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INTEGRATION OF REMOTE SENSING AND SURFACE GEOPHYSICS IN THE DETECTION OF FAULTS

P.L. Jackson
R.A. Shuchman
H. Wagner

Environmental Research Institute of Michigan
Ann Arbor, Michigan

F. Ruskey

Denver Mining Research Center
U.S. Bureau of Mines
Denver, Colorado

ABSTRACT

Possible faults indicated by remote sensing can be quickly confirmed by resistivity surveys. Anomalous resistivity values occur within the fault crush zone. In a sedimentary region in Rio Blanca County, northwest Colorado, a fault zone was inferred from LANDSAT imagery. Subsequent resistivity surveys indicated substantial resistivity highs associated with the faults. Seismic data and the drilling of an observation well confirmed the main fault.

1. INTRODUCTION

Remote sensing was included in a comprehensive investigation of the use of geophysical techniques to aid in underground mine placement. The primary objective was to detect faults and slumping, features which, due to structural weakness and excess water, cause construction difficulties and safety hazards in mine construction.

Preliminary geologic reconnaissance was performed on a potential site for an underground oil shale mine in the Piceance Creek Basin of Colorado. LANDSAT data, black and white aerial photography and 3-cm radar imagery were obtained. LANDSAT data were primarily used in optical imagery and digital tape forms, both of which were analyzed and enhanced by computer techniques. The aerial photography and radar data offered supplemental information.

Surface linears in the test area were located and mapped principally from LANDSAT data. A specific, relatively wide, linear pointed directly toward the test site, but did not extend into it. Density slicing, ratioing, and edge enhancement of the LANDSAT data all indicated the existence of this linear. Radar imagery marginally confirmed the linear, while aerial photography did not confirm it.

A resistivity mapping survey through the test site and perpendicular to the remotely sensed linear indicated a substantial resistivity anomaly (high) across an extension of the linear. A parallel resistivity survey line confirmed that the anomaly was aligned with the linear. Resistivity differences between fault zones and their environs are due to the comparatively high moisture content within the zone to produce a resistivity low, and, either calcification or drainage of moisture (leaving comparatively large interstices) to produce a resistivity high.

The existence of the faults were further confirmed by a refraction seismic survey, and by drilling an observation well in which rubble was found, indicating a fault crush zone.

2. GEOLOGIC SETTING OF TEST SITE

The area of concentration for this study is located in Fault Draw, a subtributary valley of Ryan Gulch at approximately $39^{o}55'$ north latitude and 108^{o} 20' west longitude (section 6, R 97W, T 2S). Ryan Gulch is situated in the north-central part of the Piceance Creek Basin, Rio Blanco County, Colorado. Fault Draw is important, for here the U. S. Bureau of Mines initiated a test drilling to determine the feasibility of an underground oil shale mining operation. Figure 1 is a topographic map of the test site area.

Structurally, the test site lies about 15 kilometers from the center of a domal uplift where commercial gas fields are found. The arcuate shape of Piceance Creek indicates that it is a consequent stream to this domal uplift. A graben and its associated topographical expression (Dudley Bluffs) extends at least 25 km from Collins Gulch in the domal uplift to Yellow Creek, which is about 9 km west-northwest of the test site. As this extensive structural feature passes closely by or encompasses the test site, which is also close to the large domal uplift, other structural features such as tension faulting would be plausible in this region.

Bedrock exposed at the Fault Draw/Ryan Gulch area is yellow-brown sandstone of the Uinta Formation. It can be seen along the valley walls and especially at the junction of the two valleys. Near the mouth of Fault Draw along the northwestern wall of Ryan Gulch are the best exposures, where visible evidence of the Dudley graben can be found. Running across Ryan Gulch and bordering near the mouth of Fault Draw are two normal faults which form the graben. Within the sandstone outcrop northeast of the mouth of Fault Draw can be seen a white segment of calcite, presumably filling the southern member of the pair of faults. The vertical displacement of the graben is approximately 50 feet.

Extensive jointing, characteristic of the Uinta Formation throughout the basin, results in poor resistance to weathering, and makes the formation one of the principal aquifers of the area. Random outcrops of bedrock core appear through the unconsolidated materials which blanket and shape the rolling hills.

3. REMOTE SENSING DATA

Three types of remote sensing data were used in the study: black and white aerial photography, X-band synthetic aperture radar (SAR) imagery, and four-channel MSS LANDSAT data. These three types of imagery are available to the public at nominal cost and with little delay. Particularly with the more sophisticated LANDSAT and SAR data, an array of interpretive techniques can be used. These techniques range from simply viewing and interpreting a single image to that of complexly performing computer analysis using statistical and other comparisons of several images. In this study several computer analysis techniques were used on the imagery.

The LANDSAT data was the primary source of finding unmapped linears. Aerial photography and imaging radar data provided supplemental information. The four channels of LANDSAT data are shown in Figure 2.

An alternative format of LANDSAT data is computer compatible tape, which can be exploited on the computer. Computer analysis involved level slicing single and two-channel ratio images to attempt to determine whether any structural or lithological information could be obtained about fault systems in the area. The image, a "graymap", is composed of selected symbols on a computer printout. The computer analysis was performed on the University of Michigan

AMDAHL computer using a Department of Natural Resources LIGMALs program. The black and white stereo aerial photography with a scale of 1:60,000 is shown in Figure 3. Piceance Creek and Ryan Gulch form the partially cut off "A" in the lower right-hand corner of the image. The cross of the "A" is a portion of a long linear composed of Dudley Bluffs and associated graben which is oriented approximately N25E. Aerial photography provided supplemental data in the form of topographic, vegetation and stream pattern information.

Side looking radar imagery was also utilized in the study. The synthetic aperture radar (SAR) imagery was obtained with a wavelength of 3 cm (X-band) radar (Brown and Porcello, 1969). The imagery was provided courtesy of the Strategic Air Command, and is available from Goodyear Aerospace Corporation, Litchfield, Arizona.

4. INTERPRETATION OF REMOTE SENSING

Several linear features are interpreted as faults which geologic maps of the area confirm. There are some structures noted on the imagery as suspected faults which have not been mapped on the geologic maps. Trexler (1974) mapped anticlincal and synclincal folds and faults throughout the Piceance Basin using photographic interpretive techniques on single channel LANDSAT images.

Stereo photographs (Fig. 3) confirm some but not all of the geologic structures discerned on LANDSAT. Near the test site, Dudley Bluffs with its associated fault zone are clearly visible on both LANDSAT and aerial photography. However, the aerial photography only indicates a single fault feature - Dudley graben. A more dense band of vegetation at the known location of the graben appears to be a result of the zone of brecciation and consequent moisture within the graben.

Figure 4 is a 5/7 ratio processed graymap produced by point-by-point ratioing of LANDSAT Band 5 by Band 7. The "A" (without the cross) in the upper portion of the figure is the intersection of Ryan Gulch and Piceance Creek. The ratioing process performed in this image tends to suppress variation in illumination due to topography and viewing angle. For example, Dudley Bluffs and graben (the cross of the "A") is suppressed in this figure. Thus, differences in this image can be attributed to variations in the composition (i.e., lithography, mineralogy, moisture, vegetation) rather than the topography. The 5/7 image clearly delineates the alluvial deposits (chiefly silt, sand, and gravel) from the surrounding green river bedrock (gray and yellow-brown marl-stone, siltstone, sandstone and tuff).

In the middle of the upper portion of Figure 4, above the Ryan Gulch - Piceance Creek intersection, a bright linear about 1/8 inch in width can be seen. The extension of this linear extends directly through the test site. This is the linear which aligned with the resistivity anomaly, and an observation well at Fault Draw which indicated faulting. This extension into Fault Draw is termed Burdick's Fault. Aligned with this linear, but not extending as far south as shown on LANDSAT imagery, are a series of three faults shown by Welder (1971).

It is this linear which demonstrates the utility of commencing reconnaissance with the easily available, inexpensive remote sensing data. This linear is not associated with topography, and therefore had been previously overlooked as a possible fault zone.

Figure 5 is a channel 5 density sliced image that is intended to show a series of linears in close proximity to the test site. Linear A appears to be the same linear enhanced on the 5/7 ratio image previously shown.

The final sets of results are edge enhanced images of LANDSAT band 5 and the 3 cm SAR data. The image enhancer is a spatial data color enhancer loaned to ERIM by Spatial Data Corporation of Goleta, California. An edge enhancement mode that accents subtle density differences was used for this study. Through edge enhancement a series of linears were displayed that run northeast-southwest through Piceance Dome into the test site. These linears were not indicated on geologic maps of the area. Linears in other directions were also displayed.

Figure 6 shows the normal Band 5 LANDSAT image, along with the resulting edge enhanced image of the test site. The linear aligned with the resistivity anomaly through the test site is evident on both images.

In Figure 6, note the clear indication of a linear aligned with Ryan Gulch extending northeast toward the White River uplift. Although outside our test area, this long, persistent linear concerns the test area. If this linear were subsequently proven to be a fault through further geologic or geophysical investigation, it would indicate more structural activity than previously thought to be the case within the test region. Also, the straight portion of Ryan Gulch might be fault controlled. This northeast linear is also present on the four LANDSAT channels shown in Figure 2. Figure 7 is a SAR image of the test site area which does not indicate this linear.

5. GEOPHYSICAL CONFIRMATION

Because a fault crush zone consists of broken particulate matter, it usually possesses a different resistivity than the surrounding country rock. Resistivity highs are produced by crystallization or calcification due to fluid transport within the fault, or by relatively large particles which do not retain water. Resistivity lows are produced by the retention of water by relatively small particles within the fault zone.

Mapping resistivity surveys across a suspected fault can be used to confirm the existence of a fault. An economical and timely method of resistivity mapping is that of taking successive measurements along a baseline using a Wenner array (Parasnis, 1966). This simple configuration consists of four in-line electrodes equally spaced. The two current electrodes are at the ends of the line, the two voltage electrodes near the center. Under conditions of constant current input through the current electrodes, the voltage difference between the voltage electrodes indicates the apparent resistance of the earth under the electrodes. The effective depth of measurement is proportional to the spacing of the electrodes. If the array of electrodes is moved with successive measurements along a line crossing a resistivity anomaly, a plot will indicate the location of the anomaly.

At our test site resistivity was mapped across the area which the extension of the remotely sensed linear indicated. Fifty foot electrode spacing was used. A substantial resistivity high was found. Resistivity was then mapped 400 meters away on a line parallel to the first line, and another substantial resistivity high was again found. The two resistivity highs aligned with the remote sensed linear.

Figure 8 is a photograph of the test site showing the placement of the resistivity survey lines. The dashed line represents the location of the inferred fault. Figure 9 shows the resistivity profiles of the two lines. The first had an anomalous, apparent resistivity high of 750 ohm meters, the second of 1600 ohm meters. The average resistivity in this region is approximately 100 ohm meters. In Figure 9 the two lines showing the substantial resistivity high were on elevations away from the alluvium of the draw. Two more lines, between the outer two, are on alluvium, and show modes rises when crossing the fault.

The fault was fully confirmed by drilling, and later by a seismic survey with 20-foot spaced geophone arrays.

6. DISCUSSION

One of the major geological uses of remote sensing has been the mapping of previously unknown linears. Both LANDSAT and synthetic aperture radar imagery have proven very useful in such mapping. In many cases these linears turn out to be faults.

These faults can be confirmed by surface geophysical measurements, one of the most economical and timely being resistivity. Several advantages of resistivity surveys are:

1. Instrumentation is simple and comparatively inexpensive.
2. Minimal skill is required of a small crew.
3. Data can be gathered under any noise condition, such as heavy machinery.
4. Immediate reduction of the data enables one to search out the geometry of the anomaly during the data gathering phase.
5. The data, although not uniquely interpretable, are in a straightforward form that is easily and clearly understood by the non-geophysicist.

Although the experiment conducted here was for mine placement, the confirmation of faults by resistivity can aid in solving other problems. For example, in searching for underground water sources in arid and semi-arid regions. In these regions sources of water are often fault controlled. A relatively inexpensive resistivity mapping survey would greatly improve the confidence that water might be found before commencement of expensive drilling.

Depending upon the cost of the operation to be performed--whether mine placement, water drilling, mineral exploration, etc.--other surface measurement techniques such as seismics can be used for further confirmation of the existence of faults.

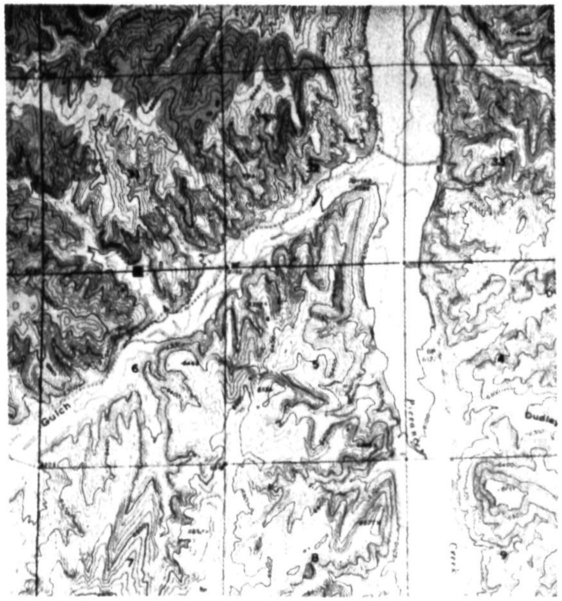

FIGURE 1. TOPOGRAPHIC MAP OF TEST SITE REGION. Black square on central horizontal section line is the location of the observation well. (USGS Square S Ranch Quadrangle, Colorado)

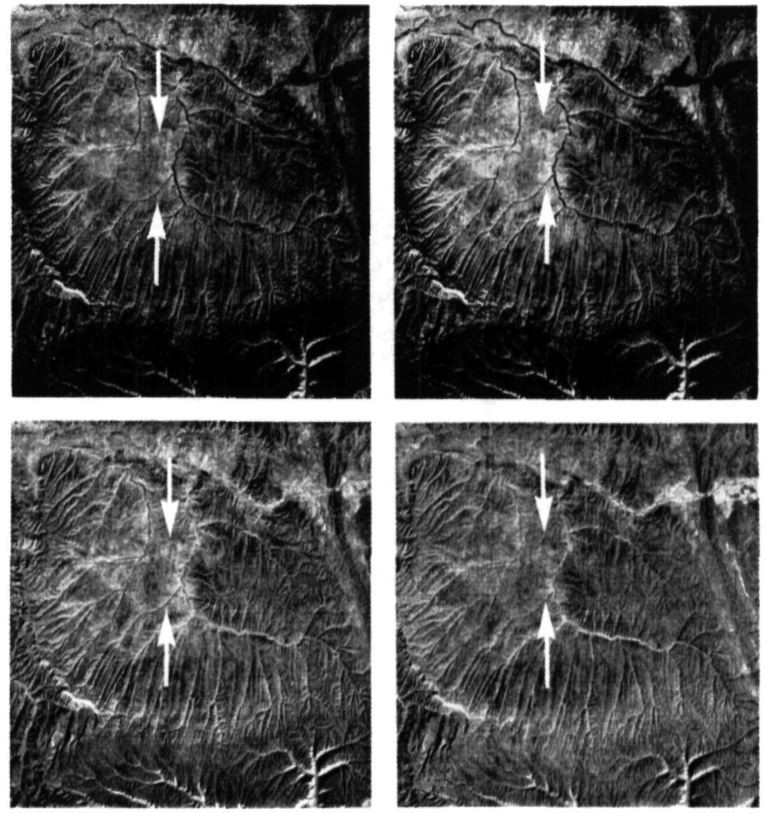

FIGURE 2. FOUR CHANNELS OF LANDSAT IMAGERY. $\begin{pmatrix} 4,5 \\ 6,7 \end{pmatrix}$ Primary linear indicating fault is between arrow heads.

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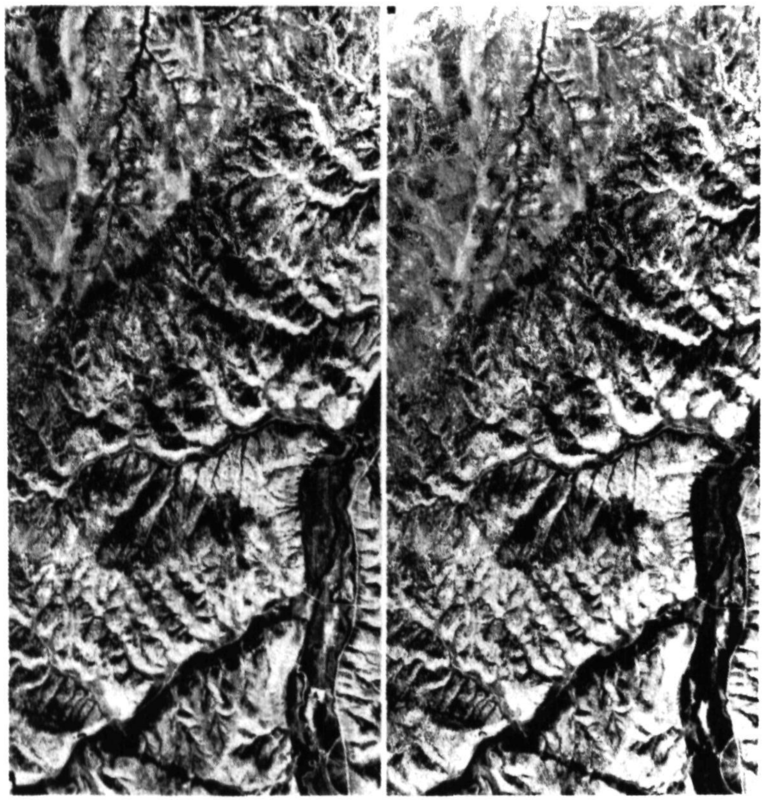

FIGURE 3. STEREO PHOTOGRAPH OF TEST SITE REGION.

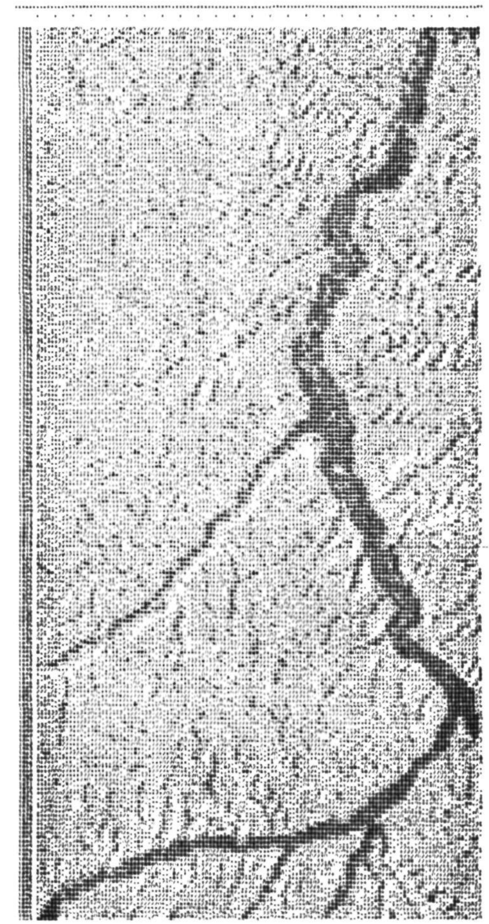

FIGURE 4. RATIO PROCESSED GRAY-MAP PRODUCED BY POINT-BY-POINT RATIOING OF LANDSAT BAND 5 BY BAND 7. Note light, relatively wide vertical linear at top center.

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FIGURE 5. DENSITY SLICED IMAGE OF LANDSAT BAND 5. Light areas occur along wide vertical linear.

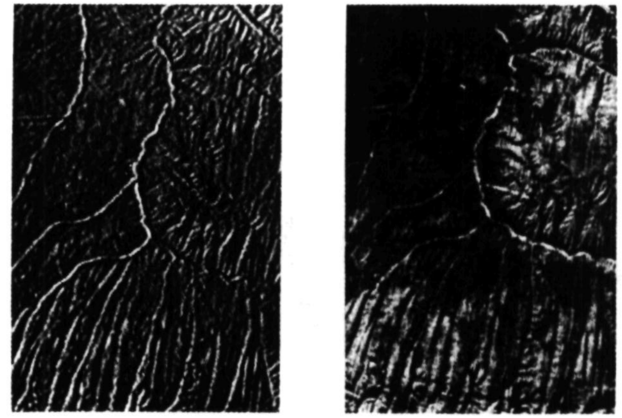

FIGURE 6. LANDSAT BAND 5 IMAGE (LEFT) AND EDGE ENHANCED IMAGE OF TEST SITE (RIGHT).

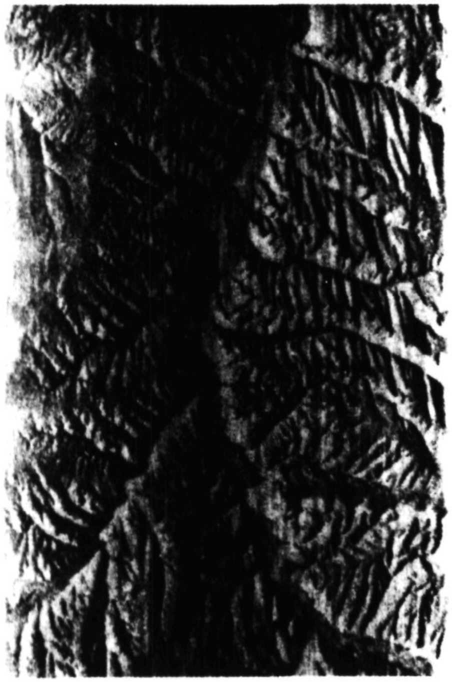

FIGURE 7. SAR IMAGE OF TEST SITE REGION.

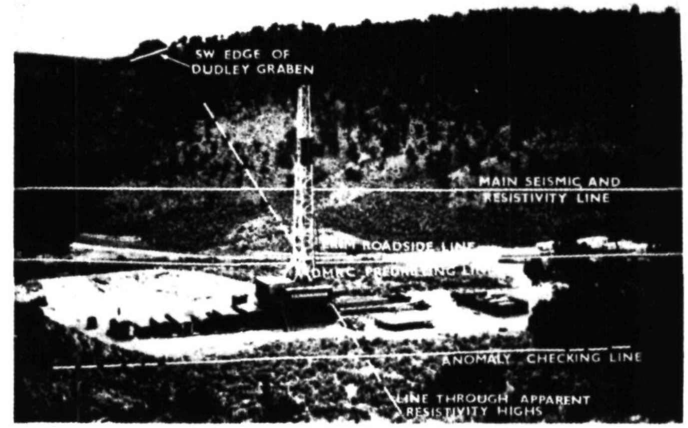

FIGURE 8. PHOTOGRAPH OF TEST SITE SHOWING OBSERVATION WELL, RESISTIVITY AND SEISMIC LINES, AND DASHED LINE THROUGH RESISTIVITY HIGHS WHICH INDICATES THE FAULT.

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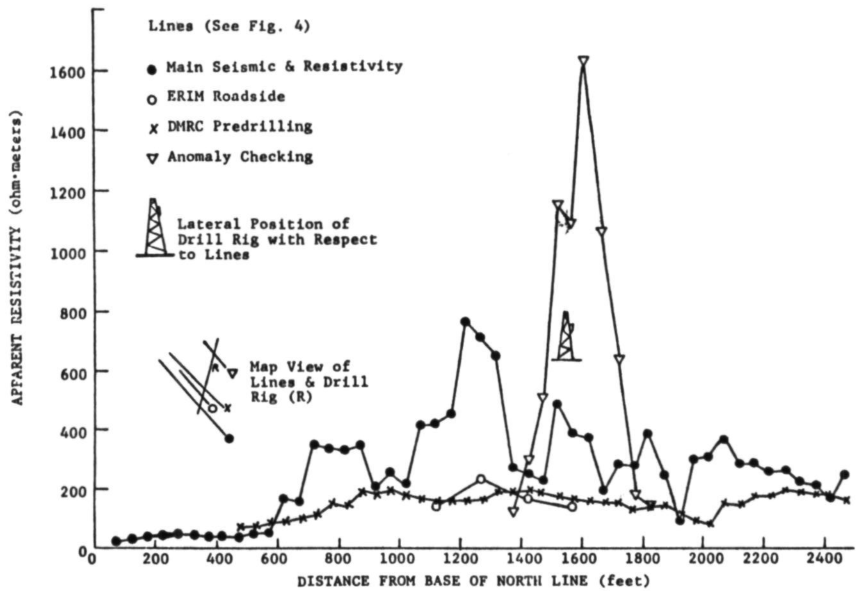

FIGURE 9. APPARENT RESISTIVITY PROFILES ON FOUR LINES IN TEST SITE. (See Fig. 8)

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