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Shallow electromagnetic data from three known fault zones in the Paradox Basin, Utah

by

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Abstract

This report describes a preliminary investigation of the effectiveness of two electromagnetic exploration methods as means of finding unmapped faults in the Paradox Basin environment. Results indicate that the Very Low Frequency (VLF) method is useful. VLF profiles were measured across three known fault traces near Gibson Dome, San Juan County, Utah. Each fault or set of faults generated a significant anomaly. In some cases, the anomaly due to the fault was superimposed on a larger scale anomaly caused by the transition from unaltered rocks away from the fault to altered rocks in or on one side of the fault zone. In one case, the lithology of the surface rocks was different on the two sides of the fault (Kayenta Formation to the northwest, Navajo Sandstone to the southeast), so the signature of the fault itself was superimposed on the signature of the transition between formations. In addition to the VLF surveys, one line of high-frequency loop-loop induction measurements was taken, using an instrument with a 4-meter loop separation. The method did not appear to locate faults successfully; further experiments using greater loop spacings need to be done.

Introduction

The U.S. Geological Survey is participating in an effort by the U.S. Department of Energy to locate a suitable site for permanent disposal of nuclear waste material in the Paradox Basin of southeastern Utah. The target medium for storage of the waste material is salt (halite) layers of the Paradox Member of the Hermosa Formation of Pennsylvanian age. At a suitable site, the repository layer would be 300 to 900 m below the surface.

The structural features of the rocks that overlie the salt are important in determining the suitability of a site. Fractures, faults, and joints (generically referred to as "faults" in this report) constitute threats to the integrity of the repository layers, as likely sources of movement (leading to physical disruption of the repository) or intrusion of groundwater (leading to dissolution of the repository host rock). It is imperative, therefore, to be able to locate faults in the Paradox geological setting.

The Permian and Mesozoic formations that overlie the salt, and that crop out near the study area at Gibson Dome, are composed of sandstone and shale. The sandstones are more resistant to erosion than the shales, so the vast majority of the surficial rocks of the area are sandstones that form nearly horizontal erosion surfaces. Most of the surficial faults in the area, therefore, have sandstone outcropping on both sides. Consequently, methods that are sensitive to material changes across a fault, such as gravity or magnetics, are unlikely to detect a fault in the Paradox environment.

Electrical methods offer a possible means of locating faults directly, as opposed to sensing changes in rock characteristics on either side of the fault. The direct detection of the fault is based on anomalous electrical properties in the fault zone. Increased groundwater penetration through fractures increases ionic conduction in the rocks during the water's presence.

Minerals that precipitate in the fracture may render the fracture either more, or less, resistive (depending on the specific minerals precipitated) — a change that persists even after water no longer occupies the fracture.

The problem of finding faults in the uniform terrane of the Paradox Basin becomes one of locating anomalous conductors or resistors. A thorough search for faults requires the use of methods that are inexpensive and rapid. This translates into a requirement for a method that needs few operators and a minimum of equipment. Field experience in the Paradox Basin indicates that contact electrical methods are difficult to apply; the combination of extremely high surface resistivity and low resistivity at shallow depths conspires to require large-surface-area current electrodes and a high-power transmitter. Non-contact electromagnetic methods are far more adaptable for reconnaissance surveys.

The study described in this report was a preliminary evaluation of two electromagnetic methods: VLF (Very Low Frequency magnetic field tilt angle and ellipticity) and short-spaced loop-loop induction. Rather than investigate an area where there was no known likelihood of finding an electrical anomaly, I surveyed several areas where there are mapped faults or inferred extensions of faults. Characterization of electromagnetic anomalies due to known faults is a useful first step in learning whether these electromagnetic methods are useful reconnaissance tools. If mapped faults cannot be detected, then there is little likelihood that these methods are useful for finding less obvious, unmapped faults.

The methods described in this report are not experimental. They have been used for many years in mineral exploration problems. What was unknown is their sensitivity to faults in a sandstone environment. The case histories that are available show successful detection of conductors in massive sulfide metal exploration. That success, however, does not reveal much information about the utility of shallow electromagnetic methods in the Paradox Basin.

The utility of any geophysical method depends on the size of an anomaly in relation to the variability in properties of the surrounding rock. That variability generates anomalies that tend to hide the significant anomaly. This is homologous to the engineer's concept of signal-to-noise ratio. This study does not go far enough in evaluating the signal-to-noise ratio for the Paradox Basin, but initial results suggest that faults are easily observable over the background noise of normal lithologic variability when using the VLF method, but not when using the short-spaced loop-loop induction method.

As with all geophysical data, interpretation is not totally straightforward. There are anomalies presented in this study (and many others) that remain unexplained. In some cases, these may be due to important structural features, such as faults, that have not been mapped because they are covered by the Quaternary eolian mantle. In other cases, they may be due to hydrologic changes in the mantle or in the underlying rock, or due to variations in thickness of the mantle. Many of the uncertainties can be resolved by taking data along parallel lines and noting what anomalies persist from line to line; these will be the important ones. In other cases, a complete interpretation requires additional knowledge that can often be gained by conducting other types of geophysical surveys.

Because the surveys presented in this report were done where faults were already known to exist, this work does not add much knowledge about the occurrence of faults in the Paradox Basin. It is hoped that the encouraging indications of the utility of the VLF method will lead to its frequent use as a reconnaissance method, pointing to those areas where more intensive work needs to be done using other methods.

The VLF Method

The United States and Soviet governments use VLF radio signals for one-way communication to their submarine fleets. The transmitter that generates the signals used in this study is located in Cutler, Maine, and transmits at a frequency of 17.8 kilohertz (KHz). The signals propagate approximately radially from the transmitter, with the electric field polarized vertically but with a small component in the radial direction; the magnetic field is polarized horizontally and perpendicular to the direction of propagation. The small component of electric field in the radial direction couples with the conductive earth surface; the electromagnetic fields penetrate the earth to an extent that is controlled by the conductivity of the rocks. An indication of the depth of penetration of the waves is given by the skindepth, δ:

$$\delta = (\pi \underline{f} \mu_o \sigma)^{-1/2} \qquad (1)$$

where σ is the electrical conductivity of the rocks in siemens/meter (S/m), $\underline{f}$ is the operating frequency of the system in hertz, and μ_o is the permeability of free space ($4\pi \times 10^{-7}$ henry/m). An analytical study by Watts (1978) indicates that a perfectly conducting narrow target (such as a buried pipe or wire) is difficult to detect at depths exceeding 1/2 skindepth. Faults and other geologic targets are not perfectly conducting, but they have greater spatial extent than the narrow perfect-conductor model; they can probably be seen at about the same depth limit. Choosing a conductivity of 0.01 S/m that is believed to be representative of sandstones in the Paradox Basin, the depth limit of detectability of a fault should then be about 20 m. The method will be useful, therefore, only in cases where the conductive electrical zone comes quite close to the surface. Many parts of the Paradox Basin are covered by a thin mantle of Quaternary eolian deposits; conductive faults should be detectable if this mantle is the only obstruction.

The VLF response to a conductor is primarily due to the following three-step process: (1) the source field induces an electric field in the host medium, (2) currents flow in the conductor in response to this primary electric field, then (3) the excess currents generate a detectable anomalous magnetic field. A resistive fault, consequently, has little VLF response because step (2) results in a small zone of reduced primary-field currents, which are not spatially concentrated, and the total anomalous current is small. The conductive fault, on the other hand, yields a compact zone of large currents. The anomalous current far exceeds the primary currents that flow in a comparable volume of the host rock. Resistive (insulating) faults or fracture zones are difficult to detect, while conductive ones are comparatively easy to detect. The essence of this study was to determine whether certain faults in the Paradox Basin are characterized by anomalously high conductivity (rather than low conductivity), thereby making them easy (rather than difficult) to detect using the VLF method.

Over a uniform earth, the magnetic field is linearly polarized in a horizontal direction. The anomalous magnetic field generated by currents flowing in buried conductors contains a significant vertical component. Because of the vertical component, the linear polarization becomes an elliptical polarization, with the major axis of the ellipse tilting away from the horizontal. The instrument used in this survey (a Geonics EM-16) measures the tangent of the major axis tilt angle and the ratio of minor axis to major axis, or ellipticity. Ellipticity can be positive or negative depending on the rotation sense of the elliptical polarization.

The interpretations of data in this report are qualitative; no comparison with modeling results has been done. There are three general principles. A transition from a less conductive to a more conductive earth or overburden is characterized by a single tilt-angle anomaly that is positive (upward tilt) when facing the more conductive region (Weaver, 1979). The maximum of the ellipticity anomaly is coincident with the maximum of the tilt angle. The signature of an isolated conductor, on the other hand, is characterized by a doublet anomaly in the tilt angle, positive as the conductor is approached (facing the conductor) and negative as it is passed (Watts, 1978). The ellipticity anomaly in this case has the same appearance as the tilt anomaly, but is broader.

Shay Graben, Line SG-1

Figure 1 shows the location of line SG-1; its bearing is S.20^{o}E. It crosses a row of small sandstone pinnacles (0 to 3 m in height) that display gouge and vertical slickensides and appear to represent the northern boundary fault of Shay Graben. Station 0 is on this row of pinnacles. The line crosses a similar but much more subdued row of pinnacles at Station 710S. The stations are located at 10 m intervals along a straight line. The station number represents the distance from Station 0 in meters, with N or S designating the direction from Station 0.

Figure 2 shows the raw data from line SG-1. The data appear somewhat noisy due to measurement uncertainty and error. Measurement error is estimated to be about ±1.5% for the tangent of the tilt angle, and ±2% for ellipticity. A smoothing filter was applied to the data to remove the jitter due to measurement errors and possibly due to small near-surface conductors in the eolian mantle. Figure 3 shows the data from line SG-1 after smoothing with a center-weighted three-point running-average filter having weights of 1/4, 1/2, 1/4. This filter removes small single-station variations in the readings and makes interpretation easier. Comparison of Figures 2 and 3 reveals no loss of significant information as a result of the smoothing process.

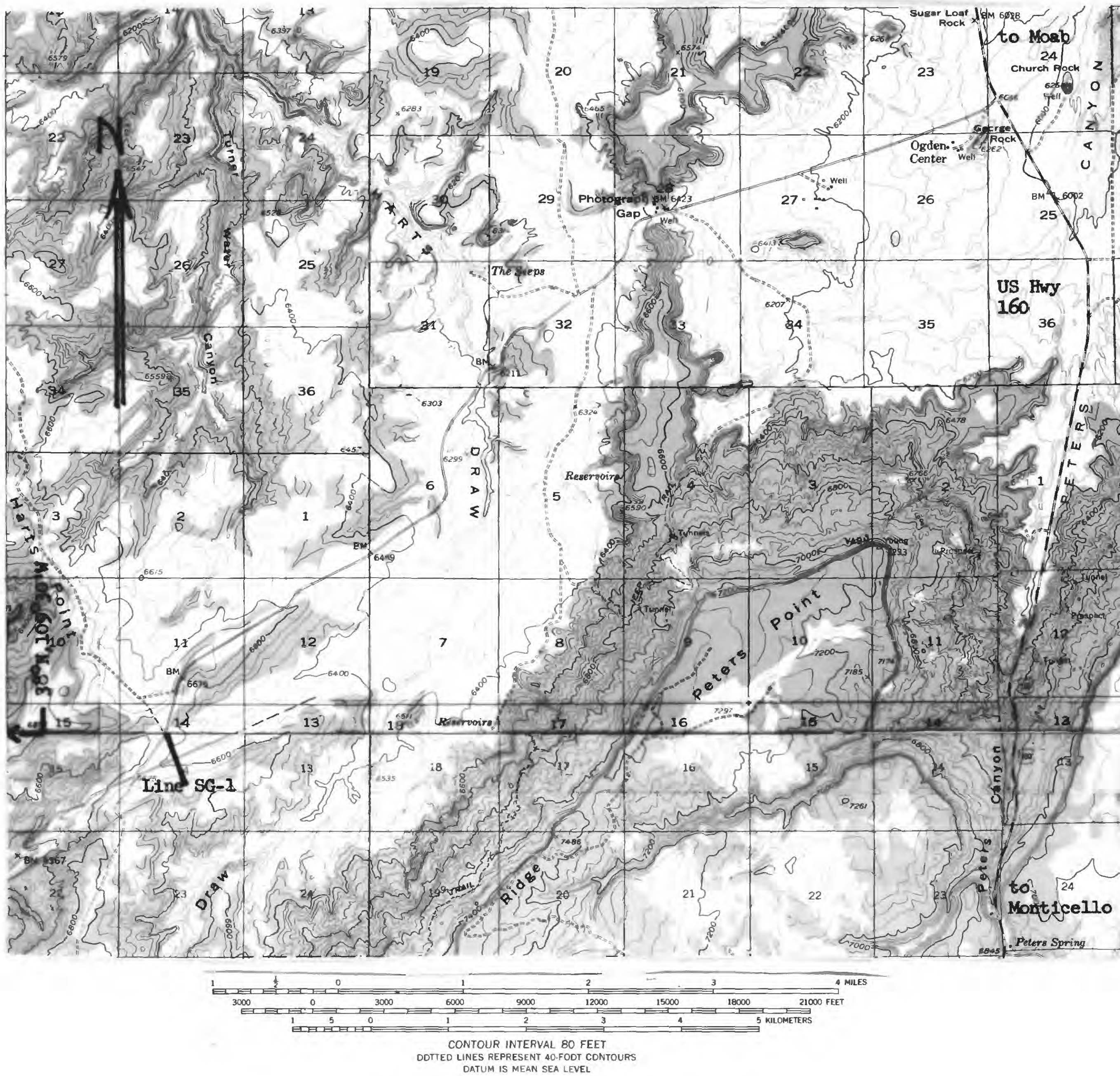


FIGURE 1.

Map showing location of line SG-1 across Shay Graben, San Juan County, Utah.

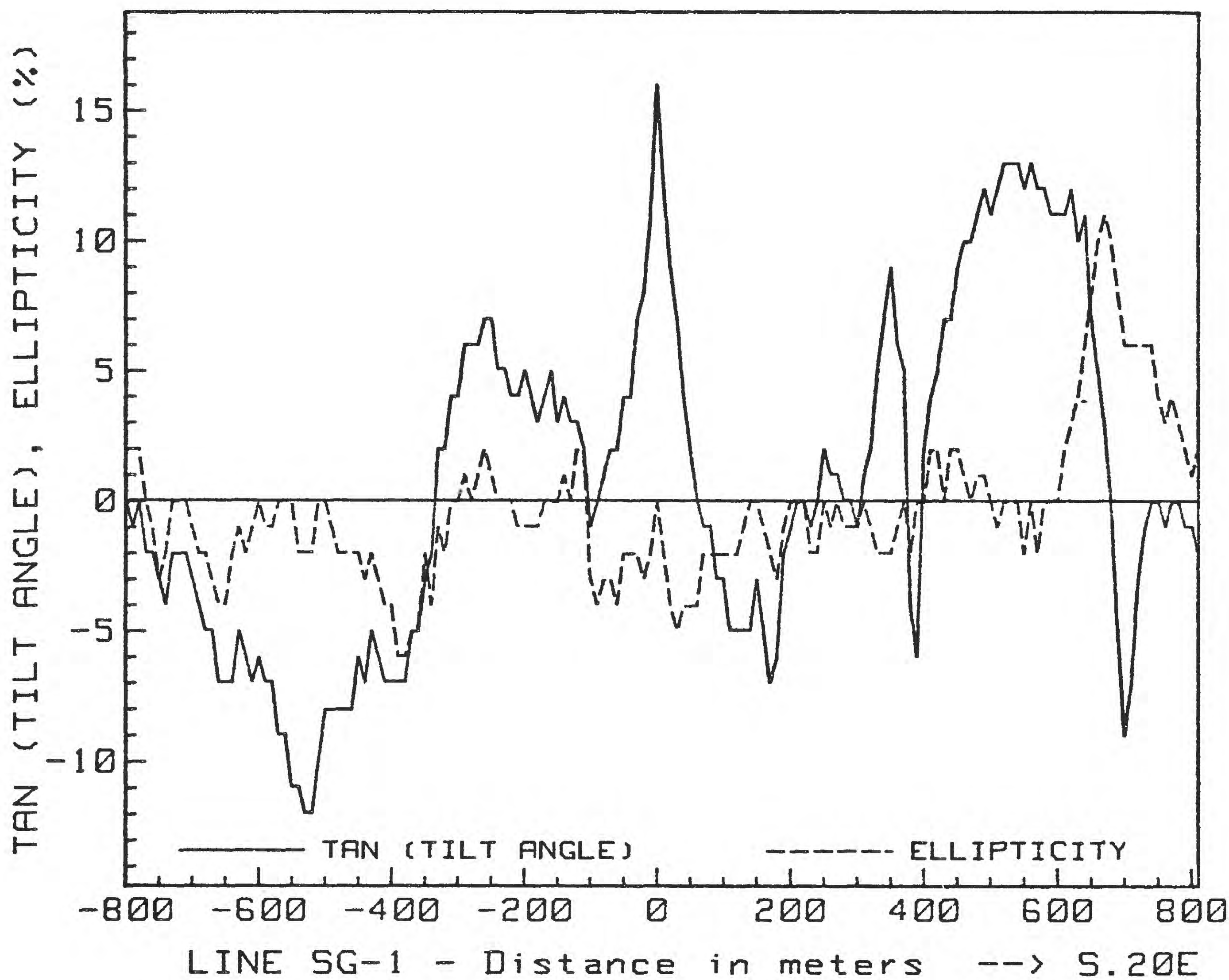


FIGURE 2. Plot of raw VLF data from Line SG-1.

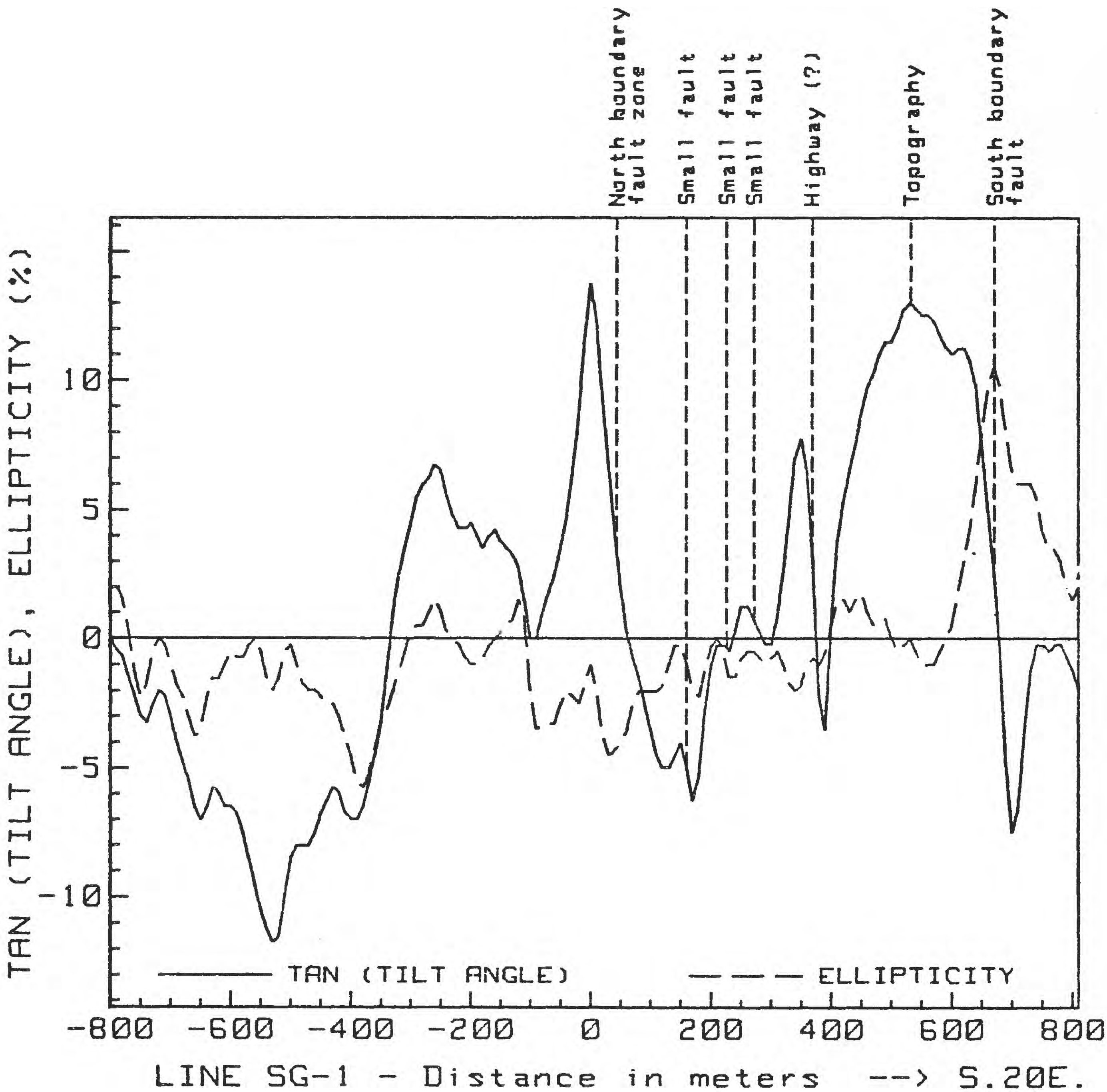


FIGURE 3. Smoothed data from Line SG-1.

The large positive tilt-angle anomaly at Station 0 is half of a doublet, with the negative peak at approximately Station 150S. The negative peak is disturbed by the superposition of a small doublet. Lack of similarity between the tilt-angle and ellipticity curves between Station 100N and 200S indicates that this large doublet results from a broad and fairly uniform zone of high conductivity. This would be the northern boundary fault zone of Shay Graben, which is offset 50 to 70 m to the south of the line of pinnacles. It is likely that this zone's conductivity is enhanced by shattering and small faulting within the downdropped block. The small superposed doublet centered at Station 160S indicates that there are small, high-quality conductors within or around this fault zone. Additional small doublets are centered at Stations 230S and 280S. Again, there are small conductive zones (possibly faults) within the downdropped block.

The large doublet centered at Station 370S may be a cultural feature, since Station 370S is on the centerline of Utah State Highway 211; it is not known whether metal is buried in or around the roadbed. If the anomaly is not cultural, then the downdropped block of Shay Graben may have a central fault, the extent of which would have to be determined by further surveys. Several short lines across the highway, offset from line SG-1, should serve to determine the natural or cultural cause of the anomaly.

South of Highway 211, the terrain rises with increasing steepness to the top of a ridge approximately 400 m away. The elevation change is about 20 m, implying a mean slope of 5%. Because the slope is not uniform but is steeper near the top, a 10% grade is estimated for the top of the slope. The strike of the slope is perpendicular to the plane of polarization of the magnetic VLF field; under these circumstances, the fields tilt to follow the terrain. The terrain-following effect is the cause of the broad positive anomaly between Stations 450S and 650S.

Superposed on the south end of the topographic anomaly, there is a doublet with the positive tilt-angle peak at Station 620S and the negative peak at Station 700S. This feature is due to the south boundary fault zone, centered at about Station 670S. Again, the anomaly center is offset from the exposed boundary fault, lying instead within the downdropped block. The reason for the large ellipticity anomaly at this point is not obvious; it may be the result of constructive superposition of anomalies due to terrain effects and the conductive zone.

Lockhart Fault System, Line LF-1

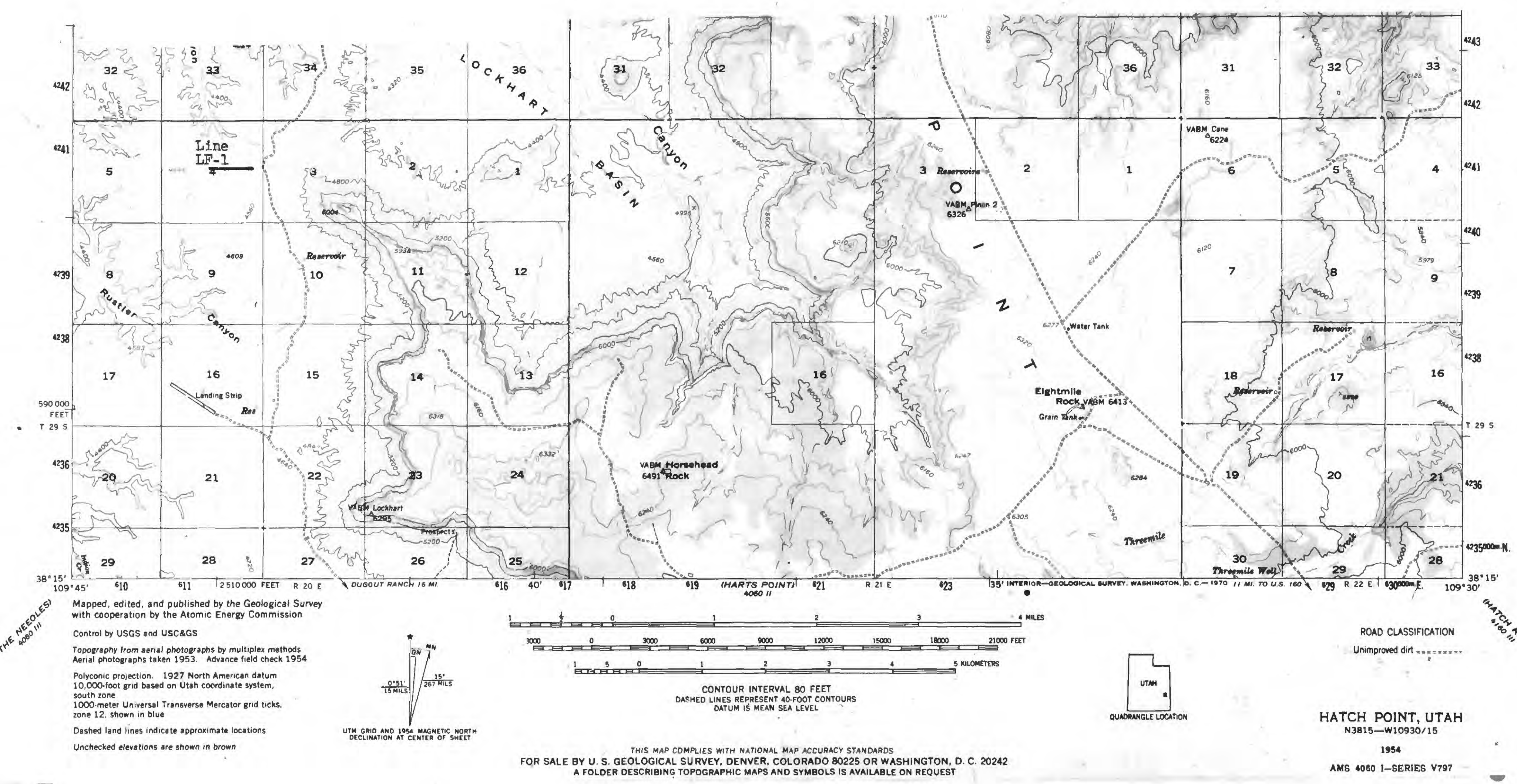
Figure 4 shows the location of line LF-1 to the west of Lockhart Basin. The line runs along an established road over a flat erosion surface that is covered with a mantle of Quaternary eolian deposits. A mapped fault is exposed in gullies to the northeast and southwest of line LF-1. Hinrichs and others (1971) show a presumed fault trace running between the two fault exposures, but hidden by the eolian cover. Their fault trace, noted as uncertain, crosses line LF-1 approximately at Station 100E.

Figure 5 shows the VLF data from line LF-1, after smoothing with the same filter that was used for line SG-1. The high correlation between the tilt-angle and ellipticity on this line is remarkable, and probably indicates that the observed anomalies are due to conductors and not to terrain effects (which would produce tilt-angle but not ellipticity anomalies). The major terrain feature is a large canyon to the north of line LF-1, which has tributary gullies that approach to within 30 m of the line near its west end. The terrain-following tendency of the fields would produce positive tilt-angles.

The major features of line LF-1 can be explained by conductors located at Stations 30E and 50W. The large positive anomaly at Station 100W is the positive part of the anomaly due to the conductor at 50W, while the large

FIGURE 4.

Portion of USGS Hatch Point 15-minute quadrangle, showing location of line LF-1.



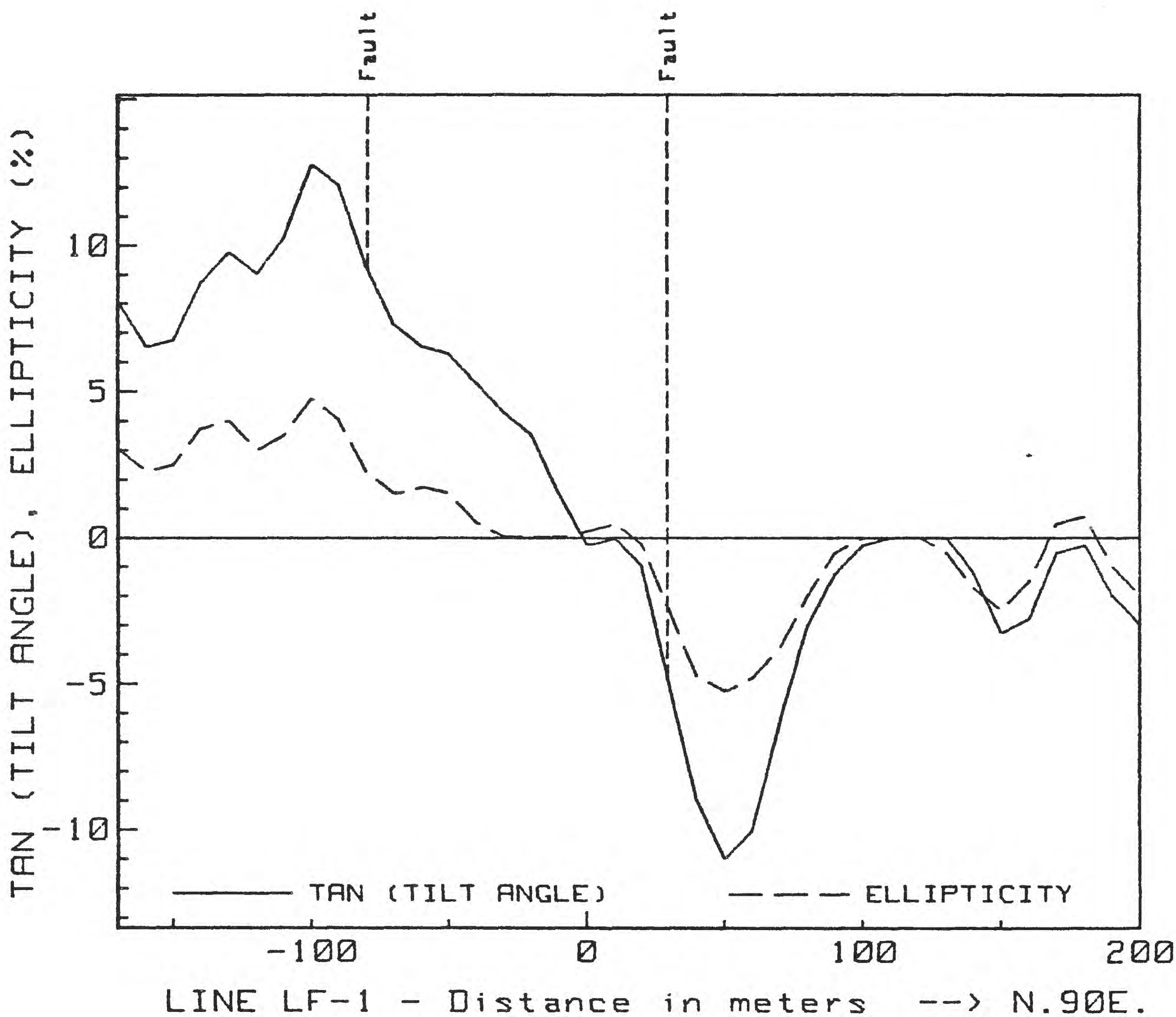


FIGURE 5. Smoothed data from Line LF-1.

negative anomaly at Station 50E is due to the conductor at Station 30E. The negative part of the western anomaly interferes with the positive part of the eastern anomaly between Station 50W and Station 0. The previously mentioned high correlation between tilt-angle and ellipticity curves indicates close correspondence to the very long strike-length condition studied by Watts (1978). In cases where the causative feature has limited strike length, the ellipticity anomaly can be of the opposite sign from the tilt anomaly (Frank Frischknecht, oral communication concerning scale model results, 1980; Patterson and Ronka, 1971).

Small anomalies centered at Stations 75W, 45W, 140E, and 190E (?) are superimposed on the large anomalies. All these are superimposed on a trend toward negative tilt-angles and ellipticity heading toward the east. Because of the amplitude of small anomalies in line LF-1, it is not possible to identify the location of a lateral change in conductivity that could be responsible for this general trend.

The fault exposures in the gully to the north of line LF-1 exhibit considerable fracturing of the rock and multiple offset zones. It is likely that the fault continuation to the southwest from that exposure has the same multiple-faulting nature. Preliminary evidence from VLF line LF-1 indicates that the fault is expressed as two conductive zones beneath the flat terrain along the line. Better definition of the nature of the faulting in this location could be obtained by making VLF measurements along a parallel line offset from line LF-1 to the south.

Hatch Point, Line HP-1

Figure 6 shows the location of line HP-1 on Hatch Point, to the northeast of Lockhart Basin. The line follows an old road that is shown on the Canyonlands National Park and Vicinity USGS topographic map (1968), which has

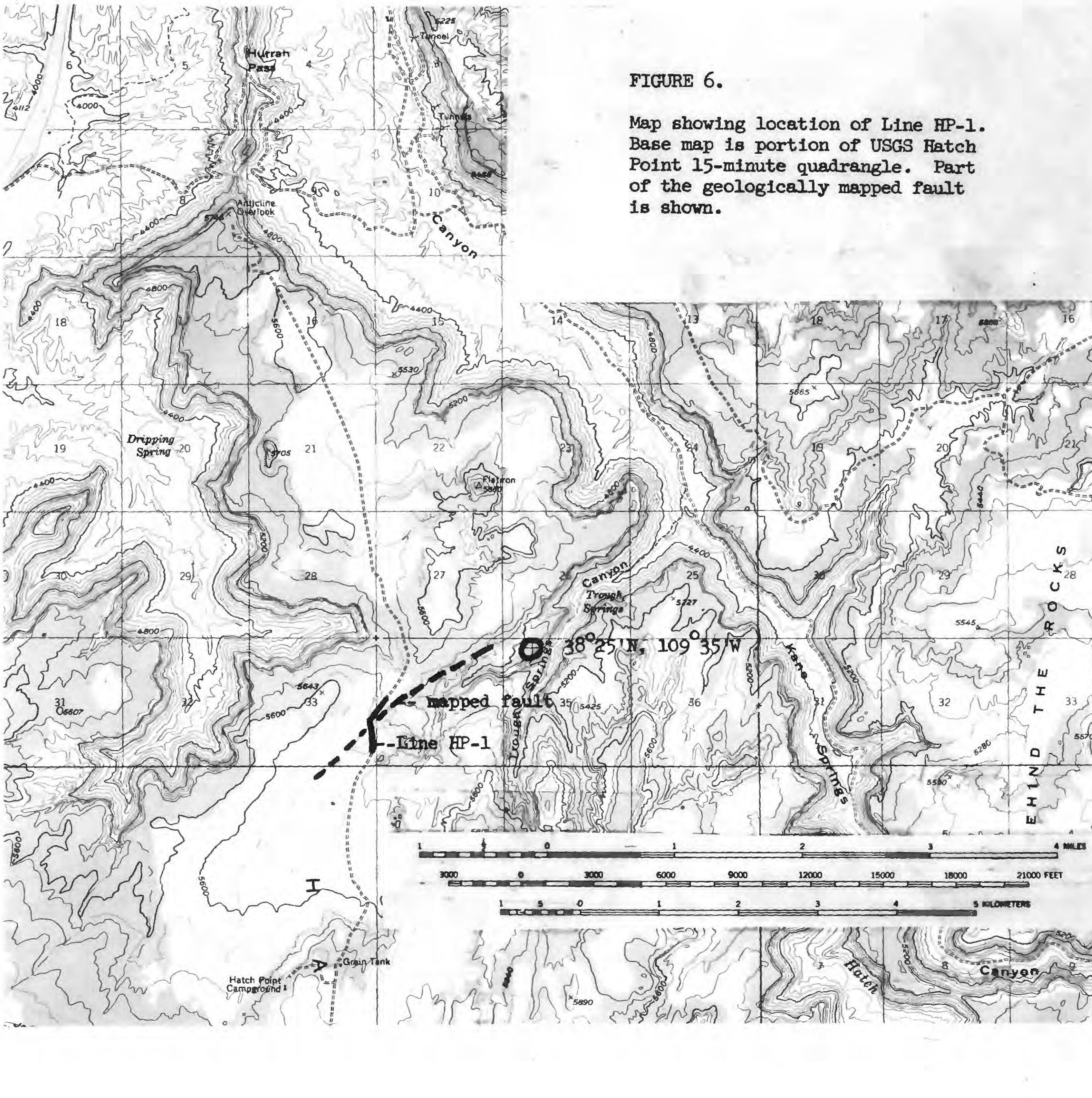


FIGURE 6.

Map showing location of Line HP-1. Base map is portion of USGS Hatch Point 15-minute quadrangle. Part of the geologically mapped fault is shown.

been replaced by a 2-lane graded road that lies farther west and north. The line crosses a fault shown on the geologic map of Hinrichs and others (1968), which forms the contact between Kayenta Formation on the northwest (upthrown) side, and Navajo Sandstone on the southeast (downthrown) side. The road does not cross the fault in a perpendicular fashion, but turns nearly parallel to the fault on its northwest side, as sketched in Figure 6.

The VLF data from line HP-1 are shown in Figure 7. It should be kept in mind when looking at these data that the line runs almost parallel to the mapped fault trace between stations 50N and 150N. These stations, therefore, would be almost coincident if they were projected onto a line perpendicular to the fault.

The expression of the fault in the data of Figure 7 is the slope from negative tilt angles and ellipticities on the left (north end of line) to positive values on the right (south end). This trend is the result of the horizontal change of lithology as the fault is crossed, with the more conductive rocks lying on the fault's south side (that is, the Navajo). Effects of small faults are superimposed on the major trend of the data. The positive tilt-angle peak at Station 0 is coincident with a negative ellipticity peak, which is a difficult situation to interpret. The anomaly cannot be due to a single, extremely long conductor, since such a feature produces matching tilt-angle and ellipticity anomalies of the same sign. Ellipticity anomalies tend to be somewhat wider than tilt-angle anomalies (Watts, 1978), so the negative ellipticity peak at Station 0 could be caused by superposition of negative ellipticities from several conductors near Stations 30S or 40S. However, as was mentioned in the discussion of line LF-1, a short conductor (which means one that is less than several skindepths long) can produce tilt and ellipticity anomalies of opposite sign; the

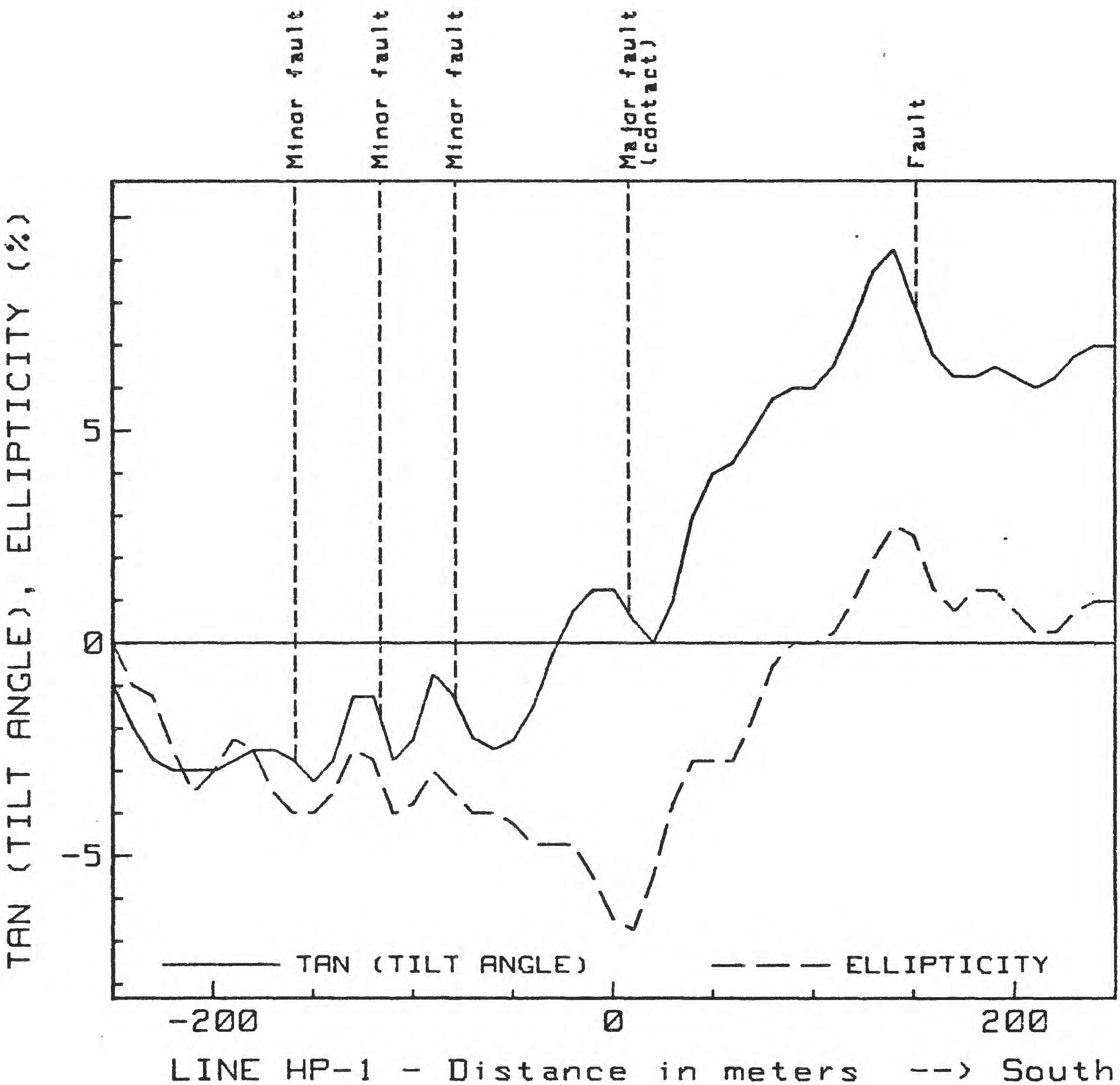


FIGURE 7. Smoothed data from Line HP-1.

existence of such a spatially limited conductor is the most likely explanation of the anomaly of Station 0.

It appears that a small conductor exists near Station 160S, which may represent an unmapped fault within the Navajo. Other small conductors are crossed at Stations 160N, 120N, and 80N; these are all quite close to the mapped fault trace because of the track of line HP-1 parallel to the fault in this part of the line.

<u>Loop-loop induction survey, Line HP-1</u>

In addition to the VLF survey presented in the previous sections, a vertical coaxial loop-loop induction survey was done. The instrument used was a Geonics EM-31, a portable instrument with a loop separation of 4 m and an operating frequency of 10 KHz. For this system, the skindepth is approximately 50 m, assuming a conductivity of 0.01 S/m for the earth. The penetration capability of the instrument is limited more by geometric factors (because of the short loop separation) than by the skindepth limit of field penetration in 100 Ohm-m materials.

Figure 8 shows the apparent conductivity of the earth as measured by this loop-loop induction system, along line HP-1. Comparison with Figure 7 reveals very little correlation between the VLF and induction measurements; the instruments apparently respond to features of different size and depth of burial. The loop-loop system does not generate anomalies that correspond to known faults in the area. It seems likely that a large part of the response can be explained by overburden conductivity and thickness. Faults in the Paradox Basin environment may not have sufficient conductivity contrast near the earth's surface to generate observable anomalies using such a small loop-loop system. There is no reason to believe that the eolian deposits on line HP-1 are especially thick for the Paradox Basin environment, so conditions on

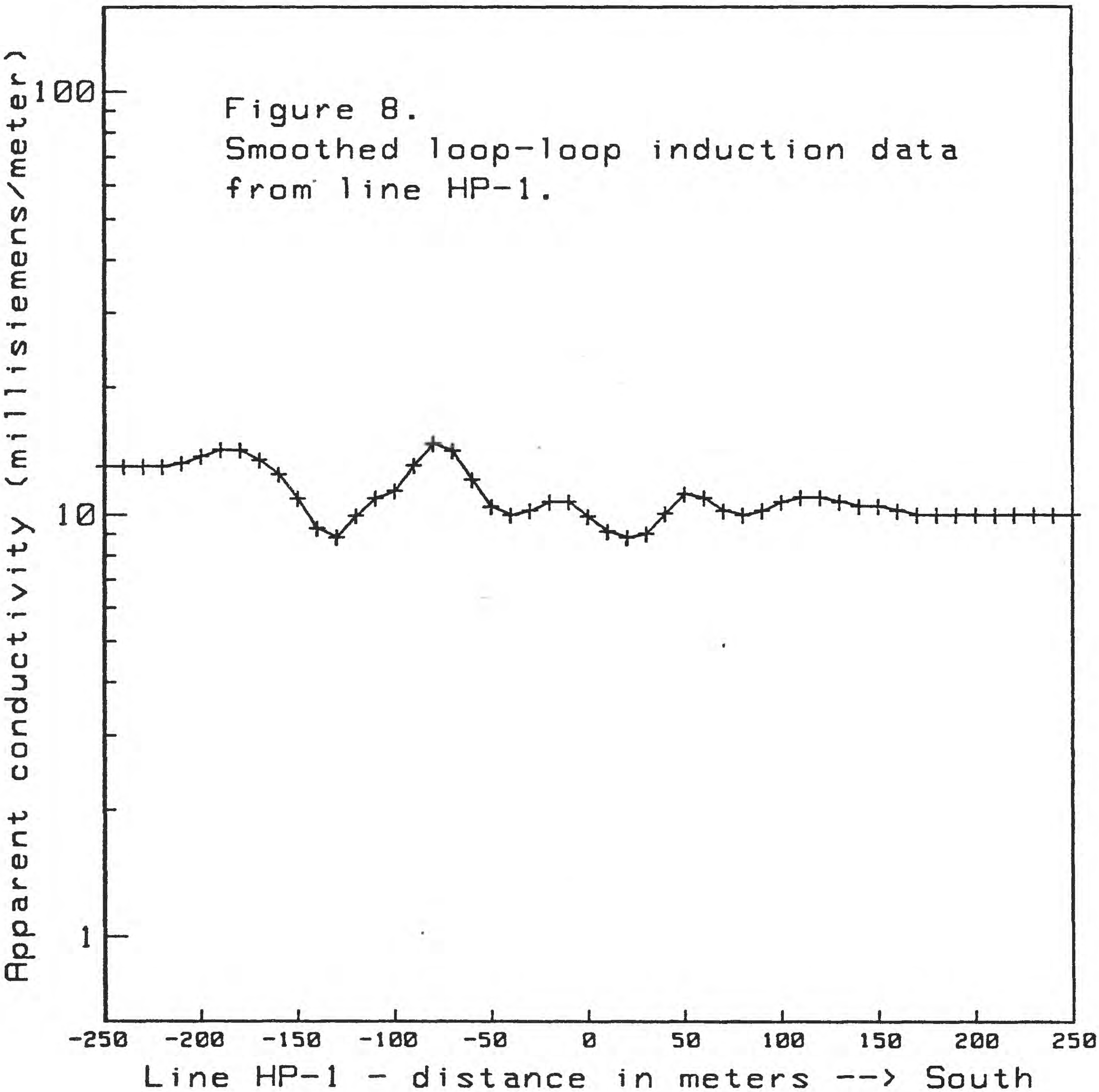


Figure 8.
Smoothed loop-loop induction data
from line HP-1.
Apparent conductivity (millisiemens/meter)
100
10
1
-250
-200
-150
-100
-50
0
50
100
150
200
250
Line HP-1 - distance in meters --> South

this line may be typical. If so, we cannot expect particularly useful fault-mapping results from this instrument.

Conclusions

The VLF magnetic fields observed with a tilt-angle and ellipticity measuring device appear to exhibit features that correspond to known faults in sandstone formations (Navajo, Kayenta, and Cutler) in the Paradox Basin. Interpretation is sometimes difficult due to multiple faults and topography, but it appears that VLF can be used successfully in mapping extensions of known fault traces in areas where the fault is hidden by thin surficial deposits.

A single line of observation with a short-spaced (4-meter) loop-loop induction instrument indicated that this instrument is not useful for defining fault traces in an area where bedrock is covered with surficial deposits. The loop-loop method may be useful in fault exploration problems in the Paradox Basin, but a larger separation between the loops appears to be required. Further work is needed to define the capabilities of this method.

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