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MAGMA Source Location Survey

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Harry C. Hardee, James C. Dunn, John L. Colp

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
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MAGMA SOURCE LOCATION SURVEY

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Harry C. Hardee
James C. Dunn
John L. Colp

Geothermal Research Division

Abstract

A survey of Industry/University geophysicists was conducted to obtain their opinions on the existence of shallow (less than 10 km from surface) magma bodies in the western conterminous United States and methods for locating and defining them. Inputs from 35 individuals were received and are included. Responses were that shallow magma bodies exist and that existing geophysical sensing systems are adequate to locate them.

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MAGMA SOURCE LOCATION SURVEY

SAND82-0219

The initial objective of the DOE-funded Sandia Magma Energy Research Project to assess the scientific feasibility of extracting energy from buried molten rock sources has been successfully concluded. The completion of the final work and issuance of the required reports will be achieved during FY-82.

A meeting was held on October 15, 1981, at the request of Mr. J. H. Scott, 4700, to discuss recommendations for future work on magma energy that Sandia could pursue. The consensus was that initial future efforts should be concentrated on the task of more specifically locating and defining magma bodies in the western conterminous United States. It was suggested that the first step be a survey of oil company and other expert geophysicists, who had not been associated directly with the ongoing Magma Energy Research Project, to obtain their opinions on the existence of shallow magma bodies and methods for locating and defining them. The purpose was to determine as the next step whether: 1) Sandia should propose a program to develop geophysical instruments and techniques for locating a magma body, or 2) Sandia should propose using existing geophysical techniques to explore and begin tests in a shallow continental magma body.

The Magma Source Location Survey consists of two parts. A postal survey was designed consisting of one page of relevant questions. This questionnaire, together with an explanatory letter (see Appendix A1) was mailed to nineteen scientists who were known to be aware of the Sandia Magma Energy Project and may or may not have been associated with it in some manner (see Appendix A2). Responses were received from eleven of the addressees and are reproduced in Appendix A3.

The second part of the Survey consisted of visits to twelve locations and personal interviews with twenty-four technical people at those locations (see Appendix B1). These visits were made by the authors of this report. Written reports of these individual interviews are reproduced in Appendix B2.

Summary of Postal Survey Results

All eleven of the respondents believe magma bodies exist within 10 kilometers of the surface in the western conterminous United States. Surface geologic expressions and passive seismic techniques were cited most frequently as evidence of magma body existence. Active seismic techniques, exhumed body studies, thermal studies, and magnetotelluric techniques were also cited.

Responses as to the minimum depth to these magma bodies ranged from 0 to 7 kilometers below the surface with the range of 4-5 kilometers being most frequently cited. Passive and active seismic techniques were cited most frequently as evidence used to form their depth estimates.

In response to the question as to which existing geophysical sensory methods are most useful for magma location, passive and active

seismic techniques were most frequently cited with electrical and magnetic methods following.

Seven of eight respondents to the question as to whether existing geophysical sensory methods were adequate to site a drill hole into magma replied affirmatively.

A ten-year, well-coordinated, stable national program using all types of geophysical techniques, especially intensive, high resolution arrays of passive and active seismic systems, was the consensus reply to the request for a plan to locate a borehole into magma.

Summary of Personal Interviews

Three points clearly came out of an assessment of all the personal interviews conducted. First, the geophysical systems recommended as most useful for locating and defining magma bodies were a) P- and shear-wave reflection active seismic techniques, b) P-wave delay passive seismic techniques, and c) controlled time-domain electro-magnetic techniques. Other geophysical sensing systems, aeromagnetic, gravity, magnetotelluric, thermal, Curie-point, and surface geology, were mentioned as suitable for reconnaissance studies.

Second, a magma location plan must consist of a well-coordinated, intensive program utilizing all geophysical systems to produce a variety of data sets. A definitive interpretation of a real magma location requires many data sets from several sensing methods. As a corollary to this point, it was pointed out that better knowledge of the geophysical properties of in situ magma was required.

Third, existing geophysical sensing hardware and interpretation software is adequate to begin a magma location project. Refinements to both may be found necessary, but can be made as the project proceeds.

APPENDIX A

Magma Source Location Postal Survey

- A1 - Letter and Form Sent Out
- A2 - List of Addressees and Respondents
- A3 - Responses Received

Al - Letter and Form Sent Out

Sandia National Laboratories

Albuquerque, New Mexico 87185

October 23, 1981

Dear

As you know, Sandia National Laboratory has been assessing the scientific feasibility of extracting energy from buried magma bodies within the top 10 kilometers of the earth's surface. This DOE/OBES-funded project has been underway since 1975. We have essentially completed that assessment and have concluded that it is scientifically feasible to extract energy from magma sources. During the current fiscal year, we are completing our assessment, documenting the completed project, and preparing recommendations for any future national effort on the utilization of this immense energy resource.

As part of our recommendations for future effort, we are conducting an informal survey on the state of the art for locating and defining magma bodies within the top 10 kilometers of the surface of the conterminous United States. Attached are 4 questions which we have composed that will help us in this survey. We would appreciate your assistance by giving us your answers to these questions. We do not expect you to spend a lot of your time in responding; but your immediate reactions to these inquiries would be very valuable to us in formulating the future direction of Magma Energy work.

Thank you for your cooperation.

Yours very truly,

John L. Colp

JLC:4743:sm

Attachment

- 1) In your opinion, do magma bodies exist within 10 km of the surface in the Western conterminous United States?

What is the evidence used to form the above opinion?

- 2) In your opinion, what are the depths to some of these magma bodies, if you think they exist?

What is the evidence used to form the above opinion?

- 3) In your opinion, what existing geophysical sensing methods are most useful for accurately locating and delineating such magma bodies, if you think they exist?

Are existing geophysical sensing methods adequate to site a drillhole into magma?

If existing methods are not adequate, what is needed to do so?

- 4) What are your suggestions, based on using existing techniques, for a plan to locate a borehole into magma?

A2 - List of Addressees and Respondents

K. Aki, Massachusetts Institute of Technology.(R)
D. Blackwell, Southern Methodist University.
G. Bodvarsson, Oregon State University(R)
R. Decker, USGS Hawaiian Volcano Observatory(R)
C. Drake, Dartmouth College.
J. Hermance, Brown University.
H. Iyer, USGS Menlo Park(R)
J. Kienle, University of Alaska.
A. McBirney, University of Oregon.(R)
D. Peterson, USGS Cascades Volcano Observatory
M. Ryan, USGS Reston
A. Sanford, New Mexico Institute of Technology(R)
H. Shaw, USGS Menlo Park(R)
R. Smith, USGS Reston.
R. Tilling, USGS Reston.(R)
P. Ward, USGS Menlo Park
R. Ward, University of Texas at Dallas(R)
H. Yoder, Carnegie Institute(R)
C. Zablocki, USGS Reston(R)

K. Aki, Massachusetts Institute of Technology

DEPARTMENT OF EARTH AND PLANETARY SCIENCES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

28 October 1981

Dr. John L. Colp
Sandia National Laboratories
Albuquerque, NM 87185

Dear John:

This is in response to your inquiry about the state of the art for locating and defining magma bodies within the top 10 kilometers of the surface of the conterminous United States.

From a seismologist's viewpoint, the most intriguing result from the geothermal areas in the western U.S. is the low velocity body discovered by the 3-D inversion of teleseismic travel time residuals. As summarized in the enclosed paper, they are ubiquitous in the geothermal areas of the western U.S. except for Cascades. I believe that the body can be reached at a depth of 10 km.

In order to locate the magma body accurately, the above method has too poor spatial resolution. For locating the magma chamber, I propose the following method which is based on our experience with Kilauea Iki. As you remember, the best method for locating the lateral extent of magma body was to map the frequency of seismic events. I believe that there will be numerous seismic events in the vicinity of a magma body because of thermal stress. Then, our strategy will be to drill a hole and listen to the seismic events by a borehole seismograph. With a three-component seismograph, we shall be able to locate them using the direction of first motion, because they would give outward first motion to every direction. Then, the directional drilling can be used to reach the magma body.

We are currently developing a borehole seismograph for this purpose. We are hoping to carry out an initial test of this method somewhere on the Kilauea volcano with the help of Sandia. We have talked about the possibility of this cooperative work with Harry Hardee, Richard Hills and Jim Dunn.

Sincerely yours,

Kei
Keiiti Aki

KA:jnb
encl.

3-D INHOMOGENEITIES IN THE UPPER MANTLE

KEIITI AKI

*Department of Earth and Planetary Sciences, Massachusetts Institute of Technology,
Cambridge, Mass. 02139 (U.S.A.)*

(Received October 28, 1980)

ABSTRACT

Aki, K., 1981. 3-D inhomogeneities in the upper mantle. In: R.E. Zartman and S.R. Taylor (Editors), *Evolution of the Upper Mantle*. *Tectonophysics*, 75: 31–40.

The method developed by Aki, Christofferson and Husebye for determining a 3-D seismic image of the earth's interior from the travel-time data obtained at a 2-D array has been applied to seventeen arrays around the world by various authors. The most outstanding results from these works are that small-scale lateral velocity anomalies exist in the lower crust and upper mantle everywhere studied. The reality of these deep-seated anomalies is supported by: (1) significant reduction of residual variance; (2) resolution analysis for decoupling from shallower anomalies; and (3) error analysis for the significance of anomalies.

In this paper, we try to strengthen the credibility of these deep-seated anomalies by drawing attention to those found where they were expected; namely, low-velocity bodies under several geothermal areas and high-velocity anomalies associated with the subducting plate.

INTRODUCTION

A new method for obtaining a three-dimensional seismic image of the earth's interior was developed by Aki, Christoffersson and Husebye using the teleseismic P-time data observed at NORSAR, Norway (Aki et al., 1977). The method was refined by Ellsworth (1977) who implemented the ray-tracing in a 3-D heterogeneous medium in the linearization–iteration procedure. The method was extended to the local earthquake data by Aki and Lee (1976), and to the combined data from global and local networks by Hirahara (1977).

So far, the method has been applied to seventeen arrays around the world. The results for the following ten arrays have already been published. They are: NORSAR, Norway (Aki et al., 1977); LASA, Montana (Aki et al., 1976); central California (Husebye et al., 1976; Zandt, 1978); Bear Valley, California (Aki and Lee, 1976); Yellowstone, Wyoming (Zandt, 1978); New Madrid,

Missouri (Mitchell et al., 1977); Tarbela, Pakistan (Menke, 1977); Japan and its vicinity (Hirahara, 1977); Island of Hawaii (Ellsworth and Koyanagi, 1977); and the United States (Romanowicz, 1979). The results for the following seven arrays are in press or in preparation. They are: Kanto, Japan (Horie and Aki, 1979); Roosevelt Hot Springs, Utah (Robinson and Iyer, 1981); Western Europe (Romanowicz, 1980); northeastern United States (Taylor and Toksöz, 1979); the Coso geothermal area, California (Reasen-berg et al., 1980); the Geyser-Clear Lake area, California (D.H. Oppenheimer, pers. commun., 1980); and Hindu Kush, Afghanistan (S. Roecker, pers. commun., 1980).

Under each array, the crust and upper mantle are sliced into several layers, and the percentage fluctuation of seismic velocity in each layer is shown in the form of a map as shown in Figs. 2 through 6 for the case of Montana LASA. The volume of earth for which we can get a reliable image is determined by the size of the array, and the resolution of the image by the spacing between seismographs. The detailed discussions of the resolution and error were given in Aki et al. (1976, 1977), and Aki (1977).

A persistent result obtained from arrays in various regions is that the velocity distribution in the uppermost crust correlates well with geology maps in young active areas such as California, Hawaii and Yellowstone. The correlation is poor in old stable areas such as eastern Montana and Norway.

Another outstanding result is that small-scale (20–50 km) velocity anomalies exist in the lower crust and upper mantle everywhere studied irrespective of the degree of recent tectonic activity. The reality of these deep-seated anomalies has been supported from the significant reduction of residual variance by their inclusion in the model, the resolution analysis indicating their independence from the influence of shallow anomalies and the error analysis based on standard error estimation for the velocity anomaly.

In the present paper, we shall try to strengthen the credibility of these deep-seated anomalies by drawing attention to those found where they were expected; namely, low-velocity bodies under several geothermal areas and high-velocity anomalies associated with the subducting plates.

LOW VELOCITY BODIES UNDER GEOTHERMAL AREAS

At shallow depths, bodies associated with geothermal energy sources may have a higher seismic velocity than the surrounding medium because of compositional or petrologic contrasts between magma and the surrounding medium or healing effect of high temperature on cracks which may be responsible for velocity reduction in the surrounding medium. In the lower crust and upper mantle, however, we expect a lower velocity for the geothermal body than for the surrounding colder region, because the velocity-reducing defects like cracks containing partial melts may be more abundant in the former. Let us look at some of the 3-D seismic images of the earth under geothermal areas starting with Coso, California.

ing the orientation of fractures in the lithosphere through which magma ascends.

(4) *Yellowstone, Wyoming*

The existence of an enormous low-velocity body under the Yellowstone National Park penetrating deep into the mantle has been known by the work of Iyer and his colleagues at the U.S. Geological Survey (Iyer, 1975). Zandt (1979) determined the 3-D seismic image using their teleseismic P-time data obtained from an array of seismographs with diameter about 100 km. The low-velocity body extends from the surface to at least a depth of 100 km. At shallow depths (0–20 km), the horizontal section of the body closely follows the Caldera boundary and has an elliptical shape elongated in the N60°E direction, with length 100 km and width 40 km. The velocity contrast is as much as 20%. The velocity contrast decreases to about 10% for depths below 20 km. The elongated shape in the N60°E direction persists to the depth of 40 km, below which it becomes roughly circular for the depth range 40 to 70 km, and again elongated in the NEE direction for the depth range 70 to 100 km. There is some indication of low-velocity anomaly extending deeper than 100 km down to perhaps 200 km. The velocity contrast, however, is only a few percent and the shape is not clearly defined for depths greater than 100 km.

As shown in Fig. 1, the N60°E direction of the elongation of the low-velocity body agrees with the trend of volcanic zone in the eastern Snake River Plain, where the initiation of volcanic activity is progressively younger toward northeast, the youngest being the Yellowstone Caldera.

By a remarkable coincidence, a large aperture seismic array (LASA) was operated for many years in the eastern Montana located precisely on the extension of the Snake River Plain in the N60°E direction about 300 km beyond the northeastern edge of the Yellowstone Caldera. Aki et al. (1976) determined a 3-D seismic image from the teleseismic P-time data as shown in Figs. 2 through 6. They found a zone of low velocity sandwiched between high-velocity regions also trending in the N60°E direction. As shown in Fig. 7, the low-velocity zone penetrates from the surface to the depth of about 100 km, and was interpreted as a zone of weakness or shear zone associated with a system of wrench faults present in the Rocky Mountains. One set of these faults trends N60°E, including the Fromberg, Vanada, Weldon and Brockton-Froid faults which form a 500 km long discontinuous fracture from a position less than 100 km northeast of Yellowstone, through LASA, to nearly the Canadian border. Thus, there is good evidence that the Snake River Plain is aligned along a zone of weakness trending N60°E that cuts deeply (~100 km) into the lithosphere, suggesting that magma found its way through fractures in the lithosphere.

From the above four cases of geothermal areas, we may say that the shape and extent of a low-velocity body determined by the 3-D inversion method

(1) Coso, California

Reasenberget al. (1980) determined a 3-D velocity structure under the Coso geothermal area using the teleseismic P-delay data from an array of seismographs about 25 km in diameter. They found an intense low-velocity body at the depth range from 5 to 20 km with the maximum velocity contrast of over 8% between 10 and 17.5 km depth beneath the surface expression (domes) of recent rhyolitic volcanism. The body has a width of approximately 5 km and becomes elongated in approximately N-S with increasing depth. The direction of elongation is roughly perpendicular to the axis of least compression in this area obtained from fault plane solutions of local earthquakes (Weaver and Hill, 1979), and they suggest that the thermal system which resulted in the deposit of rhyolite at the surface originated with the intrusion of basaltic magma into extensional fractures in the lower crust.

(2) Roosevelt Hot Spring, Utah

A similar low-velocity body was found beneath the Roosevelt Hot Spring, Utah by Robinson and Iyer (1981) using the teleseismic P-time data from an array with a diameter of about 30 km. At shallow depths (0-5 km), the velocity distribution is dominated by the geology of Basin and Range, with high velocity under the Mineral Mountains and low velocity under the neighboring valleys filled with sediments. The results for depths below 5 km are in sharp contrast to those above. A pipe-like body with a diameter about 15 km and velocity 5-7% lower than the surrounding extends from about 5 km depth down at least as far as the uppermost mantle. The horizontal section of low-velocity body is roughly circular at shallower depths centered near the Roosevelt Hot Springs geothermal area, but become somewhat elongated in the N-S direction at depth. Robinson and Iyer discussed possible causes for the low-velocity body, and preferred the abnormally high temperature and presence of a small fraction of molten rock, with acidic composition in the shallower part of the crust and basic composition in the deeper part.

(3) Geysers-Clear Lake, California

Large teleseismic P-time delays were also discovered in the Clear Lake volcanic area, California by Iyer et al. (1979). 3-D velocity anomalies have been obtained using the data from an array with a diameter of about 70 km (D.H. Oppenheimer, pers. commun., 1980). An intense low-velocity body extending to the depth of 45 km was found. The velocity contrast is more than 20% for depths from 0 to 15 km, 10% for 15 to 30 km, and 5% for 30 to 45 km. Interestingly, the anomaly has an elongated shape with the direction gradually rotating from NEE-SWW to N-S with increasing depth. The latter direction is consistent with the idea that the regional tectonic stress (with maximum compression in the N-S direction in this area) may be determin-

Fig. 1. Simplified regional geology map of the Snake River-Yellowstone area with the location of Montana LASA, reproduced from Zandt (1978).

Fig. 2. Percentage fluctuation of P-wave slowness (from the average for each layer) for Layer 1 located between depths 0 and 20 km. The positive value of slowness fluctuation corresponds to low-velocity anomaly, and thus marked by *L*. The negative value corresponds to high velocity. The contours are drawn at 1 percent interval. A circular dot is the location of array center AO, reproduced from Aki et al. (1976).

Fig. 3. Percentage fluctuation of P-wave slowness for Layer 2 located between depths 20 and 50 km, reproduced from Aki et al. (1976). See Fig. 2 for symbols.

Fig. 4. Percentage fluctuation of P-wave slowness for Layer 3 located between depths 50 and 80 km, reproduced from Aki et al. (1976). See Fig. 2 for symbols.

Fig. 5. Percentage fluctuation of P-wave slowness for Layer 4 located between depths 80 and 110 km, reproduced from Aki et al. (1976). See Fig. 2 for symbols.

Fig. 6. Percentage fluctuation of P-wave slowness for Layer 5 located between depths 110 km and 140 km, reproduced from Aki et al. (1976). See Fig. 2 for symbols.

Fig. 7. Percentage fluctuation of P-wave slowness for the vertical cross-section along the NW-SE direction. AO is the location of the center of array. The letters *H* and *L* refer to high- and low-velocity anomalies, respectively, reproduced from Aki et al. (1976).

give a tectonic framework in which a physical model of each geothermal system may be constructed. Let us now turn our attention to high-velocity anomalies where they are expected.

HIGH-VELOCITY ANOMALIES ASSOCIATED WITH THE SUBDUCTING PLATES

Hirahara (1977) and Hirahara and Mikumo (1980) determined a 3-D seismic velocity distribution to the depth of 650 km under Japan and its vicinity using P-time data obtained at 104 Japanese stations and 232 world wide stations from intermediate and deep-focus earthquakes in and near Japan. The result was a remarkable confirmation of the subducting high-velocity Pacific plate (Utsu, 1971), with new information about the thickness and velocity contrast. The thickness of the high-velocity plate is about 100 km or a little more. The seismicity is confined in the upper half of the plate. The upper boundary of the plate is clearly defined with a sharp velocity contrast against the inner low-velocity zone. The lower boundary is less clear and the velocity decreases gradually suggesting gentler temperature gradient. The velocity contrast between the plate and surrounding low-velocity zones diminishes with depth; 8% at depths 50–250 km to 4% at 350–450 km.

Hirahara (1979) also determined the shear-velocity distribution using the S-time data obtained at Japanese stations from earthquakes used in the P-velocity study. The results showed high shear-velocity anomaly coinciding with the high P-velocity anomaly obtained earlier. Combining both velocities, he was able to show a 3-D distribution of Poisson's ratio, which may be useful not only for tectonic but also for compositional interpretation.

The station network used by Hirahara and Mikumo is too sparse to define the subduction of Philippine Sea plate, except for an indication of high velocity in the uppermost mantle under the southern Kii peninsula. Horie and Aki (1979) determined a much finer-scaled 3-D velocity distribution under the Kanto region using the local earthquake data obtained by a network with a diameter of about 150 km. The velocity anomaly for the crust (0 to 32 km depth) was dominated by a low-velocity body centered in the Tokyo bay, which agrees quite well with the area of low Bouguer anomaly. This low-velocity body also coincides with the low-Q region recently discussed by Nakanishi and Horie (1979) using the intensity data.

The velocity distribution obtained by Horie and Aki for the uppermost mantle (32–65 km depth) shows that the velocity under the Tokyo bay is high. Comparing the velocity pattern with the one for the crust, we recognize very clearly the northward advance of a high-velocity zone with increasing depth corresponding to the subduction of the Philippine Sea plate. Thus, our 3-D seismic image again shows a high-velocity anomaly where it is expected.

CONCLUSION

The shape and extent of low-velocity bodies found under several geothermal areas in the United States define a tectonic framework in which a physical model of geothermal system may be constructed. This result, together with the confirmation of high-velocity anomalies coinciding with the sub-

ducting plates, give support to the credibility of deep-seated velocity anomalies found under various parts of the world by the 3-D inversion method using teleseismic and local earthquake data. The nature of these deep-seated anomalies, then, should give some constraints on the tectonic process as well as material composition of the region containing them.

ACKNOWLEDGEMENT

The author is grateful to Drs. W.L. Ellsworth, K. Hirahara, A. Horie, H.M. Iyer, D.H. Oppenheimer, P. Reasenber, R. Robinson and A. Walter who kindly sent him preprints of papers or unpublished results quoted in the text. This work was supported by the Department of Energy under contract number EY 76-S-02-2534.

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G. Bodvarsson, Oregon State University

- 1) In your opinion, do magma bodies exist within 10 km of the surface in the Western conterminous United States?

Yes, but mainly silicic magmas, less sure about mafic magmas in the conterminous United States.

What is the evidence used to form the above opinion?

The presence of a number of active calderas of fairly recent origin (Valles, Long Valley, Newberry, etc.).

- 2) In your opinion, what are the depths to some of these magma bodies, if you think they exist?

Possibly of the order of 4 to 5 km.

What is the evidence used to form the above opinion?

Temperature profiles and P-wave delays.

- 3) In your opinion, what existing geophysical sensing methods are most useful for accurately locating and delineating such magma bodies, if you think they exist?

Primary thermal methods, also electrical and possibly elasto-mechanical/rheic methods and even Curie depth techniques.

Are existing geophysical sensing methods adequate to site a drillhole into magma?

For the case of silicic magmas, I would say yes.

If existing methods are not adequate, what is needed to do so?

Obviously, more development needed.

- 4) What are your suggestions, based on using existing techniques, for a plan to locate a borehole into magma?

If the silicic magmas are a useful target, then simply drill into one of the recent calderas.

R. Decker, USGS Hawaiian Volcano Observatory

- 1) In your opinion, do magma bodies exist within 10 km of the surface in the Western conterminous United States?

Yes

What is the evidence used to form the above opinion?

Geophysics at Yellowstone, and exhumed ancient magma chambers at many locations.

- 2) In your opinion, what are the depths to some of these magma bodies, if you think they exist?

5 to 10 km

What is the evidence used to form the above opinion?

- 3) In your opinion, what existing geophysical sensing methods are most useful for accurately locating and delineating such magma bodies, if you think they exist?

Seismic P-wave delays

Are existing geophysical sensing methods adequate to site a drillhole into magma?

On a probabilistic basis, yes; on a deterministic basis, no.

If existing methods are not adequate, what is needed to do so?

Courage.

- 4) What are your suggestions, based on using existing techniques, for a plan to locate a borehole into magma?

Have a committee select a single person to make the final decision with no second guessing.

H. Iyer, USGS Menlo Park

- 1) In your opinion, do magma bodies exist within 10 km of the surface in the western conterminous United States?

Yes, large bodies with horizontal dimensions greater than 10 km occur in ten or more areas. Smaller bodies occur in numerous other regions of recent volcanism, such as the Cascade Volcanoes of California, Oregon, and Washington.

What is the evidence used to form the above opinion?

A list of regions for which fairly convincing evidence for the occurrence of large magma bodies are available, together with reported detection and delineation techniques, is given below:

- a) Yellowstone National Park, Wyoming

Geologic data
Teleseismic P-delays
Teleseismic S-delays
Seismic refraction
Thermal modeling
Gravity
Magnetics
Electrical/EM Techniques

- b) The Geysers-Clear Lake Volcanic Field

Geologic data
Teleseismic P-delays
Teleseismic P-attenuation
Gravity

- c) Long Valley, California

Geologic data
Teleseismic P-delays
Thermal modeling
Seismic refraction (marginal)
Gravity (marginal)

- d) Mono Craters, California

Geologic data

- e) Coso, California

Geologic data
Teleseismic P-delays
Teleseismic P-attenuation
Heat flow

- f) Adobe Hills, Nevada

Geologic data
Teleseismic P-delays

g) Roosevelt Hot Springs, Utah

Geologic data
Teleseismic P-delays
Teleseismic P-attenuation
Thermal modeling

h) Valles Caldera, New Mexico

Geologic data

i) Socorro Region, New Mexico (greater than 20 km deep)

Geologic data
Reflection studies using microearthquakes
Reflection using Vibroseis

j) San Francisco Mountain, Arizona

Geologic data
P-delays

- 2) In your opinion, what are the depths to some of these magma bodies? If you think they exist -- what is the evidence used to form the above opinion.

Yellowstone -- 5 to 20 km, good guess based on geophysical data.

Geysers-Clear Lake, Long Valley, Coso, Roosevelt, Valles,
San Francisco Mountain -- Less than 10 km, good guess based on
geophysical data

Mono Craters, Adobe Hills -- no data

Socorro -- nearly 20 km, most precise determination available for
a magma body.

- 3) In your opinion, what existing geophysical sensing methods are most useful for accurately locating and delineating such magma bodies, if you think they exist?

The most viable techniques are listed below. The order in which they occur is purely based on abundance of case histories.

a) Teleseismic P-delays

For detection, approximate delineation and establishing the intensity of melt. If there is a magma body in the upper crust with dimensions equal to or greater than 5 km x 5 km x 10 km, the technique has the capability to detect the body, provided a carefully planned experiment is carried out.

b) Seismic wave attenuation

Particularly S-wave attenuation is very useful for detecting and delineating magma bodies.

c) Seismic refraction, particularly fan-shooting

Very useful to delineate magma bodies. In the case of small magma bodies, fan-shooting is probably the only technique useful for detection and delineation.

d) Seismic reflection

Probably the only technique useful to delineate the top of the magma body.

e) Gravity data

Can, in some instances, be used to detect and to estimate the size of a magma body. Careful gravity modeling can give information on the density contrast inside the magma body. This information taken together with velocity contrast obtained from P-delay data can be used to establish the thermal state of the magma body.

f) Heat flow

Can be used to detect and to delineate the volume of a magma body, if hydrological problems in the upper crust do not contaminate the heat-flow measurements.

g) Electrical and electromagnetic methods

Are useful to detect and to estimate the size of magma bodies.

h) Magnetic data

Can, in some cases, be useful for establishing the approximate depth to the top surface of a magma body by using the Curie Isotherm method.

Are existing geophysical sensing methods adequate to site a drill-hole into magma?

Yes. The problem so far has been the absence of a coordinated effort to try several techniques in the seismic area and to synthesize the results.

4) What are your suggestions, based on using existing techniques, for a plan to locate a borehole into magma?

See attached chart on following page.

IVYER'S STRATEGY TO LOCATE A MAGMA BODY

FIG. 1

A. McBirney, University of Oregon

- 1) In your opinion, do magma bodies exist within 10 km of the surface in the western conterminous United States?

Yes, definitely.

What is the evidence used to form the above opinion?

They are known to be associated with the types of volcanoes that have recently been active in the western states, because we see clear evidence that this has been true of older volcanic centers that are now deeply eroded.

- 2) In your opinion, what are the depths to some of these magma bodies, if you think they exist?

Probably between 10 and 5 kilometers

What is the evidence used to form the above opinion?

Petrologic evidence shows that the mineral-liquid relations in volcanic magmas are the result of equilibration in chambers at such depths. We see the exhumed chambers in older volcanic centers.

- 3) In your opinion, what existing geophysical sensing methods are most useful for accurately locating and delineating such magma bodies, if you think they exist?

Seismology and electrical methods

Are existing geophysical sensing methods adequate to site a drill-hole into magma?

I think so, but cannot say for sure, because this is not my field.

If existing methods are not adequate, what is needed to do so?

Need more deep drilling to correlate surface measurements with subsurface conditions.

- 4) What are your suggestions, based on using existing techniques, for a plan to locate a borehole into magma?

a) Establish a team of geologists and geophysicists to select a suitable site.

b) Explore the site with all possible geophysical tools.

c) Drill to confirm field measurements.

A. Sanford, New Mexico Institute of Technology

- 1) In your opinion, do magma bodies exist within 10 km of the surface in the Western conterminous United States?

Yes

What is the evidence used to form the above opinion?

Attenuation and screening of S waves.
Anomalously low crustal velocities.
Clustering of micro-earthquake foci in space and time.

- 2) In your opinion, what are the depths to some of these magma bodies, if you think they exist?

7-10 km -- Socorro area Rio Grande rift

What is the evidence used to form the above opinion?

Attenuation and screening of S waves.
Anomalously low crustal velocities.
Clustering of micro-earthquake foci in space and time.

- 3) In your opinion, what existing geophysical sensing methods are most useful for accurately locating and delineating such magma bodies, if you think they exist?

Passive and active seismic; passive using high-frequency micro-earthquake seismic sources.

Are existing geophysical sensing methods adequate to site a drillhole into magma?

If existing methods are not adequate, what is needed to do so?

- 4) What are your suggestions, based on using existing techniques, for a plan to locate a borehole into magma?

Quantities of magma in the upper crust are likely to be small. Thus a high-resolution geophysical technique is required. We would recommend passive microearthquake studies using a large number of stations above regions known to have swarms of micro-earthquakes in conjunction with crustal reflection profiling of the type being conducted by COCORP.

H. Shaw, USGS Menlo Park

- 1) In your opinion, do magma bodies exist within 10 km of the surface in the Western conterminous United States?

Yes

What is the evidence used to form the above opinion?

Youth and longevity and apyric lavas combined with thermal models.

- 2) In your opinion, what are the depths to some of these magma bodies, if you think they exist?

5 km $\pm$ 5 km

What is the evidence used to form the above opinion?

Denudation sequences for older systems' crustal thickness; volumes, chambers and shape factors.

- 3) In your opinion, what existing geophysical sensing methods are most useful for accurately locating and delineating such magma bodies, if you think they exist?

Electrical magnetic and intensive seismic array studies at variable frequencies.

Are existing geophysical sensing methods adequate to site a drillhole into magma?

I doubt it.

If existing methods are not adequate, what is needed to do so?

Composites of many sets of geophysical and volcanic structure data. Look for convergences among data sets.

- 4) What are your suggestions, based on using existing techniques, for a plan to locate a borehole into magma?

Prayer. Have the best people on site (e.g., R. L. Smith).

R. Tilling, USGS Reston

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA. 22092

In Reply Refer To:
Mail Stop 906

November 9, 1981

Dr. John L. Colp
Sandia National Laboratories
Albuquerque, New Mexico 87185

Dear John:

With regard to your October 23 informal survey regarding magma bodies, I have taken the liberty of sending the questionnaire to Mahadeva Iyer (USGS, Menlo Park) for his opinion, which will be far more informed than mine. I understand that others have responded to you directly.

I've been shuffling papers for 5 years now, and have gotten rather out of touch with the real state of knowledge regarding magma bodies in the conterminous United States. I'll leave the specific answers to your questions to the experts inside and outside the USGS. In general, however, I believe that magma bodies probably do exist within 10 km of the surface. The problem of adequate delineation of such bodies is, as you know, no mean task but tractable. Unfortunately, despite claims by various specialists, there is no single set of present geophysical techniques that can unambiguously map subsurface magma bodies in any sufficient detail. We must work on a case-by-case basis.

The only workable approach to attempt to locate and, ultimately, penetrate a magma body is to have a well-coordinated, stable, long duration national program utilizing the combined scientific talents of Government, academia, and industry. Such a program would require considerable and guaranteed Federal funding in timeframes of at least 10 years, much along lines proposed by the Continental Scientific Drilling Committee for the Valles Caldera. Given the bleak present and near-future economic outlook, unfavorable political climate, and anticipated continued austere Federal funding, I am not optimistic about the prospects of launching such a program. But that doesn't mean we should not give it the college try! As you know, I will have been, and will continue to be, a volcano and magma energy aficionado. I keep hoping.

Best regards,

Robert I. Tilling
Chief, Office of Geochemistry
and Geophysics

R. Ward, University of Texas at Dallas

THE UNIVERSITY OF TEXAS AT DALLAS

BOX 688 RICHARDSON, TEXAS 75080 (214) 690-2445

CENTER FOR LITHOSPHERIC STUDIES

November 13, 1981

Dr. John L. Colp
Sandia National Laboratories
Albuquerque, New Mexico 87185

Dear John:

I apologize for not having responded to your letter of October 23rd; I have just found it in a stack of correspondence in my office. In each of the following four paragraphs, I will address the various questions which you posed in your letter.

Magma bodies definitely exist within 10 km of the earth's surface in the Western conterminous United States. The evidence for this is overwhelming. First, we have evidence of recent volcanism from geochronologic dating of surficial igneous rocks. Among geophysical observations are very high regional heat flow in the Western United States. There are local heat flow anomalies as high as 20 to 30 HFU. There is evidence of low density bodies located in these geothermal areas from the gravity measurements. The seismic evidence indicates large P-wave traveltime delays and attenuation anomalies. By utilizing seismic waves from different distances and azimuths, it is possible to define the three-dimensional form of such anomalies which occur in the upper crust. Seismic refraction investigations have also been conducted. The observed seismic refraction data have been fit using various modeling techniques, such as the Fuch's reflectivity technique. This indicates that the low velocity anomalies have very low moduli of rigidity or that the anomalies are actually molten.

A large magma body is believed to exist beneath the area of The Geysers geothermal field. This body is located slightly south of Mt. Hannah at a depth between 6 and 8 km. The evidence for this includes a large gravity anomaly, large teleseismic P-wave delays, and significant seismic attenuation. Sufficient data exist from the teleseismic P-wave traveltime studies at different azimuths and distances to accurately locate this body. Beneath the Yellowstone Park area, there is evidence for magma bodies at very shallow depths. The data that is most definitive is long-range seismic refraction, through potential field techniques have also been used. The traveltime anomalies in the Yellowstone area are so large that it is difficult to locate the actual magmatic body.

Dr. John Colp

-2-

November 13, 1981

The most accurate geophysical techniques for sensing a magma body within the crust are recording P-wave teleseismic traveltime delays as a first estimate. These should be followed with active seismic surveys, such as detailed seismic refraction survey or a seismic reflection survey if the area has sufficient logistical access. A seismic reflection survey would be by far the most definitive information on the location, size, thickness, and other properties of the magma body. If good seismic reflection data can be acquired above a magma body, then this would be sufficient to site a drill hole.

The following scenario could be followed for locating a magma body and siting a drill hole. First, you should go to an area with high heat flow or a thermal anomaly. Second, there should be a gravity low associated with this body. It should be an area of recent volcanism. Once these reconnaissance techniques indicate the existence of a magma body, the detailed seismic array should be deployed to observe microearthquakes and teleseismic waves. The microearthquakes should be absent within the magma body, but they may aid in delineating its extent by marking the perimeter of the magma body. Teleseisms propagating through the magma body can be used to locate the approximate extent of the velocity anomaly and the seismic attenuation anomaly. Then, active seismic source techniques can be used for the most detailed mapping of the magma body. Seismic refraction techniques using fan shooting can be used to outline the details of the magma body. If it is possible to gain access and run seismic reflection profiles, across the magma body, they should be tried unless it has been shown that they don't give good results for the area. They have the promise of providing the most definite location of the magma source.

I hope that these comments will aid you in your magma research program. I look forward to seeing you on the 7th.

Best regards,

Ronald W. Ward
Director, Center for
Lithospheric Studies

RWW:ep

H. Yoder, Carnegie Institute

- 1) In your opinion, do magma bodies exist within 10 km of the surface in the Western conterminous United States?

Yes

What is the evidence used to form the above opinion?

Long list of volcanoes active in the last 2000 years.

- 2) In your opinion, what are the depths to some of these magma bodies, if you think they exist?

3-5 km.

What is the evidence used to form the above opinion?

Seismic attenuation; tumescence; hot spring temperatures, anomolous heat flow.

- 3) In your opinion, what existing geophysical sensing methods are most useful for accurately locating and delineating such magma bodies, if you think they exist?

Mainly seismic attenuation, however, magnetic and electrical surveys provide confirmatory evidence.

Are existing geophysical sensing methods adequate to site a drillhole into magma?

Yes, see detailed three-dimensional description of Kilauea.

If existing methods are not adequate, what is needed to do so?

No lack of methods, just funding to carry out necessary measurements.

- 4) What are your suggestions, based on using existing techniques, for a plan to locate a borehole into magma?

Detailed study equivalent to that given Kilauea (and now underway for St. Helens -- but that volcano is not recommended for site) with special attention to hydrology of region.

C. Zablocki, USGS Reston

- 1) In your opinion, do magma bodies exist within 10 km of the surface in the Western conterminous United States?

Yes.

What is the evidence used to form the above opinion?

Teleseismic P-wave, seismic reflection, and refraction studies, and magnetotelluric studies.

- 2) In your opinion, what are the depths to some of these magma bodies, if you think they exist?

8-10 km. Yellowstone ~ 10-8; Long Valley ~ 8 km; Coso $\geq$ 5 km; Clear Lake ~ 4 km.

What is the evidence used to form the above opinion?

Same as question 1

- 3) In your opinion, what existing geophysical sensing methods are most useful for accurately locating and delineating such magma bodies, if you think they exist?

Teleseismic P-delay studies and possibly magnetotellurics and inferred Curie isotherms from aeromagnetic data.

Are existing geophysical sensing methods adequate to site a drillhole into magma?

Yes.

If existing methods are not adequate, what is needed to do so?

- 4) What are your suggestions, based on using existing techniques, for a plan to locate a borehole into magma?

Most inferred magma chambers (see list above) are probably deeper than present drilling technology permits -- or at its very limit.

APPENDIX B

Magma Source Location Personal Interviews

B1 - List of Persons Interviewed

B2 - Interview Results

MAGMA SOURCE LOCATION INTERVIEWS

<u>Date</u>	<u>Interviewees</u>	<u>Interviewers</u>
11/3/81	<u>University of Texas at Austin</u> F. Bostick	Hardee, Colp
11/4/81	<u>Shell Research/Houston</u> R. Thayer J. Roberts	Hardee, Colp
11/5/81	<u>Sunoco Geothermal/Dallas</u> A. Ramo	Hardee
11/9/81	<u>Phillips Research Center/Bartlesville</u> G. Hoover	Dunn, Colp
11/10/81	<u>Conoco Research and Development/Ponca City</u> R. Stolt B. Sternberg S. Sahai A. Thomas	Dunn, Colp
11/11/81	<u>Cornell University</u> S. Kaufman L. Brown	Hardee
11/16/81	<u>Chevron Geothermal/Denver</u> C. Swift	Dunn, Colp
11/16/81	<u>U. S. Geological Survey/Denver</u> F. Frischknecht D. Hoover J. Towle B. Smith	Dunn, Colp
11/17/81	<u>Colorado School of Mines/Golden</u> J. Applegate C. Barry	Hardee, Dunn
11/19/81	<u>University of Oregon/Eugene</u> H. Waff	Hardee
12/9/81	<u>Union Oil Geothermal/Santa Rosa</u> R. Dondanville T. Powell A. Schriener C. Suemnicht	Dunn, Colp
12/15/81	<u>Systems, Sciences and Software/La Jolla</u> P. Goupillaud	Hardee, Colp

MAGMA SOURCE LOCATION MEETINGS

11/3/81

University of Texas at Austin
F. Bostick, Electrical Engineering Department

Bostick attended a meeting at Napa Valley in 1979 sponsored by the USGS on the subject of geophysical methods in geothermal energy. The conclusion from that meeting was that electrical detection of magma was uncertain and future prospects were unclear. Bostick today feels that MT (magneto-telluric) is the best electrical method, but it has poor resolution. There are serious problems resolving small relief magma bodies, and it is even difficult to resolve magma bodies whose relief is half the depth to the body. Active electrical methods can only be used with very shallow bodies (such as Kilauea Iki) because of high electrical losses in the crust. Information from deep bodies is obscured by small shallow conductive bodies in the crust. Newer MT techniques, that Bostick is developing, intentionally degrade the resolution in order to increase the viewing depth into the earth. Bostick feels that many electrical measurements today are pointing to the existence of shallow magma as collections of dikes rather than large homogeneous liquid bodies.

11/4/81

Shell Research/Houston, Texas
R. E. Thayer, Geophysicist
J. Roberts, Seismic Geophysicist

Thayer sees no possibility at all for MT in magma location. He felt that gravity and potential methods might give a little information. In the seismic area he felt that refraction methods would be poor, teleseismic techniques would be somewhat useful but the resolution would be poor, and the best technique by far would be reflection seismics. By using a combined P-wave and S-wave reflection profile (Vibroseis) it should be possible not only to determine depth but also distinguish the physical nature of the transition and melt zones. Thayer said he would expect a large P-wave return at the top of the fractured transition zone and a soft P-wave reflection at the transition/melt interface while the opposite response would be expected for the S-wave reflections.

Thayer and Roberts told us that S-wave Vibroseis techniques have been successful at shallow depths (to 16 Kft) but not greater depths. The problem is with the absorption of shear waves in the first 3000 ft of the crust. This problem might be overcome by using asymmetric explosive seismic shots or by using a downhole shear wave generator. Thayer and Roberts were unaware of any existing downhole shear wave seismic sources!

Thayer and Roberts felt that field equipment and data processing techniques are currently available for P-wave reflection work and they recommended that we talk to COCORP. S-wave surface generators are available (although they may not be suitable for magma depths) but some additional processing work may be required for the data. Most major oil companies, they said, have the ability to acquire and process data but generally only process selected data. Most service companies simply acquire data as requested although a few (SEISCOM DELTA, WESTCOM

DATA) have some limited research capability. They recommended that a lot of thought be given to the P-wave and S-wave data acquisition (patterns, arrays and surface losses). They said that various patterns and sources should be compared with explosive shots initially and seismic velocity should be estimated from downhole cores and logs. It would probably cost about 1-1/2 million dollars for a minimal first site reflection survey.

They noted that Shell could do this type of survey if they wanted. They said that COCORP was a good group for this type of work although there were other groups that were even better. For P-wave reflection work they recommended:

CGG (Company Generale Geop.)
3 Park Central
1515 Arapahoe
Denver, Colorado

or

Western

or

Seiscom Delta.

For S-wave reflection work they recommended Teledyne.

11/5/81

Sunoco Geothermal/Dallas, Texas
Alan O. Ramo, Chief Geophysicist

Ramo said that geophysics, at best, would give an indication of possible magma bodies and the techniques would certainly not guarantee magma. He felt that the passive seismic techniques of Iyer (USGS) would be the best locator of magma. Ramo said that data acquisition techniques are available for reflection seismic work but more refined and extensive processing would be necessary. He recommended that we contact Jim Applegate at Colorado School of Mines Research Institute.

Ramo knew of no downhole seismic methods for our problem although he was in the process of planning a downhole geophone experiment at their new geothermal field site in Nevada. He also mentioned recent "bright spot" techniques in geothermal fields which apparently show the presence of a steam cap.

Ramo mentioned that Sunoco and several other companies had given financial support for recent deep refraction work in New Mexico, being conducted by Keller of LANL.

Ramo was very interested in recent heat extraction work and seismic work in the Magma Program. I discussed the project and left him some of our reprints on energy extraction.

11/9/81

Phillips Petroleum Research Center/Bartlesville,
Oklahoma
Gary Hoover, Geophysicist

Hoover had heard of the Magma Energy Research Project but was not familiar with our work in any detail. He said that Phillips primarily does seismic reflection profiling in sedimentary rocks, although MT is used to some extent. Phillips uses service companies for data collection but processes most of the data at Bartlesville. He recommended the following service companies: Teledyne, CGG, and Western Geophysical.

Hoover said that, in spite of Bostick's conclusion, he would not rule out MT, especially in light of the large resistivity contrast between magma and surrounding lower temperature rock. He also pointed out that reflection seismics do not work well in regions where the crust is highly fractured. For this reason, MT has been used most successfully for geothermal exploration where fractured igneous rocks are usually encountered. Hoover also thought that a combination of P- and S-wave reflection seismics would be a good method for locating magma bodies. He stated that, by combining both waves, the density, Poisson's ratio, and overpressure could be estimated. He mentioned the work of several people in this area. Bob Smith (University of Utah) has a large seismic network in Utah that records both P- and S-waves from natural seismic sources such as earthquakes. Pierre Goupillaud (Systems, Science and Software) used a combined P- and S-wave analysis in the Salton Sea Area. Jim Applegate (Colorado School of Mines) completed shear wave reflection work in The Geysers area.

Hoover was familiar with Iyer's passive seismic shadowing work and the COCORP vibroseis data that has located shallow magma bddies. Hoover stated that in his opinion these were good techniques for magma location and that the data interpretations seemed reasonable. He also spoke highly of Ron Ward's (University of Texas at Dallas) work in seismics.

Hoover thought that, by using existing geophysical exploration techniques, a program could be put together to successfully locate magma bodies in the crust. He would start with less expensive methods such as MT, passive seismics, or heat flow to obtain a large scale survey in a promising area. Then, higher resolution methods such as P- and S-wave reflection seismics would be used to define the magma bodies. He estimated reflection seismic profiling at \$5,000/mile with data processing costs about the same.

Hoover said that Phillips does not have downhole sources but they are very interested in this concept. He mentioned that Doug Johnson (University of Washington) is doing borehole-to-borehole work using downhole air and water gun sources. This is being funded by a consortium of five or six oil companies.

In parting, Hoover stated that he was quite surprised to hear how much progress had been made on the magma project and that he would like to keep informed about future work. He asked for reprints of recent journal articles and reports that we had with us and said he would be interested in future reports.

11/10/81

Conoco Research and Development/Ponca City, Oklahoma
Bob Stolt, Supervisor, Seismic Methods Group
Ben Sternberg, Supervisor, Electrical Methods
Group
Surinder Sahai, Senior Research Geophysicist

Our original contact, Gerry Ware, was suddenly transferred to Houston, with Bob Stolt promoted to his position two days prior to our arrival. Stolt was somewhat confused about the purpose of our visit, but he had arranged a conference with the above people plus four other attendees who did not contribute to the discussions. We explained our purpose of obtaining information concerning the location of magma bodies in the crust and presented a brief summary of the Magma Energy Research Project. This sparked considerable interest and initiated numerous questions about our drill bit and core recovery designs, energy extraction techniques, heat transfer measurements, source size, economics, etc.

Sternberg was aware of electrical data indicating the presence of conductors in the upper 5 km of the crust throughout the Western United States. He thought these conductors could be magma, or simply other conductive bodies such as graphite or sulphides. Sternberg suggested that the best way to locate magma would be to study its geophysical properties in the laboratory and then to use geophysical prospecting techniques that would detect those properties having the largest contrast with cool igneous rocks. He felt that the property with the largest contrast is electrical resistivity and, therefore, electrical methods should be best. When told of Bostick's comments, Sternberg said he still felt that there must be some combination of source and receiver that would detect large magma bodies at depths up to 10 km. Sternberg thought passive methods such as MT would be appropriate but also suggested active electromagnetics. He estimated that a 1 MW source might be adequate and pointed out that George Keller (Colorado School of Mines) working through Group 7 had developed a 1 MW source. Passive MT work was estimated to cost about \$2500/survey while Keller's source was thought to cost roughly \$200,000 for an extensive survey (400 sites).

Stolt pointed out that the advantage of seismics is resolution and stated that a good S-wave reflection should be obtained from a magma body. He thought combined P- and S-wave reflection seismics could locate magma. The major problem would be interpretation in geologically complex regions as well as the problems caused by fractures.

Shrinder suggested Curie point determination as a location technique. Stolt had conducted an aeromagnetic survey of Arizona where he was able to infer regional trends in the location of the Curie point. However, Stolt said this method has poor resolution and probably would not be useful for locating magma bodies. Schrinder thought heat flow measurements should be used to select promising regions for further study. He stated that this technique had been successful in geothermal exploration.

Stolt said he would like for one of us to give a seminar at some future date describing our work in more detail.

11/11/81

Cornell University

Sid Kaufman, Department of Geology of Physics

Larry Brown, Department of Geology of Physics

Kaufman feels that reflection seismics are by far the best geophysical tool for locating shallow magma. Although one seismic line may locate a possible target, additional cross lines and considerable additional processing are needed to properly define the anomaly. Once the target is defined as to size and location it may be possible to use the data to examine whether the body is magma or some other type of anomaly. Even under good circumstances it may only be possible to establish within a 50 to 80 percent certainty that the body is magma although the existence of the anomaly could be established to a 95-100% certainty. Kaufman said that the reflection seismics could be explosive shots or Vibroseis but that the Vibroseis (P-wave) offers more flexibility in various processing techniques which could be applied to the data. He felt shear wave reflection seismics would give additional information but thought there might be difficulty in getting the signal transmitted to useful depths.

Kaufman and the Cornell group use private service companies to run the Vibroseis trucks and sometimes they use service companies to reduce the data. They generally find that it is better to reduce their own data. They have their own computer and software for data reduction. Their original software codes came from Seiscom Delta and Ames. One of the problems they have is determining the seismic velocity as a function of position and depth. They use various averaging and best-fit routines to determine the proper velocity function for data reduction. There is always a problem that this could lead to erroneous conclusions.

In the COCORP studies, they normally use five trucks (vibrators). Frequently the environmental damage to the ground is a concern, particularly in a fragile desert environment. Kaufman thought this might be a serious concern with shear wave surface generators.

Besides the reflection seismic work, Kaufman felt there were no other useful techniques for locating these shallow magma bodies. He felt that refraction seismics and electrical methods would not offer reasonable resolution. He did think there might be some supportive measurements that should go along with the reflection seismic measurements. This might include uplift measurements or heat flow measurements. The most useful information, however, would come from improving the reflection seismic data processing to look at additional cross lines and to look at spectral and phase correlations.

Kaufman gave me a lot of raw data on the Socorro magma body. In addition to the 18 km deep, large magma body, they see a possible shallow body at a depth of 6 to 7 km northwest of Socorro. They do not have sufficient lines to conclusively define this anomaly. Kaufman gave me sets of various levels of processed data to show the problems and needs for proper data processing. Brown pointed out that this is only one of perhaps many shallow anomalies that exist in the area. This particular anomaly was found by accident and does not coincide with shallow bodies found by Sanford using S-wave and S/P conversions and shadowing techniques. Brown feels that lines should be run to coincide with shallow sites seen by Sanford.

September 23, 1981

Consortium for Continental Reflection Profiling (COCORP)

Executive Committee

C. L. Drake, Department of Earth Sciences, Dartmouth College, Hanover,
New Hampshire 03755
R. P. Meyer, Department of Geology and Geophysics, University of
Wisconsin, 1215 West Dayton Street, Madison, Wisconsin 53706
J. E. Oliver and S. Kaufman, Department of Geological Sciences, Cornell
University, Ithaca, New York 14853
R. A. Phinney, Department of Geological and Geophysical Sciences,
Princeton University, Princeton, New Jersey 08540
R. E. Sheriff, Department of Geology, University of Houston, Houston,
Texas 77004

Correspondents

P. R. Brett, Earth Sciences Section, National Science Foundation,
1800 G Street, NW, Washington, DC 20550
R. E. Hanson, National Academy of Sciences, 2101 Constitution Avenue,
Washington, DC 20418
P. J. Hart, Geophysics Research Board, National Academy of Sciences,
2101 Constitution Avenue, Washington, DC 20550
L. E. Johnson, Earth Sciences Section, National Science Foundation,
1800 G Street, NW, Washington, DC 20550
J. F. Lance, Earth Sciences Section, National Science Foundation,
1800 G Street, NW, Washington, DC 20550
T. L. Wright, Earth Sciences Section, National Science Foundation,
1800 G Street, NW, Washington, DC 20550

Site Selection Advisory Committee

K. Arbenz, Shell Oil Co., P. O. Box 527, Houston, Texas 77001
T. R. Bultman, Exxon Production Research Company, P. O. Box 2189,
Houston, Texas 77001
B. C. Burchfiel, Department of Earth and Planetary Sciences, MIT,
Cambridge, Massachusetts 02139
J. B. Cameron, Amoco Production Company, P. O. Box 5340A, Chicago,
Illinois 60680
J. C. Crowell, Department of Geological Sciences, University of California,
Santa Barbara, California 93106
R. H. Fakundiny, New York State Geological Survey, State Education
Building, Albany, New York 12234
J. I. Foster, Chevron Oil Field Research Company, P. O. Box 446,
La Habra, California 90631
W. Hamilton, Stop 964, USGS Federal Center, Denver, Colorado 80225
R. D. Hatcher, Department of Geology, University of South Carolina,
Columbia, South Carolina 29208
E. M. Moores, Department of Geology, University of California (Davis)
Davis, California 95616

Site Selection Advisory Committee (continued)

G. A. Thompson, Department of Geophysics, Stanford University, Stanford,
California 94305

Technical Advisory Committee

M. M. Backus, Department of Geological Sciences, University of Texas,
P. O. Box 7909, Austin, Texas 78712
K. Burke, Department of Geological Sciences, SUNY-Albany, 1400 Washington
Avenue, Albany, New York 12203
J. K. Costain, Department of Geological Sciences, VPI and SU, Blacksburg,
Virginia 24061
G. A. Crews, Cities Service Technical Center, P. O. Box 3908, Tulsa,
Oklahoma 74102
G. Crosby, 356E IC Building, Phillips Petroleum Company, Bartlesville,
Oklahoma 74004
A. F. Gangi, Department of Geophysics, Texas A&M University, College
Station, Texas 77843
T. V. McEvilly, Department of Geology and Geophysics, University of
California, Berkeley, California 94720
H. Mack, Mobil Field Research Laboratory, Box 900, Dallas, Texas 75221
F. Muir, Chevron Oil Field Research Company, P. O. Box 446, La Habra,
California 90631
S. J. Pereira, Amoco Production Company, P. O. Box 591, Tulsa, Oklahoma
74102
P. C. Wuenschel, Gulf Research and Development Company, P. O. Box 2038,
Pittsburgh, Pennsylvania 15230
M. S. Yancey, Continental Oil Company - ERD, Box 1267, Ponca City,
Oklahoma 74601

Contractor Proposal Evaluation Subcommittee

R. L. Geyer, Gulf Research and Development Company, P. O. Box 36506,
Houston, Texas 77036
R. S. Kallweit, Amoco Canada, 444 Seventh Avenue, SW, Calgary, Alberta,
Canada T2P 0Y2
J. L. Morrison, Chevron USA, 1111 Tulane Avenue, New Orleans, Louisiana
70112

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AUTHOR'S ABSTRACT

Please type, double-spaced. Send 2 copies to:
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TITLE OF PAPER Magnetotelluric Soundings of the Rio Grande Rift

COCORP Seismic Profile in New Mexico

AUTHORS *George R. Jiracek, I. K. Reddy, Roger J. Phillips, James H. Whitcomb

(Indicate with an asterisk * the author who will present paper at SEG Annual Meeting.)

Eight magnetotelluric (MT) soundings were completed in March 1977 across the geothermally promising Rio Grande rift of central New Mexico. The MT line coincides with the continuous seismic profile of the deep basement performed by the Consortium for Continental Reflection Profiling (COCORP). A portion of the seismic results have been interpreted as outlining a possible magma chamber at a depth of 18 km previously inferred from micro-earthquake studies.

The MT soundings at each site were recorded over five overlapping frequency bands using a cryogenic magnetometer. The data were recorded digitally and covered the period range 0.01 sec to 1000 sec. Electrical properties of the earth have been calculated from the apparent resistivities in the principle directions as computed from the tensor impedances in the measured directions. Four d.c. bipole-dipole equatorial resistivity soundings provided shallow (≤ 1 km) control for a portion of these calculations. Interpretation of the combined data provides information regarding continental rift structure and suggests that an electrically conductive zone is associated with the proposed magma body.

Figure 7. Location map of Abo Pass - Socorro Area

Figure 1. Locations of leveling routes and boundaries of Rio Grande rift, from Sanford and others (1972). Fault boundaries are solid lines; other types of boundaries are dashed. Area enclosed by square is shown in more detail in Figure 2.

Modern uplift associated with a proposed magma body in the vicinity of Socorro, New Mexico

Robert Reilinger, Jack Oliver
Department of Geological Sciences
Cornell University
Ithaca, New York 14853

ABSTRACT

Analysis of repeated levelings in and near a part of the Rio Grande rift in New Mexico reveals a zone of anomalous relative uplift in the vicinity of Socorro. Maximum uplift relative to nearby bench marks was about 20 cm from 1911 to 1951, corresponding to an average relative velocity of 5 mm/yr. This feature is one of the most clear-cut and striking anomalies of this scale ever detected by leveling in the United States. The principal data come from a north-south profile extending from El Paso, Texas, to Albuquerque, New Mexico. The primary anomaly extends approximately 70 km north from a point about 15 km south of Socorro; the maximum observed uplift occurs approximately 25 km north of Socorro. This zone of anomalous relative uplift overlies and closely correlates spatially with the unusual crustal discontinuity that was detected by Sanford and others and which, on the basis of a variety of evidence, was tentatively identified by them as the upper boundary of a magma body at a depth of about 18 km beneath Socorro. A simple elastic model for surface deformation associated with subsurface magmatic activity indicates that the observed movement in the Socorro area could result from the expansion of a magma chamber at a depth approximately equal to the depth of the discontinuity reported by Sanford and others, but the model is nonunique, and an elastic model may not be realistic.

INTRODUCTION

Sanford and others (1973), using reflected phases from microearthquakes in the Socorro, New Mexico, area, mapped and studied an unusual crustal discontinuity beneath a part of the Rio Grande rift. The discontinuity is at a depth of 18 km near Socorro and dips northward. At a distance of 60 km north of Socorro, the depth is about 30 km. Amplitude ratios of reflected seismic phases suggested to them that the discontinuity is underlain by a zone of very low rigidity. On the basis of the results of that study and other information (including high heat flow, the occurrence of numerous thermal springs, weak Pn phases from the GASBUGGY underground nuclear explosion, and geologic evidence for post-Pliocene uplift), Sanford and others (1973) suggested that a zone of low rigidity, in essence a magma body, exists in the crust beneath the Socorro area of the Rio Grande rift. Anomalously high seismic activity in the Socorro section of the rift as compared to other parts of the rift zone (Sanford and others, 1972) and geologic evidence for continued rifting in the Socorro area (Chapin and Seager, 1975) suggest that the magma body is not quiescent. Seismic reflection profiling under the COCORP project resulted in detection of a strong reflector at the depth of the upper surface

of the proposed magma body (Oliver and Kaufman, 1976).

A group at Cornell University, in cooperation with the National Geodetic Survey, has been investigating recent vertical movements of the crust in much of the United States; the movements are delineated by the comparison of precise leveling surveys. Data in the Socorro area of the Rio Grande rift indicate rather striking rates of relative uplift and tilts, which, on the basis of their location and spatial pattern, appear to be associated with the proposed magma body. This paper describes the data and their relation to the injection of magma at depth. The topic seems important not only because of geothermal energy potential, but also because of the fundamental importance of intrusion in the evolution of continental crust.

The Socorro anomaly is also of interest because, although somewhat smaller, it is comparable in scale to the recently described (Castle and others, 1976) uplift near Palmdale, California. The Palmdale uplift has been reported in the press as a possible forerunner to a major earthquake. Although the causes of the two anomalies are not necessarily similar (and, in fact, are probably different), both are large uplifts and apparently indicate crustal deformation of a tectonic nature, and thus are related in that sense.

Figure 2. Map showing locations of leveling routes and bench marks (crosses) in the vicinity of Socorro, New Mexico. Reflection points in vicinity of Socorro at which Sanford and others (1973) have determined depths to crustal discontinuity are indicated by solid circles (depths are shown in cross section in Fig. 3). Large circle centered approximately 26 km north of Socorro shows outer boundary of a theoretical magma body described in text. Squares indicate locations of towns.

Figure 3. Relative velocity profile from El Paso, Texas, north to Albuquerque, New Mexico. Dates of surveys of individual segments are indicated at top of figure. Topography along leveling route is also shown. Locations of a number of cities and a number of key bench marks (BM) are indicated. Cross section along a profile oriented N27°E, showing depths to crustal discontinuity as reported by Sanford and others (1973), is also given.

RECENT CRUSTAL MOVEMENT IN THE SOCORRO AREA

The procedure used here for obtaining vertical crustal movements from precise leveling surveys is identical to that commonly used by the National Geodetic Survey and described in some detail by Brown and Oliver (1976). Relative elevation changes are obtained by subtracting the elevation difference between a given bench mark and a reference bench mark at a reference time from the same difference measured at some other time. Relative velocities are obtained by dividing the relative elevation changes by the time interval between surveys—that is, only average velocities can be calculated. The resulting vertical velocity profiles are not connected to any absolute reference—therefore, only relative velocities are significant.

Figure 1 shows the locations of the leveling routes and indicates the approximate boundaries of the Rio Grande rift in New Mexico (as described in Sanford and others, 1972; for a discussion of the rift and its boundaries, see Chapin and Seager, 1975). Figure 2 shows the locations of bench marks resurveyed by first-order leveling in the Socorro area and referred to in the text and other figures. Figure 3 shows relative vertical velocities along the profile extending from El Paso, Texas, to Albuquerque, New Mexico. A cross section

showing depths to the crustal discontinuity approximately along this line and as reported by Sanford and others (1973) is also shown in this figure. Intervals between leveling traverses are noted above segments of the profile. The data are unusually homogeneous in this regard, each segment covering about the same 40-yr interval.

The velocity profile of Figure 3 shows a number of features of potential interest. There appears to be a zone of increasing relative uplift extending about 75 km to the north from near El Paso. The next 150 km show no features of particular interest, although this entire segment might be thought of as a modestly updomed region between El Paso and the vicinity of bench mark (BM) 4548, where several bench marks suggest subsidence relative to points to the south and north. Alternatively, this short zone of relative subsidence might be paired with the zone of striking and rather symmetrical uplift centered around BM 4698 north of Socorro (the Socorro anomaly). Regardless of whether this association is made and regardless of whether the datum is chosen to be (1) El Paso, (2) the flat segment from about 190 to 230 km, (3) BM 4548, or (4) a smoothed curve through points to the north and south, the Socorro anomaly is a very prominent feature. This is so not only because of the high relative velocities involved, but also because of the rapid spatial changes in velocity, or tilt rates.

The Cornell group has examined and is studying almost all of the first-order releveling information for the United States, and this anomaly is one of the most prominent that has been observed.

The Socorro uplift is located almost directly above the subsurface discontinuity reported by Sanford and others (1973). If the small zone of relative subsidence to the south is unrelated to the uplift, the leveling anomaly begins at about BM 4548 USGS, approximately 15 km south of Socorro. The uplift rate reaches a maximum of about 6.1 ± 0.4 mm/yr at BM 4698 USGS 23 km north of Socorro, and it decreases to about 3.2 ± 0.5 mm/yr at BM 4770 USGS about 55 km north of Socorro—all velocities being relative to BM 4548 USGS.¹ If BM 110 USGS is the standard, 2.2 mm/yr should be subtracted from these values, but the velocities are still quite substantial. Furthermore, tilt rates (change in velocity per unit distance along the route) between BM 4548 and BM 4698 and between BM 4698 and BM 4770 are 1.5×10^{-7} rad/yr and 9.4×10^{-8} rad/yr, respectively. Tilt rates of such large magnitude over so long a

¹ Error limits represent random errors that accumulate with distance and are calculated from relations given by Holdahl (1973). Error limits on all relative velocities represent $\pm 1\sigma$ relative to BM 4548 USGS.

Figure 4. Relative velocity profile from Belen, New Mexico, to Amarillo, Texas. Profile was derived from 1911 and 1958.5 first-order leveling surveys. Topography along leveling route is also shown. Two bench marks referred to in text are identified on figure.

distance are extremely uncommon and are observed in few other profiles throughout the entire United States. Still larger tilt rates occur between some pairs of adjacent bench marks over the Socorro anomaly.

To the north of the large domal feature, the velocity profile in Figure 3 indicates generally increasing uplift relative to BM 4548 (excluding the local deviation in the vicinity of Belen), with the uplift diminishing or perhaps ending just south of Albuquerque. Data farther to the north are second order and therefore are not included here. The last few bench marks on the profile indicate rapid tilting down to the north in the vicinity of Albuquerque. To attempt to attach tectonic significance to the rapid tilting in the vicinity of Albuquerque is risky, because this area has been subjected to considerable groundwater withdrawal (Gerlach, 1970), and the observed tilt may be due to compaction of the underlying sediments. If the northernmost bench marks of the profile in Figure 3 are ignored, a tilt rate of about 2.2×10^{-8} rad/yr remains for the northern part of the profile. This tilt rate is rather small compared to the tilt rates associated with the Socorro anomaly. Uplift of the segment north of the Socorro anomaly relative to BM 4548 (or, alternatively, El Paso) suggests possible magmatic or tectonic activity in this region as well, but the effect is not so clear nor so large as

that near Socorro. If only the north-south profile were available, much of the effect near and to the north of Belen could perhaps be explained by large cumulative error proceeding to the north, but data from the east-west profile (Fig. 4) provide rather strong evidence against this explanation.

The remaining data on vertical crustal movement in this area were observed along the route running from Belen, New Mexico, to Amarillo, Texas. The relative velocity profile derived from 1911 and 1958.5 first-order surveys is shown in Figure 4. The westernmost portion of the profile indicates uplift at a rate of about 2.5 ± 0.4 mm/yr of the central part of the rift relative to BM Y5, approximately 3 km southwest of Mountainair. This datum is typical of bench marks over much of the remainder of the profile east of the rift. The uplift corresponds to a tilt rate of approximately 5×10^{-8} rad/yr along the segment of the profile between BM 16 and BM Y5. Thus, uplift north of the Socorro anomaly seems to be real, but further study of it is not reported here.

COMPARISON WITH THEORY

The close spatial coincidence between the Socorro leveling anomaly and the area above the proposed magma body suggests that the vertical movements in the Socorro area result from processes directly

Figure 5. Observed surface deformation between BM 4509 USGS and BM 4770 USGS (circles) and theoretical deformation for a subsurface pressure source as given by Dieterich and Decker (1975). Theoretical curve shows vertical surface deformation resulting from a pressure increase within a circular cavity with a radius of 18 km and a thickness of 0.9 km centered 3 km north of BM 4698 USGS at a depth of 18 km. Cross section of this model is shown in bottom part of figure. Map view is shown in Figure 1.

related to the subsurface magma body. Persistent seismic activity and geologic evidence for long-term doming suggest that inelastic phenomena, such as faulting, are important in transferring effects from the magma body to the surface. However, it may be of some interest to consider an elastic model in this context. The simple, rather symmetric, shape of the anomaly suggests that elastic effects may be of at least transient importance, even though faulting probably dominates the vertical tectonics over the long term.

Dynamic processes in subsurface magma chambers have been modeled by pressure changes in crustal cavities (Fiske and Kinoshita, 1969; Dieterich and Decker, 1975; Stuart and Johnston, 1975). Dieterich and Decker (1975), using the finite-element method, determined surface deformations resulting from inflation of magma reservoirs of various geometries. In their analysis, the crust is modeled as a uniform elastic half-space, the magma reservoir being represented as a cavity in the elastic body. Figure 5 shows the observed deformation between BM 4509 USGS and BM 4770 USGS, with the vertical surface deformation resulting from increased pressure within a disk-shaped cavity 18 km in radius and 0.9 km in thickness, symmetric about the vertical axis, and centered 3 km north of BM 4698 USGS at a depth of 18 km. The ratio of cavity radius to thickness is fixed by the

model and not determined by fitting the data. The model is shown in map view in Figure 2 and in cross section in Figure 5. The maximum deflection of the theoretical curve is adjusted to provide the best fit of the data. The horizontal scale in Figure 5 indicates the distance of bench marks from a point on the surface directly above the center of the magma body in the model. The model presented in Figure 5 cannot be a very realistic representation of the actual magma reservoir. The discontinuity reported by Sanford and others (1973) extends well beyond the limits of the magma body in the model (Fig. 2), and recent studies (A. R. Sanford, personal commun.) suggest that the boundary is relatively complex in form. Furthermore, the model does not account for the movements north of BM 4770 that are indicated by the northward extension of the El Paso to Albuquerque profile (Fig. 3) and the western segment of the Belen to Amarillo profile (Fig. 4), nor the relative subsidence just south of the Socorro anomaly. Nor is the particular model presented here unique. The pattern of surface deformation indicated by the Socorro anomaly could be fit equally well by varying the geometry and depth of the magma body—more localized sources at greater depths or more extensive sources at shallower depths. Furthermore, if the zone of relative subsidence to the south is also a part of the Socorro anomaly, a more complex model of magma movement is required. The primary value of the simple model presented here is that the similarity between the observed and theoretical deformation shown in Figure 5 indicates in a general way that the anomalous relative uplift in the Socorro area could result from inflation of a magma body approximately 18 km below the surface.

Assuming a straight line between BM 110 and BM 4770 as a base, neglecting the relative subsidence near BM 4548, and assuming that the Socorro anomaly is circularly symmetric, we obtain a volume of about 0.2 km^3 for material uplifted above the 1912 datum as of 1950. Dieterich

and Decker (1975) did not give the relation between volumetric increase of the magma chamber and volume of uplift above such a datum, but these volumes can hardly differ by more than a factor of about two. Thus, the average inflation rate for the magma body must be on the order of $5 \times 10^{-3} \text{ km}^3/\text{yr}$. This value falls between figures of $4 \times 10^{-4} \text{ km}^3/\text{yr}$ calculated from data on the East rift zone of Kilauea (data from Dieterich and Decker, 1975), averaged over a 6-yr interval, and $1 \times 10^{-2} \text{ km}^3/\text{yr}$ for Sakurazima (data from Mogi, 1958), averaged over a 13-yr interval.

CONCLUSIONS

Comparison of observed elevations from leveled survey lines in the Socorro, New Mexico, area of the Rio Grande rift indicates rapid relative uplift centered about 25 km north of Socorro. Tilt rates associated with this leveling anomaly are at least an order of magnitude larger than those that can be ascribed to random errors in leveling. Rates of such large magnitude are observed in few other profiles throughout the entire United States. The close spatial coincidence between the area of anomalous relative uplift and the location of the magma body proposed by Sanford and others (1973) and, secondarily, the similarity between observed deformation and theoretical vertical deformation associated with a magma body indicate that these movements could result from expansion of the proposed magma body. Thus, the new information presented here provides additional support for a magma body of considerable extent in the Socorro area.

The last relevant leveling observations were made almost 25 yr ago. Since that time, the Socorro area of the rift has been seismically active and quite possibly has undergone further deformation. We urge that more information on this anomalous area with a possible magma body be obtained by carrying out additional first-order leveling in this area.

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8699 Volcanology topics
GEOMETRY AND PHYSICAL PROPERTIES OF THE SOCORRO,
NEW MEXICO, MAGMA BODIES
Thomas M. Brocher (Department of Geological and
Geophysical Sciences, Princeton University,
Princeton, New Jersey 08544; now at the Hawaii
Institute of Geophysics, University of Hawaii,
Honolulu, Hawaii 96822)

Analysis of multichannel seismic reflection profiles gathered by the Consortium for Continental Reflection Profiling (COCORP) constrains the geometry and material properties of a proposed magma body located within the Rio Grande rift. A new spectral ratio method is used to find the reflectivities of the proposed mid-crustal intrusion; large and spatially variable reflectivities support the interpretation of the reflector as a intrusive molten magma complex. Modeling of the reflectivity suggests that in one location the intrusion took the form of several thin (30 to 40 m thick) layers. Seismic wave attenuation within the rift's mid-crust is low. (Magma complex, reflectivity, attenuation, COCORP).

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11/16/81

Chevron Resources Company/Golden, Colorado
Charles M. Swift, Jr., Division Geophysicist
Domestic Minerals Division

Swift was recently transferred from Chevron's Geothermal Office near San Francisco to the Golden office. He said that his new title was indicative of Chevron's outlook for geothermal energy. Swift expressed the opinion that data do not exist that definitely show a shallow magma body in the crust. He thought a lot of work remained to be done in order to determine the best geophysical techniques for magma location. Swift said that, although three or four soundings were made, an extensive MT survey has not been conducted at Yellowstone. He thought Union Geothermal did have extensive MT data for The Geysers region but treated it as privileged information. Swift stated that present MT instrumentation should be adequate for magma location. The primary problem in MT work is interpretation. He agreed with Bostick's conclusions concerning the difficulty of distinguishing large conductors in the crust due to masking by small near-surface conductors or large deep conductors. To aid interpretation, Swift stressed the importance of conducting a complete MT survey in Yellowstone where a huge magma body is thought to exist.

Concerning other geophysical techniques, Swift said he was not impressed with the DOE-funded work at Berkeley using active electromagnetic sources. He did think Iyer's (USGS, Menlo Park) passive seismic work was good, but pointed out the poor depth resolution obtained. He thought thermal methods were poor because they are too dependent on the local geology. Magnetic methods were also viewed as poor for magma location. Swift did feel that reflection seismic techniques should be useful for magma location but there are real problems in transmitting sufficient energy through the upper 1.2 km of the crust. Swift mentioned that Jim Applegate (Colorado School of Mines) had completed a reflection seismic survey in The Geysers and that Pierre Goupillaud (Systems, Science and Software) ran a reflection seismic survey in the Imperial Valley. Swift thought that in this latter work, S-wave reflections were lost after about 1.2 km. Swift stated that reflection seismic profiling is well understood in sediments, but interpretation is difficult in complicated igneous terrain. He thought Sandia should continue to work in Hawaii where magma systems are best understood and more certain than the predicted bodies in the Western United States. Swift did, however, name other areas where he felt geophysical prospecting for magma might be fruitful. These regions are: 1) Coso Hot Springs, 2) San Francisco Peaks, and 3) Lunar Craters.

11/16/81

USGS, Office of Geochemistry and Geophysics, Branch
of Electromagnetism and Geomagnetism, Denver,
Colorado

Frank Frischknecht, Geophysicist
Don Hoover, Geophysicist
Bruce Smith, Chemist
Jim Towle, Geophysicist

All of the above expressed the opinion that magma bodies within the upper 10 km of the earth's crust could be located. Hoover described a recent integrated study in southern Nevada near the NTS.

Iyer (USGS, Menlo Park) collected passive seismic data. Magnetotelluric (MT) and Curie point isotherm surveys were also run. Approximately 50 stations were occupied. Hoover thought a combined study of this type would be needed to locate magma.

Frischknecht said that controlled source electromagnetic methods would be a good technique for magma location. He also pointed out that a major problem with electrical methods is the difficulty in discriminating among good conductors. Conductors can be located, but they may be magma, hot rock, or simply hot water. Frischknecht is developing a single-loop time-domain system that is best suited for finding cylindrical bodies. Frisknecht thought that, based on his present equipment, he could detect bodies at depths up to 3 km, possibly up to 5 km. He said that George Keller (Colorado School of Mines) could probably resolve deeper bodies with his 1 MW source.

Towle thought that MT should be used as an initial survey method and would be good for the detection of deep magma bodies. Other techniques would be better for locating very shallow (less than 1 km depth) intrusions.

Smith said he felt that more work needs to be done to develop a good physical model of a magma system. The description is needed to optimize geophysical sensing techniques. Smith stated that electrical measurements show a partial melt zone in the center of Mount St. Helens under the large dome. He thought Sandia should study this region, especially by drilling into the melt.

Hoover said that Iyer has a recent paper out on the San Francisco Peaks area that reports P-wave delays. He felt that electrical surveys should be completed in this same area.

Towle said that Ed Wolfe (USGS, Flagstaff) had recently completed a USGS professional paper on the San Francisco volcanic field. Some seismic data is included.

Geophysical data in the Puhimau/East Rift area was briefly discussed. Frischknecht mentioned Zablocki's VLF data, but said no electromagnetic work has been done. Frischknecht said he will be in Hawaii during January, 1982, and would like to conduct an EM survey in the Puhimau area. He will pursue this idea with Dallas Jackson (USGS, Hawaiian Observatory).

11/17/81

Colorado School of Mines

James K. Applegate, Director Exploration, Research
Lab
Chuck Barry

Applegate has used P-wave and S-wave reflection seismics to look for anomalies in geothermal areas. He has seen anomalies at 12-16 kft beneath The Geysers. In the Snake River Plain he has been able to see through thick surface basalt layers. Applegate has tried to get NSF funding to look for magma beneath Krafla in Iceland. He said that an amplitude anomaly should occur in the seismic signal as long as there is a change in physical properties at some boundary. He expects that a strong S-wave reflection would occur at a magma boundary. Applegate has experienced difficulty in getting S-waves to propagate through

surface sediments. Also, obtaining a good coupling with the crust has been a major problem, especially in alluvial basins. In layered igneous environments, S-waves do not penetrate well through the fractured layers. When asked about downhole sources he said that a downhole S-wave source would be very useful both for magma prospecting and other exploration work. He was familiar with some of the patents we had seen but he said he knew of no working models for downhole shear generators.

Applegate said that a combined P-wave and S-wave reflection survey would give good information about depth to a magma body and the different reflected signals would help identify the characteristics of the magma body. In addition to the reflected signals there would also be P to S conversions depending on the inclination of the magma boundary.

The Colorado School of Mines Research Institute, where Applegate works, has their own P-wave and S-wave Vibroseis trucks and recording equipment. They also do their own processing of data. They feel that their current processing capability is good and quite adequate to begin looking for magma bodies.

George Keller was out of the country, teaching in Moscow for two months, and Applegate filled us in on Keller's current progress with electrical geophysical methods. Keller uses an active transient electrical geophysical technique called time-domain electromagnetic sounding. A grounded wire 1 or 2 km in length is powered by a 1 MW generator. The ground connection is made using a backhoe to bury a large strip of corrugated metal and salt water is poured over the fill. Keller makes E-field measurements and uses cryoelectronics for magnetic field measurements. He is able to map 15-20 km deep and with a few measurements can cover 300 to 500 square miles. He has used the technique in Nevada, southern Arizona and the Snake River Plain. In some areas this technique can be used for oil exploration where reflection seismic techniques will not work. This electrical method would be a good reconnaissance method for locating possible magma bodies. A typical site survey would cost about \$300K.

PROPOSAL FOR CARRYING OUT A TIME-DOMAIN ELECTROMAGNETIC SURVEY

TO DEFINE SUBVOLCANIC SEDIMENTARY BASINS

INTRODUCTION

For the past seventeen years, research has been carried on at the Department of Geophysics, Colorado School of Mines, to evaluate the prospects for using various electrical techniques in the search for oil and gas. This research has suggested a number of ways in which electrical methods can be used, including their use for the study of geologic structure, for detecting environments favorable for the occurrence of oil and gas, and for the direct detection of oil. One of these which is closest to being possible with the present state-of-the-art for electrical surveying in the field is the approach based on detection of structure beneath volcanic or other cover. Therefore, we are proposing a demonstration survey to evaluate the merits of a highly developed electromagnetic sounding system for application in such structural studies.

The Proposed System

One of the exploration techniques that has been most intensively studied at the Colorado School of Mines is the time-domain electromagnetic sounding system. It is felt that such a system has significant advantages over other competing systems, such as direct-current sounding or magnetotelluric sounding, both in terms of the precision of results which can be obtained and costs of field operations.

In the time-domain electromagnetic sounding system as we are using it, the electromagnetic field is generated by passing a step wave of current through a grounded wire. Typically, the grounded wire is one or two kilometers in length. In the most recent applications of this method, a power source of approximately one megawatt has been used, providing current steps of the order of 2,000 amperes to the grounded wire. The current steps which are transmitted range up to several minutes in length, so that the wave form contains a sufficiently wide spectrum of low frequencies so as to permit penetration to great depths.

In making a sounding, any of the components of the electromagnetic field might be measured, but for various reasons, we have standardized on the use of the vertical magnetic field. The vertical magnetic field can be detected using either a multiple turn induction loop lying on the ground or a high sensitivity magnetometer. Over the last half dozen years, most surveys we have done have made use of a Cryogenic magnetometer of extremely high sensitivity.

Carrying out an electromagnetic survey consists of occupying a number of receiver locations for each transmitter site. With a megawatt source, the range at which the magnetic field can be detected easily is

35 to 70 kilometers. Therefore, it is possible to make many hundreds of receiver locations for a single transmitter location in a large area survey. Typically, several measurement crews operate simultaneously to improve the productivity of the operation.

When the source current reverses direction in the step wave, there will be a relatively slow transient change of the magnetic field, with the shape of the transient change being controlled by the electrical structure of the earth. For investigations to depths of many kilometers in sedimentary basins, these transient changes will persist for several tens of seconds. They are usually recorded on a digital recorder, such as the LSI 11-23. The incoming signal from the sensitive magnetometer is converted to digital form at a sampling rate of 25 to 50 samples per second. The signals are synchronously stacked with editing being carried out in real time to remove obviously spurious events. There is a trade off between the signal strength which can be accepted and the length of time required for stacking. In a commercial operation in order to maintain a relatively low cost of data acquisition, normally no more than a few tens of signals are stacked; this requires a recording period of the order of one-half hour.

The recorded signals are subsequently processed to remove system response and to reject any noise which has not been suppressed by the stacking process. The first step in interpretation is then to carry out a one-dimensional inversion of each curve, to provide resistivities of a sequence of layers representing the subsurface. Unless there has been some unusual problem in data acquisition, such inversions usually can be carried out with a precision of match of the order of one to three percent of RMS error. Inversions are typically done in terms of three to five layers representing the subsurface. Resolution decreases with depth, but is better for conductive horizons than resistive horizons.

Up to the present time, no practical numerical schemes for three-dimensional modeling of time-domain electromagnetic soundings has been carried out. Part of the intent of the project being proposed here is to develop a numerical program for such three-dimensional modeling.

Choice Of A Survey Area

The time-domain method should be effective in measuring the resistivity of the subsurface to depths as great as ten kilometers and with a resolution which will allow identification of three to five geoelectric units. Such a method may be particularly effective in areas where sedimentary basins are covered either by thick volcanic sections or by overthrusts. In such areas, it is often difficult to obtain seismic data, and information about the thickness of sedimentary rock is a minimum requirement for evaluating the potential for occurrence of oil and gas. Areas where there is current exploration interest that are of this type include the basalt-covered areas of Washington, Oregon, and Idaho, volcanic-covered areas in Utah, the Rocky Mountain Overthrust Belt, and possibly the Appalachian Overthrust Area. In each of these exploration provinces, it is reasonable to expect that electrical

methods can provide a rapid and reasonably accurate evaluation of the thickness of conductive sedimentary rocks in the subsurface. At the present time, the magnetotelluric method is being widely used in such exploration. However, the magnetotelluric method does not offer the same precision as the time-domain electromagnetic method, and is considerably more expensive. We are proposing the field evaluation of a commercial scale electromagnetic survey in one of the areas described above, to provide information about the effectiveness of the electromagnetic method for such exploration.

Structure Of The Project

The project being described here will be under the supervision of George V. Keller, Head, Department of Geophysics. Chief technical responsibility will rest with Professor Charles H. Stoyer. The field operations will be carried out by members of the Exploration Research Laboratory, which is an arm of the Department of Geophysics. The field crew will be under the supervision of a field manager to be designated by the Exploration Research Laboratory at the time operations begin.

The project will be initiated on or about February 1, 1982, providing that a sufficient number of companies have signed agreements to meet our minimum requirements for financial support. The interval from February 1 until June 1 will be spent in assembling the field system. Part of the equipment is already available at the Colorado School of Mines, including many of the vehicles, and some of the recording equipment. It will be necessary to fabricate a high-power source system, and to acquire one or two additional recording systems, depending on the scale of effort finally decided upon.

It is anticipated that approximately 45 days of field operations will be carried out for this project. It is intended that between 300 and 500 electromagnetic soundings be completed at a density of approximately one per square mile in an area of particular interest. The field operations will be carried out during June, July, and August. Data processing will be carried out during September, October, and November. This will include both the preparation of field data for inversion, and one-dimensional inversion.

A final report covering the results of the study will be completed in December of 1982, for distribution before the end of January 1983.

The support required to carry out the survey as planned will be between \$300,000 and \$400,000. We are asking a \$20,000 fee from each company participating. Thus, a minimum of 15 companies will be required in order to undertake the project. If more than 20 companies are included as members of the group, the decisions about a change in the fee structure or the addition of scope to the project will be decided by the Executive Committee.

As indicated in the accompanying provisional contract, contact between the researchers at CSM and representatives of the contracting companies will be obtained through the formation of an advisory committee, with one member from each participant, and an Executive Committee of three members elected from the Advisory Committee.

Proposed Budget

A budget to accomplish the survey described in the preceeding paragraphs has been worked out in detail, but will be given only in summary terms here. The four principal categories of cost that must be met include the acquisition of equipment and supplies, field operating expenses, cost of data processing, and cost of supervision.

Under equipment it will be necessary to construct a 2,000 ampere switching system, based on commercially available design, and to acquire a sufficiently heavy cable to carry the 2,000 amperes of current at the source. In addition, in order to provide more efficient field operations, we are planning to add one or two magnetometers and the associated recording equipment. At present, we have a single recording system and a single magnetometer. However, in order to have a realistic field trial under conditions that would be appropriate for routine application, we feel that a minimum of three receiver teams will be needed. The amount of funding required to obtain this equipment will range from \$30,000, if no new recording equipment is obtained, to approximately \$100,000 with the addition of two receiver teams.

Field expenses include the salaries and per diem expenses of a crew of no less than eight people, rental of the prime generator for a period of two months, gasoline and diesel fuel to operate field equipment, and rentals on the various field vehicles. We project that for a 45-day field operation, the field costs will be \$93,500.

Processing of the field results will be computer intensive. Two graduate research assistants plus whatever additional staff as need be supplied by the Exploration Research Laboratory will cost approximately \$20,000, while rental of computer time to complete the processing may lie in the range from \$20,000 to \$50,000 depending on the amount of three-dimensional modeling performed. Thus, data processing will require \$40,000 to \$70,000.

In addition to the operating and equipment costs outlined above, the cost of supervision of the project provided by Professors Keller and Stoyer along with their travel, will fall in the range from \$10,000 to \$20,000. Thus, the minimum overall budget will be in the neighborhood of \$300,000.

RESEARCH CONTRACT

This RESEARCH CONTRACT is made between the Colorado School of Mines Exploration Research Laboratory, Golden, Colorado 80401 (ERL) and _____ ("Company").

1. Term. The term of this contract will begin on January 1, 1982, and end on December 31, 1982 ("Project Duration"). By mutual agreement, the parties may extend this Contract on such terms as they may agree to in writing.

2. Research. ERL agrees, during the project duration, to carry out a research program related to the demonstration of a time-domain electromagnetic method for exploration and a volcanic- or thrust-covered area. Such research will be performed in accord with the proposal prepared by George V. Keller entitled, "Proposal for Carrying out a Time-domain Electromagnetic Survey to Define Subvolcanic Sedimentary Basins", a copy of which is attached to this contract.

3. Independent Contractor. ERL will conduct such research and all work related thereto as an independent contractor, and shall have complete and exclusive authority and responsibility concerning the means, manner, and methods of conducting such research and work and any and all employees or persons used in connection therewith shall be the employees of ERL.

ERL will provide a certificate of insurance verifying general liability insurance up to the state statutory limit for state institutions. All ERL employees are covered by Workmen's Compensation as prescribed by law.

ERL will secure all appropriate permits prior to conducting operations.

4. Advisory Committee. Company and other entities with whom ERL is entering into agreements similar to this contract will create an Advisory Committee. The Advisory Committee shall be composed of a representative from each entity and shall have a duly elected chairman. The Advisory Committee shall meet approximately three times per year to receive input on the research effort. The Advisory Committee will also provide recommendations for technical and scientific changes to the Executive Committee.

5. Executive Committee. An Executive Committee will be formed. The Executive Committee will consist of the Project Principal Investigator, the Director of ERL, the chairman of the Advisory Committee, and four members elected from the Advisory Committee. The Chairman of the Advisory Committee shall also be

Chairman of the Executive Committee. The Executive Committee will meet upon call of the Chairman, or the Principal Investigator to consider details of the research, budget, scope, etc. and will make recommendations to the project management, and to the Advisory Committee.

6. Project Direction. ERL will manage the project in concert with the principal investigator, Dr. George V. Keller. The project management and the Executive Committee will maintain liaison to ensure the flow of information from Company to ERL and vice versa.

7. Research Information. The Company acknowledges that the research results may be made available to the public through theses. Prior to the end of the Project Duration, ERL will invite the Company to a seminar at which the research activities will be discussed. A written report presenting research results will be sent to the Company after the end of the Project Duration. At least 90 days prior to a publication or presentation, the Company will also be furnished with manuscript or abstract, as submitted for publication or presentation, which involves research performed under this Contract.

ERL will release no data until at least six months after the Company is provided with the final report except in the case of thesis material. The Company will be provided with copies of any thesis incorporating data from this study.

ERL agrees that at any time any significant development is accomplished by ERL, it will promptly call special meetings for Advisory Committee. Written notice shall be given to the Company and such Committees of the time and place of any such meetings at least 10 days in advance thereof.

8. Patents and Licenses. Patents resulting from this work will be the property of CSM. The Company will have a royalty free license to these patents.

9. Research Fee. As consideration for the research work to be performed, Company agrees to pay \$20,000 to ERL within 60 days following the date this Contract is signed by Company if contract is signed on or before January 20, 1982. Persons committing to this contract after January 20, 1982 will be considered a late contractee and will be charged a research fee of \$30,000.

10. Changes. This contract can be changed only by mutual agreement of both parties, and with the concurrence of all of the other companies having contracts in this series, given in writing.

11. Disputes. In the event of any contractual dispute, the laws of the State of Colorado shall apply.

- 3 -

12. Cancellation. ERL reserves the right to cancel this contract if an adequate number of sponsors are not obtained.

Company

Colorado School of Mines

W. Gordon Scott
Vice President for Business
Affairs

Date

Date

11/19/81

University of Oregon/Eugene, Oregon
Harve S. Waff, Associate Professor of Geophysics

While visiting at the University of Oregon, I talked for an hour with Harve Waff concerning techniques for locating magma. Waff is building up some equipment, similar to that of Keller's at Colorado School of Mines, for the electrical detection of magma bodies. Waff plans to use an active electrical current device with a 40 KW source to sound to depths of 10 km. He inputs a square wave pulse of current into the ground and looks at the transient response in the earth with a cryo-magnetometer. Waff plans to do the inversion work at the University of Oregon using programs developed by George Keller and others. Waff expects his equipment to become operational within a year. He seemed confident about finding shallow magma bodies, particularly in the Cascades. Problems with shallow mineralized pockets of water are minimized in the Cascades as such pockets are rapidly washed out and diluted by the extensive rainfall. Waff said that a significant 1.5 second P-wave delay had been discovered recently at the Three-Sisters area in Oregon suggesting a shallow magma body there.

12/9/81

Union Oil Geothermal/Santa Rosa
Dick Dondanville, Geothermal Exploration Geologist
Tom Powell, Area Geologist
Alex Schriener, Area Geologist
Gene Suemnicht, Structural Geologist and Geochemist

At the beginning, Dondanville and Suemnicht stressed the importance of surface manifestations in selecting a promising area for magma exploration. Basically the idea is to locate an area where surface expressions in the form of hot springs, fumaroles, lava flows, etc., have been reoccurrent in the past indicating that magma has been resupplied in the area. Choice of the youngest of such regions (age < 50,000 years) should then lead to high temperature magma systems. Based on this reasoning, all of the Union people advised against looking for magma in The Geysers area due to the approximately 1 M year age of igneous activity in the region. Dondanville thought that a large, hot, solidified batholith might exist in the Clear Lake region. Schriener stated that drilling at The Geysers had encountered numerous volcanic intrusions within a few km of the surface, but they were all considerably below their solidus.

The Union people thought that the Imperial Valley should be the best area for magma exploration. Dondanville commented that George Keller (Colorado School of Mines) had conducted good electrical surveys in this region. Dondanville and Suemnicht pointed out other likely locations for young magma systems: 1) Newberry Crater region, and 2) Medicine Lake/Glass Mountain region.

Once a region is selected, geophysical prospecting techniques could be used to locate the drillhole. Suemnicht said that seismic techniques have been successfully used in The Geysers field. He stated that the fractured igneous terrain was not as difficult as one might expect due to the existence of large blocks that are seismically coherent. Dondanville said that for geothermal exploration most of Union's geophysical prospecting money is spent on electrical methods. He

recommended both active and passive techniques. The Union people did not know which geophysical technique would be best for location of magma bodies.

12/15/81

Systems, Science and Software/La Jolla, California
Pierre Goupillaud

Pierre Goupillaud is a geophysicist with Systems, Science, and Software and he is the editor of GEOPHYSICS. He worked on the early development of Vibroseis while he was associated with Continental Oil. Some of his Vibroseis testing work in the Imperial Valley used a combination of S- and P-wave reflection seismics and identified an anomolous body, possibly magma, which came to within 6000 feet of the surface.

Goupillaud felt that it would be necessary to use more than one geophysical technique to identify magma. He favored active and passive seismic and gravity methods. He felt that Vibroseis techniques would be very good, particularly if S-waves were used in addition to P-waves. He noted that a Vibroseis shear wave generator is the best controlled shear wave source available. Although there is some difficulty in propagating S-waves through unconsolidated surface layers, he still felt that with a little effort a surface S-wave Vibroseis source would be used to generate the necessary deep S-waves needed for the detection of magma. He noted that W-waves move at about half the velocity of P-waves and the resulting longer wavelength propagates more efficiently through fracture zones than does P-waves. This, he said, should compensate somewhat for the problem of surface attenuation of S-waves.

Goupillaud noted that sufficient geophysical tools currently exist to begin looking for suitable magma bodies today. He said that eventually better tools and processing techniques will need to be evolved but this will require an evolutionary type of development rather than a revolutionary development. He emphasized that a sufficient, but minimum, set of geophysical tools and techniques currently exist for our purpose.

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