SPECIAL PUBLICATION 16
DOE/ET/28365-14

GEOTHERMAL RESOURCE ASSESSMENT OF WAUNITA SPRINGS, COLORADO

edited by
Ted G. Zacharakis

Colorado Geological Survey / Department of Natural Resources / Denver, Colorado / 1981

DOE/ET/28365-14

SPECIAL PUBLICATION 16

GEOTHERMAL RESOURCE ASSESSMENT OF WAUNITA HOT SPRINGS COLORADO

Edited by

Ted G. Zacharakis

DOI: https://doi.org/10.58783/cgs.sp16.xeby1857

Prepared by the
COLORADO GEOLOGICAL SURVEY
in cooperation with the
U.S. Dept. of Energy
Under Contract No. DE-AS07-77ET28365

Colorado Geological Survey
Department of Natural Resources
State of Colorado

Denver, Colorado
1981

NOTICE

NOTICE

TABLE OF CONTENTS

FIGURES

TABLES

PREFACE

This report differs from the typical report prepared and published by the Colorado Geological Suvey in that the investigations were not done by Colorado Geological Survey staff personnel but were prepared for AMAX Exploration, Inc. and their venture partner on the project, Austral Oil Company, by consultants and AMAX company personnel. Upon conclusion of their resource evaluation program AMAX and Austral Oil Company dropped their leases to the Waunita Hot Springs and released the results of their resource assessment efforts to the general public. Realizing the value of this information the Colorado Geological Survey approached AMAX Exploration Inc. concerning the possibility of publishing the data. They graciously granted permission.

In publishing this information limited amount of editing has been done to the various reports, therefore the reader will note some duplication between various chapters.

The Colorado Geological Survey wishes to express its appreciation to AMAX Exploration, Inc., specifically William Dolan, Harry Olsen and Arthur Lange for their cooperation and assistance in releasing this information to the public.

CHAPTER I
REPORT ON
WAUNITA HOT SPRINGS PROJECT
GUNNISON COUNTY, COLORADO

by

K. W. Nickerson & Associates
Denver, Colorado 80228

INTRODUCTION

Waunita Hot Springs is located about 25 miles east of Gunnison, Colorado (Fig. 1). The area is easily accessible by turning north from U.S. Highway 50 a half mile west of Doyleville. A country road follows Hot Springs Creek to the north and east past Tomichi Dome, the dominant geographic feature in the area, to Waunita Hot Springs.

Interest in the geothermal potential of the area is based on the Waunita Hot Springs. The upper spring is situated next to the spa buildings in the southwest corner of section 11 - T49N - R4E. The lower spring is near the center of the south half of section 10 (Fig. 2).

Published geologic information for the immediate area of interest is sketchy and incomplete. Geological Society of America Bulletin 47 by Stark and Behre published in 1936 and U.S. Geological Survey Professional Paper 289 by Dings and Robinson (1957) are the only publications that were found to describe the local geology. Other material made available for this project includes (1) a groundnoise anomaly map, (2) two cross-sections, (3) two topographic maps with some geologic data, all of which were prepared by H. B. Renfro and Company; and (4) a map titled "Supplemental Report on the Waunita Project" by Senturian Sciences, Inc. (none of which are here published, ed. note).

During the present program, aerial photos and topographic maps were used for orientation and spotting geologic features. Primary emphasis was put on determining structure in the anomalous area as delineated by the groundnoise anomaly map and encompassing sections 10, 11, 14, and 15 - T49N - R4E. Samples of the Dakota Formation were taken and analyzed by Core Laboratories in Denver, Colorado to determine the reservoir characteristics of the sandstone. Water tempteratures at the upper and lower hot springs were taken by Mr. Frank Dellechaie (see Chapter III).

GEOTHERMAL EVALUATION AND RECOMMENDATIONS

Introductory Discussion

In simplified terms, a geothermal system can be characterized as having a heat source, a reservoir, and conduits permitting water and/or circulation throughout the system.

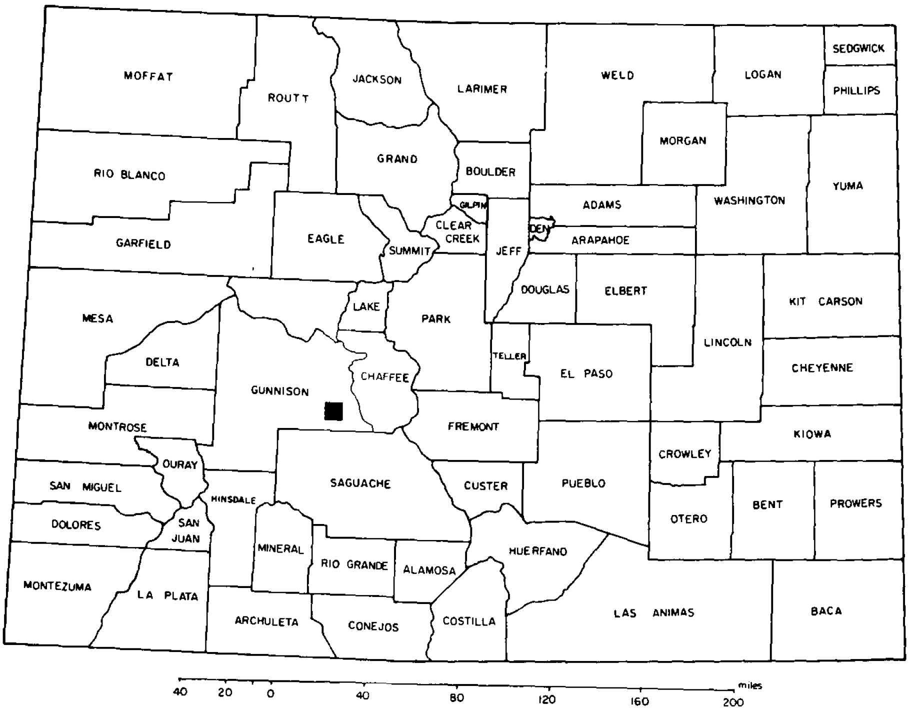
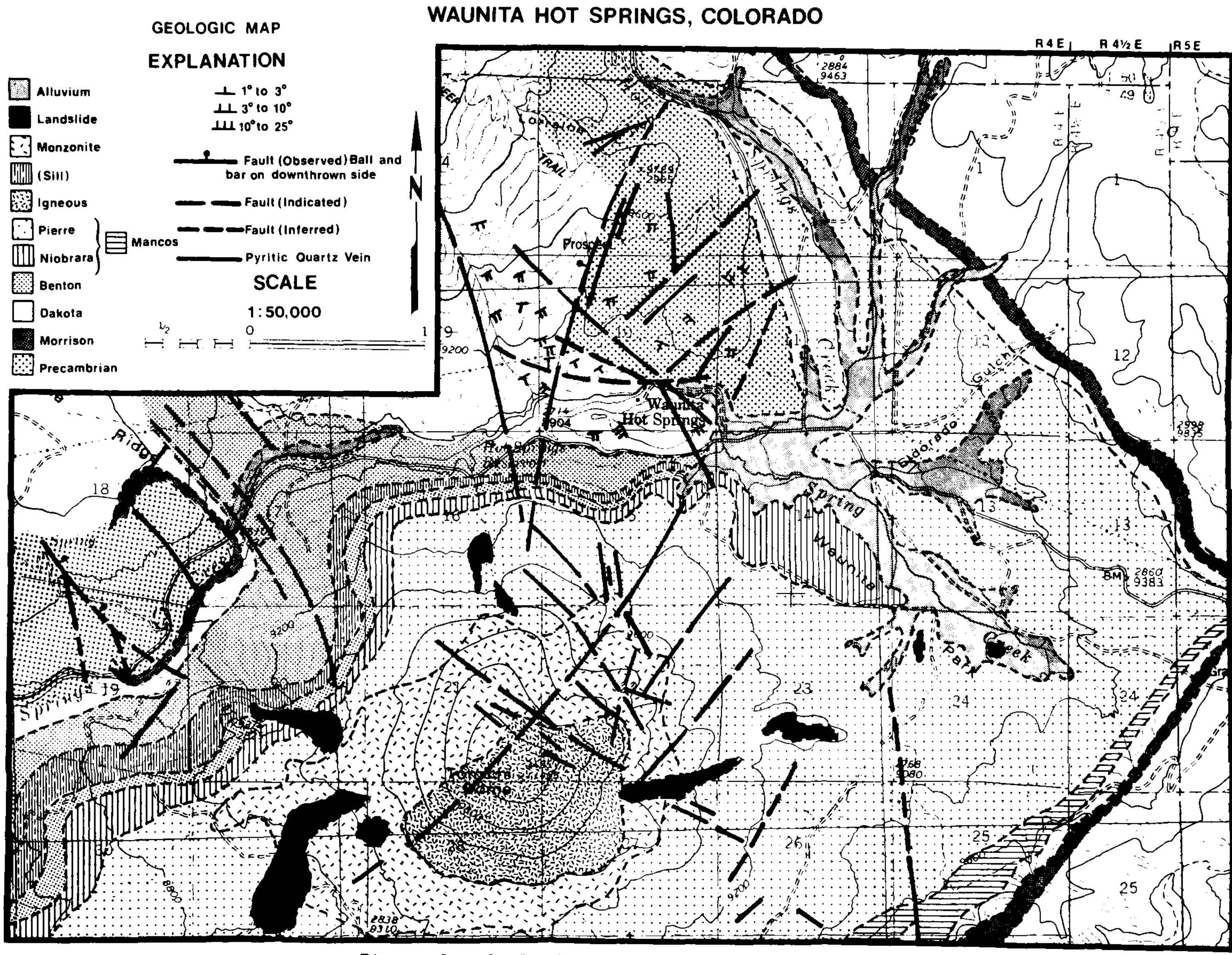


Figure 1. Index map for Waunita Hot Springs.



- 3 -

Figure 2. Geologic map of Waunita Hot Springs.

The heat source will probably be a nearby magmatic pocket, the reservoir can be either a permeable sediment with an impervious cap or an adequately fractured metamorphic or igneous rock and the plumbing system will probably comprise deep, permeable faults and fault systems.

Geologic parameters thought to be evidence for the existence of such a geothermal system include:

1. Recent silicic volcanism
2. Hot or warm springs
3. Well defined fault systems, defining horsts and grabens
4. Evidence for doming or upwarping
5. Epithermal mineralization (mercury, fluorite, antimony, barite, etc.)

Geophysical evidence considered to be favorable includes:

1. Clustered microearthquakes
2. Strong groundnoise at 1-2 Hertz
3. Electrical resistivity less than 10 ohm meters
4. Anomalous gravity and magnetic characteristics
5. Thermal gradients of more than 1°C/20 meters and favorable geothermometer criteria

It is important to study all of the above geologic and geophysical situations when evaluating a geothermal prospect. One or two favorable criteria alone are not enough to justify a positive opinion.

Existing Data

The available data pertinent to evaluation of the geothermal potential of Waunita Hot Springs consists of reconnaissance geologic mapping, aerial photo interpretation, groundnoise data and minimal geochemistry.

GEOLOGY

Introductory Remarks

In 1936, Stark and Behre published an article titled "Tomichi Dome Flow" in Bulletin 47 of the GSA. A map showing the general geologic setting of the area surrounding Tomichi Dome accompanies the report.

In 1957, Dings and Robinson published their paper (USGS Professional Paper 289) titled "Geology and Ore Deposits of the Garfield Quadarangle, Colorado." The extreme southwest corner of this quadrangle covers part of the northeast corner of the mapped area.

Figure 2 utilizes the geology as presented by Stark and Behre and Dings and Robinson. Liberal use has been made here of direct quotations from these authors. An attempt was made to map the major features in the primary area of interest centered around Waunita Hot Springs and covering sections 10, 11, 14, and 15 - T49N - R4E. The character and extent of the faulting in this area was believed to be of especial signficance as relating to the groundnoise anomaly and to the permeability and reservoir characteristics of the Dakota sandstone. The fault pattern would also probably be directly related to the deeper reservoir conditions in the Precambrian rocks. Random samples of the Dakota sand and conglomerate were taken for porosity and permeability determinations. Some grain densities were run for correlation with electric logs of future drill holes.

It is obvious from the field work and photo interpretations that faulting and fracturing is much more prevalent in the primary area than has been shown by prior work.

Precambrian Rocks

Precambrian age rocks are exposed to the northeast, east and southeast of the Waunita Hot Springs--Tomichi Dome area. As observed in the field and described in by Dings & Robinson (1957), the Precambrian rocks locally noted are:

1. Quartz-mica schist

Muscovite schist is exposed in a bank on the south side of a forest road in the extreme north central part of section 3. This gray rock is finely laminated muscovite schist with a little quartz and biotite.

Usually the rock is gray or brownish-gray fine-grained schist in which quartz, biotite, and muscovite can be recognized megascopically. Within short distances the rock can grade into dark quartz-biotite schist, light quartz-muscovite schist, or beds or lenses of pink to gray quartzite. Foliation is moderately to well developed, and in a few places the schist grades into gneiss.

2. Gneissic granite

A lightly gneissic granite occurs along the same bank as does the muscovite schist mentioned above. This rock is tan-pink in color with small smoky quartz phenocrysts and little biotite.

Just beyond the Dakota hogback at Stridiron Creek in Sec. 1, a large exposure of the gneissic granite can be found. It is typically a gray to brownish-gray, fine-grained rock having faint but generally distinct foliation. The foliation is defined by narrow bands, lenses, or streaks of biotite and less conspicuous lenses of slightly smoky quartz in a light gray granular aggregate of quartz, white and light gray feldspar, and a few small flakes of biotite. Weathered surfaces are gray, greenish-gray, or reddish-brown. The normally fine-grained granite is locally medium to coarse-grained.

3. Pikes Peak granite

The Pikes Peak granite is exposed in a small quarry at Black Sage Pass on the southeast side of the Crookton thrust fault. This rock is typically pink, coarse-to medium-grained rock, having many pink feldspar phenocrysts 1/2 to 1 inch long, and conspicuous small grains of fresh black biotite. Locally the freshly broken rock is gray, but in most places in the area surfaces are pinkish and, in some cases, light gray.

4. Hornblende diorite

This dark green hornblende-rich rock was observed in the locality of the schist and also of the gneissic granite.

Several textural and compositional varieties of the hornblende diorite have been found but most of the rock is fairly uniform. It is characteristically massive, greenish-black, and medium-grained, although grain size may range from fine to moderately coarse. Weathered surfaces are commonly greenish-gray, greenish-black, or reddish-brown. Hornblende and feldspar are the only minerals that can be identified in the hand specimens. Some of the rare basic facies consisting almost entirely of hornblende would be more properly termed hornblendite.

On the east side of Hot Springs Creek in the extreme southeast corner of section 18, a massive outcrop of igneous rock was found. This exposure had not been reported in any of the previous works on the area. The Precambrian sub-crop has quite a bit of relief throughout the area and it appears this is a local high of the Precambrian rocks that projects up towards the base of the Dakota Formation. A quartz-pyrite vein cuts through a fine-to medium-grained slightly altered hornblende diorite in a northwesterly direction and has been exposed in a surface cut. Across the Hot Springs Creek road to the west, the vein is also exposed in another prospect pit where it penetrates a highly altered hornblende diorite in a northwesterly direction and has been exposed in a surface cut. Across the Hot Springs road to the west, the vein is also exposed in another prospect pit where it penetrates a highly altered hornblende diorite. The vein is about ten feet wide here and strikes N35W with a 72° south dip. It can be traced further up the hillside to the west by surface float of the white quartz.

At the outcrop on the east side of the creek the rock is more resistant on the north side and appears to be of a monzonitic-latitic character. Because of the limited exposure of these rocks and lack of exposed contact with the sediments due to talus cover, it is remotely possible that this formation may be Tertiary (a dike?) in age. At this time, however, the indication is that it belongs in the Precambrian system. The appearance of this hornblende diorite is very similar to that observed in the northern part of the area.

Mesozoic Age Sedimentary Rocks

The Waunita Hot Springs--Tomichi Dome area is covered by a layer of sedimentary rocks ranging upward in age from the Jurassic Morrison formation to the Cretaceous Pierre shale formation. According to Stark and Behre (1957), there is from 1800 to 2250 feet of Cretaceous sediments exposed near Tomichi Dome. Adding in 250 to 350 feet of Morrison gives a total sedimentary thickness from 2000 to 2600 feet of Mesozoic rocks above the Precambrian unconformity.

1. Jurassic

a. Morrison formation

A poor exposure of the red and green Morrison shales can be seen on the west bank of the Hot Springs Creek road, a little ways south of where an unimproved road takes off to the west, in the NE quarter of section 19.

The Morrison formation consists of interbedded sandstones, shales, and limestones. The beds weather readily and outcrops are few. The sandstones are typically fine-to medium-grained and a dirty white color. The shales are mostly greenish or reddish; and the limestones are yellowish to gray. Although Dings and Robinson (1957) were unable to get accurate measurements of the Morrison, they estimated that it ranged from 250 to 375 feet thick.

The Morrison formation rests directly on the Precambrian surface. In the northeast part of the area where the Morrison and Dakota formations dip steeply to the southwest at the contact with the Precambrian, it might appear at first glance that the steep dip is due to a fault contact. However, the dip is probably due to uplift of the igneous and sedimentary rocks during the Laramide revolution in an anticlinal relationship.

2. Cretaceous

a. Dakota sandstone

As the Dakota sandstone is a resistant formation underlain and overlain by much softer beds, it forms prominent hogbacks throughout most of its extent, particularly where it is steeply dipping such as along the Crookton thrust fault and in the northeast portion of the area where it is tilted up near the Precambrian contact. The formation is composed chiefly of light-gray, crossbedded quartzose sandstone or quartzite. Most weathered surfaces are stained light brown to reddish-brown by the oxidation of pyrite. A conglomerate as much as 15 feet thick is present locally at the base and many of the lower beds contain lenses or thin beds of conglomerate a few inches thick in an otherwise medium-grained rock. The conglomerates can be observed near the Precambrian contact where the Dakota has been cut by drainages such as Stridiron Creek and Eldorado Wiley Gulches. The upper part of the formation is often poorly exposed, generally being covered by a thick layer of talus. A few gray shale beds are intercalated with the sandstones of the upper part of the Dakota in this region. Total thickness of the Dakota is estimated to be 150 to 200 feet.

b. Lower part of the Benton formation

The lower Benton consists of light-gray, calcareous clay-shale, weathering buff to light yellowish-brown.

c. Carlile sandstone (Upper Benton) formation

The upper Benton formation is alternating beds, two feet thick, of thin-bedded, dark-brown shale and of fetid, calcarious, chocolate-brown sandstone.

d. Niobrara limestone

The Niobrara is white to buff, chalky limestone, parting in thin shaley beds, two to four inches thick.

e. Pierre shale

This thick section that covers a large part of the area is a dark-brown to black fissile shale with local sandy interbeds, which become more prominent near the top. Cone-in cone structures occur in some layers.

Tertiary Age Igneous Rock

1. Tomichi Dome Rhyolite

The following description of the Tomichi Dome igneous rocks is a modification of Stark and Behre's (1936) article. Only a little time was spent in observing the Tomichi Dome rocks and the area was not covered in any detail. These Tertiary rocks have not been age dated by the U.S. Geological Survey, but U.S. Geological Survey personnel do estimate the age as being about the same as the older San Juan volcanics and the West Elk laccolith which would be in the 30-40 million year age range (personal communications with several geologists of the USGS).

Two bodies of igneous rocks are found at Tomichi Dome. The smaller, and far less conspicuous, is a sill cropping out on the northern and western slopes of the dome. This is fairly well seen in the NE1/4 of section 15 - T49N - R4E, where it has been faulted down to the east against the Benton shale. It is also well exposed near the center of section 20. Here, about 800 feet above the bed of Hot Springs Creek, are two westward spurs from Tomichi Dome, capped by the dense, resistant rock of the sill. Wherever seen, this sill lies within the Benton and appears essentially conformable with the bedding. It ranges in thickness from 20 to 35 feet and appears to die out to the southeast--that is, down the regional dip. Northeastward, it wedges out between the beds. On the east side of the Dome, just south of the center of section 23, there appears to be a remnant of the sill capping a nose and dipping gently to the east. Another remnant of the sill may be present in the SE corner of section 27. Some of this material capping the ridges may be talus that is floating down the ridges from the flow.

In hand specimens, the sill rock is light-gray, aphanitic, with platy fracture. The microscope shows a glassy matrix with phenocrysts of feldspar, biotite, and quartz. It so closely resembles the main mass of Tomichi Dome that one description will serve for both. A close genetic relationship of the two rocks, is, thus, strongly favored.

At its contacts the sill is still fine-grained. The shales above and below are brecciated, silicified, and extensively baked to a distinctive dense, black, finely crystalline hornfels, by means of which the boundary of the sill can be traced even in places where the igneous rock itself does not crop out. Carbonates are abundant on both sides of the contact, but metamorphic silicates are lacking. The recognizable contact aureole in the shale was from 5 to 10 feet thick in several localities. This figure is significant as bearing on the possible presence of a contact zone beneath the much thicker igneous cap of the dome.

Far greater in total volume than the sill just described is the igneous mass that forms the top of Tomichi Dome. It covers about three square miles and is at least 1800 feet thick.

The main part of this rock is everywhere fine-grained and light gray, but textural differences are conspicuous and prove to be essentially related to stratigraphic position: the lowest part of the rock, roughly 700 feet in thickness, has a texture suggesting tuff; above this, a "variole"-like or pisolitic texture is common for a thickness of roughly 900 feet; and the topmost part is more equigranular. It may be added that the term "variole" is here used loosely to describe a megascopic structure, and not in the strict sense as originally used. These three textural facies are believed to be significant and continuous, but because of poor exposure cannot be traced all around the dome. The sequence described is best seen on the northern slope, facing Waunita Hot Springs.

Despite its relative thinness, the topmost, and densest of the three facies is typical and is, therefore, described in greatest detail. Hand specimens are fine-grained to stony in texture, with a few megascopic phenocrysts of biotite, feldspar, and quartz. Under the microscope, a glassy matrix is everywhere recognizable and even the coarsest-grained specimens show interstitial glass, containing irregularly rounded areas that suggest sperulites. The glass matrix makes up from 15 to 30 per cent. The crystalline material is composed largely of feldspar, biotite, and quartz. Approximately equal amounts of orthoclase and oligoclase, with quartz averaging from 7 to 10 per cent, indicate a composition similar to many of the quartz monzonite intrusions of central Colorado. Brown biotite makes up 2 to 10 per cent, and is most abundant in the coarser-grained varieties; bleached biotite is also seen in some sections. Magnetite and topaz are present in small amounts in all sections. Garnet is found in the tuffaceous facies. Small quantities of apatite, hornblende, ilmenite, and titanite appear in the heavy "separates" but were not recognizable in thin section; even in the "separates" these minerals were far less conspicuous than the magnetite, topaz, and garnet.

Fluidal lines of this flow-like member are sharply outlined by limonite in somewhat-weathered specimens. In thin sections, fluidal texture is shown by the parallel orientation of the slightly elongated oligoclase crystals. Moreover, all sections show glass, and some, indeed, show little else. Embayments in the feldspar and quartz, also, contain glass and are continuous with the groundmass, thus suggesting an extrusive origin.

The "variolitic" member of the igneous mass is not sharply marked off from the topmost member just described. It is identical, mineralogically, with the rock that caps the dome. The spherules weather out, showing first as light-gray, fresh-appearing areas, surrounded by a discolored, faintly buff or brownish matrix. The spherules that finally weather out range, on the average, between .05 and .1 inch in diameter, but some diameters are much less, and the largest measured was half an inch. The microscope reveals little in the fresh rock that suggests true variolitic texture: the larger spheres are not defined at all, but the smaller ones are locally poorly outlined by spherulitic aggregates of crystallites in the glass, averaging .3 to .5 millimeter in diameter. Megascopically, the "varioles" are not suggested on the fresh surface.

The basal, tuff-like member is similar in composition. On weathering, it shows sub-angular pieces, up to an inch in maximum dimension, set in fine aggregate of the same kind of rock. This clastic texture is unmistakable, and there is reason to believe that this facies represents a highly silicified tuff or breccia that was thrown out first, in part as an ash, in part as a coarser pyroclastic, and then cemented by silica; this impression is gained equally from megascopic and microscopic features.

2. Monzonite dike

A Tertiary monzonitic dike can be traced through sections 12 and 13 - T49N - R4.5E, and section 18 - T49N - R5E where it cuts the Mancos shale (Benton through Pierre section) of Late Cretaceous age. This steeply-dipping dike, which may be as much as 25 feet thick, consists of a gray to olive-green rock with conspicuous white altered phenocrysts of feldspar.

3. Pyritic Quartz Veins

There are numerous prospect pits on northeast-trending pyritic quartz veins in the area around Waunita Hot Springs. Most of these veins are to the north and east of the springs. Several pits have been dug along the ridge and on the north slope of the hill west of the upper hot spring and south of the lower hot spring but no quartz vein material was found on the dumps. A fairly deep shaft was put down at the Mullingar mine about a mile northwest of the upper Spring. At the abandoned Eberly mine just above the Dakota hogback on Eldorado Gulch, sphalerite and argentiferous galena can still be found on the dump.

The pyritic quartz veins strike mostly from north to N35°E, although some strike northwest, and fewer still strike nearly east in the Garfield quadrangle to the northeast of Waunita Hot Springs. West and northwest dips, ranging from 50 to 90°, are by far the most common. In length and thickness the veins range from stringers a few feet long and a fraction of an inch thick to veins about a mile long and ten feet thick. In some places closely spaced veins, or vein zones, are 50 feet wide. The largest number of veins on which substantial prospecting has been done in the Garfield quadrangle are 500 to 1000 feet long and 1 to 3 feet thick. Those veins in the sedimentary rocks generally follow bedding planes.

Most of the veins are bordered by altered zones from a few inches to about two feet thick. The width of the altered zone is at many places roughly proportional to the width of the vein, although some shear zones either with or without pyrite-quartz veinlets are altered over a width of as much as fifty feet.

Very few pyritic quartz veins are in rocks younger than the Tertiary Mt. Princeton quartz monzonite and the ore deposits are related to the Mt. Princeton batholith.

The significance of the veins to the geothermal setting is that they occur in the fault and shear zones and are indicative of fractures that might otherwise go unnoticed.

Structure

1. Regional structure

Stark and Behre (1936) give the general structural features of the Tomichi area in the following paragraphs. They go into some detail in describing the Crookton thrust fault which is the major fault in the area.

The structure of the sediments immediately surrounding Tomichi Dome is, in general, monoclinal. The minor, local regional strike is northeast, with a southeast dip ranging from 6 to 40°.

A nearby feature of major structural interest is the Crookton fault. This shows well on the highway, about 4.5 miles south of the crest of Tomichi Dome, and about a mile east of the village of Crookton. Here, steeply upturned Dakota and Benton beds strike N28°E and dip 68°E, due to overturning; the Cretaceous sediments apparently dip under a granite whose lithology and continuity with the ancient rocks at Sargent clearly prove its pre-Cambrian age. Thus, the fault appears to thrust pre-Cambrian granite northwestward over the Mesozoic sediments. The fault trace has been followed northeastward for 6 miles, to a point where the road from Waunita Hot Springs crosses the hills that form the western divide of the Tomichi Creek drainage. Midway in the course as just outlined, the fault brings soft shales and impure, shaly sandstones to the surface, so that these rocks crop out between Dakota and pre-Cambrian. On lithologic grounds, these shaly beds are best correlated with the Morrison formation, of Lower Cretaceous or Jurassic age.

Immediately north of the outcrop just mentioned, the hard Dakota sandstone, here almost a quartzite, forms a steep cliff. The beds are vertical and show ripple marks, the sharp crests of which are on the western side of each exposed layer; thus, it is clear that the tops of the Dakota beds are to the west and that the formation has been dragged up by a thrust from the east. Two sets of regular joints are conspicuous on this cliff. One set trends N40°E, the other N10°E (which here is parallel to the fault trace); the bisectrix of the acute angle thus formed meets the foot-wall of the fault trace in an acute angle whose apex points south. With reasonable assumptions, it thus appears probable that the eastern side of the fault not only moved upward with respect to the western (foot-wall) side, but also northward as well.

The strike of the Crookton thrust varies, being about N35°E near the highway and about N10-20°E, where best exposed, three miles to the northeast. Its trace generally trends N35°E. The dip cannot be directly measured, but judging by the effect of the topography upon its trace, the plane must dip not less than 45 degrees. While, thus, not a low-angle fault, its displacement and the drag of the adjacent beds suggest extensive movement; hence, the fault seems to merit the appellation "thrust."

The Crookton thrust has steeply turned up the beds that underlie Tomichi Dome, where they approach the fault. This drag along the fault, especially in the plastic Pierre shales, has resulted in abrupt and irregular minor folds; such folds are suggested, but poorly exposed, in the region from Tomichi Dome southeastward to the thrust. Broadly speaking, however, the combination of the southeastward regional dip and the generally northwest dip imposed by the Crookton thrust has developed basin-like structure, in which the igneous rock and the crest of the dome are northwest of, but only about a mile away from, the structurally lowest point.

The Earth Resources Technology Satellite (ERTS) photos of Colorado show that the Waunita Hot Springs are situated near the juncture of at least three major lineaments. These are the N-S Rio Grande rift zone, a southwest trend into the San Juan Mountains, and a northwest trend to the West Elk uplift. The Crookton thrust fault appears to be a part of the San Juan lineament and it intersects the West Elk zone to the east of the hot springs. These major features may well serve as conduits for magmatic intrusions that can form heat cells or for movement of hot waters.

2. Faults

The Tomichi dome is set in a sedimentary basin that may be due to a graben setting. There are radiating and concentric faults around the dome that were most likely formed or enlarged when the lava broke through and flowed out onto the land surface ultimately resulting, after erosion, in the present topographic feature. These faults are probably the deep feeders for any potential geothermal cells.

The geologic map (Fig. 2) shows faults observed in the field, faults indicated by structural irregularities, faults inferred from topographic differences, and faults predicated from aerial photo interpretation. Jointing that is common in the Dakota sandstone, is not shown on the map. All of the observed faults appear to be normal faults. Throw on the faults, in some instances, amounts to several hundred feet; for instance, the east-west fault running from the lower hot spring to the small lake to the east has about 250 feet of throw.

At two sites the Dakota sandstone can be seen dipping steeply where it has been dragged down along a fault. The first of these is northwesterly along Yellow Pine Ridge in sections 17, 8, and 7 where the ridge has been formed by the fault. This is undoubtedly the same fault shown by Stark and Behre in section 19. There are no dips in section 19 of the magnitude shown by them. The other fault showing drag in the Dakota rocks is northerly through sections 16 and 9.

Jointing in the Dakota formation strikes from N-S to E-W and has mostly vertical dips. The joints do not appear to have continuity with depth even though they are numerous and closely spaced. However, the jointing fabric could have great affect at depth since the fault system will probably carry them to the basement. In any event, multiplicity of joints would add materially to the overall porosity and permeability providing they have not been sealed by secondary deposits.

Limonite is evident on some of the joints and could be from hot waters that mobilized pyrite and caused reprecipitation of the limonite.

A fault is inferred, with some evidence of lineation on the aerial photos, as running easterly through the gap along Hot Springs Creek in the extreme northeast edge of section 3, then southerly through section 2, more or less paralleling the Dakota outcrop to the west.

GEOTHERMAL RESERVOIR CONDITIONS

The potential reservoir at Waunita Hot Springs that will serve to recharge a geothermal steam and/or hot water project is essentially an unknown at this time. However, the information that is available allows one to make some reasonable conclusions.

The Dakota sand is not uniform in porosity and permeability, yet it should be a major contributor of water to a geothermal cell, particularly since there is a sizeable system of shears, faults, fractures, and jointing cutting the sedimentary formations. Some of the major structures, undoubtedly, extend to depth and would serve as the primary "plumbing" system.

The sedimentary Jurrasic and Cretaceous formations are not very thick in the area, there being about 2000-2500 feet of total section. A large part of the Dakota is exposed on the surface and as a consequence, some of the formation has been eroded off.

Pierre and Benton shales which cover much of the area make good impervious cap rock material. This would have no affect on the Dakota sand up-dip outcrops, but the lenticularity of the Dakota permeability would serve as a block to water movement except where faults serve as channel ways.

Seventeen surface samples of the Dakota sands and conglomerates were taken at several different sites in the Waunita Hot Springs area (Table 1). All of the samples were analyzed for porosity and permeability and eleven of the samples were tested for grain density as a check for use in correlating with electrical logs in holes that might be drilled to test the area. These analyses, which follow, were done by Core Laboratories, Inc. at their lab in Denver, Colorado.

Sample Nos. 4, 20, 21, and 23 are the only ones to show any appreciable permeability and porosity. This is not surprising because oil drilling in the Denver-Julesburg Basin has shown the Dakota sands to vary widely in reservoir characteristics in short distances. The multiplicity of wells drilled into the Dakota sand in the D-J Basin has well documented that the sand makes an

Table 1.

Sample Number	Horizontal Permeability (Millidarcys)	Porosity (percent)	Remarks	Grain Density
1	0.1	4.5	ss lt gry fn silic	2.60
2	0.1	3.4	ss lt gry med silic	2.65
3	0.1	5.2	ss gry cse silic	2.63
3A	0.1	4.3	ss gry fn silic	2.65
4	66	9.6	ss gry fn	2.63
54	0.1	1.1	ss gry fn silic	2.60
5A	0.1	1.5	ss gry fn silic	2.60
6	0.1	1.7	ss gry fn silic	2.60
7	0.1	1.4	ss gry fn silic	2.63
7A	0.1	1.7	ss gry med silic	2.61
20	13	8.2	ss wh fn cly	
21	10	8.6	ss wh vfg cly	
23	11	10.5	ss wh med-cse cly	2.62
24	0.24	4.5	ss wh vfg-fn cly	
25	0.14	3.1	ss wh vfg cly	
26	0.29	4.4	ss wh vfg cly	
27	0.79	5.1	ss wh vfg cly	

excellent reservoir where it develops porosity and permeability. Cores of the sand show that vertical fractures are common in the sand, silt, and shale phases. Similar conditions may exist in the Tomichi Dome area. The surface samples are not as reliable a measure of the reservoir characteristics of the Dakota sand as are core samples due to the possible effects of weathering, surface alteration, leaching, silicification, and secondary deposition in the pore spaces and in fractures. The present indications are that the Dakota formation is not a uniform interconnected water reservoir. In any event, the fracture system in the area should provide adequate plumbing to channel the Dakota formation water to the "boiler" of the geothermal system. Depending on the depth of the geothermal system, the faulting and fracturing of the Precambrian rocks may be the dominant feature of the recharge zone. Should the system be very shallow, the Dakota formation would be the water source. The work done by Senturion Sciences, Inc. shows the Tertiary to Recent magma injected to a shallow depth.

On the other hand, a deep-seated heat cell could have a large volume of fracture reservoir feeding it. The widespread faulting around Tomichi Dome together with the impermeable nature of the Dakota sandstone as a whole, as observed in the area, makes it appear that if a sizeable water reservoir is present to feed a geothermal heat cell much of the reservoir will be in a fairly extensive system of shears, faults, fractures, and joints occurring in the Precambrian as well as the sedimentaries. The drill will give the ultimate answer to this question.

Another factor to be considered in evaluating reservoir conditions is the amount of meteoric water available for recharging the reservoir. According to local residents questioned, only 8 inches of rainfall occurs annually at Waunita Hot Springs. On the other hand, the Colorado Water Conservation Board shows the area to average 25-30 inches of moisture per year. As you go east from Waunita Hot Springs, the average rainfall decreases until it is only 12 inches per year, 15 miles away across the continental divide in the Arkansas Valley. The high elevations ranging from 9000 feet at Waunita to 11,465 feet on Tomichi Dome insures that the winter snows accumulate and ultimately much of this moisture soaks into the ground.

The geologic aspects discussed suggest that:

1) Cooling magma, related to the Tomichi Dome intrusive may constitute a heat source.

2) Radial and concentric fault systems exist centered around Tomichi Dome. If these are open and active, they could constitute a suitable plumbing system.

3) Reservoir existence is questionable. The veneer of Mesozoic sediments seem to have very low permeability and the fracture permeability of the crystalline basement rocks is unknown.

The existing geophysical data is insufficient to form a basis for thorough evaluation of the geothermal potential, but it is, however, moderately encouraging.

The results of the microearthquake surveys run in December 1971 and February 1972 have been interpreted by Senturion to indicate the existence of fault systems radial to the Tomichi Dome. Study of their work suggests the existence of a major north-south trending structure lying just west of Waunita Hot Springs.

The area in which these clustered microearthquakes are coincident with the groundnoise anomaly discussed below constitutes the most promising geothermal target at this stage.

A groundnoise anomaly of 56 decibels power intensity at a predominant frequency of 1 Hertz is situated east from Waunita Hot Springs. The anomaly is open to the east and northeast. This anomaly is fairly encouraging and its source should be further investigated, especially near the clustered microearthquakes north of Waunita. Although the geophysical work indicates the presence of an altered zone at the anomalous area, no specific evidence of such a zone was found at the surface.

Some recent temperatures taken at the Waunita Hot Springs by Mr. Frank Dellechaie are (1) upper spring mud = 81°C, (2) upper spring water = 76°C, and lower spring water = 71°C. These are all maximum readings.

Geochemical analyses of waters collected near Lower Waunita Springs are interesting, but cannot be meaningfully interpreted without background data.

The moderately high SiO_2 values (85 mg/l) and the relatively low Ca and Mg values suggest elevated base temperatures (100°-130°C), however, the high Na/K ratio (75:1) suggests a mixed water of lower base temperature.

Conclusions

The geothermal potential of Waunita Hot Springs cannot be accurately evaluated on the basis of the existing geophysical data, however the geologic, geophysical and geochemical aspects are intriguing. The most important unknown at this time is the nature and extent of a reservoir. If this can be satisfactorily defined, the prospect will gain immense credibility.

Recommendations

In order to more carefully delineate a heat anomaly, to locate open faults and to study the groundwater system of the prospect the following exploration is recommended.

1) A groundnoise survey at close density (1/2 mile centers) should be run so as to pinpoint and close off the major anomaly, and the two adjacent anomalies to the north and southeast.

2) Additionally, a reflection seismic profile of the region should be shot so as to learn the bedrock configuration (for reservoir studies).

3) Electrical resistivity studies should be made over area defined by 1, above, and over the clustered microearthquake zone. The survey should be planned to "see" as deep as possible and to adequately study background resistivities. The work should be of both dipole-dipole and Schlumberger sounding types.

4) Thermal gradient holes of 2" diameter to 200 meter depth should be drilled in and around anomalies defined by 1 and 3 above. Enough should be drilled to statistically evaluate the full anomaly.

5) Finally, a thorough geochemical survey of all cold and hot groundwaters in the region should be made. Analyses should include SiO_2, Na, K, Ca, Mg, Cl, F, CO_2, HCO_3, Ph, Temp., and rate of flow. Geothermometric and regional ground water system data obtained from this survey will help evaluate the thermal gradient test results and the reservoir potential.

REFERENCES

Dings, M.G. and Robinson, C.S., 1957, Geology and ore deposits of the Garfield Quadrangle, Colorado: U.S. Geol. Survey Prof. Paper 289, 1 110 p.

Stark, J.T. and Behre, C.H., Jr., 1936, Tomichi Dome flow: Geol. Soc. America Bull. v. 47, no. 1, pp. 101-110.

CHAPTER II
WAUNITA HOT SPRINGS, COLORADO
GEOTHERMAL PROSPECT
RECONNAISSANCE EVALUATION AND RECOMMENDATIONS

by

GeothermEx
Berkeley, California 94707

CONCLUSIONS

1. The Waunita Hot Springs area has good to questionable potential for geothermal resource discovery and development, as discussed in the Reconnaissance Evaluation section. An undetermined heat source and a reservoir limited in thickness and areal extent by crystalline rocks require positive determinations by exploration before a more optimistic point of view may be taken.

2. Geology of the area, particularly the attitude, structure and thickness of the Mesozoic sedimentary section and the internal structure and age sequence of the igneous rocks making up Tomichi Dome, is insuffciently known. Depth to the Precambrian basement south of Waunita Hot Springs and presence of a fractured sedimentary section under the north and northwestern lips of Tomichi Dome are critical questions.

3. Hydrologic conditions in the target area are not known. A water budget including basic parameters of precipitation, recharge, storage, flow directions, depth, velocity and discharge should be determined.

4. We consider that favorable conditions for reservoir and heat source occur in Sections 10, 11, 12, 13, 14, 15, 22, 23, 24, 25, 26, 34, 35 of T.49 N., R.4 E., and Sections 13 and 24 of T.49 N., R. 4 1/2 E.

5. An explicit heat source may not be identifiable prior to drilling. No regional crustal target zone exists; the heat source must be related to either an apophysis of a late phase of the Mount Princeton or Tomichi silicic magma(s) or of the basaltic magmas comprising the latest San Juan eruptive reservoirs. Exit of several hundred million gram-calories per minute from the hot springs belies simple deep flow.

RECOMMENDATIONS

1. Accomplish a) an electrical resistivity survey that will indicate depth to high resistivity basement and extent of the thermal reservoir, and b) review and supplemental passive seismic supplemental work related to the "noise" and microearthquake data.

2. Apply the gravity survey technique to help define subsurface structure, as well as to indicate extent of the Tomichi Dome rocks in the subsurface.

3. Make a photogeologic analysis of Tomichi Dome to separate the component flows, sills, plugs, etc. into relative age units. Obtain samples from the youngest units for absolute radiometric age dates.

4. Conduct geological exploration as discussed in CONCLUSIONS, including photogeology, field geology, and geometric analysis to describe accurately the subsurface of the target area.

5. Calculate the water budget of the area and analyze the hydrology therefrom. Insufficient wells and springs exist to provide a good hydrogeochemical survey data base. It will therefore not be possible to assess the deep reservoir before drilling. Limited assistance may be provided by recommmendation #6.

6. Resample Waunita and lower Waunita Hot Springs and have chemical, isotope (H/D, O_{16}/O_{18}) and carbon age dating performed. The high HCO_3 content should provide a good C_{14} analysis, as long as C_{13}/C_{12} are used for correction.

RECONNAISSANCE EVALUATION

Waunita Hot Springs is located in the southeastern part of Gunnison County, Colorado, about 25 miles east of the city of Gunnison. There are two groups of springs about one-half mile apart on the Hot Springs Creek at favorable fault intersections through the Dakota sandstone. Resorts built at the springs are described in literature from the early 20th century (Lakes, 1905, 1906).

Monarch Pass, representing the Continental Divide, is about 10 miles eastward. The Sawatch Range including Shavano Peak and the Collegiate group of peaks in the highest Rocky Mountain, are also within 10 miles eastward. To the west, the Gunnison River and Tomichi Creek have formed a high valley, or park.

Waunita Hot Springs is in a high intermontane valley in the south-central Rocky Mountains. Steep mountain fronts typical of vigorous alpine erosion exist throughout the area with a few level valleys marking flood plains of streams which presently have less water than during the main glacial melt period.

Elevations in the area of the Waunita Hot Springs range from a low of 7,667 feet at Gunnison, situated where five main creeks join to form the Gunnison River, to Shavano Peak, 14,225 feet high, 20 miles east of the springs. The springs are at an elevation of 9,000 feet. There are many peaks above 12,000 feet elevation within a 40 mile radius of the springs. Tomichi Dome, 11,500 feet high, is less than 3 miles south of the Springs. Unlike the peaks of the Collegiate Range, Tomichi Dome is a composite of eruptive and shallow fine-grained intrusive igneous rocks. The terrain in the vicinity of the springs at Waunita Park is fairly open and gently sloped.

Climate varies considerably in this area according to altitude and exposure and Waunita Hot Springs itself has rather mild climate compared to the high mountains surrounding on three sides. At 9,000 feet, Waunita Hot Springs has an average annual temperature of 37°F, representing an average of 15°F in

January and 60°F in July. The surrounding mountains often receive snow when Waunita Hot Springs is clear. Precipitation averages 15 inches per year, with about 20 inches per year on Tomichi Peak. Of this, about half occurs as annual snowpack; the rest occurs mainly as summer thunderstorms.

Three main perennial streams drain the area: Tomichi Creek, 5 miles east of the hot springs, which loops south and west and marks the boundary between the Sawatch and San Juan Mountains; Quartz Creek, which runs south about 8 miles west of the hot springs; and Cochetopa Creek, which runs north and joins Tomichi Creek 15 miles west of the hot springs. There are 5 other perennial streams within 15 miles of the hot springs. In addition, Hot Springs Creek is a 15 mile long intermittent stream which heads at Waunita Pass and passes directly through Waunita Hot Springs on the way to join Tomichi Creek. Considerable flow occurs in this creek, augmented by the 1,000 gallons per minute flow from the springs. Local ground water averages 45°F. Most of the cattle ranches in the area have headquarters located at creeks and have only shallow wells in the creek alluvium. Seeps occur on the hillsides near Waunita Hot Springs but do not have significant discharge.

The Arkansas River main line of the Denver and Rio Grande Western Railroad passes through Salida, Colorado, 30 miles to the east, across the Continental Divide. A spur approaches as close as Monarch, 12 miles to the east of the hot springs; the track which formerly continued west, has been removed, and only the grade remains into Gunnison. The Denver and Rio Grande has another main line into Montrose, about 75 miles to the west.

U.S. Highway 50 passes six miles south of Waunita Hot Springs; it is one of the roads across the Rocky Mountains which is kept open except for immediate effects of winter storms. A paved road goes toward the springs, then turns to a graded dirt road, which continues through the mountains past the springs to the north, west and east, looping to Pitkin, Ohio City, and in season to Mount Princeton. State Highway 114 branches south from U.S. Highway 50 to loop eastward through Cochetopa Pass toward the San Luis Valley. Another paved road passes northeast from Highway 50 to Ohio and Pitkin, small populated localities on Quartz Creek about 6 miles from Waunita Hot Springs. A few unimproved ranch roads traverse the higher elevations including the slopes of Tomichi Dome, but access is not good, except seasonally.

Gunnison, with nearly 5,000 inhabitants, located approximately 35 west of Waunita Hot Springs, is the nearest populated place except for Pitkin, Ohio, the ranches, a few service station areas on U.S. Highway 50, and ranger stations. Salida, with a population of about 4,500 is 30 miles east of the hot springs. All other major communities are reached through Gunnison and Salida.

Stock raising of horses, cattle, and sheep, and farming of hay and cool weather vegetables are the principal industries of the region. Lumbering also is practiced and mining of gold, silver, lead, copper, zinc, fluorite, etc. is still accomplished. Uranium was sought during the 1950s toward Gunnison and southwest of Doyleville. Coal and building materials are also mined.

Tourism has become quite an important industry in the area. Resorts such as Waunita Springs offer dude ranching fishing the glacial lakes of the High Rockies, skiing, hunting, etc., so that a year around industry is growing in the area. Also, the hot springs are near one of the main transcontinental routes for visitors to the U.S. National Parks.

The area is served by the Colorado-Ute Electric Association, an electric cooperative, and by the U.S. Bureau of Reclamation (U.S.B.R.). U.S. Bureau of Reclamation 115 and 230 kVe lines pass within a few miles of Waunita Hot Springs.

Geology

At Waunita Hot Springs a quartzitic sandstone, the Dakota Formation, at the base of a Cretaceous sedimentary group of rocks, crops out. The Jurassic-Cretaceous sequence consists of the Morrison, Dakota, Benton, Niobrara and Pierre formations. These have been deformed into a basin structure south of the Waunita Hot Springs area, with many local folds and faults. Below the Cretaceous rocks is a Precambrian granitic and metamorphic crystalline complex. Immediately west-southwest of Waunita Hot Springs an anticline trending southwest occurs in the Mesozoic rocks. Precambrian crystalline rocks are exposed in the central part of the anticline. This is of significance in choice of possible reservoir areas; there is little possibility of fractured sedimentary reservoir immediately northwest of the hot springs. The fractured Precambrian rocks are likely to have only a relatively few fractures such as control the Waunita Hot Springs effluent. The area southward and eastward from the hot springs has greater potential for a reservoir; as the terrain rises sharply onto the dome, depth to the reservoir may be more than 5,000 feet. If the intrusive and eruptive episodes at Tomichi Dome have not deformed the section greatly, several hundred feet of Morrison and Dakota formations rocks may underlie more than 1,000 feet of Mancos Shale (Dings and Robinson, 1957).

The area north of the hot springs is part of the Southern Rocky Mountains and Sawatch Range, comprised of complex cores of granitic rocks exposed by unroofing of batholithic masses. The intrusive granitic rocks range in age from Precambrian to Tertiary. The Mount Princeton-Mount Antero-Mount Shavano group of peaks, 15 miles northeast of the springs, is comprised of a batholith of early Tertiary granite with quartz monzonite and andesite portions. An outlier or apophysis of the batholith may have been the magmatic source of the central portion of the feature known as Tomichi Dome, 2 miles south of the hot springs. Tomichi Dome is a multiple event feature composed of flows and intrusive sills of rhyolite, tuff, and granite porphyry; it is estimated to be Miocene in age. The younger intrusions are seen to warp the Cretaceous sediments into anticlines, but Stark and Behre (1936), proposed that Tomichi Dome was primarily an extrusive feature set in a basin. The Crookton (Gunnison) fault, a 30 mile long feature, runs northward from a point 15 miles southeast of the hot springs, passes about 3 miles east of the springs in Horn Gulch and continues toward Pitkin, 15 miles further north. It is a thrust fault with the east side the upthrown side.

The San Juan Mountains are an extensive Tertiary eruptive and intrusive volcanic field some 15,000 square miles in area occupying southwestern Colorado and parts of north-central New Mexico. The most recent significant geologic activity in the San Juan area has been eruption of silicic flows and pyroclastic materials from complexly nested calderas within a great subsidence cauldron. Other volcanic centers exist outside the main cauldron, at least as far east as the Rio Grande Rift zone; intermediate to silicic compositions are common as well as basalt. The main time of eruption, from radiometric dating, is Oligocene, but Miocene time was also one of frequent eruption of ash-flow tuffs and other volcanic rocks. Younger volcanic rocks occur and are mostly basaltic in composition. A steady, if episodic, record of volcanism exists from between 40 million years before present and 0.5 million years before present. There is no reason to believe that the activity is complete or waning; a new intrusive phase may have emplaced magmas quite near the surface. Slow doming of the region during the last two million years may have been due to new movement without extensive eruptions, and would possibly place a batholith within a few miles of the surface.

Topography in the area is mostly the result of glaciation; alluvial fill in the small stream valleys is probably less than 500 feet in thickness.

An aeromagnetic survey has been made of the State of Colorado by the U.S. Geological Survey (Zietz and Kirby, 1972). The scale is small, 1:500,000, but even at this scale, the area near Waunita Hot Springs and southward toward Doyleville is seen to be marked by a fairly intense magnetic low, aligned in a north-south direction. A 300 gamma gradient rises eastward toward the Collegiate range. The scale is such that Tomichi Dome does not show up at all, although the crystalline rocks east of the Crookton thrust show as a 30 gamma closure high. Low intensity sediments of the valley are probably responsible for the negative magnetic conditions. Within 10 miles to the east, however, the low is replaced along a steep gradient with a group of significant magnetic highs coincident with the young Tertiary intrusion(s) near the Continental Divide. At least 6 separate highs are present. On the southwest side of the low described near the hot springs (that low extends for nearly 100 miles through the Cochetopa Hills to the San Luis Valley), a prominent steep high occurs, coincident with Miocene-Pliocene rhyolite and quartz latite of the San Juan area near the Continental Divide. These eruptive centers and their magnetic highs become even more prominent as one proceeds southward. The Rio Grande Valley and Gunnison Valley show up as magnetic lows dividing the highs.

The U.S. Geological Survey (1972) has published in the open file a 1:500,000 scale gravity map of Colorado. Waunita Hot Springs is on a gentle northerly trending gradient and no significant anomaly is present.

We have not found any data indicating crustal thinning in the area, such as late arrival time of seismic waves. A seismic ground noise survey has been accomplished, but the data is contradictory and conclusions should not be drawn on the basis of present interpretations. That is, frequency and decibel levels do not unequivocably show an anomaly near the hot springs. Heat flow appears to be nominal, 1.5 microcalories per square centimeter per second.

No deep wells have been known to have been drilled in this area. Reports from mines in the San Juan Mountains as well as the Sawatch Mountains indicate that extensive silicification and alunitization have occurred in the San Juan Mountains, and that ore deposition has been tied to solfataric and carbon dioxide rich alteration period.

Hydrogeology

Waunita Hot Springs, also historically known as Tomichi Hot Springs, consists of 2 groups of springs about 1/2 mile apart. The hottest spring was reported to have a temperature of 158°F at one of the spring orifices near the ranch headquarters. A powerful steam source is moving through a high, cold water table. Many bubbling discharges were noted, probably from CO_2; report of 1,000 gallons per minute discharge is not exaggerated. This represents nearly 200 million gram-calories per minute outflow of heat. The springs issue in the valley bottom and intermingle rapidly with cool waters of Hot Springs Creek. Bedrock consists of a wedge of sandstone altered to quartzite.

The hot springs produce a sulfate (182 ppm) bicarbonate (175 ppm) water. Chemically, $Na>Ca>K<Mg$, and $SO_4>HCO_3>Cl$. SiO_2 was reported at 86 parts per million (ppm). Much mixing must occur; the indicators are quite favorable even if only suggestive of underground conditions. The lower, cooler group of springs has about 25% of the flow of the upper springs from a similar geologic condition. Orifices are spread over a hillside for about 0.1 mile.

There are no other thermal manifestations in the immediate area, but some points should be reviewed here about relationship to other springs within a 25 mile radius.

On the east side of the Continental Divide, across the Sawatch Mountains, are the springs which have been reputed to be the hottest in Colorado, namely Hortense Hot Spring, Mount Princeton Hot Spring, and Cottonwood Hot Springs, all in Chaffee County. These range in temperature from 140°F to 180°F. Their existence lends support to valuation of the Waunita area, insofar as a granitic magma heat source may underly the area or be rising toward a new episode of intrusion under the Sawatch Mountains. Chemical relationships at these other springs are approximately the same as at Waunita Hot Springs; silica is consistently lower (53 to 71 ppm).

Poncha Springs, about 30 miles eastward, was measured at 160°F while Poncha Springs may be related to the Rio Grande Rift geologically; chemically it is very similar to Waunita Hot Springs.

Cebolla (Powderhorn) Hot Springs, 35 miles southwest, was measured at 104°F; it is probably related to San Juan Mountain intrusions.

There may be postulated one of two major heat sources in the area. First, batholithic intrusion into the Sawatch Mountains may be occurring, or a magma may be cooling a few miles below the surface. Second, there may be Rio Grande Rift associated intrusions nearing surface. Most of the recent eruptions related chemically and mineralogically to the latest Rio Grande Rift eruptions have been basaltic.

It is more likely that the heat source is related to a batholith or group of stock-sized apophyses which is/are intruding the area on the east flank of the Sawatch Mountains. In the event this speculation is incorrect, then the heated water must originate in circulation to great depth and ascent at major throughgoing faults. Volume of CO_2 in the water argues against simple deep circulation. Depth may be only a few miles to the intruding magma. However, exploration in the areas recommended will aid in establishing limits of the hot zone and its relationship to a northern Rocky Mountain or southern San Juan source. Thermal history indicates that intrusive and extrusive phases of activity started as much as 70 million years before present and continued episodically to the most recent 1 million years. The period between 40 and 25 million years before present represents an especially active time for intrusion and eruption. Grose (1974) presented new data to indicate heat flow of 2.0 to 2.5 HFV in the area. Keller (1974) speculates that high mantle temperatures occur in the area, indicated by low residual gravity values.

It is likely that fractured ancient sedimentary rocks from the Mesozoic Era, represent the most probable reservoir. The alluvium in Hot Creek and Tomichi Creek is less than 500 feet thick; Alluvium in the area west of Doyleville may be thicker but is made up of coarse granular material of little value as a reservoir or impermeable lid. It does offer an assist to infiltration of recharge into deeper zones, perhaps along fracture zones.

The Crookton fault zone indicates that the area was once under considerable stress, and we expect that this was resolved as fractures throughout the granitic rocks. Regional dip of the Mesozoic sediments near Waunita Hot Springs is southeastward toward the fault. Tomichi Dome interferes with this east-southeasterly dip. The question to be resolved is the thickness and structure of the sedimentary formations southeast of Waunita Hot Springs. The same formations are gas-bearing reservoirs in the San Juan Basin to the southwest, although frequently too tight or impermeable to allow production without hydrofracturing or other stimulation techniques. There may be several thousand feet of thickness of these sedimentary rocks. Therefore exploration is again necessary.

The same unknowns that affect evaluation at this stage of the reservoir, affect evaluation of fluid in storage. There is sufficient precipitation and runoff to infiltrate the reservoir area. Unquestionably, rocks are saturated from a point just below surface to a depth limited by lithostatic pressure closing pores and fractures. Volume in storage and circulation is dependent upon porosity and permeability. A steam phase may be present, based upon temperature and chemistry data from Waunita Hot Spring.

CONCLUSIONS

A cautious approach to the Waunita Hot Springs target should be taken. An extensive region of surface hot waters indicates that there is a regional heat source, even if heat flow is not anomalously high. Leakage of heat on all sides of the Sawatch Mountain mass wherever there is a structural or stratigraphically controlled path, points to a very significant total available energy. The requirement is, as usual, to locate the best concentration of heat with a storage zone that is producible. Waunita Hot Springs are merely surface indicators and a start for exploration. Geological and geophysical indicators point to the Waunita Hot Springs area; depth to target, nature of a permeable reservoir, and base temperature are data to be obtained.

Detailed geological mapping extends to several miles south of Waunita Hot Springs but has been published in small scale format McQueen (1958). Mining areas nearby have been mapped in detail. The hot springs itself and a radius of up to 10 miles around it needs additional mapping to supply useful data, especially in determining the geometry of its basin and thickness of the reservoir section. The work by Stark and Behre (1936) is only reconnaissance in nature as a result of 10 man days of field work.

Photointerpretation of fracture patterns and other structural elements, alteration zones, and stratigraphy needs to be accomplished. Photoanalysis of Tomichi Dome to determine the youngest flows, and selected radiometric age dating of the youthful intrusive (?) rocks should be accomplished.

Gravity data of larger scale should be accomplished as an indicator of subsurface rock position and structure.

Heat flow and temperature gradient data appear to be sparse to non-existent for the target area. No electrical resistivity, and electromagnetic data are known to be available.

SELECTED REFERENCES

Waunita Hot Springs

Crawford, R.D., 1913, Geology and ore deposits of the Monarch and Tomichi districts, Colorado: Colo. Geol. Survey Bull. 4, 317 p.

Dings, M.G., and Robinson, C.S., 1957, Geology and ore deposits of the Garfield Quadrangle, Colorado: U.S. Geol. Survey Prof. Paper 289, 110 p.

George, R.S., et al, 1920, Mineral waters of Colorado: Colo. Geol. Survey Bull. 11, 474 p.

Goddard, E.N., 1936, The geology and ore deposits of the Tincup mining district, Gunnison County, Colorado: Colo. Geol. Soc. Proc., v. 13, no. 10, pp. 551-595.

Grose, L.T., 1974, Summary of geology of Colorado related to geothermal energy potential in Proceedings of a symposium on geothermal energy and Colorado: Colo. Geol. Survey Bull. 35, pp. 11-30.

Keller, G.V., 1974, Geophysics of Colorado and geothermal energy, in Proceedings of a symposium on geothermal energy and Colorado: Colo. Geol. Survey Bull. 35, pp. 31-44.

Lakes, A., 1905, Geology of the hot springs of Colorado: Colo. Sci. Soc. Proc. v. 8, pp. 31-38.

_____, 1906, Mineral and Hot Springs of Colo.: Mining World, v. 24, pp. 359-360.

McQueen, K., 1958, Photogeologic map of the Iris SE and Doyleville SW quadrangles, Saguache County, Colorado: U.S. Geol. Survey Misc. Geol. Investigations Map I-277.

Pearl, R. H., 1972, Geothermal resources of Colorado: Colo. Geol. Survey Spec. Pub. 2, 59 p.

Stark, J.T., 1934, Reverse faulting in the Sawatch Range: Geol. Soc. America Bull. v 45, pp. 1001-1016.

_____, and Behre, C.H., Jr., 1936, Tomichi Dome flow: Geol. Soc. America Bull., v. 47, no. 1, pp. 101-110.

U.S. Geological Survey, 1972, Bouguer gravity map of Colorado, compiled by Behrendt, J., and Bajwa, L: U.S. Geol. Survey Open File Map.

Zietz, I., and Kirby, R., 1972, Aeromagnetic map of Colorado: U.S. Geol. Survey Map GP-836.

CHAPTER III
INTERPRETATION OF WATER SAMPLE ANALYSES
WAUNITA HOT SPRINGS AREA
GUNNISON COUNTY, COLORADO

by

ROBERT H. CARPENTER
GOLDEN, COLORADO

INTRODUCTION

Water samples from the Waunita Hot Springs geothermal target area located some 25 miles east of Gunnison, Colorado, were collected on July 14th and 15th, 1974. The objective was to attempt to relate ionic content in these samples to a possible geothermal reservoir at depth.

Water samples were collected from the two hot springs, from two surface springs and from streams in the upper Hot Springs Creek drainage.

Three samples were collected from each site. Two were filtered and acidified to a pH of 2 and one was untreated. Each set of samples was analyzed for silica, sodium, potassium, calcium, magnesium, manganese, zinc, flourine, chlorine and tested for pH and conductivity by accepted laboratory methods under the supervision of Dr. T. A. Wildman.

SAMPLE SITE LOCATIONS

Because of an unusually dry summer many of the stream tributaries and cold springs dried up. However, analyses of samples from the upper Hot Springs Creek drainage and the cold springs showed important differences from analyses of the hot springs waters. The sample location sites are listed as follows:

Sample No. 1 - Hot spring at Lodge

Sample No. 2 - Hot spring - 1/2 mile downstream

Sample No. 3 - Cold spring, north slope of Tomichi dome - 1/2 mile southwest of the Lodge

Sample No. 4 - Hot Springs Creek - 2.8 miles above Sage Pass Road turnoff

Sample No. 5 - Pitkin Road branch, Hot Springs Creek, 2.8 miles above Sage Pass road junction

Sample No. 6 - Hot Springs Creek at Riley Creek turnoff, 2.2 miles above Sage Pass road junction

Sample No. 7 - Cold spring, northeast slope Tomichi dome - 1 1/2 miles southeast of Lodge

ANALYTICAL RESULTS

The element content in parts per million, the pH and conductivity of the water samples are given in Table I, at end of the chapter.

The base metal content of manganese, zinc and cadmium in all samples was very low in comparison with water typical of the Colorado Mineral Belt. As a consequence it is very doubtful that base metals will serve to distinguish between geothermal and meteoric waters in the Waunita Hot Springs area.

Water samples from the hot springs have a Na, K, Ca and Mg abundance pattern which is distinctly different from the surface waters in the area. The concentration of Na is high and Mg is low in both samples of hot springs water in relation to the surface water. The Na/K ratio is 15 for the hot springs, whereas the surface water ratio is 3 to 10. The hot springs Ca/Mg ratios are 5 to 12 as compared to a range of 1 to 6 for the surface waters. Also, as shown on Table I, the silica content in the hot springs waters is many times higher than in the meteoric waters.

Fluoride and chloride also are considerably higher in the hot springs waters than in the meteoric. Since there is not sufficient F* and Cl* ions in the hot springs waters to chemically balance the anions and cations in the waters, sulfate and bicarbonate anions were suspected. A barium precipitation test was carried out for SO_4; it was found to be present in all waters, but was particularly high in the hot springs waters.

INTERPRETATION OF RESULTS

The pattern of elemental abundance and low conductivity of the Waunita Hot Springs waters indicate a vapor dominated type of geothermal system as discussed by White and Ellis (1971) in their papers on hydrothermal systems. Table II, lists element concentrations in some of the major, vapor dominated geothermal centers of the world, for comparison with the Waunita Hot Springs element concentrations. The element concentrations in brine-dominated systems such as the Salton Sea geothermal system vary greatly from the vapor dominated systems. Most proven geothermal power producing areas utilize waters of the vapor-dominated, magmatic type.

White, Muffler and Truesdell (1971) in their paper "Vapor-dominated Hydrothermal Systems Compared With Hot-water Systems" classified geothermal systems into the following categories:

a. Chloride-carbonate
b. Chloride
c. Acid sulfate
d. Bicarbonate-sulfate

Hot water systems are those where chloride dominates and vapor dominated systems are those where chloride is low. Water can readily dissolve Cl (?) from rocks, but the transfer of Cl from the liquid phase to the vapor phase is very limited. The concentration of sulfate is high in vapor dominated systems because of the transfer of H_2S as a gas, and its subsequent oxidation to SO_4.

White and others (1971) model of a vapor dominated system may be applicable to an interpretation of subsurface geothermal conditions in the Waunita Hot Springs area.

CONCLUSIONS

The low chlorine, calcium and magnesium content of the Waunita Hot Springs waters points to a vapor dominated geothermal system at depth for if it were strictly a water dominated system, meteoric and magmatic waters would have supplied a much higher amount of these elements to the system.

Whether a potentially productive geothermal resevoir is present at depth in the Waunita Hot Springs area is dependent on an adequate geothermal gradient, sufficient permeability, an "open" fracture system for adequate recharge and other factors.

REFERENCES

White, D.E., Muffler, L.J.P. and Truesdell, A.H., (1971), Vapor-dominated hydrothermal systems compared with hot-water systems: Econ. Geol. v. 66, no. 1, pp. 75-97.

Table I. Elemental abundances in mg/l (ppm) pH, and conductivities of Gunnison Area waters.

	1 K^+	1 Ca^{2+}	1 SiO_2	2	3
SiO_2	-	135	135	95	18
Na	-	150	-	150	4.7
K	9.9	9.9	9.9	9.6	0.50
Ca	1.0	1.0	1.0	2.4	18
Mg	0.08	0.08	0.07	0.46	5.3
Mn	nd	nd	nd	nd	0.23
Zn	nd	nd	nd	nd	0.08
F	-	19	19	16	0.26
Cl	-	10	10	10	<10
pH*	7.8	-	-	7.5	6.3
Cond.**	850	-	-	850	170

1 K^+ 1 Ca^{2+} 1 SiO_2 2 3

	4	5	6	7 K^+	7 Ca^{2+}	7 SiO_2
SiO_2	14	15	15	-	18	18
Na	3.6	3.4	4.1	9.2	9.3	9.3
K	1.3	0.77	1.2	1.3	1.3	1.3
Ca	9.1	4.9	11	73	73	73
Mg	6.7	4.5	7.9	11	11	11
Mn	nd	nd	nd	nd	0.88	0.92
Zn	nd	nd	nd	nd	0.04	0.03
F	<.10	<.10	0.10	-	0.43	0.42
Cl	<10	<10	<10	<10	<10	<10
pH*	6.0	6.3	6.4	6.6	-	
Cond.**	130	90	80	220	-	-

* pH taken on 8/9/74

** Conductivity in umho/cm taken on 7/20/74

Table II. Elemental abundances in various hot water systems.

	Ouray Hot Springs 1	Amadee Spgs. Calif. 2	The Geysers Calif. 3 Vapor-DDM.	Carboli Italy 4 Hot H_2O
SiO_2	49	96	66	trace
Na	111	227	18	57
K	8.0	6.8	6	32
Ca	376	2.2	58	-
Mg	6.1	0.0	108	5.0
Mn	0.9	0.00	-	-
F	-	-	-	-
Cl	45	160	1.5	43
pH	6.8	8.5	7	-
SO_4	1030	266	766	137
temp °C		92	100	300

	Wairake, N.Z. Well 4 Hot H_2O	Wairake, N.Z. Well 5 Hot H2O	Yellowstone, Wy. Y-11 Hot H2O	Yellowstone, Wy. Norris Basin Vapor-DDM.
SiO2	386	191	-	529
Na	1130	230	105	439
K	146	17	13	74
Ca	26	12	28	5.8
Mg	0.1	1.7	0.5	0.2
Mn	-	-	-	-
F	6.2	3.7	-	4.9
Cl	1930	2.7	9.6	744
pH	16.2	3.7	8.5	38
SO4	35	11	74	7.5
temp °C	217	300	132	85

1) Ouray, Colorado, San Juan Mountains, White, 1967.
2) Lassen Co., Calif., a geothermal area, White, 1967.
3) Vapor-dominant water from a proven geothermal power area, from White et al, 1971.
4) Hot water dominant water from the Larderello geothermal area, White et al, 1971.
5) A hot water dominant water from the New Zealand geothermal fields, White et al, 1971.
6) A vapor-dominant water, from the New Zealand geothermal fields, White et al, 1971.
7) A hot water dominant water from Yellowstone, White et al, 1971.
8) A vapor-dominant water from Yellowstone, White et al, 1971.

CHAPTER IV
A HYDROGEOCHEMICAL COMPARISON OF THE WAUNITA HOT SPRINGS, HORTENSE, CASTLE ROCK and ANDERSON HOT SPRINGS

by

Frank Dellechaie
AMAX Exploration Inc.
Denver, Colorado

PURPOSE OF THIS REPORT

The Waunita Hot Spring area is located northeast of Gunnison, Colorado. An earlier memorandum indicated that the two hot springs exhibited some dry steam characteristics. This report endeavors to continue the discussion of the Waunita Hot Springs water and compare it to two thermal springs in the producing Geysers dry steam field, Lake County, California. The Waunita Hot Springs are also compared to the Hortense Hot Spring at Mt. Princeton.

INTRODUCTION

Thermal water samples were collected from the two hot springs at the Waunita Dude Ranch on April 12, 1975. The southern most spring has been used for space heating and bathing since the 1900's. The maximuim recorded temperature is 75°C (24°F) with a discharge of approximately 1000 gpm. The northern spring was used for bathing but the bath houses are now ruins and the waters are unused. The northern spring produces water at 70.5°C (21°F) with a flow of about 500 gpm. Both springs deposit small amounts of white, amorphous sulfate salts and both issue out of Dakota sandstone.

CHEMISTRY

The chemistry of the southern and northern Waunita Springs is almost identical as seen in Table 1. The pH is basic, fluroide concentrations are very high at 27 mg/1, and chloride concentrations are very low at 16 mg/1. Cl/SO and Cl/F ratios are well below unity. These thermal waters are described as follows:

Waunita: $SO_4<HCO_3<Cl$ $\quad$ $Na<K<Ca<Mg$

An analysis of Hortense Hot Spring, Mt. Princeton, Colorado, is listed for comparison in Table 1. It is a sulfate-bicarbonate-chloride water as seen below:

Hortense: $SO_4<HCO_3<Cl$ $\quad$ $Na<Ca<K<Mg$

Bicarbonate-sulfate and sulfate bicarbonate waters with low chloride concentrations are associated with the Geysers dry steam system. Castle Rock Hot Spring is intimately associated with Geysers steam production and an analysis of this spring is listed in Table 1. The Castle Rock Hot Spring water is described as follows:

Castle Rock: $HCO_3<SO_4<Cl$ $\quad$ $Na<Ca<K<Mg$

Table 1. Chemical analysis.

	Gunnison County, CO		Chaffee County, CO	Lake County, CA		
	Waunita Hot Spring (South)	Waunita Hot Spring (North)	Hortense Hot Spring	Castle Rock Hot Spring	Anderson Hot Spring	Geyser Steam Condensate
pH	8.70	8.19	9.60	7.70	6.40	8.01
Cl	15	16	8.8	8.2	1.4	2.2
F	22	27	16	0.6	0.4	<0.1
HCO_3	90	128	46	154	104	18
CO_3	18	0	16	0	0	0
SO_4	170	180	100	15	270	6
SiO_2	127	98	85	128	52	5
Na	170	170	100	70	35	0.1
K	9.4	9.0	4.0	2.9	6.7	0.1
Ca	6	9	15.0	16	9.1	<0.1
Mg	0.1	0.4	0.1	2	38	0.1
Li	0.2	0.2	0.1	<0.1	0.2	<0.1
B	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
NH_3	0.05	0.1	0.4	0.45	1.0	20
H2S	1.7	0.9	0	<0.5	4.1	2
TDS	635	644	394	404	689	60
T°C	75	70.5	85	58	52.5	74
Flow (gpm)	1000	500	50	5	10	--
$TSiO_2$°C	151	136	125	151	104	18
TNa/K°C	124	120	97.	100	274*	835*
TNa-K-Ca°C	160	155	75	60	45	7.4
Cl/SO_4	0.24	0.24	0.24	1.5	1.4	1.0
Cl/HCO_3	0.20	0.21	0.19	0.09	0.01	0.21
Cl/F	0.37	0.32	0.29	7.3	1.8	12
Cations mg/l	8.0	8.1	5.3	4.1	9.5	0.2
Anions mg/l	7.2	7.7	4.5	3.1	8.4	0.5

Does not reflect true subsurface temperature conditions.

Anderson Hot Spring also issues near the Geysers production area. It is somewhat acid and would be expected to liberate quantities of Ca and Mg as the waters rise to the surface. An analysis of Anderson Hot Springs is seen in Table 1. The major anions and cations are described as follows:

Anderson: $SO_4 < HCO_3 << Cl$ $\quad$ $Na < Ca < K < Mg$

A sample of fresh-clean steam condensate was collected from a leaking wellhead fitting at the Geysers. The well has been venting into a muffler since 8-74 when the leak was first noted. The major constitutes of the condensate are NH and HCO . The pH is basic. Note that small amounts of chloride (2.2 mg/l) are carried by this density steam, probably as an aerosol. The cations and anions are described as follows:

Geyser Condensate: $HCO_3 < SO_4 < Cl$ $\quad$ $Na = K = Mg < Ca$

The aforementioned waters beg a comparison. The concentrations of Cl, Na, K, Ca, B, NH_3, H_2S, SiO_2 and TDS in Hortense Hot Springs are very similar to these concentrations in Castle Rock Hot Spring. The ratios shown at the bottom of Table 1. for the Hortense Hot Springs are more similar to those given for the Waunita Hot Springs than to those for Castle Rock and Anderson Hot Springs. Of the two Geyser Springs, the Waunita Springs are most similar to Castle Rock Hot Springs in HCO_3, K, Li, B, Ca, Cl, SO_4 and TDS. The Waunita Springs are similar to both Anderson and Castle Rock Hot Springs in HCO_3, Cl and B. Table 2 and Figure 1 shows similarities between all springs mentioned thus far. In a gross sense, similarities do exist between the Waunita Springs and those thermal springs mentioned from the Geysers. Precise similarities do not exist.

SUBSURFACE TEMPERATURES

Hot springs associated with steam systems do not give accurate equilibrium temperatures for the following reasons:

1. Ions are left in the deep, old liquid on steam separation.

2. The very low ionic strength steam condenses as some shallow depth and re-equilibriates with ground water.

3. Maximum equilibrium temperatures can not exceed the original steam temperatures plus normal gradient of the area.

4. The volatiles in stream, NH_3 and H_2S, suffer much greater damage via cold water dilution than would the same volatile in hot water.

"Steam heated springs" are at best reflections of shallow conditions and subsurface temperatures should be in the vicinity of 100°C or below.

Table 2. The distribution of shared ions in Waunita, Hortense, Castle Rock, and Anderson Hot Springs.

Waunita H.S. Hortense H.S.	Waunita H.S. Castle Rock H.S.	Hortense H.S. Castle Rock H.S.	Waunita H.S. Anderson H.S.	Waunita, Hortense, Castle Rock, and Anderson Hot Springs
Cl	Cl	Cl	Cl	Cl
F	HCO_3	SiO_2	HCO_3	B
HCO_3	SiO_2	Na	SO_4	
SO_4	B	K	K	
Na		Ca	Ca	
Ca		NH_3	Li	
Mg		H_2S	B	
B		B	TDS	
Cl/F				
Cl/HCO_3				
Cl/SO_4				

Subsurface temperatures for Castle Rock and Anderson Hot Springs are generally below 100°C as seen in Table 1, and fit the aforementioned model. Hortense Hot Spring is very similar to Castle Rock Hot Spring with regard to subsurface temperature.

The Waunita Hot Springs exhibit excellent subsurface temperature correlation. Subsurface temperatures are probably in the range of 130-150°C. This correlation does not fit the shallow re-equilibriation model previously mentioned. However, the depth of re-equilibration is the controlling factor and the possibility of condensing steam at greater depths exists.

MINERAL EQUILIBRIA

The Gibbs Free Energies of saturated minerals for all springs discussed thus far are listed in Table 3. The most important constraints on whether or not a mineral is saturated are:

1. Water pH
2. Subsurface and surface water temperature
3. Presence of a specific mineral at depth
4. Ionic exchange of thermal water with mineral present.
5. Equilibria between ions dissolved in water.

Waunita, Hortense and Castle Rock Hot Springs contain similar numbers of saturated minerals. The same springs share only two minerals, talc and tremolite. Waunita and Castle Rock Hot Springs share seven minerals: tremolite, talc, magadite, quartz, kenyaite, chalcedony, and cristobalite. Hortense and Castle Rock Hot Springs have only talc and tremolite in common. Waunita and Hortense Hot Springs have tremolite, talc, diopside, and crysotile in common as seen in Figure 2 and Table 3.

The minerals listed for Hortense Hot Springs fit the minerals found in the Chalk Cliffs exceptionally well. Note the showing of zeolites and chlorite which have been described in the literature (Sharp, 1970).

The strong showing of metamorphic minerals in the water of the Waunita Hot Springs would indicate that the "reservoir" is in metamorphic rock probably at great depth.

CONCLUSIONS

The Waunita Hot Springs are similar to the two Geysers thermal springs as follows:

1. Qualitative anion relationships, SO_4, HCO_3, K, Li, B and TDS with Anderson Hot Spring
2. TDS, Cl, HCO_3, SiO_2 and B with Castle Rock Hot spring.
3. HCO_3, B and the Cl/CHO_3 ratio with Anderson and Castel Rock Hot Springs.

The Waunita Hot Springs exhibit dissimilarities with the Geysers Springs as follows:

1. PH, F, Na, NH_3 and the Cl/SO_4 and Cl/F ratios
2. Subsurface temperature correlation
3. Mineral suites at reservoir depth
4. Spring discharge

Correlation between the Waunita Hot Springs and the Geyser Springs is not exact; however, exact correlation would seem improbable. The correlation between Hortense Hot Spring and the Geyser Springs is more satisfactory.

The Waunita Springs prospect is interesting but somewhat ambiguous.

REFERENCES

Sharp, W. N., 1970, Extensive zeolitization associated with hot springs in central Colorado: U.S.G.S. Prof. Paper 700-B, pp. B14-B20.

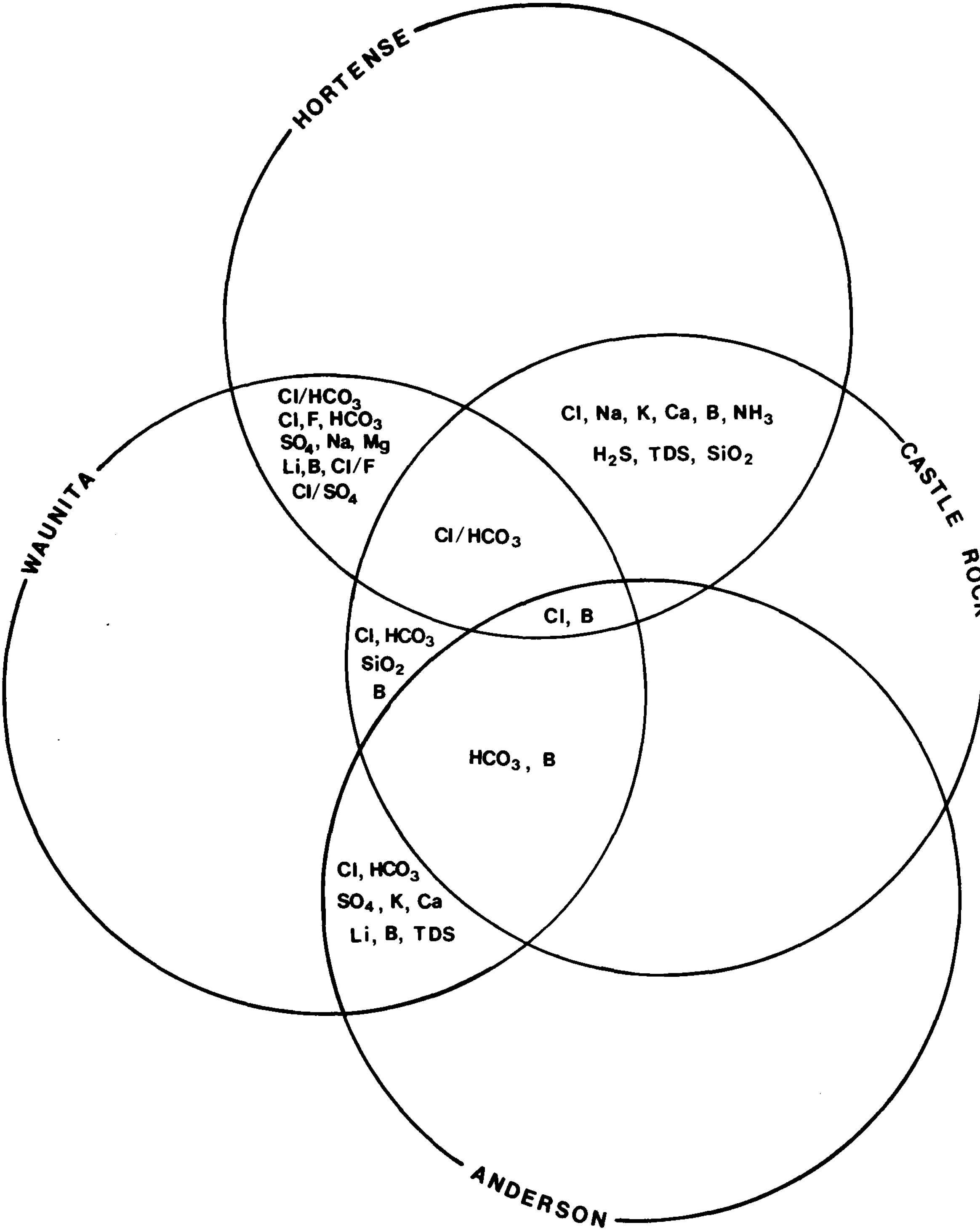


Figure 1. Distribution and congruence of various ions.

Fi

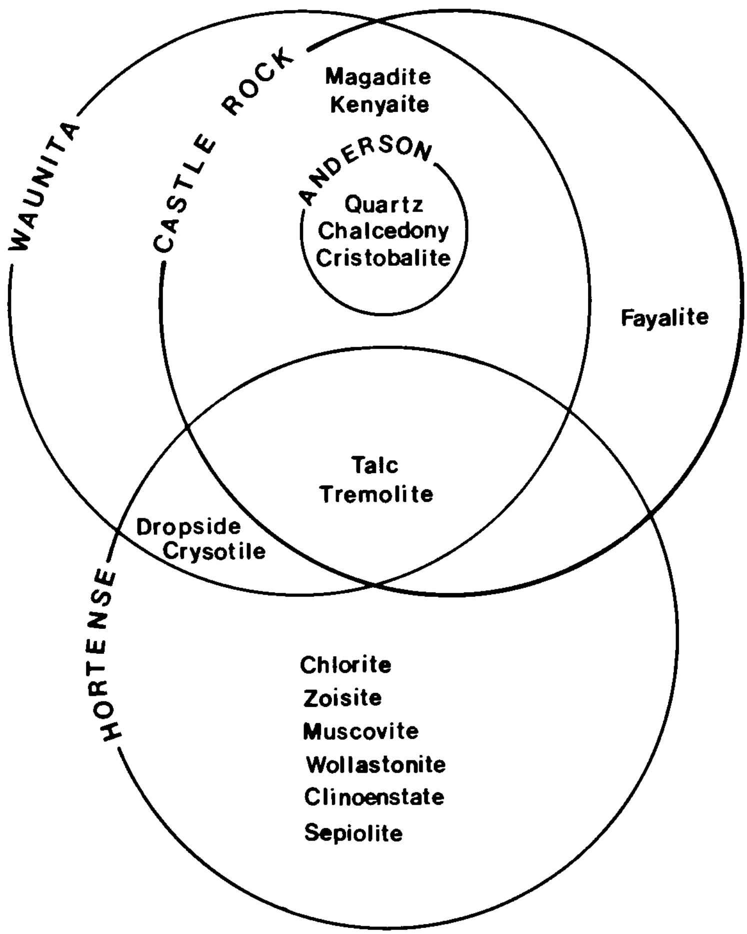


Figure 2. Distribution and congruence of various hypothetical minerals.

Table 3. Gibbs Free Energies of various hypothetical minerals in Mcal/mole. Positive values indicate saturation, 0 indicates equilibrium and negative values indicate undersaturation.

	Waunita Hot Spring South		Hortense Hot Spring North	
Carbonates	Calcite	0.5		
	Aragonite	0.4		
Silicates	Tremolite	24.0	Tremolite	35.1
	Talc	12.5	Chlorite	28.0
	Diopside	4.2	Talc	16.1
	Crysotile	3.5	Crysotile	8.6
	Magadite	1.6	Diopside	8.0
	Quartz	0.8	Zoisite	7.2
	Kenyaite	0.6	Muscovite	6.3
	Chalcedony	0.4	Wollastonite	1.3
	Cristobalite	0.1	Clinoenstatite	0.6
			Sepiolite	0.2
Zeolites			Phillipsite	11.5
			Prehnite	7.4
			Laumontite	5.3
TDS		635		394
pH		8.70		9.60

Castle Rock Hot Spring		Anderson Hot Spring		Geyser Steam Condensate	
Calcite	0.01				
Tremolite	12.5	Quartz	0.8	Talc	2.8
Talc	9.3	Chalcedony	0.3		
Fayalite	1.5	Cristobalite	0.0		
Quartz	1.3				
Magadite	1.1				
Chalcedony	0.8				
Kenyaite	0.6				
Cristobalite	0.5				
TDS	404		689		60
pH	7.70		6.4		8.1

CHAPTER V

PHASE I
GEOTHERMAL RESISTIVITY
RESOURCE EVALUATION SURVEY
WAUNITA HOT SPRINGS PROJECT
GUNNISON COUNTY, COLORADO

by

Henrichs GEOEXploration Company
Tucson, Arizona 85703

INTRODUCTION

The purpose of this reconnaissance geothermal resistivity survey was to help evaluate the geothermal resource potential of the Waunita Hot Springs area by locating and defining any significant resistivity lows which might be of sufficient extent and magnitude to be reflecting a possible geothermal reservoir.

Reference is made to the report and Preliminary Geologic Map by K. W. Nickerson & Associates on the Waunita Hot Springs Project, Chapter I.

CONCLUSIONS AND RECOMMENDATIONS

No strong electrical indications of a major geothermal reservoir were found in this survey. The most prominent anomaly found is a large elongate resistivity low trending northwesterly in the southeast portion of the area surveyed (Fig. 1). In contrast with the surroundings the GRI is only about 2.5 which is of borderline geothermal interest. And, the low can perhaps be explained by the basinal sedimentary structure with which it correlates.

However, this low cannot be completely ruled out as a geothermal target and if other data such as increased seismic noise or anomalous heat flow are seen to correlate, more work and subsequent drilling may be warranted. Additional electrical work could consist of several parallel dipole-dipole traverses across the dipole mapping low to give more detail on which to base drilling targets.

The only other resistivity low of possible geothermal significance is a narrow, northwesterly trending anomaly in Sections 10 and 15 which is probably related to a fault zone and appears to be restricted in depth extent. It is considered a poor geothermal target and further work is recommended if there are supporting and encouraging data.

INTERPRETATION

In general, rather high apparent resistivities were encountered on the dipole mapping survey although several lower resistivity areas of possible interest were defined. The most prominent low is a zone about 2.5 miles long by one mile wide elongated in a northwesterly direction, centered in the SE quarter of Section 13, T.49N., R.4E. (Fig. 1). This low would geologically appear to relate to a synclinal or basinal structure in the Mesozoic

WAUNITA HOT SPRINGS, COLORADO

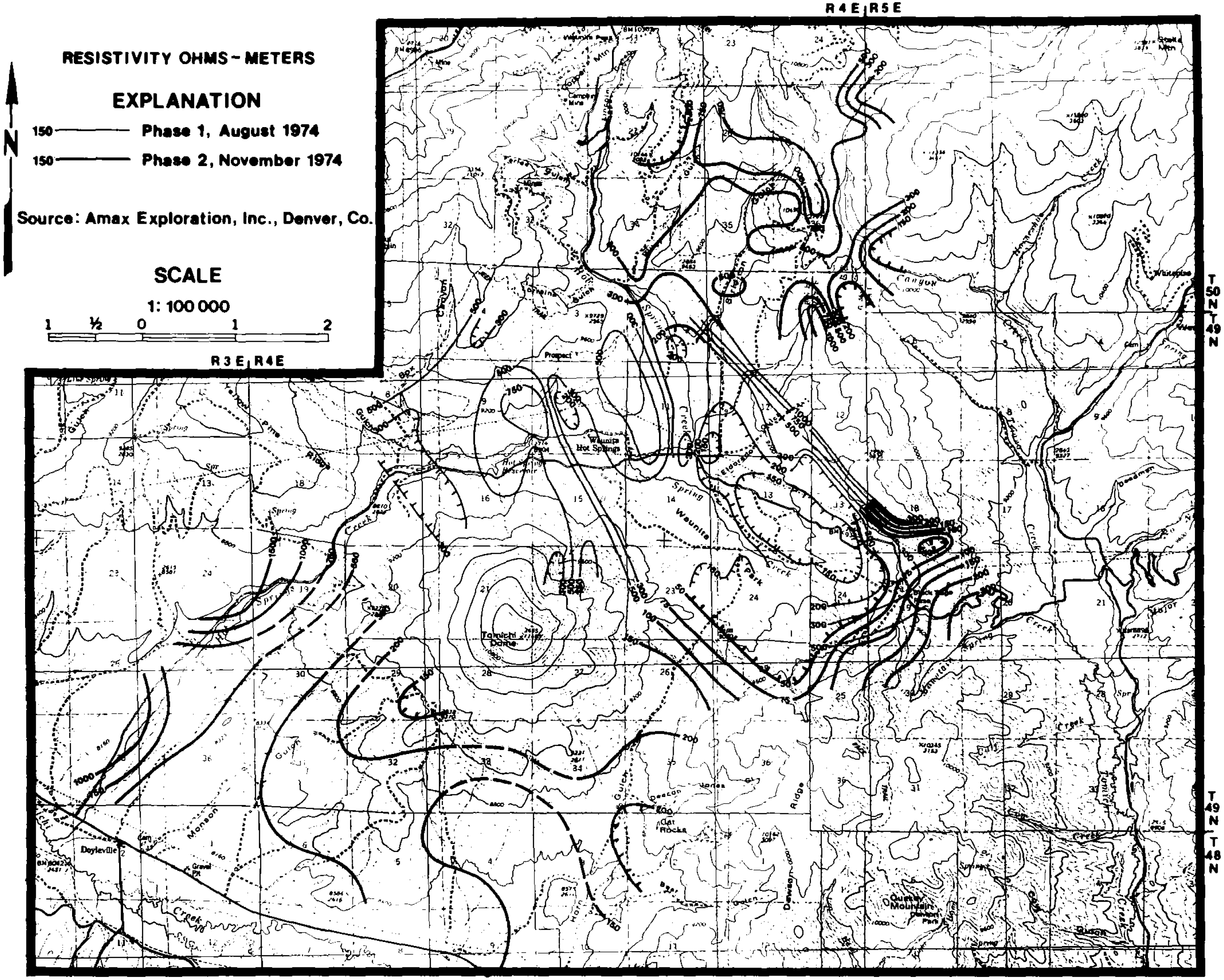


Figure 1. Resistivity dipole mapping survey.

sedimentary section and is flanked on the NE and SE by nearly vertical upturned beds resting on the Precambrian basement complex. This low has a contrast factor (GRI) of about 2.5 with apparently similar sediments directly to the west. A GRI of 2.5 (See Appendix I) is not as high as generally expected over a geothermal reservoir but there can be many mitigating factors such as the geometry of the source and its depth of burial. Therefore, a Schlumberger expander was run approximately centered on the axis of the dipole mapping low to add information in the vertical component.

The expander shows a rather clear-cut two layer situation yielding an electrical surface layer about 2600 feet thick having an average resistivity of 50 ohm-meters which rests on material having a very high resistivity, say greater than 2000 ohm-meters. This is quite compatible with the estimated 2000 to 2600 feet of Mesozoic sediments unconformably resting on the Precambrian basement complex as stated Chapter I. The basinal structure apparently present in the vicinity of the anomaly could well be expected to have the thickest section of sediments in the area and this may be the cause of the resistivity low, i.e,, the low is simply reflecting the thicker zones of the relatively more conductive Mesozoic sediments. However, as further described below, there are also significant lateral resistivity variations within the sediments.

The east end of the dipole-dipole traverse (Fig. 2) crosses the NW end of the main low and shows good correlation. However, the average resistivity of the upper layer appears to be roughly 100 ohm-meters - twice as high as seen on the Schlumberger expander centered about one half mile to the SE. This lateral variation in upper layer resistivity can perhaps be explained in several possible ways: A facies change in the sediments, e.g., they become more clayey and therefore more conductive to the SE. Or, perhaps the ground water permeating the sediments becomes more saline towards the SE, a not uncommon occurrence in basinal structures. A more interesting but less likely possibility is that the lower resistivities to the SE could be caused by increased geothermal activity.

Another dipole mapping low of possible signficance is noted in Sections 10 and 15, about 2000 to 3000 feet wide and elongated in a NNW direction (Fig. 1). The dipole-dipole traverse (Fig. 2) verifies the dipole mapping low here, but suggests that the cause is a restricted size near surface feature. Perhaps the increased faulting mapped in the area is responsible for the lower resistivities. Also, this low zone is quite near hot spring activity which may have increased the local ground water conductivity by addition of electrolytes.

Another minor dipole mapping low is noted on the west edge of the area surveyed, mainly in Sections 8 and 17. This low is likely due to an increased sedimentary thickness plus the effects of lesser current penetration as the sending dipole is neared.

The Precambrian-sedimentary contact shows very well in the dipole mapping as a linear high gradient zone trending NW along the northeastern and southeastern margins of the area surveyed. The Precambrian rocks are considerably higher in resistivity than the sediments as also indicated by the Schlumberger expander.

WAUNITA HOT SPRINGS, COLORADO

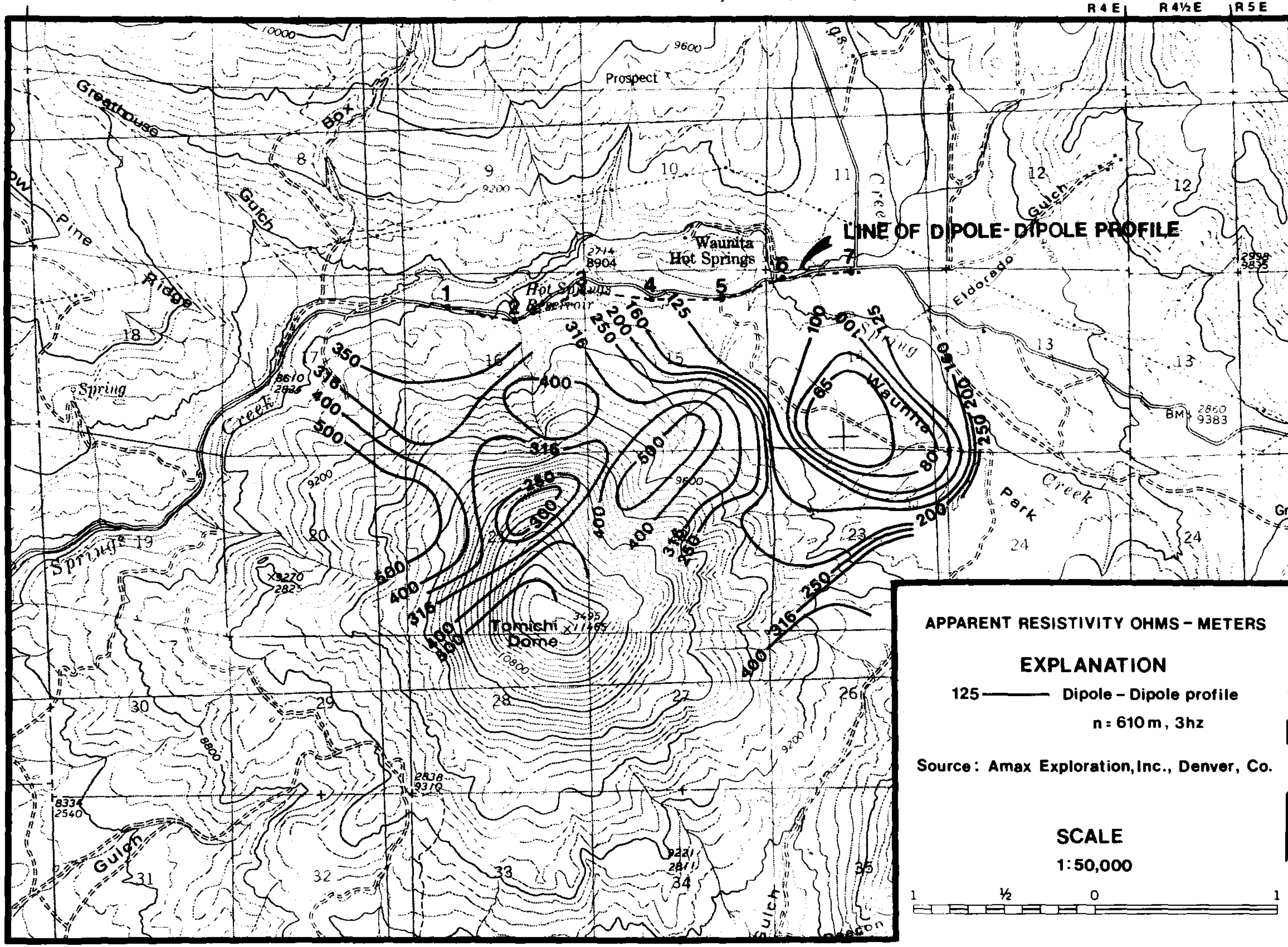


Figure 2. Resistivity dipole-dipole survey.

Another fairly pronounced linear high gradient zone is noted between the NW corner of Section 10 and the SE corner of Section 15 with higher resistivity material to the west. There is no obvious geologic correlation although several strong fracture zones seem to have a similar trend in the vicinity.

The total conductance map shows essentially just the reverse or reciprocal of the total resistivity map and adds little to the interpretation in this area. The conductance map does show that the minor resistivity low on the west edge of the area surveyed is mainly due to being near the sending dipole since there is no correlating conductance high.

PROCEDURE

A dipole mapping sending dipole, 7000 feet long, was located about one mile west of the area of interest. A total of 103 receiving stations were read, all with an orthogonal pair of 300 foot dipoles to cover the 3 by 4 mile area of interest. Stations were read along roads and trails and other points of relative accessibility and were located on the pertinent U.S.G.S. topographic quadrangles. Sending currents ranged from 6 to 8 amperes. A filtered frequency of 3.0 hz was used after spot checking that inductive coupling effects were relatively insignificant due to the high resistivities involved.

The Schlumberger expander used a sending dipole length ranging from 500 feet to 2500 feet with a 100 foot receiving dipole and from 2500 feet to 15,000 feet with a 500 foot receiving dipole. Sending currents ranged from 2 to 6 amperes with a 0.05 hz sending frequency read as a DC coupled, averaged signal by the receiver.

The dipole-dipole (Fig. 2) traverse was run with 200 feet long dipoles and sending - receiving separations ranging from one to nine dipole lengths. A sending current of 5 amperes and a 3.0 hz sending frequency were used.

All data was obtained with a GEOEX Mark 4 induced polarization-resistivity system.

APPENDIX I: RESISTIVITY THEORY

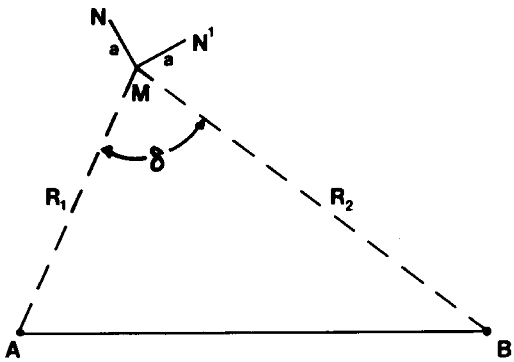
A large amount of electrical current may be made to flow in the earth between a pair of grounded contacts, i.e., a dipole. The particular flow pattern that the current assumes is depended primarily upon the resistivity structure of the earth in the vicinity of the dipole. If potential measurements are made at various points around the current dipole, the resulting data will be indicative of the current flow pattern, and hence, to some extent, the resistivity structure of the earth in that general vicinity.

The resistivity of a rock is dependent primarily upon four things: the rock type, the water content, the salinity of the water, and the temperature of the water. Of these, the water content and salinity are normally the most important factors determining resistivity. In a geothermal area, the temperature can also affect the measured resistivities to a large degree.

It has been proposed by Dr. Keller that a quantity called the Geothermal Resistivity Index (GRI) is useful in estimating the geothermal potential of a reservoir. The GRI is the ratio of resistivity of the country rock to the resistivity of the reservoir. If it is assumed that the salinity of the pore water is the same in both the host rock and the reservoir, then the GRI is a good indicator of the temperature of the reservoir. It is commonly quoted that a GRI of 5 is a good indication of a high enough temperature to give the reservoir a geothermal potential.

APPENDIX II: DIPOLE MAPPING SURVEYS

The electrode layout for a dipole mapping survey is shown in the following figure.



Here AB is the current dipole, through which current I flows, and MN and MN' are the two potential dipoles, of length "a," which are usually, but not necessarily, oriented perpendicularly to each other. The length AB is usually much greater than "a." With this setup, the receiving dipoles can easily be moved to several locations in the vicinity of the current dipole so that the resisivity variations can be mapped.

Two orthogonal potential dipoles are used in order that the total electric field may be readily calculated. Because the current flow pattern around the sending dipole is directionally dependent, a single potential measurement would only measure one component of the current flow. However, when two orthogonal measurements are taken, they can be added vectorially and the total field obtained.

The total field resisivity at any point is computed using the formula:

$$P_T = \frac{2\pi R_1 E_T}{[1+(R_1/R_2)^4 - 2(R_1/R_2)^2 \cos\delta]^{1/2} I}$$

where

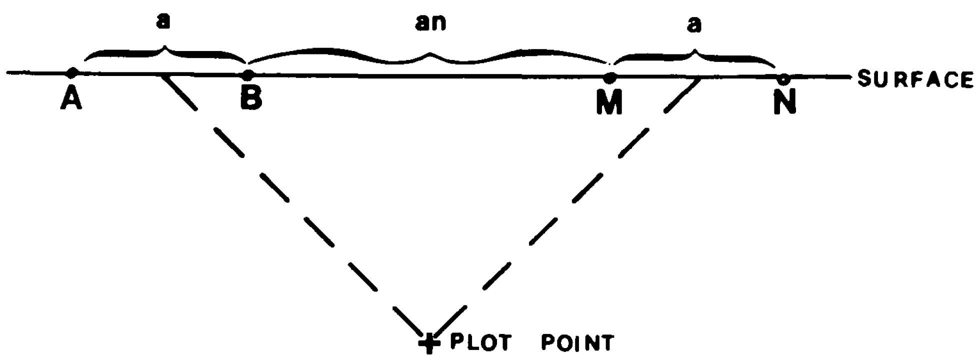
$$E_T \simeq \frac{\sqrt{V^2{}_{MN} + V^2{}_{MN^1}}}{a}$$

An apparent conductance is also computed, using the formula:

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

The apparent resistivity is calculated on the assumption that current flows radially away from the electrode in a homogenous half space. However, in many geothermal areas, it is often more informative to compute an apparent conductance based on the assumption of cylindrical spreading of current in a conductive plate above a resistive basement. For current spreading in a plate, the electric field depends on the ratio of plate thickness to resistivity. It is common practice in geothermal surveys to reduce the data according to both models.

APPENDIX III: DIPOLE-DIPOLE SURVEYS



The current (AB) and potential (MN) dipoles are of the same length "a" and moved relative to each other in a collinear manner in integral increments (usually n=1,2,3,4,5 and 6) of the dipole length. Data is reduced according to the formula:

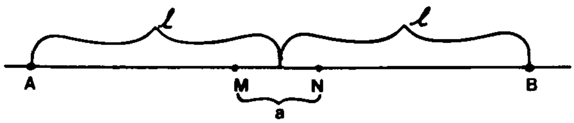
$$P_a = \pi \frac{Van\ (n + 1)\ (n + 2)}{I}$$

where V is the voltage read at the potential dipole and I is the current applied at the sending dipole. It is displayed in pseudo-section with each particular resistivity reading plotted at a point on the section where lines projecting 45 degrees from the center of both current and potential dipoles intersect.

The dipole-dipole array is probably the most often used array in electrical surveys in recent times. In most cases, it is very efficient to use in the field. Also, interpretational aids are readily available and easy to use. The reduction of dipole-dipole data is made on the assumption of current flow in a half space.

APPENDIX IV: SCHLUMBERGER SOUNDINGS

The electrode layout for a Schlumberger sounding (expander) is shown in the following figure:



The length of MN (a) is kept much smaller than the length of AB (2 l) so that, approximately, the gradient of the potential across MN is measured. In making a sounding, MN is held constant and B is increased which causes the overall current distribution of flow through a larger volume, thereby sampling a greater depth.

Should the potential across MN become too small to obtain an accurate reading, as AB is increased, the length of MN is increased providing it still remains much smaller than AB.

The apparent resistivity is reduced according to the formula:

$$P_a = \frac{\pi l^2 V}{a I}$$

where V is the potential across MN and I is the current applied at the sending dipole.

The resultant apparent resistivities are plotted as a "sounding" curve on double logarithmic graph paper and compared with similarly plotted type curves to obtain an idea of the vertical resistivity distribution. In general, Schlumberger soundings are best utilized in areas where a reasonable approximation to uniform horizontal layering is involved.

PHASE II
GEOTHERMAL RESISTIVITY
RESOURCE EVALUATION SURVEY
WAUNITA HOT SPRINGS PROJECT
GUNNISON COUNTY, COLORADO

INTRODUCTION

The purpose of the Phase II coverage was primarily to extend the initial resistivity dipole mapping coverage northeastward to help verify and assess the significance of the seismic groundnoise anomaly located by Senturion Sciences, Inc. in the Stridiron Creek vicinity. Secondarily, coverage was extended southeastward to better define and surround the large resistivity low found in the initial survey.

During the course of the survey, it was decided to broaden some remaining reconnaissance coverage, as seasonal field conditions would allow, mainly around Tomichi Dome itself. Gaining more coverage surrounding this geologic structure of possible geothermal energy significance, was considered at least desirable. Also, a very weak and indefinite indication noted in the earlier coverage near the Dome, required additional coverage to be interpretable.

The ultimate overall objective of all the work was, of course, to hopefully develop a better understanding of the geothermal resource potential in the area and suggest areas justifying further study and/or testing by drilling.

CONCLUSIONS AND RECOMMENDATIONS

The Stridiron Creek area of interest shows no well defined resistivity low correlating with the seismic groundnoise anomaly and in general the resistivity indications were rather discouraging. Based soley on the resistivity dipole mapping results, no further electrical work is recommended in the Stridiron Creek area at this time. On the other hand, the negative nature of the dipole mapping results are not sufficiently conclusive to completely rule out some consideration of further testing of the area based on the Senturion seismic groundnoise results particularly if the seismic results are felt to be encouraging enough alone, or if the project is continued based on the more encouraging electrical data obtained elsewhere.

In the area of the large resistivity low found in the Phase I coverage, the Phase II dipole mapping coverage extends the size of this low and increases its complexity somewhat, but does not appreciably modify the original interpretation although there is perhaps a better contrast factor (GRI) of about 6:1, based on the new data.

The dipole mapping results over the main low are not categorical and can be explained by several interpretations not involving a conductive geothermal cell. However, the anomalous zone is large enough and strong enough to possibly be of geothermal energy significance if caused by a geothermal cell. Therefore it is recommended that consideration be given to further study of this feature by some more direct means such as measurement of the heat flow and temperature gradient in several shallow drill holes to determine if any anomalous thermal correlation is present.

Two sites in the main low are suggested for primary thermal testing consideration: near Phase II Station 71 and the vicinity of Phase II Stations 84 and 91. Some consideration could also be given to thermally testing the north lobe of the main low where it correlates with a portion of the Senturion Sciences, Inc. zone of anomalous "seismic activity" along Hot Springs Creek near the center of Section 2, T.49N., R.4E. Also, the resistivity low directly west of Waunita Hot Springs in Sections 10 and 15, T.49N. R4E., could be thermally tested as part of an overall program, for correlation purposes and because of its proximity to obvious anomalous thermal activity.

Additional and somewhat more detailed dipole mapping is perhaps warranted around and over Tomichi Dome to determine if the present low resistivity trends, which show some seismic groundnoise correlation, develop into a closure worthy of additionaly study. Or, the Dome could be tested thermally based only on the existing evidence with the rationale of an overall thermal program as mentioned above.

INTERPRETATION

No well defined total resistivity low correlated with the Stridiron Creek seismic groundnoise anomaly in Section 35, T.50N., R.4E. A minor resistivity low lobe having about a 2 to 1 contrast does show some correlation with the "mean frequency of the integrated power" closure in the NE quadrant of Section 35. However, the "integrated power" closure seems to correlate more with a minor NE trending resistivity high, downgrading the possible significance of the minor resistivity low. Further, the absolute resistivity level in the Stridiron Creek area is quite high, generally above 300 ohm-meters, which in itself is somewhat discouraging based on correlation with other geothermal studies. However, not enough is known about the electrical expression of geothermal cells to know just how important the absolute resistivity level is.

The additional coverage on the prominent resistivity low centered in Section 13, T.49N., R.4E., found in the initial survey, extends the low further south and west and gives it a more complex appearance (Fig. 1). The interpretation of this feature has not been appreciably changed based on the new data, however. The apparent correlation of this low with a synclinal or basinal structure in the Mesozoic sediments in even more striking than before when the resistivity is overlayed on the K. W. Nickerson & Associates Preliminary Geologic Map.

The southwest margin of this low is rather well defined geophysically but its geologic cause is not obvious - being essentially entirely within the Mesozoic sediments. This is perhaps a factor tending to support a geothermal cause for the low and the Phase II data indicate a moderately favorable 6:1 contrast (a GRI of 6, see Phase I report) considering only the area of exposed Mesozoic sediments. To consider a contrast relative to an area expanded to include the Precambrian rocks, would be misleadingly high in that the Precambrian rocks tend to be higher in absolute resistivity than the Mesozoic rocks.

There are other plausible interpretations of the low as were discussed in the Phase I report, e.g., the sediments become more clayey in the area of the low, or, a more saline groundwater permeates the sediments in the vicinity of the low. And, as discussed in the Phase I report, a simple increase in thickness of the sedimentary section can, to a large degree, explain the low and is very likely the cause of at least some, if not most, of the contrast in that there is considerable evidence of a correlating basinal structure being present.

The Crookton Thrust Fault is well reflected in the data and forms the southeast margin of the low. The resistivity gradient is quite gentle across the thrust - likely reflecting the thickening wedge of Precambrian rocks overlying the more conductive sediments. The northeast margin of the low is also a sediment-Precambrian contact but it is much more abrupt, as is best seen in the Phase I data. Apparently this is a steep, more normal contact based on the resistivity evidence.

The north lobe of the main low correlates with a synclinal structure mapped in the Mesozoic rocks along Hot Springs Creek. It also correlates with a portion of a zone of "seismic activity" near the center of Section 2, T49N, R4E found by Senturion Sciences, Inc. and could therefore have some increased significance.

Several stations on the east margin of the Stridiron Creek area are appreciably lower in resistivity. They are outside of the geologically mapped area and their significance is unknown although a Tertiary monzonite dike appears to project northerly into this general area and could somehow be related.

Some widespread data was obtained around the south half of Tomichi Dome. Due to adverse accessibility factors, it was not practical to obtain data within about one mile of the peak so this area has not been completely prospected. A broad appearing zone of lower resistivity seems to be developing towards the Dome on a NE trend through Sections 29, 31 and 32, T49N, R4E and a poorly defined NW trend through Sections 34, T49N, R4E and 2 and 3, T48N, R4E. (Fig. 1). This low zone correlates in part with the Tertiary tuff which surrounds the inner Dome intrusive material and, as a general rule, tuffs are relatively conductive and could therefore be the sole cause of the low zone. The existing coverage show this low to have only about a 2.5 or 3:1 contrast factor so it is not a "strong" anomaly in the customary geothermal potential sense considered to date although conceivably it could be reflecting a deeply buried strong contrast feature of some interest.

In addition, this area south of the Dome is a zone of secondary interest in the seismic groundnoise survey which indicates a possibly anomalous noise source at depth. The limited resistivity data available is also compatible with an anomalous conductor at depth and therefore this area can not be ruled out completely at this stage.

About three miles west of Tomichi Dome, the resistivity shows a marked increase along a NE trend (Fig. 1). This trend correlates well with a window of Precambrian rocks and the Dakota-Benton formation contrast generally along the lower reaches of Hot Springs Creek.

For the most part, the total conductance data shows little variance from the total resistivity data except for the normal approximate reciprocal relation between the two parameters. The total conductance does reflect the conductive zone south of Tomichi Dome rather well and on an absolute amplitude basis it suggests a somewhat stronger anomaly than implied by the total resistivity data.

PROCEDURES

As was used during the Phase I dipole mapping survey, a 7000 foot sending dipole was used. The dipole was set up between the Stridiron Creek area of interest and the main low for logistical reasons and to expedite the survey of both areas by using the same dipole for each area. The Phase II dipole is about 4.5 miles east of the Phase I dipole and therefore the current distribution is considerably different - not allowing the two sets of data to be tied together quantitatively. Schematically, and interpretively, however, the two dipole mapping surveys have been tied together on each of the two composite plans presented with this report.

A total of 132 receiving stations were occupied, all with an orthogonal pair of 300 or 500 foot dipoles, to cover the several areas of interest. Sending currents ranged from 2 to 8 amperes and readings were made on a precisely filtered frequency of either 0.1 or 0.3 hz to essentially eliminate any inductive coupling effects. Equipment used was a GEOEX Mark 4 induced polarization-resistivity system. Please refer to the Phase I report for additional technical details.

CHAPTER VI
THE GEOPHYSICAL ENVIRONMENT AROUND WAUNITA HOT SPRINGS

by

Arthur L. Lange
AMAX Exploration, Inc.

RESISTIVITY

On the basis of two resistivity surveys, utilizing 7000-foot sending dipoles and 300- or 500-foot orthogonal dipole pairs, Heinrichs Geoexploration Company mapped a resistivity low zone 7 x 3.5 km extending NW-SE between Waunita Hot Springs and Black Sage Pass (Fig. 1, Chapter V). Resistivities in this zone ranged between 33 and 300 ohm meter. The lowest readings occurred in synclinal Mesozoic sediments between 2 and 3 km west of Black Sage Pass. A Schlumberger expander across the feature provided a two-layer interpretation of a 50 ohm (860 m) unit overlying a 2000 ohm basement. Heinrichs ascribes the condition to Mesozoic sediments resting unconformably upon precambrian crystalline rocks.

Another resistivity low is suggested underneath Tomichi Dome by the contour pattern; however, coverage was lacking beneath the Dome.

GROUNDNOISE AND MICROEARTHQUAKE

Senturion Sciences identified three groundnoise "anomalies" based on the overlap of high integrated power and high frequency contours, determined from two surveys, three years apart. The principal anomaly lies 3000 m northeast of Waunita resort in Sec. 7 and 18 T.40 N. R.4 E. and is associated with faulted, altered Paleozoic sediments. A center of microearthquake activity, mapped in 1971 (?), occurs between the resort and the groundnoise anomaly, but neither are associated with substantial resistivity lows.

Additional Senturion "anomalous zones" were found on the margins of their surveys; viz, 4.5 km northwest of the Dome and 5 km south-southwest. A zone of high integrated power but median mean frequency is suggested on the south flank of the Dome, but adequate coverage on the eminence itself was not obtained.

The groundnoise anomalies described should be viewed with some skepticism, because no evident base station was used for either of the surveys to assure that the noise levels did not change from day to day.

The presence of a large number of microearthquakes near the Springs (exact figure not provided) provides the strongest evidence that fracture permeability may be present to admit the possibility of a geothermal reservoir.

ERTS FEATURES

A prominent lineament can be traced from Animas Valley, New Mexico, northward to its junction with the Rio Grande rift at Mt. Princeton Hot

Springs, Colorado. Four volcanic features domes align themselves on this rift:

Creede Caldera, Cochetepa Dome, Tominchi Dome, and
Garfield Caldera.

A second linear extends northwestward intersecting the first near Waunita and Flat Top, an intrusive feature northeast of Gunnison.

GRAVITY AND MAGNETICS

The USGS Colorado Bouguer Gravity Map (1972) (Fig. 1) shows Waunita Hot Springs lying on the intersection of two gravity linear features, one extending NW-SE through the Cement Creek Hot Springs area and the other NE-SW through Cebolla Hot Springs at Powderhorn. Similar trends appear also in the magnetic map (Fig. 2). In addition, a North-South magnetic depression culminates in a minimum at Waunita.

CONCLUSION

Magnetics, gravity and ERTS photography all show Waunita Hot Springs to lie near the intersection of structural lineaments. This confluence is corroborated by the presence of microearthquake activity at the site. Groundnoise response, if reliable, would reinforce the pattern. The resistivity results provided, however, do not indicate a substantial reservoir, or have not penetrated adequately. Tellurics, MT and EM work, particularly if extended over Tomichi Dome, is needed to provide the necessary evidence of geothermal potential.

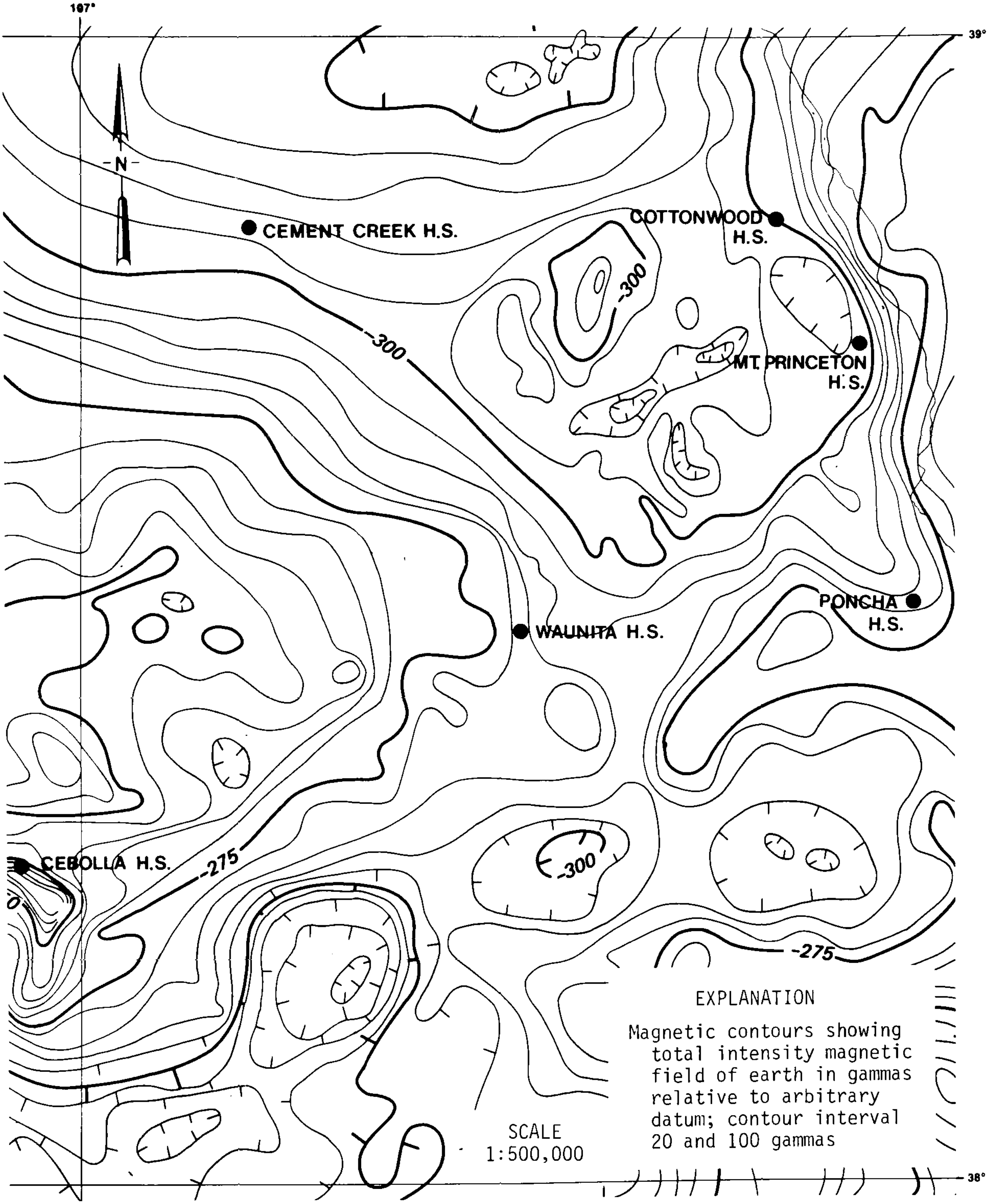


Figure 1. Bouguer gravity map (from Behrendt and Bajwa, 1974).

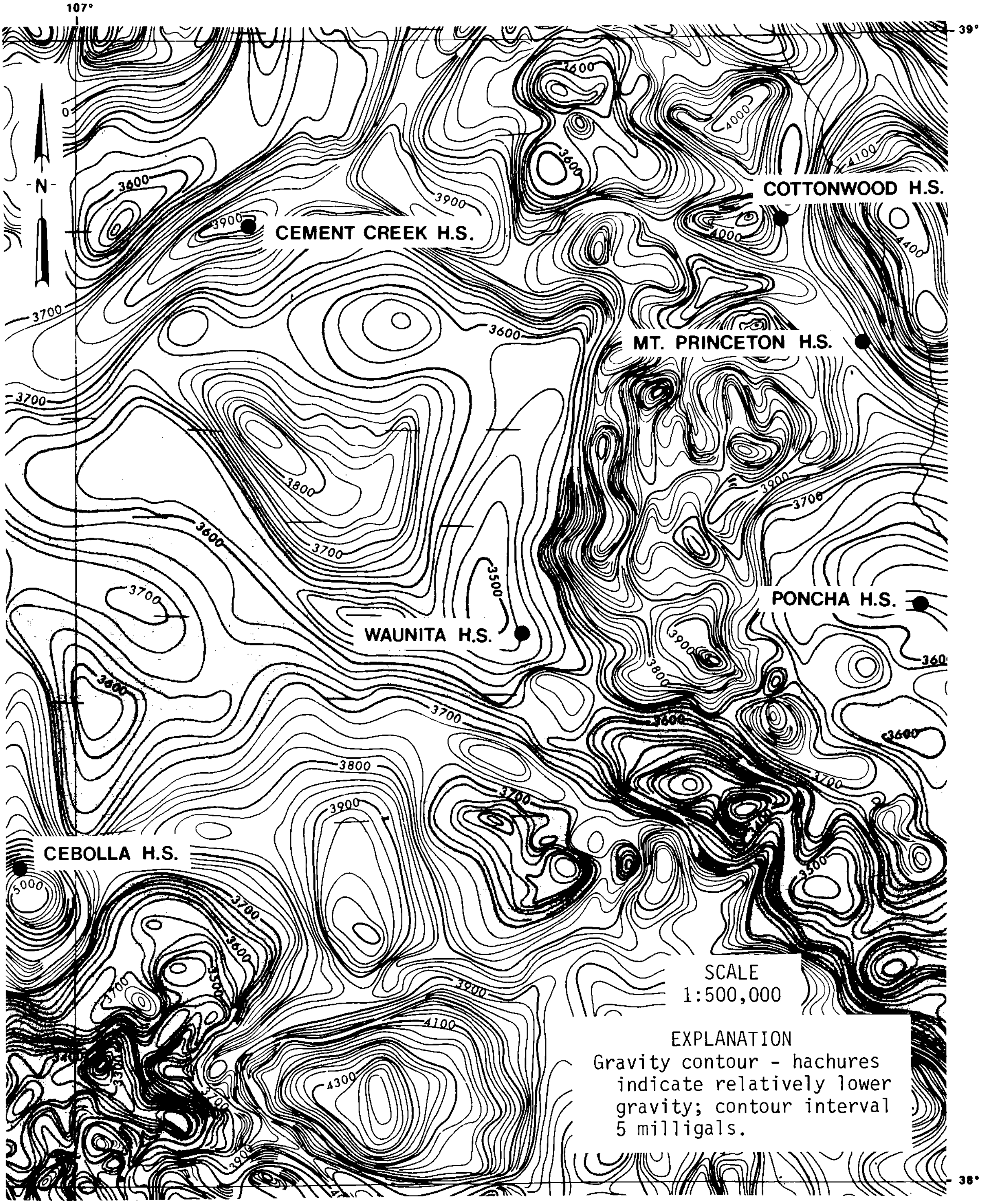


Figure 2. Aeromagnetic map (from Zietz and Kirby, 1972).

CHAPTER VII
TEMPERATURE, HEAT FLOW MAPS, AND TEMPERATURE GRADIENT HOLES

by

Ted G. Zacharakis
Colorado Geological Survey

Enclosed with the material supplied by AMAX Exploration, Inc. were four heat flow and temperature maps of the Waunita Hot Springs area that were not discussed. For the edification of the reader, these maps are presented (Figs. 1-4) with a brief explanation. No attempt is made to interpret the data presented on the four maps.

Figure 1. Heat Flow map of the Waunita Hot Springs Area in Mcal/cm2/sec. (1 HFU = 41.84 mW/m^2). As shown, the heat flow ranges from 11 HFU's in the vicinity of the hot springs to 2 HFU's approximately 1 1/2 miles from the Hot Spring area.

Figure 2. Contour map showing the depth, in kilometers, at which a 200°C temperature is obtained. As is indicated, the shallowest depth, 1 Km, at which this temperature is obtained is in the vicinity of the hot springs. It should be noted that as you move out approximately 2 miles west from the hot springs area, the depth required to obtain 200°C increases to approximately 10 kilometers.

Figure 3. Map showing temperatures in °C at a depth of 30 meters. The map shows a temperature of 25°C at the hot spring area and decreases to approximately 6.5°C, 1 1/2 miles to the west and 8.0°C, 1 1/2 miles to the east.

Figure 4. Map showing temperatures in °C at a depth of 100 meters. Temperatures of 50°C are indicated in the vicinity of the hot springs, decreasing to approximately 10°C at a distance of 1 1/2 miles.

WAUNITA HOT SPRINGS, COLORADO

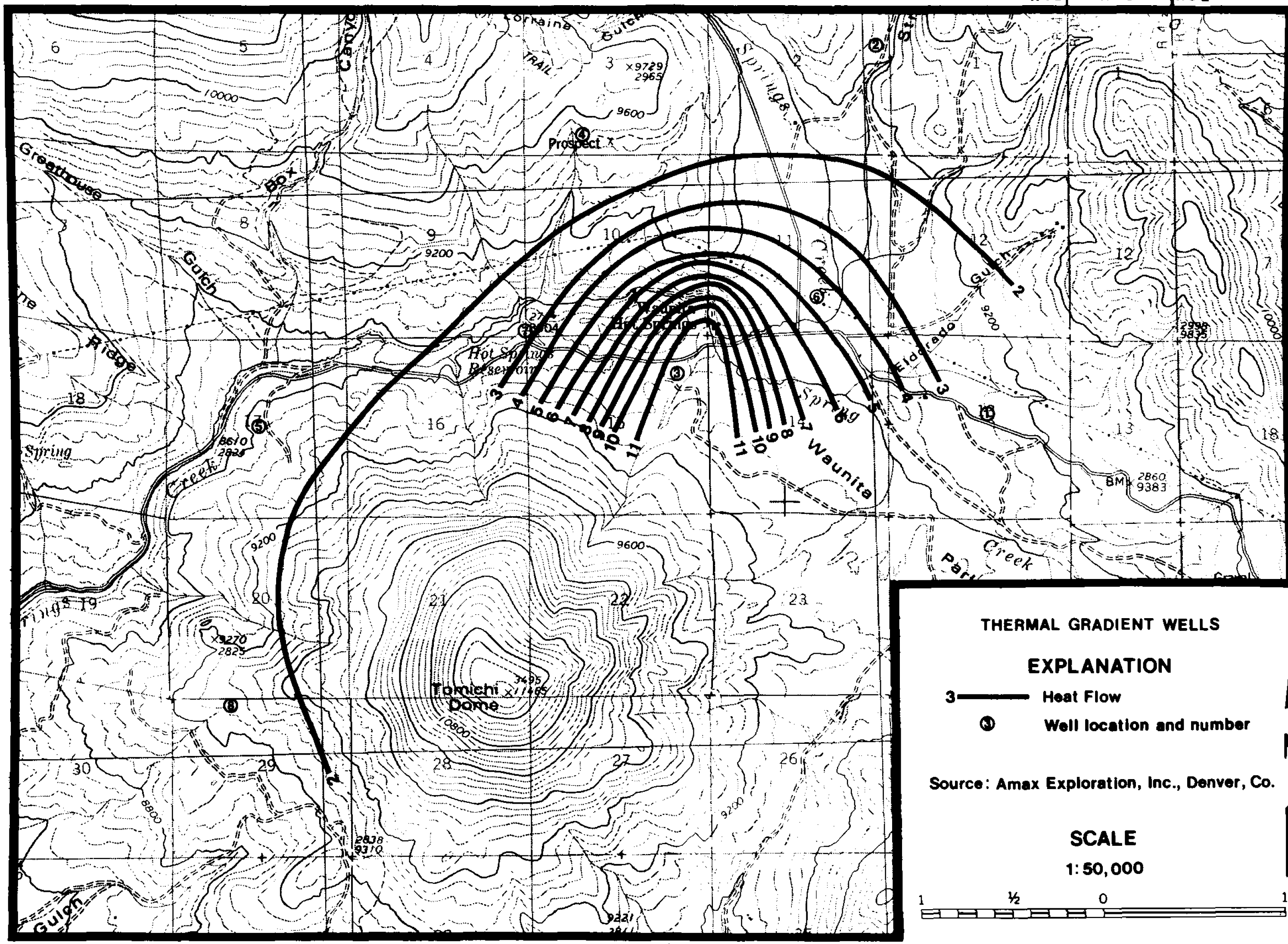


Figure 1. Heat flow map.

WAUNITA HOT SPRINGS, COLORADO

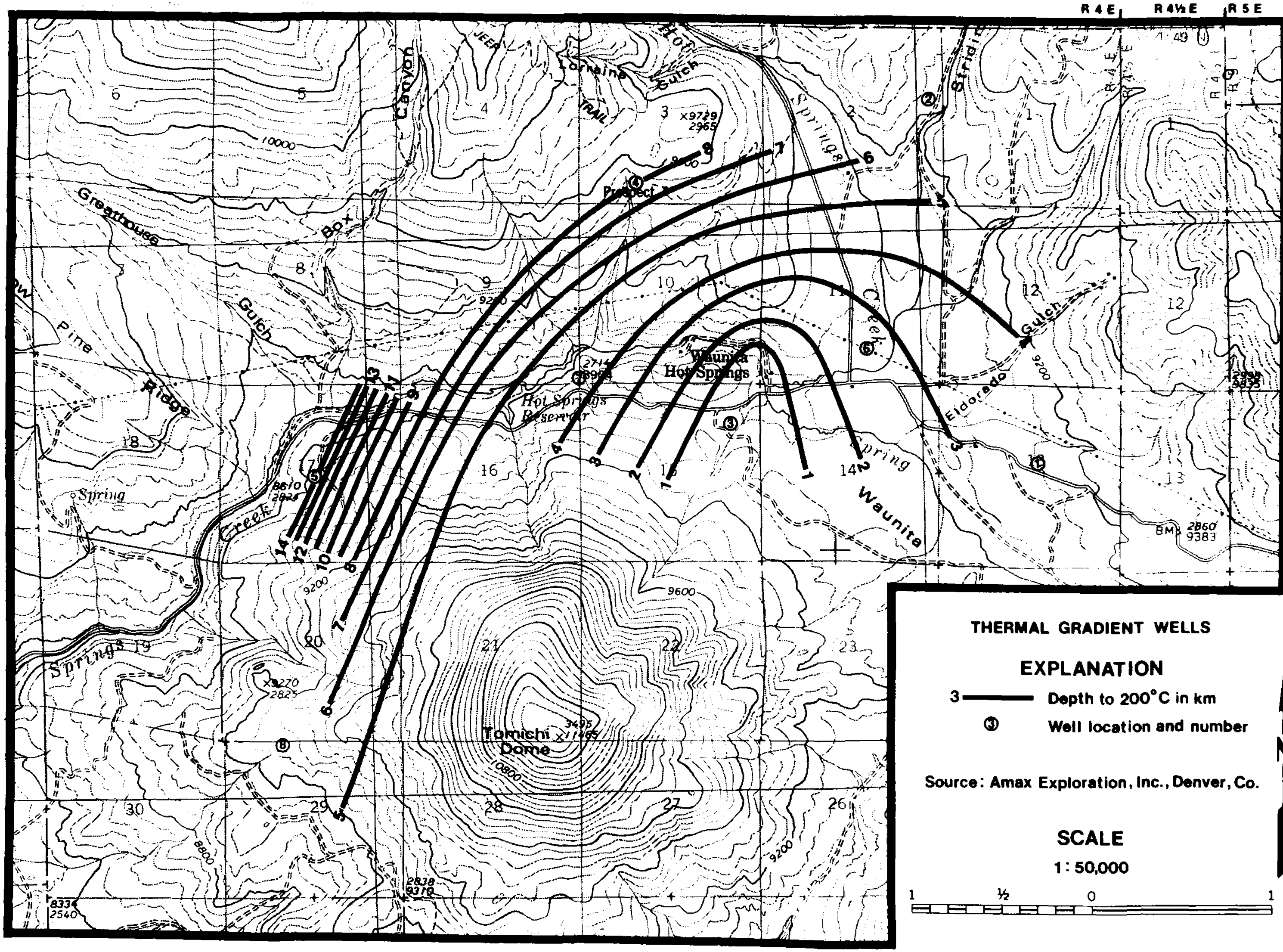


Figure 2. Depth map in km for 200° C.

WAUNITA HOT SPRINGS, COLORADO

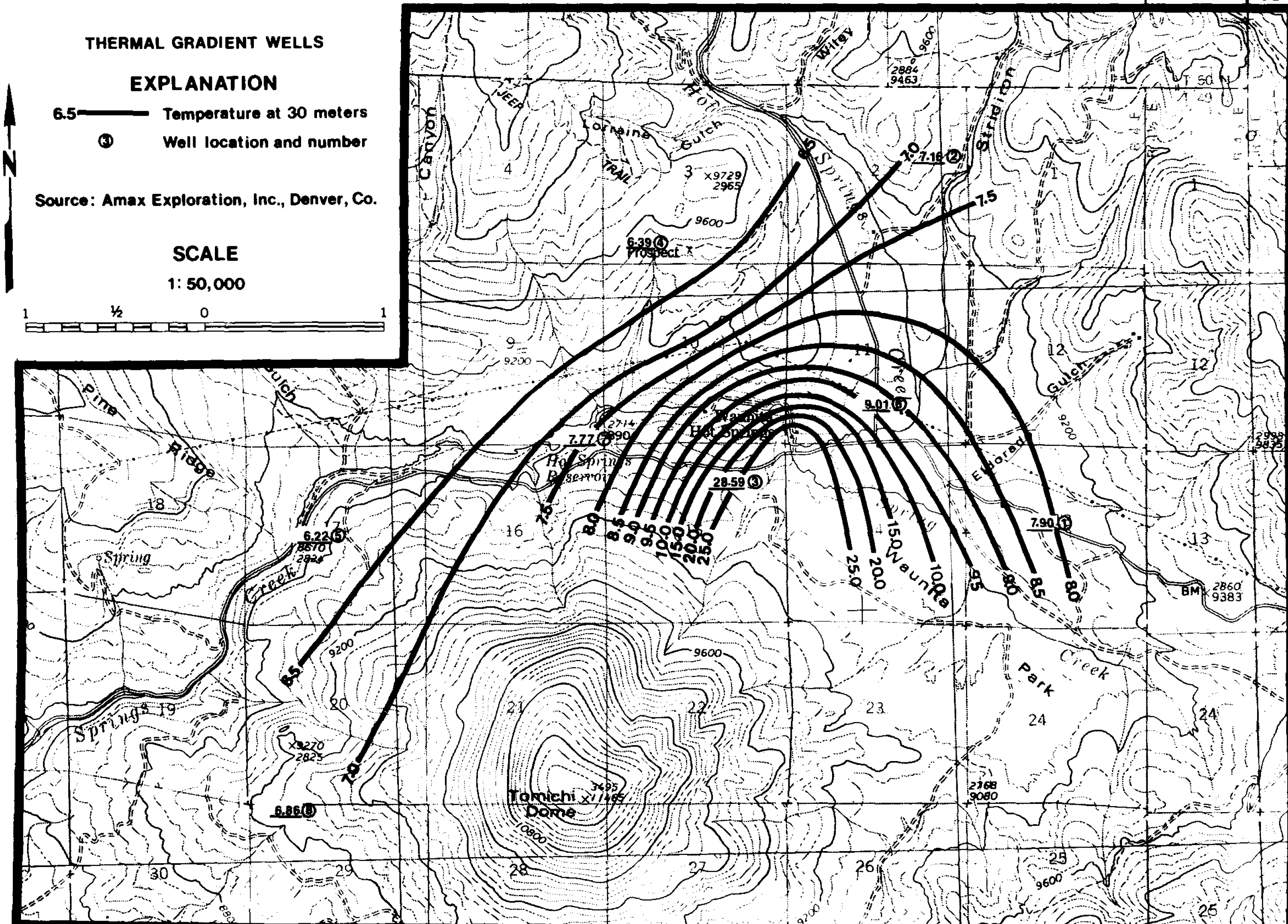


Figure 3. Temperature map in ^{o}C at 30 meters.

WAUNITA HOT SPRINGS, COLORADO

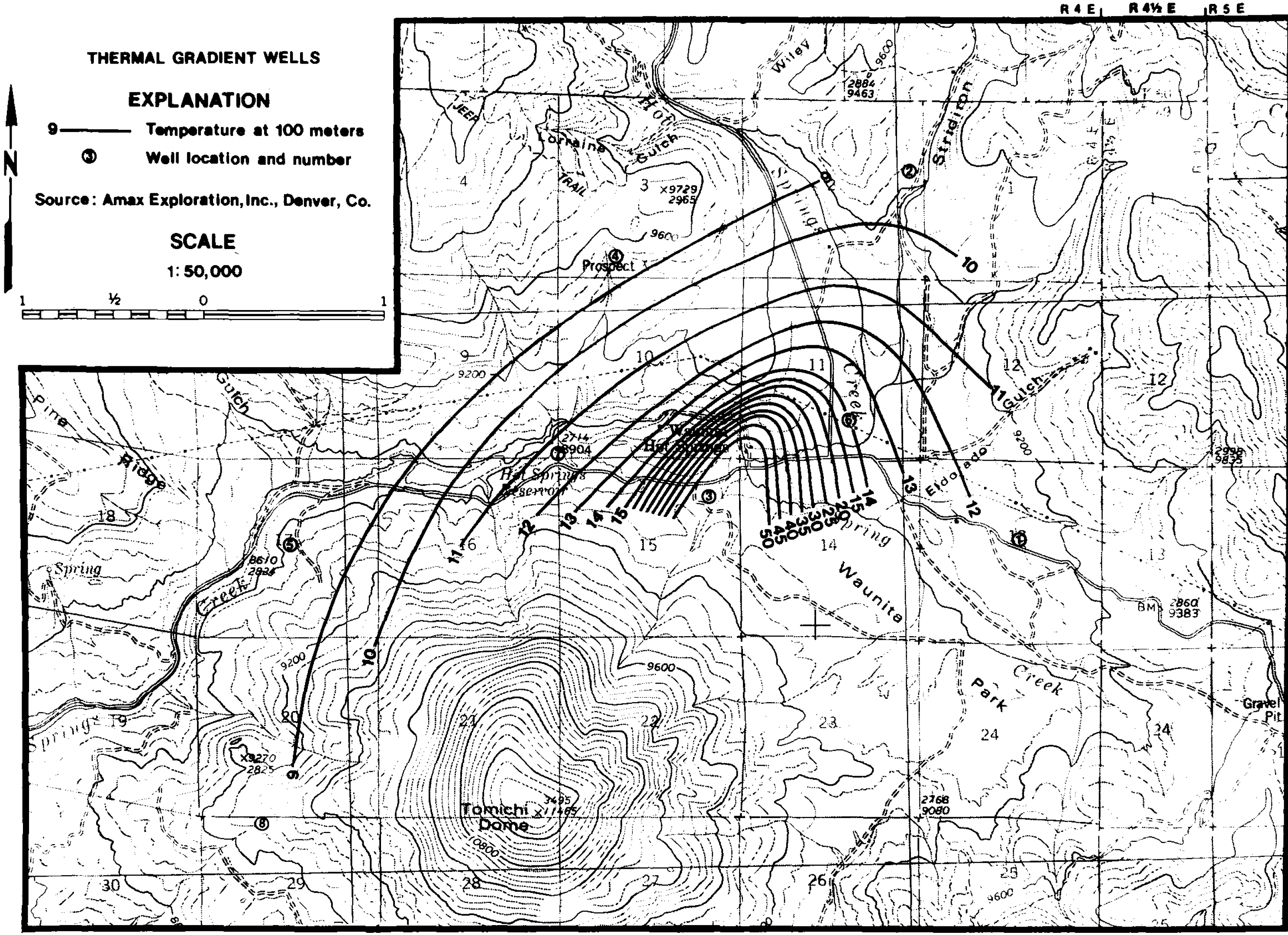


Figure 4. Temperature map in °C at 100 meters.

TEMPERATURE GRADIENT HOLES

Enclosed with the material supplied by AMAX Exploration, Inc. were lithologic logs of eight, 100 meters, temperature gradient holes in the Waunita Hot Springs area (See Fig. 1 for location of holes). A brief discussion of the lithologic cuttings, depth at which the water table was encountered and temperature gradients is here presented.

Gradient Hole #1. Depth: 100 meters

Lithology		Temperature	
0- 28 meters:	Clay and sandstone	Temperature at 10 m = 6.9°C	
28 meters:	Top of water table	Bottom hole temperature: 11.5°C	
28-100 meters:	Pierre shale	10-100 meters:	45.55 °C/Km

Gradient Hole #2. Depth: 100 meters

Lithology		Temperature	
0- 5 meters:	clay	Temperature at 8 m = 6.0°C	
5- 14 meters:	Dakota sandstone	Bottom hole temperature: 9.3°C	
14-100 meters:	Morrison formation	8- 18 meters:	70.00 °C/Km
48 meters:	Top of water table	18- 44 meters:	42.31 °C/Km
		44- 48 meters:	157.50 °C/Km
		48- 80 meters:	8.44 °C/km
		80-100 meters:	31.50 °C/Km
		8-100 meters:	36.20 °C/Km

Gradient Hole #3. Depth: 88 meters

Lithology		Temperature	
0- 88 meters:	Pierre shale	Temperature at 0 m = 14.5°C	
52 meters:	Top of water table?	Bottom hole temperature: 47.5°C	
		0- 30 meters:	469.67 °C/Km
		30- 34 meters:	340.00 °C/Km
		34- 40 meters:	1,080.00 °C/Km
		40- 88 meters:	237.08 °C/Km
		0- 88 meters:	378.52 °C/Km

Gradient Hole #4. Depth: 100 meters

Lithology		Temperature	
0- 27 meters:	Dakota sandstone	Temperature at 14 m = 6.0°C	
27- 61 meters:	Morrison formation	Bottom hole temperature: 8.2°C	
61-100 meters:	Precambrian Mica Schist	14- 52 meters:	28.16 °C/Km
		52- 80 meters:	30.36 °C/Km
		80-100 meters:	14.50 °C/Km
		14-100 meters:	25.70 °C/Km

Gradient Hole #5. Depth: 100 meters

Lithology		Temperature	
0- 2 meters:	Rhyolite	Temperature at 28 m = 6.2°C	
2- 30 meters:	sandy clay	Bottom hole temperature: 7.2°C	
55 meters:	Top of water table?	28- 36 meters:	12.50 °C/Km
30-100 meters:	Pierre shale	36- 64 meters:	41.07 °C/Km
		64- 66 meters:	125.00 °C/Km
		66-100 meters:	17.65 °C/Km
		28-100 meters:	29.17 °C/Km

Gradient Hole #6. Depth: 100 meters

Lithology		Temperature	
		Temperature at 10 m = 7.4°C	
		Bottom hole temperature: 14°C	
0-100 meters:	Precambrian mica schist	10-100 meters:	73.33 °C/Km
14 meters:	Top of water table		

Gradient Hole #7: Depth: 82 meters

0- 2 meters:	Sandy clay	Temperature at 8 m = 6.4°C	
2- 14 meters:	Benton Shale	Bottom hole temperature: 7.1°C	
14- 53 meters:	Dakota Sandstone	8- 20 meters:	83.33 °C/Km
53-100 meters:	Morrison formation	20- 26 meters:	33.33 °C/Km
55 meters:	Top of water table	26- 46 meters:	34.00 °C/Km
		46- 50 meters:	155.00 °C/Km
		50- 82 meters:	65.62 °C/Km
		8- 82 meters:	62.16 °C/Km

Gradient Hole #8: Depth: 100 meters

0- 55 meters:	Rhyolite & clay	Temperature at 14 m = 6.6°C	
55-100 meters:	Pierre Shale	Bottom hole temperature: 8.2°C	
		14- 50 meters:	24.00 °C/Km
		50-100 meters:	30.80 °C/Km
		14-100 meters:	27.78 °C/Km

CHAPTER VIII
SOIL MERCURY INVESTIGATIONS, WAUNITA HOT SPRINGS

by

Charles D. Ringrose and Richard H. Pearl
Colorado Geological Survey

INTRODUCTION

The Colorado Geological Survey, as part of its geothermal resource assessment program, in the summer of 1980, collected and analyzed 65 soil samples for contained mercury concentrations in the Waunita Hot Springs area (Fig. 1). While these surveys were not done as part of the AMAX Exploration, Inc. evaluation of the area, it was decided to publish the results of these surveys here so that any interested party would have all available exploration data to the Waunita Hot Springs area.

SOIL MERCURY INVESTIGATIONS

Strategy and Methodology

Introduction

The majority of exploration methods used in geothermal exploration are the more common ones such as geology, geophysics, and hydrogeological mapping; however new methods are beginning to be used. One of these, soil mercury surveys, has proven successful in a number of instances. For example Capuano and Bamford (1978); Cox and Cuff (1980); Klusman et al (1977); Klusman and Landress, (1979); and Matlick and Buseck (1976) have demonstrated the use of soil mercury surveying as a geothermal exploration tool. Both Matlick and Buseck (1976), and more recently, Cox and Cuff (1980), have used soil mercury surveys on a regional scale. On a detailed scale, Klusman and Landress (1979) and Capuano and Bamford (1978) have shown how soil mercury surveys can delineate faults or permeable zones in geothermal areas. The association of mercury with geothermal deposits has been shown by White (1967). Matlick and Buseck (1976) stated that areas with known thermal activity, such as Geysers in California, Wairakei, New Zealand, Geyser, Iceland; Larderello in Italy and Kamchatka in Russia contain mercury deposits.

Matlick and Buseck (1976) in presenting the geochemical theory behind the associations of mercury with geothermal deposits noted that mercury has great volatility and the elevated temperatures of most geothermal systems tends to cause the element to migrate upward and away from the geothermal reservoir. In addition they noted the work of White (1967), and White and others (1970) which showed that relative high concentrations of mercury are found in thermal waters. Matlick and Buseck (1976) then pointed out that soils in thermal areas should be enriched in mercury, with the mercury being trapped on the surfaces of clays and organic and organometallic compounds.

Matlick and Buseck (1976) presented 4 case studies where they used soil mercury concentrations as a exploration tool. Three of the four areas tested, Long Valley, California; Summer Lake and Klamath Falls, Oregon indicated positive anomalies. At the fourth area, East Mesa in the Imperial Valley of California no anomaly was observed, although isolated elevated values were recorded.

Klusman and others (1977) evaluated the soil mercury concentration at six geothermal areas in Colorado. These areas were Routt Hot Springs, Steamboat Hot Springs, Glenwood Springs, Cottonwood Hot Springs, Mt. Princeton Hot Springs, and Poncha Hot Springs. Their sampling and analysis procedures differ from Matlick and Buseck (1976) in that they first decomposed the soils using hydrogen peroxide and sulfuric acid; then a flameless atomic absorption procedure was used to determine the concentration of mercury. They presented the results for only one of the six areas sampled, Glenwood Springs. Their survey indicated anomalous zones but they noted that their data would require more analysis.

Soil Mercury surveys were run by Capuano and Bamford (1978) at the Roosevelt Utah Hot Springs Known Geothermal Resource Area. They analyzed the soil samples with a Jerome Instrument Corp. gold film mercury detector. The results of their investigation showed that mercury surveys can be useful for indentifying and mapping faults and other structures controlling the flow of thermal waters and for delineating areas overlying near-surface thermal activity.

Objectives

The aim of the geochemical sampling program by the Colorado Geological Survey was to evaluate those thermal areas deemed to have high commercial development potential. As the time alloted for this program was limited, the soil mercury surveys had to be preliminary in nature. The geochemical sampling program started in 1979 and continued into 1980. The surveys conducted during the summer of 1979 were aimed at determining the structural conditions controlling the hot springs. This approach was strongly influenced by the results of Capuano and Bamford (1978). During 1980 a slightly broader target was considered, rather than just sampling along traverses located over suspected faults, grid sampling patterns were used where possible. If anomalous mercury concentrations were detected, then follow-up samples were collected at a more detailed level. For those thermal areas where grid sampling was not possible due to lack of access, soil disturbance, or urban development, traverses were chosen in a similar method to the procedure used in 1979.

During the course of the investigations several restrictions became apparent. One of these was soil disturbance caused by urban development. One cannot really be sure whether the surface deposits in the back streets and lawns are original or have been brought in. Another problem occurred frequently in sampling alluvial and colluvial surficial deposits. Such deposits because of their origin, age and mineral content tend to mask, dilute, and/or distort any anomalies.

Sampling Methods

At selected sample sites, one to eight samples were taken at points within 15 to 20 ft of each other. The notation of sampling locality, is explained in Miesch 1976. The interval between sampling sites depends on the target being considered. For areas investigated, the sample site interval was either 100 ft to 200 ft or 400 ft. When using a 400 ft interval, the area in the immediate vicinity of the hot spring was considered the target rather than any particular fault. Sampling intervals of 200 ft or less were used where attempts were made to delineate controlling faults. This spacing was used by Capuano and Bamford (1978). However, Klusman and Landress (1979) seem to think that the sample must be taken directly over the faulting for detection. Considering the empirical result of Capuano and Bamford (1978), it was believed that some anomalous mercury values should be encountered if a grid pattern encompassing the hot spring area was used. A definite structural pattern may be obvious, but if the study area is being influenced by geothermal activity, the trend should indicate that the hot springs area entirely or partially is high in mercury relative to surrounding area.

The sampling procedure used during 1979 consisted of laying out a series of sample lines across suspected faults in the thermal areas. Samples were collected at predetermined intervals (usually 100 ft) along the lines.

In most of the areas investigated during 1980, three or more samples were taken at random sample localities. This was done to get an estimate of how the variance between sample localities compared with the variance at a sample locality. If the comparison suggested that there is as much variance at a sample locality as there is between sample localites, then the data would be interpreted on a point to point basis. Contouring the data would more than likely lead to false interpretation.

Two rationales have been used for determining the sampling depth. The method recommended by Cupuano and Bamford (1978) is to determine the profile of mercury down to a depth of approximately 40 cm; the depth at which the profile peaks determines the sampling depth. The other method consistently samples a soil horizon, such as the A or B horizon. The problem with using the A horizon is that its normally high organic content has been shown to have strong secondary effects in controlling mercury in the soil. Also, the sampling depth in the A horizon may not be deep enough to avoid the "baking" effect of the sun.

The method used during 1979 consisted of using profiles to determine sampling depths. A sampling depth of approximately 15 cm, with an interval of about 1 cm, was used for most of the profiles. During 1980, each sample was taken over an interval of 13 to 18 cm. It was hoped that some of variance due to depth would be smoothed out by sampling over a wider interval. Also at that depth it was hoped that the sun would not be affecting the soil's ability to retain mercury.

To collect a sample, the ground was broken with a shovel to a depth of 20 to 25 cm. Then a spatula and metal cup were used to collect approximately 100 grams of material. The contents of the cup were then put in a marked plastic bag. At the end of the day the material in each bag was laid out and allowed to dry over night. Sometimes it would take more than one night to dry. Normally, the following morning the dried material would be sieved down to an 80 mesh size outside in a shaded area and stored in 4 ml glass vials with screw caps. Within a period of 7 days later, the samples were analyzed for mercury using the Model 301 Jerome gold film mercury detector.

Background vs Anomaly

For an accurate analysis of geochemical data it is necessary to differentiate between background and anomalous values. There are various statistical ways of accomplishing this. For those areas where the statistical sample approaches 100 samples and a lognormal distribution can be assumed, a method which looks for a break in the accumulative frequency plot of the mercury data can be used. Hopefully, the break distinguishes the two populations - the background and the geothermal induced population (Lepelitor, 1969; Levinson, 1974; and Cupuano and Bamford, 1978).

For those cases where the data was sparce and the values were clustered near the lower detection limit of the instrument with a few high values at the opposite extreme, a more empirical method was used. This method called for arranging the data in ascending numerical order then inspecting the data for any gaps. The anomalous values are differentiated from background values. For the lack of a proper sampling design and computer facilities, the gap between background and the anomaly was chosen subjectively, rather than using a statistical test as recommended by Miesh (1976). When background was determined in this manner, sometimes the anomaly criteria of four times typical background was used to see how it compared with the anomalous results of the ranking method.

As a further aid in determining background mercury values, sample localities were chosen within a mile or two of the study area. Care was taken to try to sample on the same parent material as in the study area. It was assumed that there were no extreme regional trends.

WAUNITA HOT SPRINGS

To fully evaluate the soil mercury levels in the upper and lower Waunita Hot Springs area, a series of profile lines were sampled during the summer of 1980. The location of these lines and the analytical results are shown on Fig. 1. 65 samples were collected and analyzed. The mercury content of the samples ranged from a low of 2 ppb to a high of 179 ppb. Statistical analysis determined that the mean soil content was 19.46 ppb, with a standard deviation of 31.76.

To evaluate the area, and to determine if there were any other geothermal manifestations present, not having a surface expression, the sample lines were laid out to cross all suspected controlling structural features as well as in and adjacent to the hot springs. As noted on Fig. 1, with the exception of the one area just north of the upper Hot Springs, which has anomalously high levels, the soil mercury levels were at background levels.

The results of this survey were inconclusive and from interperation of the analytical data it is apparent that no obvious pattern exists that would tend to show the presence of a thermal system other than the ones already known.

REFERENCES

Capuano, R.M. and Bamford, R.W., 1978, Initial Investigation of Soil Mercury Geochemistry as an Aid to Drill Site Selection in Geothermal Systems, Contract: EG-78-C-07-1701, Earth Science Laboratory, University of Utah Research Institute, Salt Lake City, Utah.

Cox, M. E., and Cuff, K. G., 1980, Rn and Hg Surveys: Geothermal Exploration in N.E. Maui Hawaii in Geothermal: Energy for the Eighties, Transactions Geothermal Resources Council Annual Meeting, Salt Lake City, UT: Geothermal Res. Council, Davis, CA, p. 451-454.

Klusman, R.W. and Landress, R.A., 1979, Mercury in Soils of the Long Valley, California, Geothermal System: Jour. Volcanology, Geothermal Res., v. 5, pp. 49-65.

Klusman, R.W., Cowling, S., Culvey, B., Roberts, C., and Schwab, A.P., 1977, Preliminary evaluation of secondary controls on mercury in soils of geothermal districts: Geothermics, v. 6, pp. 1-8.

Lepeltier, Clande, 1969, A Simplified Statistical Treatment of Geochemical Data by Graphical Representation: Economic Geology, Vol. 64, pp. 538-550.

Levinson, A.A., 1974, Introduction to Exploration Geochemistry, Applied Publishing Ltd., Calgary, pp. 561-568.

Matlick, J.S. III and Buseck, P.R., 1976, Exploration for geothermal areas using mercury - a new geochemical technique; in Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, CA.: U.S. Gov. Printing Office, v. 1, pp. 785-792.

Miesh, A.T., 1976, Sampling Designs for Geochemical Surveys - syllabus for a short course: U.S. Geol. Surv. Open-file Report 76-772.

White, D.E., 1967, Mercury and base-metal deposits with associated thermal and mineral waters, in Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart and Winston, pp. 575-631.

White, D.E., Hinkle, L.G. and Barnes, I., 1970, Mercury content of natural thermal and mineral fluids: U.S. Geol. Survey Prof. Paper 713, pp. 25-28.

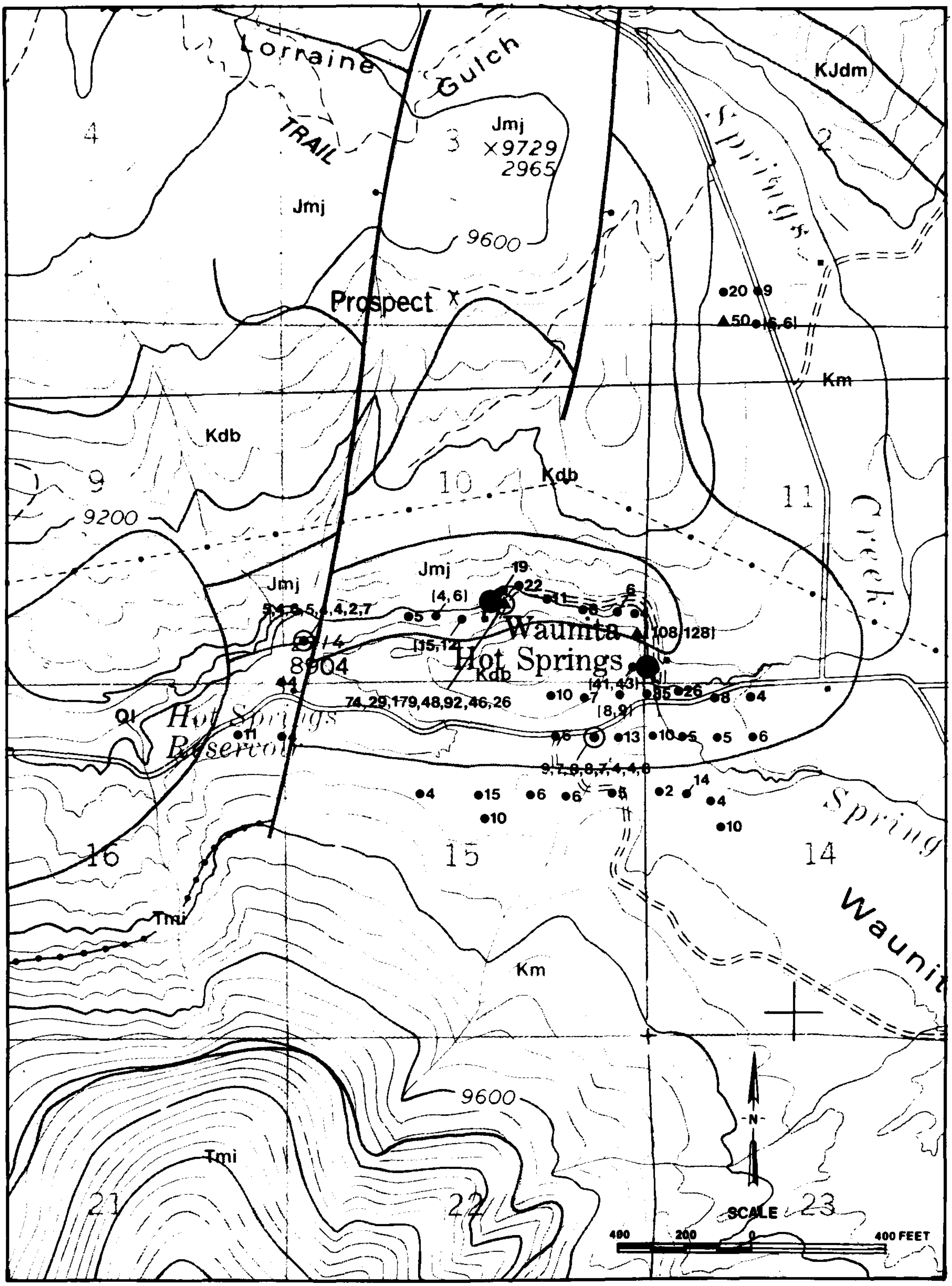


Figure 1. Geochemical soil mercury survey map.

EXPLANATION

Hot spring

Sampling locality

Anomalous sample value at a locality

Values taken at a locality with two or more samples collected approximately 20 ft apart

At least one anomalous sample value at a locality with two or more samples collected approximately 20 ft apart

7,8,345 (3,9) Each value indicates the analysis of a single sample in ppb of mercury. Values in parentheses indicate more than one analyses of a single sample.

Ql	Landslide deposits	Quaternary
Tmi	Middle Tertiary Intrusive rocks	Tertiary
Km	Mancos Shale	Cretaceous
Kdb	Dakota sandstone and Burro Canyon Formation	Cretaceous
KJdm	Dakota and Morrison Formations	Cretaceous / Jurassic
Jmj	Morrison Formation and Junction Creek Sandstone	Jurassic

Contact

Fault; ball and bar on downthrown side

Dike