DOE/ID/12063--T1

DOE/ID/12063--T1

DE84 009369

SULFUR GAS GEOCHEMICAL DETECTION
OF HYDROTHERMAL SYSTEMS

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

George E. Rouse

Earth Sciences, Inc.
Highway 93 North
Golden, CO 80401

Prepared for the
DEPARTMENT OF ENERGY
DIVISION OF GEOTHERMAL ENERGY
UNDER COOPERATIVE AGREEMENT
DE-FC07-79ID12063

NOTICE
ALL COPIES OF THIS REPORT ARE ILLEGIBLE
It has been reproduced from the best
available copy to permit the broadest
possible availability.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared to document work sponsored by the United States Government. Neither the United States nor its agent, the United States Department of Energy, nor any Federal employees, nor any of their contractors, sub-contractors of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

NOTICE

Reference to a company or product name does not imply approval or recommendation of the product by Earth Sciences Inc., or the U.S. Department of Energy to the exclusion of others that may be suitable.

CONTENTS

	<u>Page</u>
ABSTRACT	1
INTRODUCTION	3
METHODS	4
FIELD PROCEDURES	5
Sniffer Surveys	5
Soil Surveys	5
Accumulator Surveys	6
DATA PROCESSING	7
BEHAVIOR OF SULFUR IN HYDROTHERMAL SYSTEMS	9
ROOSEVELT HOT SPRINGS KGRA, UTAH	11
GEOLOGIC SETTING	11
PREVIOUS WORK - GAS GEOCHEMISTRY	11
RESULTS OF SULFUR GAS SURVEY - ROOSEVELT HOT SPRING KGRA	13
SULFUR GAS SNIFFER	13
SOIL SAMPLE SURVEY	13
ACCUMULATOR SURVEY	16
LONG VALLEY KGRA, CALIFORNIA	17
GEOLOGIC SETTING	17
RESULTS OF SULFUR GAS SURVEY	19
SOIL SAMPLE SURVEY	19
ACCUMULATOR SURVEY	19
EAST MESA KGRA, CALIFORNIA	20
GEOLOGIC SETTING	20
RESULTS OF SULFUR GAS SURVEY	21
SOIL SAMPLE SURVEY	21
ACCUMULATOR SURVEY	21
DISCUSSION	22
CONCLUSIONS	25
REFERENCES	26

ILLUSTRATIONS

		<u>Page</u>
Figure 1	Plot of sample number vs parts per billion SO ₂ , East Mesa Geothermal Area, (+) EM-S-5; East Mesa soil sample - May, (O) EM-S-6; East Mesa soil sample - June, (x) EM-S-7; East Mesa soil sample-July	8
Figure 2	Results of sulfur gas sniffer traverse along road at 9 North	14
Figure 3	Results of sulfur gas sniffer traverse along road at 2.5 North	14
Figure 4	Results of sulfur gas sniffer traverse along road at 4 South	15
Figure 5	Results of sulfur gas sniffer traverse along road at 10.5 South	15
Plate 1	Sulfur Gas in Soil-Roosevelt Hot Springs KGRA, Utah .	In Pocket
Plate II	Sulfur Gas in Accumulators-Roosevelt Hot Springs KGRA, Utah	In Pocket
Plate III	Sulfur Gas in Soil, Long Valley KGRA, California . .	In Pocket
Plate IV	Sulfur Gas in Accumulators, Long Valley KGRA, California	In Pocket
Plate V	Sulfur Gas in Soil, East Mesa KGRA, California . . .	In Pocket
Plate VI	Sulfur Gas in Accumulators, East Mesa KGRA, California	In Pocket

ABSTRACT

The purpose of this investigation was to determine whether a system of exploration using sulfur gases was capable of detecting convecting hydrothermal systems. Three surveying techniques were used at the Roosevelt Hot Springs KGRA in Utah. These were a) a sniffing technique, capable of instantaneous determinations of sulfur gas concentration, b) an accumulator technique, capable of integrating the sulfur gas emanations over a 30 day interval, and c) a method of analyzing the soils for vaporous sulfur compounds. Because of limitations in the sniffer technique, only a limited amount of surveying was done with this method. The accumulator and soil sampling techniques were conducted on a 1,000 foot grid at Roosevelt Hot Springs, and each sample site was visited three times during the spring of 1980. Thus, three soil samples and two accumulator samples were collected at each site. The results are shown as averages of three soil and two accumulator determinations of sulfur gas concentrations at each site.

Soil surveys and accumulator surveys were conducted at two additional KGRA's which were chosen based on the state of knowledge of these hydrothermal systems and upon their differences from Roosevelt Hot Springs in an effort to show that the exploration methods would be effective in detecting geothermal reservoirs in general. The Long Valley KGRA site was chosen because it was a lower temperature, water dominated system with a low concentration of sulfur in the geothermal waters. The East Mesa KGRA site was chosen because it was a system with low concentrations of sulfur in the brines and one with no surface expression.

The results at Roosevelt Hot Springs, Utah show that each of the three surveying methods was capable of detecting sulfur gas anomalies which can be interpreted to be related to the source at depth, based on resistivity mapping of that source, and also correlatable with major structural features of the area which are thought to be controlling the geometry of the geothermal reservoir. The results of the sulfur gas survey are also compatible with the results of previous gas geochemical surveys in the area where radon and mercury were the elements analyzed for. The results of the surveys at Roosevelt did not indicate that either the soil sampling technique or the accumulator technique was superior to the other.

Both the soil and the accumulator techniques were used at the Long Valley KGRA and both techniques indicated that anomalous sulfur gases are being emitted from the areas which are in the general vicinity of a resistivity low, which has been interpreted as mapping the geothermal reservoir at depth. The anomalies also correlate with the edge of the resurgent dome in the Long Valley caldera and with structures which may be related to the regional structures of the Sierra Nevada frontal faults. Other sulfur gas anomalies may be related to ring faults around the periphery of the Long Valley Caldera.

Surveys conducted at the East Mesa KGRA graphically illustrated the main advantage of the accumulator and one of the disadvantages of the soil sampling technique. The sulfur gas concentrations in the soils from the irrigated portion of the East Mesa area were two orders of magnitude higher than soils from the nonirrigated portion. This was interpreted to be the result of higher moisture content in the irrigated soils which accounts for a larger quantity of sulfur gases being trapped in the soils. By establishing separate contouring criteria for the moist and dry soils, anomalies resulted which were symmetrical with respect to the thermal reservoir as determined from subsurface temperature

measurements. Credence was given to the procedure of establishing two different contouring criteria by the results of the accumulator survey which yielded anomalies which were also symmetrical to the subsurface thermal anomaly, but in this case it was only necessary to establish one contouring criteria. The accumulators appear to be insensitive to matrix effects and moisture content of the soils, and only sensitive to the sulfur gas flux through the soils to the atmosphere.

The conclusions reached as a result of the study are that all three methods are applicable to geothermal exploration. The sniffer method has the advantage of instantaneous results, but interpretation of the results is often difficult because of the numerous variables affecting sulfur gas geochemistry. The soil sampling and analysis technique is slower than the sniffer technique, but faster, and probably cheaper than the accumulator technique, but differences in soil moisture from sample to sample can give rise to false anomalies. The accumulator surveys seem to be insensitive to soil moisture differences but are slower to conduct. Given the present state of the art of sulfur gas geochemistry it is recommended that both soil and accumulator surveys be conducted simultaneously. It is concluded that sulfur gas geochemistry is an effective method for detecting convecting hydrothermal systems, even those which are blind and deeply buried.

INTRODUCTION

The purpose of this investigation was to determine whether or not a system of gas geochemical exploration using sulfur gases was capable of detecting convecting hydrothermal systems. One of the techniques used in this study had been developed and shown to be reasonably effective in the exploration for sulfide deposits (Rouse and Stevens, 1971) and very limited test work at the Roosevelt Hot Springs KGRA in Utah had suggested that the exploration technique would also work in geothermal exploration.

The scope of the project was to conduct detailed testing of three separate surveying techniques for sulfur gases in the Roosevelt Hot Springs KGRA area to; (1) determine how applicable the exploration concept is to active hydrothermal systems, and (2) determine which of the three different techniques was best for defining anomalies as well as best adapted to reconnaissance type field work.

Following the successful demonstrations of sulfur gas exploration in the Roosevelt area, the best technique was to be tested at two other KGRA's in an effort to show the general applicability to geothermal exploration. The two additional areas chosen for testing were the Long Valley KGRA in east central California and the East Mesa KGRA in southern California.

METHODS

The three methods of determining sulfur gas concentrations used in this study are:

1. with an instrument capable of real-time read-out of sulfur gas concentrations in soil-gas (sulfur gas sniffer);
2. with a device designed to collect and store sulfur gases in soil-gas for an extended period of time (accumulators);
3. with a technique of soil collection, storage, and analysis to determine vaporous sulfur compounds adsorbed to soil particles.

The sulfur gas sniffer is a modified air pollution monitoring instrument which draws a sample of soil-gas into the instrument with a vacuum pump and determines the amount of sulfur gas present by a change in conductivity of a hydrogen peroxide solution.

The accumulator device is a glass vial filled with a hydrogen peroxide solution and equipped with a wick. The hydrogen peroxide solution saturates the wick so that sulfur gases which come in contact with it are dissolved and oxidized to sulfate. A change in pH of the solution is a measure of the sulfur gas concentration in the soil-gas over the period of time the device is left in the field.

Soil samples, moistened before collection to fix sulfur gases, are stored in vapor tight containers. Soil moisture and sulfur gases are distilled from the soil and scrubbed in hydrogen peroxide solutions of known pH. A change in pH of the scrubbing solution is a measure of the absorbed sulfur gases in the soil samples.

Field Procedures

Sniffer Survey

Previous work with the sniffer had indicated that it is a difficult method to use in the field because the instrument package is heavy and because instantaneous determinations of sulfur gases can vary widely as a result of the numerous variables effecting the gas flux from the soil. These wide variations make interpretation of the data difficult and require numerous visits to any given site in order to determine an average value. The sniffer survey was therefore restricted to an orientation survey at only one test area (Roosevelt Hot Springs). However, sufficient data were collected to compare with orientation surveys using other gases (radon and mercury) by other workers (Nielson et al, 1978 and Bamford, et al, 1980, respectively) to determine that anomalous sulfur gas concentrations were present in the area of the known geothermal reservoir.

Soil Survey

Previous, unpublished work by the author in gas geochemistry has indicated that soil moisture is one of the most important parameters in controlling the amount of a gas being emitted from the soil. In areas of the arid southwest where soil moisture has drastic seasonal variations the sulfur gas flux also varies dramatically. It has been found that extremely dry soils, such as are commonly found in Arizona in late summer and early fall, emit very low concentrations of sulfur gases. During the winter months when the soil moisture is being replenished from winter rains and snow, the sulfur gas flux at the same localities is also low. However, in the spring and early summer months when the soils are drying out, the sulfur gas flux is often very high. An interpretation of these data is that the primary flux of sulfur gas from depth is very small, probably in the parts per trillion range; essentially undetectable with the methods used to date by the author. During the winter months in the southwest when the moisture content of the soil is increasing the quantity of sulfur gases trapped in the soil is also increasing. Consequently, the sulfur gas flux for the atmosphere is very low. During the spring and summer when the soils are drying out, the sulfur gases trapped within the soil moisture are released and very high fluxes to the atmosphere are observed. However, once the soils are desicated, this secondary reservoir of sulfur gas in the soil is also depleted, and the sulfur flux observed is the primary one which, as stated above, is probably in the parts per trillion range and is essentially undetectable with instantaneous readings.

Based on the above interpretation one can conclude that moist soils should contain the highest concentrations of sulfur gases. Therefore, the procedure used in soil sampling was to sample only moist soil. Efforts were made to sample the more arid areas in the early spring before the soil "B" horizon dried out. When it was necessary to sample during the summer months the sample was collected from as deep in the soil as was necessary to find moist material. Once moist soil was found approximately 250 cc was collected, placed in a plastic disposable beaker, sprayed with some distilled water to insure that excess moisture was present while transporting to the laboratory, capped, and sealed with electricians tape to prevent further evaporation of moisture or sulfur gases before the samples were analyzed.

Accumulator Surveys

Because of the argument that the soil moisture is the medium in the soil which is actually trapping and subsequently releasing the sulfur gases, the accumulating device was designed. The objective was to devise something that could be placed in the soil to trap the sulfur gases that constitute the primary flux in a manner similar to that done by the soil moisture. The device is simply a vial which is fitted with a nylon wick, and filled with a slightly acid, hydrogen peroxide solution. The solution keeps the wick moist and the sulfur gases, which are very soluble in aqueous solutions, dissolve in the solution on the wick. Theoretically the sulfur gases are oxidized by the peroxide to sulfite or sulfate once dissolved and are thus fixed as nongaseous compounds. For each mole of sulfur gas dissolved in the peroxide solution, whether the gas species H_2S , COS , S^0 , SO_2 or other polysulfide compounds, there will be a pH change in the solution as sulfurous and/or sulfuric acid is formed upon oxidation of the sulfur compounds. Therefore, a change in pH is a measure of the amount of sulfur gases trapped.

The possibility of other compounds interfering with the pH determination as a measure of sulfur gas flux are thought to be minimal. The halogen gases Cl_2 , Br_2 , and I_2 are too difficult to oxidize to chlorates, bromates and iodates to be readily accomplished with the diluted peroxide solution used, and acid gases HCl , HBr , and HI probably do not occur in sufficient concentrations to be detectable. Carbon dioxide could effect the pH of the absorbing solution since its concentration in soil gases must be higher than in the atmosphere. As a precaution against the pH effects of CO_2 the absorbing solutions are boiled and cooled to room temperature before the pH was determined.

The field procedure for emplacing the accumulating device was to bury the vials in the holes dug to collect the soil sample. Thus most of the devices are buried approximately 15 cm deep. The vial and the wick protruding from the cap were covered with a plastic cup to keep soil from contacting the wick. This is necessary to eliminate the possibility of reactions between the soil itself and the absorbing solution in the vial and insure that only gas-liquid reactions are possible. The plastic covering cup and the vial are covered with soil to hold them in place and marked with surveyors flagging so that the sample site can be relocated and the accumulator recovered.

Since the accumulator is collecting only the sulfur gases which are streaming by the wick as the soil degasses it does not matter whether the vial is buried a few centimeters deep or a few meters deep. For practical purposes it is convenient to bury it just below the surface of the soil. This proves to be deep enough to protect it from damage by most range animals and yet relatively easy to relocate and recover. In extremely hot climates it appears to be advantageous to bury the vials somewhat deeper to take advantage of the lower temperatures at depths of about one half meter. The solution in the vials will evaporate since it is in contact with the atmosphere through the wick, and the cooler the vials can be maintained the longer the solutions will last before evaporating to dryness. The accumulators were left in the field for 30 days, plus or minus 3 or 4 days, in this study. This proved to be sufficient time for the accumulators to dissolve enough sulfur gas to be readily detectable but not so long that the evaporation of the solution to dryness was a major problem.

Data Processing

Because of the many variables which effect the quantity of gas being emitted from the soil at any given time, it has been found that a value obtained for a particular sample site on a particular day will probably not be reproducible on the following day in absolute terms. However, if a sample site is anomalous relative to a local background one day, it will likely be anomalous on the second day even though both the anomalous values and the background values change from day to day. This, of course, requires either determining the background for the area on both days in order to determine whether or not it is "anomalous" or, alternatively, it requires monitoring a base station for periodic changes in the sulfur gas flux and then making the appropriate adjustments to the readings taken on sites other than the base station. In order to average the gas geochemical values found at a given sample site on three separate occasions it is therefore most convenient to express the gas geochemical values as some multiple of background rather than in concentration units. If a station is 3 times background on day one, 4 times background on day two, and 5 times background on day three, then the average is said to be 4 times background, and this average is the only number plotted on the enclosed maps.

The method used in determining the background has been to plot the absolute value of each sample for each sample period. A base line or background value is then picked visually such that it represents the mean of 60 to 80 percent of the samples. Each sample value is then divided by the background value and this multiple of background is used in averaging with other data from the same sample site but taken on different occasions. Figure 1 shows a plot of the data from the East Mesa geothermal site which was used to determine background values. The plus symbols designate the data obtained from soil sampling in May, the circles from June, and the x symbols the data from July. The vertical logarithmic scale is in parts per billion SO_2 . The background value for the May survey is indicated by the horizontal line at 1 ppb SO_2 , that for the June survey at 5 ppb SO_2 , and the July survey at 19 ppb SO_2 .

Figure 1 Plot of sample number vs parts per billion SO_2 , East Mesa Geothermal area, (+) EM-S-5; East Mesa soil sample - May, (O) EM-S-6; East Mesa soil sample - June, (X) EM-S-7; East Mesa soil sample - July.

BEHAVIOR OF SULFUR IN HYDROTHERMAL SYSTEMS

Apparently all hydrothermal systems contain sulfur compounds (Zinder and Brock, 1977; Muffler and Truesdell, 1971; Weissberg, 1969 and Bouliqua, 1978), but the species of sulfur present is heavily dependant upon the type of hydrothermal system and the point in the system where the system is sampled and analyzed. The following discussion of the behavior of sulfur in hydrothermal systems relies heavily upon the model for convecting hydrothermal systems as outlined by White et al (1971).

Water in direct contact with a heat source at depth will contain relatively high concentrations of alkali metals, silica, chloride, sulfur and others as a result of the dissolution of silicate minerals by hot waters. The concentration of sulfur present in these brines may or may not be high, but that present will probably be dominantly in the minus two oxidation state (although there generally is some sulfur present as sulfate) (White et al, 1971; Zinder and Brock, 1977). If the supply of heat is excessive relative to the supply of water in the hydrothermal system, a zone of subsurface boiling can form. Within this zone steam and volatiles will separate from the brines and travel toward the surface through the more open parts of the plumbing system above the heat source. Because of this boiling, the brine becomes more concentrated in the alkali metals, chloride, and sulfate whereas the vapor being transportated toward the surface will consist of steam, carbon dioxide, hydrogen sulfide, and other vaporous compounds, such as helium, radon and mercury. As these volatiles approach the surface where temperatures are lower, the steam can condense and redissolve some of the vaporous compounds (White et al, 1971, p. 91). Oxidation of the hydrogen sulfide in the vapor phase prior to condensation of the steam can give rise to acid sulfate waters typical of hydrothermal systems which have gone through the subsurface boiling phase, but even in these waters there is generally a significant quantity of hydrogen sulfide present (Zinder and Brock, 1977, p. 75).

From this very brief discussion of the model for a hydrothermal system it can be seen that at almost any point in the system hydrogen sulfide is present in more than trace quantities. If subsurface boiling does not occur then the hydrothermal brines may be present at or near the surface. In this case alkaline chloride waters, with dissolved hydrogen sulfide, will form springs. In either case, hydrogen sulfide, after separating from the brines, will constitute the main sulfur compound in the vapor phase while the vapor is moving from the source to the surface.

However, the predominant form of sulfur gas found in the soils appears to be sulfur dioxide. Other workers have reported CS_2 and COS (Hinkle and Harms, 1978), but this author has consistently found gases which react as sulfur dioxide to a variety of reactants. The most definitive experiments run to date (unpublished data) were those where sulfur gases were distilled from the soils and collected in scrubbing solutions containing sodium tetrachloromercurate which stablizes sulfur dioxide. This is then analyzed for sulfur dioxide concentration by the Weste-Gaeke method, which is the standard for sulfur dioxide determinations.

Because of these results it can be reasoned that hydrogen sulfide is released from the ground water solutions at the water table and travels from there to the surface as vapor. The oxidation of hydrogen sulfide to sulfur dioxide requires the transfer of six electrons and the most likely oxidizing agent capable of this, and available in sufficient quantities, is oxygen in the soil gas and in rock pores and fractures above the ground water table.

Once oxidized to sulfur dioxide, the sulfur gas is apparently held in the soil moisture which is itself adsorbed to soil particles. Evidence for these conclusions is that very dry, sandy soil holds very small quantities of sulfur gases, whereas moist clayey soils in the same area can retain large quantities of sulfur gases.

ROOSEVELT HOT SPRINGS KGRA, UTAH

The Roosevelt Hot Springs KGRA is located in southwestern Utah, approximately 10 miles northeast of Milford, the nearest town. Details of the geology of Roosevelt Hot Springs area have been presented by Nielson et al (1978) and only a brief summary of the geology pertinent to the geothermal system will be presented here.

Geologic Setting

The geothermal system is controlled by the structure of the region which consists of four major fault systems according to Nielson et al (1978, p. 42). The geologic base of Plate I is taken from Nielson and shows the faulting described. The oldest faults in the area are low angle, west dipping faults of large scale and northwest trending fault zones, followed in time by east-west trending, steeply-dipping structures (Negro Mag Fault), and finally north- to northeast-trending normal faults (Opal Mound Fault). These later structures often localize the hot spring activity of the region.

The Opal Mound Fault is an east dipping fault which defines the eastern edge of a narrow horst and the western edge of a graben. The principal producing geothermal wells in the district appear to be confined to this graben east of the Opal Mound Fault. According to Nielson (1978, p. 48) the geothermal field may be terminated to the south near the boundary between sections 16 and 21 (see Plate I), but no structural feature has been mapped which could account for this boundary. Much of the geothermal activity is concentrated near and south of the Negro Mag Fault, an east-west trending feature near the northern part of the map, but apparently geothermal activity is not terminated by this fault since potentially producing wells have been drilled to the north of it in Salt Cove.

Previous Work - Gas Geochemistry

Nielson (1978, p. 31) described a limited radon survey over portions of the Roosevelt Hot Springs KGRA designed to test the usefulness of this method in locating buried faults which may control geothermal reservoirs. The detection method used in this survey was to place alpha sensitive film in the field for periods of approximately 30 days, and at the end of this time the standardized total dose for each sample site was determined (Nielson, 1978, p. 16). The radon anomalies defined in this work were correlative with mapped faults and with resistivity anomalies and were judged by Nielson as being indicative of open faults and fault zones which are in communication with the geothermal reservoir. It is to be noted that the highest radon flux did not necessarily coincide exactly with the mapped trace of the various faults, and most of the samples taken over the trace at the Opal Mound Fault did not have a high radon signature, although relatively high values were often found adjacent to it. Nielson (1978, p. 17) attributes this characteristic to the fact that the Opal Mound Fault must be sealed along much of its strike by silica and clays.

An extensive study by Bamford et al (1980) included the determination of mercury in soil in the Roosevelt Hot Springs KGRA. The highest values of mercury found in this study were along and near the trend of the Opal Mound Fault, but it is to be also noted that of the twelve mercury values found exceeding 1,000 ppb, only three occur along the trace of the Opal Mound Fault

and two east of it; the remaining 7 occur between 500 and 1,000 feet west of the fault trace. In contrast, the radon survey of Nielson found relatively high radon values east of the Opal Mound Fault, particularly in the northern part of the reservoir. It may also be important that of the 12 mercury values in soil which exceeded 1,000 ppb, eleven fell within regions mapped as silica and carbonate cemented alluvium, and all of the occurrences of cemented alluvium fell within the 100 ppm mercury anomalies. Because of the correspondence between silica and carbonate cement in the recent alluvium with very high mercury values, it seems likely that a good portion of the mercury was transported in solution along with the cementing materials in paleo hot springs rather than in the vapor state from the present hydrothermal system.

RESULTS OF SULFUR GAS SURVEY — ROOSEVELT HOT SPRINGS KGRA

Sulfur Gas Sniffer

Because of the necessity for 110 volt AC power to run the sulfur gas sniffer, and because of the variability in instantaneous readings utilizing this method, the survey with this instrument was limited in extent and was confined to existing roads where power could be obtained from a vehicle. Traverses were thus run in essentially east-west directions along four roads; one on the north edge of the geothermal field, one over the most productive portion of the northern end of the field, one near its center and one near the southern edge of the area. Profiles of the values found are shown on the following four figures (Figures 2-5).

Because of the limited extent of this survey, it is difficult to assign a background value, but based on the resistivity and heat flow results of Ward et al (1978) and according to Nielson et al (1978), the hydrothermal reservoir is terminated between Wells 52-21 and 72-16 by an east-west trending feature. Therefore, it is probable that the value of 14 ppb SO_2 , the average for the 10.5 South Road traverse, (see Figure 5) represents background for sulfur gases as determined with this instrument. The northern three traverses show several substantial anomalies, based on this background value and are discussed below.

The entire 9 North Road traverse is anomalous if 14 ppb is background, but even if background for this traverse were taken to be 24 ppb there would be a significant anomaly to the west of the fault which is either a continuation of the Opal Mound Fault or one parallel to it (see Plate I and Figure 2). In any case, this fault is apparently the loci for the steam vent in the bottom of Negro Mag Wash. The position of the sulfur gas anomaly also correlates well with the resistivity low in this region mapped by Ward et al (1978).

The 2.5 North Road traverse (Figure 3) is also highly anomalous in sulfur gases relative to the 14 ppb background. The main anomalous zone is to the east of the Opal Mound Fault, but the traverse did not extend far enough west to be certain that all readings in that area are near background. The east end of the anomalous zone centers well over the two producing geothermal wells in the area.

The 4 South Road traverse (Figure 4) provides some information on the western part of the area where most of the values are near the background value of 14 ppb SO_2 , except for those of the two stations immediately to the east of one of the basin forming faults. This traverse also indicates that the area to the east of the Opal Mound Fault is anomalous, although the magnitude of the anomaly here is somewhat reduced compared to those found on the two northern traverses. The portion of the anomaly near Hole 72-16 correlates with the less than 10 ohm meter resistivity low of Ward et al (1978, Figure 2). The eastern end of the anomaly lies in the vicinity of where Nielson (1978) projects the range front fault which may be a conduit for gases as it forms the eastern boundary of the reservoir.

Soil Sample Survey

Plate 1 shows the results of the analysis of soil samples from Roosevelt Hot Springs. The largest anomalies are portrayed as these areas which are greater than 5 times background. These high level anomalies are essentially centered along the trend of the Opal Mound Fault. There are a few more anomalies, or slightly larger anomalies, at the north end of the area near the

Figure 2: Results of sulfur gas sniffer traverse along road at 9 North.

Figure 3: Results of sulfur gas sniffer traverse along road at 2.5 North.

Figure 4: Results of sulfur gas sniffer traverse along road at 4 South.

Figure 5: Results of sulfur gas sniffer traverse along road at 10.5 South.

Negro Mag Fault than to the south and there are a few more anomalies to the east of the Opal Mount Fault than to the west of that feature. Although this is a very subjective evaluation, it appears reasonable since all of the productive wells are also located east of the Opal Mound Fault, and since the northern part of the reservoir is apparently more productive than the southern end.

Accumulator Survey

The results of the accumulator surveys are shown on Plate II, and the anomalies form a pattern that is very similar to the results of the soil survey. The areal extent of the anomalies on this map are definitely larger over the north end of the reservoir than over the south end, and there also appears to be some bias in the distribution of anomalies toward the eastern side of the Opal Mound Fault.

Discussion

All three methods of surveying indicate that the northern end of the area is more anomalous than the southern end, and the soil and accumulator surveys show that almost the entire area of the known geothermal reservoir is slightly to highly anomalous relative to the area extending for three miles to the west toward the valley bottom.

The comparison of the sniffer results from traverses 2.5 North and 4 south with the radon results from nearby traverses along sections A-A' and C-C' of Nielson (1978, Figures 6, 8) are quite good in that both sulfur gases and radon show higher values in the immediate vicinity of major faults and that more high values in both gases were found east of the Opal Mound Fault than to the west of this feature. Note that the Nielson's traverses and those reported here are not in exactly the same locations but are within 0.8 kilometers of each other. The sulfur gas results compared with the mercury in soil of Bamford et al (1980, Figure 8c) are similar as well, but there may be a slight shift in the mercury anomalies to the west of the Opal Mound Fault. As mentioned earlier, this could be due to the transport of mercury in thermal waters of the paleo hot springs and the fixing of mercury in the calcite and silica cemented alluvium which occurs downslope and to the west of the Opal Mound Fault. The overprinting of vapor transported mercury from the current thermal system at depth at Roosevelt upon mercury transported in solution from paleo hot springs and fixed in these same hot spring deposits could account for there not being more exact correlation amongst the anomalies of the three elements.

LONG VALLEY KGRA, CALIFORNIA

The Long Valley KGRA was chosen as the second site to test the applicability of sulfur gas geochemistry in detecting hydrothermal reservoirs because the area has been studied extensively by the U.S. Geological Survey in their geothermal research program. Furthermore, Long Valley represents a reservoir of lower temperature than the one at the Roosevelt Hot Springs KGRA, and is in fact considered by the U.S. Geological Survey as the type area for hot water geothermal systems (Muffler and Williams, 1976). According to Ward et al (1978, p. 1515) the shut-in bottom hole temperature at Roosevelt Hot Springs is near 260°C, whereas Sorey and Lewis (1976, p. 789) give a range in temperatures for the Long Valley reservoir of 184° to 225°C, based on geothermometry.

Geologic Setting

Details of the geology of the Long Valley Caldera are given by Bailey et al (1976), who also give a long list of references to other work on the area. Only a brief outline of the geology will be given here.

The Long Valley KGRA is located within the Long Valley Caldera, a 32 km by 17 km elliptical feature which sits astride a major fault system separating the Basin and Range province from the Sierra Nevada province (Lachenbruch et al, 1976, p. 770). The caldera is in fact located within a major embayment in the Sierra Nevada province.

Volcanism in the vicinity of Long Valley began about 3.2 million years ago with the eruption of basalt and andesite from widely scattered centers. Rhyolitic volcanism associated with the Long Valley Caldera apparently started with the development of the eastern Sierra Nevada escarpment along northwest trending normal faults about 1.9 million years ago. The eruptive centers from which these rhyolites came are on a 13 km arcuate zone that probably coincides with an incipient ring fracture related to the development of the Long Valley magma chamber. About 0.7 million years ago, the Long Valley volcanic center underwent a series of explosive eruptions and about 600 km of rhyolite magma was ejected, mainly as ash flow, to form the Bishop Tuff (Bailey et al, 1976, p. 740). The Long Valley Caldera, an elliptical depression about 15 km by 30 km and 23 km deep, formed when the roof of the magma chamber collapsed. The west central part of the caldera floor has been subsequently uplifted into a subcircular resurgent dome about 10 km in diameter. A 5 km wide keystone graben formed along the crest of the resurgent dome parallel to the dominant northwest-trending eastern Sierra Nevada escarpment structures of the region. Finally, basaltic and trachyandesitic lavas and pyroclastic rocks erupted from a system of north trending fissures extending from south of the caldera through the western moat to the north shore of Mono Lake. The Long Valley Caldera was occupied by a lake throughout most of its history (Bailey et al, 1976).

Hydrothermal activity within the caldera probably reached maximum intensity about 0.3 million year ago. The decline of surface activity since then is probably due to self-sealing of the intracaldera rocks by silicification and argillization. Present thermal activity is mainly on or near recently rejuvenated segments of Sierra Nevada frontal faults that extend across the caldera and have ruptured the self-sealed cap rock, according to Bailey et al (1976, p. 741). The general distribution of hydrothermal activity in Long Valley is peripheral to the resurgent dome.

Movement on the Sierra Nevada frontal faults has continued throughout postcaldera time, but the major faults that intersect the caldera rim have not displaced the caldera floor until very recently. The manner in which the Sierra Nevada faults change from single, continuous fractures outside the caldera to branching, en echelon fractures inside suggests that the caldron block is still considerable less rigid than the surrounding crust and that it may still contain magma (Bailey et al, 1976).

RESULTS OF SULFUR GAS SURVEY

The sulfur gas survey in the Long Valley area was not intended to be comprehensive, but was designed to show that sulfur gas geochemistry could be applicable to lower temperature, hydrothermal systems as well as to the higher temperature systems such as Roosevelt Hot Springs. Consequently, the survey consisted of several traverses which cross the area and appear to overlie the geothermal source, based upon resistivity and thermal gradient measurements. An attempt was made to extend the traverses into areas which would be definitely background, but this met with only limited success because of limited access to the Sierra Nevada block to the west.

Sulfur gas concentrations in the Long Valley area were determined by both the accumulator and the soil sampling methods. The results of the soil method are shown on Plate III, and the accumulator results are shown on Plate IV. Each map shows an average of three determinations at each site. The first accumulator was left in the field during the month of May, 1980, the second during June, and the third during July, and soil samples were taken in the early part of each of these months.

Plates III and IV also show the resurgent dome, the approximate location of the caldera rim, and several of the major faults in the area. Small surface displacements at four localities are shown which resulted from a series of earthquakes which occurred in the area during May, 1980. Also shown on the Plates is the 45 ohm meter resistivity contour within the caldera delineated by Hoover et al (1976).

Soil Sample Survey

The sulfur gas in soil results, shown on Plate III, indicate that sulfur gases are being emitted from a ring fracture system near the caldera boundary since intermediate or highly anomalous values were found on the east, south, and northwest traverses which were near to, or crossed the caldera rim. Although these anomalies do not occur directly on the mapped boundary faults they are located in the vicinity of the caldera boundaries where intense fracturing of the intracaldera rocks can be expected. Two additional highly anomalous areas fall within the resistivity low in an area where faulting may be controlling the escape of sulfur gases from depth. One region of highly anomalous values was found on the southeast edge of the resurgent dome in an area which is cut by the northwest trending faults, and in the immediate vicinity of where there was considerable surface displacement from the recent seismic activity.

More detailed sampling is required to determine the probable source of any of the anomalies located in this study.

Accumulator Survey

The map showing the results of the accumulator survey (Plate IV) is less complex than that showing results of the soil survey and indicates that most of the anomalous sulfur gases are being emitted from within the area of the resistivity low and are also probably intimately associated with the northwest trending fault system, the edge of the resurgent dome, and perhaps with the recent surface displacement. The only other region which was found to be highly anomalous seems to be associated with the ring fault to the east of the caldera.

EAST MESA KGRA, CALIFORNIA

The East Mesa KGRA was chosen as the third site to test the applicability of sulfur gas geochemistry for detecting buried geothermal reservoirs because this area had been studied to the point that the reservoir geometry was well defined and because the thermal waters have no surface expression. Since the thermal waters at East Mesa also contain only a few ppm of sulfide sulfur (Howard et al, 1978, p. 173), this area was considered as the ultimate test of the sulfur gas geochemical exploration technique. If the sulfur gas geochemical exploration technique method can detect the thermal reservoir at East Mesa, it should work at most potential geothermal reservoirs in the western United States.

Geologic Setting

The East Mesa KGRA is located approximately 16 km north of the Mexican border and approximately 61 km southeast of the Salton Sea in the Gulf of California physiographic province. The Salton Trough includes the Coachella and Imperial Valleys between the Peninsular Ranges of Southern California, and the south Mojave Desert mountains. Sediments in the Salton Trough are nonmarine, and in the East Mesa area they were deposited by the Colorado River which has built a delta across the trough during the Pleistocene and closed off the northern portion of the Gulf of California to form the Salton Sea. At the East Mesa KGRA the basement is at least 3,700 meters deep with the overlying sediment composed of sandstone, siltstone, shale and minor fine conglomerates with a high proportion of sand (~60%), apparently because of the KGRA's nearness to the apex of the delta (Howard et al, 1978, p. 20-22).

The surficial deposits in the area of the East Mesa KGRA are of two types. Most of the area overlying the known geothermal reservoir, which is east of the Highline Canal (see Plate V), is covered with aeolian sand that is up to 6 meters thick in some areas, whereas the area west of the canal is made up of silt and clays deposited by the fluvial processes associated with deltaic deposition (Howard et al, 1978, p. 6). Deposits of aeolian sand have caused the topographic break along which the canal was constructed and thus the soil types on opposite sides of the canal are drastically different - a feature which was very important to the results of the gas geochemical study.

The subsurface geology of the area as determined from well logs and various geophysical investigations and summarized by Howard et al (1978), is as follows. There are three seismic reflectors which are recognizable down to a depth of about 1,800 meters, and these reflectors have made it possible to map some of the structure in the area. The structure is essentially a major anticline trending southwest-northeast through the geothermal field, plunging to the southwest, and cut by a pair of northwest trending faults with displacement of 30 to 60 meters and with dips and displacements down to the southwest. Several faults with more northerly trend and smaller displacements are also present in the area (see Plate V). At some depth below the third seismic reflector there is a zone referred to by Howard et al (1978, p. 20) as "the poorly reflective zone" which is interpreted by them to be a highly fractured zone within well indurated deltaic sediments. Since the rocks of this zone have low matrix porosity and permeability, but have high yield production flow rates, it is assumed that extensive fracturing has enhanced the flow rates and decreased the seismic reflectivity. The thermal high, shown on Plates V and VI as isotherms at a depth of 6,000 feet, correlate reasonably well with the high of the poorly reflecting zone. These data, and the fact that most wells in the area are completed within or adjacent to the poorly reflecting zone indicate this to be the geothermal reservoir (Howard, 1978, p. 20).

RESULTS OF THE SULFUR GAS SURVEY

Both the soil method and the accumulator method of sulfur gas surveying were utilized at the East Mesa KGRA and the results are shown on Plates V and VI, respectively.

Soil Sample Survey

As stated previously in this report, one interpretation of the data obtained in numerous sulfur gas surveys over several years is that the sulfur gases in the soil are actually held within the moisture which is in the soil. Moist soils seem to retain more sulfur gases than dry soils, and this has led to two problems in the East Mesa area relative to soil sampling for sulfur gases.

The first problem is that two drastically different soils exist in the area on opposite sides of the Highline Canal. To the east the area is covered with the aeolian sand which holds moisture very poorly, and consequently contains low concentrations of sulfur gases. On the west side of the canal the soils are much finer grained and can retain moisture and sulfur gases much more readily. An additional complicating factor is that the area west of the canal is heavily irrigated and thus receives much more moisture than the eastern area. As a consequence, when a background value is established for the entire area and the results plotted, the entire area west of the canal is anomalous. As is indicated by the values plotted on Plate V which are multiples of the regional background.

In order to adjust for the two different soil types, two different values were established for anomalous readings on opposite sides of the canal. In the area east of the Highline Canal the areas considered to be anomalous were those which were greater than 1 time the regional background and are shown as densely stippled areas. To the west of the canal in the irrigated lands, anomalous values of sulfur gas in soil were considered as those which exceeded 8,000 times the regional background and these are also shown as densely stippled areas. The anomalies which result from contouring the data in this manner are shown on Plate V. A ring of anomalous values was found which is well centered on the isotherms at 1,800 meters and with one- and two-point anomalies to the southwest, northeast, and southeast. The single point anomaly to the northeast would appear to be related to some of the minor normal faulting in that area which is also shown on the Plate. The anomaly to the southeast could also be due to faulting if the mapped faults have extensions in this direction, because the two sets of faults should intersect in the general vicinity.

Accumulator Survey

Plate VI shows the results of the accumulator survey for sulfur gases in the East Mesa area and graphically point to one of the advantages of this method. In this case it is not necessary to establish two different background values for the different soil types since the accumulators can only collect a portion of the sulfur gases which are being transmitted through the soil to the atmosphere. In this case, the only area through which an anomalous amount of sulfur gas is being transmitted is well centered over the thermal anomaly. It is noteworthy that the same general areas which were anomalous in the soil survey to the northeast, southeast and southwest of the main anomaly are also moderately anomalous utilizing the accumulator method. This lends some credence to the procedure of establishing two different background values for the two different soil types in the soil survey.

DISCUSSION

The results of this study indicate that all three methods of surveying for sulfur gases in the soil or in soil gases are capable of detecting and defining anomalies which are probably related to convecting hydrothermal systems, and therefore could be useful in the exploration for blind geothermal reservoirs or for the delineation of the boundaries of incompletely known reservoirs. The sniffer method of surveying is the most difficult to use, both from the point of view of mobility of the necessary equipment and because instantaneous readings of sulfur concentrations in soil are subject to numerous variables, many of which are still unpredictable.

The technique of distilling off and collecting the sulfur gas compounds which are adsorbed to soil particles is perhaps the easiest to use, since most of the procedures in collecting and processing the soils are the same as has been conventionally used in soil geochemistry. However, there appear to be several variables involved in this method that are incompletely understood at the present time which can give rise to false anomalies. One of the variables which is definitely involved in the success of this method is the amount of soil moisture present, and this is often dependent upon the percentage of clay in the soil and also upon the relationship of precipitation versus evaporation for the area being surveyed. In spite of these problems, there are many places in the western United States where the soil composition over large areas is sufficiently similar, and when soil moisture is sufficiently high during certain times a year for meaningful surveys to be conducted. Under these conditions, regional background sulfur gas values can be established and anomalies easily distinguished. Soil surveys in irrigated agricultural areas may contribute to some false anomalies as happened in this study in the East Mesa area, but careful attention to soil types and soil moisture contents should make it possible to eliminate this type of false anomaly by carefully choosing background values based on soil moisture content. Further study needs to be done on the question of whether or not soil additives and fertilizers containing sulfur will effect the sulfur gas content of the soils in agricultural areas. In partial answer to the question of the effect of soil additives, such as gypsum, on sulfur gas geochemistry, a gypsiferous soil was distilled for its sulfur gas content and found to contain only a few parts per billion; essentially the same as the background values found at Roosevelt Hot Springs at the same time of year. This indicates that once the sulfur has been oxidized to the plus 6 state it is essentially fixed and does not contribute further to the sulfur gas content of the sample. Similar conclusions have been reached in sniffer surveys over gypsiferous black shale deposits and also over deposits containing up to 60 percent alunite $[K_2Al_6(OH)_2(SO_4)_4]$. The contribution of sulfur to soil gas from organo-sulfur compounds has not been assessed in this study and could be of importance if conducting surveys which cover both unvegetated and vegetated land or fertilized and unfertilized land where organo-sulfur compounds are used in the fertilizer. However, if the surveys are restricted to only one type of land the contribution of sulfur from organo-sulfur compounds should become part of the background determination for the area and thus would be of little consequence in detecting anomalies.

The accumulator method of sulfur gas geochemical surveying is perhaps the most attractive in many respects because problems of soil type, moisture content and other matrix effects in the soils are eliminated, or at least minimized. The disadvantages of the method are that each field station must be visited twice, once to emplace the device and once to recover it. A certain number of accumulators are always lost because curious animals, including people, will dig them up. Other animals will try to eat them or trample them.

The efficiency of the passive collection device used in this study is undoubtedly very low and many improvements can probably be made. However, in attempting to improve the collection efficiency of the sulfur gases one is often tempted to try active collectors and this often leads to less reliable mechanical devices to be placed in the field. It is the authors opinion that mechanical devices should be avoided and that the collection efficiency of the accumulator need only be efficient enough to give meaningful readings. Those used in this study satisfy that criteria.

One of the distinct advantages of both the soil sampling method and the accumulator method is that the field work can be done with field technicians and the analytical work can be done with laboratory technicians with a very limited amount of supervision. The cost of conducting such a survey is therefore approximately the same as for any other soil geochemical survey.

Sulfur gas surveys in themselves probably cannot be used in siting drill holes with any great certainty. However sulfur gas anomalies in conjunction with other gas geochemical anomalies such as helium, mercury, and radon; all of which have been demonstrated to occur in anomalous concentrations near geothermal reservoirs, should be obtained before any drilling is done. A coincidence, or at least a reasonable relationship among anomalies of all these gases might be sufficient data to site a drill hole, but they definitely would constitute sufficient data to justify extensive resistivity surveying. Since the gas geochemical surveying is much cheaper than geophysical surveying, the regional reconnaissance can be done geochemically, followed by detailed geophysical surveying to confirm the geochemical anomalies. Sulfur gas anomalies and mercury anomalies have been shown to be associated with metallic sulfide deposits and such anomalies could constitute "false" anomalies if the target is a geothermal reservoir. However, resistivity surveying will be able to differentiate between a disseminated sulfide deposit and a geothermal brine, and it will also yield data regarding the depth to the target which is not possible with gas geochemical techniques. A coincidence of various gas geochemical anomalies and a resistivity anomaly should be sufficient to site a well.

Sulfur gas anomalies have been detected over oxidizing sulfide deposits (Rouse and Stevens, 1971) and it is likely that similar anomalies will occur over native sulfur deposits although there is no data to substantiate this that the author is aware of. Surveys have been conducted in a variety of environments from Wisconsin to California and from British Columbia to the Mexican border, but there is no indication that decaying organic matter in swamps, peat bogs or coal deposits contribute sufficient sulfur to constitute a distinct anomaly. It cannot be categorically stated that such features do not occasionally generate significant quantities of sulfur gases, however. The author does not know of any attempts to detect sulfur gases over oil deposits but it seems likely that low level anomalies will exist over many reservoirs.

The model which seems to best account for the data regarding the emission of sulfur gases from the soil is simply that soil moisture acts as a reservoir for the sulfur gases. It appears that when a soil contains a certain "threshold" of adsorbed moisture, probably in the range of one percent, that this moisture dissolves and traps any sulfur gases that are traveling from the subsurface to the atmosphere. If the soil is constantly more moist than the threshold the soil moisture reaches a steady state with the primary flux of sulfur gas from the underlying source. The variations that are observed in such an environment are then dictated by the temperature of the soil and the soil moisture. Thus, higher sulfur gas readings are obtainable during the heat of the day and very low emissions are observed before sunrise and after

sunset. It is possible that the soil moisture is vaporized during the heat of the day and trapped sulfur gas is released to the atmosphere whereas in the cooler parts of the day, the interstitial water vapor condenses and dissolves any sulfur gases that are present in the soil horizon. Frozed soils are probably transparent to sulfur gases, and at such localities the sulfur gas flux is probably nearly the primary flux which is thought to be in the parts per trillion range.

In environments where the soil is more moist than the threshold for part of the year and less moist than the threshold for another part, the gas flux goes through tremendous variations. The period during which the soil is more moist than the threshold, the soil moisture is accumulating sulfur gases, and the quantities emitted from the soil are very low and depend heavily on the temperature of the soil and the soil moisture. During the period when the soils are dessicating, all the sulfur gas which has accumulated for the period when it was more moist than the threshold is being emitted and very high concentrations of sulfur gas are observed. After the soil has dried to below the moisture threshold limit, the sulfur gas flux must approach the primary flux from the sulfur source; apparently a very low level emission. When fresh moisture is being added to the soil as during rainstorms and when snow is melting, the sulfur gas flux is negligible and is probably less than the flux from the primary source.

Although soil moisture appears to be the principal controlling factor in determining the flux of gases (not just sulfur but also radon and helium) any number of other variables are also important. Some of these are barometric pressure, temperature, earth tides, physical properties of the soil, and wind.

CONCLUSION

The results of this study indicate that sulfur gas geochemistry is an effective method for locating convecting hydrothermal systems since readily interpretable anomalies were found and associated with each of the three known hydrothermal systems, regardless of whether they were relatively high-temperature, high-sulfur systems such as Roosevelt Hot Springs, or lower temperature low sulfur systems such as Long Valley and East Mesa. With care, even deeply buried systems such as the East Mesa reservoir can be detected.

Sulfur gas geochemistry by itself is probably not sufficiently definitive to site drills for geothermal wells, but in combination with other gas geochemical surveys such as with radon and mercury and with geophysical surveys such as resistivity, drillable targets should be identifiable. The gas geochemical anomalies should identify in plan view the best location to drill and the resistivity survey should yield good evidence regarding the depth to the target.

The cost of running either a soil survey or an accumulator survey are presently about \$400/line mile. This cost can probably be substantially reduced by training field technicians to do the sampling and laboratory technicians to do the analytical work and data processing. Resistivity surveying is estimated to cost \$1,000/line mile under similar terrain conditions. Gas geochemistry should be used to focus and to minimize the more expensive but necessary, geophysical work.

REFERENCES

- Bailey, R. A., Dalrymple, G. R., and Lanphere, M. A., 1976, Volcanism, structure, and geochronology of Long Valley Caldera, Mono County, California: Jour. Geophys. Res., v. 81, no. 5, p. 725-744.
- Bamford, R. W., Christensen, O. D., and Capuano, R. M., 1980, Multi-element geochemistry of solid materials in geothermal systems and its applications, Part 1: The hot-water system at the Roosevelt Hot Springs KGRA Utah: Univ. of Utah Research Inst., Earth Science Laboratory rept. 30., DOE contract no. DE-AC03-89ET-27002, 168 p.
- Boulegue, Jacques, 1978, Electrochemistry of reduced sulfur species in natural waters—I. The H_2S-H_2O system: Geochim. et Cosmochim. Acta, v. 42, p. 1439-1455.
- Hinkel, M. E., and Harms, T. F., 1978, CS_2 and COS in soil gases of the Roosevelt Hot Springs KGRA, Beaver County, Utah: Jour. Research U.S. Geol. Survey, v. 6, no. 5, p. 571-578.
- Hoover, D. B., Frischknecht, F. C., and Tippens, C. L., 1976, Audiomagneto-telluric sounding as a reconnaissance exploration technique in Long Valley, California: Jour. Geophys. Res., v. 81, no. 5, p. 801-809.
- Howard, J., Apps, J. A., Benson, S., Goldstein, N. E., Graf, A. N., Haney, J., Jackson, D., Juprasert, S., Majer, E., McEdwards, D., McEvilly, T. V., Narasimhan, T. N., Schechter, B., Schroeder, R., Taylor, R., van de Kamp, P., and Wolery, T., 1978, Geothermal resource and reservoir investigations of U.S. Bureau of Reclamation leaseholds at East Mesa, Imperial Valley, California: Earth Sciences Division, Lawrence Berkeley Lab., U. of California, Berkeley, Ca. 94720, 305 p.
- Nielson, D. L., 1978, Radon emanometry as a geothermal exploration technique; Theory and an example from Roosevelt Hot Springs KGRA, Utah: Univ. of Utah Research Inst., Earth Sciences Laboratory Rept. 14, DOE contract no. EG-78-07-1701, 31 p.
- Nielson, D. L., Sibbett, B. S., McKinney, D. B., Hulen, J. B., Moore, J. N., and Samberg, S. M., 1978, Geology of Roosevelt Hot Springs KGRA, Beaver County, Utah: Univ. of Utah Research Inst., Earth Sciences Laboratory Rept. 12, DOE contract no. EG-78-C-07-1701, 120 p.
- Mariner, R. H., and Willey, L. M., 1976, Geochemistry of thermal waters in Long Valley, Mono County, California: Jour. Geophys. Res., v. 81, no. 5, p. 792-800.
- Muffler, L. J. P., and Williams, D. L., 1976, Geothermal investigations of the U.S. Geological Survey in Long Valley, California, 1972-1973: Jour. Geophys. Res., v. 81, no. 5, p. 721-724.
- Raymahashay, B. C., 1968, A Geochemical Study of Rock alteration by Hot Springs in Paint Pot Hill area, Yellowstone Park: Geochim. et Cosmochim. Acta, v. 32, p. 499-522.

- Rouse, G. E. and Stevens, D. N., 1971, The Use of Sulfur Dioxide Gas Geochemistry in the Detection of Sulfide Deposits: paper presented at AIME annual meeting, March 1971, 24 p. (copies available from Earth Sciences Inc., Highway 93 North, Golden, CO 80401).
- Sorey, M. L., and Lewis, R. E., 1976, Convective heat flow from hot springs in the Long Valley Caldera, Mono County, California: Jour. Geophys. Res. v. 81, no. 5, p. 785-791.
- Ward, S. H., Parry, W. T., Nash, W. P., Sill, W. R., Cook, K. L., Smith, R. B., Chapman, D. S., Brown, F. H., Whelan, J. A., and Bowman, J. R., 1978, a summary of the Geology, geochemistry, and geophysics of the Roosevelt Hot Springs Thermal area, Utah: Geophysics, v. 43, no. 7, p. 1515-1542.
- Weissberg, B. G., 1969, Gold-silver ore grade precipitates from New Zealand thermal waters: Econ. Geol., v. 64, p. 95-108.
- 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, p. 75-97.
- White, D. E., and Waring, G. A., 1961, A review of the chemical composition of gases from volcanic fumaroles and igneous rocks: U.S. Geol. Survey Prof. Paper 424C, p. C-311-312.
- Zinder, S. and Brock, T. D., 1977, Sulfur dioxide in geothermal waters and gases: Geochim. et Cosmochim. Acta, v. 41, p. 73-79.

EXPLANATION

Geology base map From Nielson, D.L., Sibbert, B.S., McKinney, D.B., Hulen, J.B., Moore, J.N., & Samberg, S.M., 1978, Geology of Roosevelt Hot Springs KGRA, Beaver County, Utah, University of Utah Research Institute, Earth Science Laboratory Report, Department of Energy Contract Number EG-78-C-07-1701.

QUATERNARY

- Qls Landslide
- Qs Opaline and Chalcedonic sinter
- Qcal Silica-cemented alluvium
- Qh Hematite-cemented alluvium
- Qm Manganese-oxide cemented alluvium
- Qal Alluvium
- Ord Rhyolite Domes
Glassy, 1-5% phenocrysts, perlite and pumice mantles.
- Qra Pyroclastics
Air fall and non-welded ashflow tuff. White to light tan. Weakly consolidated
- Qrf Rhyolite Flow
Non-porphyrific glassy, gray, flow banded lava and obsidian. Perlite rubble on flow tops.
- Trd Rhyolite Dikes
Aphanitic, gray rhyolite dikes with approximately 5% orthoclase phenocrysts and minor biotite. Often silicified and typically strongly jointed.
- Tds Diabase Dikes
Aphanitic, light brown or light gray green, with 3% plagioclase phenocrysts. Typically strongly jointed.
- Tmd Microdiorite Dikes
Dark green, dark gray, or black fine-grained dikes, plagioclase phenocrysts often present.
- Tgr Granite Dikes
Fine-grained granitic, resistant, dark brown, closely jointed outcrops, forming blocky to rounded talus. Joints are typically limonite-stained. Unlabeled dikes are Tgr.
- Tg Granite
Coarse to medium-grained, xenomorphic, even texture with 22% quartz. Forms massive rounded outcrops, weathers to grus.
- Ts Syenite
Medium-grained, xenomorphic, with 1 to 3% sphene. Forms white or very light brown stained, massive, rounded outcrops, weathers to grus.
- Tpg Porphyritic Granite
Porphyritic with 25% 1 to 3 cm microcline phenocrysts. Medium to coarse grained matrix. Forms resistant outcrops.
- Tqm Quartz Monzonite
Coarse grained, massive, rounded light brown outcrops. Flow foliation and mafic xenoliths typical in the contact zone. 1 to 2 cm anhedral to subhedral microcline crystals present in parts of the contact zone. Forms some talus in the contact zone, but weathers to grus in the interior of the pluton.
- Td Diorite
Medium-grained hornblende diorite.
- PCqn Hornblende Gneiss
Medium-grained hornblende gneiss; weakly to strongly foliated. Forms resistant outcrops.
- PCn Biotite Gneiss
Highly variable biotite and biotite-hornblende gneisses which occur as inclusions within younger units. Typically massive to weakly foliated, dark colored, sphene rich and medium-grained. Alkalal feldspar porphyroblasts are common.
- PCs Sillimanite Schist
Dark gray to green fine-grained, finely laminated schist containing abundant biotite, fibrolitic sillimanite, and minor garnet porphyroblasts.
- PEq Quartzite
White, bedded metaquartzite containing minor biotite and feldspar.
- PCbg Banded Gneiss
Gray to white conspicuously layered biotite gneiss, schist and migmatite. Highly variable in composition. Well developed isoclinal and mylonitic folding.

TERTIARY

PRECAMBRIAN

Contact, dashed where approximate

Fault, intruded by microdiorite dike

Fault, dashed where inferred, dotted where covered. Breccia zones shown where mappable.

Fault, mapped from linears on areal photos, may have some topographic relief

Joints

Foliation

Foliation with plunge of linear

Dip of dike, thickness not shown to scale. Unlabeled dikes are Tgr

Fumarole

Spring

Geothermal well

Thermal gradient hole

Lake Bonneville shore features

Prospect pit

Shaft

Adit

Sulfur Gas "Sniffer" traverses

Sample Locations - values are multiples of background.

SULFUR GAS CONCENTRATIONS IN ACCUMULATORS

- ≥ 5 x Background
- 2-49 x Background
- < 2 x Background

NOTE: All results are the average of data from two accumulator samples which had field residence times from May-June and June-July, 1980 respectively.

REV. A

DESCRIPTION

ORIG. ISSUE

DATE

8/80

9/80

DATE

DATE

DWN. BY

LKD

DATE

DATE

DATE

DATE

APPRD. BY

DATE

DATE

DATE

DATE

PROJECT NO.

DE-FOOT-791D/2063

EARTH SCIENCES, Inc.

GOLDEN, COLORADO

SULFUR GAS IN ACCUMULATOR

ROOSEVELT HOT SPRINGS KGRA, UTAH

DSGN. BY GR

DWN. BY LKD

CHK. BY

APPRD. BY

DATE

DATE

DATE

DATE

REV. A

PLATE II

DWG. NO.

EXPLANATION

- 45 TOTAL FIELD RESISTIVITY CONTOUR IN OHM METERS
 - CALDERA BOUNDARY
 - RESURGENT DOME
 - FAULT - DASHED WHERE INFERRED BAR ON DOWN THROWN SIDE
 - SURFACE DISPLACEMENTS RESULTING FROM MAY 1960 EARTHQUAKES
 - 1.8 SAMPLE LOCATION (values are multiples above background)
- Taken from Stanley et al, 1976

SULFUR GAS CONCENTRATIONS IN SOIL

- $\geq 3 \times$ BACKGROUND
- 1.5-2.9 $\times$ BACKGROUND
- $< 1.5 \times$ BACKGROUND

NOTE: All results are the average of data from three soil samples taken from each site collected in May, June, and July, 1980.

REV.	DESCRPT.	DWN. BY	APPR'D. BY	DATE	PROJECT NO.
A	Orig. issue	LKD			DOE COOP AGREE. NO. DE-FC07-7910 2063

EARTH SCIENCES, Inc.
GOLDEN, COLORADO

SULFUR GAS IN SOIL
LONG VALLEY KGRA, CALIFORNIA

DSGN. BY	G.R.	DATE	8/80	REV.	PLATE
DWN. BY	LKD.	DATE	9/80		III
CHK. BY		DATE			DWG. NO.
APPR'D. BY		DATE			