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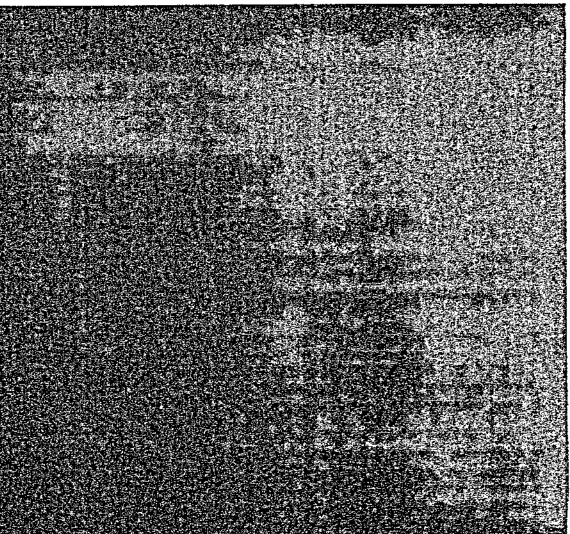
REPORT OF THE WORKSHOP ON MAGMA/HYDROTHERMAL DRILLING AND INSTRUMENTATION

MASTER

S. G. Varnado } Editors
J. L. Colp



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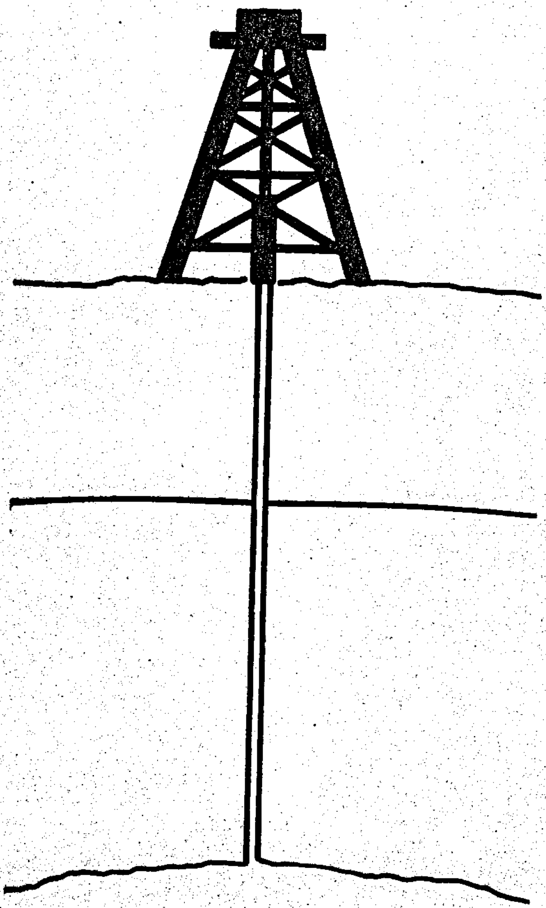

WORKSHOP ON MAGMA/HYDROTHERMAL DRILLING AND INSTRUMENTATION

AIRPORT MARINA HOTEL
ALBUQUERQUE, NEW MEXICO
MAY 31, JUNE 1 AND 2, 1978

CO-SPONSORED BY:
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SANDIA LABORATORIES

MASTER

REPORT OF THE WORKSHOP ON MAGMA/HYDROTHERMAL DRILLING AND INSTRUMENTATION

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S. G. Varnado
J. L. Colp

Editors

Abstract

This report summarizes the discussions, conclusions, and recommendations of the Magma/Hydrothermal Drilling and Instrumentation Workshop which was held in Albuquerque, NM, May 31-June 2, 1978. The purpose of the workshop was to define potential drilling environments and to assess the present state-of-the-art in drilling and instrumentation technology for a drill hole that would penetrate through deep hydrothermal systems and into a magma body. This effort is envisioned as a portion of a larger program of continental drilling for scientific purposes which has been proposed by the U. S. Geodynamics Committee of the National Academy of Sciences. For the purposes of the workshop, three working groups were organized as follows: Drilling Location and Environment, Drilling and Completion Technology, and Logging and Instrumentation Technology.

The first group discussed potential drilling sites and the environment that could be expected in drilling to magma depth at each site. Sites suggested for early detailed evaluation as candidate drilling sites were The Geysers-Clear Lake, CA, Kilauea, HI, Long Valley-Mono Craters, CA, and Yellowstone, WY. Magma at these sites is expected to range from 3-10 km deep with temperatures of 800-1100°C. Detailed discussions of the characteristics of each site are given. In addition, a list of geophysical measurements desired for the hole is presented.

The Drilling and Completion Group discussed limitations on current rotary drilling technology as a function of depth and temperature. The group concluded that present drilling systems can be routinely used to temperatures of 200°C and depths to 10 km; drilling to 350°C can be accomplished with modifications of present techniques, drilling at temperatures from 350°C to 1100°C will require the development of new drilling techniques. A summary of the limiting factors in drilling systems is presented, and recommendations for a program directed at correcting these limitations is described.

The third group discussed requirements for instrumentation and established priorities for the development of the require instruments. Of highest priority for development were high

resolution temperature tools, sampling techniques (core, formation fluids), chemical probes, and communications techniques. A description of instrumentation requirements for the postulated hole is given, and the tasks necessary to develop the required devices are delineated.

Table of Contents

REPORT OF THE WORKSHOP ON MAGMA/HYDROTHERMAL DRILLING AND INSTRUMENTATION

SAND78-1365C

Preface

The Workshop on Magma/Hydrothermal Drilling and Instrumentation was convened by Sandia Laboratories in Albuquerque, New Mexico, on May 31, June 1 and 2, 1978. The workshop was sponsored by the Department of Energy, Office of Energy Research, as part of the DOE preparation for participation in the Workshop on Continental Drilling for Scientific Purposes being convened by the National Academy of Sciences later in 1978.

The objectives of the Magma/Hydrothermal Drilling and Instrumentation Workshop were:

- To assess the present state of knowledge on drilling and instrumentation technology, possible borehole locations, and probable drilling environment for the proposed Continental Drilling Program, Magma/Hydrothermal drillhole.
- To recommend general areas of required research and development and to identify critical thrusts that should be initiated in FY-79 for the development of a detailed plan for the Magma/Hydrothermal Drilling and Instrumentation Program.

This report is the product of the three days' effort placed in the workshop by all of the participants.

The first day was devoted to the following informational presentations made to the entire group of participants:

"Sandia/DOE Continental Drilling Program and Plans as Related to the Magma/Hydrothermal Problem"
H. M. Stoller, Sandia Laboratories

"Sandia/DOE Geothermal Drilling Technology Program"
S. G. Varnado, Sandia Laboratories

"Sandia/DOE Geothermal Logging and Instrumentation Technology Program"
A. F. Veneruso, Sandia Laboratories

Possible Borehole Locations

"Summary of Status"
R. Christiansen, USGS, Menlo Park

"Yellowstone Study"
G. Eaton, USGS, Hawaiian Volcano Observatory

Possible Drilling Environment

"Thermal Characteristics of a Magmatic Location"
H. C. Hardee, Sandia Laboratories

"Interaction of Ground Water with Hot Intrusives"
H. Taylor, California Institute of Technology

"Heat Transfer in a Plutonic Environment"
D. Norton, University of Arizona

"Lava Lake Drilling Experience"
J. L. Colp, Sandia Laboratories

The second day and the morning of the third day were devoted to meetings of the three working groups for discussions and assessments of the individual assigned topics. The working groups and their leaders were:

Drilling Location and Environment
Prof. R. Decker, Dartmouth College

Drilling and Completion
B. Livesay, Livesay Consultants

Logging and Instrumentation
J. Burgen, Gearhart Owens, Inc.

On the afternoon of the third day the results of the discussions and assessments of the three working groups were presented to the assembly of all participants by each of the group leaders.

Appendix A lists the names and affiliations of all of the workshop participants.

REPORT OF THE WORKING GROUP ON DRILLING LOCATION AND ENVIRONMENT

Group Members

Prof. R. Decker, Dartmouth College (Chairman)

Dr. Hugh C. Heard, Lawrence Livermore Laboratory
Dr. Robert Christiansen, U. S. Geological Survey
Dr. Art Lachenbruch, U. S. Geological Survey
Dr. Gordon Eaton, U. S. Geological Survey
Prof. John F. Hermance, Brown University
Prof. D. Norton, University of Arizona
Prof. Hugh Taylor, California Institute of Technology
Dr. James Moore, U. S. Geological Survey
M. J. Davis, Sandia Laboratories
D. Douglass, Sandia Laboratories
T. M. Gerlach, Sandia Laboratories
H. C. Hardee, Sandia Laboratories
J. L. Colp, Sandia Laboratories

Introduction

One of the themes of continental drilling for scientific purposes is a better understanding of the thermal regime in the earth's crust, especially in areas of high heat flow. Erosional exposure of old, shallow magma bodies emplaced in the earth's crust indicate an important interrelationship between magma/hydrothermal systems and ore deposits. Yesterday's active magma/hydrothermal systems are today's ore bodies, and today's geothermal steam fields are ore bodies in the process of formation.

Direct geological examination of dead magma/hydrothermal systems exhumed by uplift and erosion provides much of our current knowledge of these important systems. Knowledge of still active magma/hydrothermal systems in the subsurface is inferred from surface geological, geophysical and geochemical investigations. Drilling is the only direct method of examination of these living systems.

Drilling Location

We selected the following general goal for our discussions and recommendations: Understanding the geometry and dynamics of thermal regimes related to geologically young volcanic centers or to regional anomalies of high heat flow. These we classified in the following way:

Classifications and Examples of Possible Drilling Targets

I. Volcanic Systems (local heat flow anomalies)

- A. Large predominately silicic volcanic systems with calderas
  - 1. Yellowstone (hot water and vapor-dominated)
  - 2. Long Valley (hot water)
- B. Predominately silicic volcanic systems without calderas
  - 1. The Geysers-Clear Lake (vapor-dominated and hot water)
  - 2. Mono Craters
  - 3. Mt. Lassen
- C. Predominately andesitic volcano
  - 1. Some Cascade or Alaskan stratovolcano
- D. Predominately basaltic shield volcano
  - 1. Kilauea
  - 2. Newberry or Medicine Lake
- E. Predominately mafic multi-center fields
  - 1. San Francisco volcanic field

II. Tectono-Magmatic Systems (regional heat-flow anomalies)

- A. Battle Mountain heat-flow high
- B. Edges of Great Basin heat-flow anomaly; such as, Sierra Front or Wasatch Front
- C. Rio Grande Rift
- D. Snake River Plain
- E. Salton Trough

Setting up such a classification identifies individual targets for drilling that should provide information on a general type of thermal anomaly rather than specific information on only one site. Many other examples could have been listed in the classification. It is of utmost importance to emphasize that present knowledge of potential drilling targets from both a geological mapping and geophysical surveying standpoint is far from complete, and comprehensive priorities cannot yet be established. However, a Continental Drilling Program aimed at better understanding of five to six major thermal systems over a ten-year period should be started.

From the above classification, our workshop group recommends the following possible drilling locations:

I. Highest priority for early detailed evaluation as candidate sites for drilling (no priorities at present within this group)

   A. The Geysers-Clear Lake, California
   B. Kilauea, Hawaii
   C. Long Valley - Mono Craters, California
   D. Yellowstone, Wyoming

II. High priority for selection of specific candidate systems to represent other major types of magmatic environments (no priorities within this group)

   A. Cascade Stratovolcano, Washington, Oregon, California
   B. Battle Mountain Heat-flow High, Nevada
   C. Medicine Lake, California, or Newberry Caldera, Oregon
   D. San Francisco Volcanic Field, Arizona, or some other young predominately basaltic volcano field

III. Other possible locations mentioned in the classification and examples table lack adequate geologic and geophysical information for analysis at present, but should receive critical attention for possible evaluation as candidate systems.

Priorities should be established among the candidate sites from all three of these groups, beyond areas on which site-specific work has already begun.

It is emphasized that these locations are only general targets, roughly circular areas about 100 km in diameter. Much more detailed work is needed to pick one or more points on a map that would yield the optimum drilling sites for each target.

The ultimate objective at each of the targets is to drill one or more holes into magma if possible. However, holes of intermediate depths and temperatures -- roughly in the range of 3 to 6 kilometers and temperatures of 200°C to 600°C -- can be expected to yield important data on the deep structure and thermal regimes in the root zones of hydrothermal systems and in the roof rocks of magma bodies. A reasonable approach from both a scientific and engineering standpoint may be a series of holes or one hole drilled to increasing depths and temperatures as new technologies and concepts evolve.

A thorough examination of the present knowledge of each target should be made, and should include the following considerations:

1) Basic scientific reasons for selection of this specific target

2) Geologic and geophysical description of the target

3) Geologic cross section, and physical and chemical conditions to be expected in drill holes

4) Specific problems expected or possible in the target area

Brief summaries of some of these considerations were prepared by various panelists. These are presented here to give some elaboration on each target, but without the benefit of second thoughts or adequate library research.

THE GEYSERS/CLEAR LAKE, CALIFORNIA (A. Truesdell)

Reasons for Study

The Geysers -- The Geysers is one of two major vapor-dominated geothermal systems in the world and the only geothermal power producer in the United States. Despite the hundreds of drill holes up to 3 km deep in this system, many scientific and practical questions remain. It is now accepted that a two-phase, water-steam reservoir exists with pressures controlled by steam although most of the fluid mass is water. The reason for the development of this sort of reservoir rather than the more usual pressurized water reservoir remains controversial. Below parts of this reservoir a deep, water-saturated reservoir is hypothesized to exist with boiling throughout and increasing salinity with depth. This reservoir has never been contacted by drilling and the thicknesses of both the two-phase reservoir and the deep water-filled reservoir are unknown. Despite the investment in power plants (500 MW_e capacity now, 900 MW_e soon) the size and longevity of the resource is unknown. Isotopic geothermometer studies of The Geysers and Laradello, Italy, (the other major vapor-dominated field) suggest that fluid temperatures of more than 350°C exist at depth. Gradients of Oxygen-18 in the steam suggest that major boiling zones may be limited in area compared with the size of the two-phase production reservoir, and that much of the reservoir is heated by lateral flow of steam from the boiling zone with counterflow of condensate. These suggestions remain highly controversial.

In summary, The Geysers is a major geothermal system which must have a major heat source. The nature of the heat source, the mechanism of heat transfer at deeper levels and the origin of the geothermal system are essentially unknown.

Clear Lake -- The Clear Lake volcanic complex also contains a geothermal system of the hot-water type. Few holes have been drilled in this system and its temperature and location are not well known. Geochemical temperature indications are ambiguous and the character of the rock under the volcanic cover is poorly known. Geophysics (gravity, teleseismic) indicate a large body of partly molten rock under the Clear Lake/Geysers area centered on Mt. Hanna. A deep drillhole in Clear Lake could help characterize the hot water system and its relation to the steam system at The Geysers. It might encounter the magma body indicated by geophysics.

Characterization of the System

The Geysers geothermal system is developed in the Franciscan formation, a complex sedimentary assemblage associated with a Jurassic subduction zone. In this formation, ophiolites, cherts, pillow basalts, glancophane schists, graywacke, and melanges are mixed largely with tectonic contacts. The structure at The Geysers consists of high angle NW-SE thrust and strike-slip faults which cause frequent repetition of the sedimentary sequence. The reservoir appears to be bounded on the NE by the Collyami strike-slip fault and less certainly on the SW by the Mercuryville-Sulfur creek fault. The reservoir is developed in graywacke of similar petrologic character which may not be the same stratigraphic unit in all parts of the field. Graywacke appears to occupy a much greater part of the area at reservoir depth than it does at the surface, possibly because it occupies the heel of the thrust faults.

Young volcanic rocks (100-500 K years with some as young as 10 K years) of the Clear Lake field are immediately to the N and NE of The Geysers, and a large gravity anomaly associated with the Clear Lake field shows an offshoot in the area of The Geysers suggesting that the geothermal activity is part of the Clear Lake volcanism. It is not certain that molten rock underlies The Geysers.

Holes in The Geysers are drilled with mud to 1-1.5 km, cased and drilled with air into the reservoir. Drilling is stopped when 100 to 200 tons/hr of steam production is achieved. Some wells have initial wet steam and water production but rapidly dry out to produce slightly superheated steam. Shut-in wellhead pressures are near 32-35 bars and downhole static temperatures are near 240-250°C. Pressure gradients are vapostatic. Some wells have perched water tables but these are almost certainly not the deep water table because temperatures are continuous with those of the steam reservoir.

Pressure drawdown behavior and gas contents within the field suggest that three or four drainage basins exist with limited flow between basins. Isotopic data is available on only one of these basis but suggests steam flow from the center as discussed earlier. Recharge to the system is from local meteoric water but natural outflow was limited compared with the size of the system suggesting very long residence times. This is supported by the lack of tritium in the steam.

Seismic studies have shown numerous microearthquakes associated with production but unproduced zones are nearly aseismic. Detailed gravity studies show that production of fluid is from the depth of the bottoms of the drillholes, not from a deeper (water-filled?) zone. Steam production from local evaporation of water is also supported by isotopic studies. Teleseisems with distinct P wave delays suggest a partially plastic zone at depth centered on the Clear Lake gravity anomaly and including the area of The Geysers. Some geophysical data suggests magma at 3-5 km in the center of Clear Lake. This magma would be deeper (7 km?) at The Geysers.

Rocks and Conditions Expected

It is suggested that three holes be drilled in The Geysers-Clear Lake area. The primary hole should be in the center of the major steam drainage basin at The Geysers with the purpose of indicating the conditions in the deep boiling water zone and the depth of circulation of water to a zone of conduction. This hole may encounter magma at depth.

The second hole should be drilled at the center of the Clear Lake gravity anomaly to drill through the hot water system and possibly into magma. A third hole could be drilled near the edge of The Geysers production field to indicate the presence or absence of boiling in the deep water zone on the periphery of the field.

The holes drilled in The Geysers will encounter Franciscan rocks through the geothermal reservoir. Below the reservoir an igneous intrusion related to the Clear Lake volcanics intrudes the Franciscan and will be encountered by a sufficiently deep hole. Drilling the Franciscan is well known. Problems are encountered in serpentine because of its plasticity but this rock type may be limited to the near-surface. Volcanic rocks under the Franciscan will be hot. Problems may be encountered drilling from the underpressured steam zone into the more normally pressured zone beneath.

Holes drilled in the Clear Lake volcanics should be typical of drilling in fine grained fractured volcanic rocks. No unusual problems are anticipated above the high temperature zone but magma has been suggested as shallow as 5 km.

Temperatures at The Geysers will be 250°C at 3-4 km and may increase to 400°C at 5 km and above that at greater depths. Temperatures at Clear Lake are not known but may be 100°C lower in the geothermal system, but may be higher at greater depths, with magma as shallow as 3 km.

Special Problems

Few special problems in siting deep holes are anticipated. This is a recreation area. Ecological conciousness is very high in this area and care in dealing with local sensitivities will be necessary. Geothermal drilling is accepted so these problems can be overcome. The producing companies at The Geysers would probably cooperate in any efforts directed at deep hole drilling.

KILAUEA VOLCANO, HAWAII (Gordon P. Eaton)

In terms of its frequency of eruption, Kilauea Volcano is one of the most active volcanoes in the world. Throughout its recorded history (from 1840 on) it has had an average eruption recurrence of 2.5 years. Radiocarbon dating of pyrolysed forest materials overwhelmed by basaltic lavas during that part of its accessible, pre-recorded history, indicate a long-lived, high rate of lava production. For this reason Kilauea is a volcano in which one can expect to encounter magma at shallow levels (< 3-5 km). At times of eruption some portion of the upper part of the magma body is, by definition, at or above the surface.

The permeability of the volcano is uniformly high, there being little or no annual surface water runoff, despite a mean annual precipitation locally exceeding 400 cm. Dozens of widely distributed fumaroles attest to the existence of vigorous hydrothermal circulation.

Kilauea is but the youngest of a series of basaltic shields that stretch across the north-central Pacific Basin in a narrow band 6,000 km long. Radiometric dating has revealed a time-systematic progression of the locus of volcanic activity south-eastward for a period of 70 million years. Although abundant earthquakes characterize both Kilauea and Mauna Loa (its active larger neighbor to the west) the Hawaiian chain is an aseismic ridge, as befits its intra-plate setting.

The edifice of Kilauea is a broad, gently convex shield constructed from thousands of pahoehoe and aa basalt flows, each generally less than 6-8 m thick. Pyroclastic layers, although locally widespread and up to a few meters thick, constitute but a tiny fraction of the total volume of the edifice. This probably accounts in part for the volcano's high, volume-average permeability. The flow rocks are both porous and permeable, the pores consisting of large primary vesicles and cavities and abundant, inter-connected open fractures. (Some notion of the porosity of the volcano can be gained from fact that the near-surface, *in situ* bulk density is only 2.35-2.40, despite a grain density exceeding 2.90).

Rain falling on Kilauea percolates downward through its edifice to a lens of fresh water floating on the depressed surface of the sea which extends entirely through the volcano. The isotopic composition of gases from some fumaroles at the summit indicate that sea water is a regular participant in hydrothermal circulation, further attesting to high permeability.

Two drill holes of shallow to intermediate depth have already been drilled on Kilauea. The first, 1,300 m deep, was drilled at the summit, immediately above the well-defined magma holding reservoir of the volcano. Its bottom, just below sea level, did not penetrate the top of the magma reservoir and was not expected to, based on projected depths of 2 to 3 km calculated from several different kinds of geophysical data. Logs are available for this hole, including the temperature-depth function, which revealed a localized temperature maximum near 90°C. This maximum is permissive of two interpretations:

1) The hole passed through one limb of a hydrothermal convection cell; or

2) It passed close to the edge of a horizontal sill of high temperature material, possibly magma, well above the principal magma chamber.

The second hole, in the east rift zone of the volcano (in the lower Puna District), has a total depth exceeding 1,900 m. It was sited regionally on the basis of both geophysical and geological data, the final target being identified by a high amplitude, electrical self-potential anomaly. It, too, did not penetrate magma, which in this case is believed to occur in the rift as steep, dike-like bodies with tops of unknown, but probably shallow, depth. They feed frequent rift eruptions there. Hydrothermal circulation is known to occur in the permeable rift zone, the well having flowed at sonic velocities for controlled periods of up to 1,000 hours. Geophysical well logs for this hole are available. Equilibrium bottomhole fluid temperatures exceed 340°C; boiling temperatures were encountered at depths as shallow as 1,000 m. At the time of the workshop a 4-megawatt generator was in a state of acquisition for the production of electricity.

Although insights relevant to the broader goals of the Continental Drilling Program could be acquired at either site by deeper (5-7 km) drilling, both to, and into, the 1200°C basaltic magma, each offers somewhat different attractions. Information of a nature critical to a more complete understanding of the structure, constitution, and eruption mechanics of shield volcanoes would come primarily from a hole at the summit. A hole in the East Rift might be more attractive from an engineering and testing point of view, possibly encountering magma with greater certainty at shallower depths in a setting with proven hydrothermal circulation.

Any scientific holes sited at the summit of the volcano would necessarily have to be drilled in Hawaii Volcanoes National Park. Drilling of the previous hole there encountered troublesome objective and resistance from some parts of the local populace. Holes in the Puna District, on the other hand, could be drilled on private land. The County of Hawaii is philosophically committed both to geothermal energy research and development and the political climate is therefore favorable. The logistical problem of (trans-ocean) shipment of both drilling equipment and staff would obviously be greater for Kilauea than for a volcano on the mainland, but many of the other problems are simpler in Hawaii.

Special Note -- Kilauea Iki -- A scientific and technological program of shallow drilling into ponded and thickly-crusted magma in Kilauea Iki Lava Lake is presently underway. The panel recognizes and acknowledges the fundamental importances of this study and vigorously urges its continued support.

LONG VALLEY, CALIFORNIA (James Moore, after Bailey, 1976, JGR, Volume 81, p. 725)

The Long Valley magma chamber, perhaps 6-9 km deep, is overlain by an active hydrothermal system. A series of two or more holes drilled within and adjacent to the caldera will provide information on the depth to the magma chamber, the characterization of the overlying hydrothermal system, and the nature of such a caldera-producing volcanic system in a region of active extensional tectonism on the margin of the basin and range province.

The Long Valley volcanic system east of the Sierra Nevada is one of several young volcanic centers which occur along the western margin of the Great Basin adjacent to the Sierra Nevada. Other such centers include Mono basin to the north, and the Big Pine and Coso volcanic fields to the south. All occur along a particularly active marginal segment of the Basin Range province where seismic activity, high heat flow, and recent faulting indicate that relatively rapid east-west crustal extension dominates the tectonic regime.

Volcanism in the Long Valley region began about three MY ago with scattered eruption of basalt and andesite, became localized about two MY ago with eruption of the Glass Mountain rhyolite, and culminated with the tremendous eruption of 600 km^3 of rhyolitic Bishop tuff 0.7 MY ago. The removal of this rhyolitic magma from the top of a shallow, zoned magma chamber caused the roof to collapse 1-3 km, producing the Long Valley Caldera 17 by 32 km in size.

Volcanism following the major eruption and collapse includes aphyric rhyolite 0.68-0.64 MY ago during resurgent doming of the caldera floor, porphyritic rhyolite from centers peripheral to the resurgent dome 0.5, 0.3, and 0.1 MY ago, and porphyritic hornblende-biotite rhyodacite from outer ring fractures 0.2 to 0.05 MY ago. This sequence apparently records progressive crystallization of the underlying magma chamber.

Holocene rhyolitic and phreatic eruptions suggest that residual magma was present as recently as 450 years ago. Hydrothermal activity began 0.3 MY ago and has since declined due to self-sealing of near-surface caldera sediments. Several drill holes within the caldera contain variable temperature distributions indicating the presence of a complex hydrothermal system overlying the heat source. One 3 km hole contains a maximum temperature of about 60°C two-thirds of the way down; another 150 m hole attains a temperature of 110°C.

Long Valley is an important recreational area, and considerable resistance to a drilling program can be expected from groups and individuals concerned with the environmental impact in this fragile area.

YELLOWSTONE, WYOMING (R. Christiansen)

The Quaternary volcanic system centered in Yellowstone National Park provides a unique opportunity for deep drilling into a large magmatic and hydrothermal system.

Such deep drilling, preferably supported by some intermediate-depth holes as well as by the extensive geologic, geochemical, and geophysical studies already done and still underway, would characterize an extremely important type of magmatic system -- large predominantly silicic systems expressed at the surface by voluminous pyroclastic eruptions and large calderas. Such systems constitute the world's largest volcanoes and in many regions support hydrothermal convection systems having enormous energy contents. Yellowstone itself is one of the largest and best-known such systems in the world. Elsewhere, older systems of this type are associated with important metallic ore deposits. Besides helping to characterize the three-dimensional structure, physical and geochemical parameters, and shallow magmatic processes of the volcanic system as a whole, deep drilling at Yellowstone would help to characterize the deep parts of a very large, active, high-temperature hydrothermal convection system below levels yet explored by commercial geothermal drilling. The nature of thermal transfer to this system from the magmatic heat source also would be an important objective of study by this drilling. Magma is inferred with some confidence to exist in this system, but present information as to its depth is ambigous. Petrologic data suggest magma temperatures of 900-1000°C.

Geologic, geochemical, and geophysical data indicate that the Yellowstone Plateau volcanic field overlies a group of plutonic bodies of batholithic size emplaced over a period of two million years. The older parts of the plutonic system are solidified but probably still hot. The youngest of these larger magma bodies has been emplaced during about the last 1.2 million years. Two higher-level parts of this magma chamber formed a pair of adjoining ring-fracture zones, through which a climactic pyroclastic eruption of more than 1,000 km^3 occurred 600,000 years ago. The magma chamber roof collapsed along the two ring fracture zones to form a 40 x 70 km caldera. Post-caldera rhyolitic volcanism has continued intermittently since 600,000 years ago, an episode of intracaldera doming and three major sequences of rhyolitic lava eruptions have occurred during the past 150,000 years, the latest being about 70,000 years ago. The distributions and ages of vents for these eruptions of the past 150,000 years clearly indicate episodic resupply of magma to shallow parts of the system form deeper levels. Heat must be continually supplied to the rhyolitic magma chamber form deeper basaltic magma, represented at the surface by basaltic lavas around the caldera margins, spanning the entire history of the rhyolitic field.

A massive system of hydrothermal convection exists above the now partly solidified Yellowstone magma chamber. Recharge to the system is principally from the north; discharge occurs at a large number of areas, both as hot-water and vapor-dominated systems. Below the levels where temperature is controlled by the P-T boiling-point curve, the system is believed to be of rather uniform composition at a temperature of 360°C. The areas of the discharge systems are controlled mainly by the two ring-fracture zones and some major near-caldera tectonic fracture systems; discharges are specifically localized by near-surface structural and topographic features.

Deep drilling within the Yellowstone caldera probably would first encounter 1-2 km of interlayered rhyolitic lavas and sediments, probably underlain by about 2 km of rhyolitic welded tuffs. A basement of Precambrian gneisses and amphibolites probably is overlain in various places by as much as 3 km of Paleozoic and Mesozoic marine sedimentary rocks and Eocene andesitic sediments and lavas.

Depending on specific drill-site location, the depth to the solidified top of the magma chamber may be 3-7 km. Again depending on specific location molten magma may be as shallow as 6-7 km, but (especially within the main areas of hydrothermal discharge) may be 10 km or deeper.

The principal problem of deep drilling in Yellowstone is that it would have to be done in an important and environmentally sensitive National Park. The environmental disturbance necessary for drilling on this scale may be unacceptable to the

National Park Service or to the public. In addition, any proposal for deep drilling at Yellowstone must convey clearly its objectives of scientific research alone. Any suggestion of utilizing the Yellowstone geothermal system for energy production or any economic use is unacceptable to the scientific community as well as to the public.

CASCADE ANDESITIC VOLCANO (R. Decker)

Subsurface data on an active stratovolcano will provide better understanding of this important class of volcanic centers related to subduction tectonics. The nearby erosional exposure of shallow chilled magma chambers related to an earlier generation of similar volcanic centers allows important comparative studies to be made.

The complex hydrologic systems on the Cascade volcanoes prevent obtaining any meaningful measurements of the heat flow from shallow drill holes; likewise the steep topography and complex geologic units make geophysical survey data difficult to interpret. Deep to intermediate depth drilling should provide some of the keys to better understanding the structure and dynamics of this important class of volcanoes and their associated hydrothermal systems.

An inferred cross section of a Cascade type volcano by Hopson, et al., constructed from erosional exposures of the previous generation of volcanic centers near the present Cascade peaks, gives some idea of the geologic structure that can be expected at depth. Several of the present Cascade volcanoes have erupted lavas and ash within the last 1,000 years, and current microseismic activity indicates some are still dynamic systems.

Specific targets might be Mount Saint Helens in Washington or Mount Shasta in California. Insufficient surface investigations preclude an intelligent choice at this time.

The expected temperatures at depths of 5 km beneath the immediate base of an active composite volcano range from 300 to 1000°C. This large uncertainty is related to the relatively small magma bodies inferred beneath this volcanic type, and the possibility of missing the target. Some thought should be given to directional drilling to penetrate beneath the volcanic center from a flank location.

BATTLE MOUNTAIN HIGH (BMH) (A. Lachenbruch)

The BMH is a region of several x 10^4 km^2 in N Nevada which at present, is distinguished only by its very high regional heat flow (3 ± HFU compared to 2 ± HFU for the rest of the Great Basin). Although it is a target for commercial geothermal exploration, the origin and significance of the BMH in terms of magmatic/hydrothermal systems is unknown.

The basic question to be answered is: "Why is the regional heat flow high?" Corallaries are: "What is the thermal regime of the underlying crust and mantle, and what is the geothermal energy potential of the region?"

A hole drilled through a sedimentary basin (with a hot-spring system) and 5 or more km into granitic basement rocks might help answer the following questions:

1) Does the high conductive heat flow persist at depth?

2) Is the BMH a thermal anomaly of hydrologic origin?

3) Does conductive flux from basement balance the heat budget of hot spring systems in the basin?

4) What is the vertical distribution of water circulation and permeable fractures?

5) What is the vertical distribution of radioactive heat production?

Except for its high conductive heat flow (subject to further confirmation) the BMH is not clearly different (according to usual physiographic, geologic, and geophysical criteria) from the rest of the Great Basin. Parts of it probably occupy a region of anomalously thin crust, a region with anomalous N Easterly trending faults, a region of very active recent faulting, and so on, but none of these anomalous regions is known to be coextensive with the BMH. The BMH is distinguished from the Snake River Plain, a region of large convective heat loss to the NE, by distinctly different crustal structure, volcanic history, and hydrothermal regime. Much of the BMH contains Mesozoic and Tertiary granitic rocks; they are favorable media for deep scientific drilling as they are relatively homogeneous and easily sampled.

We suggest that a good site for a hole would be in a sedimentary basin underlain by granitic rocks. The section will, therefore, be 1 km or so of sediments and probably crystalline rock for the remainder. Temperature gradients are expected to be about 100°C/km in the sediments and perhaps 50°C/km in the crystalline rock.

A major problem may be the rise of hot water in the borehole and its circulation in the annulus (behind the casing). This could preclude equilibrium measurements of natural formation temperature, the most important scientific measurement. Such water could, of course, flash into steam in an open hole if mud pressures are not maintained.

NEWBERRY/MEDICINE LAKE REGION (H. Hardee)

The primary scientific reason for this site selection would be to study a continental basaltic magma chamber. The basaltic magma source tends to exist at higher temperatures, lower viscosities, and higher levels of internal convection than silicic magma bodies. The basaltic magma chamber is probably the underlying source for a silicic magma chamber and, as such, the basaltic magma system is important in understanding silicic magma systems. The Newberry/Medicine Lake region represents an area where the basaltic magma chamber might exist at drillable depths. There may be some other areas such as San Francisco Peaks which could have a relatively shallow basaltic magma chamber but the Newberry/Medicine Lake region is probably the best example based on present knowledge.

This type of volcano consists of both basaltic and rhyolitic material. A hole drilled through the caldera would first encounter mixed basaltic and rhyolitic material and a hole drilled on the flank would probably encounter more basalt than rhyolite. Below the base of the volcano, a drill hole would encounter a sequence of Tertiary volcanic rocks. A molten or recently solidified rhyolitic magma chamber probably exists in the crust and is likely underlain by a basaltic magma chamber. This volcano sits on crustal material consisting of Mesozoic plutons and metamorphic rocks or older rocks that were deformed during the Mesozoic.

The main problems with this site are likely to be environmental problems. Newberry caldera is in a State Recreational Area and Oregon, in particular, is sensitive about such areas. A part of the north side of the Medicine Lake area is in a National Monument and there is talk of establishing a larger National Monument area here. Predrilling of both Newberry and Medicine Lake and consideration of the environmental questions will be important in determining the final site selection. Some preliminary drilling work has already been started at Newberry.

Drilling Environment

Expected Temperatures and Pressures at Depth

The formation temperatures expected at various depths depend primarily on the depth and emplacement age (or ages) of the magma body and are predictable within reasonable limits. D. Norton's reconstruction of the thermal profile above exhumed magma-hydrothermal systems is based on single intrusion models, are generally similar to the profile shown for the Skaergaard intrusion, Figure A. Multiple intrusions or near surface hydrologic complications could alter this profile, but it is a good first approximation of the expected temperature-depth relationship.

Expected pressures range from sub-hydrostatic to above hydrostatic in the hydrothermal region depending on the formation sequences and permeabilities. Pressures nearly lithostatic can be expected in the magmatic fluid.

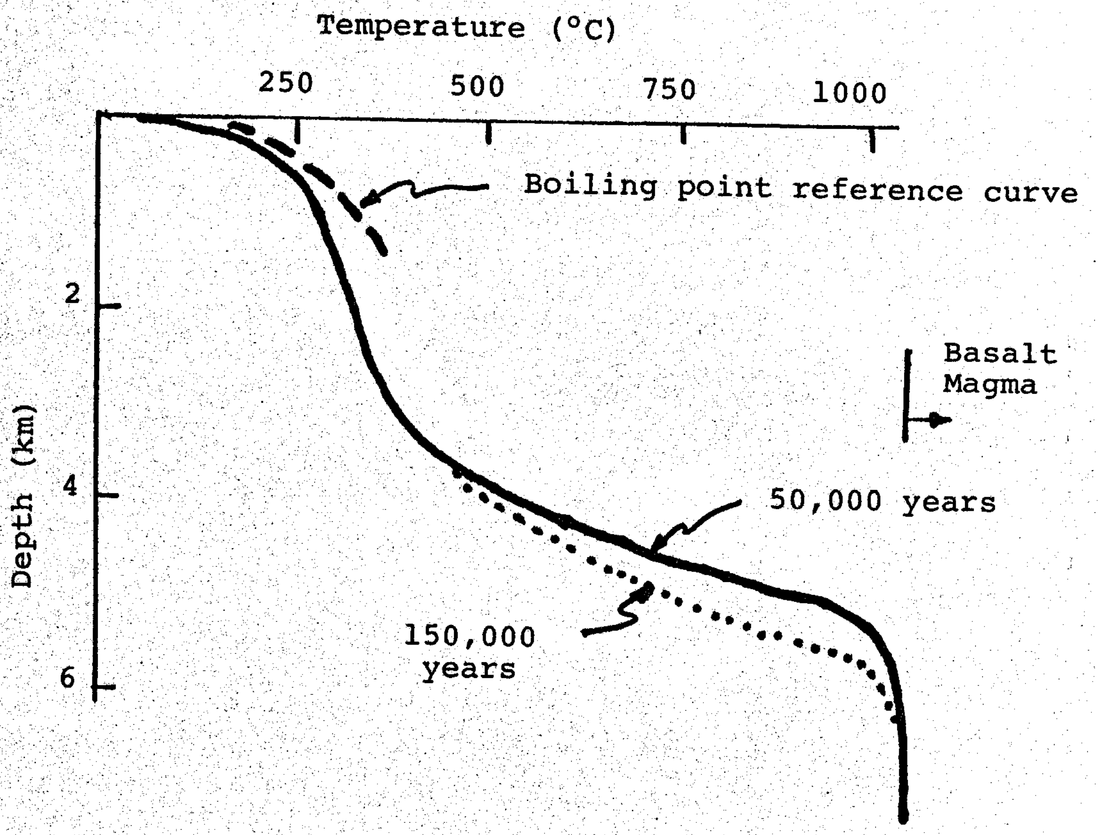

Figure A

Subsurface Data Requirements

(T. Gerlach, J. Hermance, D. Norton, H. Taylor)

Introduction

Scientific objectives* of drilling into magma/hydrothermal systems require that representative samples of rocks and formation fluids be obtained and that measurements of temperature and fluid pressure be made. If these minimum scientific objectives cannot be met, there is little point in drilling the hole. It is expected that conventional logging and advanced instrumentation technology will be applied wherever possible without jeopardizing the above objectives.

Samples

It is not necessary to have continuous core or fluid sampling, however, a systematic program of sampling is essential. This program will require scientific monitoring of drill cuttings, temperature, data from conventional logging methods, and borehole location as drilling proceeds. Core and fluid samples will be collected on the basis of this information. It will probably be necessary to core 10-25% of the hole length, however, this variable is highly site-specific. Drill cuttings must be recovered for the entire length of the hole.

It is probable that fluid sampling during active drilling will be difficult if not impossible to obtain because of contamination by drilling fluids and long sampling times required by relatively low formation permeabilities. Therefore, pristine fluid samples probably can only be obtained after well completion. Provisions should be made such that fluid samples can be collected after well completion at depths determined by preliminary scientific examination of drill cuttings, core, temperature and pressure measurements, etc.

Rock Samples (includes formation mineral assemblages and chilled melt) --

1) Cuttings -- continuous recovery necessary

2) Core -- provisions should be made for preservation of the in situ chemical and mechanical properties of core, especially for samples from the deeper portions of the system. Prevention of core oxidation and fracturing are especially important.

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*These objectives place further emphasis on the REPORT OF THE WORKSHOP ON CONTINENTAL DRILLING, E. M. Shoemaker, Editor, which includes a rather comprehensive statement of the data and samples required.

Fluid Samples (includes aqueous solutions, supercritical fluids and gases) -- Provisions must be made for preservation of the in situ chemical properties of the formation fluids during and after sampling.

Drill Hole Measurements

During Drilling -- The following is a list of types of measurements desired:

1) Shear and compressional velocity, together with seismic attenuation and density measurements. In some cases this information is needed as a function of time over long periods.

2) Strain measurements as a function of time, depth, and orientation.

3) Stress measurements involving hydrofracturing techniques and the use of the acoustic televiewer.

4) Porosity determinations; in low porosity rocks several types of log information will be required.

5) Permeability to fluid flow either by direct fluid production or by injection measurements.

6) Heat production from radioactive heat sources by spectral gamma-ray logging.

7) In situ measurement of thermal conductivity.

8) In situ measurement of bulk electrical properties.

A number of measurements are desired over long periods of time. Drill hole seismometers, tiltmeters and dilatometers would be permanently or semi-permanently installed to make some of these measurements. Temperature and temperature gradient measured intermittently over long times are required in some drill holes. Pore fluid pressure also is to be monitored over long times if possible.

In holes of exceptional research importance most logging instruments that are readily available without development presumably would be used to the limits of their ranges of operation, in particular to the limits of their temperature ranges. Logs which should be run routinely include the gamma-gamma density log, sonic log with full waveform recording, natural gamma-ray log, spectral gamma-ray log, neutron log, neutron lifetime log, neutron activation logs to determine abundances of certain chemical elements, the various electric resistivity logs, caliper, dipmeter and drill hole survey, temperature log, acoustic televiewer, nuclear magnetism log, drill hole gravimeter, magnetometer, magnetic susceptibility, electromagnetic log, and pressure (Table 1).

Developments in the area of advanced downhole geophysical measurements should be utilized, particularly for detection and delineation of structures to the side and below the bottom of the drill hole. Promising techniques appear to be directional seismic arrays and electromagnetic probing.

Instruments to be Installed in Drill Holes -- Most instruments that might be installed in a drill hole have already been used in some drill holes; these instruments may require modification for higher temperatures in order to be used at the full depth of some holes proposed in this program. Because each of these instruments would remain in the drill holes for several hours, high temperature is the main limiting factor. Electronic components and cables must be modified for performance at temperatures expected in several proposed holes.

The principal in-hole instruments are as follows:

1) Seismometers -- three types of in-hole seismometers appear to be needed:

    a) short period velocity-transducers for local events;

    b) hydrophones; and

    c) short and long period three-component instruments.

2) Tiltmeter -- The successful operation of tiltmeters at various depths is crucial for the study of fault mechanics.

3) Dilatometer -- The dilatometer measures the fractional change of volume of the rock in which it is embedded. Dilatometers presently are operated routinely in shallow drill holes. Adaptation of these instruments for use in deeper drill holes involves modification of the cable, electronics, and mechanical parts for higher temperatures. Techniques for installing the instruments in deep holes also may require development.

4) Broad-band telluric and magnetic variometry -- This technology is needed to achieve the following objectives:

    a) to complement active and passive electromagnetic probing experiments at the surface;

Table 1. Commercial well logging and sampling devices

Type of Log* or Sampler	Parameters Measured	Parameters that may be Derived	Minimum Hole Diameter (inches)	Maximum Temperature (°C)
Non-focused resistivity (and self-potential)	Resistivity of materials	Lithology, invasion	5	232
Induction	Conductivity of materials surrounding probe	Lithology, porosity water quality	4-3/4	204
Focused resistivity	Resistivity of thin segment of formation	Lithology, porosity water quality	6	204
Caliper	Average hole diameter	Lithology, fracture location, correction of other logs	4	177
Deviation	Angle and direction of hole drift	Location of hole	4-1/2	204
Natural gamma	Total gamma intensity	Lithology	3-3/4	260
Gamma-gamma	Gamma rays scattered from a source	Bulk density, porosity		
Neutron	Hydrogen density around instrument	Water-saturated porosity	5-1/4	204
Pulsed neutron	Neutron capture cross-section	Fluid identification, porosity	2	150
Nuclear magnetism	Number and state of hydrogen nuclei	Effective porosity permeability (?)	7	150
Acoustic velocity	Transit time of elastic waves	Lithology, porosity	4-1/2	204
Temperature	Temperature	Water flow, heat flow	1-5/8	204
Fluid sampler	Pad sealed against rock, charge opens formation to sampler chamber	Sample of in situ water and formation pressure	4-1/2	232
Sidewall corer	Cuts pie-shaped slice in wall	Laboratory analyses of core	6-1/8	150

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*All of these probes will operate to at least 20,000 psi.

b) monitor the evolution of spontaneous polarization anomalies;

c) to detect possible seismo-electric or seismomagnetic effects.

Experiments that use Drill Holes as Facilities

Deep drill holes in crystalline rocks provide unique opportunities for many experiments. Some experiments may be designed to investigate the properties, composition, and structures of the rocks penetrated by the drill hole and their fluids. Other experiments may use the temporal variations or the properties of the rock and fluid in order to study local or distant events. Still other experiments may use the environment of the hole itself, e.g., low seismic noise and shielding of cosmic rays by 3 to 10 km of rock. A complete list of such experiments is long. Rather than attempt to provide an extensive listing, a representative set of experiments has been assembled, each of which has been drawn from the earth sciences field.

Although this set of representative experiments has been selected from earth sciences, the potential value of the hole facility in other disciplines is recognized. Therefore, it is recommended that the entire scientific community outside the geosciences be kept informed of the opportunity to submit proposals to utilize deep continental holes. For example, the bottom of a 10 km hole may be a unique site for measuring the flux of high-energy cosmic-ray particles. Scientists developing nongeoscience experiments can coordinate their instrumentation efforts with other drill hole experiments.

Drill Hole Electromagnetic Experiments

The propagation of electromagnetic waves through rock has considerable importance in:

1) understanding the electrical properties of rocks and their fluids;

2) geophysical prospecting, and

3) communication through rocks over long distances.

Potentially useful techniques for in-hole measurements include:

1) propagation experiments in which both a transmitter and a receiver are placed in a single drill hole;

2) measurement of transmitter impedance as a function of frequency and depth;

3) dipole-dipole (low frequency) measurements in which both dipoles are placed in the drill hole and in which one dipole is placed on the surface; and

4) broad-band passive monitoring of natural sources.

Each of these techniques has been used previously, although not necessarily in deep drill holes. Thus, the experiment concepts and data interpretation are already established.

Hydraulic Fracturing -- In this experiment, short sections of 1 to 8 m of the drill hole are isolated from the rest of the hole and fluids are pumped into the rock exposed in these short sections at pressures sufficiently high to fracture the rock. The pressure at which failure occurs, and the size, shape, and orientation of the fractures are related to the stress in the rock. The technique is well established. However, the downhole equipment should be upgraded for use at temperatures higher than those that have been encountered previously.

Permeability Measurements -- The permeability to fluid flow of crystalline rocks is an extremely important parameter in certain geothermal energy projects. Yet the data for such rocks in situ are scarce. Measurements of permeability as a function of depth in each hole would thus be very useful. Because permeability is dependent on properties of cracks and because the characteristics of cracks may change with time, it is suggested that repeated measurements be taken.

Pore Pressure Measurements -- The pressure exerted by the fluids contained in the connected openings in rocks is a complex function of permeability, depth, rock stress, temperature, and fluid movement. Such bulk physical properties as the velocities of compressional waves (V_p) and shear waves (V_s) depend strongly on the pore pressure, an experimental fact that has been useful in understanding the observed behavior of the ratio of V_p/V_s accompanying some earthquakes. Thus, it is believed that the monitoring of pore pressure at several depths in the drill holes of this project would be valuable.

Precision Temperature Measurements -- The temperature at a given depth in a drill hole depends on

1) the temperature distribution at the time all drilling and fluid circulation stopped and the length of time drilling fluid circulated;

2) the thermal properties of the rocks; and

3) the movement of fluids in the rocks.

It is suggested that high precision measurements of temperature as a function of time may reveal periodic and aperiodic movements of water and may correlate with such other geophysical phenomena as stress buildup before an earthquake. The equipment is not now commercially available, but the development appears relatively simple.

Two-Hole Drilling Project

Technical considerations indicate that one of the most viable methods of penetrating deeply into hydrothermal systems involves drilling an initial reconnaissance hole in which the objective is solely to penetrate as deeply as possible. Information obtained from the first hole would allow a second hole close to the first site to be drilled and monitored in a much more effective manner. In fact, several scientific experiments require two such closely spaced holes:

1) in situ flow properties can be most unambigously obtained in flow tests utilizing two-hole geometry (e.g., permeability, flow porosity, diffusion porosity, fracture geometry);

2) horizontal gradients in all rock and fluid properties and geophysical parameters;

3) correlations of dikes, sills, fracture zones, veins, etc.

Fluid sampling in the same fracture system at two points could also provide very useful information.

Recommendations

The Working Group on Drilling Location and Environment recognizes that the U. S. Geological Survey has the prime responsibility of the Federal agencies for the assessment of the nation's earth resources. Accordingly, they should be the agency designated to undertake the effort required to define and locate one or more suitable specific sites for a magma/hydrothermal scientific experiment borehole.

It is recommended that Sandia Laboratories, in cooperation with the U. S. Geological Survey and universities, pursue an investigation of several of the targets indicated earlier in this report to establish specific proposed drill sites and depths at each target. A Department of Energy funding level of $250,000 per year for the next two years appears appropriate.

REPORT OF THE WORKING GROUP ON DRILLING AND COMPLETION

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Introduction

The Drilling and Completion Working Group focused its attention on the problem of drilling a well at the temperatures, pressures, and depths anticipated in the magma/hydrothermal portion of the Continental Drilling Program (CDP). Of equal concern was the problem of keeping the hole open after it had been drilled, i.e., completion of the well. This portion of the report will describe the discussions and recommendations of the Drilling and Completion Working Group. Primary emphasis is placed on the technology requirements for high temperature drilling and completion, although some comments concerning coring and other sampling methods are given. It was recognized early in the discussions that the purpose of drilling a well to magma depth would be for scientific purposes rather than for commercial operation. This theme provided the basis for the discussions which followed.

The magma/hydrothermal portion of the CDP has not yet been defined in sufficient detail to allow specific problem definitions, but it has been assumed that there will be a series of wells drilled to obtain information concerning the origin and current activity of magma/hydrothermal systems. With current technology, much of that work could begin now. The overall program plan will call for iterations between scientific objectives, feasibility and the cost of achieving these objectives. It is expected that at least one well will penetrate the magma; therefore, the capability of drilling at temperatures in the range of 800-1000°C and at depths of 7-10 km will be required.

For purposes of the Working Group on Drilling and Completion, the following general objectives were postulated for the magma/hydrothermal drilling project:

1) To drill in an area of an active hydrothermal body
2) To drill at least one hole to the magma
3) To penetrate and sample magma
4) To provide a reusable hole for scientific experiments.

Even though this may not be a one hole program, the major problems occur at temperatures above 350°C. Major concerns for temperatures below 350°C will be lost circulation and well control. One approach to this program would be to progressively drill the shallower, easier objectives first, allowing for the drilling and instrumentation development programs to mature. A great deal of information is within reach of the drill now. Plans to use existing holes, to deepen existing holes, and to drill shallower objectives should be considered. Progression to the deeper and hotter objectives will permit an orderly development of the required high temperature technology. As stated before, drilling to 350°C is achievable now. Drilling to 10 km has been done but the combination of depth and temperature will require new concepts to be developed.

Magma/Hydrothermal Drilling Requirements

Drilling at bottomhole temperatures of 300-350°C has been accomplished in several geothermal wells. Drilling and completing wells at temperatures in excess of 350°C is limited by the lifetime of elastomers, the unavailability of suitable drilling fluids, the lack of suitable means for setting casing (cement), and the loss of strength in steel tubulars at higher temperatures.

Elastomers are used pervasively in the drilling industry, e.g., as seals in bits, in packers, and in blowout preventers. Currently available elastomers can be used to temperatures of approximately 200°C. Research is underway to extend the useful range of operation of these materials to approximately 350°C. At temperatures in excess of 350°C, it is anticipated that new techniques will be needed to provide the functions now performed by elastomers.

Subsurface pressure gradients determine the requirements for drilling fluid density. Low density fluids, e.g., air, are required when bottomhole pressure is subnormal to prevent excessive lost circulation. Conversely, high density fluids are required when bottomhole pressures are high because of the requirement for well control. Low density fluids can potentially be formulated to operate at high temperatures (800-1000°C); however, there are limitations on well depth capability when low density fluids are utilized. On the other hand, high density fluids are usually formulated by adding clay to the fluid. The upper temperature limit on presently available high density fluids is approximately 250°C, and research is underway to extend this range to 350°C. Techniques for well control at bottomhole temperatures of greater than 350°C are not presently available.

Oil, gas, and geothermal wells are normally completed by cementing casing to the wellbore. Currently available cements are limited to approximately 200-250°C. Research is underway to extend this range to 350°C. Above this, new casing procedures will be required.

Finally, tubulars begin to lose strength in the range of 700°C. Therefore, at melt or near-melt temperatures, borehole stability will have to be studied to determine whether open hole completions are possible. Alternatively, new, high-strength materials may have to be developed for well completion.

Presently, the capability exists to drill wells at temperatures up to 350°C, if they are reasonably shallow ($<$ 4 km). However, if the depth is excessive, the temperature capability is lower because of drilling fluid problems. One of the deepest wells drilled in the continental U.S. to date is the Bertha Rogers No. 1 in Oklahoma which was drilled to a depth of $\sim$ 11 km, but the maximum temperature encountered in this well was only about 200°C. In discussing the drilling of a magma/hydrothermal well, both temperature and depth must be considered simultaneously to determine feasibility.

The temperature-depth profile shown in Figure 1 illustrates the rise in temperature anticipated as an active hydrothermal body is encountered and speculation as to the profile near a magma body. This curve is not intended to be qualitative, but merely to illustrate a probable profile. The portion of the hole above 350°C is estimated to range from 2-4 km so any program calling for magma penetration would encounter those temperatures for a considerable depth. The profile also suggests that a considerable portion of the hole would be above 700°C as well. The estimated depth of a magma body varies considerably, depending on the site, but in general the shallower the better in terms of the feasibility of drilling to and into the magma.

At a previous meeting on the CDP at Ghost Ranch, New Mexico (1974), the temperature extremes of magma penetration were not discussed. At that time, maximum depth capability was of paramount interest. The record well depth at the time was the Bertha Rogers No. 1 in western Oklahoma. Extensions in drilling capability to 17 km were discussed, but the problems

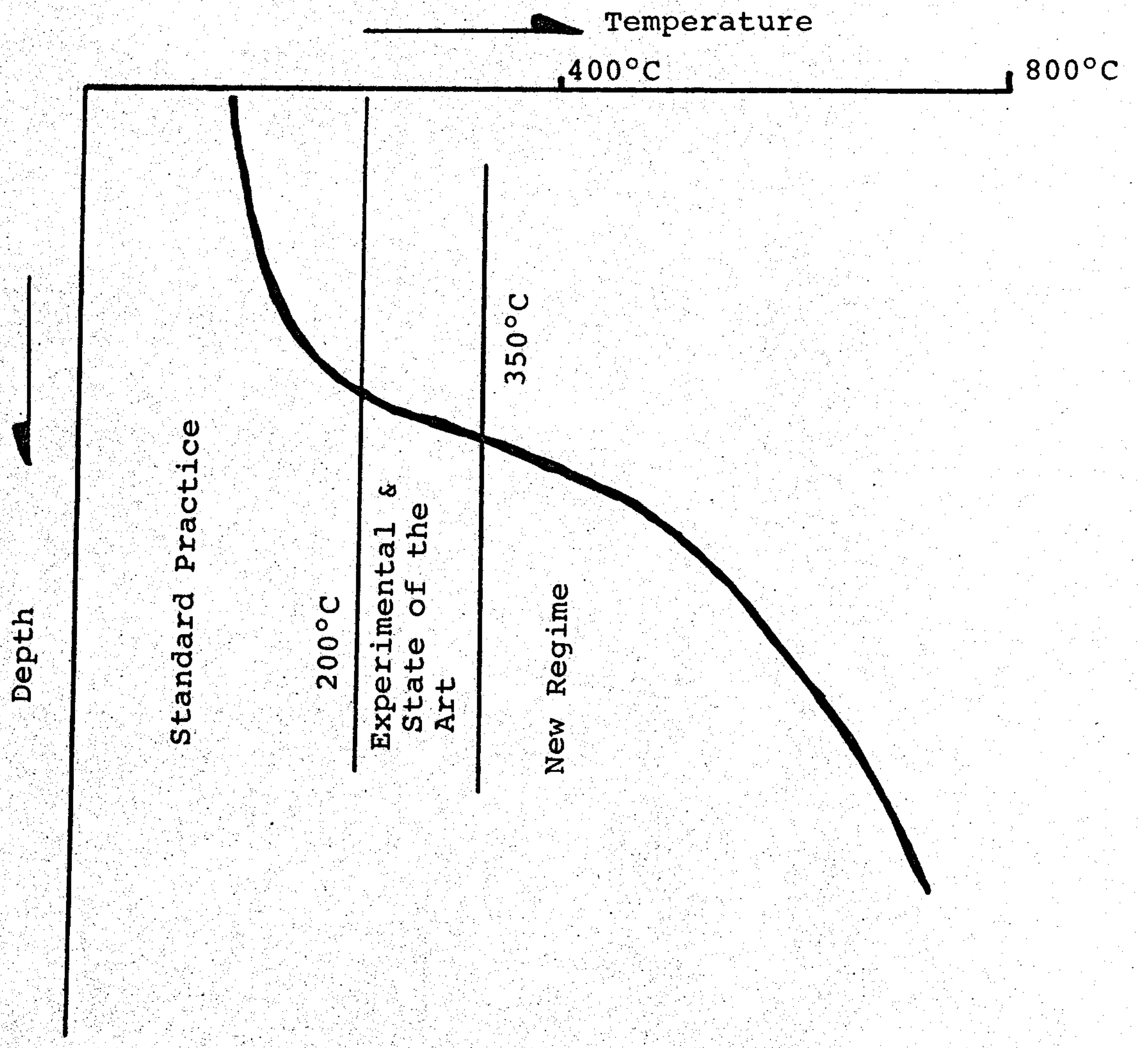

Figure 1. Generalized temperature -- depth profile

of how to handle the expected 700°C at or near total depth were not addressed. The problem of wellbore lining at depths of 12-17 km were not defined completely, although it was thought to be feasible. It is apparent now that both depth and temperature must be considered simultaneously in assessing the feasibility of a magma penetration hole.

In summary, standard techniques will allow drilling wells at temperatures to 200°C, 10 km depth. Drilling at temperatures between 200 and 350°C can presently be done on a somewhat experimental basis, and the Division of Geothermal Energy (DGE) of the Department of Energy (DOE) has a research program underway which is directed at providing the technology required for drilling and completing wells in this temperature range.

The magma/hydrothermal portion of the CDP must develop techniques and tools for drilling at temperatures between 350°C and rock melt temperature (800-1100°C), and at depths of 7-10 km. In addition, a method for penetrating into the melt will have to be devised.

Well Technology Limitations

Table I illustrates the limits of currently available technology in the various temperature ranges discussed in Figure 1. Drilling at temperatures below 200°C represents state-of-practice for the majority of items noted; although some problems are encountered with cementing, elastomers, and sampling in this temperature region.

For temperatures between 200 and 350°C, new problems arise. Elastomers fail, corrosion rapidly increases, fluid additives lose effectiveness, bit life is reduced, and drilling equipment is rapidly degraded. This is the current frontier in drilling technology. It is expected that the evolution of equipment through better materials and/or new techniques will allow drilling in this region. The current research program for DOE/DGE is directed at this temperature range. Specifically, programs directed at new bits, motors, fluids, completion equipment, and logging tools are under development.

At temperatures of 350 to 1100°C many unsolved problems exist. Conventional tools fail, and concepts to drill into the progressively hostile environment are neither obvious nor plentiful. Much of the drilling for the magma/hydrothermal well will be at temperatures below 350°C, but as the magma is approached making and maintaining hole will be a challenge. In addition, well sampling, logging and performing experiments will be challenging.

Not too much will be said here about melt penetration. Experiments to penetrate shallow magma bodies (lava lake drilling) will help define the methods for deeper bodies.

Drilling Equipment

Drilling equipment is that required to produce hole and to control the well, e.g., wellhead equipment.

A. Bits

New generation journal bearings bits so common to oilfield drilling have met with limited success in geothermal drilling. Seals fail and lubricants are contaminated causing rapid bearing failure. Boundary lubricants themselves begin to fail at bearing surface temperatures

Table I. Limits of conventional well technology

	Drilling Equipment	Fluids	Wellbore	Sampling
Standard Practice <200°C	Available Technology	Available Technology	Cement	Coring
Experimental and Geothermal <350°C	Bits Tools Tubular Wellhead	Liquids Gas Aerated Fluids Corrosion	"Casing" Packers	Samples Logging Stress State
New Regime 350° < T < 1100° C	No Technology Exists	Cooling (possible) New Technology Needed	No Technology Exists	No Technology Exists
Melt Penetration	Pending Experiments	No Technology Exists	No Technology Exists	No Technology Exists

of about 400-450°C. New work in lubricants has raised the acceptable bearing surface temperatures substantially, but contamination still is an important factor in the life of the journal bearing. The solution for increasing temperature has therefore been mainly to use open (unsealed) roller bearing bits. The flowing fluids (liquids or gases) have provided (barely) enough cooling so that the drilling tools have managed to operate at bottomhole temperatures above the materials rating limits. Mud cooling systems have helped reduce the mud temperature down the pipe and therefore the "operating temperature" of the tools. When the system is required to soak, however, temperature problems exist. Circulation must be maintained to prevent deterioration of equipment in high temperature wells.

It is thought that bearings for operating temperatures of 500-600°C can be developed using high temperature steels with roller bearings. Above that temperature entirely new concepts for drill bits may be required because of bit structure and bearing life failures. It is likely that drag bits will emerge as a viable cutting element. Bit life will still be shorter than desired, but operation at high temperatures appears possible. An effort directed at the development and testing of high temperature drag bits should be initiated.

B. Drilling Tools

Drilling tools, e.g., downhole motors, at normal temperatures (< 200°C) are sealed for increased life. Higher temperatures will require that drilling tools are designed without elastomeric seals and with high temperature metals. The life of such tools will be limited and effectiveness at elevated temperatures is unknown.

Downhole motors capable of operating at bottomhole temperatures of 250°C are under development. These motors are used in directional drilling as well as in straighthole drilling. The speeds of many of these motors are too high to be used with conventional roller cone bits. The development of high temperature drag bits, as suggested earlier, could provide impetus to the use of motors to increase penetration rate.

C. Tubular Goods

Tubular goods (pipe and casing) used at temperatures in excess of 500°C will require more exotic and costly metals. The heat treating temperatures of most steels for pipe (and bits) will be exceeded as drilling near the melt occurs. The higher temperature metals exist, but little is known about strength reductions and abrasive wear capabilities. Extensions to higher temperature appear to be possible, but studies of material strength and fatigue characteristics at higher temperatures are needed.

Corrosion at elevated temperatures will be a problem -- inhibitors tend to fail at about 300°C. In addition, erosion can be a serious problem with gas drilling. These areas require research at temperatures of 350-1100°C.

D. Wellhead Equipment

Wellhead problems are not as severe as downhole problems, but where wellhead back pressure is required, a good rotating head and choke are needed. Presently, none are available for downhole temperatures above approximately 250°C, but the design of higher temperature equipment appears to be possible.

Drilling Fluids

Whether the drilling fluid is liquid or gas has a large effect on high temperature drilling capability. Corrosion, well control and lost circulation are constant problems with present geothermal drilling. Abnormally pressured zones below sub-pressured zones demand that the well be cased, since sub-pressured zones are often fractured and result in loss of fluid returns. Drilling without returns is tolerated, but not a recommended practice.

Drilling in sub-pressured formations precludes the use of heavy muds, and drilling with low density fluids, e.g., air, gas, or foam, is the practice. Increased corrosion, erosion, and well control problems are encountered in drilling with these low density fluids. Inert gas drilling may solve some corrosion problems, but will not change significantly the well control problem. Well control without weighted liquids will require back pressure systems. The feasibility of such systems at high temperature is unknown, but will need to be investigated for the CDP.

The approximate temperature limits of various fluids are as follows:

1) Air, inert gas, mist or aerated water

without inhibitors (inert gas)	> 1000°C
with inhibitors (air)	250-300°C

2) Foams -- 250-300°C

3) Water (steam)

without inhibitors	> 1000°C (pressure dependent)
with inhibitors	250-300°C

4) Brine (without inhibitors) -- > 1000°C (pressure dependent)

5) Waterbased muds -- 250 to 300°C

6) Oil based muds -- 300 to 370°C

These estimates need further verification; nevertheless, the most difficult problems appear to be drilling abnormally pressured zones through subnormally pressured zones and controlling the well when drilling through abnormally pressured, high temperature zones where muds cannot be used. This may require the development of special downhole equipment for well control.

Wellbore

A. Casing

The limitations of strength reduction at increasing temperature affect casing design. Loss of strength, collapse failures, and thermal stress failures are major concerns. Materials with good high temperature strength characteristics will be required, and the casing program will have to be designed to accommodate thermally induced movement.

B. Cement

Cement is used in oil and gas wells to secure the casing to the wellbore. Problems are encountered when the use of cement is attempted at temperatures in excess of 200°C, and retardants are usually added to preclude premature set-up. Research is underway under DOE/DGE funding to extend the temperature limit to approximately 350°C. It does not appear feasible at the present time to further extend this limit (> 350°C). Therefore, other techniques for setting casing may be required. For example, rock melt may be employed as a way of "cementing" the casing to the wall. Explosive forming of casing to wellbore has also been suggested. In any case, this is a difficult problem which will have to be solved by innovation, not evolution.

C. Packers

Packers are used to isolate sections of the wellbore from other sections for the purposes of fracturing, sampling, or production. Packers with elastomers are not useful above 200°C. Other sealing techniques, such as glass brazing, explosive forming or flux melt, may be used for drillable packers. The use of packers can be minimized, but pore fluid testing and other sampling requirements are anticipated which will demand the use of packers.

Sampling

The sampling requirements are not defined but it can be expected that the following information would be required:

1) Borehole temperature
2) Borehole pressure
3) Pore fluid samples
4) Rock samples
5) Log sets
6) Acoustic transmission parameters
7) Fluid transport
8) In situ state of stress

Equipment or methods to perform these measurements and tests are lacking above 350°C. Below 350°C many of these measurements could be performed with present technology.

Conventional coring should be possible to about 350°C.

In situ sampling for pore fluids and rock stress are questionable at any depth, and the problem is extremely difficult at higher temperatures. Taking cores at 500°C can probably be accomplished by extensions of present technology.

Conclusions

From the prior discussion of requirements and technology limitations, some conclusions can be drawn about magma/hydrothermal drilling. As the sites and scientific programs become more specific, these conclusions may need to be reviewed.

A. For temperatures less than 200°C standard drilling and completion practices can be used.

For a large portion of the footage to be drilled, existing tools and techniques can be used. The upper portion of all holes can be conventionally drilled.

B. Current drilling research programs and industrial efforts will supply needs for drilling at temperatures between 200 and 350°C.

Much of the equipment used in conventional rotary drilling will not function at temperatures of 350°C; however, the geothermal drilling research activity is directed at this regime and industry will take a larger role in supplying materials in the future. "Work-around" methods have made it possible to drill wells having these temperatures.

One of the critical weaknesses in this area is the use of elastomers. To date, elastomers have been essential for sealing. Packers that must soak at bottomhole temperatures are simply avoided. Sealed bits are usually replaced by unsealed bits to avoid the use of elastomers. The development of new sealing materials is needed for drilling in this temperature regime.

Research supported by DOE and others is directed at improving techniques for drilling at temperatures up to 350°C. This research, coupled with industrial efforts to supply the demands of the geothermal industry, should lead to the capability to routinely drill wells to 350°C.

C. Above 350°C, concepts and methods for drilling and completing wells do not currently exist.

Extension of current rotary techniques to temperatures above 500°C appears to be extremely difficult. The range of temperatures from 350°C to melt (800-1100°C) covers a band in which most of the current ways to drill and complete wells fail. Up to 500°C it may be possible to make improvements in materials which would allow drilling and completion of wells. But beyond 500°C, it is unlikely that current methods can be extended. Therefore it will be necessary to create new concepts for drilling and completion. These concepts will be more revolutionary than evolutionary.

Alternatively, it may be possible to extend existing practice by "cooling" the hole or otherwise altering the wellbore environment. The limits on the use of this practice are not well known.

At temperatures approaching melt conditions, drilling ahead may be less of a problem than maintaining the hole. The wellbore at elevated temperatures presents uncertainties in rock mechanics, cementing (or whatever its replacement will be) and wellbore lining, where required. The maximum bottomhole temperature will determine the completion method. At 500°C, a much simpler practice can be used than near melt temperatures. Borehole stability is questionable at these temperatures.

D. Drilling fluids have a strong influence on drilling and completion concepts.

At temperatures above 350°C, the type of drilling fluid used will have a significant impact on the drilling and completion program. For control of normal or abnormal pressure, either weighted liquids or wellhead back pressure (or a combination) must be used. Subnormal pressures, which are usually associated with geothermal systems, have lost circulation problems and aerated liquids or gas drilling are commonly used. Whatever the situation, well control will require careful consideration.

Corrosion is accelerated with temperature at an alarming rate. At elevated temperature, air and water cause rapid corrosive failure, and corrosion inhibitors must be used. Drilling fluids composed of inert gas offer the potential for reducing the corrosion problem. Research in this area is needed.

The temperature limitations of high density drilling fluids are not well understood. Bentonite muds start to fail before 250°C. Sepiolite gel will extend the range considerably. Oil based muds can conceivably be used up to 500°C. The true limits are not well established at the present time.

E. Materials are temperature limited across the board.

Above 350°C, limiting temperatures are reached for all standard materials, elastomers, lubricants, muds and conventional steels. All reach their limits. New materials will have to be used. The required materials are generally available, but the performance characteristics of the more exotic materials have not been established. Fatigue life, resistance to corrosion, abrasive wear rates, and strength must be determined at the higher temperatures.

Recommendations

The strategy recommended by the Working Group on Drilling and Completion reflects how little is known about the drilling problem above 350°C. This strategy is only part of the magma/hydrothermal drilling planning strategy which includes concurrent efforts in site selection, instrumentation and sampling. The overall strategy and suggested times are as follows:

A. Determine scope of drilling and completion problem at temperatures of 350 to 1100°C (FY-79).

B. Develop new concepts and designs (FY-79-80).

C. Build and test prototypes for critical problem areas (FY-80-81).

D. Initiate Magma/Hydrothermal Field Drilling Program (FY-84).

The recommended strategy calls for a first phase study effort to put the problems into perspective. Simultaneous consideration of magma/hydrothermal drilling objectives and resulting performance requirements will allow a clear statement of the development problems to be faced (or avoided). These studies, along with an instrumentation scoping study, will allow a budgetary plan to develop for seeking program support. First reactions to such large steps in temperatures are likely to be too conservative.

Within the FY-79 scoping phase are the following subdivisions and recommended manpower levels in man-months:

1. Assess technology (36 mm)

    A. Present capabilities
    B. Capabilities with best available materials
    C. First generation new concepts

2. Develop and exercise a wellbore thermal simulator computer model (12 mm)

3. Determine drilling fluid temperature limitations (12 mm)

4. Collect and organize information on characteristics of materials at high temperature (6-18 mm)

5. Determine rock mechanics properties at higher temperatures (12 mm)

6. Determine performance requirements and specifications for new tools and equipment (18 mm)

7. Develop several concepts for new drilling systems for magma/hydrothermal applications (16 mm)

Tasks 1 - 5 can be conducted simultaneously. Task 6 must have the inputs from 1 - 5, as well as inputs from requirements dictated by the scientific program.

A more detailed description of the tasks is given below.

Task 1

In spite of the research efforts of government and industry, a clear picture of the performance limits of the various pieces and parts of the drilling system have not been achieved. Quite often economic considerations constrain the choice of materials selected for use in the drilling operation. Better, higher grade materials are needed for the magma/hydrothermal drilling systems and the performance of drilling systems with these materials should be studied. Most of the recent improvements in drilling technology have come from using better materials in older concepts. This is certainly true in drill pipe, casing, drill bits and drilling fluids. A complete assessment of the potential for extending the operational temperature range of existing rotary drilling systems through materials substitution should be performed.

This assessment should be performed first on the basis of commercially available components, and then in terms of better (and likely higher priced) materials. This task would yield a failure map of the parts and pieces required to drill and maintain hole. With this fresh view of limits, the first round of new drilling concepts follows from the new understanding of the real limitations. A word of caution is needed about limits. Limits as determined from lab test and analytical means are necessary, but field conditions must also be considered.

Task 2

A computer model which simulates the wellbore temperature under circulating conditions is required to determine the real operating and soak temperatures in which the drilling equipment must function. Due to cooling effects and some thermal barriers, seals are now operating where they would fail if circulation were stopped. The temperature and environmental factors strongly affect corrosion rates. Thermal stress is, of course, important. More detailed studies can determine the capacity of a flowing fluid to cool tools and/or the wellbore.

Task 3

The true temperature limits of drilling fluids need to be understood. Present fluid test programs will only consider temperatures up to about 350°C. Since the type of fluid and the chemistry of that fluid are very important to the other equipment requirements, a complete understanding of the behavior of candidate fluids at high temperature is required.

Task 4

A new materials "bible" which is oriented toward high temperature characteristics is needed for pipe and casing. Collecting existing information should be useful in bringing available materials to the attention of designers. Perhaps new materials have been developed under aerospace programs which would be of interest here. Unfortunately, not enough is known about higher temperature fatigue life, corrosion rates, wear rates, etc. A second step of materials testing would likely follow the collection of existing information. Of course, the material information applies to all new tool needs. This information should be catalogued so that it is readily accessible by interested users.

Task 5

Rock failure and rock behavior at temperatures between 350°C and melt is very important. Preliminary studies in support of the Magma Energy Research Program show some unexpected results in rock fracture behavior. More work is needed on fracture mechanics and wellbore stability at temperatures approaching melt conditions.

Task 6

The output of Tasks 1-5 will pinpoint strengths and weaknesses in technology. Comparison of these studies with the scientific requirements for the hole will allow deficiences to be pinpointed for further work. The resulting work plan should show clearly the conflicts between objectives, resulting requirements, and existing capabilities. At this point, the performance requirements for the magma/hydrothermal drilling system can be defined.

Task 7

Once performance requirements and technology limitations are defined, it will be possible to begin thinking of new drilling concepts. In some areas, extensions of existing methods will suffice -- in others new approaches and technical understanding must be developed so that a feasible design for magma/hydrothermal drilling results. Previously proposed systems, e.g., subterrene, should be considered under this task.

It should be emphasized that the magma/hydrothermal drilling system development must be based on a total system concept. The scoping studies proposed here will provide the basis for this approach. In addition, they will provide new information to the petroleum community relative to drilling system design.

Strategy for Consideration

One concept discussed for drilling the magma penetration hole is somewhat unique and should be analyzed further. Coring and other experiments increase the time required to drill a hole and the difficulty in maintaining the hole. On wildcat wells where subsurface parameters are not well known, it has been necessary to core and log extensively. This adds significant expense to the drilling operation.

The Working Group on Drilling and Completion discussed the concept of drilling not one deep hole, but two. Since significant interest was shown in this idea, it is presented here as food-for-thought.

The approach involves drilling the first hole as quickly as possible, performing logging and sampling sparingly. This hole would be as slim as possible to reduce costs. When this hole has been pushed as deep as practical, information from the hole can be used to plan the second hole. That is, the information would be used to:

1) Specify the zones to be cored in the second hole

2) Determine the experiments to be run

3) Determine instrumentation needs

4) Design appropriate tools

The primary advantage of this approach would be that time over the hole would be minimized, and this is known to increase the probability of successfully reaching the desired depth. It is felt that the cost of two holes drilled in the suggested manner would not be significantly higher than drilling one hole which had extensive coring and sampling requirements. This higher cost would be offset by the higher probability of having a successful scientific hole.

A secondary advantage would be that geophysical sensing experiments involving measurements between the two holes would be of great value.

It was felt that the two-hole concept should receive further consideration.

REPORT OF THE WORKING GROUP ON LOGGING AND INSTRUMENTATION

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Dr. A. Truesdell, U. S. Geological Survey
Dr. A. F. Veneruso, Sandia Laboratories

Introduction

The aim of this working group was to identify research and development tasks which must be accomplished in order to provide the instrumentation systems in a program of continental drilling for scientific purposes. We identified the tasks listed in Table 1 as requiring specific assessment and feasibility investigations as the initial effort to fulfill the instrumentation needs of the magma/hydrothermal program.

Each of these tasks was assigned to a member of the group to give a detailed description of the investigation or research activity required in each case. The group also recommended an overall schedule for the tasks in this proposed program. Following a discussion of each of the detailed task descriptions, the group leader estimated the time required for this initial assessment and feasibility investigation. Priorities were also assigned to the list of tasks on the following basis:

Priority A -- Tasks which are essential to planning and successful execution of the program

Priority B -- Tasks which are needed in an ongoing program

Priority C -- Tasks which enhance the program's productivity, but which are not essential because of alternative approaches.

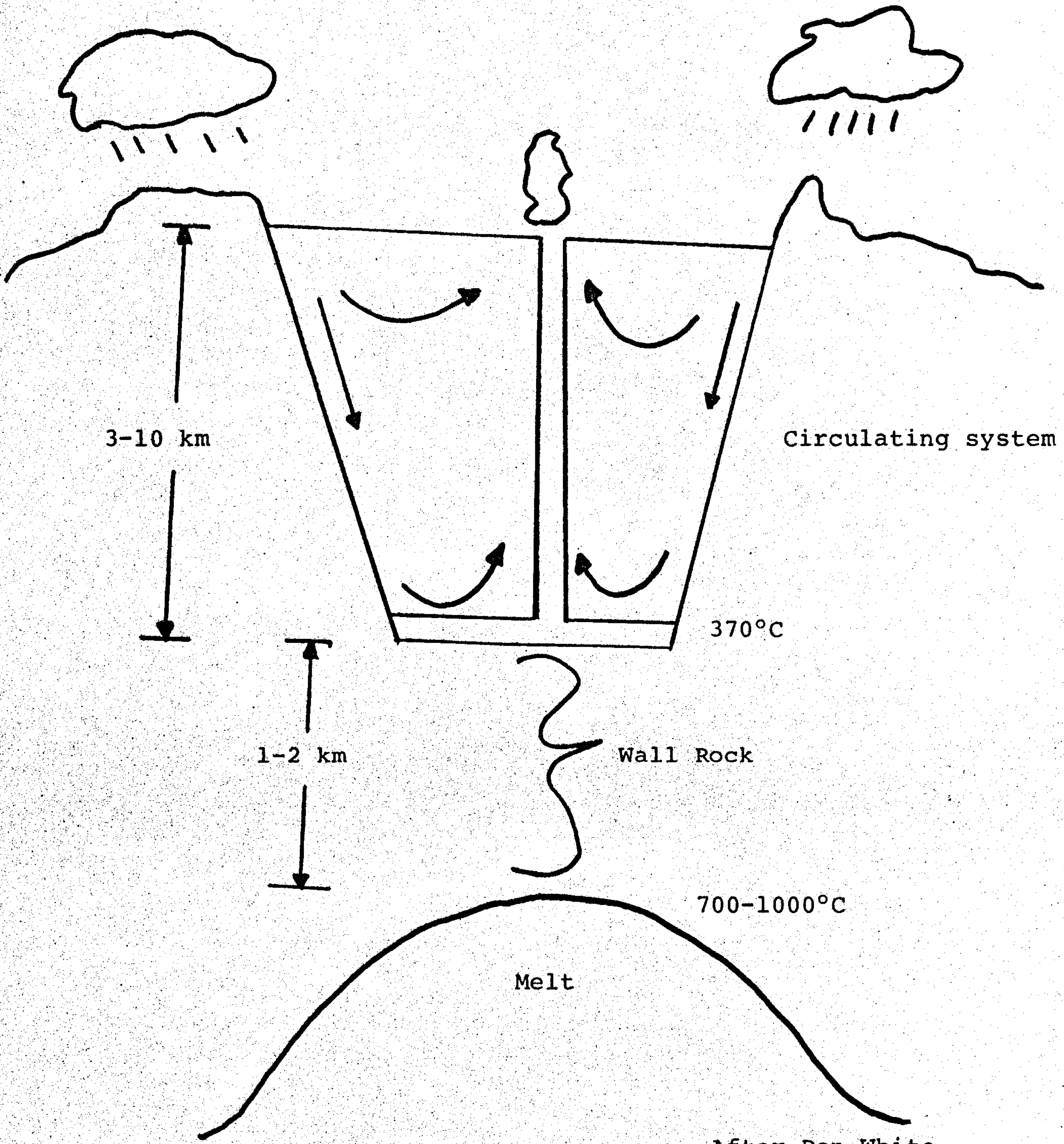
Table 1 lists the tasks, their priority and estimated labor to perform the initial recommended assessment. Table 2 gives the recommended program schedule. Figure 1 is the working model of the magma/hydrothermal reservoir used by the group for the purpose of discussing the technology needs in each task.

Table 1. Magma/Hydrothermal Instrumentation Development Tasks

Task	Priority	Feasibility Assessment (Estimated Man Months)
1. High resolution temperature measurements	A	2
2. Samples of core and melt	A	2
3. Formation fluid sampler	A	2
4. Chemical probes	A	2
5. Thermal protection for instruments	A	4
6. Communication methods	A	6
7. Lithology measurements at 370°C	B	2
8. Geothermal tools up to 370°C	B	1
9. Fracture detection	B	4
10. Liaison with LASL interpretation program	B	1
11. Selection and development of electronic techniques for 370°; 700°; 1100°C	B	1
12. Mechanical protection techniques	C	2

Table 2. Logging and Instrumentation Schedule

FY-79	Paper studies Material tests
FY-80	Prototype design for simplest measurements More study and circuit design for difficult measurements
FY-81	Prototype fabrication and laboratory testing of simple tools Bread board design for difficult tools
FY-82	First field tests



After Don White

Figure 1. Our working model

Detailed Task Descriptions

Task 1. High Resolution Temperature Measurements (P. Kasameyer)

This task was divided into two areas, depending on where the thermal measurements were taken -- in the zone above the magma chamber or within the magma chamber itself.

The following steps are recommended to develop a research plan for thermal measurements in the region above the magma.

Step 1. Determine scientific objectives

Example:

A. Estimate vertical conductive heat flow within solid rock above magma chamber

B. Determine accurately temperature at which melting occurs (accuracy determined by geochemists)

Step 2. From scientific goals, estimate appropriate measurement and necessary resolution

Example:

A. Need

1) Equilibrium temperature differences over vertical distances appropriate for desired accuracy, and

2) Measurement of bulk thermal conductivity

B. Need absolute equilibrium temperature near top of magma chamber

Step 3. Investigate transducers (literature and in laboratory). Since temperature measurements are routinely made to 1000 to 1200°C in many industrial applications, the main questions will be stability of transducer in this particular environment (or protection from environment) and resolution or sensitivity which is possible. Choice of transducer will also depend strongly on communication system used.

Examples of temperature transducers:

A. Thermocouples
B. Resistance thermometers
C. Irreversible phase changes
D. Differential thermometers

E. Thermoelastic sensors
F. "Exotic" sensors

Step 4. Design instrumentation using output from mechanical packaging electronics and communication subtasks.

Step 5. Thermal conductivity "transducers" involve perturbing temperature and measuring change or recovery. Evaluate methods for heating or cooling borehole.

Examples: Resistance heating
Frictional heating
Cooling
Chemical reactions

Step 6. Evaluate tools in whatever wells are available

The following steps are recommended to develop a research plan for thermal measurements in the magma:

Step 1: Determine scientific objectives

Example: Understand heat transfer mechanism within magma

Step 2: Estimate possible resolution and sensitivity

Step 3: Investigate transducers and heat sinks

Step 4: Design instrumentation and procedure

Step 5: Evaluate performance wherever possible, in lab or in lava.

Task 2. Samples of Core in Melt (A. Truesdell and P. Modreski)

This task is needed because the anticipated limited capability of high temperature downhole instrumentation demands efficient recovery of rock samples for surface study.

Core or large chip recovery will allow calibration of logging devices in unfamiliar rock and physical environment. Also, the chemical objectives related to ore deposition and rock alteration in deep hydrothermal and near-magma environments require recovery of rock samples. During sample collection, limited rheological and thermal measurements of the magma may be possible by measuring such parameters as the rate of penetration of the sampler and the rate of chilling with a known rate of heat removal.

Analysis of logging and drilling records will indicate zones to be cored in already drilled holes. Conventional coring may be very difficult because adequate cooling to drill the magma may not be available at the bottom of the hot, deep hole. Due to the anticipated expense and difficulty of conventional coring methods, new approaches may be required to obtain samples in already drilled holes. Some suggested candidate solutions are:

A. A special bit which continuously produces large rock pieces that can be recovered with the cuttings,

B. A sidewall coring device,

C. An open tube melt catcher with flap valves that hold the magma until quenched on withdrawal,

D. A tube with a refrigeration device to chill the magma before withdrawal of the tube.

The sidewall corer must operate at downhole ambient conditions with mechanical parts only -- no elastomers. The melt catcher may have to be entirely mechanical, including refrigeration devices (e.g., activating endotheric reaction capsule).

Task 3. Chemical Probes (P. Modreski and A. Truesdell)

These probes would utilize chemical reactions as indicators of chemical activities of components in the downhole environment. For proper functioning, those devices may require that the sampled region be packed-off to assure that the desired formation fluid is obtained or that fluid communication is made with the defined region.

Two categories of probes may be considered -- passive and active.

Passive probes are exposed to the environment of interest and then recovered, but no electrical or mechanical power is used in taking the measurements and no electric cable is required. Passive probe materials which should be considered include: metals, alloys, oxides, sulfides, hydroxides, carbonates, sulfates and silicate minerals. The techniques which should be considered include: bare metal (wire, rings, etc.,) and compounds embedded within permeable ceramics.

Active probes, such as electrochemical cells, require electrical communication to provide immediate reading of the in situ measurement. Simultaneous measurement of temperature and electrical conductivity of fluid should be made to establish a baseline for the chemical measurement. The measurements made should include the following:

Aqueous fluids to ∿ 370°C?

- H^+ (pH electrode)
- O_2 (Eh electrode)
- H_2S
- Other?

Hot fluids (gases) > 500°C?

- O_2 (ZrO_2 solid electrolyte)
- S_2 (silver sulfide cell)
- H_2 (diffusion into Pd membrane and recovery for analysis)

Task 4. Thermal Protection for Instruments (J. Archuleta)

An outline of the recommended assessment and feasibility investigation of this task is as follows:

I. Establish limits for electronic technology, for example:

  A. 125°C - general availability
  B. 275°C - Sandia hybrid circuits will extend range to 275°C
  C. 370°C - Gallium arsenide semiconductor electronics possible

II. Determine the types of thermal protection which can be used, for example:

  A. Refrigeration -- these are complex systems, but experimental prototypes exist which have been tested at 200°C

  B. Dewars (flasks)

    1. State of the art

      a. Tested at 275°C

        1) Allows 12 h downhole with 15W internal heat dissipation

        2) Electronic size limited to 2.75" dia by 26" length

      b. Uses heat sinks

        1) Cerrobent alloy is useful to 85°C

        2) Different heat sink material would permit use to 125°C

    c. Uses mil spec electronics (125°C)

2. Extended temperature range with improved electronics

    a. Use to 370°C possible with little R&D
    b. Use to 700°C probable

3. Useful downhole life can be extended using hybrid circuitry (Sandia)

Task 5. Communication Methods (S. Cohn)

These methods were divided into two categories: single and multistage. Single stage systems are descriptive of the typical logging technique, whereby a downhole probe is linked directly to the surface by means of an electric cable. Multistage systems utilize, shown in Figure 2, an intermediate downhole signal processing transceiving package, which is maintained at a particular level and transmits to the surface on a conventional cable. This intermediate package receives signals from logging instruments, at greater depth and temperature, on any possible high temperature compatible transmission system.

This working group acknowledges Dr. P. Modreski, for his formulating this multistage approach.

With regard to single stage systems:

For up to 275°C	Wire cable appears feasible.
to 375°C	Development of improved cable insulation systems is necessary.
to 700°C	Magnesium oxide insulated tubular cables are available, but there are severe limitations due to short manufacturable lengths and splicing difficulties. Developments are required to overcome these difficulties.
over 700°C	Since the cable problems are extremely severe at these temperatures, we recommend the development of thermally insulated self-contained downhole data storage and

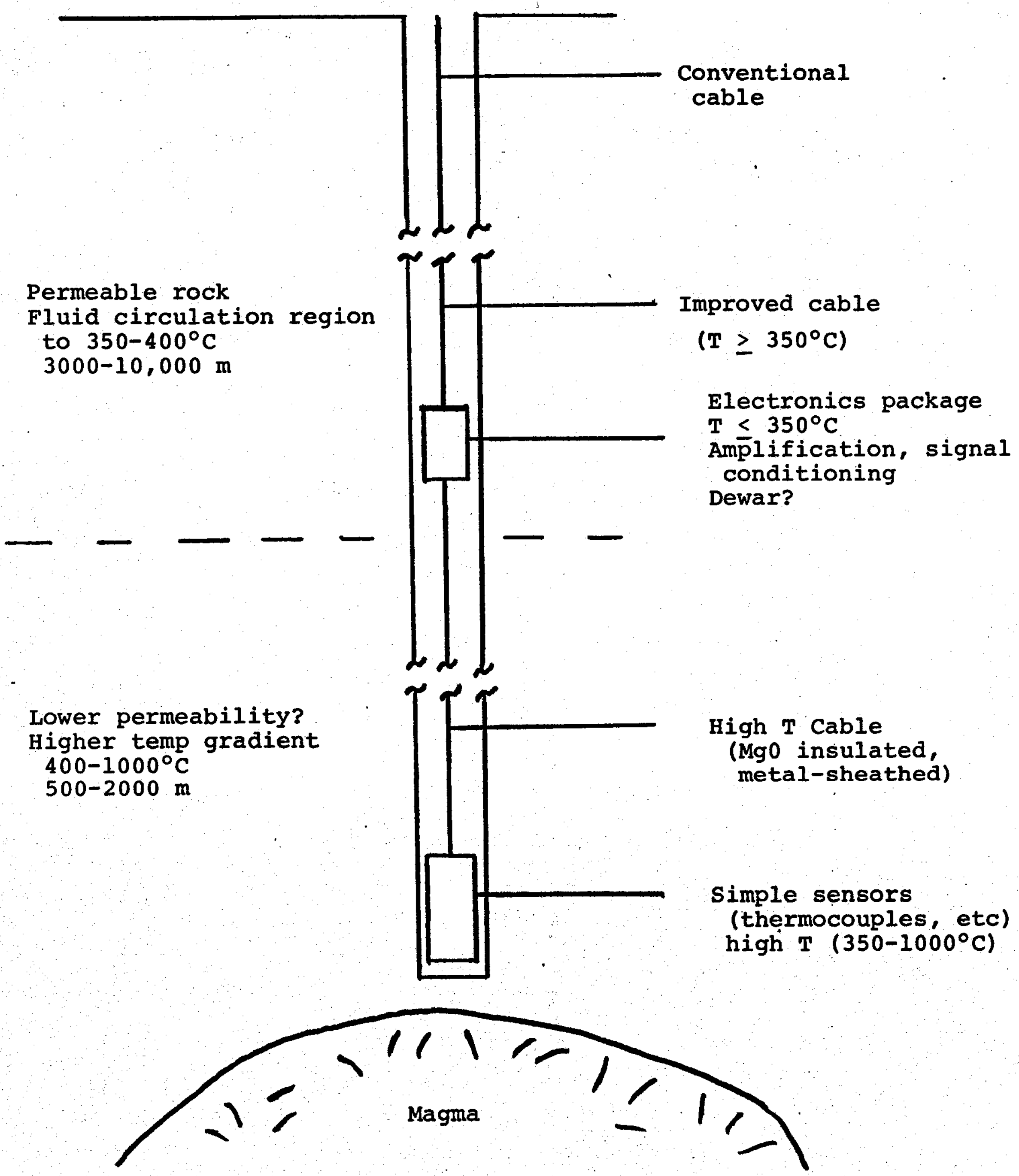


Figure 2. Multi-stage data transmission concept

control systems (not necessarily electrical). Also, other means for communication to the surface should be explored; for example: acoustic, low frequency electromagnetic, radio transmission and fiber optics.

Task 6. Lithology Measurements at 370°C (R. Lawson)

An outline of the recommended assessment and feasibility investigation of this task is as follows:

A. Determine current industry plans and status for development of high temperature (370°C) neutron, density and sonic tools.

   1. High temperature circuitry and seals
   2. Thermal protection being used
   3. What (if any) additional developments required

B. Develop in coordination with LASL plans for determining tool response curves in expected rock types.

   1. Core velocity measurements at 370°C
   2. Core porosity measurements
   3. Core bulk and matrix density measurements
   4. Field tests in known lithologies (covering a range of porosity, temperature and pressure)

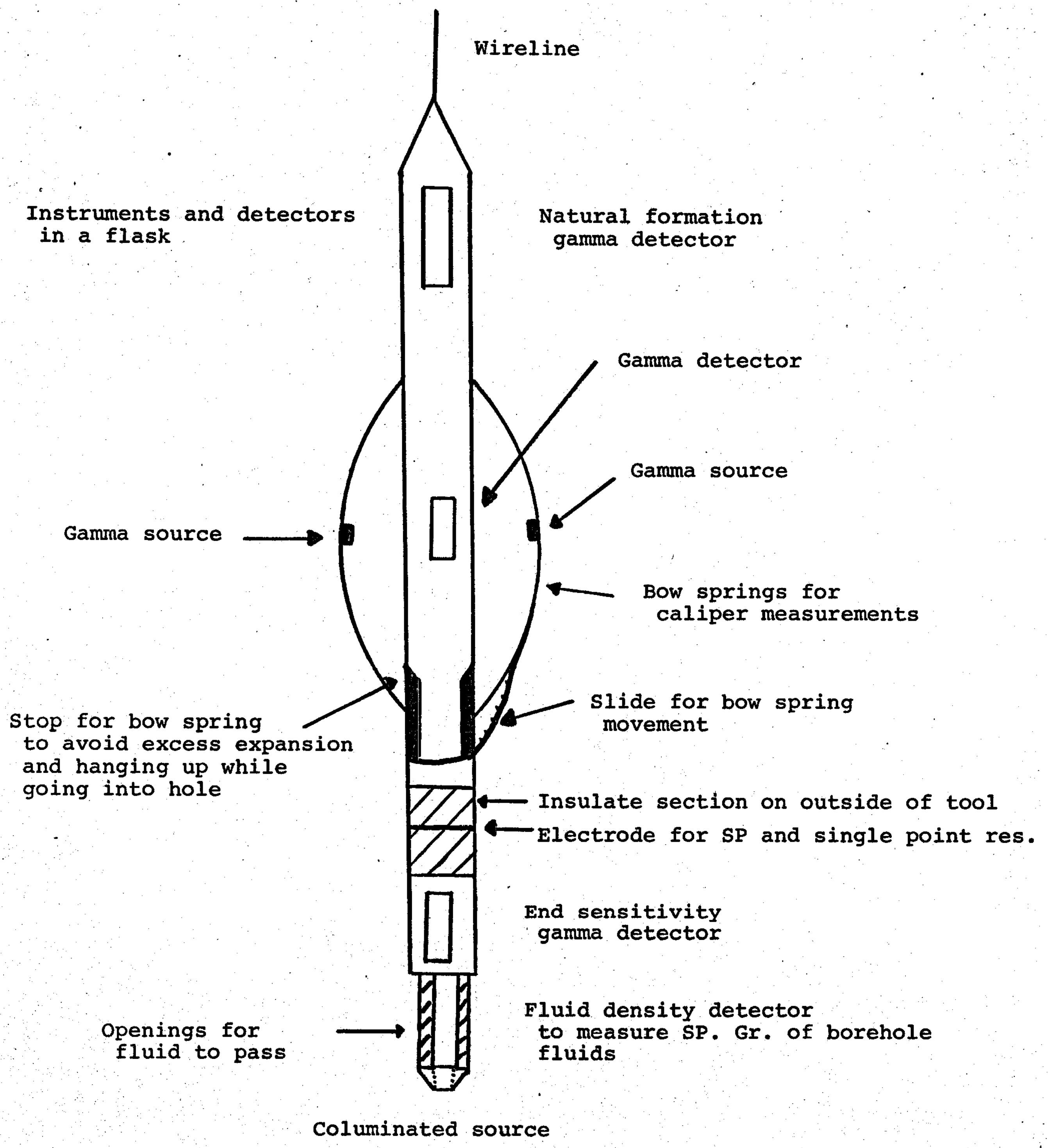
C. Determine feasibility of developing cross plots (i.e., neutron-density, sonic-neutron, and sonic-density) for identification of lithology.

D. Investigate possible use of magnetic susceptibility as a means of lithology identification.

In the course of this working group session, Mr. R. D. Clarke suggested the combination of natural formation gamma detector, gamma ray caliper and fluid density detector shown in Figure 3. This committee acknowledges and thanks Mr. Clarke for his suggestion.

Task 7. Geothermal Tools up to 370°C (A. Veneruso)

The objective of this task is to utilize geothermal logging technology for magma/hydrothermal up to 370°C. The tools of primary interests are as follows:



Will work in empty or fluid filled holes.

R. D. Clarke, DOE/NVOO
June 2, 1978

Figure 3

Temperature	High resolution (± 0.1°C or better) Platinum sensors are available.
Pressure	Low resolution (± 10 psi in 1500 psi) Formation pressure is of interest.
Resistivity	Fabrication appears to be straightforward.
Caliper	Rotary seals are difficult, therefore, use one shot open, one shot closed mechanism.
Gamma Ray	Must be in dewar flask Fracture mapping, acoustic techniques

The initial assessment effort should be directed toward establishing that the geothermal instrumentation development efforts already underway address the needs for these tools to be used in magma/hydrothermal.

Task 8. Formation Fluid Sampler (A. Skellie)

The objectives of this task are to develop techniques for:

A. Taking samples (1/2 L minimum) of formation fluid at temperatures up to 370°C; 700°C.

B. Taking samples (1/2 L minimum) of borehole fluid when "borehole" fluid is from the formation or is at temperatures up to 370°C; 700°C.

The problem areas which need to be addressed are:

A. Determine a method for actuating the tool in the absence of multi-conductor logging cable.

B. Determine a method for sealing the tool against the formation.

C. Determine a method for sealing the sample after capture.

D. Determine a means for prevention of contamination of the sample by reaction with container.

Task 9. Fracture Detection (R. Clarke)

The information desired from fracture measurement is:

A. Presence of fractures
B. Fracture width
C. Fracture orientation -- strike and dip
D. Communication between fractures

Among the candidate approaches are:

A. Acoustic
B. Resistivity
C. Mechanical -- caliper fingers
D. Pressure pulsing
E. Dissimilar liquids
F. Microdensity
G. Induction

The initial assessment should first determine the accuracy and resolution requirements for magma/hydrothermal fracture detection. Then an assessment should be made of the performance capabilities of commercial fracture mapping services along with the progress and plans of ongoing fracture mapping developments. Finally, the assessment should identify the need and scope of additional development.

Task 10. Liaison with LASL Interpretation Program (L. Edwards)

LASL now has the responsibility of specifying the desired types of logs for the production of interpretative methods that apply for instrumentation operated in geothermal environments and igneous rock. They also intend to provide central core collection and evaluation facilities, geothermal log collection, filing and evaluation facilities, and control and assignment of geothermal drill holes for testing and calibration of future instrumentation.

Except for the magma phase, the information and facilities developed above can be made available to us without cost and only a reasonable personnel time involvement.

Interpretation for measurement or logs made in the wall rock and magma zones would have to be generated separately by the magma/hydrothermal program.

Liaison should be maintained between these two groups.

Task 11. Selection and Development of Electronic Techniques for 370°C, 700°C, and 1100°C (R. Heckman)

The objective of this task is to develop high temperature electronics technologies and circuits for logging tools. The group strongly recommends that the magma/hydrothermal activities in this area follow the present geothermal instrumentation development program at Sandia Laboratories, where developments are being made first up to 275°C then to 350°C. Separate considerations must be given to each of the following temperature regimes:

Up to 300°C	Here the major reliance is on the existing Sandia program which utilizes silicon semiconductor devices and hybrid thick film technology.
Up to 370°C	Again the Sandia program will form the basis for fulfilling the needs of magma/hydrothermal, but the technology moves from silicon to gallium arsenide for active devices.
Up to 700°C	Up at these temperatures known semiconductor materials are non-functional, but thermionics and magnetic devices have the potential for fulfilling the needs for active devices. LASL has demonstrated operation of their experimental Integrated Thermionic Circuit (ITC) up to 800°C and magnetic materials and ceramic insulated wire exist from which complete magnetic circuits can be made to operate at these temperatures. Both of the above approaches are being developed as part of the geothermal instrumentation development program.
Up to 1100°C	At these temperatures, thermionics is the most likely candidate but will require extensive development. Complex circuits may not be feasible.

Up to 700°C, passive electronic devices and circuit fabrication techniques appear feasible through extension of the thick and thin film techniques being developed for the geothermal instrumentation. It is probable that to achieve 1100°C operation very extensive development will be needed.

Task 12. Mechanical Protection Techniques (J. Burgen)

Mechanical protection is needed in the form of seals and case materials which must protect the downhole instrument from the severe thermal and chemical environment as well as to provide basic structural integrity against the downhole pressure and mechanical shock and vibration in traversing the hole.

Elastomeric seals appear to be limited to at most 300°C, therefore, the initial assessment should focus on investigation of metal seals. There are many types of metal seals which may be adequate for use at high temperature. For example, conoseals made by Aeroquip Corp. appear to be satisfactory up to about 700°C. The assessment should include a review of candidate types along with some straightforward laboratory oven tests of the most promising ones.

Case materials should be investigated with regard to their strength at the temperature and in the corrosive environments of interest. The initial investigation should also explore some promising candidate materials in limited laboratory oven tests.

The group noted that there may be circumstances where it may be advantageous not to have mechanical protection, but to have provision for one or more sacrificial probes to obtain measurements in the magma/hydrothermal environment.

Appendix A

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