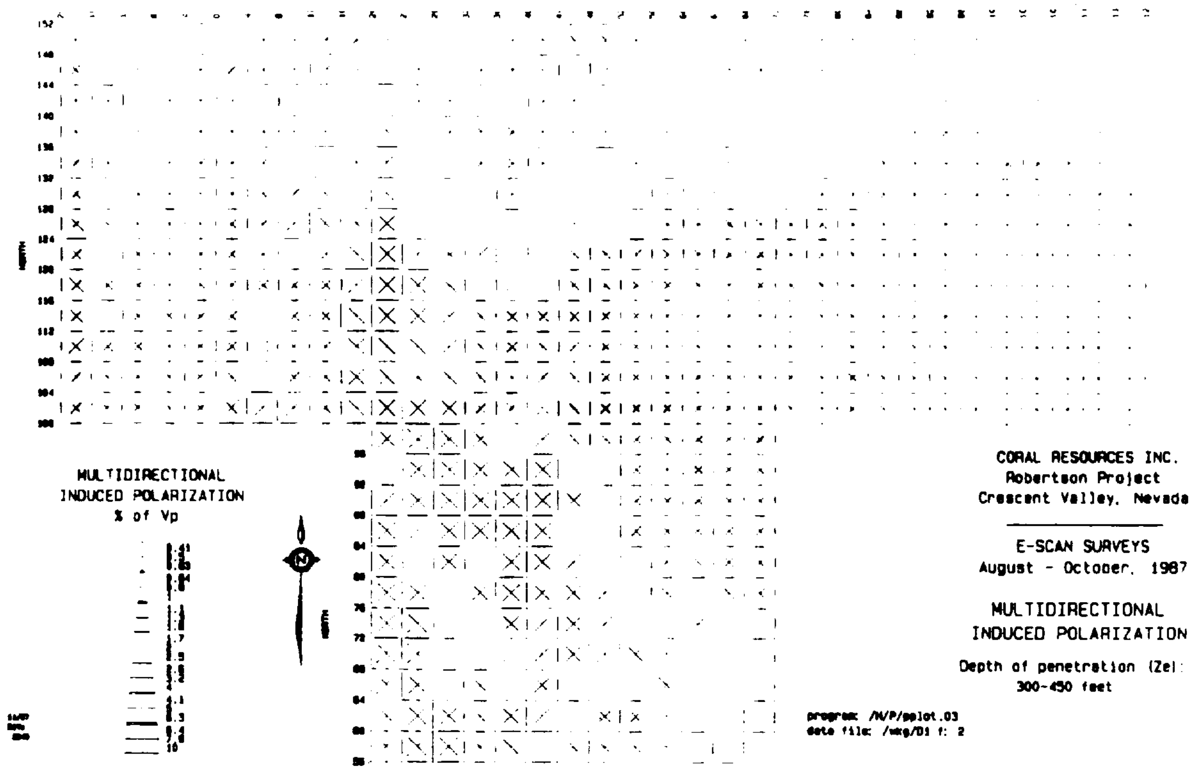


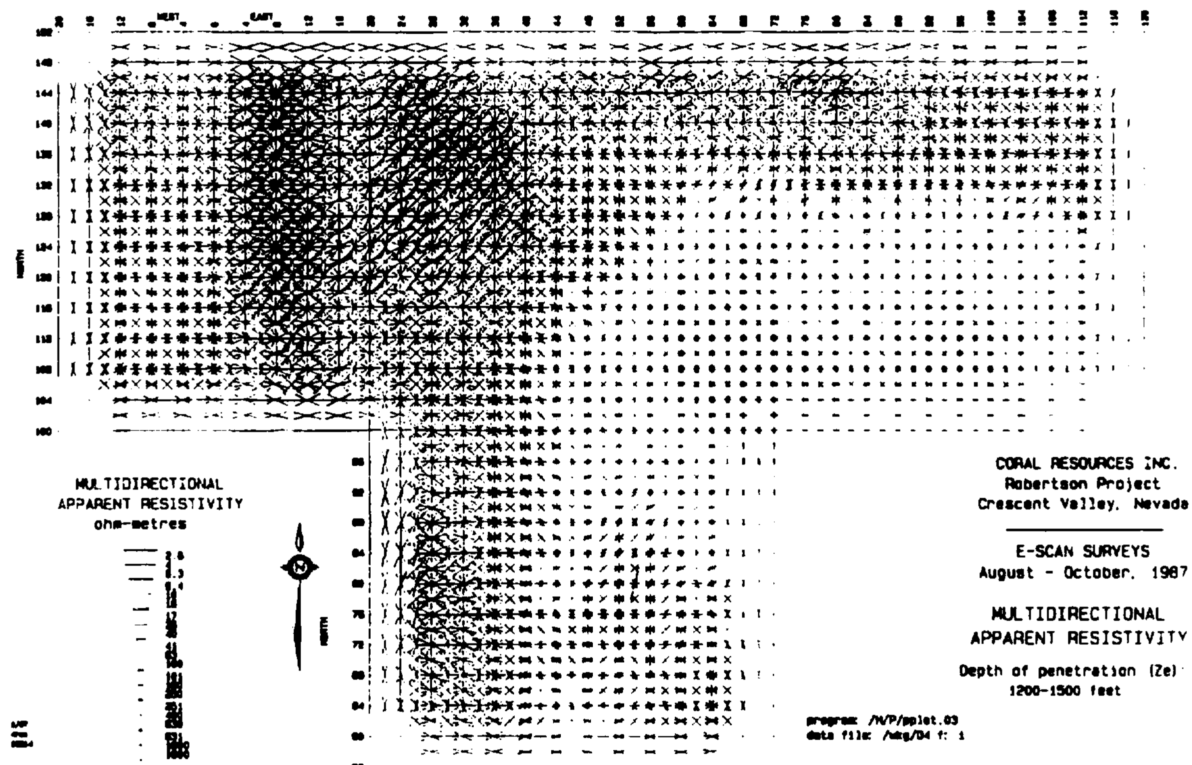
Figure 8, upper: This is the IP response, at 300 to 450 feet NDIC. Area E through F is 5% to 7% sulphides, with no graphite. Some indication of sulphide response is seen at A, but not at B, C, or D.

Figure 9, lower: The IP response, at 600 to 900 feet NDIC reveals sulphides underlying the thick, electrically neutral blanket of oxides and valley fill. The oxidized ores of sulphides are not normally detectable with electrical methods.

By probing deeply enough, with sufficient resolution, the high density E-SCAN data set maps the remaining sulphides, thereby marking the areas for exploration for overlying oxide ore.

The E-SCAN-mapped fault at G marks the downfaulting and extension of the sulphide zone (E) out under valley cover (A). Another E-SCAN mapped fault offsets the sulphide extension 1000 feet south to B, right at the edge of the grid.





Contour maps can present difficulties in judging actual survey resolution, because the individual raw data are no longer visible to be compared with the necessarily averaged and interpolated contoured result.

Figure 10, upper: These are the individual raw data used in the "shallow" IP contour plot of Figure 8. Each of the individual IP measurements is plotted as a vector (tic). Each tic is plotted midway between, and in line with, the electrodes involved. The tic length, and its colour, signify the magnitude of the measurement, according to the key. The tic orientation also indicates the direction of current flow through the sampled area. In this plot, the electrodes for each measurement are at the nearest grid dots in line with each tic.

Figure 11, lower: This is the data set at 1200 to 1500 feet NDIC, as used for the deep apparent resistivity contour plot of Figure 7. Several thousand data of all orientations illustrate good repeatability and low noise in this data set, partly a function of the superior signal levels delivered by the pole-pole array. A single "bad" measurement has been left in to show how, even if a rabbit-chewed wire gets past the in-field technical safeguards, the resulting bad datum simply cannot hide among the densely overlapping data set.

Note the high resistivity unit, and the deep conductive linears. Compare this plot to the contoured equivalent, Figure 7.

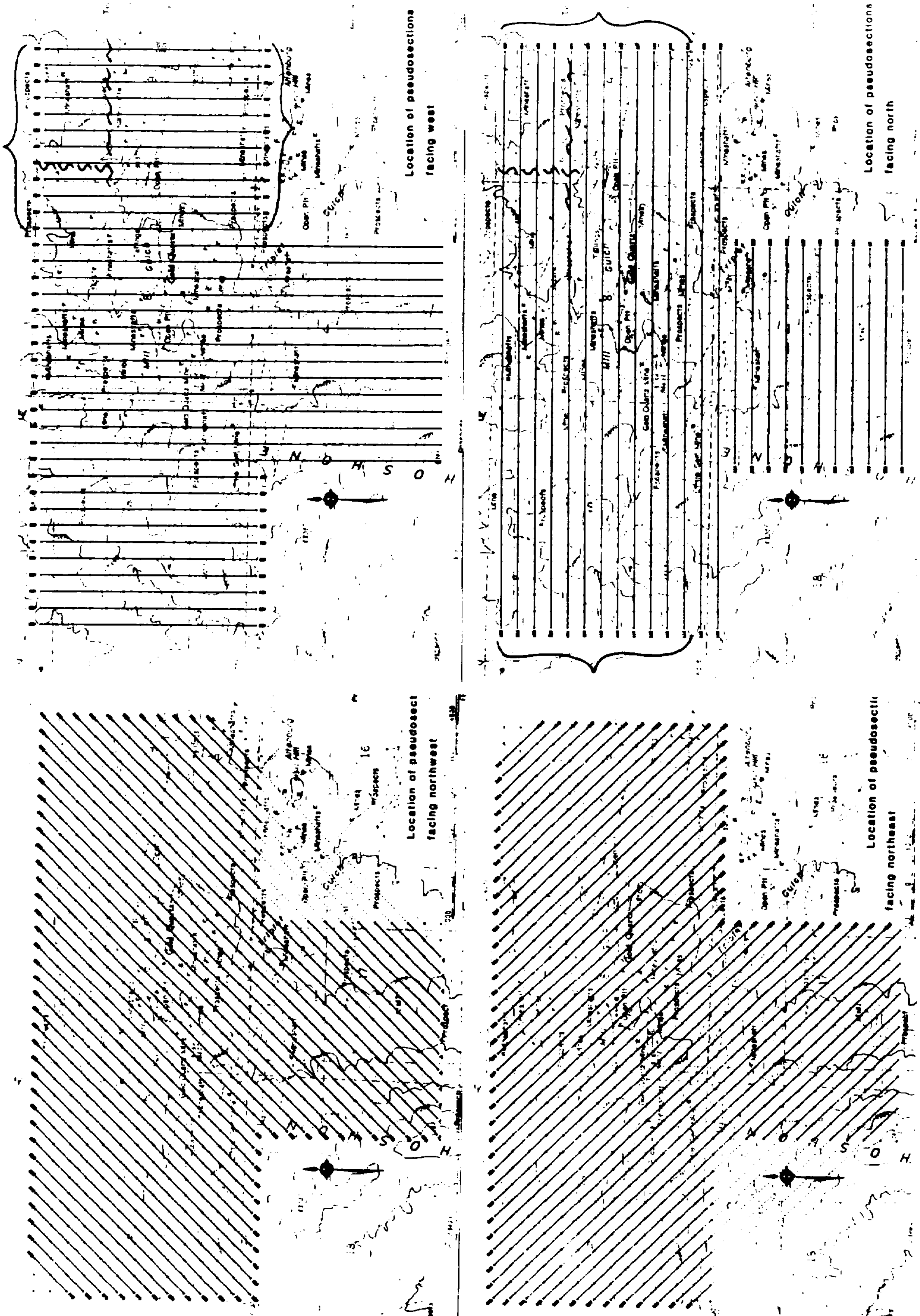


Figure 12: The master data set is "sectioned" four ways, providing complete sets of pseudosections facing west, northwest, north and northeast. Over 200 line miles of pseudosections, each covering 300 to 1500 feet of depth (NDIC), were generated for apparent resistivity, and the same for IP.

Pseudosections are the ultimate tool for the detection of subtle linear features. Having four orientations ds flexibility, in that any orientation of structure withi ie property will have a set of pseudosections optimally oriented for detection and analysis, including computer modeling if necessary.

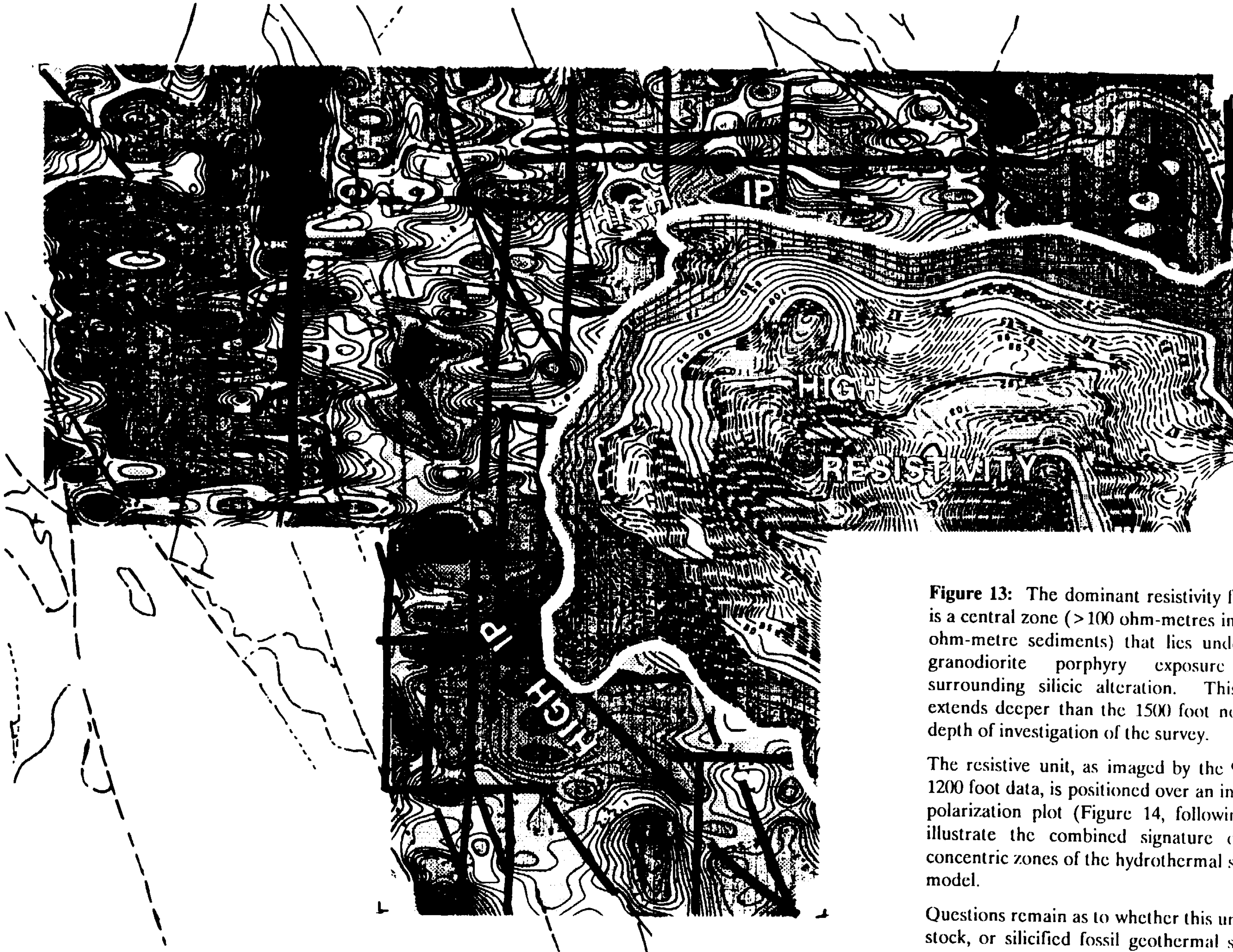


Figure 13: The dominant resistivity feature is a central zone (>100 ohm-metres in 15-20 ohm-metre sediments) that lies under the granodiorite porphyry exposure and surrounding silicic alteration. This unit extends deeper than the 1500 foot nominal depth of investigation of the survey.

The resistive unit, as imaged by the 900 to 1200 foot data, is positioned over an induced polarization plot (Figure 14, following) to illustrate the combined signature of the concentric zones of the hydrothermal system model.

Questions remain as to whether this unit is a stock, or silicified fossil geothermal system capped by a granodiorite sill or raft. In either case, it has been the focus of large scale hydrothermal activity.

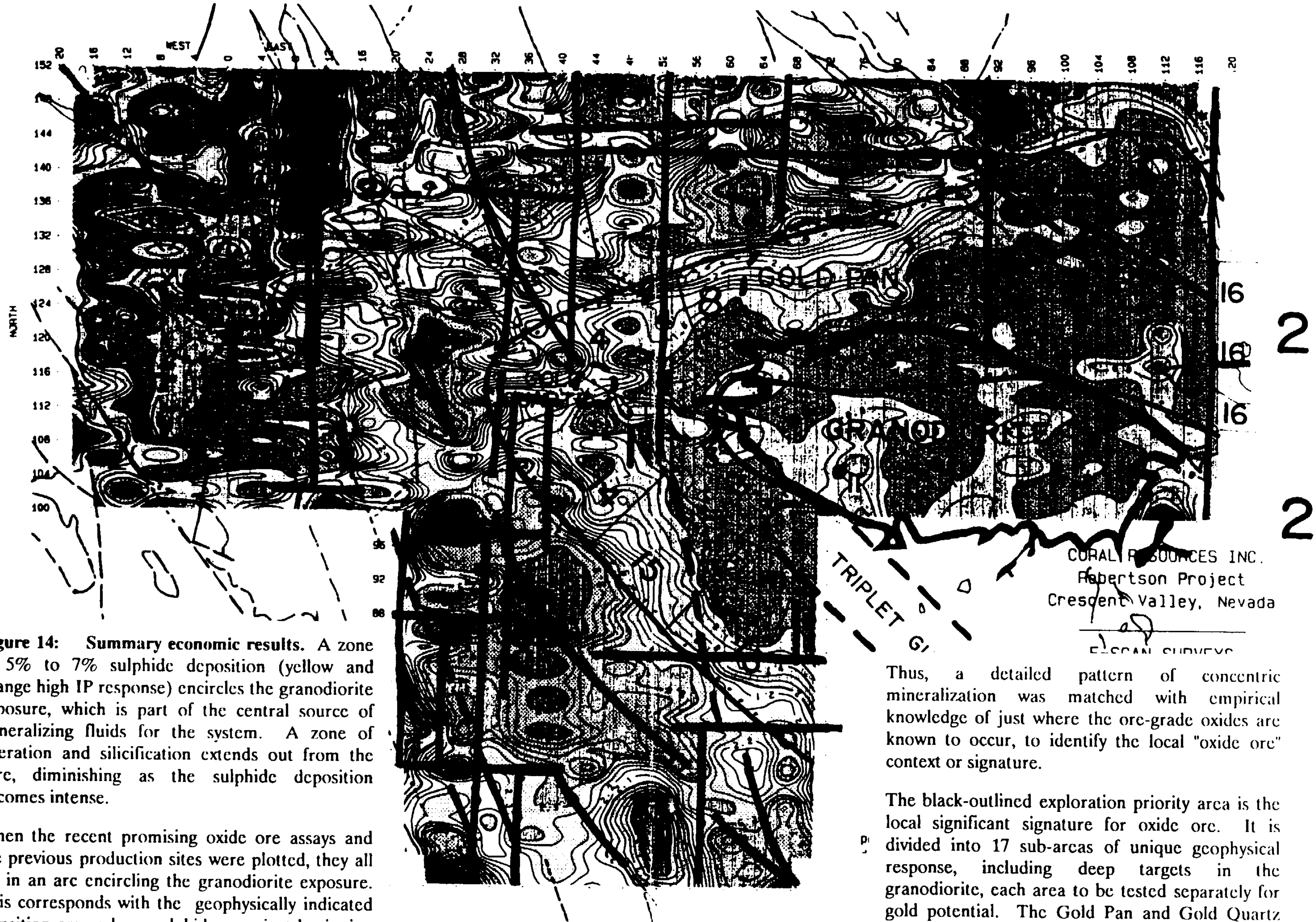
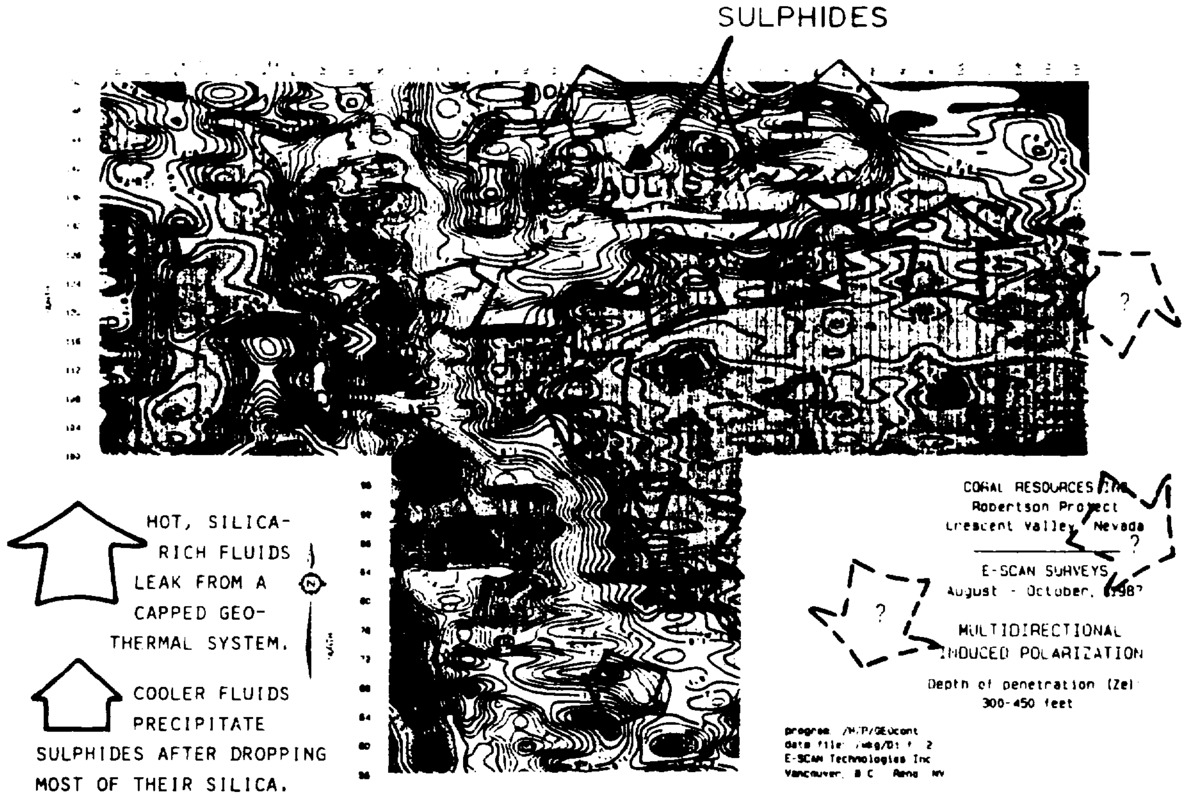


Figure 14: Summary economic results. A zone of 5% to 7% sulphide deposition (yellow and orange high IP response) encircles the granodiorite exposure, which is part of the central source of mineralizing fluids for the system. A zone of alteration and silicification extends out from the core, diminishing as the sulphide deposition becomes intense.

When the recent promising oxide ore assays and the previous production sites were plotted, they all lay in an arc encircling the granodiorite exposure. This corresponds with the geophysically indicated transition area where sulphides are just beginning to be precipitated (green contour levels of IP), and the last of the silica is being precipitated.

Thus, a detailed pattern of concentric mineralization was matched with empirical knowledge of just where the ore-grade oxides are known to occur, to identify the local "oxide ore" context or signature.

The black-outlined exploration priority area is the local significant signature for oxide ore. It is divided into 17 sub-areas of unique geophysical response, including deep targets in the granodiorite, each area to be tested separately for gold potential. The Gold Pan and Gold Quartz areas have seen production in the past. New production has started in areas 4 and 3 (extending down Triplet Gulch).



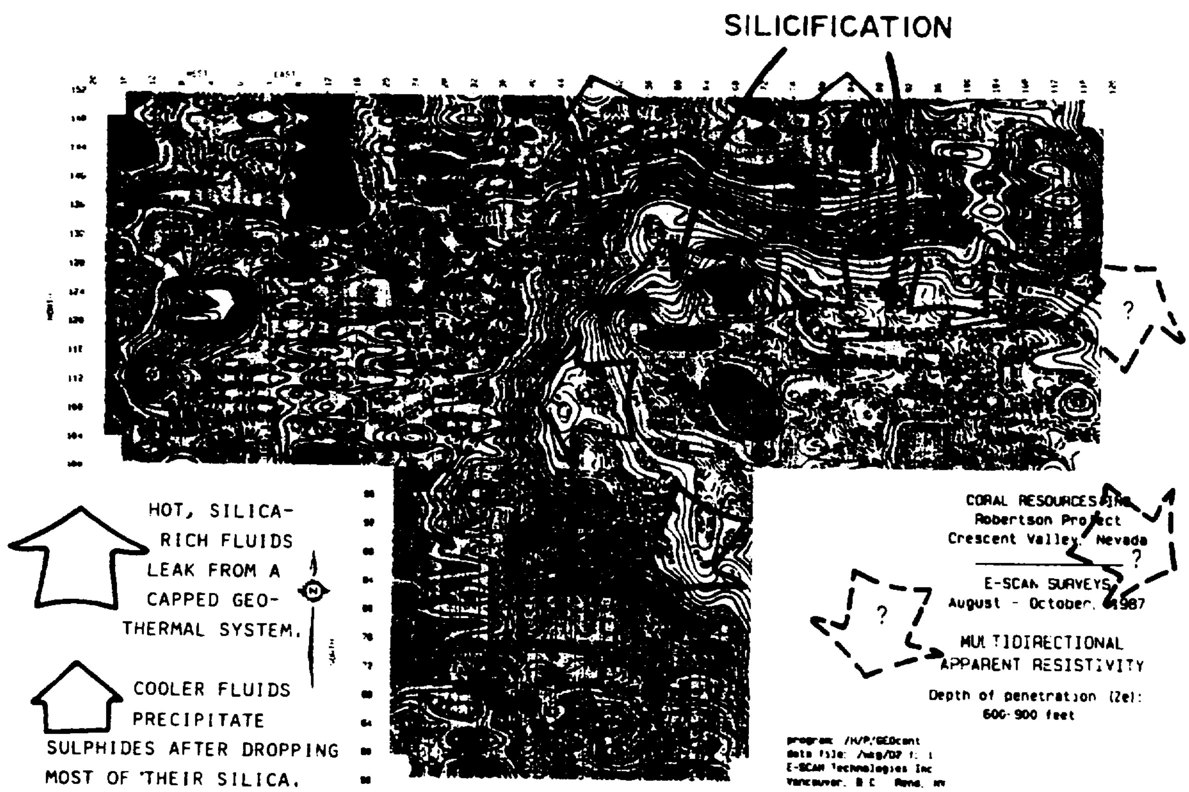
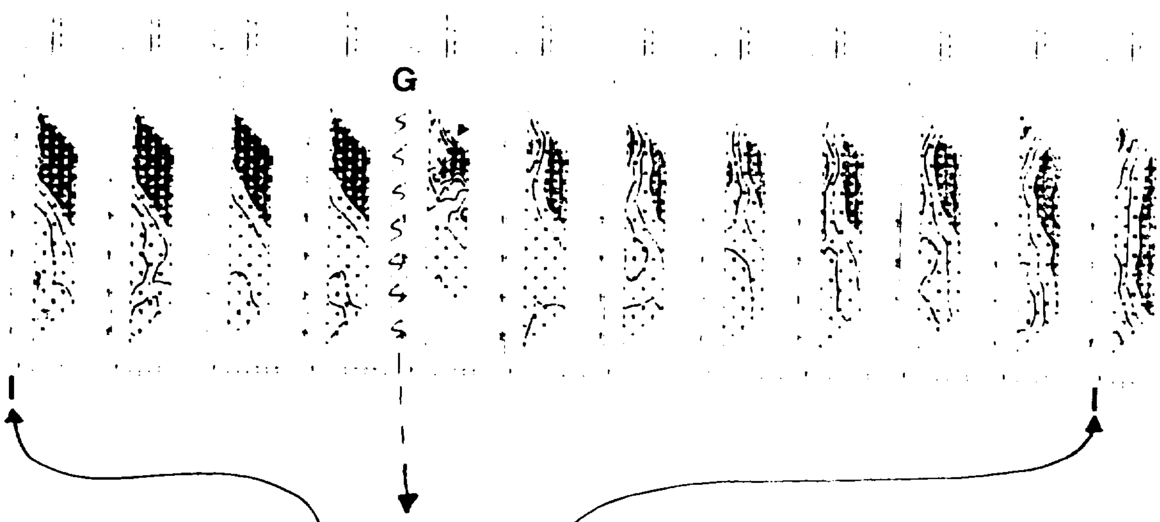
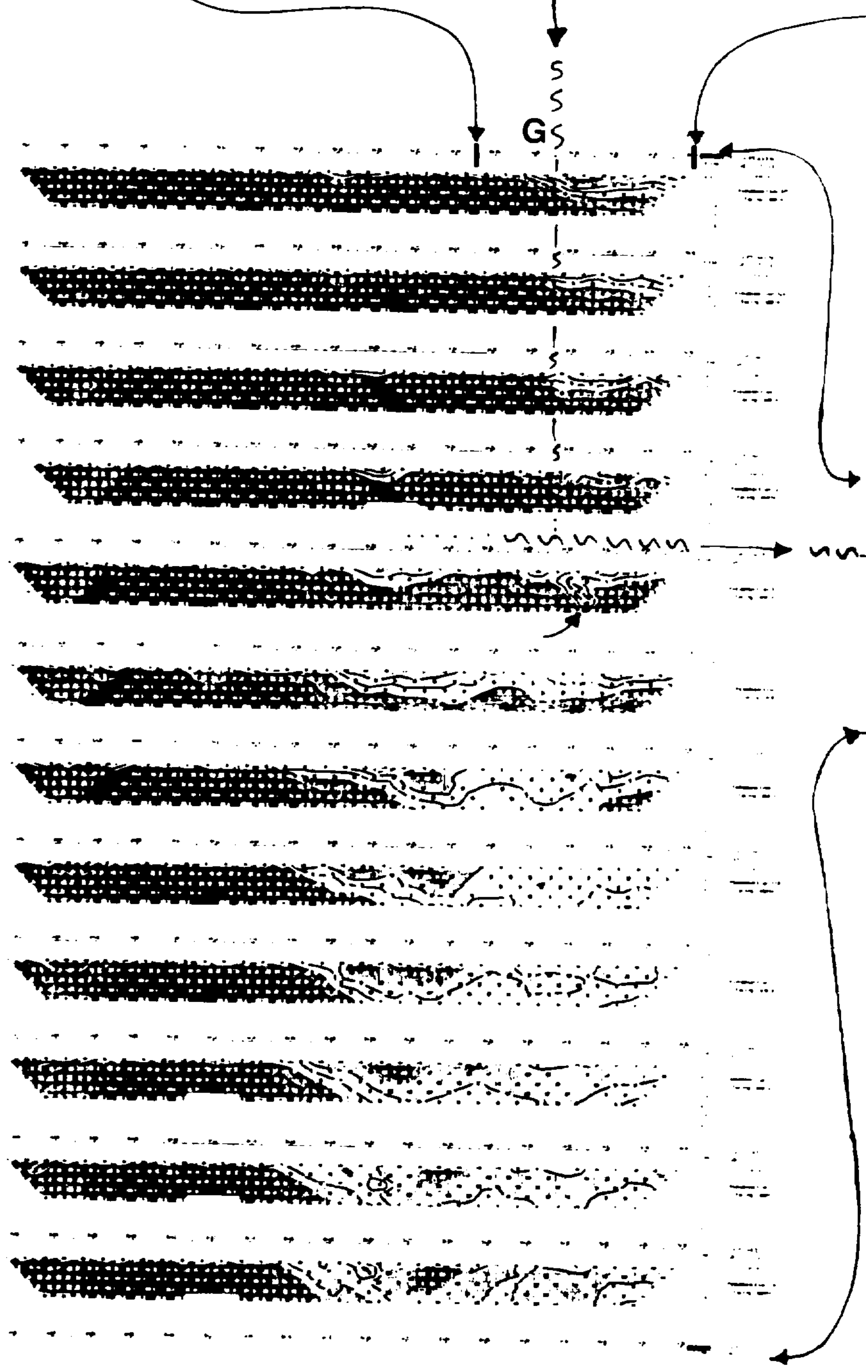


Figure 15, upper: Hydrothermal solutions may have migrated outward from the central core, cooling and precipitating silica in the area covered by the fat arrows (which indicating fluid flow). The fluids moved through vertically confined layers in the surrounding sediments.

Figure 16, lower: The fluids began to precipitate sulphides as the last silica was dropped. Gold dropped out with the sulphides here as well, and is now recoverable as oxide ore. The fat arrows are in the same locations as in Figure 15.

Two possibilities explain the large IP responses: in one the fluids migrating outward encountered intense faulting, and moved rapidly vertically and laterally, cooling and precipitating sulphides rapidly. In another model, some or all of these sulphides could have precipitated from solutions rising vertically along the fault systems, from sources which may be associated with the deep extension of the resistive feature.





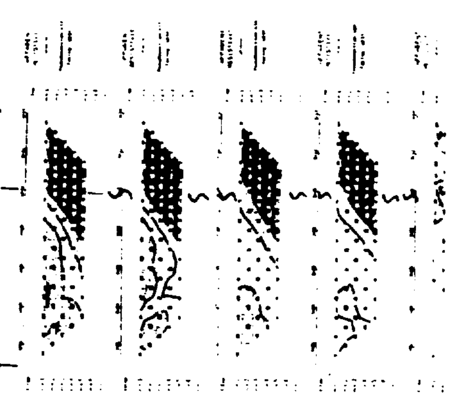


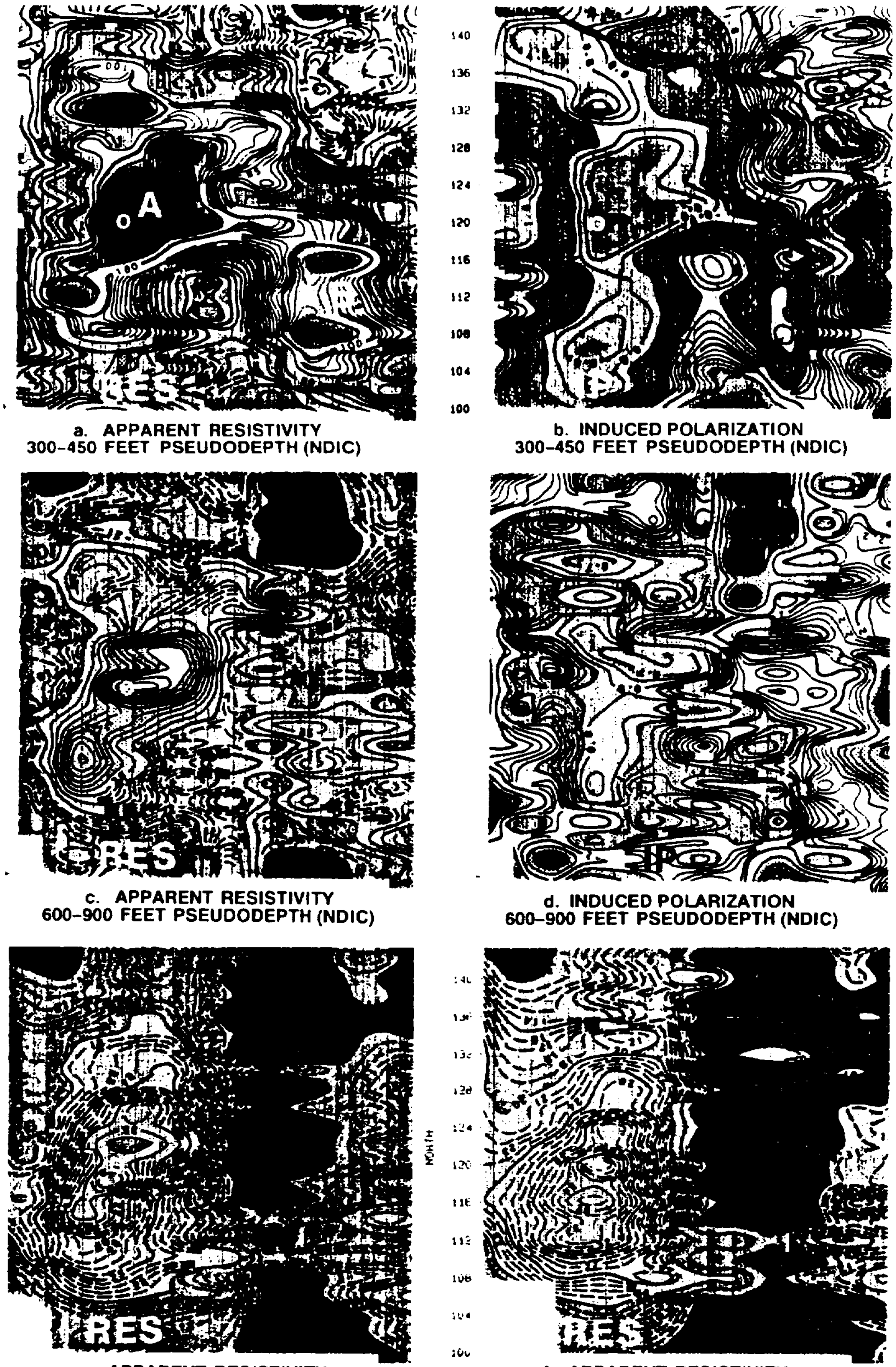
Figure 17: Pole-pole pseudosections facing north, and across the top, facing west. Those facing north are 3 miles across, and cover most of the broad upper area of the grid.

All of the pseudosections extend from a depth (NDIC) of 300 feet to 1500 feet.

The fault marked "G" on Figures 4, 8 and 9 is plotted in the corresponding position across the north facing pseudosections, dividing the western regime from the downfaulted eastern regime.

Its location in the west facing pseudosections is also clearly evident, as it again separates the two regimes, and shows the typically distorted response of a pseudosection oriented along a conductive linear, in this case the fault.

This opportunity for multiple viewing and confirmation of features is a typical example of the resolving power of a fully multidirectional data set.



a. APPARENT RESISTIVITY
300-450 FEET PSEUDODEPTH (NDIC)

b. INDUCED POLARIZATION
300-450 FEET PSEUDODEPTH (NDIC)

c. APPARENT RESISTIVITY
600-900 FEET PSEUDODEPTH (NDIC)

d. INDUCED POLARIZATION
600-900 FEET PSEUDODEPTH (NDIC)

e. APPARENT RESISTIVITY
900-1200 FEET PSEUDODEPTH (NDIC)

f. APPARENT RESISTIVITY
1200-1500 FEET PSEUDODEPTH (NDIC)

Figure 18: The vertical pattern of the 2500 foot wide western resistivity feature is typical of the pattern mapped by E-SCAN over some epithermal orebodies: a resistive "mushroom cap" (a) is underlain by a resistive "stem" (c, e, f) which could be a silicified breccia pipe of other fluid conduit.

The IP signatures to 900 feet show neglible IP response (blue), indicating a lack of sulphides and alteration clays.

A second, smaller system (B) is also indicated; its extension of resistive plumbing descends to a break in the strongly conductive north-south feature at depth (black).

Absolute values of resistivity are less important than the overall pattern, since varying intensities of silicification within a whole range of host rock types permits a wide range of absolute values.

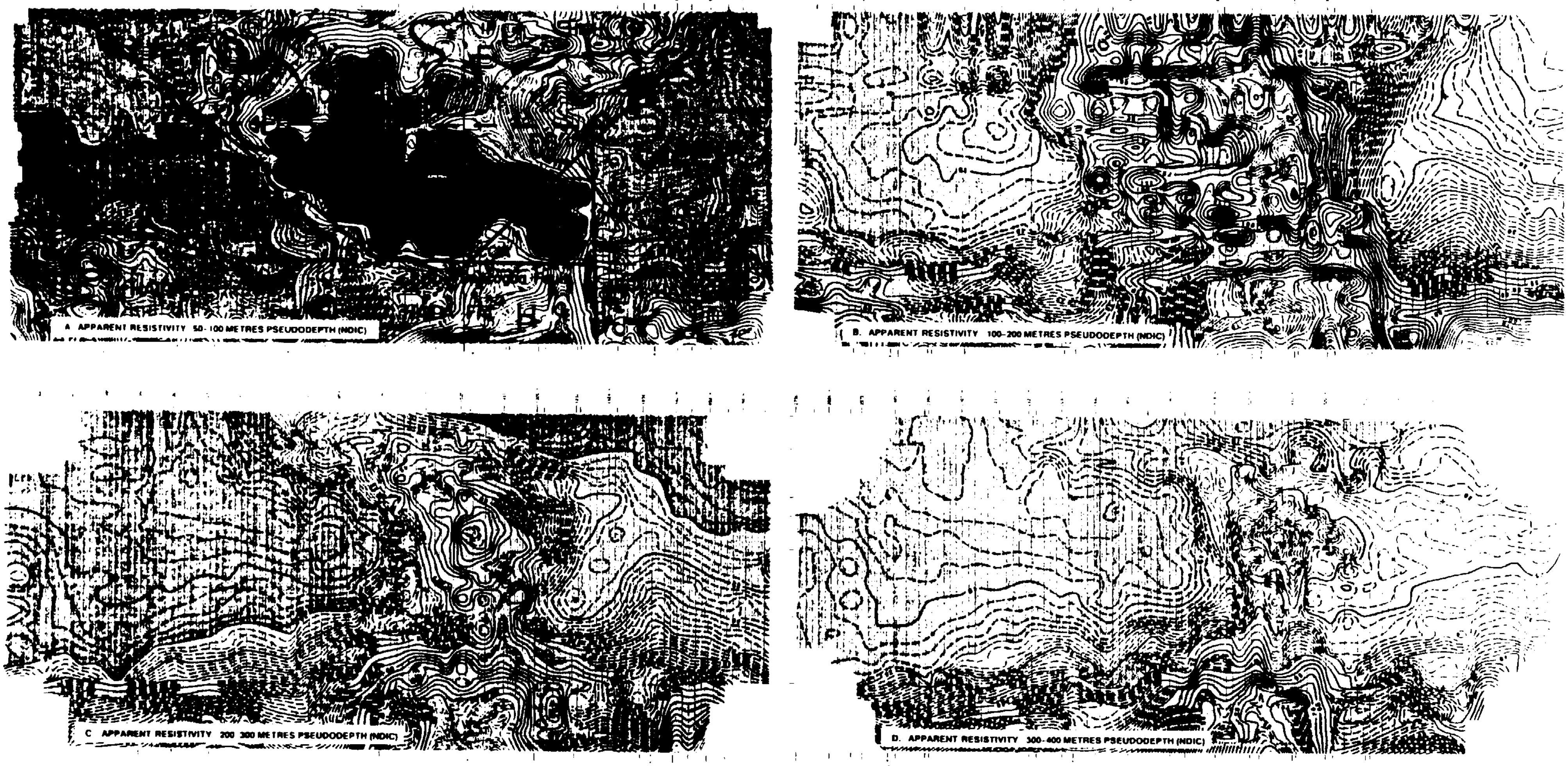


Figure 19: Abbreviated E-SCAN results over the million-ounce Cinola epithermal gold orebody on Graham Island, British Columbia, viewed facing northeast, for comparison to the Robertson signature.

A. AT 50 to 100 metres (180 to 330 feet) NDIC the broad lateral extent of the gold bearing, highly silicic cap (3000 feet across) is mapped. The breccia pipe which fed this system reaches surface against the fault, at the apex of the cross-breaking structures.

B. Immediately beneath, at 100 to 200 metres (330 to 660 feet) NDIC, the resistive signature narrows. In the foreground is the main breccia pipe, lying against a 45 degree normal fault dipping to the northeast (top of page). A secondary vertical branch of the pipe is seen at the top of the plot.

C. Deeper still (200 to 300 metres, 660 to 1000 feet NDIC) the now-single breccia pipe is still visible, plotting up further northeast as it follows down the fault plane.

D. At 300 to 400 metres (1000 to 1300 feet) NDIC, the pipe is still visible, but its response is being heavily averaged with the surrounding 20 ohm-metre conglomerates.

There is a diffuse, unfocused IP response at Cinola, due to sulphides and alteration clays in and beside the system.

The resistivity signature (pattern) of this silicic-cap, silicic-stem epithermal system is similar to that at Robertson and at Hasbrouck Peak (Figure 13).

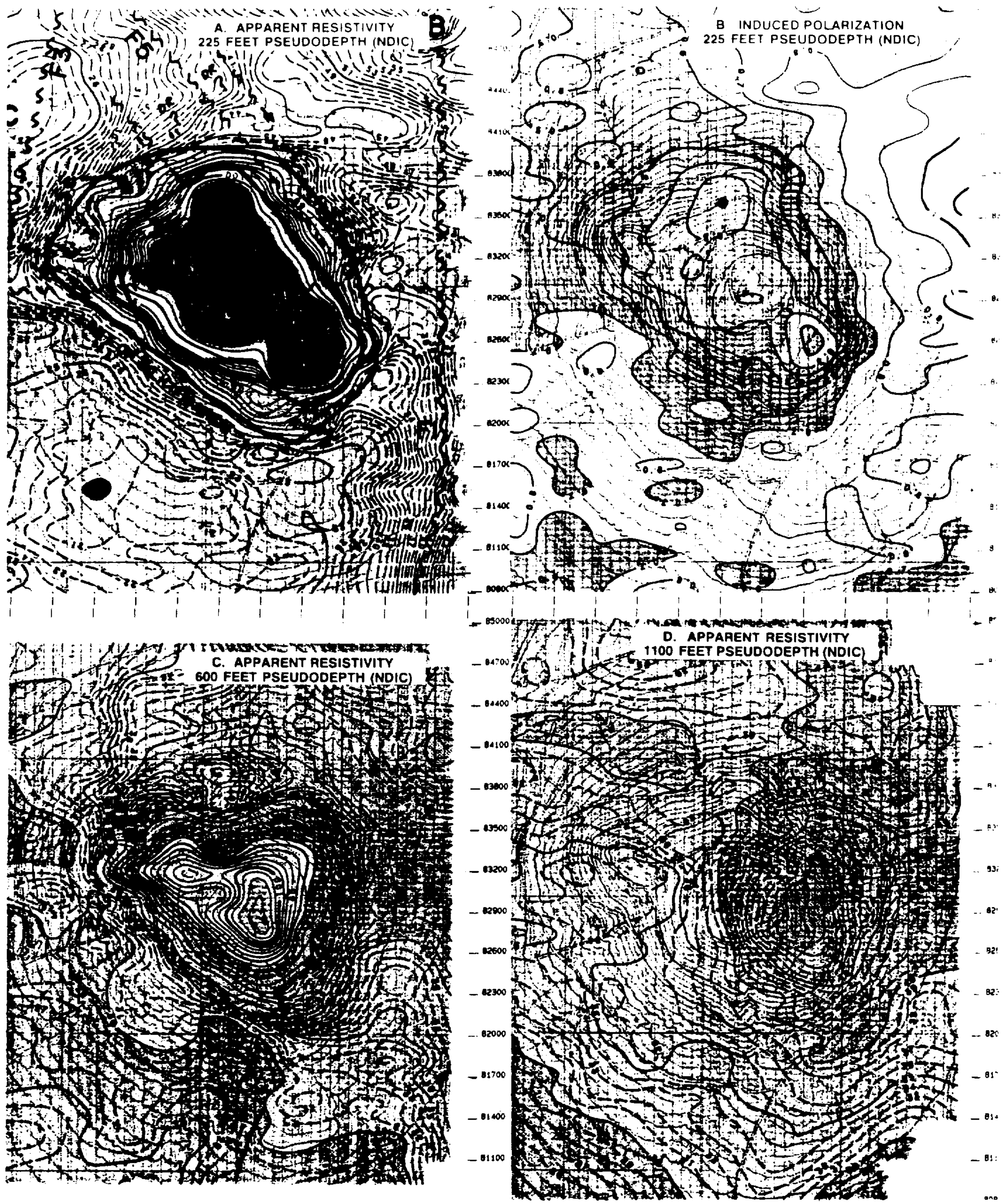


Figure 20: Abbreviated E-SCAN results over the Hasbrouck Peak epithermal gold deposit near Tonopah, Nevada, for comparison to the Robertson signature.

A. At 225 feet NDIC, the 1500 foot wide gold-bearing, highly silicic cap is defined. This deposit appears to be centered on a cross-breaking fault intersection.

B. The IP plot (d) shows very low IP responses in general (equivalent to about 1% sulphides, but probably clay), and virtually nil response in the area of the silicification. This low IP signature persists to depth, as it does at Robertson.

C. In the resistivity plot at about 600 feet NDIC, the vertical conduit remains clearly defined, resistive, and centered directly under the cap as at Robertson.

D. Several plots deeper, at about 1200 feet NDIC, the much-diluted signature of a resistive vertical structure persists, consistent with the signatures at Cinola, Robertson, and other E-SCAN silicic-cap silicic-stem epithermal studies.

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The Unalaska Island (Mount Makushin) E-SCAN Geothermal Case History (1984)

This is an "expanded abstract" rather than a full case history. The paper illustrates the no-assumptions approach of E-SCAN. It also reinforces the concept that the reliability of our interpretation of the near-surface (upper 1000 feet) regime is vastly improved when the next several thousand feet down is imaged and understood. This $250,000 survey firmly eliminated over $3 million in planned deep drill holes, rejecting the possibility of extensions of (or new) geothermal zones which in the absence of deep data, would have been erroneously supported by the shallow (to 1000') data.

The plots are crude (a new case history with color contoured plots is in preparation), for which I apologize. However, the message common to most E-SCAN programs comes through clearly: "Get the big picture, if you possibly can, in order to better understand your smaller focus of interest".

The paper also illustrates E-SCAN's ability to operate in rough terrain conditions, and to substantial depths (although more recent Nevada surveys often test routinely to 7500 feet or more).

The deeply buried east-west fault zone reported in the results was years later confirmed by other tests. It turns out to have island-wide significance, a major break between the intensive hydrothermal regime under Mount Makushin, and the relatively unaltered rock suite of the rest of the island. It's signature was/is too subtle for any conventional system to detect. With 3-D inversion (unavailable at that time), this important structural feature would stand out clearly.

Geothermal Resources Council TRANSACTIONS Vol 10, September 1986

Mapping the Makushin reservoir with 3-D E-SCAN resistivity

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Abstract

In 1983, a high-temperature geothermal reservoir was identified at well ST-1 in an area of extreme terrain on the southeast flank of Makushin Volcano. The lateral extent of the reservoir had not been defined, and it was thought that it might extend to the northeast, into an area of road access and more economically viable development costs. The severe terrain had ruled out the use of conventional resistivity methods for reservoir mapping, and the delineation of the reservoir appeared to require the continuation of the successful (but expensive) program of temperature gradient drilling. On learning of E-SCAN's rough terrain resistivity capability, the Alaska Power Authority requested a 3-D E-SCAN of the Unalaska Geothermal Project area in 1984. The 3-D E-SCAN survey results unambiguously defined the boundaries of the reservoir, confining it to the area of extreme terrain in the vicinity of producing well ST-1. The northeastern boundary of the resource is marked by an inclined fault that appears to control the production intersected in well ST-1. Extension of the reservoir into adjacent areas of easier and more economic access was ruled out by the E-SCAN resistivity results.

By the end of 1983, the Makushin Volcano geothermal project of the Alaska Power Authority on Unalaska Island had progressed to an advanced but still unresolved pre-development stage. Flow-testing of well ST-1 confirmed the presence of a geothermal resource in the upper Makushin River valley, but the various types of exploration data (geologic mapping, temperature gradient drilling, geochemistry, SP) accumulated to that date could not provide a definition of the geometry and in particular the lateral extent of the resource.

The successful well ST-1 was located in rough terrain along an alignment of surface thermal manifestations extending around part of the southern flank of Makushin Volcano (Figure 1). The cost to develop the resource at that site would be considerably higher than the cost of development in an area of road-accessible terrain some 2 km northeast, down the valley from ST-1. Little was known about this area, except that it was in line with the trend of thermal manifestations leading to ST-1, and that a steam vent provided evidence of elevated temperatures in the area. Much of the geology of potential exploration interest lay hidden beneath a fresh, glassy flow which blanketed the area. Prior to consideration of the feasibility of development at the site of well ST-1, it was appropriate to test the more economically accessible areas down the valley, for either a northeast extension of the high-temperature system identified at well ST-1, or perhaps a separate resource occurrence.

Resistivity methods had not been used on the island, because of prohibitively rough terrain. Producing well ST-1 had been discovered principally on the basis of geological mapping and temperature gradient drilling. When in 1983 the rough terrain capability of the E-SCAN resistivity method was presented to the GRC annual meeting at Portland, representatives of project managers Republic Geothermal Inc. and of the Alaska Department of Geological and Geophysical Surveys decided to try the method at Makushin.

The E-SCAN resistivity survey objectives were established as twofold:

- map the characteristics and extent of the high-temperature resource identified at well ST-1, and,

- test the economically more accessible area down the valley for resource potential, either an extension of the ST-1 resource or a separate system.

A third area was appended to this survey coverage, extending further northeast down the valley, to test an area of outcropping crystalline rocks similar to those intimately associated with the surface thermal manifestations near well ST-1. While there was no evidence of thermal activity in the surface geology of this area, an assessment of deeper conditions with resistivity was considered prudent, given the potentially favorable geologic setting and direct road access.

In the summer of 1984, a 3-D E-SCAN resistivity survey was operated over the 26 square kilometer map area to test the objectives described above. The planning of the survey was straightforward: within an outline of the total area of interest, an electrode grid at 300 meters spacing was established, using air photos and maps for location. No other survey parameters were required. The survey swept from one end of the area to the other in four weeks, obtaining over 10,000 individual resistivity measurements of every orientation and at depths to 2000 meters. The survey results were continuously updated on an eight-color plotter, allowing the survey operator (and project geologist) to observe as the data outlined the extent and boundaries of the reservoir and tested the road-accessible areas along the valley.

The survey results clearly and unambiguously answered all of the unresolved exploration questions (Figure 2). The boundary of the reservoir beneath well ST-1 was found to lie just 200 meters northeast of well ST-1, sharply cutting off the possibility that the reservoir would extend down-valley to the lower-cost road-access area. As the survey coverage proceeded, the road-accessible area was intensively tested for the presence of a separate resource zone; no resistivity signatures typical of those marking the ST-1 reservoir were mapped. The more resistive, non-resource resistivity signatures persisted through the remaining area of survey coverage. Verification of a lack of deep thermal activity in the area of crystalline rock completed the E-SCAN assessment of the project area.

The exploitable reservoir was thus defined as being fault-bounded and limited in down-valley extent to just a few hundred meters beyond the producing ST-1 well. The remaining portions of the 26 square kilometer test area, including all of the low-cost road accessible area, were unequivocally shown to be devoid of the resistivity conditions typifying the reservoir at well ST-1.

The master data set was divided into four plan plots of multidirectional data at four horizontal levels, 200-500, 500-1000, 1000-1500, and 1500-2000 meters depth (Figure 3, 4). These plots identified the gross three-dimensional distribution of resistivities, outlining the boundary of the reservoir area, and clearly distinguishing the reservoir from an adjacent 1 km thick conductive non-reservoir rock unit overlying a resistive basement. A third conductive feature near a steam vent in the high-interest road-accessible area was also identified as a shallow (500 meters) skim of conductive material over a uniformly more resistive lower unit, and thus of no potential resource significance.

The master data set was also sliced vertically into four sets of parallel pseudosections through the survey area, separate sets of sections facing west, northwest, north, and northeast (Figure 5). These pseudosections provided additional correlation of the initial three-dimensional observations obtained from the plan plots, confirming the initial assessment of reservoir boundaries and the explanations of the other shallow conductive zones. The equivalent of over 320 line kilometers of resistivity pseudosections extending to depths over 2000 meters were constructed from the data set. Using the great density of measurements to advantage, subsets of data were organized and digitally stacked to provide emphasis of subtle resistivity features indistinguishable in individual pseudosections. A number of structural features (faults, contacts) were thus mapped at various orientations throughout the area. The largest of these features bisects the area, and marks a sharp transition from general lower resistivity of all rock types on one side, to a universally higher resistivity mode (10 times higher) for the same suite of rocks on the other side. This large scale, buried structure had not been previously mapped and was not identifiable from ground or airphoto observations.

Computer-assisted 2 1/2 dimensional forward modeling of selected pseudosections yielded a unique 3-dimensional model of the reservoir geometry and boundary locations (Figure 7). The identification of a dipping fault plane underlying the reservoir corresponds with the depth of intersection of open fractures from which steam is produced in well ST-1. The fault dips westward beneath the area of hot springs and fumaroles lying in inaccessible terrain southwest of the survey area. The presence of this fault and its associated permeability (encountered in well ST-1) indicates that a backup production well may be obtained by deepening the adjacent (presently non-producing) well E-1 to intersect the fault 300 to 500 meters below E-1's present drilled depth.

The possibility of an extension of the resource into the economically favorable road-access area was eliminated by the E-SCAN results, while a simultaneous temperature gradient hole (TGH A-1) in the same area provided potential encouragement in terms of favorable temperatures (185 degrees C), The temperature in A-1 is close to that recorded in producing well ST-1 and adjacent non-producing well E-1, and from a strictly temperature gradient and BHT point of view, would support further drilling in the area to test for permeabilities associated with a possible resource extension or separate resource. The intensive mapping of this area with 3-D E-SCAN demonstrated that deep conditions were not similar to those around producing well ST-1, and that permeabilities capable of supporting commercial steam production likely did not exist. No further drilling in the area has been undertaken.

The E-SCAN resistivity survey provided the first firm mapping of the resource's boundaries, and unambiguously rejected all other proposed possible sites. This enabled project evaluation and feasibility studies to focus on the single, confirmed resource site.

E-SCAN's major contribution to geothermal exploration is its ability to simultaneously cost-effectively map every resistivity possibility through a given area, regardless of terrain conditions, without requiring assumptions or pre-survey guesses on the part of the explorationist. The Makushin Volcano case history is an illustration of the effective use of this new exploration approach in an integrated multi-method program of exploration, in this case at an advanced stage of exploration.

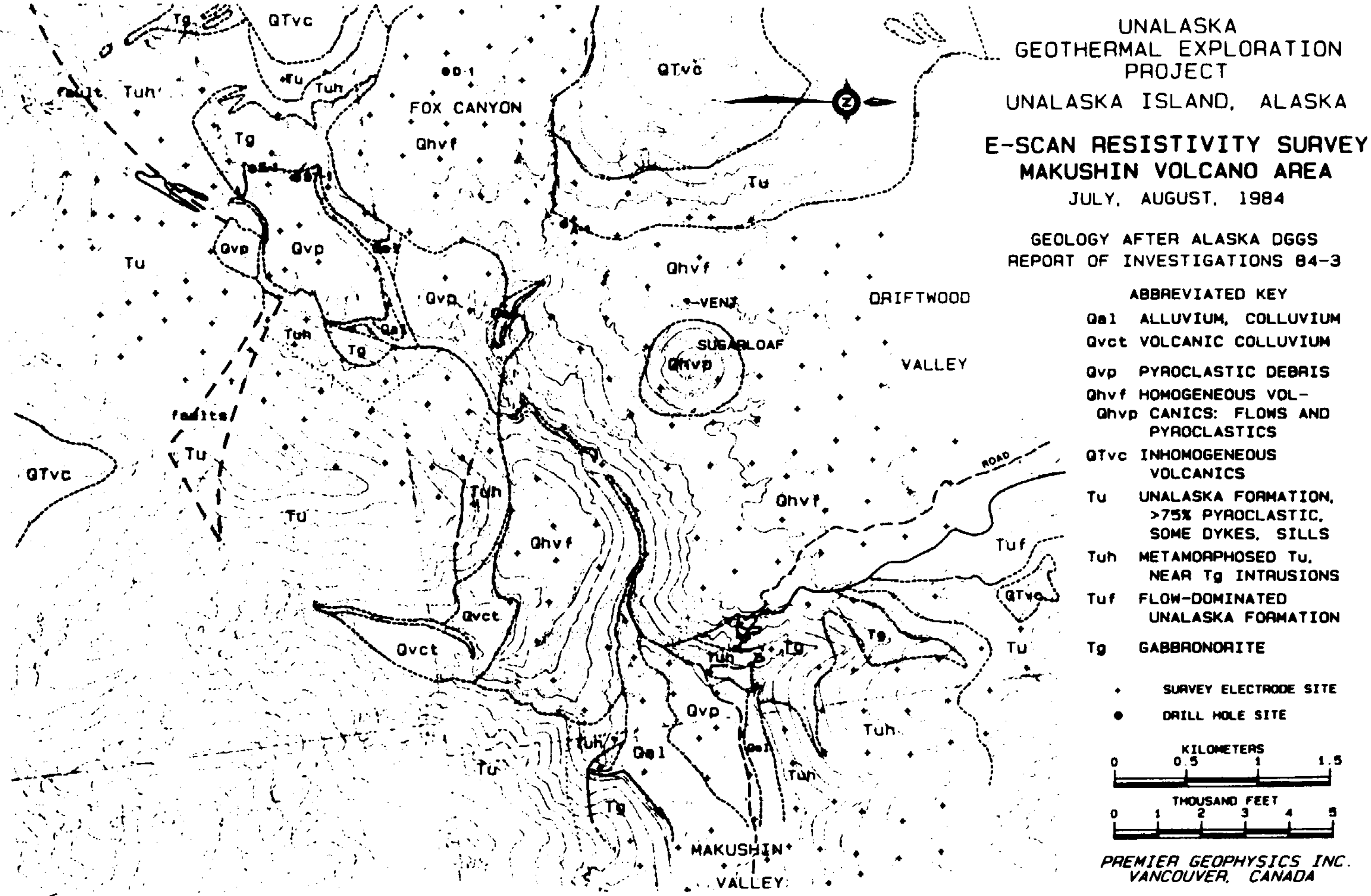


Figure 1 Prior to the E-SCAN resistivity survey, the geothermal resource was known to exist at well site ST-1 (upper left part of the map). The geometry and extent of the resource was unknown. The possibility that the resource extended down the valley to the northeast was of interest, since the cost of access and roadbuilding would be decreased substantially if the resource could be exploited from an area accessible from an existing road.

The survey plan employed a strategy which was not practical before the development of E-SCAN array technology, which is...
"When in doubt, assume nothing and measure everything."
Survey coverage would start with intensive mapping of the known resource area around ST-1, and sweep northeast along the defined area of interest into the Sugarloaf and lower road areas, measuring resistivities in every orientation, to depths of 2000 meters.

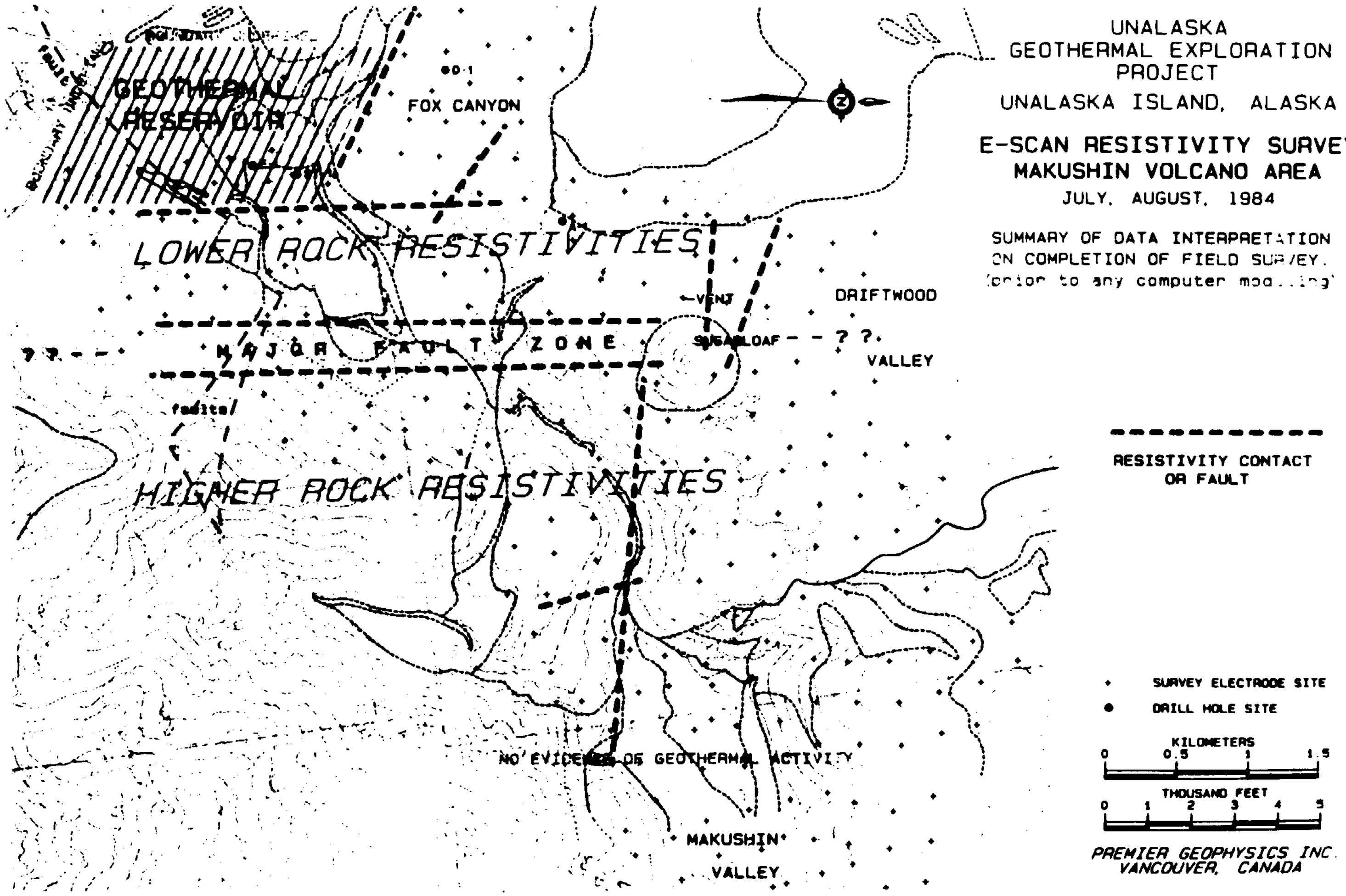
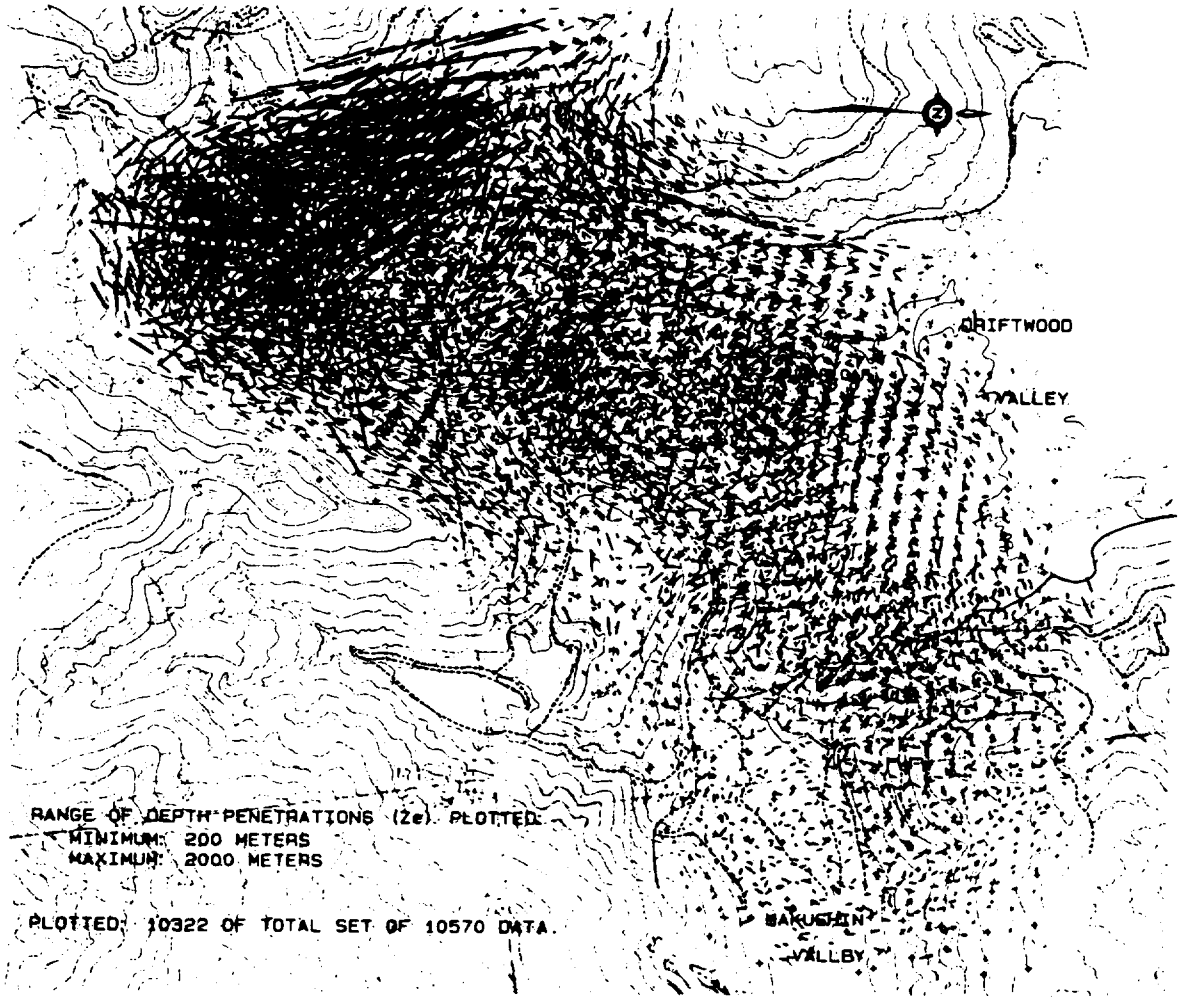


Figure 2 Interpreted results of the 3-D E-SCAN survey, prior to computer modeling of some aspects. The reservoir is sharply bounded by faults on the north and east, within a few hundred meters of producing well ST-1. Based on the resistivity data, there is no evidence of a continuation of the known system or of a separate resource within the 20 square kilometers of survey area northeast of ST-1.



UNALASKA
GEOTHERMAL EXPLORATION
PROJECT
UNALASKA ISLAND, ALASKA

E-SCAN RESISTIVITY SURVEY
MAKUSHIN VOLCANO AREA
JULY, AUGUST, 1984

PLAN PLOT OF POLE-POLE ARRAY APPARENT RESISTIVITY IN OHM-METERS. RANGE OF EFFECTIVE PENETRATION (Ze) IS APPROX: 200 TO 2000 METERS

APPARENT RESISTIVITY
OHM-METERS

< 30
50
70
71
100
150
151
200
300
301
500
700
701
1000
1500
2000
3000

+ SURVEY ELECTRODE SITE
• DRILL HOLE SITE

KILOMETERS
0 0.5 1 1.5

THOUSAND FEET
0 1 2 3 4 5

PREMIER GEOPHYSICS INC.
VANCOUVER, CANADA

Figure 3 This is a summary plot of all 10,322 apparent resistivity measurements comprising the master data set for the area. Each datum is plotted nominally at the mid-point between the two electrode sites (+) from which the measurement originates. The length of the line segment indicates the apparent resistivity value as per the scale at right. In working plots, resistivity value is also indicated by color coding.

The orientation of each line segment indicates the orientation of the measurement. The plot shows that most of the survey area is repeatedly sampled with measurements oriented in different directions. Thus, while achieving a dense sampling across the survey area, a comprehensive testing of resistivity isotropy characteristics is also obtained. Anisotropic conditions may indicate linear features such as fissures, fracture sets, faults, or boundary conditions.

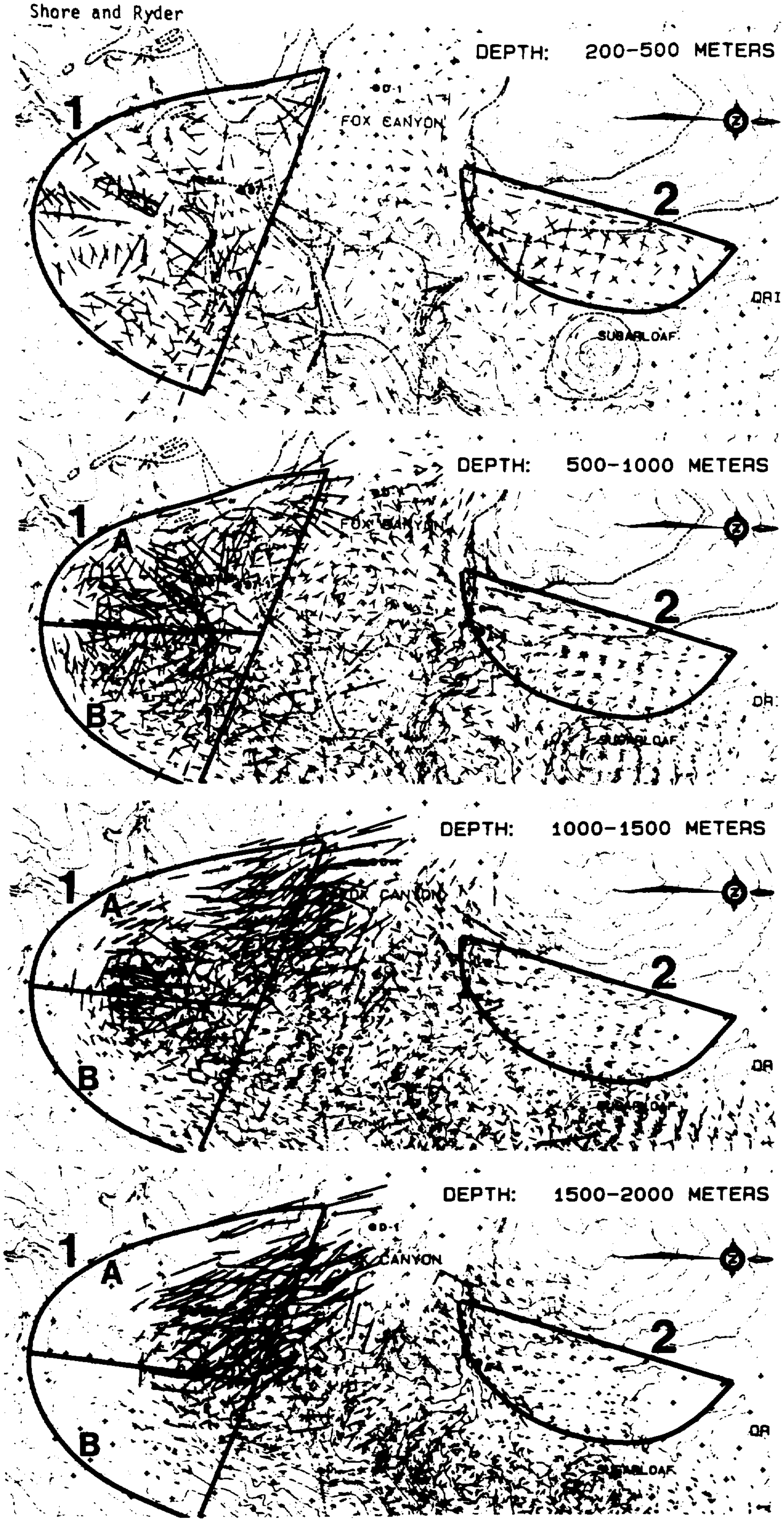


Figure 4 A sequence of progressively deeper horizontal "slices" through the master data set reveals the gross three-dimensional resistivity characteristics of the project area. The working field plots use color coded resistivity values, providing simpler visual grouping of values.

Left,- At shallow depths of investigation, the data show two areas of anomalous low resistivity. The fresh, glassy flow (Fox Canyon past Sugarloaf) is highly resistive.

Deeper, anomaly 1 shows two subzones, A and B. In subzone B more resistive values are becoming apparent.

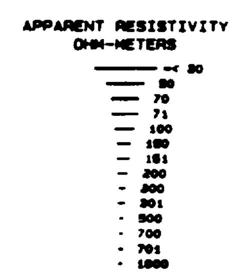
Anomaly 2 is no longer seen. Resistive rocks beneath the shallow conductive zone now prevail.

Deeper Still, Anomaly 1A continues to show low resistivity values.

Anomaly 1B shows only the resistive rock unit underlying the shallower conductive layer.

Anomaly 2 area reports continuing high resistivities at depth.

At 1500-2000 meters depth, anomaly 1A remains strongly conductive. Nominal mid-array plotting positions for data accounts for the anomaly's apparent displacement.



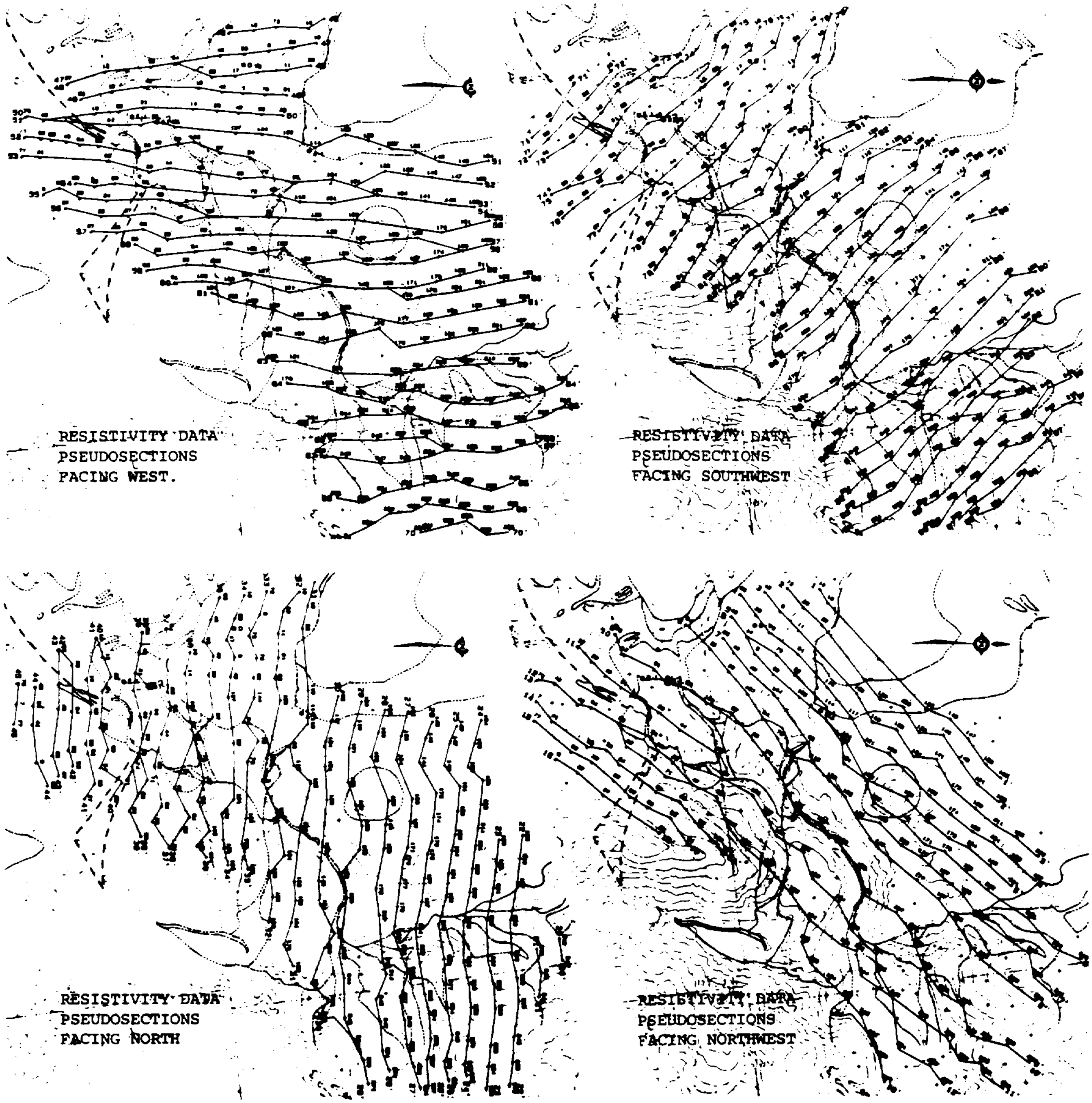


Figure 5 The master data set contains the individual measurements for a wide range of plan and section plots. Above are plan plots showing the locations of four sets of resistivity pseudosections extracted from the master data set. The pseudosections are plotted in sequence, exactly as they would be if a conventional survey system had operated survey traverses along the routes shown above. The reader is reminded that virtually all of the "traverse" locations shown above could not be physically traversed by a survey crew. The E-SCAN pseudosections of data are available because once the electrodes were installed, all of the "traversing" was accomplished by electronic signals over the scanning network. As a result, features of interest anywhere on the property can be examined in detail, calling on plan and pseudosection data plots which slice through the area of interest from every orientation and depth. Interpretations suggested by data from one pseudosection are checked against data plots of other orientations.

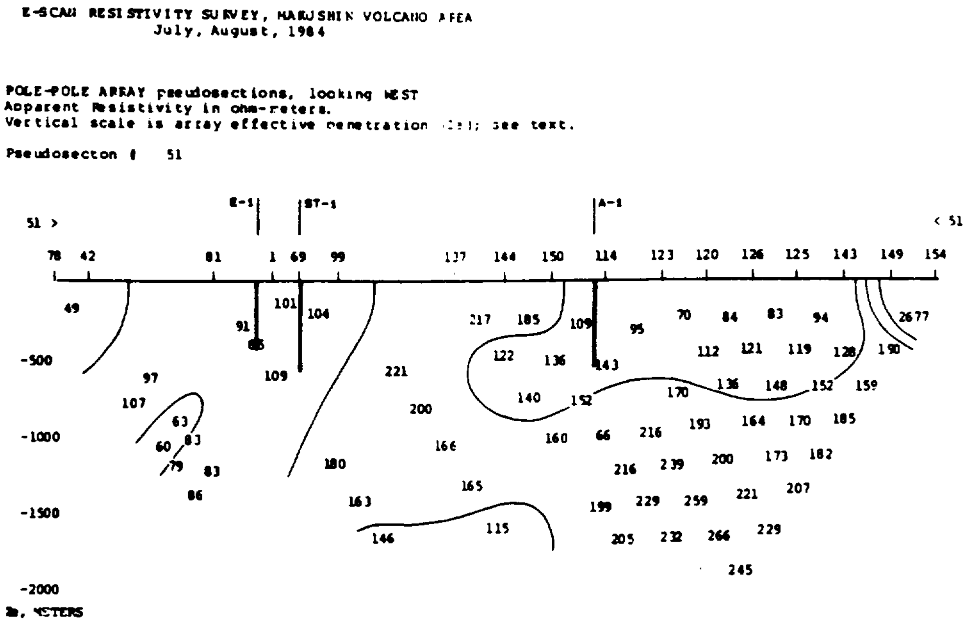


Figure 6 This is one of the pseudosections shown in the location plots of Figure 5. It passes through three wells, E-1 and ST-1 within the identified reservoir area, and A-1 southwest of Sugarloaf. Some of the characteristics illustrated in Figure 4 plots can be seen in the pseudosection above. At left, the deep, low resistivities of Anomaly 1A are identified in section. At right, the data show the shallow conductive zone measurements of the area west of Sugarloaf (Anomaly 2), which yield to more resistive values in the underlying rock (as in Figure 4).

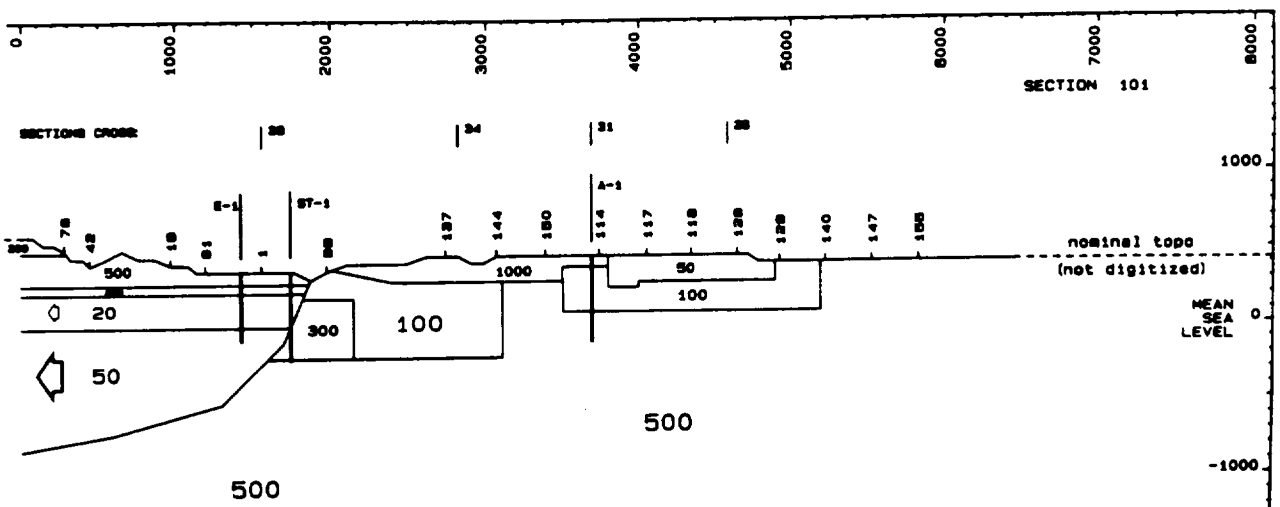


Figure 7 This is one of many two-dimensional sections through a common three-dimensional model which describes a wedge-shaped reservoir connected to extensive low resistivity conditions (reservoir) off the section to the left.

Well ST-1 achieves production from open fractures near the bottom of the well; the rock above is tight and impermeable. The sloping fault mapped by 3-D resistivity as the lower boundary of the reservoir may be the conduit supplying hot fluids from the extended low resistivity zone off the section to the left.

If this is the case, then additional production might be achieved by deepening well E-1 to intersect the fault plane.

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E-SCAN LINEAR traverse mapping.

The following 3-page promotional material describes E-SCAN in its LINEAR traverse mode, which is typically used for broad area coverage, looking for "elephants" through deep or pervasive cover. 3-D E-SCAN can be considered as a block of data through which any pseudosection in any position or orientation will look like the LINEAR pseudosection shown.

Following is a page with three adjacent pseudosections, shot at 500 foot grid spacing, with a NDIC maximum of about 3500 feet. This is part of a real case history to be published in 1991. E-SCAN maps numerous complete 3-part epithermal systems consisting of deep heat-driving source (intrusive), plumbing 2-D features, and mushrooming silicic upper levels. The raw pseudosection images correspond with the shape of the theoretical geologic model of the preceding pages, as one would expect for a resistive-in-conductive model. Like the suggested theoretical material, this Imperial Valley case involved deep cover, and also quite confusing drill geology in the upper 700 feet. Prior to E-SCAN, there was no suggestion of the presence of an in-situ hydrothermal source for the mineralization; in fact the suggestion was that the ore-bearing lithology had been rafted into place (gravels underlay the gabbro unit).

The E-SCAN data show that, regardless at least four phases of local, upper-1000' deformation and "jumbling", in both drilled cases the ore mineralization is of hydrothermal origin, and remains positioned directly above the hydrothermal system that flooded the rocks 14 million years previously.

There are also a few plots that show the array components available in a LINEAR E-SCAN traverse such as could be used to anchor any deep transect. Not all data need be acquired, but all data CAN be acquired in a single pass. For example, a 20 km geothermal traverse done for the Geological Survey of Canada measured the pole-dipole and pole-pole array components at an electrode spacing of 1000 feet, with NDIC from 500' to 8500 feet, providing adequate resolution at low cost.

Figure 1 EPITHERMAL GOLD EXPLORATION

DETECTION OF LARGE-SCALE EPITHERMAL SYSTEMS BENEATH VOLCANIC OR ALLUVIAL COVER.

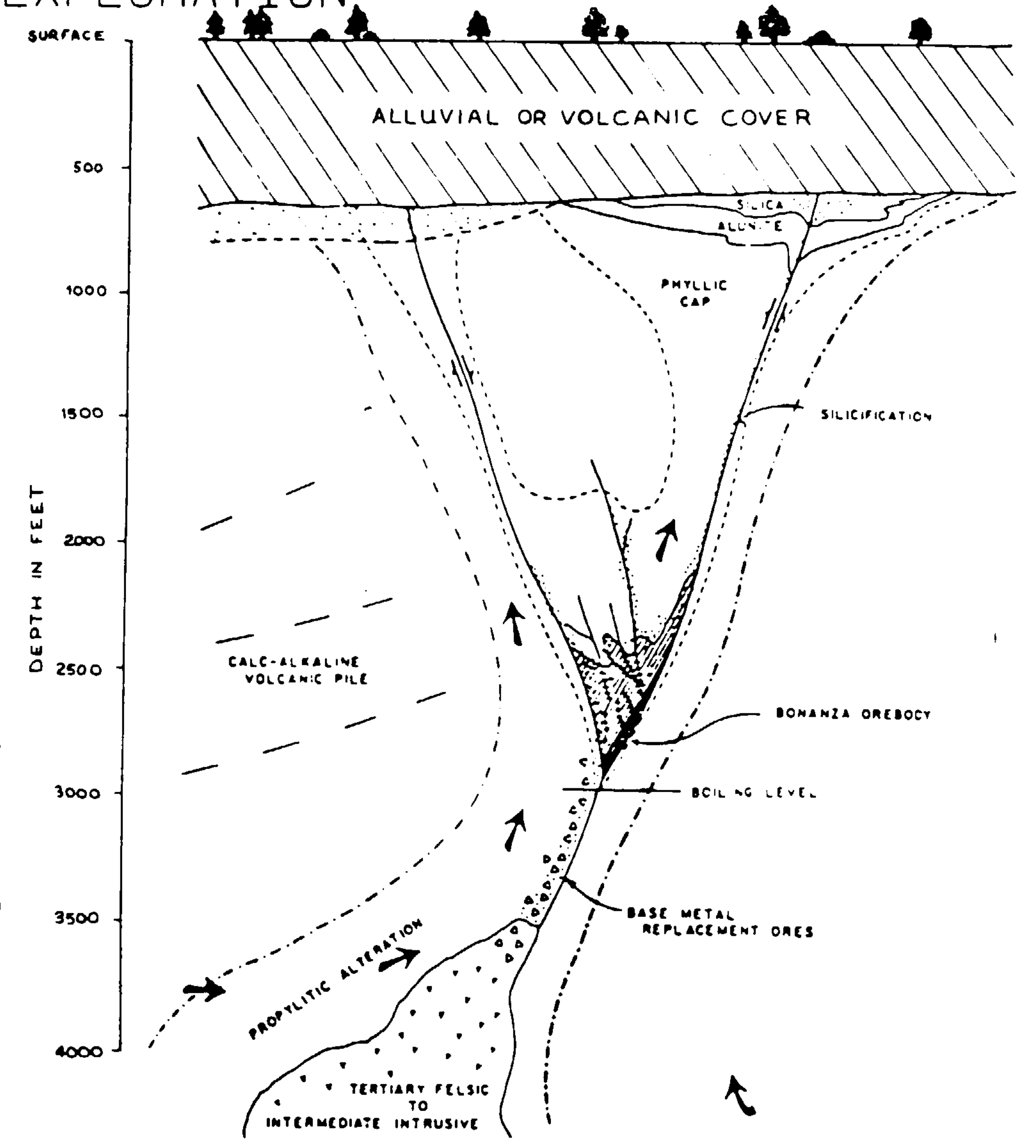
E-SCAN MAPPING POWER OPENS UP THOUSANDS OF SQUARE MILES OF PEDIMENT AND VOLCANIC-COVER PLAYS TO FIRST-TIME, HIGH RESOLUTION 3-D DIRECT IMAGING OF EPITHERMAL BODIES.

E-SCAN's intensive resistivity mapping is proving to be highly successful in mapping epithermal gold deposits in sedimentary and permeable-volcanic terrain. In case after case it is the resistivity signatures that are consistently definitive, while induced polarization responses are hit-and-miss, sometimes blurred or non-existent. E-SCAN continues to measure both IP and resistivity, but if your system does not have the resolving power of E-SCAN's 3-D multidirectional data set, then the subtleties of resistivity signatures that have given E-SCAN an almost 100% drill success rate will not be available to you.

Unlike conventional dipole surveys, E-SCAN measures at every important level simultaneously:

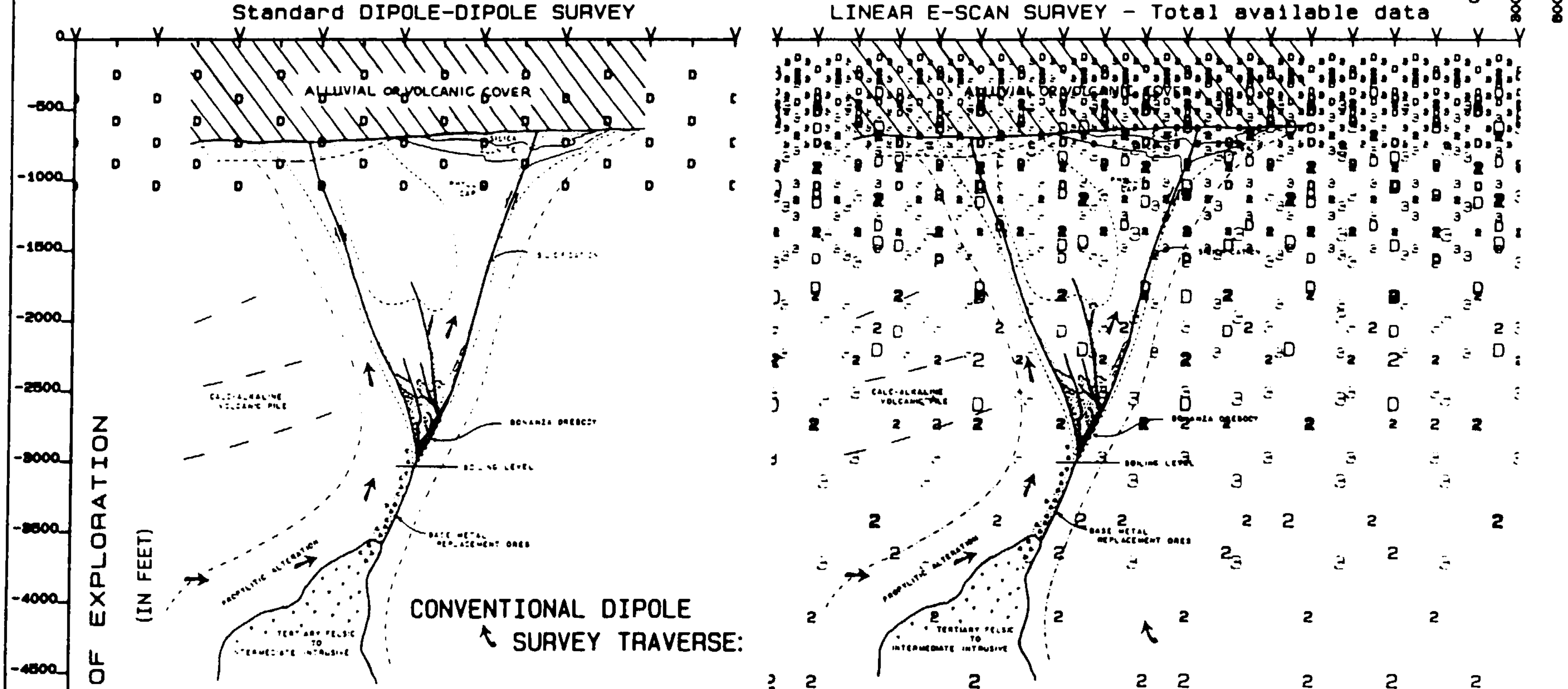
1. at the shallow depths where you hope your ore zone is, but where cover depth may vary considerably and unexpectedly,
2. at the mid-range depths where you will accept a richer disseminated ore zone under a few hundred feet of cover, or a highgrade bonanza structure, and,
3. at the super-deep levels where high resolution of underlying structures provides the key discrimination between near-surface resistive flows or gravels, and near-surface silicification and mineralization (not to mention identification of deep breccia pipes, basement fault intersections and other mineralization controls which may themselves be targets for bonanza mineralization).

The following plots show E-SCAN in a single pseudosection form, to compare with dipole-dipole survey results coverage. Keep in mind that multidirectional E-SCAN provides pseudosections in four different orientations across your property, as well as 8 to 15 contoured plan view slices through the E-SCAN results, from near surface to thousands of feet down.



SCHEMATIC CROSS SECTION, BONANZA LODE GOLD DEPOSITS (Modified after Buchanan 1981 Randall 1980.)

Figure 2 CONVENTIONAL DIPOLE SURVEY DATA compared to E-SCAN ALL-DEPTH DATA SET



A conventional dipole survey gets a bite of the target but may have difficulty recognizing its significance with such minimal data, especially in the presence of near-surface features like dry lakebeds, etc.

STANDARD LINEAR E-SCAN TRAVERSE:

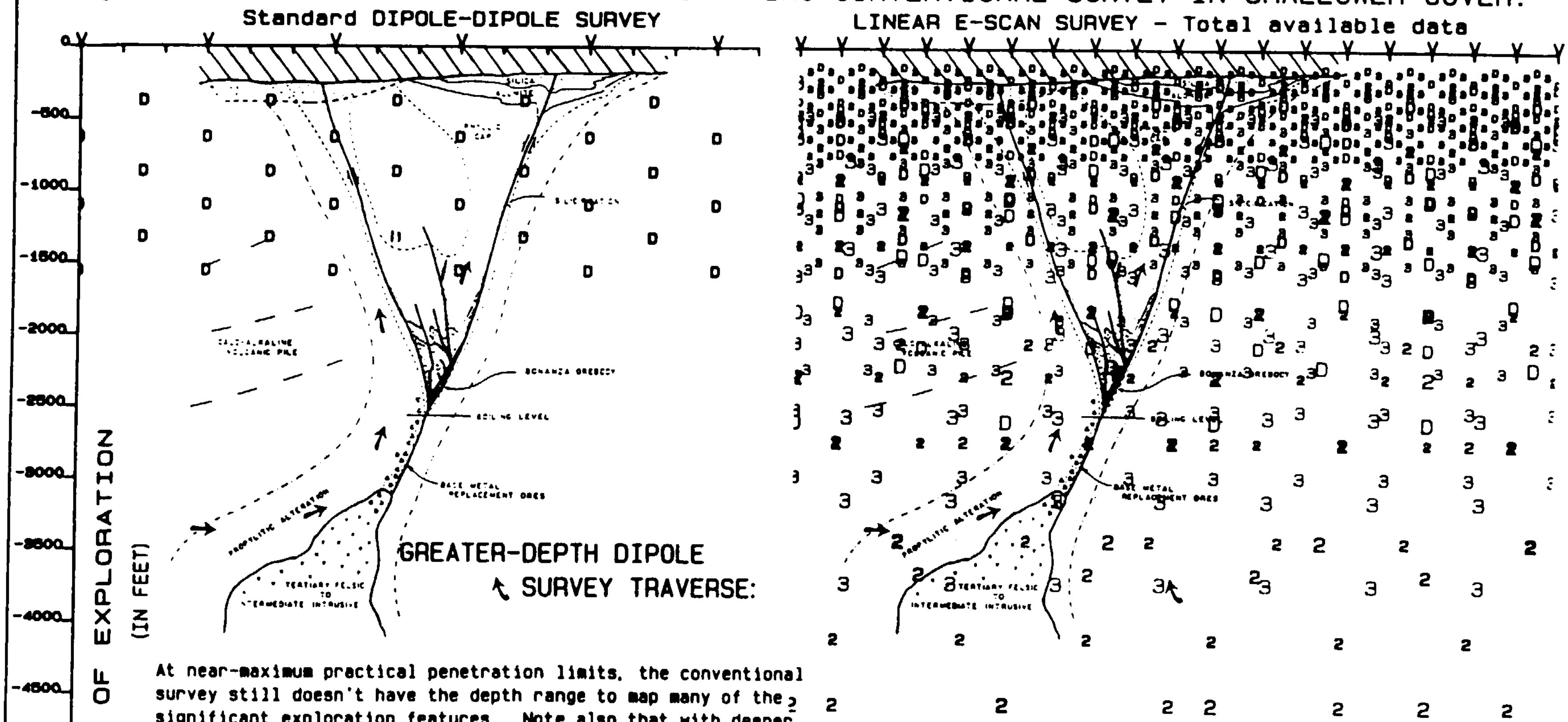
Note the dense data coverage through all significant exploration zones. The depth of cover is mapped. The width of the hydrothermal system, its wedge shape at depth, and its main fault structures can all be evaluated from the single-pass E-SCAN data set. 3-D E-SCAN mapping would be applied immediately to any reconnaissance anomaly suggesting the above features.

-5000 -5500 -6000 -6500 -7000

POINTS PLOTTED AT EFFECTIVE PENETRATION (Ze) FOR ALL ARRAY TYPES. (EDWARDS, GEOPHYSICS, VOL 42, NO 5)

D - DIPOLE-DIPOLE PLOTTED POINT, N = 1 TO 6
3 - POLE-DIPOLE PLOTTED POINT, SIX EXPANSIONS
2 - POLE-POLE PLOTTED POINT, SIX EXPANSIONS

Figure 3 WHAT ABOUT A DEEPER PENETRATING CONVENTIONAL SURVEY IN SHALLOWER COVER?



At near-maximum practical penetration limits, the conventional survey still doesn't have the depth range to map many of the significant exploration features. Note also that with deeper conventional arrays, the data density (resolution) decreases. Costs and operational complexity also increase substantially. *QUESTION: Why try to GUESS IN ADVANCE how deep the cover is, or at what level the (erosional remnant) hydrothermal system sits?* E-SCAN maps every possibility, every time, eliminating guesswork.

STANDARD LINEAR E-SCAN TRAVERSE:

Note the dense data coverage through all significant exploration zones. The depth of cover is mapped. The width of the hydrothermal system, its wedge shape at depth, and its main fault structures can all be evaluated from the single-pass E-SCAN data set. 3-D E-SCAN mapping would be applied immediately to any reconnaissance anomaly suggesting the above features.

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2 - POLE-POLE PLOTTED POINT, SIX EXPANSIONS

(Next Page)

E-SCAN apparent resistivity image of a fossil epithermal hydrothermal system: 1990 results.

Edwards type pseudosection; 500 foot electrode spacing.

The classic three-part signature of an epithermal mineralization system is illustrated in these unfiltered, raw data pseudosections from the Imperial Valley, California. The deep, resistive signature (grey-purple) of an intrusive body lies about 2000 feet below surface. Permeable conduits are images as resistive streams leading upward from the intrusive. As the hydrothermal fluids reached the upper 1000 feet, they began to flow outward in permeable rocks, forming the characteristic resistive mushroom caps of the systems. This is a low-sulphur system, meaning that most of the alteration is silicic, and therefore resistive.

Two gold deposits, the Indian Rose and Ocatillo orebodies lie in the caps of the two systems that have been drilled. No drilling has yet taken place on the other systems, or into the deeper plumbing where bonanza mineralization could characteristically occur.

No evidence of the epithermal systems, the intrusive, or the location of the faults which have served as conduits (the stems of the mushrooms) is available from the upper 700 feet of drill geology. This is a case where the development of a large scale E-SCAN resistivity image, working from the depths upward, has permitted recognition of potentially economically interesting geologic processes, and identified the morphology and geometry of the controlling features. E-SCAN's highly resolving, noise averaged data set can directly image resistive features that are an order of magnitude too weak to see in conventional traverse resistivity results.

In the Yucca Mountain area, evidence of hydrothermal systems as resistive or conductive mushroom, or other shaped features, would signal three things of potential interest:

1. possible economic potential.
2. presence of a structure which once conducted fluids vertically.
3. by deduction, probable presence of a deep thermal feature, possibly cooled down, possibly still hot.

Failure to image a similar response in the Yucca Mountain area would stand as positive evidence of the absence of a historical presence of items 1. and 2., above, eliminating the rationale for the deductive conclusion 3.

The absence of such a feature in a single conventional survey traverse or a series of parallel lines is questionable evidence, since a catalog of response levels, orientations and depth characteristics could be present and not recognized or simply not specifically tested for by the surveys applied. The intensity and universality of sampling of a full E-SCAN survey lends credibility to a negative investigation result: a uniformly multidirectional and multidepth range of possibilities will have been exhaustively sampled and tested for with demonstrably high resolving power.

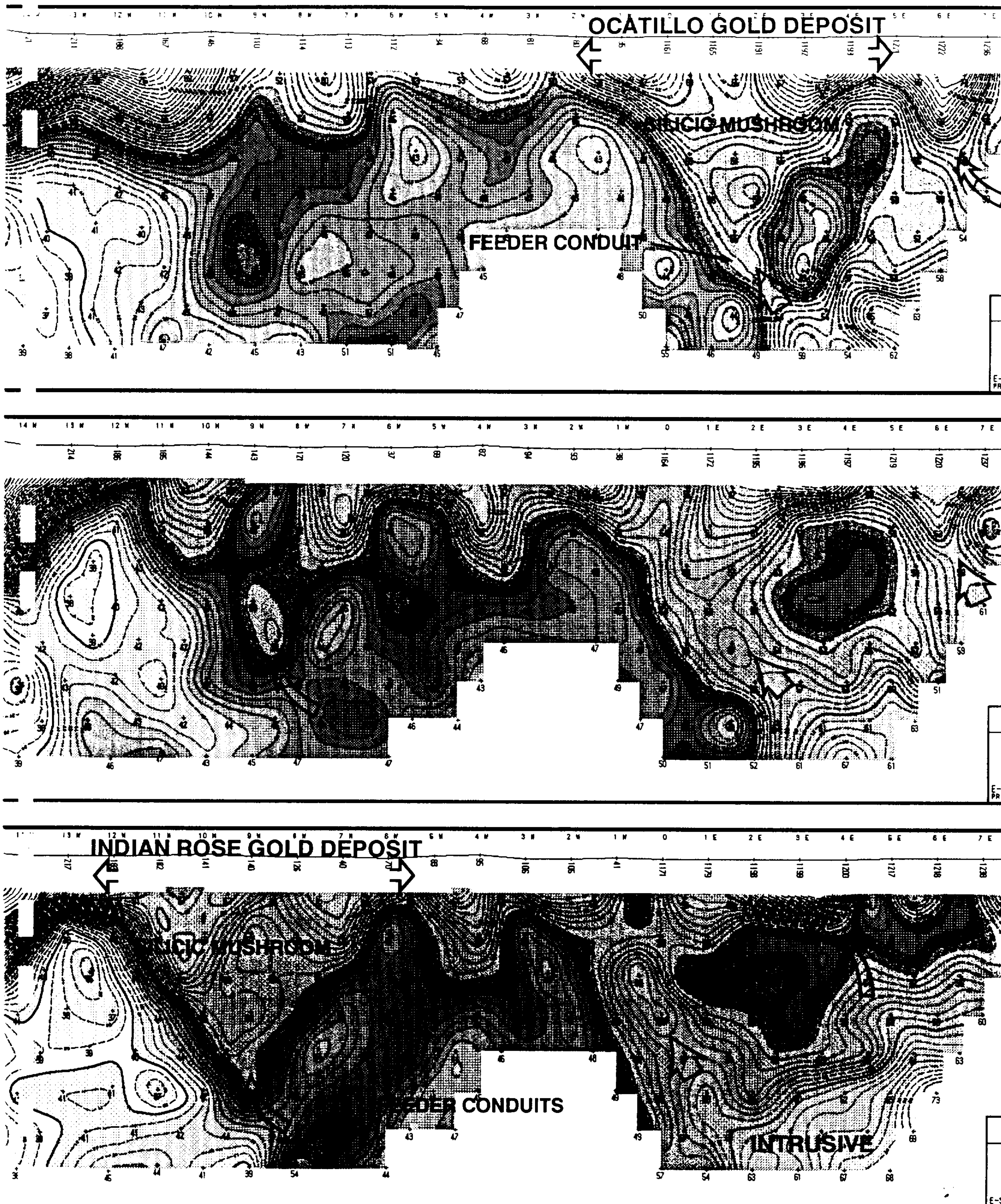
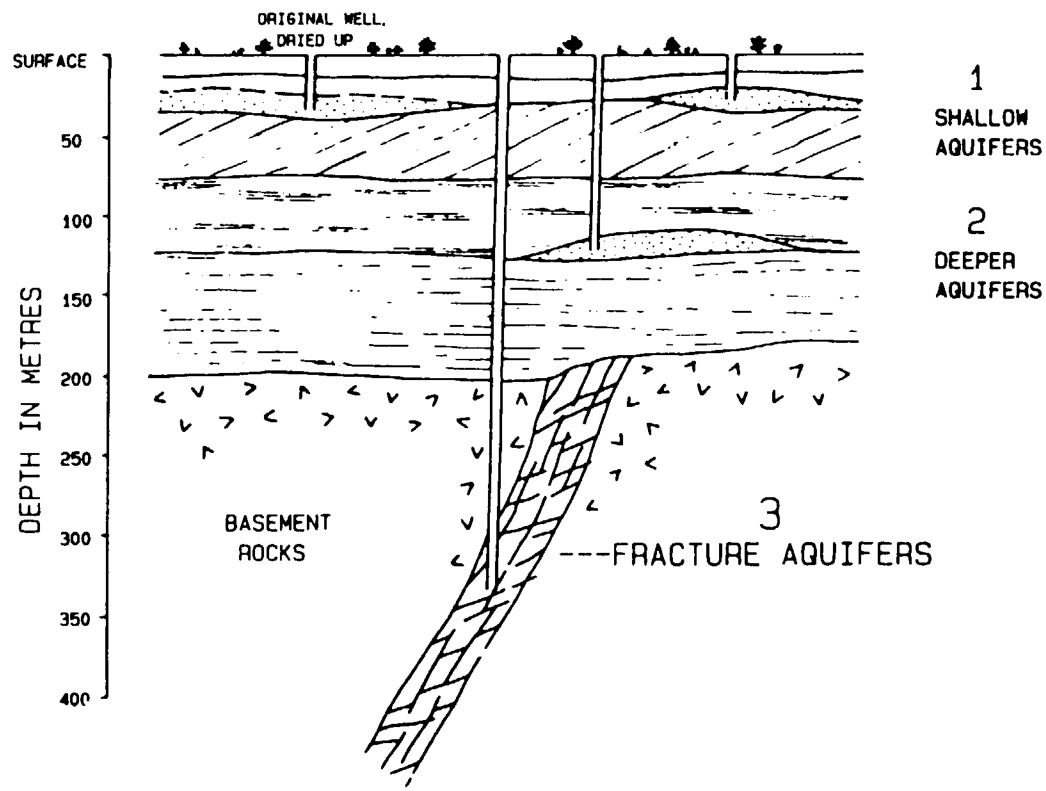

OCATILLO GOLD DEPOSIT
SILICIC MUSHROOM
FEEDER CONDUIT
INDIAN ROSE GOLD DEPOSIT
INTRUSIVE

Figure 1   SEARCHING FOR WATER RESOURCES: THREE AQUIFER POSSIBILITIES

AQUIFERS AT SHALLOW DEPTHS represent the lowest cost and fastest resource development, when they can be found.

DEEPER AQUIFERS cost more to tap. If shallower aquifers are not found, the cost of deeper resources may be justified by local need. Deeper aquifers tend to be less sensitive than shallow aquifers to drought-induced fluctuations in the water table, and may represent a better long-term solution.

BASEMENT FRACTURE AQUIFERS are a more costly alternative that may be exploited in the absence of shallower, flat-lying aquifers. Fracture aquifers can be very stable (drought-resistant), since they often draw on very large fault/fracture feeder networks reaching tens to hundreds of kilometres away, into higher-rainfall mountain areas, for example.



NEW CANADIAN EXPLORATION TECHNOLOGY is expected to provide a tenfold improvement in regional groundwater exploration effectiveness, and to reduce overall well drilling costs.

The E-SCAN resource mapping system can provide simultaneous testing for all three aquifer types shown schematically above, at the same cost as the single-depth dipole traverses or Schlumberger array profiles now in common use.

If the favoured shallow, low-cost resources are not detected, project managers can assess the next-best aquifer possibilities from the existing E-SCAN all-depths data set, eliminating the need to commission a complete new survey to test deeper levels.

E-SCAN's unprecedented mapping capabilities translate into fewer dry holes and substantially better prospects for resource discovery, for each program dollar expended.

Figure 2 CONVENTIONAL 'SHALLOW' SURVEY DATA compared to E-SCAN ALL-DEPTH DATA

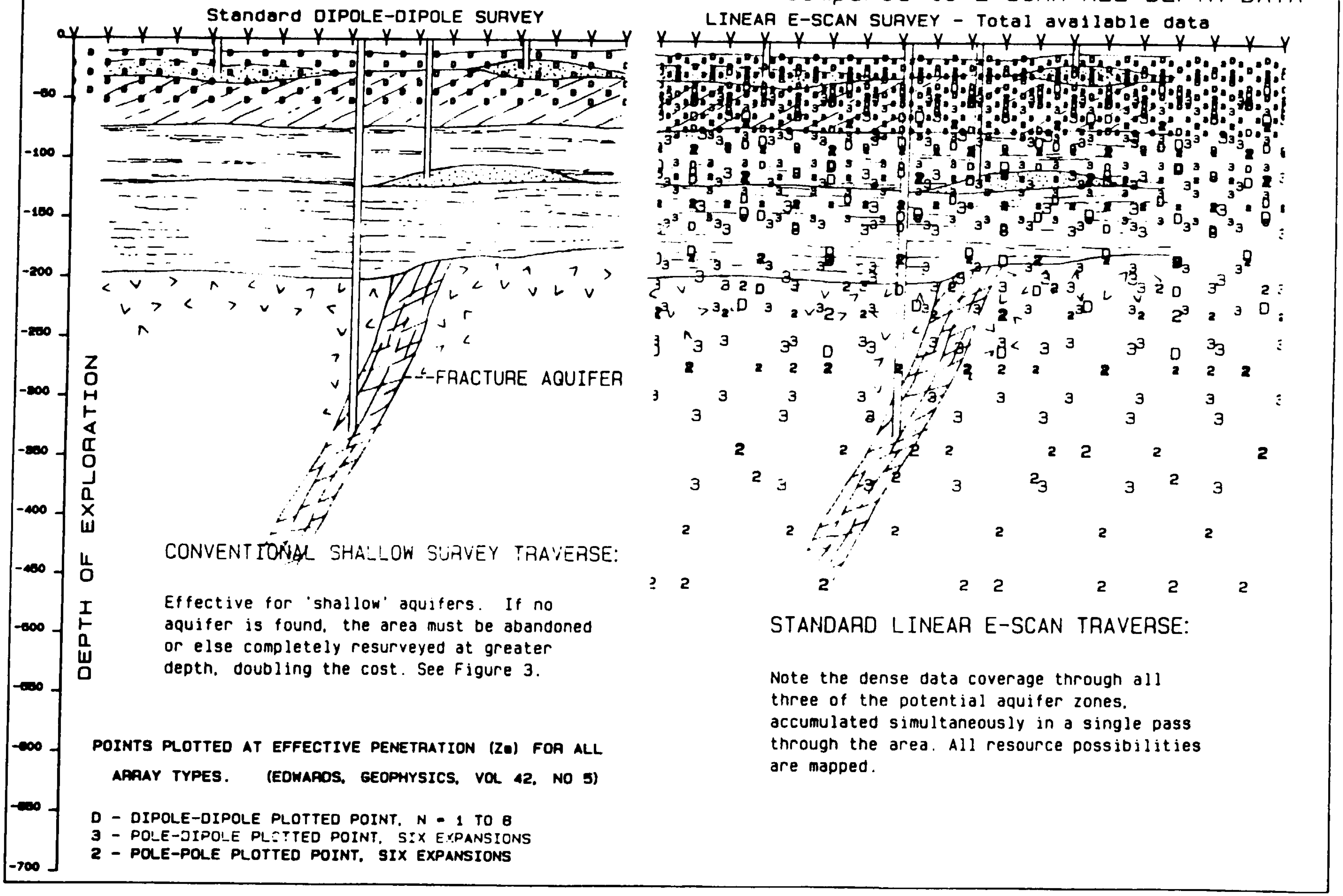
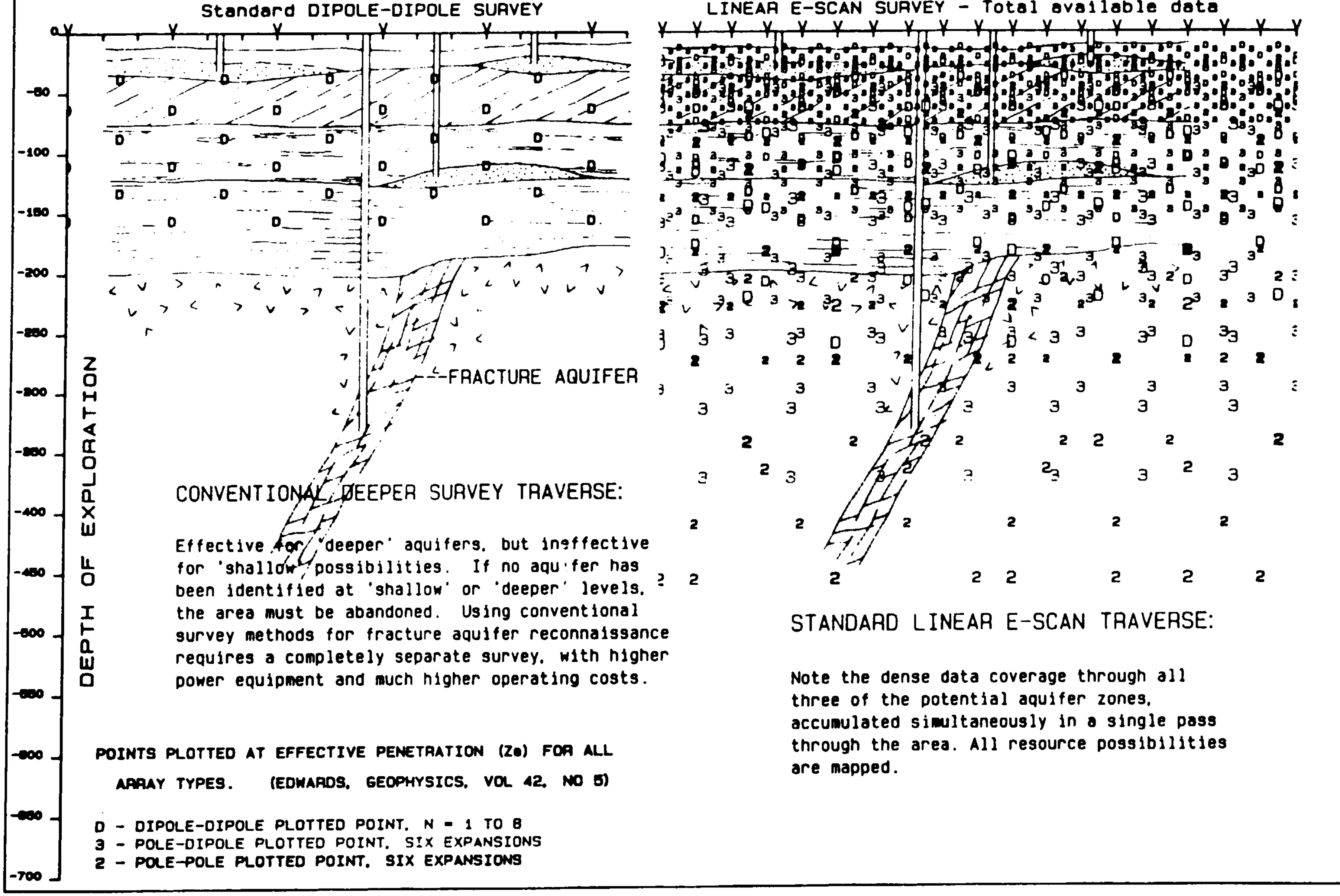


Figure 3 CONVENTIONAL 'DEEPER' SURVEY DATA compared to E-SCAN ALL-DEPTH DATA

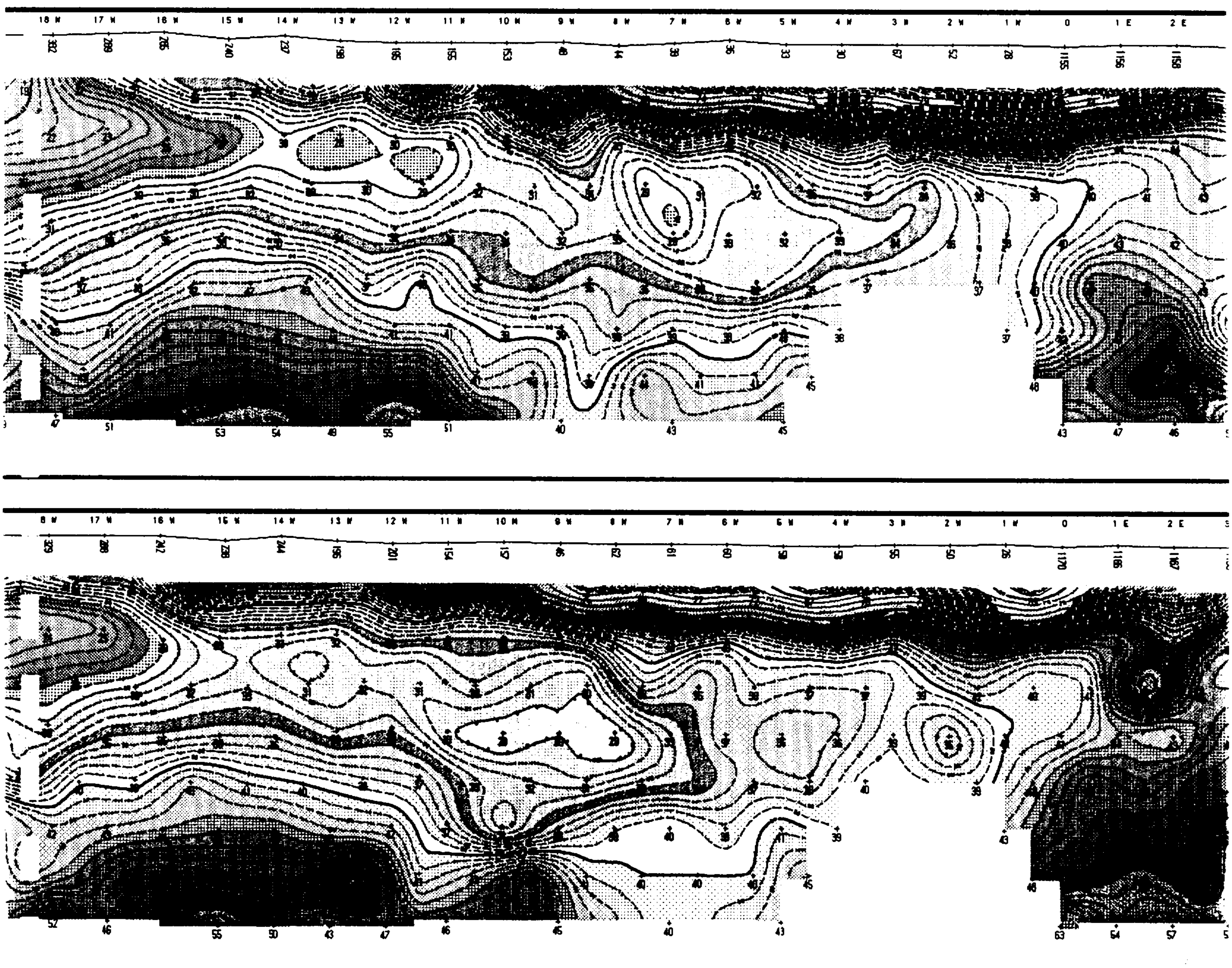


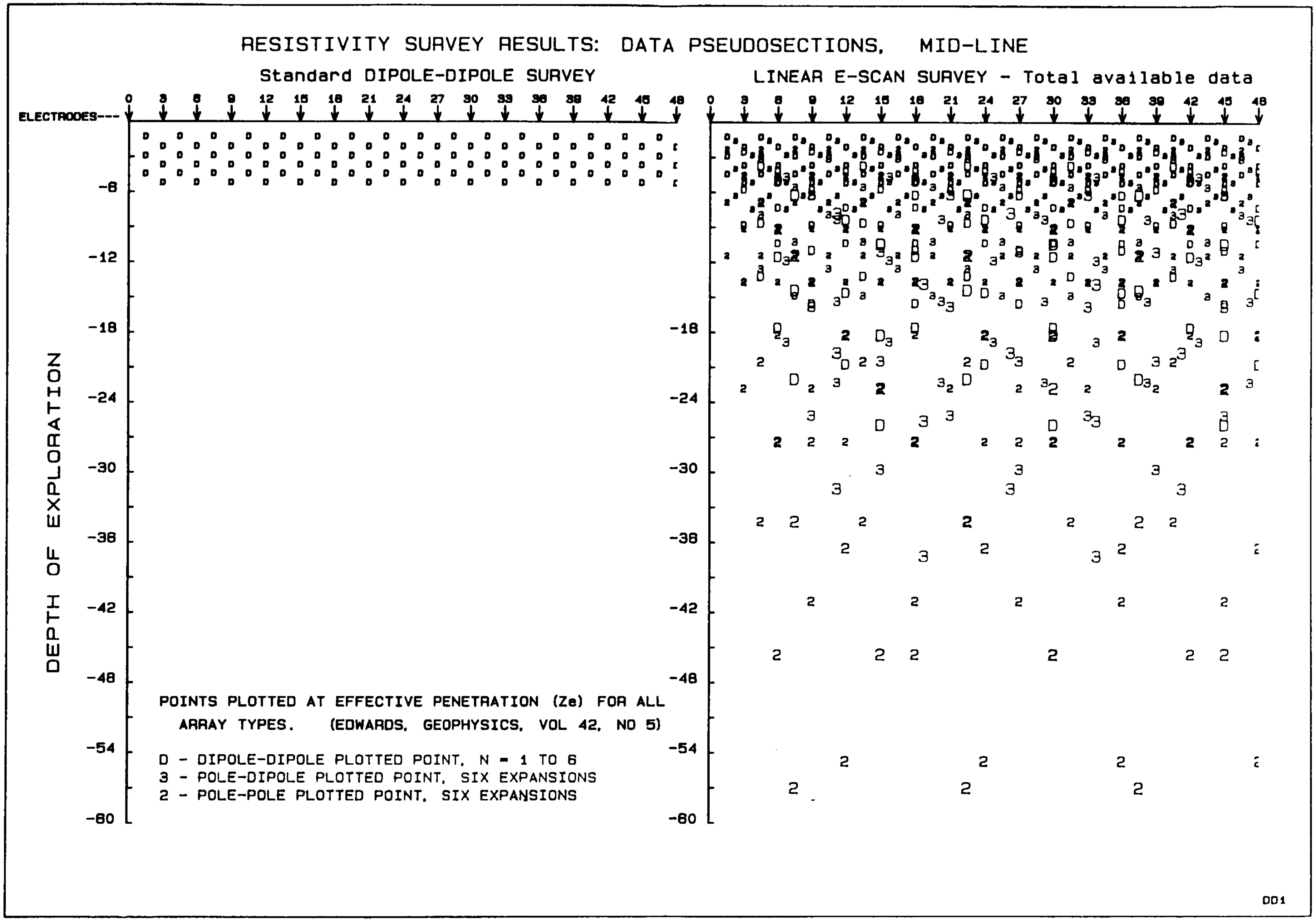
E-SCAN apparent resistivity image of an aquifer.
Edwards type pseudosection; 500 foot electrode spacing.

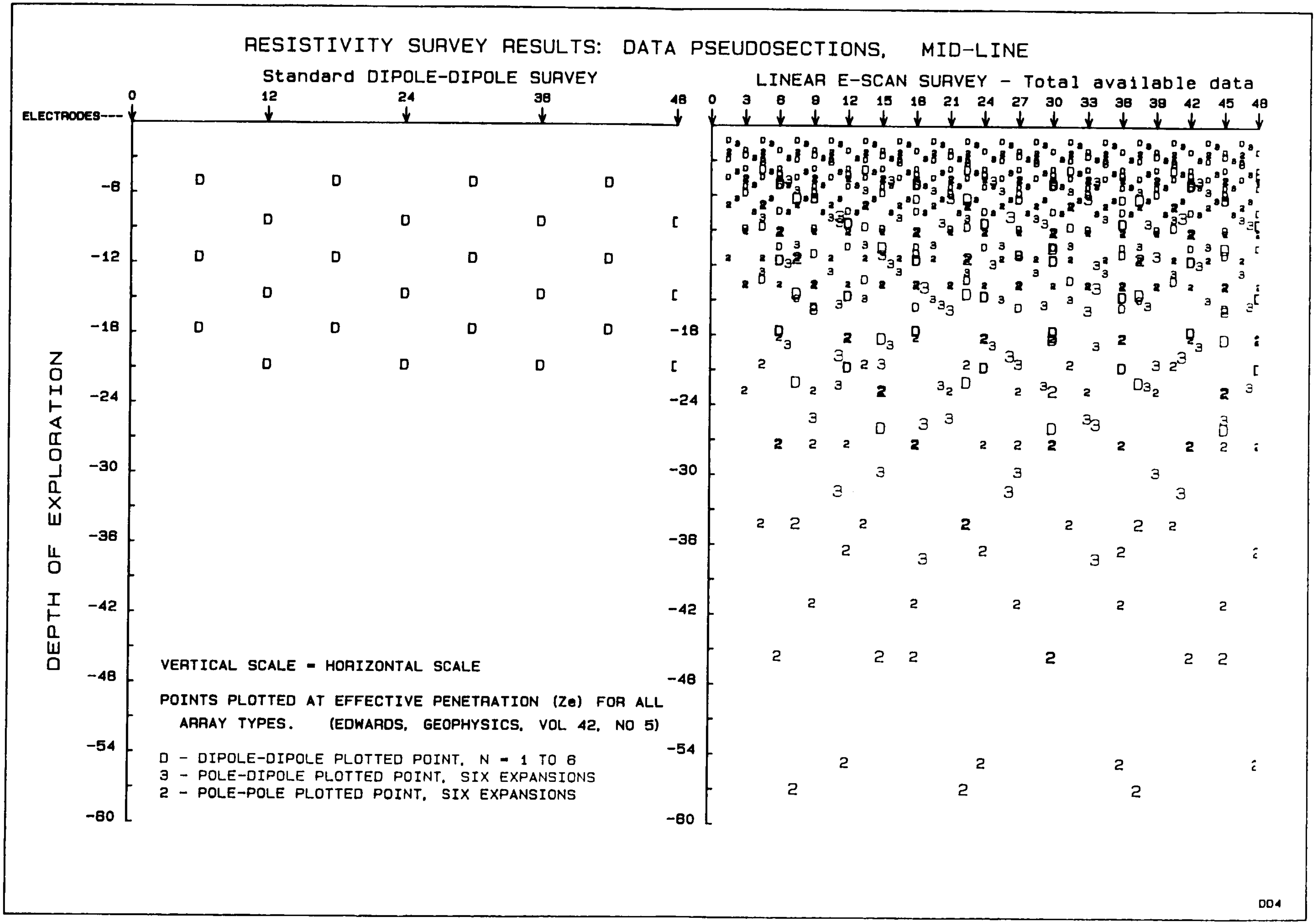
The conductive response area (25-35 ohm-meters, blue and green) is caused by a fresh water aquifer lying between 750' and 2000' beneath the surface. The thin purple-grey material to the right is resistive, silicic hydrothermal alteration. Resistive basement rocks underlying the aquifer unit (orange, pink) are estimated at about 2500 feet below surface.

Drilling at Yucca Mountain has established the level of the water table, information that will help in calibrating and understanding the changes in E-SCAN resistivity response through the water table transition area. Lateral variation in water table level may be mappable from the E-SCAN data.

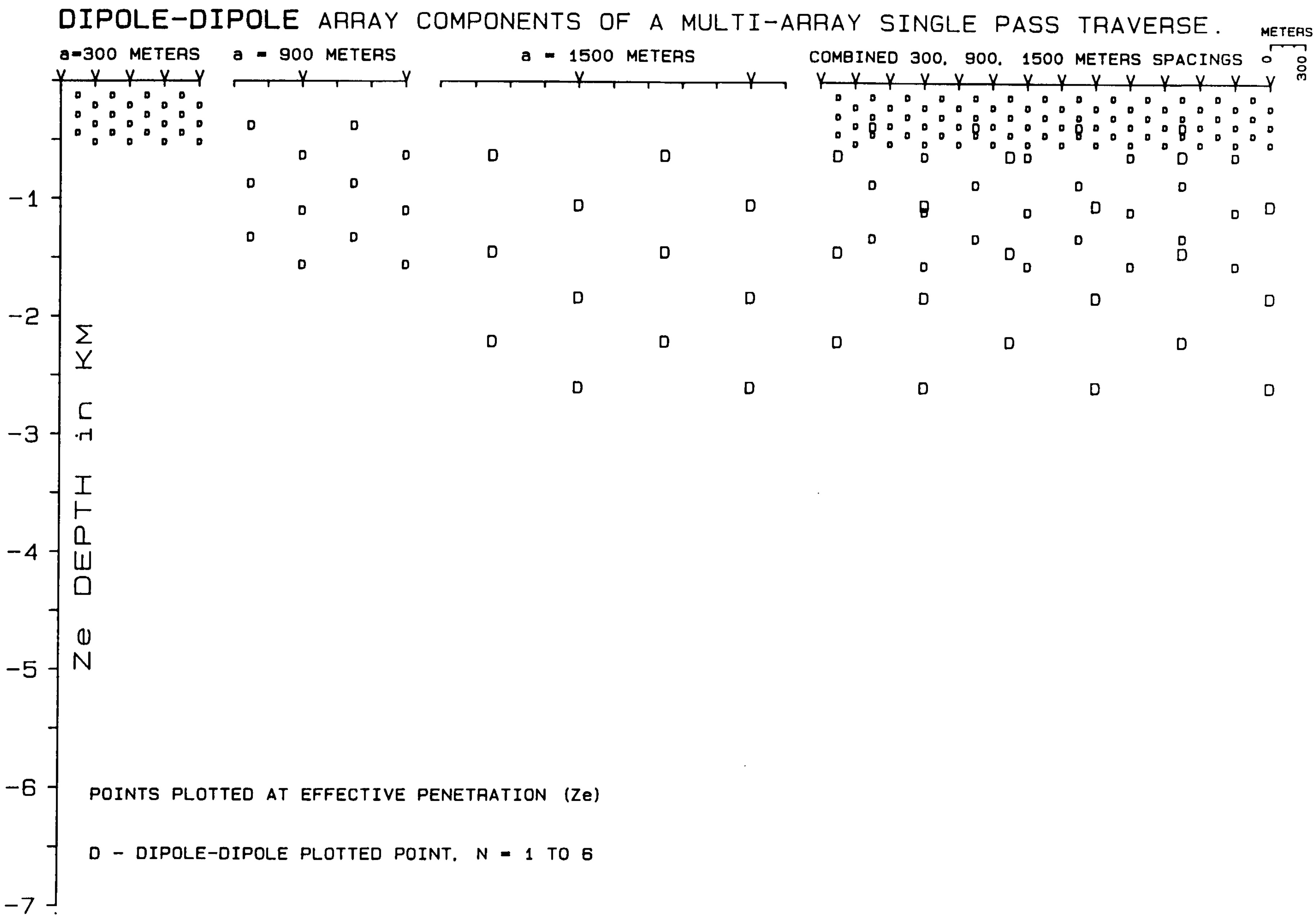
F7



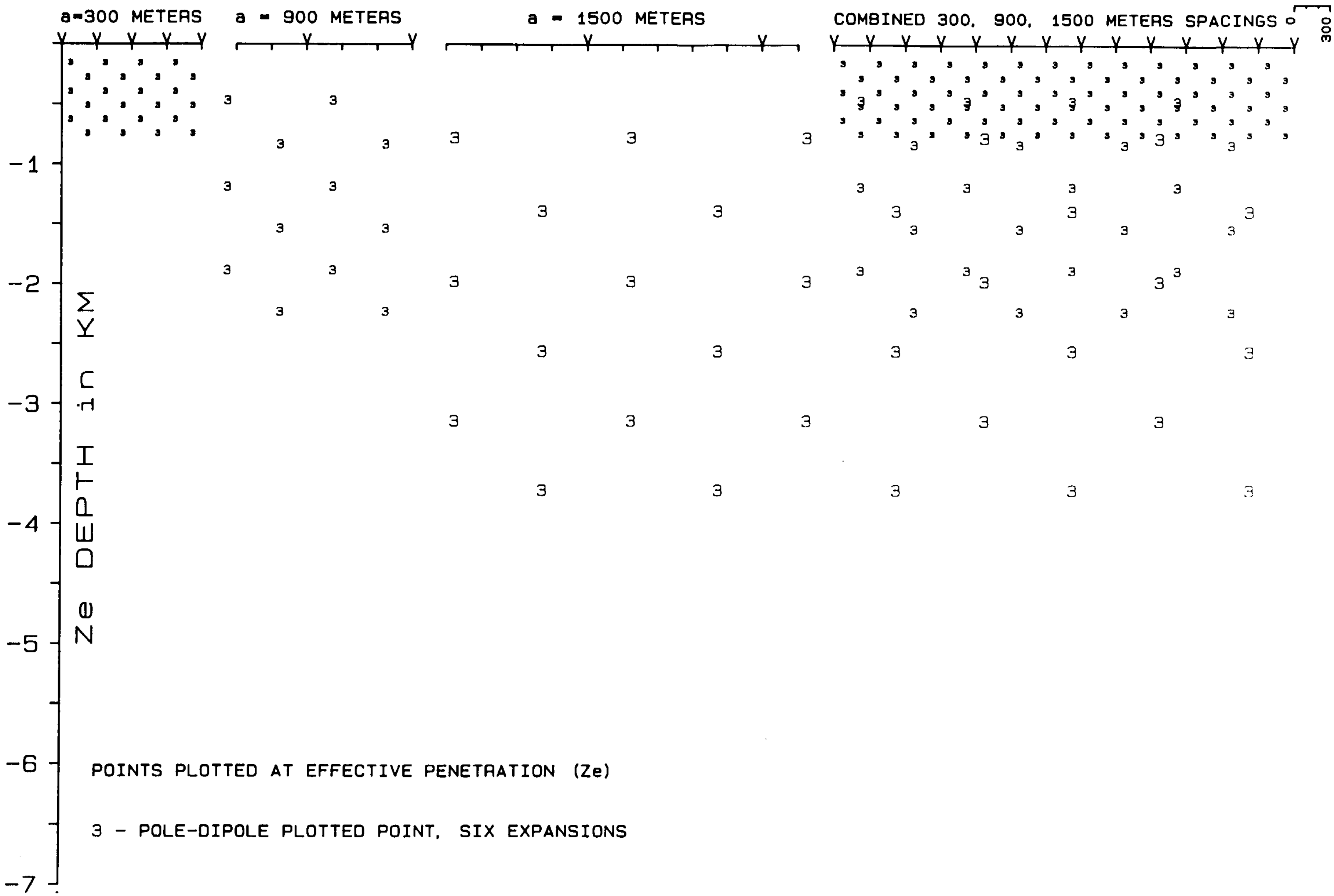

RESISTIVITY SURVEY RESULTS: DATA PSEUDOSECTIONS, MID-LINE
Standard DIPOLE-DIPOLE SURVEY
LINEAR E-SCAN SURVEY - Total available data
ELECTRODES---
DEPTH OF EXPLORATION
POINTS PLOTTED AT EFFECTIVE PENETRATION (Ze) FOR ALL ARRAY TYPES. (EDWARDS, GEOPHYSICS, VOL 42, NO 5)
D - DIPOLE-DIPOLE PLOTTED POINT, N = 1 TO 6
3 - POLE-DIPOLE PLOTTED POINT, SIX EXPANSIONS
2 - POLE-POLE PLOTTED POINT, SIX EXPANSIONS
DD1

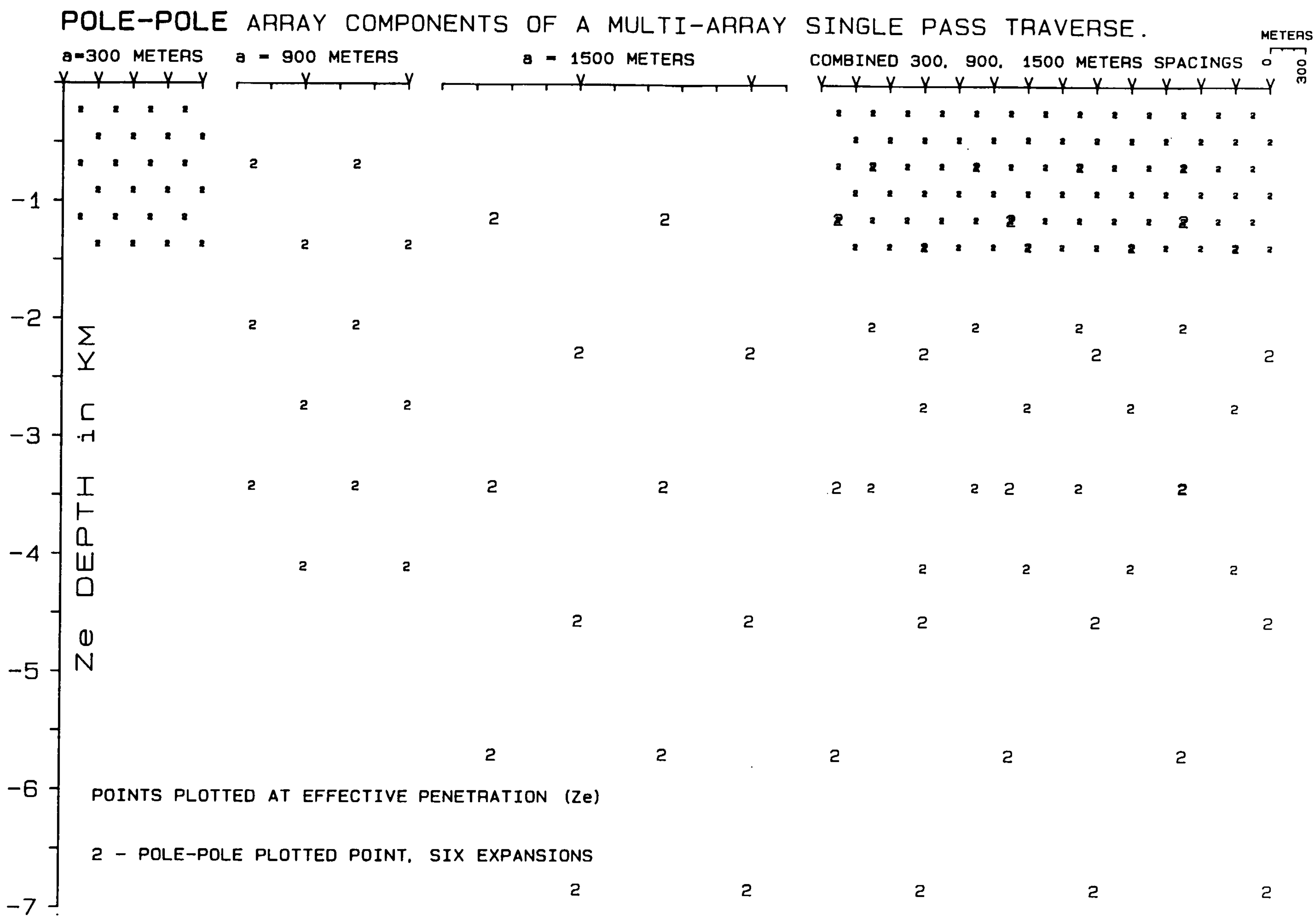


RESISTIVITY SURVEY RESULTS: DATA PSEUDOSECTIONS, MID-LINE
Standard DIPOLE-DIPOLE SURVEY
LINEAR E-SCAN SURVEY - Total available data
ELECTRODES---
DEPTH OF EXPLORATION
VERTICAL SCALE = HORIZONTAL SCALE
POINTS PLOTTED AT EFFECTIVE PENETRATION (Ze) FOR ALL ARRAY TYPES. (EDWARDS, GEOPHYSICS, VOL 42, NO 5)
D - DIPOLE-DIPOLE PLOTTED POINT, N = 1 TO 6
3 - POLE-DIPOLE PLOTTED POINT, SIX EXPANSIONS
2 - POLE-POLE PLOTTED POINT, SIX EXPANSIONS
DD4


DIPOLE-DIPOLE ARRAY COMPONENTS OF A MULTI-ARRAY SINGLE PASS TRAVERSE.
a=300 METERS
a = 900 METERS
a = 1500 METERS
COMBINED 300, 900, 1500 METERS SPACINGS
METERS
0
300
-1
-2
-3
-4
-5
-6
-7
Ze DEPTH in KM
POINTS PLOTTED AT EFFECTIVE PENETRATION (Ze)
D - DIPOLE-DIPOLE PLOTTED POINT, N = 1 TO 6

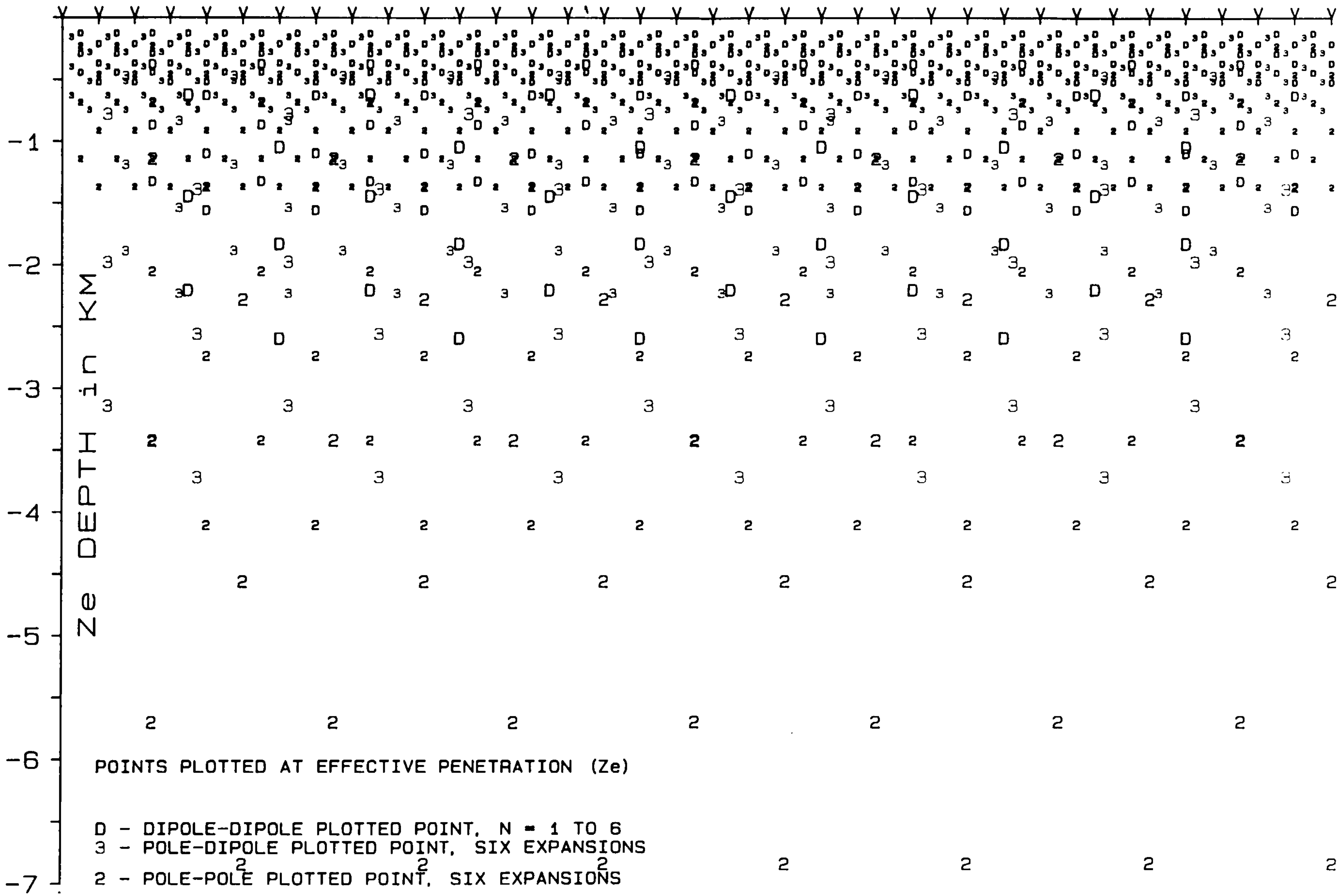
POLE-DIPOLE ARRAY COMPONENTS OF A MULTI-ARRAY SINGLE PASS TRAVERSE.




POLE-POLE ARRAY COMPONENTS OF A MULTI-ARRAY SINGLE PASS TRAVERSE.
a=300 METERS
a = 900 METERS
a = 1500 METERS
COMBINED 300, 900, 1500 METERS SPACINGS
METERS
0
300
Ze DEPTH in KM
-1
-2
-3
-4
-5
-6
-7
POINTS PLOTTED AT EFFECTIVE PENETRATION (Ze)
2 - POLE-POLE PLOTTED POINT, SIX EXPANSIONS

COMBINED ARRAY COMPONENTS OF A MULTI-ARRAY SINGLE PASS TRAVERSE.

300 METERS BASIC ELECTRODE SPACING, - 300, 900 AND 1500 METER SEPARATIONS SELECTED.



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Abstracts and Titles of some recent Papers concerning the 2-D and 3-D inversion and modeling of E-SCAN data

by

members of the research team investigating the E-SCAN data set at the University of British Columbia, Vancouver. B.C.

Research co-sponsored by

the Natural Sciences and Engineering Research Council (NSERC)

and

Premier Geophysics Inc.

Approximate 3d Inversion of E-SCAN dc Resistivity Data

Yaoguo Li and D.W. Oldenburg, University of British Columbia, Vancouver, Canada

SUMMARY

We present a semi-quantitative algorithm to invert for *3d* conductivity structure using surface pole-pole dc resistivity data. The *3d* subsurface conductivity is represented in the factorized form of a base model (chosen as a uniform halfspace) and a scaling function. With this representation, the surface data can be related to conductivity structure by a depth integral of a log conductivity perturbation convolved with a kernel in horizontal directions. The kernel has, as parameters, the separation and orientation of specific current and potential electrode pairs.

Fourier transforming the data equation decouples wavenumber components so that the surface response of a given pole-pole configuration at any wavenumber is obtained by carrying out a single integral with respect to depth. This decomposition allows a full *3d* inversion to be carried out by solving a *1d* linear inverse problem at each wavenumber. The number of (complex) data to be inverted at each wavenumber is equal to the number of distinct pole-pole configurations used; this is usually about 20–40. Inversions are typically done at a few hundred wavenumbers and the *3d* spatial distribution of electrical conductivity is recovered by inverse *2d* Fourier transforming with respect to the horizontal coordinates. The method is extremely efficient computationally. In the example presented in this paper, conductivity estimates for 40960 cells were generated in about 3000 sec on a SUN 4/330 computer.

INTRODUCTION

The dc resistivity problem is by its nature a *3d* problem. Firstly, the source in dc resistivity experiments is always a point source so the field is always *3d*. Secondly, geo-electrical structures are generally *3d*; *1d* and *2d* structures represent only highly idealized models. Although the study of *1d* and *2d* problems can provide much insight into theoretical work and practical data interpretation, in practice their application is rather limited. Only when the *3d* problem is tackled, can we use the dc resistivity method to its fullest advantage. Inversions of *1d* and *2d* dc resistivity data have been studied extensively. In contrast, the work regarding *3d* problems is rather limited. Alfano (1959) proposed a general approach to *3d* inversion based on rectangularly gridded models and the theory of charge accumulation. Vozoff (1960) applied that theory to simple *3d* problems and proposed an algorithm to invert for a conductivity model consisting of a number of blocks. The geometry of the model must be specified in advance. Petrick *et.al* (1980) devised a method which uses the concept of alpha centers to invert for the locations of conductive anomalies. However, an algorithm which recovers a general *3d* model has not yet appeared in the literature.

One of the reasons for this may be the lack of practical data for attacking *3d* problems. As shown by Backus (see Vozoff, 1960), the number of dimensions sought for the conductivity structure must be equivalent to the number of dimensions of the data. Conventional dc surveys make measurements with fixed array configurations along sparsely distributed traverses and the collected data do not suffice to recover complex *3d* structures. The newly available E-SCAN data, however, meets the requirement and allows inversion for complex *3d* conductivity structures.

In a typical E-SCAN experiment, electrodes are planted according to a pre-designed grid over the target area. Each electrode is used as a current electrode, and when activated, the potentials are measured at the remaining electrodes. Thus an E-SCAN data set consists of multiple groups of common source potentials. The data which would be acquired with many array configurations can be synthesized from the E-SCAN data set. In the study reported here, we choose the pole-pole array for its simplicity and large signal amplitude and depth of investigation. Our goal is to develop an approximate inversion algorithm for E-SCAN data which could serve as the basis for a complete *3d* solution or from which a preliminary interpretation can be made.

In this paper, we first present an integral equation for surface pole-pole data. We then discuss the algorithm which generates a *3d* conductivity model and illustrate it with a synthetic example.

THEORY AND INVERSION TECHNIQUE

Let $\sigma(\vec{r})$ be the conductivity structure in a lower halfspace whose upper surface is flat. The potential on the surface resulting from a point source of strength I placed on the surface can be expressed as

$$\varphi(\vec{r}_{obs}) = \frac{I}{2\pi \mid \vec{r}_s - \vec{r}_{obs} \mid \sigma_s} + \frac{1}{2\pi} \int_v \frac{\nabla\sigma(\vec{r})}{\sigma(\vec{r})} \cdot \frac{\nabla\varphi(\vec{r})}{\mid \vec{r} - \vec{r}_{obs} \mid} dv, \qquad (1)$$

where $\vec{r}_s$ and $\vec{r}_{obs}$ are source and observation point, respectively, and $\sigma_s = \sigma(\vec{r}_s)$.

Let the conductivity be represented by $\sigma(\vec{r}) = \sigma_0\mu(\vec{r})$. Here σ_0 is the conductivity of a uniform background and $\mu(\vec{r})$ is a dimensionless function of spatial position $\vec{r}$. Assume that the deviation of the conductivity from the background is small over the entire model, i.e. $\mu(\vec{r})$ is close to unity, and the surface conductivity is equal to σ_0. We can then use the Born approximation to derive the integral equation for the surface pole-

pole apparent resistivity data,

$$\rho_a\left(\vec{r}_0,\vec{l}\right) = \frac{1}{\sigma_0}\left(1 + \int_0^\infty \ln\mu(\vec{r}) \odot\odot g\left(\vec{r};\vec{l}\right) dz\right), \quad (2)$$

where $\vec{r}_0 = (x, y, 0)$ is the midpoint of the pole-pole array, $g(\vec{r};\vec{l})$ is the kernel function, and $2\vec{l}$ is the vector pointing from the current electrode to the potential electrode. We choose a Cartesian coordinate system with origin at the surface and z positive down. The symbol $\otimes\otimes$ denotes the *2d* convolution operation in the x-y domain. If, for a particular pole-pole configuration (specified by $\vec{l}$), ρ_a is known over the surface, then a *2d* Fourier transform may be applied to obtain the data in the wavenumber domain. Applying the transform to equation (2) yields

$$\tilde{e}_j(p,q) = \int_0^\infty \tilde{m}(p,q,z)\,\tilde{g}_j(p,q,z)\,dz, \quad j = 1,\cdots,n \quad (3)$$

where (p,q) are transform variables,

$$\begin{aligned} \tilde{e}_j(p,q) &= \mathcal{F}_{xy}\left[\sigma_0\rho_a\left(\vec{r}_o,\vec{l}_j\right) - 1\right], \\ \tilde{m}(p,q,z) &= \mathcal{F}_{xy}\left[\ln\mu(\vec{r})\right], \\ \tilde{g}_j(p,q,z) &= \mathcal{F}_{xy}\left[g\left(\vec{r};\vec{l}_j\right)\right]. \end{aligned} \quad (4)$$

The index j identifies the j'th pole-pole array. Equation (3) is the basic equation for the inversion. It is a Fredholm equation of the first kind in which the data $\tilde{e}_j$ $(j = 1,\cdots,n)$ and the model $\tilde{m}(p,q,z)$ are complex and the kernels $\tilde{g}_j(p,q,z)$ are real due to the symmetry of $g(\vec{r};\vec{l})$. At each wavenumber pair (p,q) we solve a *1d* inverse problem by minimizing

$$\phi = \int |\tilde{m}(p,q,z)|^2\,dz \quad (5)$$

subject to (3) as constraints. The inversion procedure is as follows.

1. Generate data maps by gathering E-SCAN apparent resistivities corresponding to given separations and directions specified by $\vec{l}_j$. The allowable separations and directions are controlled by the grid geometry.

2. Estimate the background conductivity σ_0.

3. Take a *2d* Fourier transform of each apparent resistivity map to generate data $\tilde{e}_j(p,q)$ in the wavenumber domain. This provides one (complex) datum at each wavenumber. Thus at each wavenumber we have the same number of data as apparent resistivity maps.

4. For each (p,q) generate the kernel $\tilde{g}_j(p,q,z)$ as a function of z for all $\vec{l}_j$'s.

5. At each wavenumber (p,q), invert for $\tilde{m}(p,q,z)$ as a function of z by using Backus-Gilbert inverse theory to construct an l_2 smallest model. This recovers $\tilde{m}$ in the wavenumber-depth domain. This is the heart of the algorithm. The quality of the final result depends upon each individual *1d* inversion. In order to stabilize the process, a ridge regression parameter is introduced to allow data misfit and to account for the data noise and the approximation error.

6. Take the inverse *2d* transform of $\tilde{m}(p,q,z)$ at each depth to recover the conductivity model in the spatial domain.

SYNTHETIC EXAMPLE

To illustrate the algorithm, we present the inversion result of a synthetic model which consists of five prisms buried in a uniform halfspace. The plan view layout is shown in Fig.1. Prisms B1 and B2 are the buried targets. Prisms S1, S2, and S3 simulate near surface variations in the conductivity.

A full E-SCAN data set over a 21 x 21 grid of 50m spacing is generated using a boundary element program. The apparent resistivity maps of separations ranging from 1 to 8 grid spacings are gathered in both x- and y-directions. These 16 data maps are used in the inversion (i.e., there are 16 complex data for each *1d* inversion in the wavenumber domain). No a priori information except the background conductivity is given. Fig.2 is the comparison of the true and recovered model in a section at x = 450m which cuts through the four major prisms. We see the recovered model appears as a depth varying filtered version of the true model. The four conductivity anomalies are well resolved. Despite the influence of the surface conductivity variations, the buried conductive prism (B2) is clearly defined. In general, the conductivity of the surface blocks are over-estimated while those of the deeper ones are under-estimated. Both the resolution and the magnitude of the anomaly decrease with the depth. The loss of resolution is due to limited bandwidth of the data and the fact that the kernel function in the wavenumber domain decays more rapidly with depth at higher wavenumbers. The loss of amplitude is due to the nature of smallest model construction, where a ridge regression parameter is used to regularize the solution.

It is noteworthy that three conductivity blocks with high contrasts are placed just beneath the surface. This is apparently in violation of the assumption that the surface conductivity is constant and the conductivity deviation is small. Even with such violations in the model, the algorithm still recovers the model reasonably well. This shows that the algorithm is quite robust.

CONCLUSION

We have presented an integral equation for surface apparent resistivity data and developed a *3d* inversion algorithm based upon the equation. The algorithm is designed to work for general complex *3d* models composed of perturbations to a background conductivity. Synthetic examples show that it can handle fairly large conductivity contrasts and, to a certain degree, surface variations. The inversion is only approximate, so results are semi-quantitative.

The approach we have taken has some general implications. The algorithm can be viewed from the different aspects. By applying a linear operator (*2d* Fourier transform) to the basic data equation, the *3d* inverse problem is broken into a set of parallel *1d* inverse problems. Each *1d* problem can be solved easily and efficiently. This results in an algorithm which is much more efficient than solving the original problem directly. From the view point of inversion, this approach also has merits. The Fourier transform separates the large scale features (low wavenumber components) and small scale features (high wavenumber components) in the data. The dominant (large scale) features are fit first by finding the large scale changes in the model. Successively finer features are then fit at different stages. This process makes the inversion very stable.

Since the algorithm is based upon the Born approximation, we cannot hope it will recover the model exactly. However, as a one-step inversion algorithm it is very encouraging. It also has the potential to be expanded into a full inversion algorithm.

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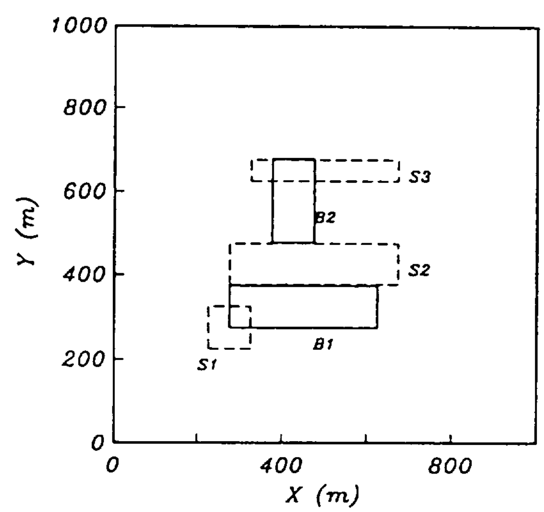

	DEPTH (m)	σ (S/m)
S1:	0 – 40	0.01
S2:	0 – 40	0.005
S3:	0 – 40	0.0005
B1:	50 – 250	0.0005
B2:	75 – 275	0.01

Figure 1. The test model consists of five buried prisms in a uniform halfspace of conductivity 0.001 S/m.

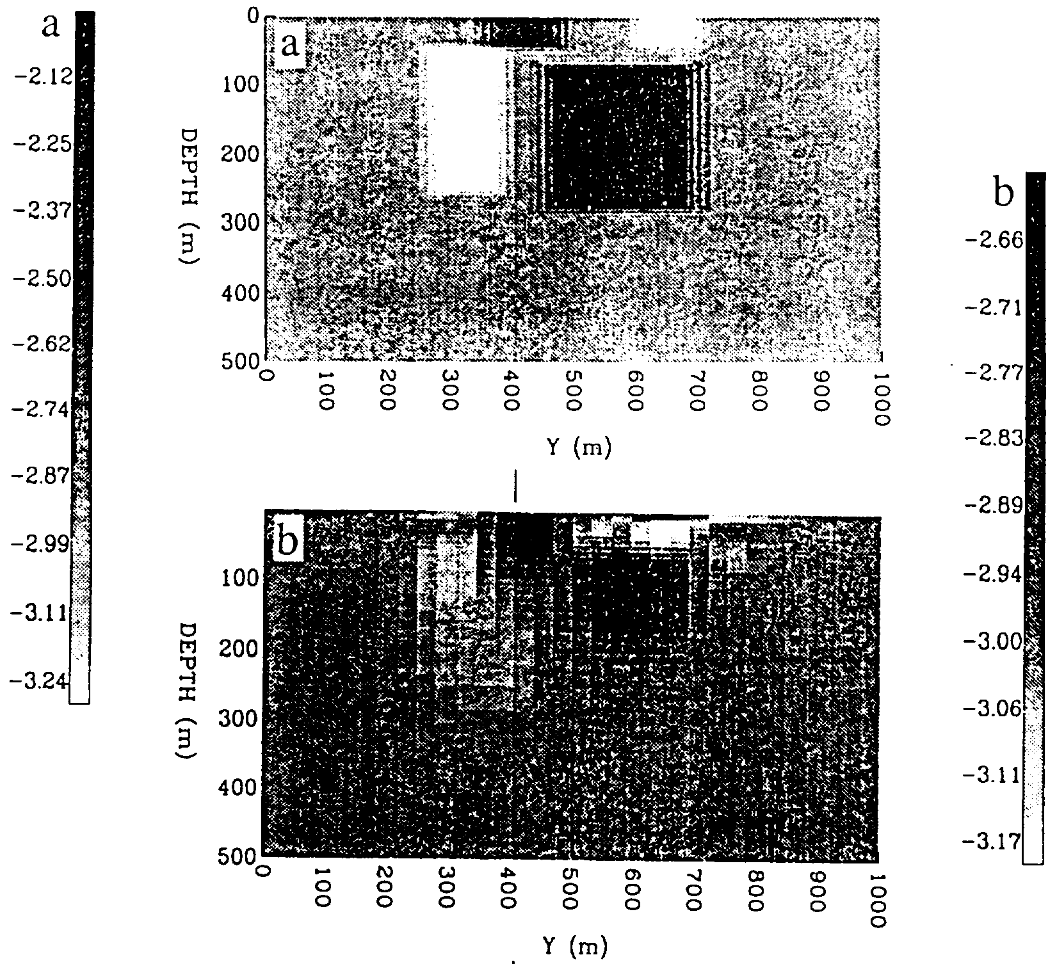

Figure 2. The comparison of the true model (a) and the recovered model (b) at the slice along $x = 450$(m) which cuts through the four prisms S2, S3, B1, and B2. The gray scales show the logarithmic conductivity.

Inversion of Pole-pole dc Resistivity Data for 3d Conductivity Models

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We present a semi-quantitative algorithm to invert for *3d* conductivity structure using surface pole-pole dc resistivity data. The *3d* subsurface conductivity is represented in the factorized form of a base model (chosen as a uniform halfspace) and a scaling function. With this representation, the surface data can be related to conductivity structure by a depth integral of a log conductivity perturbation convolved with a kernel in horizontal directions. The kernel has, as parameters, the separation and orientation of specific current and potential electrode pairs. Fourier transforming the data equation decouples wavenumber components so that the surface response of a given pole-pole configuration at any wavenumber is obtained by carrying out a single integral with respect to depth. This decomposition allows a full *3d* inversion to be carried out by solving a *1d* linear inverse problem at each wavenumber. The *1d* problem to be solved has real kernels, complex data and a complex model. The data are the Fourier transform of the apparent resistivity percentage anomalies. Thus the number of data is equal to the number of distinct pole-pole configurations used; this is usually about 20–40. The model is the Fourier transform of the log conductivity perturbation and solved for by constructing an l_2 smallest model using Backus-Gilbert inverse theory. In this manner, the *2d* Fourier transform of the conductivity model is recoverered in the wavenumber-depth domain. Inversions are typically done at a few hundred wavenumbers and the *3d* spatial distribution of electrical conductivity is recovered by inverse *2d* Fourier transforming with respect to the horizontal coordinates. The algorithm is illustrated with a synthetic example in which 16 pole-pole data maps are used to recover a *3d* conductivity model represented by 40960 cells.

Understanding and Using Charge Accumulation in DC Resistivity Problems

Y. Li and D.W. Oldenburg
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When a dc current is input into the ground, electric charges are accumulated in the locations where the conductivity gradient is nonzero. When the geologic model consists of isolated homogeneous conductive bodies buried in a halfspace, the charges are confined to the boundaries of the bodies and their distribution can be found by solving a Fredholm equation of the second kind. Once the charge distribution is established, the electric potential at the earth's surface is computed by solving a Fredholm equation of the first kind. This understanding allows us to tackle two problems of importance in dc resistivity experiments. The effects of topographic distortion can be removed by first estimating the accumulated surface charge density and then subtracting off its effect. By also removing the primary potential from the observation we are left with secondary potential fields which are due solely to anomalous charge accumulations on subsurface conductors. If the geologic structure is 2–dimensional then, with suitable approximations, it is possible to derive a linear system of equations to convert a $2\frac{1}{2}$–d problem to a 2–d inverse problem which can be solved using standard techniques. We use a linear programming approach (analogous to that given by Stinson in inverting magnetic field data) to find a sparse representation of a pseudo-charge density which is concentrated at the boundary of a conductive block. Image analysis, applied to results from different configurations of surface electrodes are combined in an attempt to answer the existence question: 'Is there a buried body beneath the surface?'

ASPECTS OF CHARGE ACCUMULATION IN DC RESISTIVITY EXPERIMENTS

by
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METHODS FOR CALCULATING FRÉCHET DERIVATIVES AND SENSITIVITIES FOR THE NONLINEAR INVERSE PROBLEM — A COMPARATIVE STUDY

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ABSTRACT

A fundamental step in the solution of most nonlinear inverse problems is to establish a relationship between changes in a proposed model and resulting changes in the forward modeled data. Once this relationship has been established, it becomes possible to refine an initial model to obtain an improved fit to the observed data. In a linearized analysis the Fréchet derivative is the connecting link between changes in the model and changes in the data. In some simple cases an analytic expression for the Fréchet derivative may be derived. In this paper we present three techniques to accomplish this and illustrate them by computing the Fréchet derivative for the 1D resistivity problem. For more complicated problems where it is not possible to obtain an expression for the Fréchet derivative, it is necessary to parameterize the model and numerically solve for the sensitivities — partial derivatives of the data with respect to model parameters. The standard perturbation method for computing first order sensitivities is discussed and compared to the more efficient sensitivity equation and adjoint equation methods. Extensions to allow for the calculation of higher order, directional and objective function sensitivities are also presented. Finally, the application of these various techniques is illustrated for both the 1D and 2D resistivity problems.

The Joint Inversion of Pole-pole Potential and Magnetometric Resistivity Data

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The E-SCAN pole-pole resistivity experiment is a geophysical technique which has been used primarily in mining and geothermal exploration. The experiment involves injecting current into the ground and then measuring the resulting voltages using a grid of electrodes set up over a survey area. Each electrode in the grid can serve as either a voltage or current electrode, and consequently a high density of data over the area of interest is recorded. By using sensitive magnetometers it is also possible to record the magnetic field responses due to the subsurface current flow. These MMR (magnetometric resistivity) data also contain information about the electrical structure of the earth. In this paper we develop a non-linear inverse algorithm to invert both electric potential and magnetic field data over a 2*d* earth. Our inverse method minimizes a global objective function of the model subject to an appropriate data misfit, and the type of model obtained depends upon the choice of objective function to be minimized. The algorithm is robust and flexible. To assess the relative importance and the information content in electric potentials and magnetic field data we invert these data sets individually and jointly. Because of the large degree of non-uniqueness inherent in the inverse problem when only surface measurements are used we investigate the added information obtained by incorporating voltage data from cross-borehole measurements. We illustrate our algorithm by inverting data from electrical conductivity structures simulating the presence of a conductive contaminant plume flowing in an acquifer and a fire front in an enhanced oil recovery problem.

Presented at the annual CSEG conference - May 1983

Direct Modeling of Discrete Frechet Derivatives in Nonlinear Inverse Problems

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Abstract:

A fundamental step in the solution of most nonlinear inverse problems is to establish a relationship between changes in a proposed model and resulting changes in the forward modeled data. Once this relationship has been established, it becomes possible to refine an initial model to obtain an improved estimate which better fits the observed data. For the continuous case, changes in the data are related to changes in the model by the "Frechet Derivatives" for the problem, which, for simple situations, can sometimes be obtained analytically. For more complicated problems, however, it becomes necessary to compute discrete approximations to the Frechet Derivatives. The standard method for computing these approximate derivatives, or sensitivities, will be compared to a more efficient direct modeling procedure, suitable for problems with large numbers of data. An alternate approach, which makes use of a Green's function solution to an adjoint problem, and is more suitable for problems with a large number of parameters, will

Fifth Canadian/American Conference on Hydrogeology: Parameter Identification and Reservoir Characterization - Calgary, Alberta - September 1990

The Inversion of Pole-pole Resistivity Data in the Solution of Groundwater Contamination and Enhanced Oil Recovery Problems

P. R. McGillivray and **D. W. Oldenburg**

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Topic: A method of inverting pole-pole resistivity data to recover the electrical conductivity distribution within an aquifer or petroleum reservoir will be presented.

Type of Presentation Preferred: Oral

Abstract:

The pole-pole resistivity experiment is a geophysical technique which has been used primarily in mining and geothermal exploration. The experiment involves injecting current into the ground and then measuring the resulting voltages using a grid of electrodes set up over a survey area. Each electrode in the grid can serve as either a voltage or current electrode, and consequently a high density of data over the area of interest is recorded. An interpretation of this data set based on forward modeling and inversion can then be used to delineate regions of anomalously high or low electrical conductivity at depth. Since electrical conductivity can be related to

properties of the aquifer and the distribution of fluids within the aquifer, the technique could be applied to a wide variety of problems in both groundwater and petroleum reservoir evaluation. The goal of this paper is to describe a method for recovering the conductivity distribution of the subsurface from pole-pole voltage measurements using a non-linear parametric inverse approach. The importance of selecting the appropriate global norm to minimize and the use of a priori information to help resolve non-uniqueness in the solution will be emphasized. The use of voltage data from cross-borehole measurements to further constrain the inversion will also be discussed. Finally, the inversion of synthetic data sets over a contaminant plume and an enhanced oil recovery site will be used to illustrate applications of the technique.

Biographical Sketches:

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Mr. McGillivray received his B.Sc. in geophysics from the University of British Columbia in 1984. He was employed as an exploration geophysicist by Canadian Superior Oil Ltd. and Mobil Oil Canada Ltd. from 1984 to 1986. He is presently a Ph.D. candidate with the University of British Columbia. His current research interests include the solution of large scale modeling problems using adaptive multigrid techniques and the solution of inverse problems in groundwater and geophysics.

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Dr. Oldenburg received a B.Sc.(Hons.) in physics in 1967 and an M.Sc. degree in earth science in 1969, both from the University of Alberta and a Ph.D. degree in earth sciences in 1974 from Scripps Institute of Oceanography. He was a Killam postdoctoral fellow at the University of Alberta from 1974 to 1976. Since 1977 he has been with the Department of Geophysics and Astronomy at the University of British Columbia where he is currently a professor. His interests center around the application of inverse theory to problems in electromagnetic and seismic data processing. He is a member of SEG, EAEG and the CSEG.

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A Modified Pseudosection for Resistivity and IP
L. S. Edwards

This paper from Geophysics (Vol. 42, No. 5) is reproduced here for the convenience of readers who wish to delve further into the NDIC and Ze issue. We use and frequently refer to "Edwards type pseudosections" in E-SCAN work; here is the paper that by combining the theoretical math with day-to-day commercial exploration demands has yielded a useful "new" version of the pseudosection.

Since E-SCAN maps the absolute potentials rather than the array-dependent derivatives measured by dipole arrays, we have the opportunity to display E-SCAN values in many ways. While the greatest value has been demonstrated by working with pole-pole representations of the measurements, we can display the results in everything from potential fields (for each current site) to calculated derivative array data such as dipole-dipole or pole-dipole. LINEAR E-SCAN traverses record hard-wired pole-pole, pole-dipole, and dipole-dipole data simultaneously. Thus, a practical pseudosection plotting technique, such as Edwards', that allows the plotting of different arrays on the same pseudosection is of great value to us.

The caveats associated with the more standard 90 degree plotted pseudosections are equally applicable to Edwards pseudosections; no interpretive liberties or assumptions are conveyed by the simple re-plotting of apparent resistivity data by another technique. We still prefer (as should you) to characterize data initially as a function of "electrode array separation", a known fact devoid of assumptions of earth conditions and "penetration" factors. "Depth of penetration" then becomes an interpreted assessment obtained case by case on the merits of the immediately involved data set.

Thus, when you see "NDIC = 9600 feet" on the preceding Yucca Mountain sketches, pause and remember that the term "Nominal" is not to be taken lightly.

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Questions and Answers

Anticipation of a few Yucca Mountain site-specific questions.

QUESTIONS AND ANSWERS

ANTICIPATION OF A FEW YUCCA MOUNTAIN SITE-SPECIFIC QUESTIONS.

How complicated is it to get going with an E-SCAN survey?

It is always much easier to get decisions made and start the project with E-SCAN than with most other survey types. Only two decisions must be made:

1. What grid spacing? Large for large scale features, extra deep; smaller for finer resolution, less depth. Usually, review of other projects at spacings from 50 feet through to 1000' helps get the spacing right for the task at hand. Pre-survey forward modeling is sometimes of help, if enough is known in advance of the electrical response of a particular feature.

2. Where to run it? Outline the area of interest on a map.

That constitutes the planning for an E-SCAN survey. The dense, multiidrectional nature of the data set takes care of all other variables, without having to specifically plan for them.

To start, a grid must be installed, with a per station accuracy of about 3% to 5% of the station spacing being good enough, so long as accumulated error stays low and the grid is periodically tied to monuments.

Premier arrives, wires up the starting section, and within 3 to 4 days begins a cycle of 700 to 1500 measurements per shift, day in and day out, until the program is finished. The electrode network rolls across the survey area, being picked up behind and reinstalled ahead as shots are made. A one or two day cleanup leaves the area as if we were never there.

Premier has its own specialized vehicles, radio system including mountaintop repeaters, all the accoutrements for survey operations over several square miles at a time.

What problems do you expect in getting data from NDIC's of 15,000 feet?

Few to none. By measuring the absolute potentials (equivalent to a pole-pole array), the signal at NDIC or Ze of 15000 feet (or at any NDIC) will be 100 times stronger than those derived from a dipole-dipole array. This means that 100 times less current needs to be injected to get the same signal for the same nominal "depth". Instead of reporting to a backhoe to bury salt-water saturated metal screen and foil, we will need only a couple of conventional steel stakes. The entire Unalaska survey, while testing only to NDIC 7500 to 9000 feet, required less than 2 amperes of transmitted current. Geothermal surveys in British Columbia to NDIC >5000' were done with entirely adequate signal using a 200 watt battery powered transmitter. Our standard 3200 volt, 20 amp, 7.5 kilowatt transmitters are a more than sufficient power source, using standard electrodes.

Yucca is very dry...still no problem?

No problem. E-SCAN surveys were operated in the desert (Imperial Valley) all summer (130 degrees F) this year, and indeed many of our dry season Nevada projects (Tonopah, Gabbs, etc.) are as dry as the Yucca area.

Sometimes talus slopes present difficult contact situations for any system, with much of the power being applied through arcing, with its ragged and usually tapering DC pulses. When we have found ourselves in this position, we have still obtained good quality data. E-SCAN provides an optically isolated image of the transmitter current waveform, so that the two channel integrating DVM receiver can simultaneously integrate both the transmitted and received signals over the same window. This eliminates the principal source of error, the DC offset, which would occur if the output waveform was assumed to be square.

What about signal attenuation in the dry?

A good question, already anticipated in the early design of E-SCAN. Proprietary circuitry and software can continuously monitor potential electrode contact resistance throughout the network, alerting operators to unacceptably high resistance sites. Where the resistance cannot be improved, other proprietary circuitry determines the contact resistance and computes a corrected potential level. For the remaining noise, increased stacking is the answer.

Our main concern with dry contacts is on the quality of subtle IP signals for Stage 1, if elected. Among other measures, we can use porous copper-copper sulfate electrodes to improve IP quality and stability. The Robertson case history results were derived from the use of almost 600 disposable pots of our own manufacture.

Are tellurics a problem with the big infinite and long wires?

For resistivity, we can usually use with a high enough frequency to ride any tellurics waveform, except in the case of pulses from nearby thunderstorms. By digitizing all waveform measurements as absolute voltages, we are not concerned with the traditional problem of re-zeroing the SP/tellurics level each pulse, preferring to use much more reliable and efficient digital filtering of the telluric component.

For IP, the question of waveform attracts as many opinions as there are geophysicists, it seems. If IP is to be considered, I would want to review the work done at Yucca to date, and get a consensus on how to approach the subject. E-SCAN can be programmed to measure any waveform components. The longer the time taken for a measurement, the more costly the program (at 224,000 measurements contemplated). There will be an identifiable "crossing of curves" between cost and information content for IP; we must simply evaluate where it is.

Would lightning storms at Yucca Mountain pose a problem?

We shut down during lightning storms, both for personnel safety and because data will be noisy. The wire and equipment can withstand lightning strikes in the immediate vicinity, an event experienced in some 40-50 storms so far with E-SCAN. A direct hit on a wire or a switchbox would likely fry the nearest two or three boxes in each direction. So far it hasn't happened, except to blow a few fuses and diodes. The CMOS-laden switchboxes are intensely engineered and protected to withstand lightning strikes, using virtually military specification engineering standards, and a range of clamping and gas discharge devices. Damage due to lightning is our responsibility, in most contracts.

You mention SP.. how is it measured?

Since each point on the waveform is recorded as an absolute voltage, rather than a difference from some previous measurement, we are continually logging the voltage difference between the infinite reference point and the measurement electrodes. By the time we are finished, we will have at least 30 values associated with each electrode point, spread over different times of the day, some obtained before, during, or after some minor near-surface moisture variation (rain?). These data can be merged and averaged to provide an SP map resolved to the grid spacing interval. As I said, there may be value in the data, maybe not. The data are going to be there on the disks, available for the price of reading them, averaging them, and plotting them.

The Yucca Mountain site will have considerable other industrial activity on-going...will that interfere with E-SCAN?

Not likely. Operationally, E-SCAN has been operated on a 300 foot grid right through an operating (blasting, digging, hauling, grading) open pit mine with virtually no disruption of mining activity or hazard to workers, and only a 20% slowdown of E-SCAN productivity (1989). Where roads cross an E-SCAN area, we automatically lay down "road-crossings", heavy sections of cable that can be driven over without slowing down.
From day 1, we arrive prepared and take responsibility for not disrupting other activity while protecting our own productivity.

From a data quality standpoint, E-SCAN has a unique capability, based on the densely overlapped (not repeated, but overlapped, always with one electrode different) data set. If there is a grounded fence or pipeline distortion, it will affect the few measurements that are physically or electrically linked. The majority of the multidirectional measurements also testing that specific part of the ground will be unaffected. Not only can the affected readings be logically and positively identified, but after removing them, the verifiably competent measurements that remain will cover the data gap.

A good illustration is a geothermal case history at Lakelse, B.C., a program run for the Geological Survey of Canada in 1983. This survey was conducted over an area featuring a transition from marsh to outcropping crystalline rock, with the main electrical power transmission corridor for the Alcan aluminum smelter at Kitimat running right through the survey area, at the transition zone. The data set is verifiably correct and useful. The case history can be presented on request.

How do you handle terrain variation?

Electrode co-ordinates are recorded in three dimensions. All measurements are recorded and computed in three dimensional units, from which a number of plotting options are available, e.g. plot perpendicular to the local surface (OK in moderate terrain), or vertically beneath the array mid-point (necessary in extreme terrain).

The 3-D co-ordinates of course feed directly into the 3-D inversion routines.

Operationally, since no wires are dragged, wiring up rough terrain is almost as simple as wiring up flat ground, except that we walk more, and ride our 5-wheel wire-layers less.

What about terrain sensitivity from an interpretation standpoint?

First, the 2-D and 3-D forward modeling and inversion routines are all 3-D adapted in terms of handling surface terrain.

Second, the measurement of absolute potentials rather than dipoles seems to eliminate a large portion of the terrain-induced distortion. Terrain corrections applied to the Unalaska geothermal data by the 2-D modeling routine were not greater than 18%, and that was in one area where a 1200 foot bluff was involved. Such corrections are nominal compared to the size of corrections applied to dipole data. I suppose you could say that the less correction the modeling routines must apply, the more reliable the result.

How long does it take to measure 224,000 readings?

This will depend on the waveform selected, and the number of cycles stacked for each reading (IP or not), and whether we use 1 or 2 channels of input. The range is 3 to 6 months, less if two shifts are employed. There is only about a second of time spent on overhead between each measurement, so that in 8 hours of measuring time, a thousand measurements a shift is feasible. Double shifts, and two input channels can increase potential measurement accumulation to 3000 to 4000 per day.

Cost factors?

E-SCAN works either by the shift, with production being whatever our crew can achieve, or on the basis of readings measured, with the client representative refereeing on acceptable data quality (for his own comfort). We most often operate in the latter mode, with fixed unit costs per measurement. This removes budget uncertainty from the client's shoulders, while leaving flexibility if sample stacking needs to be increased, for example. Unalaska was operated for the Alaska Power Authority on a fixed cost budget, estimated from a desktop in San Francisco. Later, halfway down the Aleutians in inhospitable terrain and weather, both the time and cost budgets were met, as we expected, with 10 square miles of terrain mapped in 25 days. E-SCAN, by its operating flexibility, is virtually never slowed by on-site surprises such as canyons (not on the map), or swamps (that were forgotten at contract time). E-SCAN has even operated through lakes (30 grid stations under water) without skipping a beat. Yucca would be no different.

The cost is tied closely to the number of grid points being measured. A 200' grid involves four times as many electrodes as a 400' grid, and therefore yields about 4 times as many measurements per unit area. Unit area costs for a 200' square grid will be about 3 times higher than for a 400' grid. By the time we are measuring the 800 foot grid, with a hybrid 1600' potential electrode spacing and 800 foot current injection interval, the cost can be as low as $13,000 to $15,000 per square mile of coverage. Fairly dense coverage with all of the bells and whistles can cost $100,000 per square mile.
This accounts for the acquisition and basic organizational processing costs. Plot and report generation proceeds on a separate budget, obviously a fraction of acquisition costs, mostly because we can not predict in advance how many plots of which type will be appropriate or required, until we see the data. Advanced interpretive reporting, and computer modeling are also post-acquisition budget items, since again there is no way to predict how much will be appropriate. Reasonable estimates can be made, however.

Our spreadsheet can compute acquisition costs quickly for any combination of spacings and options such as increased sample stacking for IP measurements. It is a matter of sitting down and reviewing technical requirements, and balancing costs and benefits.

Perhaps we don't need ALL of the E-SCAN data...can we do half?

Once the network is set up, the difference between getting all of the data available and just some is a not large, in terms of money saved. There is no saving of manpower, just a matter of cutting short each computer run through the available electrodes.

We do run E-SCAN according to a "Scan Pattern", in which a selected pattern of the available electrodes is measured, leaving out some of the distant, overly redundant measurements, while making sure we have everything we need for the four basic orientations of pseudosections, plus adequate plan view density. Having measurement points only at 400' grid intervals while shooting current every 200' cuts costs almost in half, while delivering most of the useful data that would have been mapped at the more expensive 200' measurement, 200' current shot survey. In this sense, money can be saved. The tradeoff is mainly a reduction in pseudosection spacings, from every 200 feet to every 400 feet. If we can live with that, the cost benefit is available.

Rodents, cattle and mustangs...they eat wires for breakfast.

Always a problem, but we have learned to keep the worst Nevada pests (rabbits are bad, cows are bad) limited to less than 1 hour of disruption per day on average.

The E-SCAN system's continuous diagnostics will immediately identify any section of wire that has been severed, shorted or partially grounded, allowing a crewmember to go straight to the section and repair it while readings proceed on unaffected parts. No bad data will get through as a result of animal activity.

We have developed such obvious systems as a suspended infinite system, the long infinite lines placed up on steel poles for long-duration surveys. First, the 2-D and 3-D forward modeling and inversion routines are all 3-D adapted in terms of surface terrain.

What about the hazard to people from all the wires?

Most of the wires are signal level only, not dangerous.

Apart from an industrial site awareness effort for site workers, we make sure that the very few wires that carry high voltage are well and clearly marked with multilingual warnings. These wires are usually also suspended in the air from steel poles, so they even look like serious business, and not scrap wire. Premier has had no injuries to public or crew in 25 years of operation worldwide, in part because of this diligence.

What about environmental disruption from E-SCAN surveys?

E-SCAN is always a clean survey in the sense of leaving absolutely nothing behind. Electrode pits and holes are never needed; the steel stakes we use leave no noticeable surface disturbance. In some areas we use 5 wheel balloon-tire golf-green maintenance vehicles (John Deere AMT-600) to minimize surface damage. We can and do operate on foot, without vehicles, if the land requires it. In the Imperial Valley, we covered 7 square miles of strictly controlled desert tortoise habitat on foot, with the enthusiastic approval of the BLM who acknowledged both the minimal nature of our disturbance, and the even greater benefit of a reduced requirement for blind drilling, with its associated surface disruptions and road-building.

GS Oct 28/90