THE NEWCASTLE GEOTHERMAL SYSTEM
IRON COUNTY, UTAH
GEOLOGY, HYDROLOGY, AND CONCEPTUAL MODEL
VOLUME 1: FINAL REPORT

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ABSTRACT

Geological, geophysical and geochemical studies contributed to a conceptual hydrologic model of the "blind" (no surface expression), moderate-temperature (greater than 130°C) Newcastle geothermal system, located in the Basin and Range-Colorado Plateau transition zone of southwestern Utah. Temperature gradient measurements define a thermal anomaly centered near the surface trace of the range-bounding Antelope Range fault with an elongate dissipative plume extending north into the adjacent Escalante Valley. Spontaneous potential and resistivity surveys sharply define the geometry of the dominant upflow zone (not yet explored), indicating that most of the thermal fluid issues from a short segment along the Antelope Range fault and discharges into a gently-dipping aquifer. Production wells show that this aquifer lies at a depth between 85 and 95 meters. Electrical surveys also show that some leakage of thermal fluid occurs over a 1.5 km (minimum) interval along the trace of the Antelope Range fault. Major element, oxygen and hydrogen isotopic analyses of water samples indicate that the thermal fluid is a mixture of meteoric water derived from recharge areas in the Pine Valley Mountains and cold, shallow groundwater. A northwest-southeast trending system of faults, encompassing a zone of increased fracture permeability, collects meteoric water from the recharge area, allows circulation to a depth of 3 to 5 kilometers, and intersects the northeast-striking Antelope Range fault. We postulate that mineral precipitates form a seal along the Antelope Range fault, preventing the discharge of thermal fluids into basin-fill sediments at depth, and allowing heated fluid to approach the surface. Eventually, continued mineral deposition could result in the development of hot springs at the ground surface.

EXECUTIVE SUMMARY

Overview

The volcanic and tectonic setting of southwestern Utah provides a unique opportunity for studying hydrothermal systems. Within the region, widespread mid- to late-Tertiary rhyolitic and andesitic volcanic and intrusive rocks, invaded folded and thrust Paleozoic and Mesozoic marine sedimentary rocks. Volcanic products of the recent geologic past include Quaternary rhyolitic domes and basaltic flows. Basin and Range tectonism, active over the past several million years, overprints this already complex setting with numerous, roughly north-south trending extensional faults and less obvious oblique fault and fracture zones. Two broad east-west trending belts of mineralization -- the Pioche-Marysvale and the Delamar-Iron Springs belts -- provide evidence of past hydrothermal activity in the region. The region is still undergoing active tectonism as evidenced by earthquakes generated within the Intermountain seismic belt and elevated regional heat flow. Physiography, reflective of the region's complex geologic past, comprises low-lying mountain ranges situated westward from the high plateaus of the Colorado Plateau-Basin and Range transition, surrounding broad, deep, sediment-filled basins. Over the past 10 to 15 years, researchers have compiled abundant new geologic data on both local and regional scales within southwestern Utah, making possible better understanding of geologic and hydrologic controls of hydrothermal convection systems.

The region contains two of the nation's commercially significant geothermal fields - Roosevelt Hot Springs and Cove Fort-Sulphurdale KGRAs -- and a number of other systems that possess future geothermal development potential for binary electric and non-electric applications. The Newcastle area, located on southeast edge of the Escalante Valley and the focus of our work, is particularly intriguing because it is a completely concealed hydrothermal system. No surface expression of hydrothermal activity -- hot springs, fumaroles, or alteration minerals -- exists. Water well drillers discovered the system in 1975 as result of pump-testing a newly drilled well. A temperature profile of the well depicted a geothermal aquifer at depths between 280 and 310 feet. Upon pumping, the well delivered water at temperatures near boiling. After discovery, geologists from the U.S. Geological Survey, and researchers at the University of Utah studied the system to a limited extent. Several private geothermal companies also studied the Newcastle area and drilled a number of exploratory wells. Presently, three commercial greenhouses, a Mormon church building, and various residences in Newcastle use the hot water for space heating.

Geoscientists have postulated that such "blind" hydrothermal systems exist and estimate that blind systems could contain several times more energy than that presently accessible in known hydrothermal systems. In an effort to characterize the Newcastle system, we augmented existing studies by performing more detailed geological, geophysical, and geochemical investigations, in order to formulate a conceptual model.

Such a model might be useful as an analog for other undiscovered geothermal systems in the region. Moreover, the added resource information will help with better reservoir management as geothermal development continues at Newcastle.

About the Project

Our project consisted of several activities, or tasks, designed to characterize some aspect of the system, and lead to the development of a conceptual model. Primary project tasks consisted of:

1. geologic mapping of Quaternary valley-fill units
2. geologic mapping of bedrock units and structural analysis
3. acquisition and modelling of detailed gravity data
4. common ion and hydrogen/oxygen isotopic analysis of water samples from wells and springs
5. soil-mercury and radon surveys
6. shallow, temperature gradient drilling to better define the extent of the thermal plume, and
7. numerical and conceptual modeling of the hydrothermal system

Additional work included an electrical resistivity survey and a spontaneous potential (SP) survey performed by researchers from the Earth Science Laboratory, University of Utah Research Institute with assistance from UGMS staff geologists.

Geologic Mapping

Utah Geological and Mineral Survey (UGMS) geologists performed geologic mapping of surficial units in the Escalante Valley. Quaternary geologic units that comprise the valley fill generally terminate at the Antelope Range Fault, a major north-northeast trending, range-bounding normal fault that marks the southeast edge of the Escalante Valley. A smaller-scale normal fault faces opposite the Antelope Range fault and cross-cuts the valley fill a few thousand feet to the northwest. These two structures enclose a geologic feature termed the Newcastle graben, a subset of the Escalante Valley, indirectly observed through geophysical studies. Scarp morphology along the Antelope Range fault suggests a middle to late-Pleistocene age for the last surface-rupturing event.

Geologic mapping of bedrock units within the northwest extension of the Pine Valley Mountains, performed by geologists from the UGMS and U.S. Geological Survey (USGS), provided many insights about the structural history of the area. Oligocene and Miocene ash-flow tuffs, debris flows, and rhyolite flows provide good stratigraphic markers for determining fault locations, displacements, and attitudes. Detailed mapping revealed a complex network of faults and fracture zones where the greatest stratigraphic separation (2,000 to 3,000 feet) occurs along northwest-striking faults and fault zones. Fracture density appears greater within a northwest-trending zone projecting through the geothermal area. Several map-scale bedrock faults within this zone, when projected onto the buried surface of the Antelope Range fault, coincide with the center of the thermal anomaly.

Fault slip studies involved the gathering of fault-slip data (strike, dip, rake, and sense of slip) from bedrock terrain at four sites in and around Newcastle. These data, input into computer software acquired from other researchers and modified for our work here, yielded results suggesting that two principal tectonic events are responsible for the fault and fracture systems seen in the study area. An older event occurred between 21 and 8.5 million years ago, associated with regional southwest-directed extension, and produced the northwest-trending zone of faults mapped in bedrock. A second event, active between 8.5 million years ago and the present, produced the Antelope Range fault and adjacent Newcastle graben. Of the faults produced during the older event, few were reactivated during the younger event. The younger event appears to have generated relatively few new faults away from the Antelope Range fault, contributing little to the bedrock permeability.

Thermal Gradient and Heat Flow Investigations

Scientists from the University of Utah, Department of Geology and Geophysics performed temperature monitoring within previously drilled holes and within holes drilled specifically for this project. Previous workers, because of a lack of survey control and a more complete data set, had mistakenly mapped the center of upflow for the geothermal system at a location displaced a few thousand feet away from the mountain front. Using the results of twelve new temperature gradient holes and better location/elevation control, University of Utah scientists accurately defined the location of the Newcastle temperature anomaly and constructed a new heat flow map. The results of this work indicate that the near surface thermal anomaly is spatially associated with a short segment of the Antelope Range fault.

Geophysical Surveys

Geophysical investigations at Newcastle included detailed gravity studies, a limited magnetic investigation which yielded little useful information due to interference with power transmission lines, a resistivity survey, and a spontaneous potential (SP) survey.

We carried out the gravity and magnetic studies in an effort to define bedrock structures beneath the Escalante Valley sediments. Resistivity and SP studies, performed in cooperation with the University of Utah Research Institute, helped better determine the location of upflowing geothermal fluid and the dispersion of the outflow plume.

Gravity studies entailed two separate field investigations, performed by University of Utah scientists and students, whereby a total of 394 close-spaced gravity stations were occupied. After compiling and applying routine reductions to the data, numerical modeling (along with the results from surface geologic mapping) provided an interpretation of the subsurface geology. The interpretation depicts the northwest extension of the Pine Valley Mountains separated from the Escalante Valley by the Antelope Range fault. Prisms with densities of 2400 kg m^{-3} represent Cretaceous and lower Tertiary sedimentary rocks, and Tertiary volcanic units. These units are exposed in the mountains in the southeast portion of the study area, and are present in the subsurface beneath the Escalante Valley. Prisms of densities ranging from 1900 to 2125 kg m^{-3} represent alluvial, fluvial, and lacustrine deposits of the Newcastle graben and the Pinto graben. The model depicts the Antelope Range fault dipping at an angle of $65^\circ (\pm 5^\circ)$ to the northwest.

Researchers from the Earth Science Laboratory, University of Utah Research Institute, assisted by UGMS personnel, conducted electrical resistivity and SP surveys. Within the area of suspected upflowing thermal fluid (in close proximity to the surface trace of the Antelope Range fault), these surveys disclosed sharply defined electrical anomalies. The anomalies are likely caused by fluids moving upward along narrow channelways associated with the Antelope Range fault. Permeable horizons within alluvium allow the hot fluid to discharge beneath the floor of the Escalante Valley into a shallow aquifer.

Hydrochemistry

We collected water samples from six wells in the study area for analysis of major anions and cations. Two of the wells sampled were geothermal production wells, one was a warm irrigation well, and the remaining three wells were all cold irrigation wells. Water chemistries suggest that geothermal fluid possesses a distinct character (moderate total dissolved solids) and mixes to varying degrees with cool, fresh groundwater. The geothermal fluid, after entering the shallow aquifer disperses to the north and west into the Escalante Valley becoming increasingly mixed.

We collected fluid samples from two geothermal wells, one mine dewatering well on the west side of the Escalante Valley, and four springs located in the highlands off to the east of the study area for determination of δD and $\delta^{18}O$. The results of the analyses suggest that the geothermal fluid has undergone little isotopic exchange with reservoir

rocks and that the water is of local meteoric origin. The most likely recharge area is the Pine Valley mountains located to the southeast.

Soil-Gas Investigations

Because of the mobility of mercury and radon within geothermal systems, we initiated a sampling program to determine the soil mercury content and radon flux across the temperature anomaly at Newcastle. We gathered soil samples for the mercury determinations, and placed radon detectors in shallow, 2 foot-deep holes. Presently, the results of these studies are inconclusive. From 110 soil samples, we expected to see relatively high mercury values over the thermal anomaly with respect to background. The highest mercury values recorded, however, were only two standard deviations above the mean, and occurred in only three samples. Moreover, high readings formed relatively isolated patterns of only marginal interpretive value. Patterns of high radon flux were observed at places along the trace of the Antelope Range fault and near the center of the thermal anomaly.

Conceptual Model

The working model we use for groundwater movement in this blind geothermal system consists of:

1. **Recharge in the Pine Valley Mountains** circulates to a depth of 5 kilometers within a postulated northwest- trending structural zone and is heated in a region of elevated heat flow ($\sim 90 \text{ mW}^2$).
2. **The northeast-trending Antelope Range fault** and its intersection with the northwest-trending structural zone provides preferred pathway(s) for localizing discharge of geothermal fluid at the basin-fill/bedrock contact beneath the Escalante Valley.
3. **Siliceous or carbonate precipitates** formed at the interface between thermal and non-thermal water in the basin-fill possibly form a low-permeability "seal" forcing geothermal fluid to flow upward.
4. **Geothermal fluid discharges** at a temperature of 130°C or greater into alluvium, near the ground surface, forming an outflowing "plume" of thermal water, eventually mixing with shallow groundwater and cooling.

Conclusions and Recommendations

The thermal water produced from wells at Newcastle results from the upflow of hot water near the range front and subsurface outflow within a shallow aquifer. Our mapped temperature anomaly near the surface trace of the Antelope Range fault is based mostly upon shallow (less than 20 m) drill holes that did not encounter hot fluid. Electrical geophysical surveys have provided more detail regarding the near-surface character of the upflow zone. To date, however, no drilling has taken place to adequately test the throat of the system.

We recommend (1) deep drilling to test SP and resistivity anomalies near our mapped temperature anomaly; (2) fluid sampling for common ion and isotopic analyses from the upflow portion of the geothermal system; (3) additional structural mapping and analysis in the Pine Valley mountains to test the integrity of our postulated northwest-trending structural (recharge) zone; and (4) a regional review of temperature, water chemistry, and geologic information to help identify prospective targets for other blind geothermal systems.

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Gravity data were acquired during the Fall of 1987 and Fall of 1988 by students and teaching assistants in Dr. Charles M. Schlinger's gravity and magnetic methods course (Department of Geology and Geophysics, University of Utah). Participants included Susanne Janecke, Joann Hollaway, Rick Hulse, Peter Eick, Jim Hollis, Farhang Namdar, Tim Chisholm, Tony Robertson, and Sean Willett. Reductions of gravity data were made possible using computer programs written by Peter Eick and Jim Hollis.

Dr. Howard Ross of the Earth Science Laboratory, University of Utah Research Institute provided technical guidance on certain geophysical aspects of the project, in addition to directing resistivity and spontaneous potential surveys. Mr. Claron Mackelprang, an independent consultant, assisted Dr. Ross with the resistivity data collection and interpretations. Bea Mayes of the UGMS also helped in the performing of the resistivity survey and with the placement of radon detectors.

Brian J. (B.J.) Macpherson, a graduate student at the University of Utah, assisted with the gathering of temperature gradient and fault-slip data. B.J. was also responsible for compiling thermal conductivity and heat flow information.

Archie Smith, formerly of the UGMS, helped originally conceive the study and became an advocate for the project. He was instrumental in organizing the proposal effort and obtained support for the acquisition of detailed gravity and magnetic data, and the purchase of aeromagnetic maps acquired from USX Corporation.

We wish to express our thanks to Boyd Christensen, Carroll Tullis, Dan Tullis, Steven Christensen, George Becham, and the other residents of Newcastle for their assistance. We also thank Mary Siders, Peter Rowley, Gary Christenson, and G. Galyardt for permission to use unpublished mapping, and Ze'ev Reches for the use of his stress tensor programs.

1.0 INTRODUCTION

1.1 General Statement

Undiscovered hydrothermal systems represent a significant portion of the total hydrothermal accessible resource base in the United States, estimated between 3 and 5 times that of identified hydrothermal systems (Muffler, 1979, p. 157). Many of these undiscovered systems are so-called "blind" systems where no surface expression of hydrothermal activity, such as thermal springs, sinter mounds, alteration minerals, etc., exists. Our work effort characterizes one such blind system located in southwestern Utah, discovered by accident, near the community of Newcastle.

1.2 Purpose and Scope

This work is the result of a response to a Program Research and Development Announcement (PRDA) for state cooperative geothermal research. The U.S. Department of Energy (DOE) solicited studies through the PRDA in April 1987. In response to the PRDA, the Utah Geological and Mineral Survey (UGMS) and the University of Utah Department of Geology and Geophysics (UUGG), prepared a joint proposal for cost-shared research at Newcastle. The original proposal was submitted in June 1987. At DOE's request, clarifications to the original proposal were made and a revised proposal was submitted for consideration in October 1987. The revised technical proposal and budget was eventually accepted and funding was allocated for the work. The project officially began in June 1988, with technical tasks continuing until November 1989.

One goal of this project was to better define the geothermal system at Newcastle. Another goal was to help establish a basis for an exploration methodology for other blind hydrothermal systems that may be present in the Basin and Range province. This report describes in detail a multidisciplinary study of the Newcastle geothermal area, situated in Iron County, Utah. The broad objective was to construct a refined, conceptual model of the hydrothermal system.

A major component to the determination of a correct geologic/geohydrologic model was to define the geometry of controlling geologic structures, the configuration of the enclosing basin fill, and postulate the movement of geothermal fluid. To this end, the project tasks consisted of several coordinated activities including: (1) geologic mapping of Quaternary deposits; (2) geologic mapping of bedrock in the adjacent mountains; (3) acquisition and analysis of gravity data and aeromagnetic data; (4) collection and analyses of water samples for common ions and light stable isotopes, plus investigations of mercury and radon concentrations in the soils around the thermal area; (5) thermal gradient monitoring in shallow, exploratory drill holes; and (6) numerical modelling of the hydrothermal system. An electrical resistivity survey and a spontaneous potential (SP) survey was later performed by researchers from the Earth Science Laboratory/University of Utah Research Institute.

potential (SP) survey was later performed by researchers from the Earth Science Laboratory/University of Utah Research Institute.

1.3 Background and Previous Work

Newcastle is a rural farming community situated in southwestern Utah (Figure 1) where, in 1975 during test pumping of an irrigation well, a local farming company (known as the Christensen Brothers) discovered thermal water (Rush, 1983, p.19). The discovery well encountered a hot-water aquifer with a maximum temperature of 108°C (226°F) between depths of 85 and 95 m (279 and 312 ft). This was the first record of geothermal activity at Newcastle, although local residents describe an incident during the early settlement history of the valley when settlers, hand-digging a water well, abandoned the endeavor because of excessive heat in the well.

Since the drilling of the discovery well, several organizations and individuals have studied the system. Denton (1976) conducted a helium-gas survey across the area and detected a broad helium anomaly around the discovery well and along the nearby range-front fault. Rush (1977) compiled temperature-gradient data for the Escalante Valley and other areas in Utah, and reported the results. Pe and Cook (1980) conducted a gravity survey in the region and defined a large, northeast-trending gravity low centered northwest of the town of Newcastle, which they interpreted as representing a deep graben.

Chapman and others (1981), using temperature gradient data obtained from various geothermal companies, calculated the thermal power loss of 13 megawatts from an area of 9.4 km² (3.6 mi²), assuming a water temperature of 110°C (230°F) and a discharge rate of 32 l s⁻¹ (507 g m⁻¹). Rush (1983), using chemical geothermometry, estimated a reservoir temperature of 140°C to 170°C (284°F to 338°F) and published a chemical analysis of the Newcastle thermal water, temperature profile of the Christensen Brother's discovery well, potentiometric map of the area, temperature map at a depth of 100 m (328 ft), and a heat flow map of the principal hot water aquifer. Hoover (1987) reported the results of eight audio-magnetotelluric soundings in the Newcastle area, with the lowest resistivity values measured at a station east of the Christensen Brother's well. Mabey and Budding (1987) compiled available data on the Newcastle system and presented a geothermal model suggesting that hot water rising along a fault zone near the base of the hills southeast of Newcastle discharges into an aquifer in unconsolidated Quaternary sediments. Blackett (and others, 1989) briefly reported the results of temperature gradient drilling, geologic mapping, and water chemistry as part of this project.

Figure 1. Location map showing the study area in relation to the communities of Cedar City and Enterprise, Utah. Geographic features are labeled.

1.4 Location and Regional Setting

Newcastle is located about 48 km (30 mi) west of Cedar City, Utah along SR 56. Cedar City lies approximately 440 km (275 mi) southwest of Salt Lake City via Interstate 15. The communities of Enterprise and St. George lie approximately 13 km (8 mi) to the southwest and 64 km (40 mi) to the south of Newcastle, respectively. Other notable geothermal areas within the region include Roosevelt Hot Springs, located roughly 105 km (65 mi) to the northeast, and Cove Fort -- Sulphurdale, located roughly 120 km (75 mi) to the northeast.

The Sevier thermal area was defined by Mabey and Budding (1987) to include a large area of western Utah where young igneous rocks, complex geologic structure, high regional heat flow, and seven high- and moderate-temperature geothermal systems are

present. The seven geothermal systems within the Sevier thermal area (Figure 2) occur in or along the margins of intermontane valleys in the eastern part of the Basin and Range geologic province. Six of the systems occur within 70 km (44 mi) of the eastern province boundary.

The area is characterized by many late-Cenozoic normal faults. The Intermountain seismic belt, a zone of increased earthquake activity identified by Smith and Sbar (1974) that trends through northern and southwestern Utah, changes direction in the area from

Figure 2. Map showing the location of the project area with respect to Utah's physiographic provinces and other major geothermal systems. The approximate outline of the Sevier thermal area, described by Mabey and Budding (1987), is also shown.

a northerly orientation to a more southwesterly one. Oligocene and Miocene intrusive and extrusive igneous rocks are widespread in the southern part of the Sevier thermal area. A zone of younger extrusive igneous rocks, containing abundant Quaternary age basalt, trends across the northern part of the Sevier thermal area.

The presence of these higher-temperature geothermal systems in southwestern Utah relates to a high regional heat flow, and to complex geologic structures -- conditions that do not exist elsewhere in the state. High heat flow and complex structure, coupled with ample recharge fluids, creates conditions favorable for the development of hydrothermal convection systems. In addition, young igneous systems may supply heat to some of the geothermal systems in the Sevier thermal area (Mabey and Budding, 1987, p.4).

The Escalante Valley, sometimes termed "Escalante Desert," lies within the Sevier thermal area. It is an elliptical depression extending over an area measuring approximately 70 x 45 km (44 x 28 mi) and is surrounded by mountain ranges and hills composed dominantly of Tertiary ash-flow tuff units ranging in age from 32 to 19 million years ago (Ma), and rhyolite and dacite flows and domes ranging in age from 13 to 8.5 Ma. The valley is filled with more than 300 m (1,000 ft) of alluvial, colluvial, fluvial, lacustrine, and aeolian unconsolidated and semi-consolidated deposits (Klauck and Gourley, 1983, p.3).

Klauck and Gourley (1983, p.3) describe four significant events that have affected the Escalante Valley: (1) large scale thrust faulting of the Sevier orogeny; (2) east-west trending igneous activity; (3) Basin and Range tectonism; and (4) periods of intensive volcanism with associated intrusive activity. Sevier age thrust faults have been mapped near the Escalante Valley, and evidence of Paleozoic strata thrust upon Jurassic strata is present in at least one deep exploratory well within the valley (Mike Shubat, personal comm.).

The valley is situated between two major, roughly east-west trending mineral (or igneous) belts. The Pioche-Marysville mineral belt (26 Ma) lies to the north, and the Delamar-Iron Springs mineral belt (20 Ma) lies to the south (Rowley and others, 1979). The Pioche-Marysville and the Delamar-Iron Springs igneous belts are thought to be structurally controlled, and are associated with two east-west oriented lineaments -- the Blue Ribbon lineament to the north and the Timpahute lineament to the south (Figure 3).

Figure 3. Physiographic and major structural features of southwestern Utah – Colorado Plateaus boundary shown by heavy dotted line. Central part of Ploche-Marysville Igneous belt on the north, and Delamar-Iron Springs Igneous belt on the south are shown in the stipple pattern. Heavy dashed lines indicate axes of lineaments – from north to south – the Black Rock, Blue Ribbon, and Timpahute lineaments. Towns and cities are noted. Geothermal areas are shown as solid triangles and include NC-Newcastle, LU-Lund, TH-Thermo, RO-Roosevelt, and CF-Cove Fort (modified from Rowley and others, 1979).

2.0 GEOLOGIC INVESTIGATIONS

2.1 Mapping of Bedrock and Surficial Units

Plates 1 and 2 are a geologic map and an accompanying sheet of cross sections and explanatory material for the Newcastle geothermal area. The geologic map shown in Plate 1 was taken from Siders and others (1989) and modified during this study.

2.1.1 Stratigraphy

Exposed bedrock units at Newcastle (described in detail by Siders and others, 1989) range in age from Upper Cretaceous to upper Miocene, and consist of older sedimentary rocks overlain by a series of middle Tertiary ash-flow tuffs of regional extent, and capped by local rhyolite and dacite flows. The oldest unit exposed is the Upper Cretaceous Iron Springs Formation, which consists of light-colored, thin- to thick-bedded sandstone and lesser shale, conglomerate, limestone, and carbonaceous shale. The unit was deposited in braided fluvial and lacustrine environments with sediment derived from the now-foundered Sevier orogenic highland that was located to the west. The minimum exposed thickness is 430 m (1400 ft). The Eocene to Oligocene Claron Formation unconformably overlies the Iron Springs Formation and consists of fluvial and lacustrine shale, sandstone, limestone, siltstone and conglomerate. The unit has a minimum exposed thickness of 130 m (430 ft) and is estimated to be about 210 m (700 ft) thick.

Overlying the Claron Formation is the Oligocene Isom Formation, which consists of two densely-welded, crystal-poor, ash-flow tuff members of regional extent, the lower Baldhills Tuff Member and upper Hole-in-the-Wall Tuff Member. Both members contain sparse phenocrysts of plagioclase, clinopyroxene, and magnetite and range in color from dark brown to black. Extreme welding produced flattened pumice clasts as much as 0.6 m (2 ft) in length, and secondary flowage produced stretched vesicles as much as 0.3 m (1 ft) in length. Intercalated with densely-welded tuff near the base of the Baldhills Tuff Member are probable andesitic flows marked by autobrecciation and flow-top scoria, and thin beds of volcanic sandstone. The minimum thickness of the Baldhills Tuff is 330 m (1,080 ft). The Hole-in-the-Wall Tuff Member consists of a single cooling unit that is about 79 m (260 ft) thick. The concealed source caldera or vent for the Isom Formation probably lies beneath the southern margin of Hamblin Valley or the northern margin of the Escalante Desert (Best, 1987), approximately 35 km (22 mi) northwest of Newcastle. The age of the Isom Formation is approximately 26 Ma (Rowley and others, 1979).

Three regional rhyodacitic to dacitic ash-flow tuffs of the Quichapa Group overlie the Isom Formation and were probably erupted from sources in the Caliente caldera complex depression (Williams, 1967). The rhyodacitic, moderately-welded Leach Canyon Tuff, consisting of several cooling units, is approximately 25 Ma (Rowley and others, 1979), and contains 20 to 30 percent phenocrysts of plagioclase, quartz, sanidine, and

biotite and reddish lithic fragments. It is about 580 feet (177 m) thick in the map area. The Bauers Tuff of the Condor Canyon Formation is rhyodacitic, crystal-poor, densely-welded, approximately 23 Ma (Rowley and others, 1979), and about 130 m (430 ft) thick. The tuff contains phenocrysts of plagioclase, sanidine, and bronze biotite and abundant highly-flattened pumice clasts. The Bauers Tuff erupted from the Clover Creek caldera located in Lincoln County, Nevada (Rowley and Siders, 1988). The Harmony Hills Tuff is a distinctive crystal-rich, dacitic, moderately-welded tuff dated at about 21 Ma (Rowley and others, 1979). It consists of nearly 50 percent crystals of plagioclase, biotite, hornblende, quartz, and pyroxene and is 146 m (480 ft) thick. An unnamed aerially-extensive volcanoclastic unit, approximately 40 m (130 ft) thick, overlies Harmony Hills Tuff and contains abundant clasts and crystal fragment, of Harmony Hills Tuff as well as andesite cobbles. This northward-thickening unit is probably a distal debris-flow deposit shed from an andesitic highland to the north.

The Racer Canyon Tuff overlies the Quichapa Group rocks and is the youngest regional ash-flow tuff present at Newcastle. The tuff is crystal-rich, rhyodacitic, poorly to moderately welded, and greater than 150 m (490 feet) thick. Southeast of the map area the Racer Canyon Tuff consists of at least 3 cooling units and its age is approximately 19 Ma (Siders, in press). An informally named unit, the Volcanoclastic rocks of Newcastle Reservoir, overlies the Racer Canyon tuff and is greater than 300 m (980 ft) thick. The unit is correlative with the informally named mine series of Siders (1985), which has a minimum age of 11.6 Ma. The unit consists of intercalated lenses of conglomerate, mudflow breccia, and sandstone, and most clasts are volcanic rocks. Rhyolite and dacite lava flows and domes overlie and intrude Racer Canyon Tuff in the northeast corner of the map area. These informally named units, the Rhyolite of Silver Peak and Dacite of Bullion Canyon, yielded K-Ar ages of 8.4 and 8.5 Ma, respectively (Shubat and Siders, 1988).

Overlying the bedrock units are a variety of unconsolidated to semi-consolidated deposits described in detail by Siders and others (1989). The oldest of the semi-consolidated deposits is upper Miocene to Pliocene in age (labeled Ts in plate 1) and consists of moderately consolidated boulder, cobble, and pebble conglomerate and sandstone. This coarse fluvial material was deposited at the margin of the Escalante Valley and probably underlies the geothermal area at depth. This may be the unit that was encountered below a depth of 670 m (2200 ft) in the Christiansen #1 well (Plate 3). It corresponds to the higher density valley-fill material used in the gravity model (see later section). Overlying this unit is lower Pleistocene to Pliocene piedmont-slope alluvium (QTpo). This material is poorly- to moderately-consolidated and consists of boulder, cobble, and pebble conglomerate and sandstone. It contains a distinctive lithology, black magnetite ore, derived from Iron Mountain, located 10 km (6.2 mi) to the east.

Units younger than the semi-consolidated deposits include several types of unconsolidated deposits of Pleistocene age. Stream-terrace alluvium (Qtm) consists of gravel, sand, and silt deposited in stream channels and flood plains at an elevation of approximately 15 to 25 m (50 to 80 ft) above modern channels. Piedmont-slope alluvium (Qpm) consists of sandy gravel forming dissected remnants of a surface in mountain front re-entrants that are older and higher than the modern one. Alluvial-fan deposits (Qfm) consist of sand and silt that form the dissected remnants of older and higher alluvial-fan deposits in the Escalante Valley. These older fans were largely deposited by ancestral Pinto Creek.

The youngest unconsolidated deposits consist of sand, silt, gravel, and clay divided on the basis of depositional environment and geomorphic expression. Colluvium and talus (Qct) includes deposits on steep slopes below rock outcrops. Alluvium and colluvium (Qac) includes material deposited in intermittent stream channels and on lower slopes as sheetwash and talus. Distal alluvial-fan deposits (Qpy) in the northwest past of the map consist of silt and clay deposited in the distal parts of the alluvial fans of Pinto Creek and other drainages to the southwest. They are derived principally from sheetwash and stream erosion of the coarser Pleistocene alluvial-fan deposits. Young alluvial-fan deposits (Qfy) are those deposited by Pinto Creek in the Escalante Valley, during Holocene and late Pleistocene time. Young stream-terrace alluvial deposits (Qty) occur about 2 to 3 m (6 to 10 ft) above the modern channel of Pinto Creek, and are chiefly Holocene-age. Alluvium (Qal) is restricted to modern channels and artificial fill (Qf) represents the earthen dam of Newcastle Reservoir.

2.1.2 Structure

Structural investigations at Newcastle included mapping of bedrock structures (M.A. Shubat), Quaternary structures (G.E. Christenson), and measurement of slip directions of minor faults (M.A. Shubat and R.E. Blackett) from four sites near Newcastle. The goal of these studies was to document the surface expression of structures that localize the geothermal resource at Newcastle.

The Antelope Range fault, as defined by Quaternary fault scarps, is a north-northeast striking normal fault that extends from Newcastle at its southwestern end to the northern tip of the Antelope Range, spanning a distance of 26 km (16 mi). At Newcastle, the fault separates the Escalante Valley to the northwest from the uplifted bedrock of the Antelope Range to the southeast. Although not marked by distinctive Quaternary-age scarps, the fault probably continues an additional 14 km (9 mi) to the southwest, terminating near Mountain Meadow. As mapped by Siders and others (1989), the fault breaks into three right-stepping en echelon strands east of Newcastle (Plate 1). Anderson and Christenson (1989) assign a middle to late Pleistocene age for the last surface-rupturing event, based on scarp morphology. Scarps on Pleistocene alluvium northeast of Newcastle, mapped by Grant and Proctor (1988) and Shubat and Siders

(1988), are multiple-event scarps. Without additional information, it is not possible to determine if the southwestern limit of Quaternary scarps marking the fault represents the southwestern tip of the most recent surface-rupturing event or if scarps were simply not preserved southwest of Newcastle. Mapping by Siders and others (1989) and Shubat and Siders (1988) shows that the Antelope Range fault cuts 8.5 Ma rhyolite and dacite flows, indicating that initiation of the Antelope Range fault began in the late Miocene.

Gravity data indicate that the Antelope Range fault marks the southeastern margin of a northeast-trending, alluvium-filled graben named the Newcastle graben by Pe and Cook (1980). This graben, centered approximately 3.7 km (2.3 mi) northwest of Newcastle, contains a thick section of alluvium. Modeling of detailed gravity data collected during this study (see later section) indicates that the dip of the Antelope Range fault is steep (approximately 65°) and that the Newcastle graben contains about 1600 m (5,250 ft) of alluvium. This corresponds to nearly 1800 m (6,000 ft) of dip slip separation along the fault.

Geologic mapping of the range south and east of Newcastle revealed a complex pattern of steeply- to moderately-dipping faults that strike in all directions (Plate 1). Most faults show apparent normal separation, as determined by stratigraphic separation and dips from three-point solutions. However, the dominant displacement on map-scale faults, if similar to minor faults, may be strike-slip, as shown by the dominantly sub-horizontal rakes of minor fault striae measured from several sites near Newcastle (Figure 4). Because of the absence of piercing points, we could not determine the net slip for any of the map-scale faults. Stratigraphic separation appears to be the greatest (610 to 910 m; 2,000 to 3,000 ft) and the most variable along northwest-striking faults and fault zones. One of these faults contains a very coarse breccia body (megabreccia) lying between two fault splays located in the northeast 1/4 of section 29, T36S, R15W. This is a steep, apparent reverse fault and in the subsurface it projects northwesterly toward the center of the thermal anomaly (near holes NC-18 and NC-19, Plate 1). Plate 1 shows the map-view projection of this and other faults and contacts onto the footwall of the Antelope Range fault, assuming that it dips steeply ($65-70^\circ$) toward the valley and strikes parallel to its surface trace. This projection shows that the center of the thermal anomaly coincides with an area where two prominent high-angle faults intersect in the plane of the range-front fault.

2.2 Fault Slip Analysis

We undertook a fault slip study at Newcastle in order to better understand the chronology of deformational events by collecting data from rocks of different ages and different locations. Fault slip analysis involves the fitting of a mean stress tensor to a population of fault slip measurements. Angelier (1979; 1984), Angelier and others (1985), and Reches (1987) developed the methods used in this study. To apply this technique, we measured many minor fault orientations from several outcrop-scale areas

Figure 4a. Slip axes orientations, strike and dip of fault planes, and rake of slickensides for sites A, and B near Newcastle, Utah. Locations of sites shown in Figure 5 and described in text. For stereo plots, plus (+) = dextral faults, diamond = sinistral faults, box = normal faults, and x = reverse faults.

Figure 4b. Slip axes orientations, strike and dip of fault planes, and rake of slickensides for sites C and D near Newcastle, Utah. Locations of sites shown in Figure 5 and described in text. For stereo plots, plus (+) = dextral faults, diamond = sinistral faults, box = normal faults, and x = reverse faults.

and for each fault recorded the strike, dip, rake, and sense of slip. These raw data appear in Appendix A. Petit (1987) and Angelier and others (1985) document the use of minor structures on fault planes to determine the sense of slip. In this study we found that riedel shears, tension gashes, and corniced margins of void spaces were the most consistent indicators of slip. On fault surfaces with only very minor displacement (on the scale of a few centimeters) we observed "tool-and-groove" indicators of slip, where a tool on one side of the fault (usually a quartz phenocryst) scratched a groove on the other side of the fault and then lodged in the head of the groove. We found that the Harmony Hills tuff contained a much higher density of minor fault surfaces than any other unit, probably as a result of favorable rock mechanic properties and preservation characteristics. In general, we were able to confidently determine the slip direction for only a fraction (1/3) of the minor fault surfaces exposed in the field.

We collected data from four sites, three of which lie within the area of Figure 5 (sites A, B, and C). Faults at sites A and B cut the 21 Ma Harmony Hills Tuff, which yields the maximum age of these faults. Faults at site C cut 8.5 Ma rhyolite and dacite, again yielding the maximum age of this set of faults. The number of faults measured for sites A, B, and C are 108, 134, and 20, respectively. A fourth site, site D, located in the NW $\frac{1}{4}$, NE $\frac{1}{4}$, SW $\frac{1}{4}$, section 19, T. 35 S., R. 14 W., was also sampled and yielded 55 measurements. This site lies about 12 km (7.5 mi) northeast of Newcastle, in Chloride Canyon, and was selected to provide a contrast to the Newcastle sites. Figure 4 shows the basic geometric data for the four sites (strike, dip, rake, and orientation of slickensides lineations).

We performed the analysis using software generously provided by Z. Reches (Version 1.6). The method developed by Reches (1987) allows the user to interactively select a solution that satisfies the criteria listed by Reches (1987) and that minimizes two measures of misfit. These criteria are that the coefficient of friction be near 0.8, the mean misfit angle be as small as possible, and the mean cohesion be greater than zero. One of the measures of misfit is the mean of the angle between the observed slip axis and the maximum resolved shear stress (calculated from an inversion-derived stress tensor) for each fault in the population. This tensor is derived by inverting a $2k \times 5$ matrix and solving the overdetermined system by the least squares method. Elements of the matrix are the coefficients of the components of the reduced stress tensor (Celerier, 1988). The first k rows (where k is the number of fault measurements) satisfy the constraint that slip is parallel to the maximum resolved shear stress and the remaining k rows satisfy the Coulomb yield criteria (Reches, 1987). The second measure of misfit is the mean of the average angle between the three principal axes of the general tensor solution for the population and the axes of the ideal stress tensor solution for each fault. The ideal tensor is one that minimizes the differential stress for a fault.

Figure 5. Index map of the Newcastle geothermal area showing the location of fault slip data collection sites (heavy circles with letter in center). Also shown are predicted slip directions for some map-scale faults using reduced stress tensors determined in this study. Arrows and numbers show the trend and plunge of slip axes. Hachures and numbers show the dip direction and dip of the fault planes. Solid circle is the center of the thermal anomaly, near thermal gradient holes NC-18 and NC-19.

These methods, and the results of fault slip analysis using software provided by Z. Reches, were checked using a program written by the authors, closely following the algorithm of Reches (1987). This program (INVERT), written in Turbo Pascal, version 4.0, uses the singular value decomposition and chi-square minimization fitting procedures (and code) published by Press and others (1986). The program also uses an eigenvector determination procedure incorporated in the Turbo Pascal Numerical Methods Toolbox. Two other supporting programs were written to supplement Reches (1987) software; REFORMAT, which translates field data into the format required for Reches' software and the INVERT program, and SLIP, which calculates the predicted slip on a fault from the reduced tensor. All three of these programs are in Appendix B.

Table 1 lists the results of the analysis. We rotated the orientations of fault slip data for sites A and B to restore bedding to horizontal (rotation about the line of strike). The bedding orientations at sites A and B are $5^\circ, 6^\circ$ and $274^\circ, 13^\circ$ respectively (dip direction and dip). Data from site C were not rotated because of the absence of bedding information. Data from site D were not rotated because the large dip at this site, $220^\circ, 44^\circ$ (dip direction and dip), and large slip axes misfit angles (Table 1) made interpretation of these data problematic.

Next, we performed a step wise removal of statistical outliers for sites A, B, and C by examining histograms of the misfit angles. Each of these data sets yielded lognormal distributions of slip axis misfit angles and normal distributions of principal axes misfit angles. For each iteration, we removed data above the 95th percentile and recalculated the solution tensor and misfit angles. The percent of original data retained for each set, after removal of outliers, ranged from 65 to 87 percent. Removal of this data did not significantly alter the orientations of the axes of the solution tensors (Table 1), but greatly improved the accuracy of the solutions and reduced the mean misfit angles. Many factors probably account for the presence of these outliers, such as slumping of exposures and a failure for some of the faults to meet the assumption of the method. These assumptions are that the deformation occurred under a homogeneous state of stress, that slip along each fault occurred independently, and that slip was in the direction of maximum resolved sheer stress. Principal axes misfit results for site A showed a distinct bimodal distribution (Figure 6) that allowed us to separate these data into two subsets, listed as sites A_1 and A_2 in Table 1.

Results of this somewhat subjective interpretation of the data (interpretive in the sense of rotation of bedding, removal of statistical outliers, and the selection of a coefficient of friction) are shown in Figure 7. The very similar results obtained for sites A_1 , B, and D suggest that the same tectonic event (T_1) produced these faults. The mean angular difference between the principal axes of solution tensors for these three sites is less than 3° . Likewise, the similar results obtained for sites A_2 and C suggest that a separate tectonic event (T_2) produced these faults. The mean angular difference between the principal axes of solution tensors for these two sites is about 11° . The dominance

Table 1 - Results of Fault Slip Analysis, Newcastle, Utah

	Site A	Site A ₁	Site A ₁	Site A ₁	Site A ₂	Site A ₂	Site A ₂	Site B	Site B	Site B	Site C	Site C	Site D
	Unproces. Data	Unrotated	Unrotated, Outliers Removed	Rotated, Outliers Removed	Unrotated	Unrotated Outliers Removed	Rotated, Outliers Removed	Unproces. Data	Unrotated, Outliers Removed	Rotated Outliers Removed	Unproces. Data	Outliers Removed	Unproces. Data
Number of Measurements (% Data Retained)	108 (100%)	84 (100%)	65 (77%)	65 (77%)	24 (100%)	21 (87%)	21 (87%)	134 (100%)	96 (72%)	93 (69%)	20 (100%)	13 (65%)	55 (100%)
Sigma 1 Trend/Plunge	355/17	355/14	347/29	354/6	173/81	195/77	207/83	352/10	356/16	352/7	25/85	358/81	355/8
Sigma 2 Trend/ Plunge	190/71	185/74	178/59	177/82	33/6	34/11	39/6	114/69	147/71	166/82	122/0	218/6	189/80
Sigma 3 Trend/ Plunge	87/4	85/2	80/4	84/0	303/5	304/3	309/1	259/16	263/8	262/0	212/4	127/5	85/2
Phi Value	0.76	0.70	0.77	0.58	0.56	0.88	0.55	0.55	0.75	0.53	0.31	0.05	0.78
Coefficient of Friction	0.00	0.00	0.40	0.00	0.40	0.31	0.40	0.00	0.40	0.21	0.00	0.40	0.00
Average Slip-axis Misfit	39.99	19.18	16.96	16.59	28.89	19.22	24.09	33.96	22.13	18.36	27.14	13.49	49.16

Figure 6. Frequency histogram of principal axes misfit angles for site A. The prominent bimodal distribution was used to separate the data into two subsets, labeled A₁ and A₂ in Table 1.

of the T₁ event in the fault population from site A, the high density of minor faults associated with the T₁ event (sites A and B), and the absence of expression of the T₁ event at site C argue that the T₁ event occurred prior to the eruption of the 8.5 Ma rhyolite at site C and that the T₂ event occurred after this eruption. From our data, we bracket the T₁ event between 21 and 8.5 Ma and associate it with regional 17-8 Ma, southwest-directed extension recognized by many workers (Angelier and others, 1985; Anderson, 1987; Axen and Wernicke, 1987) in southeastern Nevada and southwestern Utah. Wernicke and others (1989) suggest that this extensional episode, in the Las Vegas region, was most intense between 15 and 11 Ma and was characterized by a S70°W extension direction. This is close to the 262° azimuth of sigma 3 obtained for sites A, B, and D (Figure 7). At Newcastle, this event probably produced most (if not all) of the faults exposed in the range south and east of Newcastle. We associate the T₂ event with the formation of the Antelope Range fault and the Newcastle graben and interpret these structures to be less than 8.5 Ma. The T₁ and T₂ events resemble the "pre-basin-range" and "basin-range" events described by Zoback and others (1981) in terms of timing, orientation, and style. Following from this interpretation we note that of the faults produced during the T₁ event, relatively few were reactivated during the T₂ event (at sites A and B) and that the T₂ event generated only sparse new faults near the footwall of the

T1 Tectonic Event

T2 Tectonic Event

Figure 7. Lower hemisphere stereoplots (Wulff nets) showing the orientations of principal axes (s_1 , s_2 , and s_3) of solution tensors generated by fault slip analysis (Table 1). Stars = results from site A₁, squares = site A₂, triangles = site B, diamonds = site C, circles = site D.

Antelope Range fault (site C), apparently contributing little to the fault and fracture permeability of the bedrock away from the Antelope Range fault.

As in other studies of this type, the use of somewhat subjective form of data interpretation is defended by the coherent results obtained. The success of the method at sites A₁ and B, gauged by the close correspondence of results (Figure 7), suggests that the formation of most of the minor faults at these locations occurred prior to rotation of bedding. The close correspondence of unrotated results from site D with rotated results from sites A₁ and B suggest that most of the minor faults produced at site D occurred after rotation of bedding.

2.2.1 Relationship Between Map-scale Faults and the Fault Slip Analysis

Because of the absence of piercing-points for map-scale faults, we cannot directly compare the observed slip with predicted slip using the stress tensors calculated above. In a qualitative sense, however, we note that slickensides observed adjacent to west-northwest-striking faults throughout the map area have nearly horizontal rakes and are right-lateral in their sense of displacement, which matches the predicted slip for the T₁ event (Siders and others, 1989; written comm., P.D. Rowley, 1989; this study). We note that the predicted slip on the Antelope Range fault using the T₁ stress tensor yields a slip vector trending 220° and plunging -2° (dominantly left-lateral with a slight reverse component, Figure 5). Clearly, slip along the Antelope Range fault during the T₁ event alone could not have produced the Newcastle graben as defined by gravity data. Applying the T₂ stress tensor to the geometry of the Antelope Range fault yields a slip vector trending 297° and plunging 64°, suggesting nearly pure dip slip (Figure 5). To summarize our interpretations, Figure 5 shows the predicted slip for many map-scale faults with well-defined geometries, assuming that faults internal to the range formed during the T₁ event and that the Antelope Range fault formed during the T₂ event.

3.0 GEOPHYSICAL INVESTIGATIONS

3.1 Gravity and Magnetic Surveys

3.1.1 Objectives

Because fracture permeability dominates control of fluid migration within hydrothermal systems, structural analysis becomes an important component of a geothermal investigation. At Newcastle, we proposed a combination of gravity and magnetic investigations to help determine subsurface geologic structure. Because high-resolution, high cost methods such as seismic reflection were beyond the scope of the project, more affordable gravity and magnetic methods offered the best potential for low-to moderate-resolution of subsurface structure. The goals of the geophysical surveys included (1) determining the geometry (mainly attitude) of the Antelope Range fault, (2) determining if buried, hanging-wall structures exist, and (3) estimating the depth to bedrock within the Escalante Valley. Consequently, we worked to interpret data along profiles both normal and parallel to the trace of the Antelope Range fault. This work included some experimentation aimed at defining the utility of close-spaced, high-precision gravity surveys within tectonic environments characterized by Basin and Range-type normal faulting. We devoted the majority of effort to acquisition and interpretation of gravity data, because ground magnetic surveys proved ineffective due to various problems.

3.1.2 Previous Work

Eaton and others (1978) describe the relation of regional gravity and tectonic patterns in the Great Basin. Previous gravity and magnetic investigations of the Escalante Desert and vicinity, Iron and Washington Counties, Utah, by Pe (1980) focussed on regional variations. The principal regional gravity feature (Figure 8) is a northeast-southwest trending gravity low, interpreted by Pe (1980) as a graben. The Newcastle geothermal system is located along the southeast margin of this graben. This margin is defined by the Antelope Range fault lying about one km east of the Newcastle town center and striking northeast-southwest (Plate 1). The regional magnetic anomaly map (Figure 9) shows no distinctive features associated with this graben structure. In general, there is little indication within existing data sets of small-scale subsurface structures.

3.1.3 Magnetic Survey

Initially, we had hoped to obtain useful information using both magnetic and gravity surveys. Other than regional aeromagnetic data, described above, no detailed magnetic data were available. A United States Steel Corporation (USX) aeromagnetic data set, although known to exist, was initially unavailable. Our first effort, during November 1987, involved acquiring ground-based magnetic data. Problems with instru-

Figure 8. Complete Bouguer gravity anomaly map of southwestern Utah (after Pe, 1980).

Figure 9. Aeromagnetic map of southwestern Utah (after Pe 1980).

mentation, electrical interference from numerous high-tension power lines, and severe terrain noise in the acquired magnetic data, severely limited the interpretational utility of our magnetic data. Subsequently, we concentrated our efforts on a detailed gravity survey.

We later acquired the USX aeromagnetic data, which were in the form of contour maps, compiled from several different blocks of data. Unfortunately, one block was flown over the mountains east of Newcastle, and another block was flown over the valley area. A gap occurs between this coverage along the range front, the area critical to this study. Moreover, the data for these two blocks were evidently acquired by means of flights at two different elevations. Without reprocessing of the raw digital data, the contour maps are of limited use for studying detailed subsurface structure relative to the Antelope Range fault. We therefore made no attempt to interpret the USX maps.

3.1.4 Gravity Survey

Instrumentation and Field Procedures

Instruments used in the survey consisted of two La Coste and Romberg gravity meters with electronic readout (models G-264 and G-461). We established a local gravity base station at the edge of a field, approximately 15 m (50 ft) south from the Newcastle cemetery, about a mile west of the town center. At the Newcastle base station (referred to as 'GBS') and at all gravity stations established in the survey, we determined absolute gravity by means of a tie to the regional gravity base station in Enterprise, Utah established by Cook (and others, 1971).

We gathered gravity data along profiles established both normal and parallel to the range front (Figure 10). Data along lines SS (short) (Figure 11) and LL (long) (Figure 12) were acquired in November 1987, and data along lines A through L were acquired in September 1988. A total of 153 stations were initially occupied during 1987 and 240 more stations were occupied during 1988, for a total of 393 stations.

We established diurnal, or time, variation of the earth's gravity field along with instrument drift by taking daily, initial readings with each meter at GBS. Readings were repeated every three to five hours, and final readings taken at the end of each day.

Locations and elevations of GBS and all gravity points were established using a Pentax semi-total-station electronic theodolite with electronic distance meter (theodolite/EDM). Vertical control was established with a tie to a USGS bench mark (#10JDB, elevation 5314 feet [1620 m]) located in Newcastle. Horizontal control was established by a tie to a section corner marker (corner of sections 19, 20, 29 and 30, township 36S range 15W in Iron County [USGS 7.5' quadrangle Newcastle]), where Utah Power and Light Company established state plane coordinates.

Figure 10. Gravity survey station locations, lines SS, LL, and A through K, plotted from Utah state-plane coordinates (Appendix C). Map base is the USGS Newcastle, Utah 7.5' quadrangle.

Figure 11. Station locations (a), Bouguer gravity (b), and station elevations (c) along line SS of the detailed gravity survey. The horizontal scale is easting, Utah state-plane coordinates.

Figure 12. Station locations (a), Bouguer gravity (b), and station elevations (c) along line LL of the detailed gravity survey. The horizontal scale is easting, Utah state-plane coordinates.

Data Reduction

After reducing theodolite and EDM data, an error analysis showed that survey base locations (points occupied by the theodolite/EDM) had only a few feet of horizontal error and less than one foot of vertical error throughout all survey bases -- an acceptable margin of error. Because we determined gravity station locations with foreshots only, we could not estimate gravity station location errors. The smoothness of variations in the gravity data, however, indicates that with the exception of only a few stations, surveying errors were minimal. Because of format requirements for various data reduction programs, all gravity station locations were assigned both latitude-longitude and Utah state plane coordinates.

For an overview of gravity data reduction the reader should refer to Telford (and others, 1976) or Dobrin and Savit (1988). Gravity data were first corrected for diurnal variations related to the solid earth tides, using a modified version of U.S. Geological Survey (USGS) program CON77. Gravity data were then corrected for instrument drift, using a modified version of USGS program LSADJ. Once we applied corrections for time variations, we then corrected for known conditions (earth's rotation, terrain) that give rise to spatial variations. The programs CON77 and LSADJ, originally written by R. Jachens, USGS, Menlo Park, California, were slightly modified for our purposes.

Because much of the region surrounding the project area is mountainous, terrain corrections were essential. We digitized USGS topography using the Newcastle 7.5' and relevant, surrounding quadrangle maps for applying two-step terrain corrections. Corrections for topography within a radius of 1.6 km (1 mi) about each station were applied using the digitized terrain data and a program, known as TRITER (Rupert, 1988), available from the Canadian Geological Survey. A density of 2400 kg m^{-3} ($149.8 \text{ lbs ft}^{-3}$) was used for these inner zone corrections. Corrections for topography outside this zone, to a distance of 166.7 km (104 mi), were applied using USGS terrain data and USGS program BOUGUER (Godson, 1978; Plouff, 1977). We selected a density of 2400 kg m^{-3} ($149.8 \text{ lbs ft}^{-3}$) for terrain corrections based upon previous studies of rock densities in this area (e.g., Pe, 1980).

The program BOUGUER was also used to compute the Bouguer anomaly by applying the latitude correction and the Bouguer and free air reductions (reduction to sea level). A density of 2400 kg m^{-3} ($149.8 \text{ lbs ft}^{-3}$) was used for the Bouguer correction. The density of middle and lower crustal rocks must increase above this value, however, taking this into account yields what is essentially a constant correction for all stations, which would simply shift the baseline (the zero value) of our anomaly. Future studies could benefit from modification of the program BOUGUER so that a depth-dependent density could be used for the Bouguer correction.

Since we had referenced all of our gravity readings to the regional gravity base station at Enterprise, Utah, where absolute gravity is known to be 979446.73 milligal (Cook and others, 1971) we were able to obtain observed gravity in an absolute sense at each station, and then calculate the complete Bouguer anomaly:

$$g_{\text{obs}} - g_{\text{theoretical}}$$

where g_{obs} is absolute gravity at each station, reduced to sea level using the free air and Bouguer reductions, with terrain corrections applied; and where $g_{\text{theoretical}}$ is theoretical gravity (1967 Gravity Formula) at sea level at the same latitude and longitude.

Principal facts of observations made during the 1987 and 1988 Newcastle gravity survey have been accumulated in four data files. Hard copies of these data files are contained in appendices C and D.

Data files 87stn.dat and 88stn.dat contain eastings, northings, elevation (all in feet above sea level (1927 datum), latitude and longitude (decimal degrees) of all gravity stations from the 1987 and 1988 surveys.

Data files 1987.dat and 1988.dat contain the raw gravity data (dial readings, meter number, time and date). The dial readings are directly from the indicated La Coste & Romberg gravity meters. Times are Mountain standard time for the 1987 survey and Mountain daylight savings time for the 1988 survey.

The presentation format of gravity results reflects the fact that the data were acquired mostly along profiles. Because profile lines were often slightly crooked, station locations were projected onto best-fit, least-squares lines. Gravity readings and station elevations were plotted as a function of the easting (Utah state-plane) coordinates.

The Bouguer anomaly and elevation along line SS and line LL are presented in Figures 11 and 12. Also presented in these figures is an xy-map of the projection adopted for each line. The Bouguer anomaly and elevation along lines B through K are displayed in Appendix D (figures D1 through D8). Data along lines H, I, and J were combined to form line HIJ. Because lines A and L are short, separate plots were not prepared. Gravimeter or survey data are in obvious error for about a dozen points. For completeness, however, these outliers remain in the gravity and location data.

Interpretation

The principal variations in Bouguer gravity in the Newcastle area are related to the Antelope Range fault. This is evident on line LL (Figure 12), and to a lesser extent on lines F and G (figures D5 and D6, Appendix D) as a large lateral gradient in gravity extending northwest-southeast, normal to the range front.

The long profile (LL) across the Antelope Range fault shows no obvious variations that may relate to footwall or hanging-wall structures. Non-linearity in the profiles, however, cannot entirely account for a minor gravity inflection seen along line G. We interpret the inflection as due to either (1) excess mass present in the hanging wall (e.g., higher density alluvium near the fault plane, or small slide blocks at depth), or (2) a small step in the Antelope Range fault.

Relatively high-frequency variations in gravity occur along profiles near the range front fault. Two high-frequency variations seen on lines C and D (figures D2 and D3, Appendix D) are in all likelihood due to terrain effects (outcropping terrain) in the hanging wall. Apparent variation in gravity along line K is due to the marked deviation of this particular profile from a straight line (Figure D8, Appendix D). Starting at either end of the profile, the line deviates toward the range front, causing an apparent increase in gravity, and then away from the range front, causing an apparent decrease in gravity.

Moving from the southwest end of the survey area towards the northeast end, there is a consistent decrease in Bouguer gravity, which can be seen along line SS and lines B through E, and lines HIJ and K. Although this variation is not evident in Pe's (1980) regional map (Figure 8), it possibly reflects the apparent splaying along the Antelope Range fault (map of Siders and others, 1989), or may indicate deepening of the Newcastle graben to the northeast.

Forward modeling of gravity data was adopted as a means of estimating the subsurface geometry near Newcastle. Dip and total offset along the Antelope Range fault are important parameters in the development of a conceptual model of the Newcastle hydrothermal system. In our modelling, we used a 2.5 dimensional routine written by J.H. Luetgert of the USGS, based on the algorithm of Cady (1980), and modified by C.M. Schlenger for operation on UNIX-based and PC-type computers. The 2.5 D algorithm of Cady's uses constant density horizontal prisms, polygonal in cross-section, and invariant along strike. The strike length of the prisms is finite. The model discussed in this report is based on a model developed by Chisholm and Robertson (1988), with modifications to include the effect of the "Pinto graben" (Pe, 1980).

The final model adopted as a result of the forward modeling is illustrated in Figure 13. The model consists of a cross-section along the long line (LL) in Figure 12. This model includes the following features:

1. The rock in which the structure sits has a density of 2525 kg m^{-3} ($157.6 \text{ lbs ft}^{-3}$), which is appropriate for the combination of Mesozoic sedimentary and igneous rocks present in the upper crust at this locality (Siders and others, 1989).
2. Sedimentary rocks of the Iron Springs and Claron formations along with volcanic rocks of the Isom formation and Quichapa group and various other unnamed units (rhyolite domes, volcaniclastic units, etc.) are represented by prisms with density of 2400 kg m^{-3} ($149.8 \text{ lbs ft}^{-3}$).
3. The Antelope Range fault was assigned a dip of 65° .
4. The Newcastle graben was represented by a combination of alluvial wedges.
5. A wedge of alluvium at depth, with a density of 2125 kg m^{-3} ($132.7 \text{ lbs ft}^{-3}$), thins basinward, and an overlying wedge, with a density of 1900 kg m^{-3} ($118.6 \text{ lbs ft}^{-3}$), thickens basinward.
6. The small "Pinto graben" (Pe, 1980) is represented by a thin wedge of alluvial fan material with average density of 2000 kg m^{-3} ($124.9 \text{ lbs ft}^{-3}$), and a strike length of 4 km.

Figure 13. Model of subsurface structure in the vicinity of Newcastle. Densities shown are in kg m^{-3} . With the exception of the shallow "Pinto graben" structure (density of 2000 kg m^{-3}), the polygonal-cross-section structures that make up the model have strike lengths of 20 km (± 10 km). The Pinto 'graben' has a strike length of 4 km (± 2 km). The 0 km mark corresponds to the NW end of gravity line LL (Figure 12).

The strike length of the above model components, except for the Pinto graben, is 20 km (12.4 mi). The northwest edge of the Newcastle graben is not well defined and, therefore, not considered in the model. The upturn in the gravity anomaly on the northwest end of line LL, however, is evidence supporting the presence of a northwest boundary fault (Figure 12).

A comparison between the observed data and the calculated gravity anomaly from modeling are shown in Figure 14. Modeling by Chisholm and Robertson (1988) has shown that the effect of dip angle is moderate. Fault dips varying from 60 to 70 degrees yield model results that adequately fit the observed data. Our model uses an appropriate dip of 65 degrees along the Antelope Range fault with total offset of about 1.6 km (1 mi). The model also suggests that the fault persists to at least 5 km (3 mi) depth.

Figure 14. Comparison between observed data (small dots) and the gravity anomaly calculated (large dots) using the model in Figure 13.

The results of the Newcastle gravity survey have shown the utility of gravity data for interpretation of subsurface structure in the Newcastle area. This is particularly true in this situation where other detailed geophysical information is unavailable. Other important results from this work include: (1) The Antelope Range fault dips about 65 degrees, and apparently persists to depths of at least 5 km; and (2) Total offset along the Antelope Range Fault is about 1.6 km (1 mi), while gravity data suggest a deepening of the Newcastle graben to the northwest. High-resolution gravity surveys offer promise for geothermal site investigations, however, the non-uniqueness of gravity interpretation suggests that greater benefits will come from constrained interpretation in the presence of other geophysical data.

The Newcastle gravity data were reduced following standard procedures that include the free air and Bouguer reductions. The observed data should eventually be reprocessed using a different scheme. Gravity observations should be corrected for latitude effects (arising due to the rotation of the earth and the equatorial bulge), and rather than reducing the observations to sea level, by means of the free air and Bouguer reductions, the observations should be interpreted without any further reductions. This means that once the latitude correction has been applied, the data should be modeled, using a two-step process. The first step would be to strip the effects of terrain in the area, accounting for terrain effects down to an arbitrary datum, of say 1500 m (5000 ft) (elevation). The gravitational effect of all the terrain within a certain distance, say 10 km (6.2 mi), of each station, would be calculated and removed. This would leave an observation of gravity corrected for terrain and latitude variation at some particular elevation, with corrected terrain and latitude. Following the removal of terrain effects, the effects of deep structure, including the normal fault, should be modeled using a scheme similar to the one used for this study.

Such a reduction scheme offers a more intuitive solution to the interpretation problem. No defined reductions such as the free air or Bouguer correction are introduced. These types of reductions are not corrections. They are defined procedures, nearly universally followed, which introduce not only an element of ambiguity, but also errors to the interpretation of gravity data acquired in areas of high topographic relief.

3.2 Resistivity and Spontaneous Potential (SP) Surveys

3.2.1 Electrical Resistivity Survey

An electrical resistivity survey was completed over much of the temperature anomaly by University of Utah Research Institute (UURI) and UGMS personnel in July 1989. The objectives of the survey were to (1) map the location of the rising thermal fluids and the distribution of the outflow plume, and (2) to document the electrical resistivity expression of the higher temperature portions of the geothermal system. Utah's two high-temperature geothermal systems, Roosevelt Hot Springs and Cove Fort-

Sulphurdale, are both well expressed in resistivity data (Ross and others, 1982; Ross and Moore, 1985). The interpretation of these data has contributed to a better understanding of the resources.

Three high voltage electric power transmission lines which traverse northeasterly across the temperature anomaly restrict the locations available for conducting resistivity profiles. Figure 15 shows the location of the four resistivity profiles. The dipole-dipole array was chosen because it offers considerable flexibility in avoiding interference from grounded structures, simultaneously maps lateral and vertical resistivity changes, and because it can map subsurface bodies with a higher spatial resolution than other arrays. A dipole length of 152 m (500 ft) was selected as the best compromise for spatial resolutions from the surface to depths of 305 m (1000 ft) and for adequate lateral coverage.

The contoured apparent resistivity data for the third separation (Figure 15) indicates the net effect of resistivities from the surface to a depth of approximately one dipole length, i.e. 152 m (500 ft). Apparent resistivities of 4-10 ohm-m were recorded on the northwest portions of Lines 2 and 3, and from Stations 3-4 SW on Line 1. This area includes the higher temperatures observed in shallow temperature holes, which are believed to arise from a plume of low resistivity thermal waters.

A detailed numerical model interpretation of these data (Ross and others, in prep.) provides additional detail on the probable source of the thermal fluids from which this plume originates. Figure 16 illustrates a numerical model solution for Line 2. A low resistivity zone extends to depth near Station 1 SE, approaches the surface, and extends laterally to the northwest. The depth to the conductive layer, north of Station 2 NW, is modeled as approximately 45 m (152 ft). The sharp resistivity contrasts between Station 1 and Station 2 SE are suggestive of a buried fault, apparently dipping to the northwest.

The 4 ohm-m resistivity assigned to the thermal plume is consistent with low resistivity zones modeled for Roosevelt Hot Springs and Cove Fort-Sulphurdale, and requires low resistivity fluids (about 1 ohm-m) and fairly high (20-40 percent) porosities in the alluvium or volcanics. The presence of substantial amounts of clay minerals would decrease the porosity or increase the fluid resistivity needed to account for the 4 ohm-m body.

Low resistivity zones indicating probable conduits for rising thermal fluids and outflow plumes were determined through numerical models for Lines 1, 2, and 3, and are indicated on Figure 15. The lowest resistivities modeled for Line 4 were 10 ohm-m. These occur north of Station 5 NW and could represent slightly saline fluids at depths of approximately 500 feet.

Figure 15. Contoured apparent resistivity for 3rd separation. Contour Interval is 5 ohm-m.

Figure 16. Numerical model solution for resistivity line 2. Hatched pattern denotes 4 ohm-m resistivity zone assigned to the upwelling thermal plume.

The dipole-dipole resistivity data have clearly mapped the thermal plume at Newcastle and have probably defined the principal structures, on Lines 2 and 3, along which the thermal fluids may be rising.

3.2.1 SP Survey

A spontaneous-potential (self-potential, or SP) survey was also completed at the Newcastle thermal area in November 1989 (Ross and others, in prep.). This survey identified a near circular (150 m, or 500 ft diameter) 108 millivolt low nearly coincident with the low resistivity zone at Station 0-1 SE on Line 2 (Figure 17). No similar anomaly was noted on Line 3, perhaps indicating that the zone on Line 3 is altered and fluid

bearing but sealed, while the zone on Line 2 is open and a primary upflow zone for the Newcastle thermal water plume. A smaller, 30 millivolt low was observed which could indicate a minor zone of leakage along the Antelope Range fault.

Figure 17. Contour map of spontaneous potential (SP) data.

4.0 SOIL-GAS GEOCHEMICAL INVESTIGATIONS

4.1 Soil-Mercury Survey

Evidence of a linkage between mercury occurrences and hot spring activity has been previously documented. Areas of economic mercury occurrences, although not usually located near present day hot springs, exhibit evidence of past geothermal activity. Areas of present geothermal activity that have been mined for mercury in the past include Ngawha, New Zealand; Skaggs Springs, Sulfur Bank, Wilbur Springs and Coso Hot Springs, California; and Steamboat Springs, Nevada. In addition, mercury minerals (cinnabar and metacinnabar) have been noted to be depositing in some hot springs such as at Sulfur Bank and Amedee Springs, California; Steamboat Springs, Nevada; Boiling Springs, Idaho (Weissberg and others, 1979, p. 757).

Detailed mercury surveys by Parry, Benson and Miller (1976) and by Capuano and Bamford (1978) have also shown that mercury anomalies are associated with faults in close proximity to near-surface thermal activity. Capuano and Bamford (1978), using a technique of soil-sampling and analysis on gold film, noted that at Roosevelt Hot Springs mercury values dropped to "background concentrations" in nearby locations with little or no indication of subsurface thermal activity.

During the process of hydrothermal alteration of sulfides and other minerals containing Hg in trace amounts, Hg is released in the $2+$ valence state. Hg^{+2} can then be reduced by Fe^{+2} or by organic material to Hg^+ or Hg^0 . The result is a net production of Hg^0 (Klusman and Landress, 1978). High vapor pressure of Hg^0 makes it an extremely mobile, volatile component in a gas-water system. Elevated temperatures encountered in and near a geothermal system serve to increase this mobility resulting in the migration of Hg upward and away from a geothermal reservoir. The overall result is that soils in geothermal areas tend to become Hg-enriched by trapping vapor phase Hg onto clay surfaces and within organic materials.

Because of the apparent success of these types of surveys, we performed a soil-mercury survey at Newcastle across the area of suspected geothermal upflow. Some 110 soil samples were taken on a sample grid of 200 feet by 500 feet within the geothermal area. Five additional samples were also collected away from the geothermal area in an effort to determine background values. The samples were then delivered to the Earth Science Laboratory -- University of Utah Research Institute for analyses using a Model 301 Gold Film Mercury Detector (Jerome Instrument Corp., Jerome, Arizona). By this method, a weighed sample of soil is heated with a propane torch to a temperature of over $600^{\circ}C$. Mercury vapor is released and collected onto a gold film. The quantity of mercury is measured by the change in electrical resistance of the gold film (R. Kroneman, pers. comm.).

The mean and standard deviation for the sample set taken from the geothermal area, reported in parts per billion were 30 and 10 respectively. The general distribution of sample points falling within the 4th quartile (≥ 40 ppb) forms irregular patterns near the range front (Figure 18). One area is within close proximity of drill holes NC-18 and NC-19, possibly corresponding to thermal and geophysical anomalies in this area. Another area lies a short distance to the northeast along the surface trace of the Antelope Range fault. The mean and standard deviation for the sample set taken away from the geothermal area were 26 and 8 respectively.

The results of the soil-mercury survey were disappointing with respect to utilizing this method as an exploration tool for blind hydrothermal systems such as at Newcastle. We expected to see very distinct soil-mercury anomalies corresponding to zones of hot water. Instead we observed only subtle variations in the concentration of soil mercury. The outcome does suggest, however, that the use of this method (soil sampling rather than gas sampling) in areas lacking of a surface geothermal expression, should be looked upon with a degree of caution. Other methods that sample larger volumes of soil-gas, such as described by Jensen and Qidwai (no date) might prove more applicable for studying buried hydrothermal systems.

4.2 Radon Survey

Radon is a ubiquitous, chemically inert, radioactive noble gas. It is soluble in cold water with solubility decreasing with increasing temperature, and can migrate freely through porous and fractured media. Radon occurs in nature principally as three isotopes -- Rn^{219} , Rn^{220} , and Rn^{222} -- produced as part of the U^{235} , Th^{232} , and U^{238} decay series, respectively. Because of duration of half-life, U^{238} is the most important of the three parent elements in the production of radon. Rn^{222} has a half-life of 3.825 days, while the other isotopes have half-lives of less than one minute. Because of its relative abundance and a half-life much longer than the other isotopes, Rn^{222} is used often as a geologic tracer in geothermal systems, and is normally the isotope referred to in "radon" studies. Rn^{219} is referred to as actinon, and Rn^{220} is often called thoron (Nielson, 1978, p. 6).

The principal link between radon gas and geothermal systems relates primarily to geologic structures that control those systems -- usually a major fault, or system of faults, which act as conduits for the upward migration of thermal fluid. Radon is steadily generated by radioactive elements found in geologic materials, and migrates through the subsurface by diffusion and transport processes. Because of its relative short half-life (3.825 days), radon anomalies typically mark the approximate location of their source.

Radon concentration in soil can vary up to four orders of magnitude. These wide variations occur because of the wide range in the rate in which radon can be generated from its sources. Variations are a result of numerous factors including rates of fluid flow,

Figure 18. Map showing soil-mercury sample locations, sample values (in ppb), and areas of 40 ppb or greater of mercury concentrations.

secular equilibrium within the U^{238} decay chain, climatic conditions, and local geology. Because of these variables, which affect concentration, radon surveys cannot be used in a quantitative way. Their use, however, as an exploration tool to detect faults and geothermal upflow has been documented (Nielson, D.L., 1978).

Radon is measured indirectly by detection of alpha particles emitted as part of natural radioactive decay. The detection method normally used is direct exposure of alpha track material to ambient radon -- a film of alpha track material (in a detector) is placed into a cup, which is filtered to remove the progeny. The cup is placed at the desired location and left over a period of time. Radon diffuses into the upside-down cup, where it decays. The alpha emissions from the decay leave microscopic damage along the track left by each alpha particle. After exposure for the desired period of time, the film is removed from the cup and etched in an acidic or basic solution. The exposure of the detectors is determined and standardized for the amount of exposure time.

The objective of our study at Newcastle was to observe radon concentrations across the mapped thermal anomaly and the Antelope Range fault -- thought to be a major factor controlling the geothermal system. We measured radon using alpha particle detectors. The detector system consisted of an alpha-sensitive dosimeter attached to the inside of a plastic cup. The cups were placed in eight-inch diameter holes 20 to 24 inches beneath ground level. The holes were lined with PCP pipe and sealed at the top. The detectors were left at the bottom of the holes for about six weeks. At the end of the exposure time the detectors were recovered and returned to the marketing laboratory for analysis.

Our survey utilized 48 alpha radon detectors, placed along three transverse lines, laid out at right angles to the Antelope Range fault and crossing the thermal anomaly (Figure 19). A fourth, short line was also laid out across the Antelope Range fault a distance south from the thermal anomaly. Detectors were normally placed at intervals of 60 m (200 ft) along each line, with closer spacings of 15 m (50 ft) used near the trace of the Antelope Range fault.

The mean radon concentration of the survey was 354 pico-curies per liter (Pc/L). Figure 19 shows the survey lines and the area(s) of anomalous radon concentration. Along the margins of the thermal anomaly, radon anomalies appear more closely associated with the trace of the Antelope Range fault. Within the thermal anomaly, however, radon anomalies appear to be displaced westward from the mapped fault trace, possibly reflecting movement of fluid in the subsurface.

The southwest end of traverse line 1 (figures 19 and 20a) crosses the Antelope Range fault and exhibits anomalous radon flux over the fault. Moving along the traverse to the northwest, radon concentrations appear to drop to background levels. Radon concentrations along traverse line 2 (Figure 20b) are generally above background. In

Figure 19. Map showing location of radon traverse lines, sample points, and radon concentrations.

Figure 20. Radon traverses 1, 2, and 3 indicated as a, b, and c respectively. Error bars represent standard deviation of the sample population.

contrast to line one, however, anomalously low radon values are seen along the southeast end of line 2 where it crosses the surface trace of the Antelope Range fault. In similar fashion to line 2, traverse line 3 (Figure 20c) shows relatively low radon flux over the Antelope Range fault. Radon values then increase gradually to the northwest, and show some of the highest readings throughout the survey.

One interpretation of the radon pattern seen in the soil is that radon is likely moving upward in association with the Antelope Range fault and the geothermal fluid. In the area where the geothermal fluid moves closest to the surface and begins to flow down the hydraulic gradient, radon becomes displaced to the northwest, away from the fault. The soil-gas expression of this situation then is a negative anomaly over the trace of the fault and relatively high radon values across the outflow portion of the system.

5.0 A CONCEPTUAL MODEL FOR FLUID FLOW AND HEAT TRANSPORT IN THE NEWCASTLE GEOTHERMAL SYSTEM

5.1 Background

Drilling and completion of the Christiansen Brothers irrigation well near Newcastle, Utah revealed groundwater temperatures in excess of 100°C between depths of 60 and 152 m. Subsequent measurements of groundwater temperature in water wells and geothermal exploration holes (Chapman and others, 1981; Clement, 1981; Mower, 1982; Rush, 1983; Mabey and Budding, 1987) indicates a 25 km² (9.7 mi²) region where groundwater temperatures are elevated above the mean annual air temperature of 15°C. Because hydrothermal phenomena such as hot springs or mud pots are absent, the Newcastle geothermal area is termed a blind geothermal system. Although reservoir temperatures in excess of 140°C (284°F) are predicted (Rush 1983), temperatures reached only 130°C (266°F) in a 912 m (2992 ft) geothermal exploration hole drilled a short distance from the Christian Brothers well. The presence of several geothermal prospects marked by thermal springs located on the rim of the Escalante Desert indicates that other blind geothermal systems may be present in the region (Rush, 1983). Exploration experience at Newcastle suggests, however, that the lack of surface expression of a geothermal resource and the apparent localization of elevated temperatures complicates the siting of geothermal exploration wells. Developing a better understanding of the Newcastle geothermal system is expected to aid in reassessing the potential of the Newcastle system and provide a framework for developing the strategies needed to explore for blind geothermal systems elsewhere in the Basin and Range Province.

Our working model of the inferred pathways for groundwater flow in blind geothermal systems similar to that found at Newcastle is shown in Figure 21. Groundwater recharge is presumed to become heated during circulation in this region of elevated heat flow (about 90 mW m⁻²). A zone of high-permeability, located at the contact between valley fill and bedrock, likely provides a preferred pathway for upflow and localized discharge of heated groundwater to the valley-fill deposits. Minerals precipitating within the valley-fill deposits may form a low-permeability seal that enhances upward groundwater flow at the bedrock-sediment interface. Heated groundwater discharged from the high-permeability zone may mix with the cool groundwater flowing in alluvial fan deposits found along the valley margin.

This section of our report outlines the results of a study designed to 1) obtain a better understanding of the factors controlling the localized thermal anomaly identified at Newcastle, 2) help refine the working model shown in Figure 21, and 3) provide guidelines for exploration and testing of blind geothermal systems that may exist in similar environments. The following tasks were performed to meet these objectives:

Figure 21. Working model for fluid flow and heat transfer in the hydrothermal system found at Newcastle, Utah.

- 1) Use existing data to characterize the Newcastle geothermal area and design a strategy for collecting additional thermal, hydrologic, and geochemical data.
- 2) Install thermal monitoring wells and collect a series of temperature-depth logs from these and existing wells to expand current understanding of the subsurface thermal regime and revise previous estimates of heat loss from the geothermal system.
- 3) Collect groundwater samples to perform the geochemical and stable isotope analyses needed to better understand the process of mixing of hot and cold groundwater at shallow depths.
- 4) Use the new and existing data to constrain numerical models of groundwater flow and heat transport in idealized versions for the Newcastle area.
- 5) Propose a most probable conceptual model for the Newcastle geothermal area that is consistent with field data and numerical modeling results.

5.2 The Newcastle Geothermal Area

Figure 22 is a composite plot of temperature-depth profiles obtained by Rush (1977) from shallow wells in the vicinity of Newcastle (labelled NC-2 through 12 in Figure 23). Temperature-depth data and individual temperature-depth plots for these and subsequent wells are presented in Appendices E and F, respectively. The profiles exhibit many features such as subnormal gradients, downward curvature, isothermal sections, and temperature reversals that are characteristic of many geothermal systems (Bodvarsson, 1973; Lachenbruch and others, 1976; Lachenbruch and Sass, 1978; Sass and Sammel, 1976; Sorey and others, 1978; Mase and others, 1978, 1979). These features are caused by fluid motion in recharge, discharge, and lateral flux regions, respectively, where a substantial quantity of heat is being transferred by moving groundwater. Only one site (NC-12, located 3 km northeast of Newcastle) has a subnormal gradient ($21^{\circ}\text{C km}^{-1}$) indicative of a hydrologic recharge zone. The remaining ten sites have near-surface gradients that range from $89^{\circ}\text{C km}^{-1}$ to $1870^{\circ}\text{C km}^{-1}$. Whereas NC-2, 3, and 4 exhibit constant gradients, the temperature patterns at NC-6, 8, 9, and 11 become isothermal, or reverse, between 75 and 100 m (246 and 328 ft). These data lead Chapman (and others, 1981) to suggest that heated groundwater is flowing laterally in a more permeable zone located at a depth of 75 to 100 m (246 to 328 ft). Heat is presumed to be released from this region of elevated temperature by conduction through the surrounding lower-temperature material and by mixing with cooler groundwater.

Figure 22. Temperature-Depth plots for pre-existing wells NC-2 through 12. From Clement (1981) and Chapman and others, 1981.

Figure 23. Well location map. Well symbols indicate: small solid circles = thermal gradient holes drilled prior to this study (NC-2 through NC-11, Union Geothermal well CHR-1); thermal monitoring wells available or drilled for this study (NC-13 through NC-27); irrigation wells sampled for water analyses (WS-1, WS-4, WS-5, WS-6); large solid circles = geothermal supply wells drilled for greenhouse space heating, also sampled for fluid analysis: WS-2 (Hildebrand), WS-3 (Troy Hygro).

Figure 24. Temperature-Depth log for Union Geothermal - Christiansen #1 Well (CHR-1). Detailed temperature profile is also shown on the well log composite (Plate 3).

Union Geothermal Division (UNOCAL Corp.) generously provided unpublished results of thermal, geophysical, and lithology logging carried out in a deep exploration well (Christiansen #1, designated in this study as CHR-1). These data are presented in Plate 3. The temperature-depth data are tabulated in Appendix E and plotted in both Appendix F and Figure 24. Temperatures exceeded 120°C (248°F) only between depths of 79 m and 183 m (259 ft and 600 ft) with approximately isothermal conditions (114°C to 119°C) found between 183 m and 912 m (600 ft and 2992 ft). Because the temperature log contains a temperature reversal at shallow depth (106 m or 348 ft), it seems reasonable to assume that the well penetrated a tongue of heated groundwater and missed the main upflow zone. If this is the case, temperatures greater than those observed in CHR-1, or boiling, might be expected at shallow depth in the center of the upflow zone.

Clement (1981) derived the heat flow map shown in Figure 25 using the temperature-depth data obtained from holes NC 2 through NC 12 and from 3 irrigation wells. Heat flow maxima exceed 3 W m⁻² at NC-5 and NC-10. A minimum anomalous heat loss of 13 MW is computed within the 9.4 km² bounded by the 500 mW m⁻² contour (Figure 25); assuming a background flux of 100 mW m⁻² (Clement, 1981). The minimum volume discharge required to create the estimated heat loss is 0.032 m³ s⁻¹. Rush (1983) independently estimated a similar volume discharge of 0.013 m³ s⁻¹ and, using the results of chemical analyses of groundwater samples, proposed a reservoir temperature of 140°C to 170°C (284°F to 338°F).

Although the heat flow map shown in Figure 25 is poorly constrained to the north, northwest, and southeast, these and other data suggest the presence of a thermal plume of heated groundwater moving to the north from a source located at the mountain front (Chapman and others, 1981; Rush, 1983). A contour plot of groundwater temperature measured in water wells throughout the region (Figure 26, taken from Mower, 1982) outlines the approximate size of the thermal plume and reinforces the possibility that a blind geothermal system also exists near Beryl (Rush, 1983). A helium gas sniffer survey (Denton, 1976) reveals elevated values of helium concentration (Figure 27) located within the region of elevated heat flow indicated in Figure 25. Although maximum concentrations were obtained in a localized region in the immediate vicinity of NC-10, elevated values were also found near the mountain front. Rush (1983) suggests that the helium is released from solution in the groundwater as temperature and pressure decline in a region of lateral groundwater flow.

The data used to construct the heat flow map shown in Figure 25 are insufficient to accurately define either 1) the distribution and magnitude of maximum heat flow or 2) the size and location of the source of heated groundwater. Subsequent sections of this report describe a field-based study designed to obtain the information needed to clarify these issues and to help in refining the working model of the Newcastle geothermal system shown in Figure 21.

Figure 25. Heat flow map for the Newcastle geothermal system based on thermal data obtained from pre-existing NC wells and several irrigation wells. Heat flow contour values are given in mW m^{-2} . Solid circles indicate sites where heat flow is computed from actual temperature-depth and conductivity measurements. Open circles indicate sites where estimates were based on temperatures in irrigation wells. From Clement (1981) and Chapman (and others, 1981).

Figure 26. Contour map of the temperature of groundwater measured in wells of the Beryl-Enterprise area. From Mower (1982).

Figure 27. Contour map of helium concentrations in the Newcastle area at a depth of 0.6 m below the ground surface in the vicinity of Newcastle. From Denton (1976). Concentrations are parts per billion above atmosphere.

5.3 Subsurface Temperature Field and Heat Flow Data

The principal objectives for the 1988-89 thermal measurement program were to delineate more precisely the margins and hence area of the geothermal system, the geometry of the outflow system, and in particular, the control exerted on the fluid discharge system by the range-front fault. To satisfy these objectives, twelve additional holes, designated NC-16 through NC-27, were drilled in September, 1988. Three additional existing water wells drilled by other parties, designated NC-13 through NC-15, were also logged. The drill hole locations are shown on Figure 23.

The 12 new holes were drilled to a depth of 18 m (60 ft). Although deeper holes would have been desirable, on a fixed drilling budget there is a tradeoff between number of holes and depth of holes. On the basis of the existing temperature-depth data (Figure 22), it was argued that a depth of 120-150 m would be required to detect a temperature overturn. Shallower holes reveal principally a linear temperature profile, and there is little difference in information gained from holes 20, 40, 60, or 80 m deep. Thus, a 20 m depth was selected as being sufficiently deep to avoid the "noise" of annual surface temperature variations, and yet the minimum depth required to reveal the signature of the geothermal system. All holes were completed by inserting a bottom-capped 1.25" ID schedule 40 PVC pipe in the hole, filling the pipe with water, and back filling with drill cuttings.

5.3.1 Temperature-depth results

Temperatures were measured with thermistor transducers connected by four-wire cable to a digital ohmmeter. Fenwal K212E thermistors having a nominal 10K ohm resistance at 20°C, a power dissipation of 50 mWK⁻¹ in still water, and a response time of 7 seconds were used. The thermistors were calibrated against a Hewlett Packard digital quartz thermometer. Precision of the probes is 0.004 K; accuracy of the temperature measurements considering calibration errors, field conditions, and ohmmeter resolution is considered to be 0.01 K.

Temperature measurements are made most efficiently in drill holes filled with water because of the short equilibration time for the probe in water. Measurements made in air, above the water table in unsealed holes, require several minutes to arrive at thermal equilibrium. In the case of air-filled holes, a temperature-time series was obtained at each depth by measuring temperature every 20 seconds for a 5-minute period, and equilibrium temperatures for those depths were determined using the extrapolation method of Parasnis (1971).

Temperature-depth data for the 15 new holes designated NC-13 through NC-27 are shown in Figure 28. Temperature-depth plots for two holes from the initial study

Figure 28. Composite plot of temperature-depth logs obtained from the thermal monitoring wells NC-14 through NC-27 installed in this study. Individual logs and tabulated temperature-depth data are contained in appendices E and F. Temperature-depth logs for NC-5 and NC-7 are also shown to provide a reference to pre-existing thermal data.

(NC-5 and NC-7) are included for comparison. Drill hole NC-5 has the highest thermal gradient previously determined, while the gradient in NC-7 is intermediate.

The first striking feature of the temperature field exhibited in the new drill holes is the extreme, near-surface geothermal gradient observed in the three holes drilled on the alluvial fan SSE of the developed geothermal system. Gradients in NC-14, NC-18 and NC-19 over the upper 15 m are about 5°C m^{-1} . Although holes NC-18 and NC-19 were drilled to a depth of 18 m, the holes could only be logged to about 12 m, presumably because the PVC casing lost strength and collapsed at temperatures above 70°C . NC-14 was completed with a black iron pipe and exhibits 94°C at a depth of 15 m, below which the hole is isothermal. This temperature field is somewhat enigmatic. None of these three holes intersected the water table. We considered the possibility that the deeper, open-hole NC-14 could be acting as a "chimney," providing for efficient vapor transport to the near surface (14 m depth) environment, or that boiling water convecting in the pipe could produce the isothermal condition. The similar thermal regime observed in NC-18 and NC-19, shallow holes completed with air-filled plastic pipe, argues against the thermal field seen in NC-14 being simply a borehole effect, rather, that it is a property of the SSE extremity of the geothermal system. We speculate that the isothermal temperature field at 94°C may result from vapor circulating within the alluvial fan at or near the boiling point of water at this elevation, with the upper 15 m being a conductive boundary on the vapor system. This speculation should be checked with further field measurements and model studies.

A second noteworthy aspect of Figure 28 is the regular behavior of temperature-depth profiles in general. The curved profiles in the uppermost 6 m are an expected transient effect of an annual temperature variation at the ground surface and is not of importance in understanding the geothermal system. Between depths of 6 and 20 m, however, most of the profiles are linear, indicating that heat transfer through this region is predominantly conductive. The wide range in gradients observed in these very shallow holes carry a strong signal of the Newcastle geothermal system and vindicate the use of 20 m holes for geothermal exploration in this circumstance.

5.3.2 Heat flow map for the Newcastle geothermal system

Heat flow was calculated for each well by combining the thermal gradient information with thermal conductivity measured on drill cuttings or interpolated from nearby wells. Because laboratory measurements yield the solid rock matrix thermal conductivity, a porosity of 30% was assumed to compute the bulk conductivity of the alluvial fan material in situ. Basic information on thermal gradient, depth interval over which the gradient was calculated, thermal conductivity measurement, and heat flow is given in Table 2. A new heat flow map for the Newcastle geothermal system is shown in Figure 29.

NC Well	Depth Interval (m)	Thermal Gradient (K/km)	N (# thermal conductivity measurements)	(a) Thermal Cond. (W/m K)	(b) Heat Flow (mW/m m)	(c) Thermal Cond. (W/m K)	(d) Heat Flow (mW/m m)
2	46 to 89	89	0	2.27	200	2.27	200
3	46 to 89	116	0	1.7	200	1.7	200
4	8 to 40	220	0	1.7	370	1.7	370
5	8 to 20	1,998	0	1.7	3,400	1.7	3,400
6	5 to 38	1,065	0	1.7	1,810	1.73	1,840
7	8 to 47	370	0	1.7	630	1.7	630
8	17 to 41	1,028	0	1.7	1,750	1.7	1,750
9	8 to 56	710	0	1.7	1,210	1.7	1,210
10	0 to 40	1,833	0	1.7	3,120	1.76	3,230
11	15 to 46	1,292	0	1.7	2,200	1.74	2,250
12	49 to 118	21	0	1.7	40	1.7	40
13	5 to 20	729	0	1.7	1,240	1.7	1,240
14	0 to 14	>5,000	0	1.7	>8,500	1.72	>8,600
15	5 to 40	1,010	0	1.7	1,720	1.68	1,700
16	5 to 18	931	6	1.7	1,580	1.8	1,680
17	5 to 18	847	6	1.7	1,440	1.67	1,410
18	0 to 13	5,737	7	1.7	9,750	1.83	10,500
19	0 to 14	4,615	7	1.7	7,850	1.83	8,450
20	5 to 20	1,409	7	1.7	2,400	1.7	2,400
21	5 to 17.5	1,943	6	1.7	3,300	1.64	3,190
22	5 to 18	1,267	6	1.7	2,150	1.57	1,990
23	5 to 18	582	6	1.7	990	1.8	1,050
24	5 to 17	1,914	5	1.7	3,250	1.55	2,970
25	5 to 18	982	6	1.7	1,670	1.72	1,690
26	7 to 18	521	4	1.7	890	1.54	800
27	5 to 18	412	6	1.7	700	1.6	660

Notes

- (a) Thermal conductivity for all wells in alluvium have been assigned a value of 1.7 W/m K based on a mean matrix conductivity of 2.64 W/m K and assumed porosity of 30%; conductivity for NC 2 in volcanic tuff assumes a 10% porosity.
- (b) Heat flow computed using thermal gradients given in column 3 and conductivities from column (a).
- (c) Actual thermal conductivity measurements used for NC 16-NC 27; conductivity for other wells estimated by interpolation from measured wells.
- (d) Heat flow computed using thermal gradients given in column 3 and conductivities from column (c).

Table 2. Summary of temperature gradient, thermal conductivity, and heat flow data for thermal monitoring wells NC-2 through NC-27.

Figure 29. Revised heat flow map for the Newcastle geothermal system updated using data obtained in this study. Heat flow values and contour values are given in mW m^{-2} . Compare this map to the previous heat flow map shown in Figure 25.

The lowest thermal gradients in Figure 28, and lowest heat flow values in Table 2 (with the exception of holes clearly away from the geothermal area), are observed in NC-27 and NC-26 at the northern and northwestern boundaries of the thermal anomaly (see Figure 29). These results are significant because they now provide firm constraints on the lateral extent of the system, previously based on low-quality irrigation well data and speculation. Likewise, the thermal gradients and heat flow for NC-20 and NC-23 limit the northeast and southwest extent of the geothermal system along strike of the Antelope Range fault respectively. Wells NC-13, NC-15, NC-16 and NC-17, all situated near the western edge of the town of Newcastle, clearly show that the town is located over a distal part of the outflow region, and that geothermal development in the town itself is limited.

New extreme heat flow results from NC-14, NC-18 and NC-19, on the other hand, indicate that the hottest part of the geothermal system extends further to the southeast than is suggested in the previous heat flow map (Figure 13 of Chapman et. al, 1981, and Figure 25 of this report). The new heat flow map (Figure 29) suggests a much more direct role for the range bounding Antelope Range fault in controlling leakage of hot fluids up to the water table.

We have made a new heat loss estimate for the Newcastle geothermal system by integrating the anomalous flux over the heat flow map shown in Figure 29. Details of the integration are given in Table 3. Anomalous heat loss above the background heat flow of 100 mW m^{-2} , and contained within the 500 mW m^{-2} contour, is 12.4 MW. This value is slightly less than the 12.8 MW computed previously by Chapman et. al (1981) because the increased heat flow over a small area on the alluvial fan is offset by a shrinking of several contour areas in the better constrained new map. The revised fluid discharge, based on our new estimates of heat loss, but otherwise using the same parameters proposed by Chapman et. al (1981) is $0.031 \text{ m}^3 \text{ s}^{-1}$.

Heat flow contour interval (W m^{-2})	Area (10^6 m^2)	Average heat flow (W m^{-2})	Heat loss (MW)
0.5 to 1.0	3.1	0.75	2.3
1.0 to 1.5	1.8	1.25	2.2
1.5 to 2.0	1.5	1.75	2.6
2.0 to 3.0	0.83	2.50	2.1
3.0 to 6.0	0.64	4.50	2.9
6.0 to 9.0	0.10	7.50	0.8
>9.0	<u>0.033</u>	<u>9.00</u>	<u>0.3</u>
Total	8.0		13.2
Background heat loss	8.0	0.10	0.8
Heat loss above background			12.4

Table 3. Heat loss for the Newcastle geothermal system.

5.4 Hydrochemistry and Stable Isotopes

Mower (1982) presents a contour map of the electrical conductance of groundwater found in water wells in the Beryl-Enterprise area (Figure 30). Because electrical conductance is directly influenced by the total dissolved solids content (TDS) of the groundwater (Freeze and Cherry, 1979), the map shown in Figure 30 indicates several regions of groundwater containing elevated concentrations of TDS. We interpret the rough correspondence between regions of elevated groundwater conductance, shown in Figure 30, and regions of elevated groundwater temperature shown in Figure 26 as evidence for movement of that heated, more evolved groundwater, from a deeper flow system to the shallow freshwater system that predominates in the valley-fill alluvium.

CONCENTRATION (ppm)

SPECIES	WS-1	WS-2	WS-3	WS-4	WS-5 *	WS-6 *
Na	24.58	273.28	290.24	249.61	63.98	104.80
K	2.76	15.24	16.97	11.74	2.64	5.05
Ca	54.05	64.57	78.68	64.36	63.82	62.34
Mg	25.57	0.75	0.69	5.51	25.59	13.32
Fe	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Al	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
SiO ₂	42.12	79.19	69.37	63.24	31.89	46.80
B	N.D.	0.34	N.D.	0.62	0.15	0.19
Li	0.50	0.52	0.60	0.33	N.D.	0.09
Sr	N.D.	1.3	1.56	0.36	0.55	0.35
HCO ₃	181.0	58.00	44.00	104.00	182.00	228.00
CO ₃	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cl	48.00	69.00	104.00	76.00	44.00	82.00
F	0.30	7.30	6.30	4.70	0.48	1.03
SO ₄	82.00	569.00	637.00	478.00	208.00	115.00
Total. Diss. Solids. measured [m]	364.00	1154.00	1236.00	1016.00	530.00	545.00
calculated[c]	368.88	1109.01	1227.03	1005.60	530.59	543.00
100 x (m/c)	98.68	104.06	100.73	101.03	99.89	100.35
pH	7.74	8.03	7.98	7.89	7.48	7.60

NOTE: * Because contamination of acidified splits was suspected, non-acidified splits were analyzed.

Table 4. Results of chemical analyses of groundwater samples from the Newcastle area.

Figure 30. Specific conductance of groundwater measured in wells in the vicinity of Newcastle, Utah. The locations of groundwater samples collected in this study for water chemistry and stable isotope analyses are also indicated. From Mower (1982).

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Figure 31. Tri-linear Piper diagram of water chemistry analyses obtained for groundwater samples WS-1 through WS-6. Scales shown are in total milliequivalent per liter.

re-equilibrium takes place after the fluid leaves the reservoir, and 5) reservoir fluid does not mix with other meteoric water.

Several inferences can be made given the results shown in Table 5. First, computed temperatures are low. Only the NC-10 sample collected by Rush (1983) yields estimated temperatures in excess of 120°C (248°F). Although the temperature of 166°C (331°F) calculated for the NC-10 sample using the Na-K-Ca geothermometer is within the temperature range computed by Rush (140°C to 170°C), this result may be an artifact of choosing an inappropriate scaling factor in the calculation (M. Adams, pers. comm., 1989). Results computed for WS-1, 5, and 6 indicate temperatures that fall below the range where geothermometry calculations are applicable. Second, the maximum computed temperatures (100°C to 120°C) approach the maximum temperature of 130°C measured at a depth of 106 m in CHR-1. This suggests that the fluid chemistry may reflect conditions more representative of the shallow outflow portion of the hydrothermal system, rather than those of a deep geothermal reservoir. Third, from a qualitative perspective, samples WS-3, 2, 4 and 1 indicate a progression of increasingly mixed fluid with the sample from WS-3 and 2 being about 90% of original, WS-4 about 40% , and WS-1 about 5% (Adams, pers. comm., 1989). The distinctive chemical character of sample WS-1 suggests that this sample may be a dilute version of the groundwater discharging to the valley-fill deposits, or the sample may be typical of groundwater chemistry found throughout the valley-fill deposits. In either case, computed temperatures shown in Table 5 for this sample, and for samples WS-5 and 6, do not provide a reliable indication of groundwater temperatures at greater depths in the hydrothermal system.

TEMPERATURE (°C)

GEOOTHERMOMETER (Reference)	WS-1	WS-2	WS-3	WS-4	WS-5	WS-6	Rush NC-10
Chalcedony (1)	64	97	89	84	51	69	110
Na-K-Ca (2)	28	99	99	89	32	54	114 or 166
Na/L (3)	63	115	120	92	32	69	-
K/Mg (4)	30	110	114	7	30	48	129

(1) Fournier (1981)

(2) Fournier and Truesdell (1973)

(3) Fouillac and Michard (1981)

(4) Giggenbach (1988)

Table 5. Results of geothermometry calculations carried out using chemical analyses of groundwater samples obtained near Newcastle, Utah.

5.4.3 Light Stable Isotope Analyses

Stable isotope data obtained from groundwater samples collected at several wells and springs in the vicinity of Newcastle (Figure 30) are tabulated in Table 6 and plotted in Figure 32. Isotope analyses were carried out by Dr. J. Bowman of the University of Utah. Uncertainty in the analytical results is approximately ± 1 in δD and ± 0.15 in $\delta^{18}O$. Where two values are reported for δD or $\delta^{18}O$, each determination was made on different aliquots of the water sample. The average of these data pairs was used in plotting the results shown in Figure 32.

SAMPLE LOCATION	$\delta^{18}O$	δD
Cove Spring	-13.0	-95
Pinto Spring	-13.9, -14.0	-104, -103
Hildbrand Well (WS-2)	-14.2	-107
Troy Hygro Well (WS-3)	-14.0, -14.3	-108
Joel Spring	-14.0	-103
Escalante Mine	-13.0	-94
Hamblin Spring	-12.6, -12.4	-91, -92

Table 6. Results of light stable isotope analyses (δD and $\delta^{18}O$ expressed as per mil relative to V-SMOW) carried out on groundwater samples obtained from springs and wells near Newcastle, Utah.

Stable isotope data obtained from springs and wells in the Newcastle area spans a relatively narrow range of values in both δD and $\delta^{18}O$ (Figure 32). The fact that the results of all analyses lie close to the Meteoric Water Line defined by Dansgaard (1964) suggests that each water sample originated as meteoric water with little isotope fractionation or exchange during flow through the subsurface. The meteoric signature of samples WS-3 and 4, obtained within the thermal-chemical plume identified previously, suggest that the heated groundwater is derived from meteoric water recharged in the adjacent highlands, rather than generated by the loss of volatiles from an underlying igneous intrusion.

The commonly noted correlation between decreasing δD and increasing elevation of groundwater recharge suggests that groundwater in the thermal-chemical plume was recharged at higher elevations than groundwater sampled at the springs. Review of topographic maps in the Newcastle area indicates that the springs may represent discharge from relatively shallow groundwater flow systems with recharge at higher elevations on the same slope. Relatively deep circulation in a regional-scale flow system

with a recharge area that extends to the Pine Valley Mountains 20 km (12 mi) southeast of Newcastle may contribute to the relatively low δD values found in the well samples.

Figure 32. Plot of δD against $\delta^{18}O$ showing the results of stable isotope analyses for groundwater samples obtained from springs and wells located near Newcastle, Utah. Sample locations are indicated in Figure 30.

5.5 Hydrologic Interpretation of Geophysical Studies

Land-based gravity surveys performed as part of this study, and described in a previous section, provide insight into the character and thickness of the valley-fill deposits shown in the working model of Figure 21. In addition to indicating the possible depth to bedrock beneath the valley floor (about 1.6 km or 1 mi), the gravity results also suggest that a wedge-shaped region with density slightly elevated above that of the adjacent valley-fill deposits (2125 kg m^{-3} as compared to 1900 kg m^{-3}) may abut the bedrock-alluvium contact (Figure 13). This apparent increase in density could reflect a reduction in porosity caused by mineral precipitation within the unconsolidated deposits or sediment compaction. Geophysical logs obtained from the Union Geothermal Christiansen #1 Well (Plate 3) indicate a uniform density of about 2300 kg m^{-3} between 300 m (984 ft) and the total depth of 912 m (2992 ft). This value is intermediate

between those indicated in the gravity model (2125 kg m^{-3} in the unconsolidated wedge and 2400 kg m^{-3} in the underlying bedrock).

The results of regional-scale gravity surveys compiled by Pe (1980) are shown in Figure 8. Given the relatively flat topography of the valley floor, it is clear that the Newcastle system is situated near the center of a significant gravity low that marks the intersection of two lines of gravity lows -- a dominant trend oriented northeast and another, discontinuous trend oriented northwest. It seems reasonable to assume that the gravity lows coincide with unconsolidated to moderately consolidated deposits filling isolated basins caused by regional-scale normal faulting. The northeast-southwest line of gravity lows coincides with the Antelope Range fault and its extension that marks the southeast boundary of the Escalante Valley. Field mapping has not identified a regional-scale fault zone that coincides with the northwest-southeast trending line of gravity lows, although structural analysis within the adjacent range has revealed a complex network of bedrock faults, about 3 km wide, that lies along this trend. It is possible that the northwest trend of gravity lows represent basin fill deposits generated during regional southwest-directed (detachment style?) extension that were dismembered by later basin-range extension that produced the dominant northeast-trending set of lows. Increased fracture density may provide for locally enhanced bedrock permeability in the vicinity of the gravity lows. Alignment of these presumed regions of enhanced permeability in northwest-southeast and northeast-southwest directions likely provides preferred pathways for groundwater flow in bedrock that place important constraints on the character of the Newcastle geothermal system.

Electrical resistivity surveys carried out as part of this study, and summarized in a previous section, indicate a pattern of reduced resistivity that suggests a plume-like discharge of groundwater with elevated TDS from a subsurface source to the adjacent valley-fill deposits (Figure 15). Review of the apparent resistivity data suggests that the plume emanates from a 1.5 km (0.9 mi) (minimum) region aligned with the mountain front. The presence of a bulls-eye like SP anomaly (see section 3.2.2) appears to indicate a primary zone of localized upflow near wells NC-18 and NC-19.

5.6 Numerical Modeling

The numerical modeling component of this study was originally intended to provide insight into the rates and patterns of fluid flow that might contribute to the thermal observations described in previous sections. It was anticipated that a series of steady state simulations of coupled fluid flow and heat transfer in systems with 2-dimensional symmetry could be used to explore the nature of the hydrothermal system. It became apparent during the modeling studies; however, that the Newcastle system has a strong 3-dimensional character that precludes using 2-dimensional models to gain anything more than rudimentary clues regarding the details of the hydrothermal system. Although inconclusive, the modeling effort provides the important result that the thermal regime

likely has a complex 3-dimensional character that can only be represented with a full 3-D modeling approach.

5.6.1 Modelling Approach

Figure 33 shows the generalized boundary value problems solved in exploring the characteristics of the working model for the Newcastle hydrothermal system shown in Figure 21. The full-length problem has planar symmetry (Figure 33a) while both planar and radial symmetry were modeled with the smaller problem (Figure 33b). In each case, vertical boundaries are insulated and have specified fluid flux. The horizontal basal boundary is assumed impervious to fluid flow. Regional conductive heat flow is represented by a uniform heat flux applied across the basal boundary. The upper boundary of the domain is the ground surface. The thin cover of discontinuous surficial deposits typical of upland areas of mountain slopes is viewed as a thin skin of variable thickness that is not explicitly included in the model. Resistance to heat transfer in the thin surficial deposits (soils, colluvium, etc.) is assumed negligible so temperatures at the bedrock surface in the mountain range match those at the ground surface. Surface temperature conditions are defined in terms of a reference surface temperature and a thermal lapse rate.

A free-surface method is used to solve for the position of the water table within the constraints of groundwater recharge rate, basal heat flow, and permeability. An upper limit for recharge to the groundwater flow system is represented by the available infiltration rate. Where the water table coincides with the ground surface, only a portion of the available infiltration is transmitted to the subsurface. The remainder is contributed to surface runoff. The ability of the flow system to transmit the incoming fluid depends upon a variety of factors including topographic relief, permeability, and basal heat flow (Forster and Smith, 1988b). Where the water table lies below the ground surface, the entire available infiltration rate is assumed to be transmitted directly to the water table via one-dimensional flow through an unsaturated zone. Adopting this approach enables us to control the pattern and magnitude of groundwater recharge without specifying, a priori, the position of the water table.

Heat is transferred by both conduction and advection throughout the domains shown in Figure 33. Advective heat transfer above the water table is represented by one-dimensional movement of fluid, in the liquid phase, at a rate determined by the available infiltration rate.

Although values of bulk permeability for the bedrock are likely controlled by the degree of fracturing, we treat both the bedrock and valley fill deposits as equivalent porous media. Exceptions to this assumption are represented as discrete permeable fracture zones with a homogeneous permeability k_f and width b (Figure 33).

The mathematical model describing the systems shown in Figure 33 is expressed by coupled partial differential equations for heat transfer and fluid flow, by equations

Figure 33. Generalized boundary value problems solved in the modeling study shown with no vertical exaggeration; a) full-length section (18km long) and b) short, local-scale section (8km long).

of state for the fluid properties, and by boundary conditions for the thermal and fluid flow problems. Details of the mathematical model are outlined by Forster and Smith (1988a). Key assumptions include (1) steady state fluid flow and heat transfer in a saturated porous medium with one-dimensional fluid flow through the unsaturated zone at the available infiltration rate, (2) thermal equilibrium between fluid and solid, (3) the fluid is pure liquid water with density and viscosity a function only of temperature and pressure, (4) the heat capacity and thermal conductivity of the fluid is constant, and (5) porosity, permeability, and thermal conductivity vary in space but not as a function of temperature or pressure.

The equations describing fluid flow and heat transfer are solved using a Galerkin finite element technique. The water table elevation is estimated using an iterative free-surface method that is constrained by the available infiltration rate applied at the ground surface. Two-dimensional vertical sections with planar or radial symmetry are represented by linear triangular elements. Thin high-permeability fracture zones are included by embedding one-dimensional line elements in the field of triangular elements. Details of the computational procedure are given by Forster and Smith (1988a).

5.6.2 Model Parameterization

Figure 33 illustrates one of several distributions of permeability used in the modeling effort. In most cases, permeability of the valley-fill alluvium was estimated to range from a minimum of 10^{-14} m^2 at the base of the valley-fill to a maximum of 10^{-12} m^2 near the ground surface. These estimates are based on the results of pumping tests reported by Mower (1982) and typical values reported in the literature for similar lithologies.

The permeability of the mountain massif was estimated through an iterative modeling approach by solving the full-length boundary value problem (Figure 33a) using the free-surface method to find the position of the water table within the constraints of estimated water table elevations and limits on groundwater recharge rates. The presence of several springs at elevations of 1900 m (400 m above the valley floor) provides evidence for a water table that is located at relatively high elevations in the mountain massif. Calculated water table elevations were found at high elevations within the model domain when a value of 10^{-16} m^2 is assigned for the permeability of the mountain massif and a recharge rate of 1 mm per year is specified throughout regions elevated above the valley floor. The apparent character of the temperature-depth profiles measured at the valley floor provide an upper limit for direct recharge to the valley fill deposits of 0.3 mm y^{-1} . Because the water table elevation depends upon the ratio of recharge rate to permeability, there is a certain degree of uncertainty associated with our estimates. If we assume that recharge rate corresponds to a percentage of the mean annual precipitation in the highlands, it seems reasonable that the mean annual recharge rate falls between 1 to 30 % of annual precipitation. Estimating the mean annual precipitation to be about

0.25 m y⁻¹ yields a range in estimated recharge rate of 2.5 to 75 mm y⁻¹. Lower values of recharge are expected at the valley floor where precipitation is reduced below that of the adjacent highlands. Therefore, maintaining the computed water table at the assumed elevation requires a bulk permeability in the range of 10⁻¹⁷ to 10⁻¹⁵ m². Several runs were made with k values for the mountain massif ranging from 10⁻¹⁷ to 10⁻¹⁵ m².

Throughout all simulations, the lower 1 km of the domain was assigned a permeability of 10⁻²² m² and the precipitate seal was assigned a value of 10⁻¹⁸ m². Fault zone permeability was assumed to be 10⁻¹² m² and a variety of fault zone widths ranging from 0.1 to 20 m (0.33 to 66 ft) were considered in the simulations.

Values of thermal conductivity (λ), porosity (n), and specific heat capacity (C_r) were held at the same values in all simulation studies. Although different values of λ and n were specified in different units shown in Figure 33, C_r was held constant throughout the model domain. Thermal conductivity of the valley-fill alluvium was assumed to be 1.6 W m⁻¹ °C⁻¹ and the corresponding porosity was specified as 0.25. The bedrock units were assigned a uniform value of 2.5 W m⁻¹ °C⁻¹ for λ and 0.05 for n. Thermal conductivity values were selected to be similar to those estimated from our laboratory measurements described in a previous sub-section while porosity values were assumed to be typical of the lithologies present within the modeled domain. Intermediate values of $\lambda=2.0$ W m⁻¹ °C⁻¹ and n=0.1 were assigned to the precipitate seal, while values of $\lambda=2.5$ W m⁻¹ °C⁻¹ and n=0.10 were assigned to the fault zone.

The fluid is assumed to be pure liquid water with a constant thermal conductivity and specific heat capacity. Fluid density and viscosity are assumed to vary as a function of both temperature and pressure.

5.6.3 Modelling Results

The primary goal of the modeling study was to define the groundwater flow system needed to mimic the gross character of the thermal regime observed at Newcastle.

Although the regional heat flow and general geometry of the geologic units are known with reasonable certainty, the permeability structure that controls the pattern and rate of groundwater flow is poorly constrained. We modeled a variety of permeability structures by solving both the full-length and short boundary value problems (Figure 33) but were unable to generate the elevated temperatures observed at shallow depths in the valley-fill alluvium. We attribute this difficulty to the inability of the selected model parameters to provide sufficient groundwater heating at depth within the fault zone.

We suspect that our inability to mimic the observed thermal regime was caused, in large part, because modeling a 3-dimensional system with a 2-dimensional approach fails to account for heat transported into the system by components of groundwater flow and conduction heat transfer oriented perpendicular to the plane of the sections shown

in Figure 33. Although a localized source of elevated heat flow (perhaps a shallow intrusion) could contribute the necessary heat that was unavailable in the modeled flow system, the absence of recent volcanic activity in the area suggests that this is an unlikely explanation. The stable isotope data discussed previously suggests (1) that minimal fractionation has occurred in high-temperature rock-water exchange processes and (2) thermal water sampled in the valley-fill deposits is derived from a meteoric, rather than a plutonic, source. Furthermore, the regional heat flow applied at the base of the modeled domain must be increased by a factor greater than 2 to obtain the required temperatures at shallow depths in the flow system. Good quality heat flow measurements made at a variety of sites in the vicinity of Newcastle (Chapman and others, 1981); however, consistently suggest a regional heat flow in the range of 90 to 110 mW m⁻². Although testing the relative merits of each of the above explanations requires simulations involving a fully 3-dimensional numerical model, the thermal and permeability data needed to adequately parameterize and constrain such a model are currently unavailable.

Simulations performed by solving the short boundary value problem (Figure 33b), in both planar and radial symmetry modes, provides additional insight. In these simulations a source of heated fluid specified near the base of the fault zone represents the net effect of fluid flow and heat transfer within the mountain massif. A series of radial symmetry runs indicate that highly unrealistic fluid flow rates and temperatures are required to generate a thermal regime akin to that observed at Newcastle. Although more realistic rates could be specified in the planar mode (consistent with the 0.032 m³ s⁻¹ computed on the basis of heat loss calculations) computed temperatures were much lower than observed. Although unable to match the observed thermal regime, we think that fluid discharge to the valley-fill alluvium is best viewed as outflow from a linear source with local variations along the outflow zone, rather than from a single point source. This view is consistent with the results of the resistivity survey that suggests the thermal-chemical plume emanates from a 1.5 km (0.9 mi) (minimum) region aligned with the mountain front with a localized region of enhanced discharge in the vicinity of the SP anomaly.

6.0 DISCUSSION

We initiated our modelling of fluid flow and heat transport with a working model for the Newcastle hydrothermal system shown in Figure 21. Data collected in this study and further interpretation of existing data has helped us to propose a more refined conceptual model for the hydrothermal system (Figure 34). In this conceptual model a fully 3-dimensional view is adopted.

Figure 34. Updated conceptual model indicating possible patterns of groundwater flow in the Newcastle hydrothermal system.

Inferred patterns of fluid flow are indicated by the apparent directions of flow identified within the various planes shown in Figure 34. Note that, in most cases, the arrows represent only the components of flow within the indicated plane. Topographic relief on the water table is assumed to provide the dominant driving force for fluid flow within the system. Therefore, meteoric water recharged in the highlands circulates deeply within the mountain massif before discharging to the valley-fill sediments.

The northwest-southeast trend of gravity lows, which may represent a structural zone, and geologic mapping from our study (Section 2) form a critical element of the conceptual model (hatched zone in Figure 34). Enhanced permeability associated with higher density fracturing associated in turn with a high density of faulting in this zone is presumed to provide for active fluid flow and efficient extraction of heat to depths on the order of 5 km below the valley floor. Because fluid flow in the adjacent lower-permeability protolith is more sluggish, temperatures are likely warmer in the surrounding protolith. As a consequence, additional heat is provided to fluid moving within the fault zone by conductive and advective heat transfer from the protolith to the fault zone. A further focussing of fluid flow and advective heat transport is expected as the Antelope Range fault zone transmits fluid and heat along the fault to the region of lower head located at the intersection of the structures.

Groundwater with elevated temperature and TDS that discharges from the fault zone intersection must mix with cool and relatively fresh groundwater circulating in the valley-fill deposits. This mixing process may contribute to the precipitation of siliceous and/or carbonate minerals within the porous sediments that, in turn, cause a reduction in permeability in the vicinity of the zone of mixing. In early stages of system development, the region of mixing was likely located at the base of the valley-fill sediments. Through time, however, the mixing of fluids in the sediments may contribute to progressive development of a low-permeability seal that extends upwards from the original point of discharge from bedrock to a position relatively close to the ground surface (Figure 34). Concurrent downward movement of the hanging wall block of the Antelope Range fault likely contributed to upward growth of the precipitate seal. Development of a precipitate seal may be enhanced where boiling occurs at the water table.

Heated groundwater discharging to the valley-fill deposits forms a thermal-chemical plume with a size and shape controlled, in large part, by the near-surface groundwater flow system. Previous studies of the groundwater regime near Newcastle (Mower, 1982) indicate a northward trend to the predominant direction of groundwater flow. This interpretation provides the basis for inferring relatively widely spaced heat flow contours when traversing the geothermal system from south to north (see the revised heat flow map shown in Figure 29). Further evidence for an elongate thermal-chemical plume is also provided by the chemistry of groundwater samples WS-1 and 4 (both wells are located near the 500 mW m² contour in Figure 29). Because both samples WS-1 and 4 were collected at a similar distance from the mountain front (Figure 23), the strong contrast in chemistry between samples WS-1 and 4 suggests that the plume of more heated groundwater discharging to the valley-fill deposits is preferentially moving in a northerly direction away from a source in the vicinity of NC-18 and NC-19.

The conceptual model described here may provide a general model for the character and evolution of blind geothermal systems throughout the Basin and Range

province. For example, travertine mounds found at the Monroe and Joseph hot springs may represent a later stage in evolution of the class of hydrothermal systems exhibited at Newcastle. Continued upward development of the precipitate seal would be expected to culminate in discharge of the heated fluid at the ground surface and the formation of hot spring controlled mounds. Water level elevations measured in wells completed in the vicinity of the Monroe and Red Hill hot springs indicate a sharp drop in the water table as one moves from the hot springs towards the center of the valley. This strong variation in water table elevation might develop where groundwater movement in the surficial deposits is dammed by the development of a precipitate seal that constrains flow of heated fluid within a well-defined, more permeable, conduit structure. Because monitoring wells drilled on the alluvial fan adjacent to the mountain front failed to penetrate the water table, this feature of the Newcastle system remains unresolved.

Other blind hydrothermal systems at different stages in their development are likely to be found elsewhere in the Basin and Range province. The Newcastle geothermal system is located in one of several regions of elevated groundwater temperature found in the southern portion of the Escalante Desert (Figure 26). Temperatures measured in water wells drilled to a maximum depth of 300 m (984 ft) indicate that groundwater temperatures exceed the mean annual air temperature of 15°C at 4 locations; at Newcastle, 10 km (6.2 mi) north of Newcastle, 5 km (3.1 mi) northeast of Beryl, and 15 km (9.3 mi) southwest of Beryl (Figure 26). Although locally elevated heat flow is indicated near both Newcastle and Beryl (Clement, 1981; Chapman and others, 1981; Rush, 1983), hot springs and other surface indications of a hydrothermal system are lacking at all locations.

Our revised conceptual model for fluid flow and heat transfer at the Newcastle geothermal area provides a framework for confirming current strategies used to explore for blind geothermal systems in the Basin and Range Province. The first step in any exploration program should involve measuring groundwater temperatures in water wells, obtaining electrical conductivity measurements of well water, and collecting water samples for later analyses of major ion concentrations, total dissolved solids, and stable isotope chemistry. Exploration sites should be targeted where linear gravity lows and geologic mapping suggest the intersection of regional-scale faults that may, in turn, indicate regions of enhanced permeability. Electrical geophysical surveys (resistivity and self-potential) provide an excellent means of delineating thermal-chemical plumes and targeting the probable source of each plume. Shallow thermal monitoring wells (120 to 150 m deep) strategically placed within the resistivity and S.P. anomalies provide the information needed to assess the overall heat loss from the blind geothermal system and map the details of the shallow thermal regime. Deeper holes (150 to 400 m deep) are required to collect water samples for isotopic analyses and geothermometry calculations in the region of maximum upflow. Results of studies related to the shallow drilling activities and geophysical surveys, when interpreted within the context of a conceptual

model of the hydrologic system, yield a solid basis for establishing the worth of drilling a deep exploration well.

7.0 CONCLUSIONS

A detailed conceptual model has been developed to describe the processes of fluid flow and heat transfer in a blind geothermal system found at Newcastle, Utah. A localized fluid upflow zone, identified using shallow heat flow studies and surface geophysical surveys, lies at the intersection of the Antelope Range fault and a 3 km (1.9 mi) wide northwest-trending structural zone with enhanced fracture permeability. In detail, the upflow zone coincides with the intersection of two prominent faults of the structural zone with the Antelope Range fault. Hydrogeochemical evidence, and inferences regarding the character of the subsurface hydrogeologic regime, suggest that heated fluid discharging from the upflow zone to the valley-fill deposits originated as meteoric water recharged in the adjacent Pine Valley Mountains. A thermal-chemical plume mapped in the valley-fill deposits indicates that the heated fluid is transported in a northerly direction away from the source in a shallow groundwater flow system. Temperatures measured in shallow wells located directly above the upflow zone indicate a localized region of boiling and a zone where heat transport above the water table may be controlled by free convection of vapor. Although untested, we hypothesize that localization of fluid upflow is caused by the development of a sub-vertical precipitate seal within the valley-fill deposits that prohibits lateral flow. We view the Newcastle geothermal system as having achieved an intermediate stage in an evolutionary sequence that begins with deep discharge of heated fluid at the base of a sediment-filled basin and ends with the development of hot springs located within mounds of siliceous sinter that represent the outcropping of the postulated precipitate seal. We postulate that additional blind geothermal systems may exist, at different stages in this evolutionary process, throughout the Basin and Range province.

The anomalous heat loss from the Newcastle geothermal system is estimated to be 12.4 MW and the corresponding fluid discharge is estimated to be $0.031 \text{ m}^3 \text{ s}^{-1}$. These revised estimates differ little from those made in previous studies. The new heat flow map provides a more reliable image of the general nature of the shallow hydrothermal system than previous studies.

Temperature-depth data obtained from the Christiansen #1 exploration well, drilled and logged to a depth of 913 m (2995 ft) by Union Geothermal, indicates a lower limit to the equilibrium temperature for the geothermal system of 130°C (266°F) encountered in the well at a depth of 100 m. This temperature is slightly higher than equilibrium temperatures computed using chemical geothermometry on analyses of groundwater obtained from shallow wells located within the thermal-chemical plume. At depths greater than 100 m in CHR#1, temperatures fall to a low of 105°C before returning to 115° at the bottom of the drill hole. The roughly isothermal character of the temperature-depth log, at depths in excess of about 200 m, provides additional evidence for the presence of a sub-vertical upflow zone carrying groundwater at a temperature of 130°C or greater up-dip along the Antelope Range fault.

8.0 RECOMMENDATIONS

Further studies at Newcastle would help to better understand the character and evolution of blind geothermal systems located throughout the Basin and Range province. Installing additional shallow thermal monitoring wells in the region of maximum heat flow and replacing the collapsed plastic casings in NC-18 and NC-19 with black iron pipe will provide the thermal data needed to characterize the mechanisms of heat transfer operating in the immediate vicinity of the upflow zone and help explain the origin of the strong S.P. anomaly associated with the upflow zone. By completing each well below the water table we would be able to measure the elevation of the water table and collect groundwater samples within the upflow zone. A deep exploration hole should be drilled into the center of the upflow zone, or "throat," to measure the variation of temperature with depth, obtain water samples from the deeper, unstudied part of the system, and test reservoir parameters. Stable isotope and geochemical analyses of the water samples will aid in unravelling the chemical evolution of groundwater during its passage from the highland recharge areas to the thermal-chemical plume found in the adjacent valley-fill deposits.

Central to our conceptual model is the presence of a northwest trending structural zone of enhanced fracture permeability. Additional geologic mapping of the adjacent Pinto (7.5') quadrangle and compilation of new, unpublished mapping in the recharge area of the Newcastle system would allow us to check our conceptual model against the regional distribution of mappable faults. One goal of this mapping would be to establish the integrity of the structural zone as it is traced into the recharge area. Another goal would be to search for evidence concerning the origin and character of this zone. Additional detailed gravity profiles along northeast-southwest trends could also be made to help strengthen the evidence for the northwest trending structural zone.

Several recently developed techniques are available for quantifying the hydraulic conductivity of fractured rocks. Some of these techniques could be applied to the Newcastle area to better understand the "enhanced permeability" of the northwest-trending structural zone presented in the conceptual model. In particular, detailed measurements of fracture orientations and aperture widths could be measured from several sites both within and outside of the structural zone to better characterize permeability variations of our conceptual model.

Finally, we recommend a regional-scale review of existing groundwater temperature and chemistry information to test our hypothesis that similar fault-controlled geothermal systems may be found, at different stages in their evolution, throughout the Basin and Range province and to identify promising locations to explore for previously unidentified blind geothermal systems.

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4

Geology from Siders and others (1989), Geologic map of the Newcastle quadrangle, modified during this study.

9
Plate 2. Geologic cross sections A-A', B-B', C-C'

Correlation of Map Units

SYSTEM	SERIES	FORMATION	MAP SYMBOL	THICKNESS (Feet)	RADIOMETRIC AGE (in Millions of Years)
Tertiary	Miocene	Dacite of Bullion Canyon	Td	?	8.5
		Rhyolite of Silver Peak	Trs	?	8.5
		Volcaniclastic Rocks of Newcastle Reservoir	Tnv	>980	>11.6
		Racer Canyon Tuff	Tr	>490	19
		Volcaniclastic Rocks	Tv	130	
		Harmony Hills Tuff	Th	480	21
		Bauers Tuff	Tcb	430	23
		Leach Canyon Tuff	Tl	580	25
		Hole-in-the-Wall Tuff	Tih	260	26
		Baldhills Tuff	Tib	1100	26
Tertiary	Oligocene				
Tertiary	Eocene	Claron	Tc	700	
Cretaceous	Upper Cretaceous	Iron Springs	Kis	>1400	

STRATIGRAPHIC COLUMN