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DRILLING, INSTRUMENTATION AND SAMPLING
CONSIDERATIONS FOR GEOSCIENCE STUDIES OF
MAGMA-HYDROTHERMAL REGIMES

R. K. Traeger
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DRILLING, INSTRUMENTATION AND SAMPLING CONSIDERATIONS
FOR GEOSCIENCE STUDIES OF MAGMA-HYDROTHERMAL REGIMES

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Abstract

A deep drill hole into a magma-hydrothermal system would provide access to the third dimension needed to understand processes in the earth's crust and to resolve the ambiguities in existing models derived from two-dimensional, surface geoscience studies. Magma-hydrothermal systems are of interest for basic understanding of heat and mass transport in the earth's crust, for evaluation of geothermal energy resources, an understanding of mineral deposition processes and for assessment of such hazards as volcanic eruptions, earthquakes and waste disposal.

The purpose of this paper is not to promote drilling a deep well, but to identify technological limitations, point out potential scientific-technology conflicts, provide an estimate of times and costs and to initiate interaction between the scientific and engineering community for an effective Continental Scientific Drilling Program (CSDP). This paper reviews the drilling, diagnostic and sampling technologies needed to provide data from the third dimension for the scientific studies.

Deep gas wells are frequently drilled to depths of 7-10 km at temperatures to 220°C in sedimentary formations. Geothermal wells are drilled to 3-5 km, 250-350°C in metamorphic and igneous formations. Holes have been drilled to a depth of 60 m into partially molten rock in lava lakes. However, the technology is not available to drill and perform measurements in formations at depths of 6-10 km at temperatures over 350°C as needed for studies of magma-hydrothermal systems. The major technological limitation is the ability to recover solid, liquid and gas samples at in situ conditions at temperatures exceeding 200°C. Deep drilling into hot formations and logging diagnostics using dewared instruments appear feasible if the well is kept at low temperatures by circulating coolant. However, a cold well negates meaningful temperature and heat flow measurements. In addition, the wellbore may collapse when the equilibrium formation temperature is attained because of thermal stresses and the lack of a casing cement that retains strength at temperatures over 350°C.

A cursory estimate suggests that time for completion of a 7 km deep well in a magma-hydrothermal system and intensive geoscience experiments will be on the order of 10 years and costs (not including scientific experiments) will range from \$40-60 million. A possible procedure would be to use conventional drilling to its limit (3.0 km, 350°C used in this paper) and perform detailed scientific experiments prior to committing to the deep hole. Estimates for this first phase are five years and \$5 million (again, not including the scientific experiments).

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INTRODUCTION

Knowledge of the geostatics and geodynamics of the earth's crust is needed to understand geological processes and to evaluate resources, hazards and the potential ecological impacts of proposed in situ energy related technologies. Since surface studies of geology, geochemistry and geophysics can only provide non-unique concepts of the earth, drilling to provide data from the third dimension is needed to resolve conflicts and validate specific concepts. Such an approach in the Deep Sea Drilling Program has been successful in detailing the concepts of plate tectonics and describing the structure of the ocean floor. A similar program has been initiated to study the ocean margins, possible sources of fuels and minerals. However, no comprehensive scientific drilling program has been undertaken to understand the processes occurring on the continents. Such a program has been proposed, the Continental Scientific Drilling Program (CSDP), to provide fundamental information on the structure, evolution and genesis of the continents [Continental Drilling (1975), CSDP Report (1979)].

CSDP workshops identified four major scientific thrusts -- Basement Structures and Deep Continental Basins, Thermal Regimes, Mineral Resources and Earthquakes [CSDP Report (1979)]. This paper reviews the drilling and instrumentation capabilities needed to study thermal regimes; specifically, magma-hydrothermal systems. The review is not intended to endorse or deny the need for a deep drill hole but rather to identify technological limitations and potential technological-scientific conflicts, and to initiate dialogue between the scientific and engineering community. Consequently, the following discourse reviews scientific needs, reviews the state-of-the-art for drilling and diagnostics and finally uses a "strawman" CSDP drill hole for identifying scientific and technological limitations.

SCIENTIFIC INTERESTS

Scientific objectives and interests of the CSDP have been reviewed [Continental Drilling (1975), CSDP Report (1979)] with recent studies emphasizing thermal regimes [Varnado and Colp (1978), Hardee (1980), Luth and Hardee (1980), Goff (1980), Kasameyer (1980), White (1980)]. All reviews indicate an extensive background of geoscience data obtained from the surface and the existence of a large number of models of the in situ magma-hydrothermal systems. However, the surface measurements cannot provide a unique description of the three dimensional geological systems and consequently models cannot be effectively evaluated. This inability to quantify geological models severely limits the exploration for and evaluation of geothermal resources, the evaluation of repositories for chemical and nuclear wastes, the discovery of mineral resources and the planning of in situ fossil fuel recovery processes.

The drilling of slim holes (5-10 cm diameter) to depths of 1 km to resolve scientific questions is an important part of the CSDP. Although slim holes limit the opportunity for downhole sampling and diagnostics, the acquisition of conventional core samples can provide the basis for numerous and fruitful research activities concerned with physical, chemical, and mineralogical properties in the third dimension. Data obtained from slim holes are essential to plan deep, large-diameter holes necessary for gas and fluid sampling, passive and active downhole measurements and other scientific experiments. Subsequent discussions

are based on the premise that extensive slim hole drilling and coring is done prior to any deep drilling program.

A drill hole into a magma-hydrothermal region could provide much of the in situ data needed for understanding and modeling a geologic system. Table 1 lists some scientific information that is needed and could be provided by a drill hole. Additional in situ experiments will be defined when the scientific questions are detailed and a specific site defined.

Definition of experiments with appropriate measurement techniques is needed prior to designing a drilling program. For example, the use of casing to maintain an open borehole may negate some downhole measurements; drilling fluids can physically and chemically alter formation materials; drilling operations will "chill" the well and extended equilibration times may be required for effective measurements; surface safety requirements may compromise experimental design; hole sizes must be adequate to accommodate the experimental packages, etc. All this indicates that the experimental goals and plans must be defined before developing a drilling sequence and the experimenters must work closely with the engineers in developing field plans. This preplanning phase is critical as evidenced over 50 man years of technical preplanning expended by Exxon [Bleakley (1980)] for their 7 km, McDonald Unit No. 1 well. Although the field and drilling problems were known for the McDonald well, extra design was needed because of the depth, anticipated temperature (200°C), pressure (1.5 kb), and the possible presence of hydrogen sulfide in copious quantities.

STATE-OF-THE-ART DRILLING AND DIAGNOSTICS

Rotary drilling, primarily for oil and gas, was expected to provide 56,000 wells with over 82,000 km of hole drilled in the United States in 1980 [Anon (February 1980a)]. Deep drilling activities continue to expand with 621 wells drilled deeper than 4.5 km in 1979; 64 of these wells were deeper than 6 km [McNally and Ellis (1980)]. In addition, symposia have considered deep drilling [Deep Drilling and Production Symposium (1974), Varnado and Colp (1978)] and studies were made on technologies needed to drill and log a 15 km hole [Fennix and Scisson (1969), Moran and Attali (1971)]. Deep drilling and diagnostic needs for CSDP were also considered in the 1975 Continental Drilling report. In the last five years, the U. S. DOE's Division of Geothermal Energy has supported development of drilling, sampling and instrumentation capabilities applicable to hot geothermal resources [Anon (January 1980)].

This section of the paper surveys the capabilities for deep drilling, sampling and diagnostics. The survey will provide a basis for considering the developments needed to provide a CSDP well into a magma-hydrothermal environment.

Drilling and Completions

Current technology allows drilling to depths exceeding 10 km in formations with nominal thermal gradients. Information collected on some deep wells is summarized in Table 2. It is important to note, from CSDP interests, that drilling costs limit logging and coring activities to those required to complete a well. Rig costs of \$7,500-10,000 per day and the possibility of losing a hole do not allow for scientific studies in commercial wells.

INFORMATION	COMMENTS
1. SAMPLES CORE; MINEROLOGY, GEOCHEMISTRY LIQUIDS; COMPOSITION, P,T GASES; COMPOSITION, P,T	TO BE RETAINED AT IN SITU CONDITIONS; POSSIBLE USE OF PRESSURE CORING SYSTEMS, SURFACE PROCEDURES AND DIAGNOSTICS NEED TO BE DEVELOPED TO SAMPLE, ANALYZE AND INTERPRET MEASUREMENTS FROM A CORE SYSTEM.
2. IN SITU PROPERTIES TEMPERATURE PORE PRESSURE DENSITY POROSITY THERMAL CONDUCTIVITY ELECTRICAL RESISTIVITY SHEAR AND COMPRESSIONAL WAVE VELOCITIES STRAIN STRESS	SOME DATA NEEDS TO BE OBTAINED CONTINUOUSLY OVER LONG PERIODS OF TIME. CONVENTIONAL LOGS SHOULD ALSO BE RUN AS AVAILABLE FOR THE ENVIRONMENT.
3. IN SITU EXPERIMENTS ACTIVE AND PASSIVE SEISMIC PERMEABILITY ELECTROMAGNETICS	THESE EXPERIMENTS WOULD REQUIRE SEMIPERMANENT INSTALLATION OF SENSORS AND ELECTRONICS FOR LONG PERIODS OF TIME.
NOTE: A MORE COMPLETE DISCUSSION OF GENERAL EXPERIMENTAL NEEDS FOR CSDP IS GIVEN ON p. 37-45 OF THE 1975 REPORT, CONTINENTAL DRILLING.	

Table 1. Scientific information provided by a drill hole

DEPTH (km)	LOCATION	GEOLOGICAL FORMATIONS	BOTTOMHOLE		COSTS (\$10 ⁶)	REFERENCE	COMMENTS
			T (°C)	P (kb)			
(1) 10.6 GOING TO 15 km	USSR, SG-3, KOLA PENINSULA	GRANITE	180			ANON, MARCH 1981 ANON, DEC. 1980	NO DETAILS AVAILABLE
(2) 8 GOING TO 15 km	USSR, SG-1 SAATLEY IN AZERBAIJAN					ANON, MAY 1980 ANON, DEC. 1980	NO DETAILS AVAILABLE
(3) 5.9	DELAWARE BASINS OF WEST TEXAS	WOLFCAMP-PENNSYLVANIA INTO FUSSELMAN	150	1.2	3.5	GOULD & SWIFT, 1980	116 DAYS DRILLING
(4) ~6 ~8 ~8	WEST TEXAS OKLAHOMA LOUISIANA				~ 4.5 10-15 ~ 5	ANON(a), 1980	675 WELLS, w 15,000; DRILLED IN 1979
(5) 6.3	FREMONT COUNTY, WYOMING; MADDEN GAS AREA	UPPER CRETACEOUS, SHANNON	196	1.1	10	ANON, 1980	
(6) 6.5	ISLETA #2, NEW MEXICO		(220)			PRIVATE COMM.	
(7) 6.8	BULLFROG UNIT 1 NATRONA COUNTY, WYOMING	SUNDANCE	165	1.0		PRIVATE COMM.	
(8) 7.1	TERRY, MISSISSIPPI; McDONALD NO. 1	NORPLET SANDSTONE, JURASSIC	200	1.6	42	BLEAKLEY, 1980	400 DAYS DRILLING; HIGH P; ANTICIPATED CO ₂ , H ₂ S
(9) 9	EMMA LOU UNIT 1, WELL 2 PECOS COUNTY, TEXAS	ELLENBURGER	215	0.8	8	FINDLEY, 1980	492 DAYS DRILLING; TEMPS LIMIT TOOL USE DOWNHOLE
(10) 9.2	NO. 1 BADEN			>1.6		ANON, JULY 1974	543 DAYS; PERMEABILITY AND POROSITY LOGS
(11) 9.6	NO. 1 BERTHA RODGERS, WASHITA COUNTY, OK ANADARKO BASIN	HUNTON & ARBUCKLE	(230)	1.6		ANON, JULY 1974	ENCOUNTERED LIQUID SULFUR; 504 DAYS; ELEC. LOGS

Table 2. Deep drilling activities

Current technology is being applied to drilling geothermal wells into hot, hard, fractured formations. Drilling depths are nominally 1-4 km with maximum temperatures to 400°C. Geothermal drilling costs are 2-6 times the costs of drilling conventional oil and gas wells with a significant portion of the cost due to unpredicted drilling problems [Carson and Lin (1981)]. A number of problems such as borehole stability and lost circulation, are due to the highly fractured formations which will also be encountered in penetrating a magma-hydrothermal regime. The current U.S. DOE, Division of Geothermal Energy effort to reduce the cost of geothermal wells is addressing many of the problem areas [Varnado (1981)] and could provide a basis for any further development needed for CSDP. Technologies are being developed by Los Alamos National Scientific Laboratory [Cremer, et al., (1980)] to drill into hot, dry rock will also be directly applicable to a CSDP effort in thermal regimes.

Of particular relevance to the magma-hydrothermal drilling, was a successful attempt to core into a shallow, molten rock mass in the Kilauea Iki lava lake. The drilling was performed as a part of the Magma Energy Research Program [Colp and Traeger (1980)] in evaluation of the scientific feasibility of extracting energy from magma bodies. Kilauea Iki lava lake provides an accessible microcosm of a geothermal system (Figure 1). Drilling into the molten lense has all the elements of drilling into a magma body except depth, pressure and fugative content. The lense is partially molten ($> 1000^{\circ}\text{C}$), surrounded by a hot dryout region and topped with a convecting hydrothermal region. Attempts were made to drill into the liquid to define the bounds, compositions and properties of the various layers. Results of a major drilling effort have been summarized [Neel, Striker and Curlee (1979)].

The drilling was done with conventional and water jet augmented drill bits. Attempts to push a probe into the hot region were unsuccessful and a special, high temperature drilling system (discussed in the Neel report) was not used. Water was used as the drilling fluid with no recirculation; it was lost in the highly fractured formation. A high flow rate was used to cool the drill bits and stabilize the wellbore.

Drilling 10 m below the first encounter of molten rock was successful. Some observations follow:

- 1) Initial melt was encountered in thin (~ 1 mm) seams. The melt extruded into the borehole would freeze the string. Chilling by the water and mechanical fracturing of the frozen rock enabled continuous drilling.
- 2) Water jet augmented core and drag bits successfully drilled into $1000^{\circ}\text{C}+$ crystal-liquid material when pressure was maintained in the hole to prevent flow back and cooling was continuous.
- 3) In one instance, a conventional core bit successfully drilled into the two-phase lense and the borehole remained open for over 24 hours.
- 4) Interruption in pressure or coolant maintenance allows melt to collapse or move up in the hole. Figure 2 shows cores obtained from the two-phase region. The two-phase core extruded up the core barrel often yielding greater than 100% core recovery.

Figure 1. Kilauea Iki lava lake cross section (Hermance)

**SEMI MELT,
EXTRUDED CORE**

**COMPETENT CORE
SHOWING CRYSTALS AND
QUENCHED MELT
(56m)**

**MELT EXTRUDED
INTO VEIN
(58m)**

Figure 2. Kilauea Iki core samples

Drilling was completed through a lava flow in Heimaey, Iceland, in March, 1974. The drilling log [Bjornsson, 1980] indicated molten lava extended from 32-67m with temperatures to 914°C. Problems included wellbore narrowing, failure of bits due to high temperatures, sand filling the hole and steam explosions. A representative excerpt from the log indicates some of the problems.

"3/15 27-70.6m. Drillbit Varel HI 3-1/2" 45.91. Stop in 27m. Water applied, intermittent drilling to 59.6 m. Powerful explosions so the drill was hopping like a kangaroo and it took 5 hours to cool the well down and reach bottom (59.6 m). From there drilling proceeds smoothly down to 67 m where the drill suddenly strikes harder rock (bottom of molten lava)."

Conclusions from these Kilauea and Heimaey tests suggest one can drill into a hot magma melt if the borehole is kept cool and the lithostatic pressure is balanced by a constantly maintained borehole pressure.

Figure 3 shows depths and temperatures encountered in a number of wells. The area of interest to the CSDP program, i.e., the lower right portion of Figure 3, has not been penetrated by drilling to date and consequently we have limited knowledge of the problems that may be encountered.

Instrumentation

Downhole instrumentation, or logging, has been developed to provide geophysical data in sedimentary formations for fossil fuel exploration. Such instrumentation may or may not provide useful information in igneous or metamorphic formations because the instruments are designed for sedimentary lithology and data reduction and interpretation techniques are oriented to fossil fuel needs [Sanyal, S. K., et al., (1980)]. Sanyal and Meidav (1977) summarized the utility of several well logs as given in Table 3. Limits of some of the logging tools are listed in Table 4 and some of the problem areas are noted in Table 5; the major limitation to existing tools is the temperature. This lack of capability at elevated temperatures has limited the use of logging tools in the diagnostics of geothermal wells, particularly when the instruments have to survive the downhole environment for more than several hours.

In programs sponsored by the U.S. Department of Energy, Division of Geothermal Energy, development activities are providing cables and electronics capable of higher temperature [Anon (January 1980)]. A high temperature seven conductor cable, now commercially available [Veneruso, et al., (1980)] is capable of operating at 300°C for at least 10 hours. A cable head, with no temperature limiting plastic or rubber parts has also been developed for use to 275°C [Veneruso, et al., (1980)]. A high temperature single conductor cable for use to 700°C is in the process of being developed using the existing technology for sheathed thermocouple manufacture [Halpenny, A. S. (1981)].

With current developments, downhole instrumentation should be available for CSDP use to 300-350°C. Temperature and possible corrosion limits on exposed sensors and cables will restrict downhole lifetimes at 300°C. Since a generic increase of instrumentation capabilities above 350°C would be expensive in time and dollars, identification of the prime geoscience questions is needed to focus development of advanced instrumentation.

Figure 3. Drilling depths and temperatures

LOG TYPE	COMMENTS
1. SELF POTENTIAL	OFTEN POORLY DEVELOPED, UNRELIABLE IN MASSIVE IGNEOUS OR METAMORPHIC SECTIONS, WORKS IN SOME FRACTURED IGNEOUS AND METAMORPHIC SECTIONS, USUALLY NOT USEFUL FOR CORRELATION.
2. ELECTRICAL RESISTIVITY	MOSTLY OFF SCALE IN MASSIVE IGNEOUS AND METAMORPHIC SECTIONS, CAN BE HELPFUL IN LOCATING FRACTURES, SHORT SPACING RESISTIVITY MAY BE AFFECTED BY THE SHORT-CIRCUITING EFFECT OF BOREHOLE FLUID, FOCUSED DEVICES MAY BE HELPFUL FOR VERY RESISTIVE FORMATION.
3. ACOUSTIC DEVICES	BHC SONIC LOG WORKS WELL UNLESS THERE IS SIGNIFICANT HOLE ENLARGEMENT, MAY BE USEFUL FOR CORRELATION, MATRIX VELOCITY VALUES MAY NOT KNOWN, USEFUL FOR OVERLAY AND CROSSPLOT TECHNIQUES, FULL-WAVE SONIC LOG VALUABLE IN LOCATING FRACTURES, BOREHOLE TELEVIEWER VALUABLE FOR LOCATING FRACTURES AND DELINEATING ITS ORIENTATION, FRAC FINDER LOG MAY BE USEFUL.
4. NEUTRON DEVICES	RESPONSES FROM UNFAMILIAR LITHOLOGY MAY BE DIFFICULT TO ASSESS, MAY BE USEFUL FOR CORRELATION.
5. DENSITY	USEFUL IN ESTIMATING POROSITY AND LITHOLOGY, CAVING MAY BE A PROBLEM, LOG RESPONSE FROM UNFAMILIAR LITHOLOGY DIFFICULT TO ASSESS, USEFUL FOR CORRELATION.
6. GAMMA RAY	USEFUL FOR CORRELATION, SPECTRAL GAMMA RAY USEFUL FOR LITHOLOGY IDENTIFICATION.
7. DRILLING LOG	DRILLING RATE USEFUL FOR LOCATING FRACTURE ZONES AND CHANGES IN LITHOLOGY IDENTIFICATION, USEFUL FOR CORRELATION.
8. CALIPER	USEFUL IN RESOLVING MANY LOG QUALITY PROBLEMS; 6-ARM CALIPER CAN BE USED IN DETERMINING DIP OF FRACTURE-ZONE WASHOUT, USE IN JUDGING HOLE CONDITION.
9. DIPMETER	NOT ALWAYS USEFUL BECAUSE OF LACK OF LAMINATED STRUCTURE, DIP OF FRACTURES MAY BE UNRELIABLE.
10. TEMPERATURE	USEFUL FOR ASSESSING TEMPERATURE GRADIENT, AND OTHER STANDARD USES OF TEMPERATURE LOG.

Table 3. Utility of various well logs in non-sedimentary lithology
(from Sanyal and Meidav, 1977)

INSTRUMENT	STANDARD TOOLS (°C)	HIGH TEMPERATURE VERSION (°C)	APPROX. MAX. LENGTH CABLE FOR ELECTRICAL TOOL OPERATION (km)	NOTES
ES SONDES	180	320	13	1
TEMPERATURE SONDE	340	340	13	1
PRESSURE TOOL	150	270	13	1
CALIPER SONDE	180	200	13	
FLUID SAMPLER	320	320	13	1
GAMMA RAY TOOLS	200	320	9.1	2,3
NEUTRON TOOLS	200	320	9.1	2,3
DENSITY TOOLS	180	200	9.1	3
ACOUSTIC TOOLS	180	320	7.9	2,3
INDUCTION SONDE	180	320	13	2
DIPMETER	180	---	8.2	3
<p>*SEVEN CONDUCTOR, 0.46-inch (1.17-cm) DIAMETER CABLE, MAXIMUM LENGTHS LIMITED BY CABLE STRENGTH AND CONTROLLED BY THE CABLE AND TOOL WEIGHTS AND MUD DENSITY</p> <p>1. HIGH TEMPERATURE VERSIONS HAVE NO ELECTRONICS AND LOW RESOLUTION</p> <p>2. THERMALLY INSULATED BY DEWAR</p> <p>3. CAN BE UPGRADED TO GREATER LENGTH WITH MINOR MODIFICATIONS</p>				

Table 4. Current logging tool temperature and cable length ratings
(modified from Moran and Attali, 1971)

INSTRUMENT	TEMPERATURE RATING STANDARD TOOL	FEATURES LIMITED BY TEMPERATURE
CATEGORY I (CONTAIN NO ELECTRONICS BUT HAVE SENSOR EXPOSED TO FORMATION ENVIRONMENT)		
ES SONDES	180°C	SONDE BODY - RUBBER ELECTRODE OIL - LEAD WIRING INSULATION - RUBBER, TEFLON
TEMPERATURE SONDE	340°C	RELAY
CALIPER SONDE (NO ELECTRICAL SENSOR)	180°C	POTENTIOMETER WIRING INSULATION
FLUID SAMPLE (NO ELECTRICAL SENSOR)	320°C	SEALS
CATEGORY II (CONTAIN ELECTRONICS BUT HAVE NO SENSORS EXPOSED TO FORMATION ENVIRONMENT)		
GAMMA RAY TOOLS	180°C	DETECTOR GM* TUBE ELECTRONICS
NEUTRON TOOLS	150°C	DETECTOR CRYSTAL, PM† TUBE, ELECTRONICS
DENSITY TOOLS	180°C	DETECTOR CRYSTAL, PM† TUBE, POWER SECTION, LEAD IN SKID (500°F, 260°C), ELECTRICAL FEED-THROUGHS
CATEGORY III (CONTAIN ELECTRONICS, SENSORS EXPOSED TO FORMATION ENVIRONMENT)		
ACOUSTIC TOOL	180°C	WIRING, FLUID, ELASTOMERS, TRANSDUCERS, ELECTRONICS, ELECTRICAL FEED-THROUGHS
INDUCTION SONDE	180°C	SONDE BODY, ELECTRODES, COILS, WIRING, ELECTRONICS, SEALS, ELECTRICAL FEED-THROUGHS
DIPMETER	180°C	ELECTRONICS, MOTOR, POTENTIOMETER
PRESSURE TOOL	150°C	TRANSDUCER, ELECTRONICS
*GM - GIEGER-MUELLER DETECTOR †PM - PHOTOMULTIPLIER TUBE		

Table 5. Logging instruments -- temperature limiting features
(modified from Moran and Attale, 1971)

Sampling

A common requirement of all CSDP drilling activities is to recover solid, liquid and gas samples at in situ conditions. Because of the time, cost and danger of losing a well, current drilling activities seldom recover cores or downhole samples; usual needs are satisfied by the analysis of drill cuttings brought to the surface in muds. One of the greatest concerns in deep coring operations is sticking the core barrel in the bottom of the hole [Mallory, private communication]. Gathering of samples at in situ conditions via pressure coring is even more limited; prior to 1975 less than 8 pressure cores were attempted per year, however, recent interest in assessing depleted oil reservoirs, tight gas sands, tar sands and other fossil fuel sources has resulted in development and application of an improved pressure coring system [McFall (1980)]. This system, commercially available, includes a fluid to coat the core thereby minimizing invasion of drilling fluids into the core. The current system is capable of operations to 0.5 kbar pressure and 100°C. Similar advances in pressure coring are being made in the Deep Sea Drilling Program where four or five gas hydrate pressure cores were successfully obtained at about 320 bars pressure [McLerran (1980)].

The majority of the logging service companies have fluid sampling devices, [e.g., Smalen and Litsey (1977)]; these devices generally have limitations of 200°C and 1.5 kb. A tool for sampling geothermal gases and liquids was developed by the USGS and successfully used in sampling 240°C fluids from 330 m research drillholes at Yellowstone National Park [Fournier and Morgenstern (1971)]. Other current development activities are aimed at providing improved samplers [Archuleta, J. R., et al., (1978); Goldstein, N., (1981)].

THERMAL REGIMES DRILLING AND DIAGNOSTICS

Major factors that must be defined before drilling a scientific hole into a magma-hydrothermal system include:

- 1) The specific scientific questions being answered,
- 2) The geology of the selected site,
- 3) The temperature-depth profiles, and
- 4) The presence of unusual, corrosive environments.

Since these are not yet defined, a model magma-hydrothermal system (Figure 4) is used to provide a focus for a drilling-diagnostics straw-man plan. Purposes of the model are to identify potential conflicts between scientific needs and practical operations, to emphasize limitations of current technology and to initiate interactions between the scientists and drillers.

Discussions of this model system will include borehole stability, drilling and completion sequences, in situ diagnostics and sampling. A preliminary estimate will also be made of drilling times and costs.

Borehole Stability

A structurally stable, open borehole is needed for geoscience experiments [Continental Drilling (1975)], for effective drilling, and for safe completion practice. The question of borehole stability has been addressed in the Magma Energy Research Program by Friedman of Texas A&M University [Friedman, M., et al., (1980)].

Figure 4. Model region for CSDP hole

Friedman (1980) determined failure strengths, strains and deformation mechanisms at temperatures to 1050°C, confining pressures of 0, 50 and 100 MPa and a strain rate of 10^{-4} s^{-1} for Mt. Hood Andesite, Cuerbio Basalt, Charcoal Granodiorite and Newberry Rhyolite Obsidian. An example of the experimental results is shown in Figure 5. Mt. Hood Andesite maintains strength to about 900°C, thereafter its strength decreases rapidly. Increased confining pressure increases the ultimate strength but water saturation degrades the strength.

Friedman (1980) also made a preliminary estimate of borehole stability using the experimental data at horizontal to vertical stress ratios (σ_h/σ_v) of 0.5, 1.0 and 2.0. He assumed homogeneous materials, stresses and smooth borehole walls (no stress concentrations). The results, shown in Table 6, suggest open holes may be stable at 700°C if the σ_h/σ_v is less than 1.0. Balancing the pressure in the hole (through use of a drilling fluid that will be stable at 700°C) or maintaining a low wellbore temperature will enhance stability.

Conclusions from the Texas A&M work [Friedman (1980)] include:

1) Drillability

- a) Rocks remain brittle to partial melting with cataclasis the major mechanism of deformation.
- b) Rocks weaken with increasing temperature.
- c) Strengthening effect of the effective confining pressure diminishes with increasing temperature.

Conclusion: Rocks should be drillable, even by conventional techniques and penetration rates should increase as temperatures increase toward partial melting.

2) Borehole Stability

- a) Instantaneous failure strengths are apt to be more important than creep effects.
- b) Boreholes in "water-filled" holes will be stable to 10 km at temperatures less than the melting point.
- c) Open boreholes in andesite are more unstable than those in granodiorite.
- d) If temperatures are kept to $< 700^\circ\text{C}$, even unfilled boreholes in granodiorite are apt to be stable to $> 10 \text{ km}$.
- e) At similar temperatures, boreholes in andesite are apt to fail at 1-3 km depth.

3) Engineering Solutions

- a) Maintain borehole temperatures below approximately 500°C.
- b) Maintain borehole internal pressure equivalent to that of a "water-filled" hole.

Serious consideration of a deep, hot CSDP well will require definition of the stratigraphy, detailed analyses on wellbore stabilities including the effects of inhomogeneties, and identification of completion restrictions imposed by the geoscience experiments.

Figure 5. Mt. Hood Andesite -- ultimate strength versus temperature plot for Mt. Hood Andesite. Solid and open circles are data from room-dry specimens at confining pressures of 0, 50, and 100 MPa. Solid diamonds are data for water-saturated specimens with zero effective pressure. Triangles represent dry specimens heated to 930-1000°C, cooled and deformed at 25°C, 50 MPa. The unconfined, dry strength at 25°C is virtually the same whether or not a specimen has been preheated and cooled [Friedman, et al., (1980)].

CONDITIONS		σ_h/σ_v	25°C	400°C	700°C	>900°C	
ANDESITE	DRY	OPEN HOLE	2.0 1.0 0.5	2* 5 >10	2 4 >10	1 3 >10	1 2 4
		FILLED HOLE	2.0 1.0 0.5	4 >10 >10	3 >10 >10	2 >10 >10	1 >10 >10
		OPEN HOLE	2.0 1.0 0.5	2 9 >10	2 7 >10	1 5 >10	1 3 >10
		FILLED HOLE	2.0 1.0 0.5	5 >10 **	4 >10 **	3 >10 **	2 >10 **
		OPEN HOLE	2.0 1.0 0.5	7 >10 >10	4 >10 >10	1 >10 >10	1 > 2 >10
		FILLED HOLE	2.0 1.0 0.5	>10 >10 >10	>10 >10 >10	6 >10 >10	1 >10 >10
	SATURATED	OPEN HOLE	2.0 1.0 0.5	6 >10 >10	2 >10 >10	1 >10 >10	1 2 4
		FILLED HOLE	2.0 1.0 0.5	>10 >10 **	>10 >10 **	>10 >10 **	2 >10 **
		OPEN HOLE	2.0 1.0 0.5	4 >10 >10	-- -- >10	2 6 >10	1 2 4
		FILLED HOLE	2.0 1.0 0.5	>10 >10 >10	-- >10 >10	4 >10 >10	1 5 >10
		OPEN HOLE	2.0 1.0 0.5	4 >10 >10	-- -- >10	3 9 >10	1 3 7
		FILLED HOLE	2.0 1.0 0.5	>10 >10 **	-- >10 **	5 >10 **	2 >10 **

* ROUNDED TO NEAREST KILOMETER.

** TANGENTIAL STRESS IS TENSILE.

Table 6. Maximum depth (km) of a stable borehole based on strength and mean stress data for dry rocks [Friedman, et al., (1980)]

Drilling and Completion Considerations

The accomplishment of the scientific objectives of the Continental Scientific Drilling Program (CSDP) will depend to a great extent upon the ability to drill a hole at the desired depth. The drilling operation involves the use of drilling rigs, drill pipe, drilling bits, and a circulating fluid, either liquid or gas, to remove cuttings. After the well is drilled, it is completed by inserting pipe into the wellbore and cementing the pipe to the formation. These operations are routinely done in drilling for oil and gas. In the CSDP program, however, it is anticipated that extremely high temperatures and great depths will be encountered in attempting to drill the required investigatory borehole. For the CSDP hole drilled into the environment shown in Figure 4, temperatures of 350°C are anticipated at a depth of 3 kilometers while the temperature is expected to reach 900°C at a depth of 7 kilometers. These high temperatures and great depths provide an extremely harsh environment for drilling equipment.

As previously discussed, standard rotary techniques will allow the drilling to temperatures to 350°C and depths to 10 kilometers. Drilling to depths of 16 kilometers should be possible if temperatures are less than 200°C [Fenix and Scisson (May 1969)]. Drilling and completing large wells at temperatures in excess of 400°C has never been done and will be severely limited by the lifetime of elastomers, the lack of suitable drilling fluids and cement, and the loss of strength in steel tubular goods at higher temperatures. While much of the drilling in the CSDP will be at temperatures below 400°C, it is clear that as that temperature is approached and exceeded, drilling and maintaining the hole constitute major technical challenges. This section will attempt to describe some of the problems which may be encountered in drilling the CSDP hole and will attempt to identify technology that must be developed in order to allow the drilling of the required wellbore.

Well Planning for the Model Region

Hole Size and Casing Points -- In order to define the drilling program and to identify some of the potential problems in drilling the CSDP hole, it is necessary to first propose a casing profile which will then dictate the hole size and the completion requirements. The CSDP hole presents a severe drilling environment and it is impossible to predict all the problems that may be encountered in drilling this well. Consequently, the well plan should be flexible to reflect the unpredictable nature of the hole being drilled. Frequently, in drilling in problem areas, casing has to be set at more shallow points than originally planned because of the variety of drilling problems, such as lost circulation, heaving shale, and unpredictable pressure transitions that may be encountered. The result is that the hole diameter at depth is reduced significantly. Therefore, in planning the CSDP well, large casing should be used in the upper part of the hole so that if problems are encountered, additional casing can be set without restricting the hole to a small diameter at total depth. In reviewing the stratigraphy of the model region shown in Figure 4, it is evident that casing should be set at approximately 2 km depth and then again at approximately 3 km depth. This casing is necessary to seal off the highly permeable formations that are in the upper part of the well. The vuggy nature of the limestone formation, shown in Figure 4 at a depth of 2.3-3 km, may require the use of air as the drilling fluid in this part of the hole. In this case, the wellbore must be sealed from any invasion of fluids from the upper part of the hole; hence, the need for the casing at the 2 km point. Cementing casing in the interval between 2 and 3 km will be difficult and expensive because of the temperature and the vuggy nature of the formation.

The interval from 3-5 km is assumed to be pre-cambrian granite and may or may not require casing. This decision will depend upon the stability of the borehole and whether sloughing or other forms of borehole stability are encountered. The safest approach is to case the hole from 3-5 km since it is anticipated that the hole will be reentered many times for scientific experiments.

The interval from 5-7 km in which the melt is to be encountered should probably be left in an open hole configuration because of temperature problems and the lack of high temperature casing and cement for this interval. However, special casing and pressure maintenance may be required to prevent melt from extruding into the borehole.

Based on these considerations, the casing program shown in Figure 6 is suggested. The drilling and completion program would be as follows:

- 1) Set 36" OD, 1" wall, drive-pipe at 100 meter depth.
- 2) Drill at 17-1/2" hole to 2 km.
- 3) Open the 17-1/2" hole to 26" in diameter.
- 4) Set 20" OD casing in the 26" hole, cement back to surface.
- 5) Drill 17-1/2" hole from 2-3 km.
- 6) Set 13-3/8" casing, cement back to surface.
- 7) Drill 12-1/4" hole from 3-4.5 km.
- 8) Set 9-5/8" casing from 3-4.5 km.
- 9) Drill 8-1/2" hole to 7 km.

Two points need to be made about this proposed casing program. First, other casing profiles are possible; this is not necessarily the optimal completion. The attempt here is to guarantee a hole of at least 8-1/2" diameter to total depth. Secondly, since the hole being drilled to 2 km is 17-1/2" in diameter, the decision on setting the casing at 2 km can be made after that depth is reached. If no fluid inflow into the wellbore is encountered, it may be possible to drill all the way to 3 km before setting the 13-3/8" casing. If, on the other hand, the casing is needed at 2 km, the 17-1/2" hole can be opened up to 26", and 20" casing can then be set at 2 km. This approach provides some flexibility in selecting the casing set points for the first 3 km of the hole.

If casing is in fact needed in the 3-4.5 km interval, special consideration must be given to the cementing process which is used. This will be discussed more fully in a later section in this report.

Drilling Fluids -- Drilling fluids are required to cool and lubricate the bits (and the drill string in hot holes), to maintain an open wellbore and to remove cuttings. Drilling fluids will physically and chemically alter the formation. Potential impacts of such alteration on the geoscience experiments must be identified prior to defining a drilling program.

- 1) Interval from Surface to 3 km -- The interval from the surface down to 3 km can probably be drilled with conventional rotary practice using techniques and fluids developed for drilling in geothermal wells in The Geysers or the Imperial Valley. In general, mud would be used as deep as possible, probably to a depth of about 2.3 km. At this point it is anticipated that vuggy limestone formations will be encountered. If this proves to be true, it would be necessary to case the hole to this depth and then switch to the use of air or foam as a drilling fluid. The maximum temperature expected is 350°C at a depth of 3 km. Drilling has been

Figure 6. Proposed casing program

accomplished at temperatures in this range, and while the drilling will be difficult, the technology is available to perform the task. However, it should be pointed out that nearly all the factors known to adversely affect drilling system performance will be present. Namely, the bit materials will reach extremely high temperatures and bit life will be short. Hard formations will be encountered which will slow the penetration rate. Abrasive formations, if encountered, will cause severe wear of the bit, particularly on the gauge, and finally, a significant amount of reaming will be required to keep the hole to proper gauge. These factors will result in a high interval cost.

- 2) Interval Below 3 km -- In the interval from 3-7 km, temperatures will be encountered at which most existing drilling equipment is inoperable. Elastomers used in bit seals will fail, bearing materials will soften and cause the bits to lock up, drill pipe will lose strength, and conventional drilling muds will be totally useless. Polymer muds have recently been formulated which have a temperature limit of 200°C, and sepiolite clay-based muds have been used at temperatures up to 300°C. However, there are no drilling muds in existence which can operate at temperatures above 350°C. There are therefore two choices for drilling this particular interval -- namely, sufficient quantities of water can be pumped down the hole to cool the wellbore so that the conventional techniques can be used, or air or inert gas can be used as the drilling fluid. This section will briefly describe the consequences of using these two fluids.

The intuitive approach to drilling this well is to circulate enough water down the wellbore to cool the hole down to a temperature at which conventional hardware can be used. The question then becomes one of determining the amount of water which must be used in order to reduce the temperature to around 300°C. A computer code, "GEOTEMP" [Wooley (1979)] has recently been developed which allows the calculation of the temperature of a circulating fluid when the initial thermal gradient is defined, heat transfer is conduction dominated and strata have constant, uniform properties. This code has been used to calculate the temperature of water circulating in the wellbore for the model hole shown in Figure 4. The results of these calculations are shown in Figure 7 where the water temperature is plotted as a function of the depth of the well for a flow rate of 1000 gal/min. Curves are shown for the wellbore temperature after drilling to depths of 4.5, 6, and 7 km. In computing these temperature distributions, it has been assumed that drilling occurs for a period of 24 hours at a rate of 20 ft per hour. Then, drilling is terminated for a period of 3.3 hours per kilometer of depth to replace the bit.

As shown in Figure 7, the wellbore temperature can be cooled to 180°C at a depth of 4.5 km after 24 hours of drilling and circulation. Single-phase flow is maintained during continuous circulation to a 4.5 km depth because the circulating pressure is well in excess of the local vapor pressure at the temperatures expected.

Figure 8 plots the recovery characteristics of the bottomhole temperature after circulation is stopped. The temperature will increase to approximately 510°C in 24 hours and approximately 540°C in 48 hours. Also shown in this figure is the temperature as a function of time

Figure 7. Wellbore temperature after drilling to depth

Figure 8. Temperature response at 4.5 km

after circulation is resumed. A circulation rate of 1000 gal/min for approximately 24 hours is required to cool the hole back down to a reasonable temperature. After 120 hours of cooling, the temperature response following termination of circulation is shown in Curve 3. The temperature after 48 hours is approximately 50° cooler than the temperature reached immediately after the drilling operation. These curves indicate that drilling to 4.5 km can be done by cooling the hole; however, during bit changes it will be necessary to circulate the well as the bit is entering the hole in order to prevent heat damage to the downhole tubulars and to regain stable, single-phase circulation. This will result in extremely long tripping times and will substantially increase the drilling cost.

At depths below 4.5 km, the temperature calculations are more susceptible to error due to the fact that thermal properties will certainly be varying with temperature. However, an attempt has been made to estimate the magnitude of the problem. In performing calculations at depths of 6 and 7 km, water viscosity changes are included to 250°C; the viscosity is then assumed to be constant. The density and thermal conductivity are assumed constant at ambient temperature values. The wellbore temperature as a function of depth after drilling to 6 and 7 km is also shown in Figure 7. After drilling to 6 km the maximum temperature in the wellbore is approximately 315°C and approximately 450°C when the depth of the well is 7 km. In drilling to the 7 km depth, the critical temperature of water is exceeded at a depth of approximately 4 km and the pressure is sufficient to maintain the fluid in a supercritical, single phase. However, when initiating flow in the hot hole it will be necessary to circulate while entering the hole in order to overcome very high heating rates. Flashing cannot be suppressed in an unpressurized hole until the wellbore has been cooled to the proper temperature conditions. Figure 8 indicates that this cooling occurs within 24 hours.

When drilling from 6-7 km, the wellbore cannot be cooled below the critical temperature of water in the normal 24 hour drilling period. The circulating pressure will be in excess of the critical pressure, but since the critical temperature is exceeded, the water in the wellbore below 4 km is supercritical and highly unstable. If circulation is continued to 120 hours after depth is achieved, the bottomhole temperature can be decreased to approximately 250°C at 6 km as shown in Figure 9, but will be close to the critical temperature at a depth of 7 km (see Figure 10).

Any loss of circulating pressure during drilling at supercritical temperatures or loss of static pressure during shut-in periods is conceivably very hazardous. As an example, consider the wellbore temperature distribution after drilling to 7 km shown in Figure 7. As long as the wellbore is fluid-filled such that hydrostatic pressure is maintained, the local fluid pressure is everywhere greater than the vapor pressure at temperature. Below 4 km the fluid is supercritical. If hydrostatic pressure is lost, for example by losing fluid to a lost circulation zone, it is conceivable that local fluid vaporization may occur. The rate at which boiling (or flashing) may occur is dependent upon the rate at which pressure is relieved. In any hypothetical case where a boiling front propagates in the return annulus beginning at the lost circulation zone to the bottom, it is likely that the highly unstable supercritical fluid at the lower reaches of the borehole will eventually flash. If pressure is lost rapidly enough the instantaneous phase change could be explosive.

In summary, it is theoretically possible to cool the wellbore to an acceptable temperature with massive amounts of water circulated for

Figure 9. Temperature response at 6 km

Figure 10. Temperature response at 7 km

days. However, as the depth increases, the potential for a steam explosion and resultant loss of the hole is high.

For flow rates of less than 1000 gal/min the water temperature is entirely too high to allow any significant rates of drilling. It should also be pointed out that the computer model as currently configured is not capable of calculating temperature under two-phase flow conditions. It is very likely that the water being used to cool the hole will boil at some point during the cycle. In order to determine this, the computer model needs to be further developed to account for two-phase flow (this development work is currently underway). If the water does flash in the borehole, it will be necessary to use large cooling towers on the surface to recondense the steam after it comes out of the wellbore so that the water can be reused, otherwise the cost of the water itself would be prohibitive in a well of this type.

In addition to lengthening the time required to change worn bits and increasing the cost of the well, the consequences of the heating and cooling cycle during the starting and stopping of circulation also can cause severe thermal stress on the 13-3/8" casing string. This string of pipe will be subjected to repeated heating and cooling, and unless the cement is properly implaced and of sufficient strength, problems with casing buckling and casing collapse will certainly occur.

The alternative to using water as the drilling fluid is to use air or inert gas. This technique would circumvent the potential problems associated with boiling of the drilling fluid. However, past experience has shown that when air is used, very little cooling occurs so that all the downhole tubulars and tools have to be used at or near the formation temperature. While this is an acceptable practice to a temperature of approximately 350°C, it would be unacceptable at higher temperatures. For example, if the temperature of the drill pipe approached the formation temperature of 600°C at 5 km, the strength of the pipe would be severely degraded and the bit life would be practically zero. Further problems arise with air drilling in terms of the tensile strength of the drill pipe due to the fact that there is no resultant buoyancy from the wellbore fluid in the hole and the pipe must be strong enough to support its own weight. Cuttings removal would be an additional problem. The use of air as a drilling fluid will require the development of high temperature drill pipe and bits capable of drilling at temperatures approaching 900°C.

Drilling Hardware --

- 1) Bit Selection -- During the first 3 km of drilling, the bits used would typically be standard insert-type roller cone bits. If the interval from 2-3 km is drilled with air, then commercially available, unsealed air bits would be used. The critical area is the depth below 3 km where the temperatures may be expected to exceed 350°C. In this case, roller bits will probably be useless unless adequate water cooling is maintained during the tripping in of the bit and during the drilling operation. Even so, with conventional geothermal roller bits it is unlikely that bit life will be long enough to allow reliable operation when formation temperatures exceed 400°C. It may be possible to use drag type bits for this region of the hole. The polycrystalline diamond compact bits which are currently under investigation for use in geothermal drilling have a temperature limitation on the diamond itself of around 750°C. These bits could then theoretically be used

throughout the interval from 3-4.5 km; however, much of the heating of the cutters arises from frictional heat input as the cutter is moved through the rock. So far these bits have not been used successfully at formation temperatures above 250°C. Testing in the near-term will help to define the upper temperature limits of these new, drag-type cutters. If the use of the diamonds is precluded by temperature considerations, it will be necessary to use a drag bit made of harder, high temperature materials. Currently no bits of this nature are available and the technology will have to be developed. As an example of this type of bit, Figure 11 is a picture of the bit that was developed for drilling into molten rock in the Kilauea Iki experiments. The bit is made from an aerospace material called Mar-M-509 and has a temperature capability in excess of 1200°C. While this bit should provide adequate lifetime, it is anticipated that the drilling rate will be extremely low and that the required bit weights will be very high. These higher bit weights could very easily lead to problems of hole deviation. In addition, high torques will be required and if the drill pipe is hot, strength will be greatly reduced. These questions must be answered in a laboratory-type setting before field drilling is attempted. However, it is clear that there are no commercially available bits proven for use at temperatures above 400°C and technology development is required.

- 2) Rig Requirements -- The drilling rig chosen for this experiment must have sufficient capacity to lift the casing and the drill pipe from the depths anticipated. The maximum weight anticipated on the hook load will be attributable to the 2 km string of 20" casing. This load, with the casing hanging in air, will be of the order of 640,000 lbs. Rigs with a hook load capacity of 1,500,000 lbs are common, so that no special requirements are anticipated. The hanging weight of the 5-1/2" drill pipe, even in an air filled hole, would approach only 460,000 lbs and would therefore not be as limiting as the casing in terms of hook load capacity.
- 3) Drill Pipe Considerations -- 5-1/2", 21.9 lb/ft drill pipe will be adequate for handling the required drilling operation. Tensile strength of this pipe is approximately 786,000 lbs and therefore it would support its own weight, even in an air filled hole. The strength of the drill pipe will, of course, degrade as a function of temperature. Data on the tensile strength and the yield strength of drill pipe as a function of temperature are not readily available. However, data on the strength of different casing material indicates its strength is reduced to 40% of its room temperature value at a temperature of 450°C. At temperatures near 540°C, most conventional steels will begin to severely soften and lose the capability to transmit torque. Therefore, in order to drill in a formation at temperatures above 500°C, it will be necessary to keep the drill pipe cool by using high coolant flow rates. This means that during times when the bit is being changed, the pipe will have to be tripped into the hole in stages and circulation will have to be maintained. This process will greatly increase the time required for a bit change,

Figure 11. High temperature drag bit. The bit body is cast from MAR-M 509 and the cutters are titanium carbide in an inconel matrix. Successfully drilled 1050°C rock in a limited laboratory test.

and a normal 15 hour tripping operation may take as much as 4 days because of the need to cool the drill pipe. Alternatively, new high strength, high temperature alloys need to be developed in order to reduce the overall cost of the drilling operation.

- 4) Surface Equipment -- The surface equipment required in the drilling operation includes the rig, pumps, cooling towers, and facilities for removing the cuttings from the drilling fluid. To maintain the 1000 gal/min flow rate throughout the total depth of the well will require a pressure of approximately 3500 psi at the rig pump. This translates into a pump horsepower of about 2000 BHP. Most new electrical rigs with commercially available engines can produce the required horsepower. It therefore seems that the flow rate can be maintained while drilling the well. Cooling towers will be needed to reduce the water temperature to a manageable level at the surface.

Completion Considerations -- A proposed casing program for the CSDP well is depicted in Figure 6. There are several potential problems in accomplishing the proposed completion that should be briefly discussed. First, the setting of 20" casing at a depth of 2 km will be difficult because of the weight of the casing string and the volume of cement required. However, there are very few temperature problems involved in setting this string. In addition, calculations indicate that the collapse strength of the 20" casing is sufficiently high to avoid problems of burst or collapse.

Once a depth of 3 km is reached, the 13-3/8" casing should then be set and cemented back to the surface. The first severe problems in cementing will occur at this point. There are two major problems; the first is temperature-related, and the second is that of obtaining good cement placement behind the pipe in the cavernous limestone formation. Most wells that are drilled at temperatures in excess of 200°C are left in the open hole configuration or they use a slotted liner hanging from the casing. This is the standard completion in geothermal wells where the formations are typically hot, highly fractured and underpressured. The reason is that existing oil field cementing technology is difficult to use at temperatures in excess of about 200°C. New high temperature cements are currently being developed with a goal of providing adequate compressive strength and pumpability at temperatures near 350°C. We can therefore cautiously assume that the materials and technology will be available for cementing the 13-3/8" string back to the surface, although this has not been accomplished in any well at the present time. It should be possible to cool the wellbore sufficiently at this depth to allow the setting of the cement to occur without extreme difficulty.

The second problem, however, may be more severe. If the formation encountered is similar to that depicted in Figure 4, it will be extremely difficult to get good cement placement behind the casing. This creates an unstable condition in the casing string because of the thermal cycling that will occur in the wellbore as circulation is stopped and started for bit changes. Extremely high thermal stresses will be built up in this casing string, and if the pipe is unrestrained, problems with casing buckling, casing collapse, and exterior corrosion can be expected to occur. It is likely that the continued temperature cycling during the drilling operation could cause a total loss of the well due to casing failure. For this reason, it will be necessary to insure the integrity of the casing-cement bond. The required care will add significantly to the cost of the completion operation. In summary, it should

be possible to set the 13-3/8" casing to 3 km, but due to the care required during the cementing process, it will be a long and costly procedure.

After the 13-3/8" casing is set at 3 km the plan is to deepen the hole to approximately 4.5 km. Then, 9-5/8" casing will be set between 3-4.5 km. The setting of the 9-5/8" casing presents extremely difficult problems because of the high temperatures encountered. Casing and cement have never been used at the formation temperatures expected in the CSDP well. In order to assess the feasibility of setting the 9-5/8" string to a depth of 4.5 km, the GEOTEMP computer code was used to simulate the cementing operation. Figure 12 illustrates the wellbore temperatures as a function of depth from the end of the drilling sequence to the end of the cementing sequence. Curve 1 is a plot of the undisturbed temperature gradient used in simulating the problem. Curve 2 shows the temperature of the wellbore fluids immediately after the drilling operation has ceased. It can be seen that the maximum temperature (180°C) occurs at a depth of approximately 4 km. Curve 3 shows the fluid temperature in the wellbore after circulation has been interrupted for a period of fifty-two hours for removal of the drill pipe and insertion of the casing. It can be seen that the fluid temperature increases rapidly to temperatures exceeding 500°C, thus precooling is a necessity before cement placement can be achieved.

To accomplish the cooling required, water is pumped at a rate of 1000 gpm for two days which lowers the maximum fluid temperature to approximately 175°C as shown in Figure 12 as Curve 4. Current industry practice indicates that Class H cement can be retarded to 4-1/2 hours of pumpability with a bottomhole temperature of approximately 150°C. This would indicate that the well is cool enough to cement and a cement slurry weighing 14 lbs/gal is pumped at a rate of 1000 gpm down the casing and back up the annulus for 1.5 hours to simulate the cementing operation. The temperature of the cement in the annulus is shown as Curve 5 in Figure 12. Due to the increased heat capacity of the cement, the maximum cement temperature decreases even more, compared to that of the water, to approximately 150°C. This indicates that a pumpability on the order of 2 hours for a bottomhole circulating temperature of 150°C is required which is commercial state-of-the-art for pumpability.

After the cement has been placed, circulation is again ceased and shut-in conditions are observed during the time required for the cement to set. Figure 13 is a time-temperature profile that the cement will see in the annulus during this period. Curve 2 in Figure 13 represents the temperature at the moment circulation is stopped. One can see that at the end of 48 hours the maximum cement temperature is approximately 300°C. Although it is felt that the cement will certainly be set after 48 hours at the casing shoe, no guarantees can be made at this time with regard to the set time in the upper annulus or the cement strength after it does set. The cement, after placement, can potentially see very high temperatures which could lead to strength retrogression with time.

Competent cement bonding between the casing and the formation is also required in the 9-5/8" string. This is because of the problems occurring during the thermal cycling of the well during periods of starting and stopping circulation. Since the thermal gradients will be extremely high, adequate bonding of the cement to the pipe in the formation is essential. The cementing operation, while theoretically possible, will be very difficult because of the extremely high temperatures. Careful studies of the effects of high temperature on the collapse strength of the casing and on the cement properties will be required before any confidence can be established that the cementing and casing operation can be safely accomplished.

Figure 12. Temperature profiles -- end of drilling to end of cementing

Figure 13. Temperature profiles in cement during setting time

Downhole Diagnostics

As previously reviewed, maximum temperature provides the major constraint on the use of cables, electronics and sensors in the magma-hydrothermal environment. Three approaches have the potential to overcome this limitation: 1) cool the borehole, 2) use dewared and/or refrigerated systems, 3) develop components capable of withstanding the elevated temperatures.

Cool Borehole -- Thermal calculations (Figures 8, 9 and 10) indicate that a borehole into the hypothetical geothermal system could be maintained below 200°C by circulating 1000 gpm of water continuously through the hole. Thus all cable, electronics and sensor temperature problems would be solved.

Potential restrictions to obtaining scientific data due to the flowing water would have to be evaluated [Fertl (1978)]. For example, meaningful temperature measurements would be negated and extensive chemical alteration of the formation may occur. The injection string needed to pump the coolant to the bottom of the hole would interfere with gathering and interpretation of downhole data. Alternating between downhole cooling and natural thermal gradients to accommodate different scientific experiments would have to be thoroughly evaluated since thermal cycling stresses could result in failure of the open borehole or the casing.

Dewared/Refrigerated Systems -- Dewared tools are used in commercial logging at elevated temperatures. Moran and Attali (1971) reviewed the needs and limitations of logging to 15 km in a nominal thermal gradient hole. The thermal relaxation characteristics of the dewared system described in Moran and Attali's paper (representative of conventional 13 cm diameter tools) were used to estimate the response of a dewared tool in the model magma-hydrothermal environment. The results shown in Figure 14 indicate that logging speeds in excess of 1800 m/h are required if conventional electronics are used (temperatures less than 200°C) and in excess of 700 to 1000 m/h if the high temperature electronics (275°C circuits now under development) are used. These preliminary results do not account for radiative heat transfer which would make failure occur more rapidly nor do the results assume any advances in radiation shielding or advanced insulation concepts which would make the dewared tools more useful. In addition, a dewar cannot protect sensors that must be exposed to the environment (e.g., acoustic tools) nor does the dewar protect cables and cable heads.

One potential solution to the problem of limited operating time for dewars is to cool the instrument package. Mechanical and thermoelectric refrigerator concepts, considered for geothermal production logging [Fukuzawa (1979)] have not been satisfactorily developed because of mechanical design problems, the requirement to dump energy into a high temperature environment, short lifetime, and low efficiencies. Use of a concentric pipe arrangement to circulate coolant through downhole packages may be viable for this scientific program since logging times may be hours to days. A concentric tubing design, with cables inside of the cooled tubing, would also solve the temperature limitation problems of the cable. Use of structural tubing would decrease the possibility of losing the instrumentation in the hole. Heat transfer calculations are needed to verify the feasibility of circulating fluid coolant and detailed design would be needed to effectively field install 3-10 km of concentric tubing with internal electrical cabling.

Figure 14. Dewared logging tool temperatures

Instrumentation for > 350°C -- Development of generic electronic components and cabling would be expensive and could not be justified without definition of the scientific needs. One alternative could be to exploit simple sensors (thermocouples, resistance thermometers, etc.) that do not require downhole electronics. Some formation properties could be evaluated by measuring transient behavior of, for example, a temperature pulse. However, evaluation of potential line losses, noise and junction effects would have to be considered in detail. If the geoscience data critical to CSDP is defined, then a development plan can be detailed to provide the appropriate sensors and electronics. Moran and Attali (1971) offer a number of different solutions; these are given in Table 7.

Cables -- A major restriction to using electronics in hot, deep wells is the temperature and structural limits of electrical cables. Conventional cable insulation and jacketing is made of polymeric materials which are thermally unstable when temperatures exceed 200-350°C. Attempts over the past 20 years to provide a processable, usable high temperature (> 350°C) polymer have been unsuccessful; thus, one is forced to use mineral or other inorganic insulation. Lengths of metal sheathed, mineral insulated thermocouples are produced commercially and as mentioned previously, a single conductor cable is being developed [Halpenny (1981)] using this technology. However, problems of maintaining the integrity of the high temperature, low strength insulation in long lengths during field applications need to be identified and solved.

The strength of the cable must be adequate to support its own weight plus that of the diagnostic instrumentation. For example, 7 km of a conventional seven conductor logging cable will weight approximately 37,500 kg if hung in a dry wellbore. The buoyancy of dense drilling fluids used in oil and gas wells alleviates a major portion of that load. Consequently, the design of the cable will depend on the status of the wellbore during diagnostics, the thermal gradients, downhole times and the availability of manufacturing capabilities to produce a specialty cable.

Sampling

Continuous cooling of the wellbore would allow the use of current sampling technology with minor modifications. However, continuous cooling would prevent the collection of representative gas and liquid samples. We do not currently have adequate information on the limitations of downhole samplers for liquids and gases. Non-pressurized, solid cores could probably be obtained using high temperature alloys in special bits. A major development effort would be required to design a pressurized coring system to mechanically function at high temperature and pressure and maintain pressure during retrieval to ambient temperatures and pressures.

LOGISTICS AND COSTS

Since this drilling activity should be driven by the scientific needs, development of a detailed drilling plan and specification of needed engineering developments require definition of scientific experiments and selection of a drilling area. Nevertheless, a preliminary review of time and costs are useful for formulating long-range plans.

Times and costs previously estimated for drilling scientific holes are summarized in Table 8 with some data -- from Table 2's list of existing wells -- included for comparison. The proposed CSDP hole will, however, be drilled in geothermal environments where drilling costs are 2-6 times those costs listed in Table 8 [Carson and Lin (1981)]. The reason for

INSTRUMENT	POSSIBLE SOLUTIONS	TEMP. RATING OBTAINING (°C)	ESTIMATED COMPONENT LIFE AT 117°F (635°C) DEWAR (hours)
CATEGORY I ES SONDES	SONDE BODY--CERAMIC OR GLASS ELECTRODE COILS--SILVER OR NICKEL WIRING--OXIDE FILM INSULATION	650 650 650	--- --- ---
TEMPERATURE SONDE	SENSOR--SiC THERMISTOR WIRING--OXIDE FILM INSULATION RELAY--CERAMIC, GLASS INS. COIL WIRE (ANACONDA) OR DIODE SWITCH, RECTIFIER, SiC	980 650 650 980	--- --- --- ---
CALIPER SONDE	DIFFERENTIAL TRANSFORMER USING CERAMIC, GLASS INS. COIL WIRE WIRING--OXIDE FILM INSULATION	650 650	--- ---
CATEGORY II GAMMA RAY TOOLS	GM* TUBE PM† TUBE WITH SCINTILLATOR ELECTRONICS--CERAMIC SiC, ETC., IN A DEWAR	260 180 480	5.5 3.2 15.2
NEUTRON TOOLS	GM* TUBE HE ³ DETECTOR PM† TUBE WITH SCINTILLATOR LITHIUM OR BORON GLASS SCINTILLATOR ELECTRONICS--CERAMIC SiC, ETC., IN DEWAR	260 260 ‡180 280 480	5.5 5.5 3.2 15.2
DENSITY TOOLS	GM* TUBE PM† TUBE WITH SCINTILLATOR NO POWERED LINKAGE BRAZED CERAMIC SEALS FOR ELECTRICAL FEED THRU	260 ‡180 650	3.2
CATEGORY III SONIC TOOL	WIRING--OXIDE FILM INSULATION SILICONE JEL FOR PRESSURE BALANCE ELASTOMER CARBORANE-SILOXANE POLYMERS PIEZOELECTRIC LEAD METANIOMATE TRANSDUCERS ELECTRONICS--CERAMIC SiC, ETC., IN A DEWAR BRAZED CERAMIC SEALS FOR ELECTRICAL FEED THRU	650 450 500 480 480 650	15.2
INDUCTION SONDE	SONDE BODY--CERAMIC OR GLASS (SOLID, NO OIL) ELECTRODES--SILVER OR NICKEL COILS--CERAMIC, GLASS INS. COIL WIRE (ANACONDA) WIRING--OXIDE FILM INSULATION ELECTRONICS--CERAMIC SiC, ETC., IN A DEWAR BRAZED CERAMIC SEALS FOR ELECTRICAL FEED THRU	650 + 650 + 650 650 480 650	15.2
DIPMETER	ELECTRONICS--CERAMIC, SiC, ETC., IN A DEWAR CALIPER WITH DIFFERENTIAL TRANSFORMERS	480 650	15.2
* GM--GEIGER-MUELLER DETECTOR † PM--PHOTOMULTIPLIER TUBE ‡ NEW CONSTRUCTION			

Table 7. Possible solutions for deep-well logging instruments (modified from Moran & Attali, 1971)

REFERENCE	FORMATION	DEPTH (km)	TIME (years)		COSTS CITED	(\$ million) 1981 \$
			DEVELOPMENT	DRILLING		
CONTINENTAL DRILLING (1975)	CRYSTALLINE ROCK (NOMINAL THERMAL GRADIENT)	4.5	-	0.4-0.7	0.6-0.9	1.5-2.2
		7.6	-	1.2-2.1	3.0-4.5	7.4-11
		15	-	7-11	25-40	60-100
FENNIX & SCISSION (1969)	GRANITIC OR SEDIMENTARY/ GRANITIC (NOMINAL THERMAL GRADIENT)	15		5-7	20-26	78-100
TABLE 2, THIS PAPER	SEDIMENTARY (NOMINAL THERMAL GRADIENT)	8	-	1-2	10-15	11-16
BLEAKLEY (1980)	SEDIMENTARY (SPECIAL CONCERN OVER PRESSURE AND H ₂ S)	7	50 MANYEARS	1.1	42	42
HART (1981)	SEVERAL BEING CONSIDERED IN GERMANY	8	4	3-4	55	55
● THESE DO NOT INCLUDE ANY TIMES OR COSTS FOR CORING OR SCIENTIFIC EXPERIMENTS.						

Table 8. Estimated drilling time and costs

higher costs is higher temperature, fractured formations and harder rock. These reasons plus others result in unexpected (i.e., not predicted prior to drilling) troubles such as lost circulation, well-bore collapse, drill string twist-off, casing buckling, etc. The probability of encountering unexpected trouble depends on the regional geology and the depth as shown in Figure 15. These data suggest that unexpected problems and costs will be encountered in drilling a 10-15 km well through a hydrothermal system.

With these caveats in mind, a strawman drilling, completing and experimenting plan is developed and costs and times estimated for a CSDP scientific drill hole. The purpose of this plan is not to propose a schedule or cost, but to initiate scientific and technological considerations which would lead to a meaningful scientific program. The boundary conditions posed for this strawman will be outlined, a time line developed for the science-drilling activity and costs estimated.

Boundary Conditions for Strawman CSDP Hole

Geologic and Physical Constraints -- Figure 4.

Casing Plan -- Figure 6.

Hardware -- No development costs or times are included. It is assumed that all scientific equipment, drilling hardware, etc., exists and is at the site.

Predrilling Characterization -- All surface geophysics, geochemistry and geological studies have been combined with shallow (100-300 m) slim hole data to provide the best model available of that area.

Drilling Sequence -- Initial drilling will extend conventional technology to the extent of its capability; for this exercise we assume this is 350°C at 3 km per Figure 4. At this point, the rig will be moved off the drill hole and two years allowed for scientific experiments. Costs for a workover rig are included, but cost of the scientific experiments are not included.

After the scientific experiments are completed, a drill rig will be moved to the site and drilling continued to 7 km. After reaching 7 km, the drill rig will be replaced by a workover rig for an additional two years for research.

Scientific Studies -- As previously noted, costs for the intensive two-year research programs at mid and final depth are not estimated since they have not yet been defined. Although experiments during drilling also have not been defined, coring and fluid sampling at 500 m intervals for 10 m and a suite of "conventional" logs run at each kilometer has been assumed.

Since much more scientific investigation is anticipated, the estimated costs and times should be minimum.

Operational Sequence

Figure 16 summarizes a drilling sequence for the 7 km hole and includes preliminary cost estimates. The planning stages, based on slim hole results plus complete geological and geophysical data, include items such as detailed casing design, drilling mud schedules, rig selection

Figure 15. Probability of encountering first trouble
[Carson and Lin (1981)]

ACTIVITY \ YEAR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
PLANNING & STAGING				GO-NOGO ON FURTHER DRILLING												
DRILLING																
CORING/SAMPLING			xxxxxx				x x x x	x x x x	x x x x							
LOGGING			x x x				x x	x x	x x							
WORKOVER RIG FOR SCIENTIFIC DOWNHOLE STUDIES																
COSTS (\$000.00)																
PLANNING	300	500		200	500	800	800	200								
STAGING		150	20	50	20	110			20	110			200			
DRILLING, CORING, SAMPLING			3000				10000	12000	15000							
LOGGING			50				100	100	100							
WORK OVER RIG				500	500					500	500	500				
TOTAL \$000	300	650	3070	750	1020	910	10900	12300	15120	610	500	500	200	GRAND TOTAL \$46,830		

Figure 16. Estimated times and costs for a 7 km CSDP drill hole

and contracting, bit selection, site assessment and preparation and many other requirements to allow drilling.

The staging includes moving the rig to the site, setting it up with appropriate safety, environmental and operational requirements and actual drilling. Currently 3 km deep holes in hydrothermal fields cost \$1.2-1.5 million and require 45-60 days for drilling if no major problems occur. A year is scheduled for the drilling since extensive coring and logging is proposed; also since additional scientific experiments will undoubtedly be run. A nominal \$8,000/day rig cost is assumed for rig time beyond a "60 day" drilling to depth. The final drilling will be slow since extensive cooling is needed to allow drilling. Major engineering and development costs (planning) may be incurred in years 6 and 7 in designing equipment for the hot, possibly molten environments. Drilling costs are assumed to escalate rapidly in the hot (400-700°C) portions of the hole because of reduced bit life, extended tripping time needed to keep the hole cool, and use of special materials to prevent hole loss. As mentioned earlier, no cements have been identified that can be used in these environments; the cement question must be answered during or before the second planning exercise. Also new concepts are needed for sampling, coring and logging instrumentation.

A manned workover rig is on site for the downhole scientific experiments when the more expensive rigs are not being used. In these time periods, intensive experimentation is expected. Again, no costs are indicated for scientific experiments but experience suggests [Hermance (1981)] that such experiments can be expensive and must be considered in the overall CSDP plan.

Costs

First estimate of operational -- not scientific -- costs for this 7 km hole are on the order of \$50 million. This estimate is somewhat higher than other estimates listed in Table 8 as expected because of higher temperature drilling. Drilling to the 3.4 km depth with coring, logging and facilities for scientific studies would take 5 years and an expenditure of approximately \$5 million. Such a scientific hole, if appropriately sited, could provide extensive, valuable scientific data on hydrothermal systems, mineral deposition processes and insight into other geological processes. Scientific results at this point and scientific requirements would then be used to evaluate the need for the additional \$40-50 million expenditure to go deeper, or lesser expenditures to drill alternate shallow wells. Multiple wells are obviously desirable to sample various areas and to run well-to-well, downhole geophysics studies.

Many other options are available including extensive slim hole drilling to 0.2-1 km. Slim holes can provide core and thermal measurements. Special instrumentation could probably be developed for fluid sampling and downhole diagnostics in limited studies. In any case, slim holes should be drilled prior to any commitment for a deep hole program.

SUMMARY

Drilling to depths of 7-10 km in nominal temperature gradient, sedimentary formations is currently done for exploitation of natural gas resources. Commercial logging, using dewared instruments, is used to characterize the formations at bottomhole temperatures to 200°C. Drilling to depths of 3-5 km with bottomhole temperatures to 400°C is done in igneous or metamorphic systems for exploitation of geothermal resources. However, sampling technologies are limited for use at these temperatures and dewared logging diagnostics are restricted to short time measurements. Thus, the proposed CSDP scientific hole into a magma-hydrothermal regime will require technology development if scientific objectives are to be met. A hypothetical magma-hydrothermal system was used as a model to identify technological limitations.

The recovery of solid, liquid and gases at in situ conditions is needed for all aspects of the scientific program. Since conventional hardware is limited to 150-200°C, the most pressing need is to develop high temperature pressure coring and fluid sampling systems. The use of dewared logging tools containing the 300°C instrumentation currently in development could allow limited diagnostics at depth. However, improved dewar designs and temperature limitations of sensors exposed to the formation environments would have to be investigated. The logging system would also have to rely on a sheathed, mineral insulated, mono-conductor logging cable now under development for temperatures over 300°C.

Drilling to 7 km and 900°C is possible using massive cooling. However, the drilling schedule would have to be carefully detailed since vaporization of the water coolant could lead to a catastrophic blowout. Air drilling would not provide adequate cooling and other fluids were not considered because of cost. Maintaining low temperatures in the borehole allows drilling and logging; however, low temperatures negate any meaningful temperature/heat flow measurements and the fluids may chemically alter the formation materials unacceptably. Thus, low temperatures needed for drilling may decrease the scientific value of the experiment. Further evaluation is needed.

When the well is allowed to heat to equilibrium temperature with the formation, tremendous thermal stresses may cause casing failure. Calculations are needed. No cements have been proven for use over 400°C. Therefore a new temperature cement, a different method of casing support or the ability to use and maintain an open hole is required.

The model magma-hydrothermal system was also used to provide a time and cost estimate for this scientific drill hole. The purpose of the estimate was to provide a focus to discuss scientific desires and identify technological needs as well as a basis for further planning. Prior to any deep drilling of a large borehole, extensive slim hole drilling to 1 km should be used as a portion of the geophysics site evaluation and to give guidance to the deep hole plan. Drilling of the scientific hole to 7 km, 900°C was broken into two efforts. The first drilling to 3.5 km, 400°C (including planning and experiment time) would take 5 years and \$5 million. If the decision were made to go to 7 km, another 5 years and \$40-50 million expenditure is estimated. The estimates do not include costs for scientific studies.

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5512 A. Ortega
5541 W. C. Luth
5541 T. M. Gerlach
5830 M. J. Davis
8266 E. A. Aas
3141 T. L. Werner (5)
3151 W. L. Garner (3)
3154-4 J. Hernandez (25)
(for DOE/TIC)