Resistivity studies in the upper Arkansas Valley and northern San Luis Valley, Colorado

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FOCUS TARGET
RESISTIVITY STUDIES IN THE
UPPER ARKANSAS VALLEY AND NORTHERN SAN LUIS VALLEY,
COLORADO

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science, Geophysics.

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The upper Arkansas and northern San Luis Valleys lie along the northern extent of the Rio Grande depression. This possible rift feature was developed between middle Miocene and Holocene times. These two valleys are bounded by high mountains of Precambrian igneous and metamorphic and Tertiary volcanic rocks and are filled with Tertiary, Quaternary and lower middle Paleozoic sediments. The presence of thermal springs and elevated heat flow suggest that this area may be one of the best regions in Colorado to explore for geothermal systems.

Dipole and quadripole mapping resistivity surveys conducted in a reconnaissance mode can help to outline potential geothermal target areas. These two methods can detect lateral changes in resistivity over large areas with minimal amounts of time invested in field operations. The quadripole mapping method was used for this study. Over 500 stations were surveyed employing six sources located between Buena Vista and Mineral Hot Springs. Dipole electric field direction maps proved to be extremely useful for detecting anomalous areas. Dipole apparent resistivities and electric fields were modeled for a few simple resistivity configurations to substantiate interpretations. Some resistivity soundings provided depth information, which aided the interpretation of the quadripole mapping survey.

Several interesting features have been outlined by this
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The order reserves any corrections for final review.

The work that we have done has been primarily theoretical. We have used the computer example of the genogram program. This paper is based on the use of the genogram program to develop a strategy for...
study and indicate a need for additional detailed geophysical work to further determine the nature of these features. A roughly east-west linear low apparent resistivity anomaly along Chalk Creek, south of Buena Vista, may be dominated by the thermal waters of Mount Princeton Hot Springs. This linear resistivity feature may be caused by a subsurface hydrothermally altered, east-west fault zone containing thermal waters. The Salida Basin shows quite low resistivities and may be over a kilometer deep in some places. A northwest trending apparent resistivity low at Shirley, near Poncha Pass, may show the structural linkage of the Tertiary sediment filled trough, north of Shirley, with a block of the same sediments south of Poncha Pass. Two low resistivity zones are present in the northern San Luis Valley, one north of Villa Grove and one east of Mineral Hot Springs. The Villa Grove low shows a conductive zone at depth. The low apparent resistivity zone near Mineral Hot Springs may be as much as 1800 meters deep. This low shows a good conductive zone at depth.
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INTRODUCTION

With the increasing dependence of the United States on foreign sources of energy and the increased costs of this energy, interest in non-petroleum based energy sources has increased. Intensified research in the fields of solar, wind, coal, nuclear, tidal and geothermal power, as well as other possible forms of energy production, is underway.

One such effort is the search for economic geothermal energy sources. At present, the only producing geothermal field in the U.S. is The Geysers in California. Geophysical methods play an important role in the search for other geothermal fields. Crewdson (1976b) discusses geophysical studies and a possible exploration model for a Basin and Range geothermal system in the Black Rock Desert, Nevada.

Dipole mapping and quadripole mapping resistivity methods are geophysical tools used in the exploration for geothermal "target" areas. The ability of these methods to cover large areas in relatively short time makes them effective reconnaissance tools. These resistivity methods are used to determine lateral changes in earth resistivity. Areas of low relative resistivity are of interest to the geothermal explorationist, since increases in temperature of rocks lower the resistivity of them (Keller and Frischknecht, 1966). Discussions of the use of these resistivity techniques in geothermal exploration have been published by Jordan (1974), Morris (1975), Keller and others (1975) and Crewdson (1975b).
The Rio Grande depression is an area of geothermal potential. Heat flow studies point to the feature as a potential major geothermal prospect area (Reiter, et al., 1975). The presence of numerous hot springs in the northern portion of the rift is encouraging to researchers and exploration groups. The Department of Geophysics at the Colorado School of Mines in Golden, Colorado conducted four geophysical surveys during 1976 for the Colorado Division of Water Resources in the northern San Luis and upper Arkansas Valleys, Colorado. A quadripole mapping resistivity survey, an electrical resistivity sounding survey using the Schlumberger method, a magneto-telluric survey and a reflection seismic survey were carried out in this area. A summary of these surveys is contained in a report to the Colorado Division of Water Resources by the Colorado School of Mines Geophysics Department (1977). Stoughton (in progress) and Arestad (this study) have done extended analyses of some of the surveys for thesis research.

The author took part in the quadripole mapping resistivity survey, which was conducted in May and June, 1976, and with the magneto-telluric survey. Interpretation of the quadripole mapping survey is the subject of this thesis.
THE STUDY AREA

Location and Accessibility

The study area is located in central Colorado between latitudes 38° 5' N and 38° 55' N and between longitudes 105° 45' W and 106° 15' W (see Figure 1). The town of Salida is situated near the center of the area. The area is about 70 kilometers north of Alamosa, Colorado; 110 kilometers west of Pueblo, Colorado; 70 kilometers east of Gunnison, Colorado; and 140 kilometers southwest of Denver, Colorado.

The area may be reached by U.S. Highway 285, U.S. Highway 24, U.S. Highway 50, and Colorado Highway 17. Nearly the entire survey area may be reached with a two wheel drive vehicle.
Figure 1. Location map.
General Tectonic and Physiographic Setting

The upper Arkansas Valley and northern San Luis Valley are down-dropped late Cenozoic basins. These valleys are fault controlled, sediment filled graben features. The upper Arkansas Valley is bordered on the west by the high mountains of the Sawatch Range. The Arkansas Hills and the Mosquito Range bound the upper Arkansas Valley to the east (see Figure 1). The Poncha Pass area to the south separates this valley from the northern San Luis Valley. The northern San Luis Valley is flanked to the east by the spectacular Sangre de Cristo Range. This valley is bordered to the west by the Cochetopa Hills volcanic mountains, which are a northeastern extension of the San Juan Mountains. The northern San Luis Valley widens to the south towards the Grand Sand Dunes, Alamosa and Del Norte.

Van Alstine (1968) demonstrated that these two valleys are connected by a structural trough containing late Tertiary sediments. The trough crosses the Poncha Pass topographic feature west of U.S. 285. The two valleys and the structural trough are interpreted to be on the northern end of the Rio Grande rift zone. Chapin (1971) argues that the existence of this structural feature between the valleys implies that the Rio Grande rift extends through the Arkansas Valley at least to the continental divide north of Leadville. However, Knepper (1974) believes that the valleys never formed a continuous depression.
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The upper Aroarul Valley and surroundings can form valleys
are composed of a unique geo-stratigraphic formation that
are characterized by a prominent geologic correlative layer.
These are complex, the Upper Aroarul can form valleys
and the Aroarul Range. The Aroarul Range is a
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are characterized by a prominent geologic correlative layer.
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and the Aroarul Range. The Aroarul Range is a
form valley. An example of this is the Aroarul Range.
The Rio Grande rift extends from northern Mexico northward for about 1000 kilometers into central Colorado. Topographic relief along the rift zone in the study area is as much as 1800 meters in the upper Arkansas Valley at Mt. Princeton (4,328 meters elevation above sea level) and over 1500 meters in the northern San Luis Valley along the Sangre de Cristo Range. Basin depths in the study area along the rift in the northern San Luis Valley, near Mineral Hot Springs, have been interpreted to be as much as 1800 meters (Jordan, 1974). The earliest period of rifting produced the two valleys separated by a topographic high south of Poncha Pass in middle Miocene and Pliocene time (Knepper, 1974). Knepper (1974) believes that the most recent tectonic activity along the rift zone was less than 10,000 years ago.

The Rio Grande rift has formed due to westward movement of the Colorado Plateau block (plate) away from the interior (Great Plains plate) (Chapin, 1971). This movement of the Colorado Plateau plate is hinged on the north. This rotational movement may account for the widening of the rift feature to the south.
Area Geology

The upper Arkansas Valley is a north-south trending graben feature bounded by steeply dipping normal faults (see Plate 1). The valley is filled with unconsolidated Miocene, Pliocene and Quaternary sediments. The Browns Canyon Formation (Miocene), the Dry Union Formation (Miocene and Pliocene), terrace and pediment gravels (Quaternary) form the majority of these sediments (Knepper, 1974). The Dry Union Formation is dominant and may be more than one kilometer thick in the Salida Basin (Knepper, 1974).

The upper Arkansas Valley is separated by a narrow fault zone from the Precambrian metamorphic and igneous core of the Sawatch anticline to the west. This area was intruded by the Mount Princeton igneous complex, a series of early Tertiary intrusives (Dings and Robinson, 1957). The small Mount Princeton quartz monzonite batholith dominates these intrusives. At the mouth of Chalk Creek canyon, thermal waters have altered this quartz monzonite to produce the "Chalk Cliffs", a well known local landmark. The mouth of Cottonwood Creek canyon also shows alteration, but to a lesser degree than near Chalk Creek. Limbach (1975) postulates east-west faults in the mouths of Chalk Creek and Cottonwood Creek canyons.

To the east of the upper Arkansas Valley, a series of parallel normal faults separate the valley from the Mosquito
Range-Arkansas Hills region (Knepper, 1974). This region contains predominately Precambrian igneous and metamorphic rocks overlain by Tertiary volcanic and sedimentary rocks (Van Alstine, 1969). The Browns Canyon horst block bounds the northern part of the Salida graben.

The Poncha Pass topographic feature between the upper Arkansas and northern San Luis Valleys exposes a trough of late Tertiary sediments in Precambrian igneous and metamorphic rocks (Van Alstine, 1968). The Dry Union Formation (Miocene and Pliocene) dominates this structural trough. This structural feature is known as the South Arkansas tilted block (Knepper, 1974). Van Alstine (1970) describes a series of Paleozoic detachment blocks along the Little Cochetopa Creek drainage area. Tertiary volcanic flows from the Bonanza Volcanic center to the south cover much of the area (Perry, 1971; Knepper, 1974).

The northern San Luis Valley is a northwest trending, fault-controlled structural and sedimentary basin. The basin is filled with Tertiary and Quaternary sediments. The Dry Union Formation, Tertiary volcanics from the Bonanza volcanic center, Paleozoic sediments and Quaternary alluvium and alluvial fans are found in the northern San Luis Valley (Knepper and Marrs, 1971; Knepper, 1974). The west side of the valley along the Sangre de Cristo range displays many alluvial fans, some of which are of glacial outwash origin (Wisconsinian). Displacement of these alluvial surfaces up to 7.5 meters along the Sangre de Cristo fault
zone occurred less than 10,000 years ago (Knepper, 1974). One branch of this fault zone continues along the front of the Sangre de Cristo Range. The Villa Grove fault zone departs from the Sangre de Cristo fault zone and branches out into the valley towards Villa Grove from the southeast (Knepper, 1974). The Kerber Creek-Major Creek fault zone is projected across the valley in a west-northwest orientation at Mineral Hot Springs by Knepper (1974).

The northern San Luis Valley is separated from the Sangre de Cristo Range to the east by the Sangre de Cristo fault. The Sangre de Cristo Range is a horst block consisting of Precambrian igneous and metamorphic rocks along with folded and complexly faulted Paleozoic sedimentary rocks (Knepper, 1974).

The Cochetopa Hills volcanic mountains border the northern San Luis Valley to the west. These volcanic rocks are Tertiary in age and originated from the Bonanza volcanic center. Burbank (1932) first recognized the existence of a volcanic collapse caldera around the town of Bonanza. The Bonanza center was mineralized with ore veins containing silver, gold, lead and zinc. This area was extensively mined in the past and has very minor mining activity at present.
Thermal Features

The study area contains numerous hot springs including Hortense Hot Spring, which is the hottest spring in the state. Many of these hot springs occur along basin margin faults. These faults may possibly act as plumbing systems, enabling the thermal waters to reach the surface.

The Cottonwood Hot Springs are located about 8 kilometers southwest of Buena Vista at the base of Mount Princeton. Crewdson (1976a) reports a surface temperature of 52°C with a discharge of 100 gallons per minute.

The Mount Princeton Hot Springs are situated approximately 12 kilometers south of Buena Vista near the mouth of Chalk Creek canyon at the base of the "Chalk Cliffs". The Chalk Cliffs are altered Mount Princeton quartz monzonite (Knepper, 1974). This alteration is due to the presence of the thermal waters, possibly originating from the source for the Mount Princeton Hot Springs. These hot springs include Heywood (Chalk Creek) Hot Springs and Hortense Hot Springs. Heywood Hot Springs discharge 200 to 300 gallons per minute at 52 to 63°C and Hortense Hot Spring is 84°C at the surface with a flow of 30 gallons per minute (Crewdson, 1976a).

At the southern end of the upper Arkansas Valley, the hot springs near Poncha Springs are situated along another basin-margin fault. The springs flow at 135 gallons per minute with a temperature of 69°C (Crewdson, 1976a).

The Wellsville Warm Spring flows from a tunnel in
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THE STUDY SHOWS COOPERATIVE RESOLUTION FOR MANUFACTURING

The research was conducted to investigate the potential of the

surface treatment process for improving the wear resistance of

metallic materials. The test samples were subjected to various

heat treatments and were then subjected to a sliding wear test to

evaluate their performance. The results showed a significant

improvement in wear resistance for the treated samples.

These findings are important for the development of new

wear-resistant materials. Further research is needed to

explore the full potential of this technology.

The council recommended the following steps for the future:

1. Conduct additional research to understand the

mechanistic aspects of the treatment process.
2. Develop a comprehensive database to aid in the

standardization of the treatment process.
3. Implement the technology in various industries to

evaluate its practical applications.

In conclusion, the research has demonstrated the

capabilities of the surface treatment process for

improving wear resistance. Further efforts are needed

to bring this technology to the market.
limestone about 8 kilometers southeast of Salida. The discharge is 150-200 gallons per minute at 34°C (Crewdson, 1976a). Nearby, Swissvale Warm Springs discharge approximately 150 gallons per minute at 20-28°C (Barrett and Pearl, 1976).

In addition to these hot springs in the upper Arkansas Valley, Romero (oral communication, 1977) and Barrett (oral communication, 1977) report some small warm springs north of Salida along the Browns Canyon horst mountain front.

The northern San Luis Valley has two main hot spring systems. The Mineral Hot Springs are located about 9 kilometers south of Villa Grove. Mineral Hot Springs discharge about 350 gallons per minute at 57°C (Crewdson, 1976a). Knepper (1974) projects the Kerber Creek-Major Creek fault zone across the northern San Luis Valley at Mineral Hot Springs.

Approximately 10 kilometers east of Mineral Hot Springs along the Sangre de Cristo fault zone, lies Valley View Hot Springs. This local bathing spot discharges 275 gallons per minute at 36°C (Crewdson, 1976a). Knepper (1974) reports numerous cold water springs along the trace of the Sangre de Cristo fault zone. These springs may possibly derive some of their discharge from depth, as well as contributions from subsurface damming effects due to fault surfaces (Knepper and Marrs, 1971).

In addition to these hot springs in the northern
FOCUS TARGET
San Luis Valley, Barrett and Pearl report that Fullinwider Warm Spring, 7 kilometers north of Villa Grove, is discharging $18^\circ$C water at 11 gallons per minute (Barrett and Pearl, 1976).
Previous Geophysical Studies

One of the first geophysical surveys covering the study area was a regional gravity survey of Colorado (Holmer, 1954). Gaca (1965) interpreted gravity data in the San Luis Valley, including the southernmost end of the thesis area. This interpretation showed a minimum depth to basement of 4880 meters near Villa Grove. A revised gravity interpretation of these data indicated a depth to basement of 1890 meters at this location (Jordan, 1974). Isaacson and Smithson (1976) have interpreted a gravity low just east of the Mount Princeton batholith in the upper Arkansas Valley to represent a one kilometer wedge of Tertiary sediments.

Jordan (1974) conducted geothermal studies in the San Luis Valley near Mineral Hot Springs. Thermal infra-red imagery was flown over the Valley View and Mineral Hot Springs. However, only the hot springs and some ponds produced thermally anomalous features on the imagery. A dipole mapping electrical resistivity survey was conducted over this area. Equatorial dipole resistivity soundings, Schlumberger resistivity soundings and time-domain electromagnetic soundings were conducted by Jordan (1974) in the Mineral Hot Springs area. Zohdy and others (1971) interpreted 1400 meters of valley-fill in the upper Arkansas Valley, south of Buena Vista, from resistivity sounding data.

An active seismic reconnaissance survey of the Mount Princeton area in the upper Arkansas Valley monitored large blasts from nearby mining operations (Crompton, 1976).
Refractions from boundary features of the upper Arkansas Valley graben were correlated with the extension of the Rio Grande rift. A probable subsurface normal fault at Chalk Creek, south of Buena Vista, was indicated by a velocity anomaly. Keller and Adams (1976) report that the San Luis Valley exhibited extremely low seismic activity in a three week microearthquake survey.

Geophysical exploration for geothermal and petroleum occurrences has been conducted in the San Luis and upper Arkansas Valleys by private industry. However, no economic discoveries have been reported to date.

Description of Dipole Mapping Resistivity

The dipole mapping or double-dipole mapping resistivity method is not a conventional in-line resistivity technique. Dipole mapping is a direct current resistivity method, which provides areal coverage. This method is used primarily in a reconnaissance mode to detect lateral changes in earth resistivity. However, it should be noted that vertical changes in earth resistivity affect the results and may not be distinguishable from lateral changes. This method has been applied mostly to geothermal exploration, but has also found use in mining exploration and engineering applications (Keller, et al., 1975).

An electric field is established in the earth by applying a direct current to a pair of electrodes in the ground. The
THE METHOD

This area of the Rio Grande depression (rift zone) exhibits features encouraging to geothermal explorationists. Previous geological and geophysical studies, as well as surface thermal manifestations in the area indicate possible geothermal potential. Reconnaissance geophysical studies can indicate potential geothermal target areas. Dipole and quadripole mapping resistivity surveys are used in a reconnaissance mode to find areas of low apparent resistivity, which may indicate subsurface thermal features. A quadripole resistivity survey was conducted in the study area for this purpose.

Description of Dipole Mapping Resistivity

The dipole mapping or bipole-dipole mapping resistivity method is not a conventional in-line resistivity technique. Dipole mapping is a direct current resistivity method, which provides areal coverage. This method is used predominately in a reconnaissance mode to detect lateral changes in earth resistivity. However, it should be noted that vertical changes in earth resistivity affect the results and may not be distinguishable from lateral changes. The method has been applied mostly to geothermal exploration, but has also found use in mining exploration and engineering applications (Keller, et al., 1975).

An electric field is established in the earth by supplying current to a pair of electrodes in the ground. The
THE HISTORY

The area of the Rio Grande Resolution (1940) and
the efforts to resolve it have been a subject of
considerable discussion and controversy. The
area has been the subject of numerous
legal, political, and economic discussions,
resulting in various resolutions and
agreements. The Rio Grande Resolution
was initially initiated to address issues
related to water usage and distribution,
and has since evolved into a broader
discussion of jurisdictional boundaries,
water rights, and environmental
concerns. The area is significant not only
for its natural resources but also for its
historical and cultural significance. The
resolution has been a topic of ongoing
debate and negotiation, reflecting the
complexities of managing shared
resources in a region with diverse
stakeholders.
separation between these electrodes must be much greater than the receiver lengths, in order for the current source to approximate two separate pole sources or a bipole source. In practice, this source bipole is commonly longer than one kilometer and the receiver dipoles are ten to one hundred meters in length. The electric field produced by the bipole source is mapped in detail. The direction and magnitude of the electric field vector at each station is determined by measuring the electric field in the ground with two receiver dipoles with different orientations. The general scheme of dipole mapping is depicted in Figure 2.

From the magnitude of the electric field, the source current and the source-receiver geometry, an apparent resistivity \( \rho_a \) and an apparent conductance \( S_a \) can be calculated for each receiver location. The apparent resistivity is computed assuming spherical spreading of current in a homogeneous earth. Furgerson and Keller (1974) have developed the following expression for the apparent resistivity applicable to the dipole mapping method:

\[
\rho_a = 2\pi R_1^2 \left[ 1 + \left( \frac{R_1}{R_2} \right)^4 - 2 \left( \frac{R_1}{R_2} \right)^2 \cos \delta \right]^{-\frac{1}{2}} \frac{E_T}{I},
\]

where \( \rho_a \) is apparent resistivity in ohm-meters, \( R_1 \) and \( R_2 \) are distances in meters, \( E_T \) is the magnitude of the electric field in volts/meter, and \( I \) is current in amperes (see Figure 2).

Apparent conductance is an alternate way of representing apparent resistivity when the current spreads out in a
FOCUS TARGET
Figure 2. General dipole scheme.

(after Furgerson and Keller, 1974)
conductive sheet. Cylindrical spreading of current is assumed for the case of a conductive layer over a resistive basement. This is often the case when layered sediments cover crystalline basement. Conductance is defined as the ratio of layer thickness to the resistivity of the layer \((S = \frac{h}{\rho})\). The formula to compute apparent conductance for dipole mapping data is given by (Furgerson and Keller, 1974):

\[
S_a = \frac{1}{2\pi R_1} \left[ 1 + \left( \frac{R_1}{R_2} \right)^2 - 2 \left( \frac{R_1}{R_2} \right) \cos \delta \right]^{1/2} \frac{I}{E_T}
\]

where \(S_a\) is apparent conductance in mhos, \(R_1\) and \(R_2\) are distances in meters, \(E_T\) is the magnitude of the electric field in volts/meter, and \(I\) is current in amperes.
congruence groups. Congruence groups of order $n$ for $n \geq 2$ have a natural \[ \frac{1}{n} \sum_{k=1}^{n-1} \left[ \cos \left( \frac{2\pi k}{n} \right) - 1 \right] = 0 \]
Quadripole Resistivity

Resistivity or conductance maps from a single bipole source often show "false" anomalies produced by the channelling of current along various earth structural configurations (Furgerson, 1970; Furgerson and Keller, 1974). In some cases, these false anomalies can be of use in structural interpretations (Morris, 1975). Vertical fault and dike models have been discussed by Furgerson and Keller (1974) and the dipping layer case has been studied (Lee, 1973).

In order to eliminate false anomalies, multiple coverage from different bipole sources must be obtained or quadripole mapping must be done. Quadripole mapping employs two nearly orthogonal bipole sources at the same location. Electric field measurements are made for each source. This provides two electric field vectors at each station. By combining these two electric field vectors in various proportions with similar directional proportions of the currents from the two sources, a resistivity ellipse can be determined for each receiver station. This process of rotation can be done in the office on a digital computer. Morris (1975) has discussed the mathematics of rotation in detail. Quadripole mapping cannot only eliminate false anomalies, but rotation can determine the resistivity ellipse orientation and the coefficient of anisotropy (Keller and Frischknecht, 1966) for each station, which may be helpful interpretation of the resistivity data (Morris 1975). The coefficient of anisotropy is defined as the square root of the ratio of
maximum to minimum resistivities from the ellipse. Morris (1975) has shown that the average resistivity (mean of the maximum and minimum resistivities of the ellipse) can be an effective means of finding the true resistivity of the medium containing the source and removing false anomalies along structural features.
Field Methods and Instrumentation

Two nearly orthogonal bipole sources were set up at each source location. Culverts and metal-cased wells were used as electrodes for the source bipoles, in order to obtain low grounding resistance. The source bipole electrodes were between 1.7 and 3.2 kilometers apart for this study. Insulated cable was used to carry current to the electrodes.

The sources were powered by a 27 kVA gasoline powered motor generator. The three phase, 220 VAC, 60 hertz generator output was transformed to 880 VAC through a variac and transformer. This output was then rectified to direct current. The polarity of this direct current was switched to produce an asymmetric square wave with a period of approximately 20 seconds. One bipole was powered with this output for a few minutes and after a short period of no transmission, the other bipole source was powered. The current output of the bipole sources was recorded on a chart recorder or digital voltmeter. The current output varied between 25 and 65 amperes peak-to-peak for this study.

The electric field measuring equipment consisted of two 30 or 100 meter nearly orthogonal receiver wires (18 AWG) connected to non-polarizing electrodes, an amplifier and a chart recorder. The azimuths of the dipole receiver legs were measured and the polarity of the electric field in each leg was determined from the asymmetrical signal.
Thus, it was possible to determine the direction and magnitude of the electric field due to each bipole source.

A time schedule was maintained for transmission at the source to insure measurement of the proper bipole source signal by the receiver operators. Two receiver sets were employed for most of the survey. Receiver station separation was between one and two kilometers. The electric field was measured as far away from the common bipole electrode as 17 kilometers.
Data Reduction and Handling

After each day or two in the field, the data were compiled from the field records to calculate apparent resistivities and conductances. This was done in order to improve the receiver coverage in the areas of potential interest. Electric field polarities and magnitudes and source currents were picked from chart paper records. Locations of stations were determined by each receiver operator and marked on 1:62,500 scale topographic maps. This method of location is well within the necessary accuracy for the computations.

After this step, apparent resistivities, apparent conductances, electric field directions and electric field magnitudes at each station for each of the two bipole sources were calculated using a programmable, hand calculator. Preliminary field maps of resistivity were then prepared.

Upon completion of the survey, approximately fifteen percent of the field records and locations were rescaled. Human error can be quite significant in this type of survey with large numbers of stations. The corrected field data were then recomputed on the CSM computer (Digital Equipment Corporation PDP-10). The bipole source computations were done with a program adapted by the author from DIPOLE. F4 (G. V. Keller). Rotated quadripole resistivities were computed using the rotation program, RCON. F4. A discussion
FOCUS TARGET
of the rotation technique is contained in Morris (1975).

The various results were plotted on the CSM Houston Plotter. This provided a quick and accurate method of presenting the various data to be studied. Scatter plots and resistivity sounding plots were also prepared in this manner. Statistical evaluation of the data was also done on the CSM computer using a user interactive statistical program (Stat Pack). This package contains all the statistical routines normally used in statistical studies and was useful in the evaluation of the study area resistivities.
The various markers were located on the CSS Etoile.

Plotted. This provided a dynamic and interactive overview of
the various markers. The data were then analyzed and
utilized in various forms. The analysis revealed some patterns
and correlations that were not previously noticeable.

Additional information on the data was also given to
assist in understanding the results.

The CSS computer made a neat information structure

problem (refer back). This because certain fit the criteria:

Cross. The impact correlation may be represented visually
and
was crucial to the continuation of the work into later
characteristics.
Resistivity Modeling

The complexity of interpreting dipole mapping resistivity data has been discussed in the literature (Keller, et al., 1975). Modeling of simple structures has been done and has proven helpful in interpretation of dipole mapping resistivity data (Morris, 1975). Furgerson (1970) has modeled a vertical fault and two horizontal layers. Contour maps for the dipping layer case have been computed and studied (Lee, 1974). The effect of anisotropy on apparent resistivities and electric field directions has been demonstrated by Keller and Crewdson (1976).

Models have been computed for some possible resistivity features using the method of Furgerson and Keller (1974). The method employs the use of "image theory" (Heiland, 1940; Keller and Frischknecht, 1966; Van Nostrand and Cook, 1966). A thorough discussion of the use of the method and its computer application has been made by Furgerson and Keller (1974).

This computer technique was employed to study modeled apparent resistivities and electric field vector directions over possible subsurface structural features. The fact that the models are more simple than real earth structures somewhat limits the use of these models in interpretation. However, these models can be helpful in giving the interpreter insight as to possible explanations for observed resistivity and electric field direction data.
The capability of modeling more complex structures for dipole mapping will be necessary for the dipole and quadripole techniques to meet with wider acceptance and use. This desirable complex modeling will probably need to use schemes other than "image theory" in order to be implemented. The use of "image theory" is limited to simple cases. Finite difference and the method of moments may be possible methods to evaluate more complex structures.
The capability of existing shoe material technologies and
the adipose deposits in the human foot will make wide
variety of materials and structures meet with proper
needs. This makes it possible to create new shoes that
are very similar to the ones that were designed to
accommodate the human foot. The use of "fused shoe" to
refer to a shoe designed with "shoe" in mind in
simply means "fusion". This fusion of new (or existing) and
classical designs of shoes will make it possible to
create shoes that are more comfortable and
functional.
Source Locations and Coverage

Six quadripole source locations were occupied during the survey, with 511 receiver stations mapped. Three sources were in the upper Arkansas Valley; one source was located near Poncha Pass; and two more sources were mapped in the northern San Luis Valley (see Plate 2). There is a small amount of coverage overlap between most of the sources. For most of the sources, the receiver station spacing was approximately 1.5 kilometers. Sources 2 and 4 have a higher station density and source 3 has limited coverage due to limited accessibility in this area (see Figures 3-8).

Source 1 was located at Maxwell School, approximately 5 kilometers south southwest of Buena Vista. Source 2 was located 3 kilometers north northwest of Poncha Pass with one bipole leg along U.S. Highway 285. Source 3 was situated near Browns Canyon, 14 kilometers north of Poncha Springs along U.S. 285. Source 4 was located near the Salida Airport, approximately 6 kilometers west of Salida. The source 5 location was 8 kilometers north northwest of Villa Grove along U.S. 285. Source 6 was located 1.6 kilometers west of Mineral Hot Springs along U.S. 285 and Colorado 17. The source 6 location was previously covered by Jordan (1974), but was repeated in more detail in this study. This was done as a test for repeatability of the method and to achieve better areal coverage in this area of interest.
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Figure 3. Station locations for source 1.
Figure 4. Station locations for source 2.
Figure 5. Station locations for source 3.
Figure 6. Station locations for source 4.
Figure 7. Station locations for source 5.
Figure 8. Station locations for source 6.
INTERPRETATION OF RESULTS

The survey was originally designed and carried out as a quadripole mapping survey with two nearly orthogonal bipole sources at each of six locations. When the rotation program was run on the data to obtain quadripole resistivities, it was discovered that up to 50 percent of the data points did not meet the criterion for good rotation.

Accurate determination of the resistivity ellipse for any station using the rotational method requires that the electric field vector from each bipole source be oriented nearly orthogonally to the other. Reasonable accuracy can be obtained by allowing the angle between the vectors to vary between 35 and 145 degrees. The use of angles outside of this range produces rotated resistivities that probably are not accurate.

Many of the stations did not have suitable angles between the electric field vectors. This can be attributed to one or more of several factors. The first and most obvious factor may be operator error. However, it is felt that this is not the major contributor, although probably a substantial one. A second factor can be the effect of anisotropy. This effect is considered to be a minimal factor for this survey. The presence of anomalous resistive and conductive zones in the earth can distort the electric field sufficiently to be another factor (see Figures 29-40). This effect may be the major contributor to unsuitable angles between electric field vectors in this survey.
Since the quadripole resistivity data for this survey have only half as many reliable stations as the dipole resistivity, the author has chosen to interpret the dipole data and relate these results to a quadripole average resistivity map of the survey area. (Plate 2).
Scatter Plots

The use of scatter plots of apparent resistivity versus distance from closest source electrode can be helpful in discerning an earth model for field data. Furgerson and Keller (1974) have demonstrated that, for an earth model of a conductive layer over a resistive basement, the apparent resistivity contour map shows lowest apparent resistivity closest to the source and increasing apparent resistivity away from the source. For this model, increased apparent resistivity with increased source-receiver separation should be expected for any resistivity array. If such a relationship is observed in field data, the parameter of apparent conductance may be more appropriate to represent data. For such a layered earth model, a scatter plot of apparent resistivity versus distance from closest electrode should show a general linear increase of resistivity versus increased spacing.

Scatter plots were prepared for both bipole sources of each source location (Figures 9-14). The obvious scatter of these plots suggests that a layered earth model is not generally applicable in the thesis area. The plot for the north-south leg of source 1 (Figure 9) shows some degree of increasing apparent resistivity versus spacing. This shows that a layered earth model may apply to part of the map area, but lateral changes in resistivity contribute to the scatter.

The data in this thesis area will be presented as
FOCUS TARGET
Figure 9. Apparent resistivity scatter plots for source 1.
FOCUS TARGET
Figure 10. Apparent resistivity scatter plots for source 2.
Figure 11. Apparent resistivity scatter plots for source 3.
Figure 12. Apparent resistivity scatter plots for source 4.
Figure 13. Apparent resistivity scatter plots for source 5.
Figure 14. Apparent resistivity scatter plots for source 6.
apparent resistivity rather than apparent conductance due to the scatter of the plots. However, it should be noted that the layered earth model applies for much of the thesis area in the valleys, where relatively conductive valley-fill sediments cover resistive basement.
Statistical Evaluation

Statistical measures were computed on the apparent resistivities from all twelve bipole sources. Table 1 is a summary of some basic statistical measures (mean, standard deviation and median).

The apparent resistivity populations for all of the twelve bipole sources are generally lognormally distributed (see Figure 15). This can be characteristic of dipole mapping apparent resistivities with the source bipole located on a conductive layer over a resistive basement. A reasonable uniform areal distribution of stations around a source for the layered case can generate a similar population trend. Lateral variations in resistivity can skew or alter the population distributions for non-uniform areas. For example, the presence of an areally large, lateral resistor can skew the apparent resistivity distribution towards higher resistivities.

An examination of the arithmetic mean apparent resistivities in Table 1 shows the source 2 resistivities to be high. The source 4 apparent resistivities are anomalously low. High resistivities for source 2 (Poncha Pass area) should be expected, since most of this area is covered with Tertiary volcanics and Precambrian igneous and metamorphic rocks, which are more resistive than valley-fill sediments. The low mean apparent resistivities for source 4 (Salida basin) suggest the presence of a large horizontal conductive and possibly relatively deep section of valley sediments.
### TABLE 1

Apparent Resistivity Statistical Summary

<table>
<thead>
<tr>
<th>Source</th>
<th>Bipole</th>
<th>Mean*</th>
<th>Standard Deviation</th>
<th>Median</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N-S</td>
<td>66.2</td>
<td>153.1</td>
<td>20.3</td>
<td>83</td>
</tr>
<tr>
<td>1</td>
<td>E-W</td>
<td>69.8</td>
<td>178.6</td>
<td>42.6</td>
<td>83</td>
</tr>
<tr>
<td>2</td>
<td>N-S</td>
<td>529.2</td>
<td>1163.5</td>
<td>251.5</td>
<td>79</td>
</tr>
<tr>
<td>2</td>
<td>E-W</td>
<td>340.9</td>
<td>532.2</td>
<td>190.5</td>
<td>79</td>
</tr>
<tr>
<td>3</td>
<td>N-S</td>
<td>61.5</td>
<td>62.4</td>
<td>44.4</td>
<td>43</td>
</tr>
<tr>
<td>3</td>
<td>E-W</td>
<td>144.4</td>
<td>139.4</td>
<td>101.8</td>
<td>43</td>
</tr>
<tr>
<td>4</td>
<td>N-S</td>
<td>41.8</td>
<td>71.6</td>
<td>13.6</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>E-W</td>
<td>21.9</td>
<td>34.4</td>
<td>10.4</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>N-S</td>
<td>98.1</td>
<td>97.5</td>
<td>72.0</td>
<td>83</td>
</tr>
<tr>
<td>5</td>
<td>E-W</td>
<td>126.7</td>
<td>117.9</td>
<td>96.4</td>
<td>83</td>
</tr>
<tr>
<td>6</td>
<td>N-S</td>
<td>193.9</td>
<td>252.6</td>
<td>122.3</td>
<td>124</td>
</tr>
<tr>
<td>6</td>
<td>E-W</td>
<td>365.2</td>
<td>610.4</td>
<td>188.4</td>
<td>124</td>
</tr>
</tbody>
</table>

*Arithmetic mean

**Note:** Units of mean, standard deviation and median are ohm-meters.
Figure 15. Histogram of source 5, E-W bipole resistivities.
Figure 16. Histogram of source 4, E-W bipole resistivities.
The high mean values for source 6 may be due to a larger percentage of stations out of and on the edges of the valley than for the other sources (see Figure 8) and/or high resistivities in fresh water saturated alluvium. A smaller percentage of valley edge stations may also contribute to the low mean apparent resistivity of source 4.

Since the resistivity populations exhibit logarithmic normal distributions (Figures 15 and 16), the contour intervals used for the maps of apparent resistivity are logarithmic. The lognormal distribution in Figure 16 for the E-W bipole of source 4 is skewed to the lower side. This observed characteristic and low mean resistivities point to the Salida basin as an anomalous resistivity feature.

The logarithmic mean is known to be a better mean value for lognormal populations. For a lognormal population, the arithmetic mean is not an appropriate averaging method to obtain accurate central tendency. This mean will be lower than the arithmetic mean and much closer to the median. The median values in Table 1 are considerably lower than the arithmetic means and may be used as a rough estimate of the logarithmic mean.
The problem means for source are now put to use in a linear button of transition at one or on the status of the area put for the other sources (see figure 1). Another step of the transition in the manner parallel of another phase. The area containing the two source section may the contributor to improve the apparent transition of source and possibly improve the transition. The contributor to improve the apparent transition of source and possibly improve the transition. The contributor to improve the apparent transition of source and possibly improve the transition. The contributor to improve the apparent transition of source and possibly improve the transition. The contributor to improve the apparent transition of source and possibly improve the transition. The contributor to improve the apparent transition of source and possibly improve the transition. The contributor to improve the apparent transition of source and possibly improve the transition.
Dipole Mapping Apparent Resistivity Maps

The apparent resistivity maps generally outline the valleys very well with the most conductive rocks in the valleys and resistive rocks bounding the valleys (see Figures 17-28). The lowest apparent resistivities are located in the upper Arkansas Valley, near Salida and near Chalk Creek. The terms resistor and conductor will be used in this study to mean resistive rocks and conductive sediments or rocks, respectively.

**Source 1:** The apparent resistivities for the N-S bipole near Buena Vista point out an interesting feature at Chalk Creek (Figure 17). Resistivity lows around the electrodes indicate a conductor over resistor (Furgerson and Keller, 1974). The resistive valley boundaries are roughly outlined to the east and west by the 50 ohm-meter contour lines. A low anomaly to the north of the source appears to be a largely source-produced feature. The east-west trending linear low to the south appears to be an expression of the Mount Princeton Hot Springs and/or a subsurface structure along Chalk Creek (Crompton, 1976). There appears to be very little expression of any feature near Cottonwood Hot Springs, except for the possible source-related low anomaly.

The E-W bipole for source 1 displays a somewhat different pattern (Figure 18). The valley is not as well outlined by any contour, although, the 50 ohm-meter contour is a fairly reasonable valley outline to the east and west
Figure 17. Apparent resistivities (ohm-meters) for N-S bipole, source 1.
Figure 18. Apparent resistivities (ohm-meters) for E-W bipole, source 1.
of the source area. The east electrode displays a conductor over resistor pattern. The large anomaly to the east of the source is probably source-related, since it doesn't appear on the N-S bipole map. There exists no anomalous feature north of the source that would correspond with the anomaly from the N-S bipole in that area. An east-west trending resistivity low south of the source corresponds with the low from the previous source at Chalk Creek. This is one of the most interesting resistivity features observed in this study.

**Source 2:** The second area to be surveyed was near Poncha Pass and had very high apparent resistivities. This is due to the large amount of volcanic, igneous and metamorphic rocks in the area. The resistivity maps from both source bipoles are very similar, indicating a minimal number of false anomalies (Figures 19 and 20). Poncha Springs Hot Springs produces a low anomaly near 35 ohm-meters on both maps. A northwest trending relative low just north of the source is seen for both bipoles. This is interpreted as an expression of the synclinal trough of Tertiary sediments over the Poncha Pass area (Knepper, 1974, Van Alstine, 1968). This anomaly correlates well with the southern fault-truncated end of this trough showing exposed Dry Union Formation. The apparent resistivities over this trough increases northward, as the resistive basement affects the observed data more with increased distance from the source. The small lower resistivity regions 3 to 4 kilometers
Figure 19. Apparent resistivities (ohm-meters) for N-S bipole, source 2.
Figure 20. Apparent resistivities (ohm-meters) for E-W bipole, source 2.
south of the south electrode for the N-S bipole is not apparent for the E-W bipole and is probably a source-enhanced resistivity expression of exposed Dry Union Formation south of Poncha Pass. A northwest-southwest low resistivity anomaly is observed on both bipole maps off the west end of the E-W bipole. The linearity of this anomaly suggests a relatively narrow zone with lowered rock resistivity. This anomaly is associated with exposed Dry Union Formation near the anomaly center. This anomaly trends into the south low anomaly, but is separated from the northern low by a small highly resistive zone of intrusive granitic rocks. A southward continuation of the west bounding fault of the Tertiary sediment-filled trough may be a possible explanation for this feature.

Source 3: The limited coverage on source 3 near Browns Canyon provides a marginally useful set of data to work with (Figures 21 and 22). The 50 ohm-meter contour may yield an approximate shape of the valley-fill for the N-S bipole data. The westernmost extent of the Browns Canyon horst is very close to the common electrode to both bipoles and is expressed by high apparent resistivities. The closed resistivity low at the west end of the E-W bipole on both maps indicates a conductor over resistor near the common electrode. This conductor is most likely Dry Union Formation. Both bipole maps show a small resistivity high to the southeast of the source. This occurs along the southwest flank of the Browns Canyon horst block.
Figure 21. Apparent resistivities (ohm-meters) for N-S bipole, source 3.
Figure 22. Apparent resistivities (ohm-meters) for E-W bipole, source 3.
and may indicate a covered portion of the horst.

Source 4: The Salida basin area is an area of low resistivity. The Dry Union Formation, which is a combination of alluvial fan, mudflow, flood plain and lake deposits, is exposed over much of this area. Quaternary gravels and alluvial fans cover most of the rest of the valley (Knepper, 1974). The presence of the Dry Union Formation in sufficient thickness may significantly contribute to these low resistivities.

For both bipole sources, a closed high resistivity anomaly around the common electrode indicates a surface resistor over a conductor at depth (Figures 23 and 24). This resistive layer may be caused by the downward leaching of electrolytes by ground water movement and partial desaturation of the sediments above the water table yielding lower salinity and higher resistivity for the leached surface layer.

Source orientation produces relatively low "false" anomalies (10 ohm-meters and less) off each end of both bipole sources. A large, low apparent resistivity anomaly west and northwest of the common electrode is a potentially interesting feature. A resistivity low to the south of Salida is also of interest. Poncha Springs Hot Springs vicinity has apparent resistivities of 10 and 14 ohm-meters. This is most likely a thermally-produced low, since the hot springs are located in Precambrian rocks (Knepper, 1974).
FOCUS TARGET
Figure 23. Apparent resistivities (ohm-meters) for N-S bipole, source 4.
FOCUS TARGET
Figure 24. Apparent resistivities (ohm-meters) for E-W bipole, source 4.
A probable, high resistivity expression of the Browns Canyon horst block is seen at the northern extent of source 4 coverage. Apparent resistivities along the mountain fronts to the east, west and south of the valley are not as large as in other areas of this study. An inflection of the resistivity low south of Salida down the Arkansas River towards the southwest and the presence of low resistivities along the mountain front north of Salida may be of geothermal interest. High apparent resistivities north of Salida for the E-W bipole and at Salida for the N-S bipole lie along the Arkansas River and may be caused by less saline ground water near the Arkansas River.

**Source 5:** The apparent resistivity maps from both bipole sources point out several very interesting structural features (Figures 25 and 26). The resistive rocks on both sides of the northern San Luis Valley are reasonably well outlined by the 100 ohm-meter contour line on the N-S bipole map. The N-S bipole tends to elongate and enhance the low resistivities of the valley-fill sediments. The E-W bipole map shows a source-related, "false" anomaly along the axis of bipole extending across the valley. This anomaly does not appear on the N-S bipole map. Both maps show a low resistivity anomaly southeast of the source. A lower resistivity zone extending onto the alluvial fans towards Oak and Hayden springs appears on both maps with a low anomaly (less than 20 ohm-meters) just west of the springs on the
Figure 25. Apparent resistivities (ohm-meters) for N-S bipole, source 5.
Figure 26. Apparent resistivities (ohm-meters) for E-W bipole, source 5.
N-S bipole apparent resistivity map. A small moderately high resistivity feature 4 kilometers west of Villa Grove correlates well with a shallower portion of the basin (Stoughton, in progress). Thinning of valley-fill sediments and increasing distance from the source causes the apparent resistivities to increase northward in the valley. The presence of igneous and volcanic rocks from Alder westward is expressed on both maps. South of the source along Kerber Creek, a northwest trending apparent resistivity high shown on both bipole maps is the expression of the Precambrian crystalline core of the Eastern anticline (Knepper, 1947). Westward from this feature, low and then high apparent resistivities express the Clayton syncline and the Central anticline, respectively.

The 50 and 100 ohm-meter contours on the E-W bipole map exhibit a peculiar spreading pattern. The contours are close to the source west of the highway and spread out in the valley east of U.S. 285. An unexposed northwest trending normal fault or the eastern limb of a north trending anticline with the valley side down dropped may exist just west of the eastern electrode. A sudden eastward thickening of the relatively conductive section at or just west of U.S. 285 could produce such a pattern.

Source 6: The apparent resistivities of the area near Mineral Hot Springs are higher than the apparent resistivities for the other four valley source areas (Figures 27 and 28).
Figure 27. Apparent resistivities (ohm-meters) for N-S bipole, source 6.
Figure 28. Apparent resistivities (ohm-meters) for E-W bipole, source 6.
This fact is partially due to a much larger area of coverage
with resistive basement contributing more to the apparent
resistivities at receiver stations farther from the source.

A check of the repeatability of the method with data
collected by Jordan (1974) at this location shows good
agreement of results (see Figures 27 and 28 and Jordan,
1974). The source used in this study was not situated
the same as the source for the previous study, but was in
the same area.

Both E-W and N-S sources show the presence of a resis-
tor below the source area. The high apparent resistivities
to the west of the source area are due to the quartz mon-
zonite (Knepper, 1974) exposed there. The high resistivities
on the east side of the valley show the presence of resis-
tive Precambrian rocks of the Sangre de Cristo Range under
the alluvial fans. Both source maps display a northwest
trending resistivity high along Kerber Creek which is due
to the resistive core of the Eastern anticline. The N-S
source map also shows the resistive igneous core of the
Central anticline west of the Eastern anticline and the
less resistive Clayton syncline filled with Paleozoic sedi-
ments between the anticlines. Neither of the two hot spring
systems in the area exhibit low apparent resistivities.

The N-S source bipole map has decreasing resistivity
to the north, which is probably due to increasing depth
of the basin to the north. Jordan (1974) indicates that
this is probably fault-controlled. The deepest part of
of the basin (Jordan, 1974), about 5 to 8 kilometers east of the north electrode is not expressed significantly in the N-S bipole data.

The E-W bipole resistivity data displays higher apparent resistivities in the valley than for the N-S bipole. An east-west resistivity low south of the source may be source-caused. This feature is not seen on the N-S bipole map. The deep part of the basin is expressed by a resistivity low. A lower resistivity zone extends up onto the alluvial fans north of the Orient mine.
Electric Field Directions

The observed electric field directions due to each bipole source were plotted and studied to help detect any resistive or conductive trends in the study area. Any coherent deviations from the pattern for the uniform earth case must be due to changes in earth resistivities. Induced current tries to follow the path of least resistance. Therefore, current will tend to concentrate in a conductor and will try to flow out of a resistor. Along a resistor-conductor boundary orthogonal to the axis of a bipole source, electric field vectors in the conductor will be nearly parallel to the boundary and the vectors in the resistor should be approximately orthogonal to the boundary. Keller and Crewdson (1976) demonstrated that the effect of horizontal anisotropy can also produce large deviations in electric field directions from the directions for the isotropic case. A dipole mapping survey at the Warm Springs in Bath County, Virginia, was strongly affected by anisotropy (Keller and Crewdson, 1976). However, the effect of anisotropy is not a strong factor in the study area.

Despite the obvious scatter of the electric field directions for the study area, the dominant electric field patterns and deflections can be observed (see Figures 29-40). The results of this technique can be quite informative and helpful in interpretation.

The south axial electric field line for the N-S bipole of source 1 is curved westward towards a conductor at
Mount Princeton Hot Springs (Figure 29). This would indicate that the low east-west resistivity feature at Chalk Creek is dominated by a more conductive zone at Mount Princeton Hot Springs. The electric field east of the N-S bipole appears to be skewed to the south. This is most likely due to the low resistivity feature at Chalk Creek. The electric field for the E-W bipole of source 1 shows no obvious distortion (Figure 30).

The electric field for the N-S bipole of source 2 shows no obvious deflections (Figure 31). The electric field for the E-W bipole of source 2 shows a sudden spreading southwest of the west electrode (Figure 32). This is particularly noticeable towards the south. This suggests the presence of a northwest trending conductive zone at this location.

The data for source 3 are too sparse to recognize any unusual disturbances in the electric fields for either bipole (Figures 33 and 34).

To the west of the N-S bipole of source 4, the electric field appears to be shifted to the south towards Salida (Figure 35). An apparent resistivity low is situated in the south Salida area. The electric field from the E-W bipole may be slightly skewed towards this area southwest of the source (Figure 36). No other features are apparent on the source 4 map.

The electric field due to the N-S bipole of source 5
FOCUS TARGET
Figure 29. Electric field directions for N-S bipole, source 1.
Figure 30. Electric field directions for E-W bipole, source 1.
Figure 31. Electric field directions for N-S bipole, source 2.
Figure 32. Electric field directions for E-W bipole, source 2.
Figure 33. Electric field directions for N-S bipole, source 3.
Figure 34. Electric field directions for E-W bipole, source 3.
Figure 35. Electric field directions for N-S bipole, source 4.
Figure 36. Electric field directions for E-W bipole, source 4.
appears relatively undistorted with only a slight bending of the north axial line towards the more conductive valley (Figure 37). The electric field pattern for the E-W bipole looks relatively undisrupted upon first examination (Figure 38). However, the vectors south of the east electrode along the highway and eastward have radically changed directions. This type of electric field behavior is indicative of the effects along a resistor-conductor boundary. A sudden increase in depth of valley-fill sediments eastward just west of the highway would cause such a change in electric field directions. Despite the obvious scatter of the data south of the E-W bipole, the continuity of this trend suggests that this feature is real.

The electric field for the N-S bipole of source 6 is skewed towards the south on the east side of the source (Figure 39). The north axial line is bent to the east towards the deepest part of the valley east of Villa Grove and the south axial line is distorted slightly west. These are effects of the southward skewing of the electric field. The electric field for the E-W bipole of source 6 shows an eastward shift, south of the bipole, with a southward attraction of the west axial line towards the more conductive valley-fill sediments (Figure 40). The southward skewing of both of the Source 6 electric fields is probably caused by widening of the San Luis Valley to the south.
Figure 37. Electric field directions for N-S bipole, source 5.
Figure 38. Electric field directions for E-W bipole, source 5.
Figure 39. Electric field directions for N-S bipole, source 6.
Figure 40. Electric field directions for E-W bipole, source 6.
Models of Some Resistivity Features

Three of the resistivity features that can be approximated by simple vertical dike-like or fault models were studied to confirm the interpretations of observed apparent resistivity and electric field anomalies. The vertical dike-like models are tabular bodies of differing resistivity than the surrounding medium and do not refer to an intrusive body. The features modeled are the east-west low resistivity zone at Chalk Creek, the northwest trending resistivity low just west of source 2 on the Marshall Pass road, and the possible valley fault or anticline limb near the east electrode of the E-W bipole of source 5.

The simplistic nature of the available models allows only a qualitative interpretation. The presence of alluvial cover over subsurface structures tends to smooth out observed resistivity and electric field changes. Changing basement configuration also has a strong effect on these data. The available modeling programs cannot compensate for these two factors. However, the use of these models allows for better understanding of the apparent resistivity and electric field changes encountered. The parameters for the models have been selected so that the modeled results reasonably agree with the observed field data. All of the models used had a very resistive basement at a depth of one kilometer.

The electric field for the N-S bipole of source 1 is skewed southward, west of the source and the south axial line is bent towards the west. The model of a very conductive
The area of the participating enterprises may be studied in the
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can be tested for the occurrence of ore bodies and the amount of
material. A model of the material can be made. The model
material and extractive fields can be tested for the occurrence of
ore bodies and the amount of material. A model of the material
can be made.
east-west "dike" (2 ohm-meters) at Chalk Creek with 30 ohm-meter sediments on each side of it with a resistive basement seems appropriate, but the two kilometer wide "dike" must not be orthogonal to the N-S source bipole to produce the observed electric field distortions (Figure 29). This model (Figure 41) is not entirely appropriate, but serves to demonstrate this type of field distortion and suggests that the Mount Princeton Hot Springs area is more conductive than the rest of the Chalk Creek low resistivity zone. The apparent resistivity model for this "dike" (Figure 42) is a reasonable approximation to the observed data (Figure 17). A model of an east-west conductive "dike" with a more conductive area at Mount Princeton Hot Springs would be more realistic, but not obtainable with present modeling schemes.

A similar model for the E-W bipole of source 1 was used to model apparent resistivities for the Chalk Creek feature. Figure 43 shows fair agreement with the field data (Figure 18).

The northwest trending low resistivity feature west of source 2 was modeled by a 20 ohm-meter, two kilometer-wide "dike" bounded by 100 ohm-meter material on each side with a very resistive basement. The modeled resistivities for the N-S bipole (Figure 44) show that a conductive dike-like feature can produce apparent resistivities similar to the observed data (Figure 19). The electric field
Figure 41. Electric field directions for a conductive dike-like model (N-S bipole, source 1).
Figure 42. Apparent resistivities (ohm-meters) for a conductive dike-like model (N-S bipole, source 1).
Figure 43. Apparent resistivities (ohm-meters) for a conductive dike-like model (E-W bipole, source 1).
Figure 44. Apparent resistivities (ohm-meters) for a conductive dike-like model (N-S bipole, source 2).
distortion off the west end of the E-W bipole (Figure 32) can be produced by such a model (Figure 45). The modeled apparent resistivities (Figure 46) are in good agreement with the field results for the E-W bipole of the source with the lowest values near the west end of the bipole.

A vertical fault or contact model was used to simulate the observed resistivity and electric field patterns for the E-W bipole of source 5 north of Villa Grove. The east side of the fault model was assigned a 30 ohm-meter resistivity and the west side was 100 ohm-meters with the fault trace placed west of U.S. Highway 285 (see Figure 47). The computed apparent resistivities (Figure 47) show a spreading pattern of the contours similar to the pattern observed in the field results (Figure 26). The spreading of the contours across the modeled contact is not as great as observed for the real data. The presence of a conductive layer over this lateral resistivity change will tend to spread the contours more. The electric field directions for the model (Figure 48) behave similarly to the pattern of the observed electric field to the south of the east electrode along U.S. Highway 285 and eastward.

It must again be emphasized that the three models used are only approximations to possible earth configurations and are used to demonstrate the validity of the interpretations of these anomalous resistivity features.
A suitable model or computer model may need to simulate the appearance of the electric field for the 3D pictures of the source and Vujanovic's work on the source and 3D models. The computer pictures will meet the 3D field quickly (see Figure 13). The computer pictures will meet the 3D field quickly (see Figure 13). The computer pictures will meet the 3D field quickly (see Figure 13).
Figure 45. Electric field directions for a conductive dike-like model (E-W bipole, source 2).
Figure 46. Apparent resistivities (ohm-meters) for a conductive dike-like model (E-W bipole, source 2).
Figure 47. Apparent resistivities (ohm-meters) for a vertical fault model (E-W bipole, source 5).
Figure 48. Electric field directions for a vertical fault model (E-W bipole, source 5).
Quadripole Resistivity Map

A composite average quadripole apparent resistivity (CAQAR) map of the thesis area (Plate 2) shows most of the features described in the previous discussion. The average quadripole apparent resistivity is the arithmetic mean of the maximum and minimum of the resistivity ellipse determined by the method of rotation. This map was made using only the stations that could be rotated with reasonable accuracy. Therefore, the map is based on about half of the stations surveyed in the study area (Appendix A). The result is a smoother looking apparent resistivity map with not as much detail in complex areas. This CAQAR map is a good representation of the general lateral apparent resistivity character of the study area.

The upper Arkansas Valley has two major areas of low apparent resistivity. The area south of Buena Vista and the Salida area show lower apparent resistivities, probably indicating deeper portions of the upper Arkansas graben. Both show high resistivity zones small in area very close to sources 1 and 4, which are probably source-related. The expression of the Chalk Creek feature is minimal, but this feature is the lowest apparent resistivity zone near Buena Vista. The Salida basin area is predominantly less than 20 ohm-meters. The 50 ohm-meter contour correlates well with the mountain fronts to the south and north of
Salida. The Browns Canyon horst block is well defined by the higher resistivity contours.

The apparent resistivity low near Poncha Pass displays the general northwest trend seen in the dipole data. The anomaly has an eastern lobe at Poncha Pass. The Dry Union Formation exposed south of the pass is the probable cause for this lobe.

The CAQAR resistivities in the northern San Luis Valley are higher than in the upper Arkansas Valley. The 100 ohm-meter contour points out two low resistivity regions that may reflect deeper basins. The area north of Villa Grove has resistivities less than 50 ohm-meters up to the foot of the Sangre de Cristo Range near Hayden and Oak Springs. Increased subsurface temperatures and/or a deeper portion of the valley may account for these lower resistivities near the mountains. The 100 ohm-meter resistivity lobe west of Villa Grove is most likely due to lower resistivities on the Clayton syncline sediments. Another low resistivity zone northeast of Mineral Hot Springs suggests a deeper part of the basin here, which has been shown previously by Jordan (1974).
Resistivity Soundings

A few resistivity soundings were made using the quadripole mapping bipole sources in order to obtain some subsurface geoelectric section and electrical basement control. Seven resistivity soundings were made in conjunction with the quadripole survey (see Figures 49-55). The sounding method used is similar to the polar-dipole configuration. A 100 meter dipole receiver was moved in line away from one source electrode, either towards the center of the source or away from one end of the source. This type of sounding, sometimes termed as the Lögner configuration (Van Nostrand and Cook, 1966), is an approximation to the Schlumberger method and can sometimes be interpreted similarly. The results are plotted on log-log paper with apparent resistivity (ohm-meters) on the vertical axis and spacing (distance from source electrode to center of receiver dipole) in meters on the horizontal axis (Figures 49-55). Forty Schlumberger resistivity soundings were also made in the survey area and have been interpreted by curve-matching and kernel-domain computer inversion (Keller, 1977).

The seven resistivity soundings were interpreted using rising asymptotic lines to determine the apparent conductance of the sediments above the basement (Keller and Frischknecht, 1966). Since the basement is an insulator, the apparent resistivity curve plotted on log-log paper should rise asymptotically approaching a rising 45° line for spacings where basement limits current penetration.
The ratio of spacing to apparent resistivity for any point along this line defines the conductance of the section above the basement. Since conductance is the ratio of layer thickness to resistivity, the product of apparent conductance and the probable minimum apparent resistivity of the conductive section will yield the minimum probable depth to basement.

The principle of equivalence (Maillet, 1947; Keller and Frischknecht, 1966) is well known and points out that more than one combination of layer thicknesses and resistivities can produce sounding curves that are nearly identical. From electrical sounding graphs, transverse resistance (product of layer thickness and resistivity) can be determined for resistive layers and longitudinal conductance (ratio of thickness to resistivity) is determined for conductive layers. These two terms are the only accurate values for layers between the surface layer and the basement without control from another method. If either the resistivities or thicknesses can be determined through the use of well control or other means, the other values can be computed and the accuracy of sounding interpretations will be much improved. Despite this limitation, interpretation of sounding curves without outside control can be valuable and with reasonable limits of accuracy.

Sounding 1 was taken from the north electrode of the N-S bipole of source 1 moving the receiver southward. Sounding 2 used the E-W bipole of source 1 expanding eastward.
The FOCUS TARGET is a method of applying co-operative research to our work. By using the techniques of co-operative research, we can enhance the efficiency of the team and improve the quality of the project. This method involves the use of various tools and techniques to facilitate effective communication and collaboration among team members. The principles of co-operative research include the use of participatory research methods, the development of shared knowledge, and the creation of a supportive and inclusive environment.

The principle of enhancement (enhance) tells us that we should strive to make our project as efficient and effective as possible. This involves ensuring that all team members are fully engaged in the project and that their contributions are valued and recognized. Co-operative research provides a framework for enhancing the efficiency of our work and ensuring that all team members are working towards a common goal.

Co-operative research also involves the use of various tools and techniques to facilitate effective communication and collaboration among team members. This includes the use of participatory research methods, the development of shared knowledge, and the creation of a supportive and inclusive environment. By using these tools and techniques, we can enhance the efficiency of our work and ensure that all team members are working towards a common goal.

In conclusion, the FOCUS TARGET is an effective method of applying co-operative research to our work. By using this method, we can enhance the efficiency of our project and ensure that all team members are fully engaged and valued.

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FOCUS TARGET
from the west electrode. Sounding 3 was made using the E-W bipole of source 2 and was expanded westward from the west electrode. Sounding 4 was expanded northward from the south electrode of the N-S bipole of source 3. Sounding 5 was expanded westward from the east electrode of the source 4, E-W bipole. Sounding 6 was made on the N-S bipole of source 5 and the receiver was moved southward from the north electrode. Sounding 7 was expanded from east electrode of the source 6, E-W bipole to the west.

All of the seven resistivity sounding curves indicate that three main layers are present at all of the source locations (see Figures 49-55). These layers include a relatively thin highly resistive surface layer over a sizeable conductive layer of sediments over resistive basement rocks. The surface resistive layer may be produced by the downward migration of electrolytes to the water table and only partial saturation of the zone above the water table. The apparent conductance of the conductive layer was computed by the asymptotic method described previously. A minimum apparent resistivity for the conductor was picked from the curves and substantiated by curve matching and comparison with Schlumberger sounding interpretations nearby (Keller, 1977). The scatter of data for sounding 5 (Figure 53) makes this sounding relatively useless. The distortion of the basement resistivities for sounding 7 (Figure 55) may introduce some error in the interpretation of this sounding.
The apparent conductance of 20.9 mhos for Resistivity Sounding 1 with a minimum resistivity of 53 ohm-meters yields a minimum depth of 1100 meters to resistive basement. Sounding 2 has an apparent conductance of 14.3 mhos, a minimum resistivity of 70 ohm-meters, and a minimum depth of 1000 meters to basement. Soundings 1 and 2 are near Maxwell School, south of Buena Vista. The Schlumberger soundings (Keller, 1977) in this area agree with these soundings well. The basement is 550 meters deep immediately west of source 1 increasing to deeper than 800 meters 1.5 kilometers northward, to around 1100 meters near Maxwell School. Zohdy and others (1971) determined a depth to basement of approximately 1400 meters south of Buena Vista using electrical soundings.

Sounding 3 shows an apparent conductance of 49.6 mhos with a minimum resistivity of 21.5 ohm-meters, yielding a minimum depth to basement of 1000 meters. It should be noted that this sounding is near the conductive northwest trending feature west of Poncha Pass pointed out by the dipole mapping data.

Sounding 4 has an apparent conductance of 6.9 mhos, a minimum resistivity of 123 ohm-meters and a minimum depth of 840 meters to basement.

Sounding 5 is of questionable use due to scatter of data. However, a possible apparent conductance is 40 mhos. The minimum resistivity of 18.8 ohm-meters indicates
Figure 49. Plot of resistivity sounding 1.
Figure 50. Plot of resistivity sounding 2.
Figure 51. Plot of resistivity sounding 3.
Figure 52. Plot of resistivity sounding 4.
a minimum basement depth of 750 meters. The Schlumberger sounding done at this location showed a basement depth of 710 meters. The basement is 500 meters, 1.5 kilometers west of source 4 and is greater than 1900 meters 3 kilometers south of source 5. A Schlumberger sounding 20 kilometers south of source 5 indicated 720 meters to basement.

Sounding 6 has an apparent conductivity of 3.02 milli Siemens, a minimum resistivity of 5 ohm-meters, and a minimum depth to basement of 680 meters. A Schlumberger sounding 20 kilometers north of Villa Grove to the east of Villa Grove, indicated a basement deep 4 kilometers with a deep well around 4 kilometers deep east of Villa Grove near the Sangre. Figure 53. Plot of resistivity sounding 5.
a minimum basement depth of 750 meters. The Schlumberger sounding done at this location showed a basement depth of 710 meters. The basement is 400 meters, 1.5 kilometers west of source 4 and is greater than 1000 meters 3 kilometers west of the source.

Sounding 6 has an apparent conductance of 9.02 mhos, a minimum resistivity of 75 ohm-meters, and a minimum depth to basement of 680 meters. A Schlumberger sounding just south of source 5 indicated 720 meters to basement. Schlumberger soundings also showed the basement depth may increase to nearly 1400 meters two kilometers northwest of Villa Grove. Resistive basement was not encountered 3 kilometers east of Villa Grove, possibly indicating a deep basin. Other Schlumberger soundings show the basement to be 320 meters deep 4 kilometers west of Villa Grove and around 600 meters deep east of Villa Grove near the Sangre de Cristo range.

Sounding 7 has an apparent conductance of 12.19 mhos. The minimum resistivity of 30 ohm-meters yields a minimum basement depth of 370 meters west of Mineral Hot Springs. The Schlumberger sounding data (Keller, 1977) shows the basement to be over 1100 meters for much of the area to the east and south of Mineral Hot Springs, with a deeper basin (1800 meters) 3 kilometers east of Mineral Hot Springs. This agrees reasonably well with the electrical sounding data previously interpreted (Jordan, 1974).
Figure 54. Plot of resistivity sounding 6.
Figure 55. Plot of resistivity sounding 7.
SUMMARY AND CONCLUSIONS

The dipole and quadripole mapping resistivity methods used in a reconnaissance mode can provide valuable structural information over large areas with a minimal amount of field time invested. The use of these methods in the search for geothermal reservoirs requires additional types of information in areas of interest in order to quantify the parameters influencing the apparent resistivity anomalies. Apparent resistivities for dipole or quadripole mapping surveys are affected by effective rock porosity, rock saturation, fluid salinity, rock temperature, thickness of layers, rock age, depth of burial, distance from source, structural features and cultural features. Anomalies are produced by changes in these parameters, and often more than one parameter will change. Without additional geophysical and geological information, an interpreter cannot determine whether temperature, salinity, basin depth or any other parameter is the source of anomalous resistivity changes.

The portion of the upper Arkansas graben in the study area shows two possible deeper basin features, one near Buena Vista and one near Salida, in the dipole mapping and sounding apparent resistivity data. Only a small resistivity feature exists east of Cottonwood Hot Springs with no observed resistivity expression at the hot springs. The Mount Princeton Hot Springs area shows a dominant east-west
The state of the art is reviewed in this section, which starts with an introduction to the field of the topic. The review includes a discussion of key research papers and recent developments. The section concludes with a summary of the current state of the art and future directions.

The next section focuses on the development of new techniques and methods for addressing the challenges in the field. The section includes a detailed description of the methods used, along with examples of their application. The section concludes with a discussion of the limitations of the methods and suggestions for future research.

The final section provides a general overview of the field, including a discussion of the major research directions and the potential impact of the field on industry and society. The section concludes with a summary of the key findings and recommendations for future research.
trending low resistivity pattern along Chalk Creek. The distortion of the electric field directions indicates that the most conductive portion of this feature is at the Mount Princeton Hot Springs. This low resistivity feature lies over a seismic velocity anomaly (Crompton, 1976) and is felt to be caused by thermal rock alteration, faulting and the presence of subsurface thermal waters. Further detailed geophysical work (seismic reflection, electrical soundings, etc.) would help to substantiate and delineate this feature.

The Salida graben exhibits very low apparent resistivities, which may be affected by a relatively deep sediment-filled basement, conductive Dry Union Formation, subsurface thermal waters or a combination of these factors. The area northwest of Poncha Springs exhibits low apparent resistivities and may be a deeper part of the basin, as suggested by resistivity soundings. Poncha Springs Hot Springs show a resistivity low most likely due to anomalous heat. These springs lie on the west end of a resistivity low south of Salida. This feature may indicate a deeper part of the basin or may be strongly influenced by the exposed Dry Union Formation there. It is of interest to note that there are lower resistivities along the Browns Canyon horst block north of Salida and some warm springs are reported near the edge of the horst block. However, this feature may just express conductive sediments in the valley separated by a fault from the resistive igneous
and metamorphic horst block. Detailed gravity surveying, seismic reflection and additional electrical soundings should be undertaken to provide additional subsurface information in the Salida basin.

The lower apparent resistivity features in the Poncha Pass area may have interesting implications. Both the synclinal trough filled with Tertiary sediments north of Shirley and the exposed Tertiary sediments south on Poncha Pass are Dry Union Formation and exhibit lower apparent resistivities. There exists a northwest trending conductive zone at Shirley which lines up reasonably well with the west bounding faults of both of these sedimentary features. Some Dry Union Formation is exposed just west of Shirley along this resistivity trend. However, not enough Dry Union Formation is exposed to account for this resistivity feature. This conductive zone could possibly be the resistivity expression of a fault zone extension of the two previously described west bounding faults. This conductive feature must be close to or at the surface, as indicated by the close proximity of the source.

The northern San Luis Valley apparent resistivities indicate the presence of two separate deeper subsurface basins, one northeast of Villa Grove and the other east of Mineral Hot Springs. The lowest resistivities correlate well with these deeper basins determined with seismic reflection profile data (Stoughton, in progress). Resistivity
soundings over both of these features indicated increased depths (near 1800 meters east of Mineral Hot Springs) with good conductors at depth (Jordan, 1974; Keller, 1977). Fullinwider Warm Spring is located just north of the Villa Grove low resistivity zone and may be supplied by waters from this area. A resistivity sounding over this low did not detect resistive basement with only a deep conductive layer encountered (Keller, 1977). This conductor might indicate the presence of fine-grained Paleozoic sediments at depth. Both of these low apparent resistivity areas may be potential geothermal targets. In addition, an eastward extension of the Villa Grove low towards Oak and Hayden Springs may be of interest.

The spreading apparent resistivity pattern displayed on the E-W bipole map for source 5 and the corresponding electric field distortions indicate a sudden eastward deepening of the valley. This may be attributed to a normal fault with the basin-side dropped, the eastern limb of a north trending anticline (possibly the northern extension of the Eastern anticline), or a combination of both. Taylor and others (1975) postulate a normal fault along this trend and Stoughton (in progress) interpreted both an anticlinal fold and normal faults from seismic reflection data near Kerber Creek. A high-low-high resistivity pattern along Kerber Creek correlates very well with the Central anticline, Clayton syncline and Eastern anticline. Detailed gravity surveying and additional electrical
soundings would further clarify the subsurface features in the northern San Luis Valley.

The interpretation of the dipole and quadripole mapping resistivity data with the aid of electric field maps, dipole modeling and resistivity soundings has outlined some structural features and indicated potential geothermal target areas. The Buena Vista, Salida basin and northern San. Luis Valley areas warrant further geothermally-oriented geophysical investigations.
REFERENCES


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APPENDIX A

BIPOLE AND QUADRIPOLE MAPPING DATA

STA - Station number (first number denotes source number). Station locations can be found in Figures 3-8.

RHO 1 - Apparent resistivity in ohm-meters for N-S bipole source.

RHO 2 - Apparent resistivity in ohm-meters for E-W bipole source.

E 1 - Electric field direction for N-S bipole source.*

E 2 - Electric field direction for E-W bipole source.*

RHO A - Average quadripole apparent resistivity in ohm-meters due to both bipole sources (defined in text).

*Note: Half of the electric field directions are 180 degrees from the given value, due to a difference in the polarities of the amplifiers used. Plotting was done without directional arrows using only a bar.
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