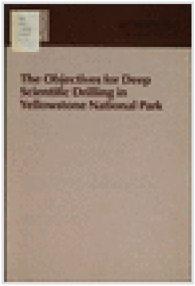

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The Objectives for Deep Scientific Drilling in Yellowstone National Park

A Report by
the Yellowstone National Park Task Group
to the Continental Scientific Drilling Committee

Board on Earth Sciences
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

National Academy Press
Washington, D.C. 1987

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Summary and Recommendations

The western area of the United States contains three young silicic calderas, all of which contain attractive targets for scientific drilling. Of the three, the Yellowstone caldera complex is the largest, has the most intense geothermal anomalies, and is the most seismically active. On the basis of scientific objectives alone, it is easily the first choice for investigating active hydrothermal processes.

But Yellowstone Park is a national treasure—the first and perhaps most unusual of our national parks—and no activity such as drilling should be undertaken without assurance that the unique environment will be protected. Before any specific proposal for deep scientific drilling is approved, the Park Administration must be satisfied that there are compelling reasons to drill in Yellowstone Park and that there is no possibility (even remote) that the hot springs and geysers will be affected by that drilling.

A specific proposal to drill in Yellowstone is likely to have credibility only after the technology to core-drill safely into hydrothermal environments at the proposed depth and expected temperatures has been developed and demonstrated elsewhere. Prior development and testing of the technology elsewhere will also demonstrate that there is a high probability of securing the samples and data that the Yellowstone drilling would be designed to obtain. In addition, after drilling other high-temperature systems, a better assessment can be made of the scientific necessity to drill in Yellowstone. There would have to be widespread agreement within the scientific community that compelling reasons remained to drill into the Yellowstone caldera, namely, (1) that the information to be obtained would be fundamental to gaining an improved understanding of important earth processes, (2) that this information could not be attained then or in the foreseeable future by methods other than drilling, and (3) that drilling at another location would not provide the same data.

At Yellowstone the selection of specific drill sites would be strongly influenced by environmental considerations. Deep scientific drilling would have to be conducted near an existing road, far from the major geyser basins, and in a part of the Park that is not devoted to the preservation of endangered or diminishing species. But there are several potential sites for deep scientific drilling at old dumps and quarries in Yellowstone that may well satisfy both the scientific objectives and the stringent environmental constraints.

There have been many geological, geophysical, and geochemical studies conducted in and around the Park that provide a solid data base upon which to construct models that can be tested by drilling. The silicic caldera complex at Yellowstone is one of the largest in the Quaternary geologic record, it is related to an even larger igneous system that has been active for at least 15 million years (a slowly migrating "hot spot"), and it shows signs of continued igneous activity right up to the present. These "signs" include: (1) an exceptionally high conductive and advective heat flux (the largest known natural discharge of thermal water in the world, apparently with continuous activity at about the present rate for more than 10,000 years), (2) a variety of geophysical data that are consistent with the presence of magma in a large subcaldera chamber, (3) uplift of the central part of the caldera floor at an average rate of about 1.5 cm/yr since 1923, and (4) isotopic ratios of helium, sampled from the Yellowstone hydrothermal system, that are the same as those obtained from active volcanic, mantle-derived, basaltic systems in Hawaii and Iceland.

At Yellowstone it is very likely that scientific drilling to depths of 5 to 6 km would attain magmatic temperatures and penetrate environments that would provide information about mechanisms of heat transfer in the world's largest coupled hydrothermal-magma system, limits of meteoric water circulation, the evolution of fluids from crystallizing magmas, the formation of brines at high temperatures and moderate to relatively low pressures, and how the above processes relate to ore deposition. Drilling also would provide vital information about physical and chemical rock properties at depth and information required to calibrate surface geophysical results in order to improve caldera-wide models.

The Yellowstone region is one of the most seismically active in the United States. Outside the caldera, earthquake foci are as deep as 20 km. Inside the main caldera ring-fracture zone, they seldom are deeper than 4 km. A major reason for drilling at Yellowstone would be to investigate the transition where the mode of rock deformation changes from brittle fracture to quasi-plastic flow.

In addition to Yellowstone, this report summarizes in moderate detail what is known about two other large silicic caldera complexes, Long Valley and Valles. At Valles, information is available from the many intermediate to deep wells that have been drilled there by private industry and the U.S. Department of Energy. Extrapolation to depth of thermal-gradient data places the 500°C isotherm at about 5 km (Hulen and Nielson, 1986). However, as yet there is no compelling geophysical evidence that magma still exists at depths of less than 10 km in the crust beneath the Valles caldera, or that the linear extrapolation of the thermal gradient is valid. The hydrothermal system at Valles appears to be very mature; it could bottom at a depth of about 2.5 km at about 300°C or extend into a hot crystalline pluton at depths of 4-5 km.

At Long Valley, seismic and gravity data are consistent with the presence of magma at a depth as shallow as 5 km beneath the western part of the caldera. Increased seismic activity starting in 1978 and a 35-cm uplift of the resurgent dome over a period of several years have been interpreted to be the result of upward injection of magma. If there is new movement of magma from a relatively deep (10 km) source to a relatively shallow level (7 km or less), there may have been too little time to establish steady-state conductive thermal or convecting hydrothermal regimes around the intrusive. The present hydrothermal activity may date from two pulses of volcanic activity, one about 3000 yr B.P. and the other 200 to 700 yr B.P. It is likely that deep drilling at Long Valley would provide information about evolutionary stages of hydrothermal-magma interactions different from those that would be explored at Yellowstone.

Seismic monitoring at Yellowstone should be continued and the net of recording stations expanded, as necessary, to obtain detailed information about locations and focal depths of earthquakes in the vicinities of potential drill sites. This seismic information would be an important factor in determining a target depth for a deep drill hole (about 1 km into the aseismic region). Knowledge of the thermal regime in the southeast part of the Park should be expanded through detailed heat-flow measurements in the bottom of Yellowstone Lake and the drilling of 100-m heat-flow holes at potential deep drill sites. Seismic refraction, magnetotelluric, and detailed seismic attenuation experiments in the vicinities of potential deep drill sites would provide valuable information about likely crustal structures. One or more intermediate-depth holes should be drilled before selecting a final deep drill site.

Deep drilling at Yellowstone should be initiated only after the technology for core-drilling and sampling at the proposed depth and expected temperatures has been developed and demonstrated elsewhere.

1
Introduction

The Thermal Regimes Panel of the Continental Scientific Drilling Committee (CSDC) considered the scientific rationale for research drilling into various types of hydrothermal systems (CSDC, 1984). They concluded that the highest priority should be given to dedicated deep drilling into silicic caldera complexes to study the roots of active hydrothermal systems related to young magmatic intrusions. Benefits that might accrue regarding societal problems include the acquisition of information for the better understanding of the processes that control volcanic and earthquake hazards, the formation of hydrothermal ore deposits, and the nature and evolution of hydrothermal systems relative to the exploitation of geothermal energy. A determination of the processes that control the movement of fluids through rocks and the chemical reactions that take place during that movement also should be of great value for modeling the behavior of radioactive waste materials that may be emplaced in various geologic environments.

Within the western conterminous United States there are three young, large silicic caldera complexes: the Yellowstone caldera in Wyoming, the Valles caldera in New Mexico, and the Long Valley caldera in California. Information about different aspects of the dynamics of coupled hydrothermal-magma systems is likely to be obtained by research drilling at each of these localities because of differences in the ages, sizes, shapes, depths, temperatures, and times of emplacement of the heat sources and the different tectonic environments. The Panel on Thermal Regimes concluded that the Yellowstone caldera clearly is the largest of the above magmatic systems and represents the most intense geothermal anomaly, but the area is environmentally very sensitive (CSDC, 1984). Accordingly, the Thermal Regimes Panel did not recommend research drilling at Yellowstone at the time of their report, but did urge that this area continue to be considered for possible research drilling in the future. In particular, the Panel recommended that "the scientific merits of research drilling in Yellowstone National Park should be more sharply defined and full consideration should be given to the environmental impact of drilling in this area." This report is in response to that recommendation. In addition to focusing upon the objectives for scientific drilling in Yellowstone, this report summarizes in moderate detail what is known about the other large silicic caldera complexes, Long Valley and Valles. This was done because the Panel believes that it is important to assess the likelihood of attaining in a non-national park setting the same major scientific goals that would be attained by drilling at Yellowstone.

Yellowstone National Park is a national treasure. It was the first place in the world to be designated a National Park (about 70 countries now have national parks based on this prototype), and it has received international acclaim for its unparalleled geyser activity, abundant wild life, and spectacular scenery. It is indeed an awesome responsibility of the U.S. National Park Service both to administer it as a place for our citizens to enjoy and yet to preserve it unspoiled for future generations. In carrying out its responsibilities, the Park Service has fostered research designed to gain a better understanding of the natural processes that have shaped and continue to shape the National Parks. This has been done both to help the staff do a better job of interpreting the Parks to the public and to help administer the Parks. Knowledge of baseline natural processes must be obtained in order to determine when, where, and how man is effecting changes.

At Yellowstone, gaining an understanding of natural processes is especially important because geologically it is an exceptionally dynamic place. Cataclysmic volcanic processes shaped the landscape and it is unlikely that these processes have ended, as shown by the nature of the extensive recent seismic activity and tectonic movements in the Yellowstone region. Much of the geophysical and geologic data obtained at Yellowstone lead to the inference that magma or partially melted rock is present deep (and perhaps not so deep) underground, but the resolution is poor, the degree of uncertainty large, and the total volume of melt unknown. However, the spectacular, long-lived geyser and hot-spring activity attest to the large amount of heat that is present at relatively shallow depths. The floor of the Yellowstone caldera has undergone repeated episodes of upward bulging and subsidence over a period of hundreds or perhaps thousands of years—a phenomenon that is continuing to the present—and large, devastating earthquakes and earthquake swarms frequently rock the region. Geologically, Yellowstone is truly one of the most restless continental regions on Earth. Enhancing our understanding of the geologic processes that are active at Yellowstone will enlarge the Park as a national treasure and benefit all the people who come to marvel at the spectacle.

At present Yellowstone is unique among the active volcanic structures of the world in regard to its tectonic setting, unparalleled geysers, earthquake history, and the magnitude of its past volcanic activity. However, over geologic time systems like Yellowstone have been common and appear to have played major roles in the formation of many plutons of batholithic size. They also have been responsible for the formation of many important base-metal and precious-metal ore deposits. Both its uniqueness in regard to present activity and its similarity in regard to past processes make Yellowstone attractive for detailed scientific examination.

This report briefly reviews what is known about the geology of Yellowstone National Park and highlights unique information that could be acquired by research drilling only in Yellowstone. However, it is not the purpose of this report to recommend specific drill sites or to put forth a specific drilling proposal.

2 Results of Previous Scientific Investigations

There is a long history of geologic, geophysical, and geochemical studies of the volcanic system at Yellowstone and its related hydrothermal activity. Relevant published reports are summarized in Table 1. Figure 1 is a generalized geologic map of the Yellowstone Plateau volcanic field, one of the largest Quaternary silicic caldera complexes in the world. This volcanic plateau occupies a very tectonically and seismically active portion of the Rocky Mountains (Figure 2). The Yellowstone caldera complex is part of a major crustal anomaly marked by low seismic velocities, high attenuation, low density, and high temperature (Smith and Christiansen, 1980). A variety of geophysical evidence has been interpreted to suggest the continued presence of magma in a large subcaldera chamber (Eaton *et al.*, 1975; Smith and Christiansen, 1980; Lehman *et al.*, 1982; Smith and Braile, 1984).

SEISMICITY AND THE CURRENT STRESS REGIME

The regional stress field of the Yellowstone Plateau is primarily controlled by its location at an active intraplate boundary dominated by lithospheric extension (Smith and Sbar, 1974). North-south normal faulting on the south and east-west to northwest-southeast normal faulting along the west on the Hebgen Lake-Norris Junction zone have accommodated regional extension since

TABLE 1 Selected Published Reports Relative to the Volcanic System and Related Hydrothermal Activity at Yellowstone National Park.

Geologic Investigations
- Hague et al. (1896; 1899)
- Boyd (1961)
- Christiansen and Blank (1972)
- Richmond et al. (1972)
- Ruppel (1972)
- Smedes and Prostka (1972)
- Christiansen (1982)
- Christiansen (1984)

Geophysical Investigations

Gravity
- Blank and Gettings (1974)
- Evoy (1977)

Magnetic
- Smith et al. (1974)
- Eaton et al. (1975)
- Bhattacharyya and Leu (1975)
- Reynolds (1977)
- Shuey et al. (1977)

Electrical
- Zhody et al. (1973)
- Stanley et al. (1977)

Geothermal Noise
- Iyer and Hitchcock (1973)

Natural Source Seismic
- Pitt et al. (1979)
- Benz and Smith (1981, 1984)
- Iyer et al. (1981)
- Pitt (1981)
- Daniel and Boore (1982)
- Doser and Smith (1983)
- Doser (1985)
- Smith et al. (1985)
- Smith et al. (1986)

Controlled Source Seismic
- Benz and Smith (1981, 1984)
- Clawson and Smith (1981)
- Braile et al. (1982)
- Lehman et al. (1982)
- Schilly et al. (1982)
- Smith et al. (1982)

Heat Flow
- Fournier et al. (1976)
- Morgan et al. (1977)
- White (1978)

Ground Deformation
- Pelton and Smith (1979; 1982)
- Dzurisin et al. (1986)
- Hamilton (1985)
- Jackson et al. (1984)
- Meyer and Lock (1986)

Geochemical Investigations

Hydrothermal Waters
- Gooch and Whitfield (1888)
- Allen and Day (1935)
- Noguchi and Nix (1963)
- Scott (1964)
- Mazor and Wasserburg (1965)
- Gunter and Musgrave (1966)
- Schoen and Rye (1970)
- Muffler et al. (1971)
- Gunter (1973)
- Mazor and Fournier (1973)
- Rowe et al. (1973)
- Thompson et al. (1975)
- Truesdell et al. (1977)
- Craig et al. (1978)
- Kim and Craig (1979)
- Thompson and Yadau (1979)
- Kennedy et al. (1982)
- Mazor and Thompson (1982)
- Kennedy et al. (1985)

Hydrothermal Alteration Products
- Raymahashay (1968)
- Honda and Muffler (1970)
- Keith and Muffler (1978)
- Keith et al. (1978)
- Bargar and Beeson (1981)
- Bargar and Muffler (1982)

Isotopic Studies Related to Petrologic Problems
- Leeman et al. (1977)
- Doe et al. (1982)
- Hildreth et al. (1984)

Drilling
- Fenner (1936)
- White et al. (1975)

Summaries and Syntheses
- Smith et al. (1974; 1977)
- Eaton et al. (1975)
- Iyer (1979; 1984a; 1984b)
- Savino et al. (1979)
- Weaver et al. (1979)
- Smith and Christiansen (1980)
- Lehman et al. (1982)
- Christiansen (1982; 1984)
- Smith and Braile (1984)
- Fournier and Pitt (1985)
- Hoover et al. (1985)

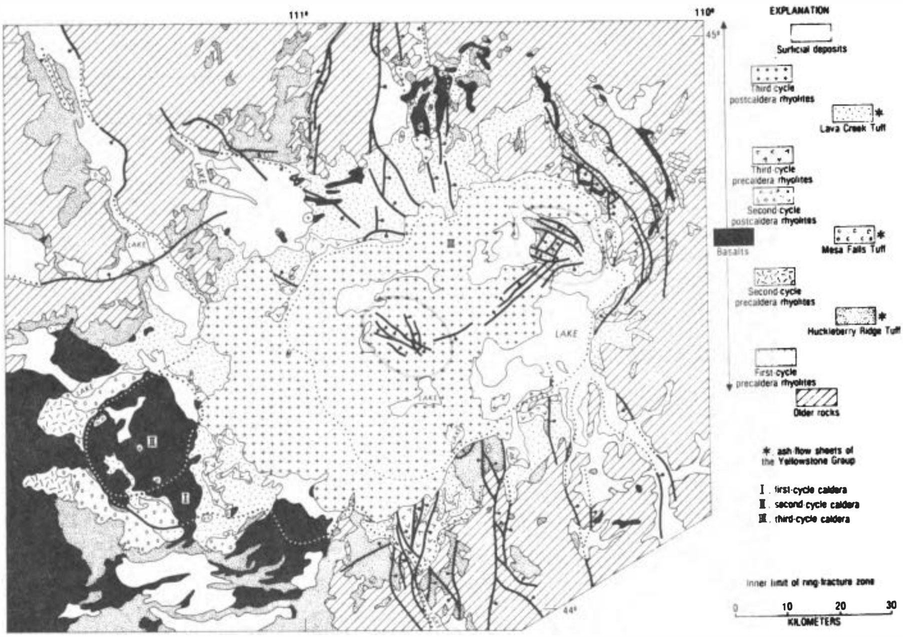

FIGURE 1 Geologic map of the Yellowstone volcanic field (from Christiansen, 1984). Dark lines are faults.

Late Cenozoic time (Christiansen, 1984). Data collected over the period 1971-1979 show a broad belt of relatively intense seismic activity extending from near Salt Lake City through Yellowstone National Park into Montana (Doser and Smith, 1983). To the south of Yellowstone the seismic belt trends about N25°E, and at the north edge of the Yellowstone caldera it bends sharply to the northwest. The Hebgen Lake-Yellowstone region (Figure 2) has been the most seismically active area of the Rocky Mountains in historic time (Smith and Braile, 1984). Major earthquakes (one M7.5 and six M6 earthquakes have been recorded in the Hebgen Lake-Yellowstone region) characterize the seismicity with maximum focal depths of ~20 km external to the caldera (Smith and Christiansen, 1980; Smith and Braile, 1984). Within the region bounded by the outer edge of the ring-fracture zone of the caldera, focal depths seldom exceed 4 km (Fournier and Pitt, 1985) (Figure 3), and earthquakes of magnitude greater than M5 have not been observed.

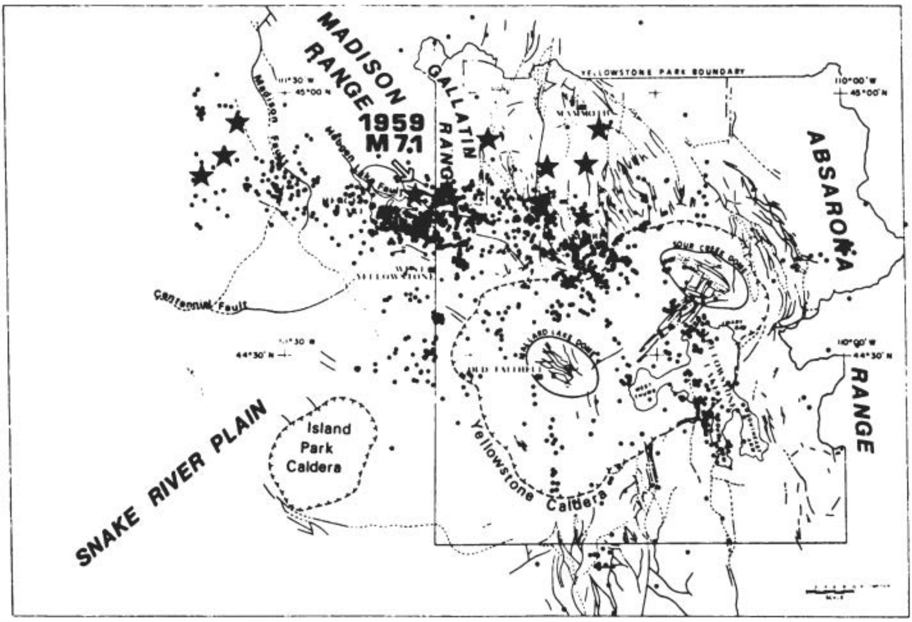

FIGURE 2 Earthquake distribution of the Yellowstone-Hebgen Lake region (1971-1979). Large stars correspond to epicenters of magnitude 6 to 7.1 historical earthquakes. From Smith and Braile (1984).

R. B. Smith (University of Utah, written commun., 1985; Smith and Bruhn, 1984) constructed a rheologic model of the Yellowstone caldera region based on frequency of earthquake focal depths and calculated shear stress and strain rates as functions of rock type, temperature, and depth (Figure 4). In his model the transition from rock deformation primarily by brittle fracture to quasi-plastic flow takes place at about the depth above which 80 percent of the earthquake focal points occur. Also, calculations show that the transition from brittle fracture to quasi-plastic flow commonly takes place at a temperature of about 350°C. In Figure 4 the idealized model of the 80-percent focal-depth contour rises from about 16 km outside the caldera to about 4-5 km beneath the caldera. The more precisely located focal depths determined by Fournier and Pitt (1985) and shown in Figure 3 would move the 80-percent focal-depth contour up slightly to within 3-4 km beneath much of the caldera. The depth to the 350°C contour is likely to be irregular beneath the Yellowstone caldera owing

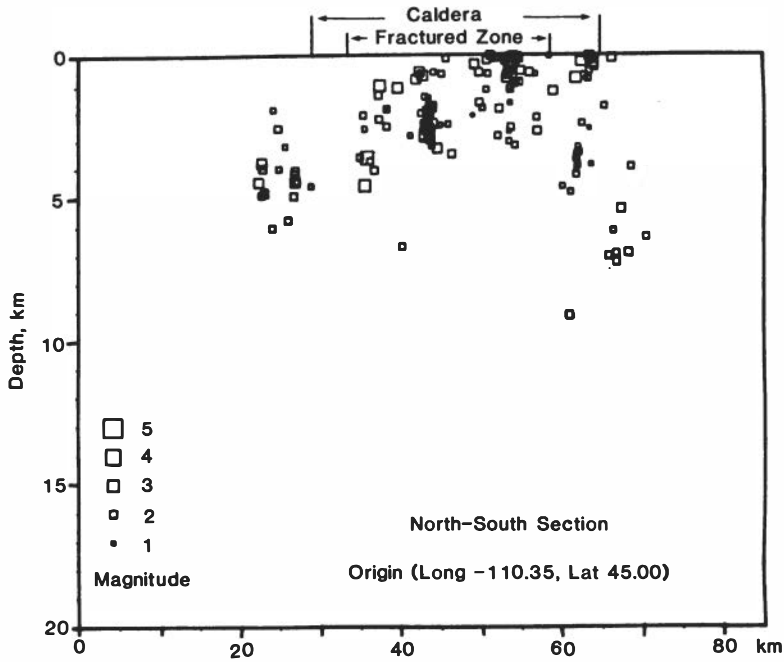

FIGURE 3 Focal depths of earthquakes in and adjacent to the Yellowstone Caldera that can be located with above-average precision. Modified from Fournier and Pitt (1985).

to local downflow of cold water and upflow of hot water along favorable structures.

Emplacement of high-level magmatic systems during the Quaternary Yellowstone volcano-tectonic episode, beginning 2.0 m.y. B.P., has produced localized deformation including plateau uplift and intra-caldera subsidence along circular and radial extensional faults. Thermally driven stresses localized at the Yellowstone Plateau are thus superimposed upon the regional extensional stress field producing the current stress regime.

CONTEMPORANEOUS UPLIFT WITHIN THE YELLOWSTONE CALDERA

Geodetic releveling and precise repeated gravity observations show that the Yellowstone caldera has undergone relative uplift

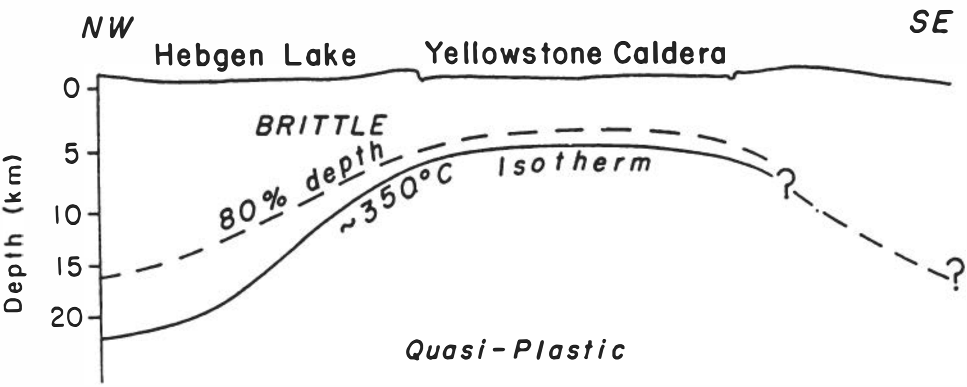

FIGURE 4 Cross section through the Yellowstone Caldera showing the contour above which 80 percent of the earthquake focal depths occur and the estimated depth to the 350°C isotherm. From R. B. Smith (University of Utah, written communication, 1985).

from 1923 to 1984 affecting an area of about 2500 km² (Figure 5) with an average rate of about 1.5 cm/yr centered on the main northeast-southwest axis of the caldera (Pelton and Smith, 1982; Dzurisin and Yamashita, 1986; Dzurisin *et al.*, 1986). This uplift has been episodic, however, and no relative uplift was detected over the period 1984-1985 (D. Dzurisin, U.S. Geological Survey, written commun., 1986). Figure 6 shows the relative uplift along the road from Canyon Junction to Lake Butte (Figure 5) in Yellowstone Park during 1976-1984.

The cause of the uplift at Yellowstone is unknown. Apparently uplift has occurred repeatedly since early Holocene (Hamilton, 1985) and could result from various causes, such as injection of basaltic magma from the mantle into the crust deep beneath the Yellowstone caldera, or the injection of magma higher in the crust, accumulation of a magmatic gas phase at lithostatic pressure evolved during crystallization of rhyolitic magma. Meertens and Levine (1985) suggested that horizontal tectonic compressive strain of material within the caldera that has a lower elastic moduli and a larger Poisson's ratio than the surrounding material could account for the uplift. However, the Meertens and Levine model is very speculative and in apparent contradiction with large-scale

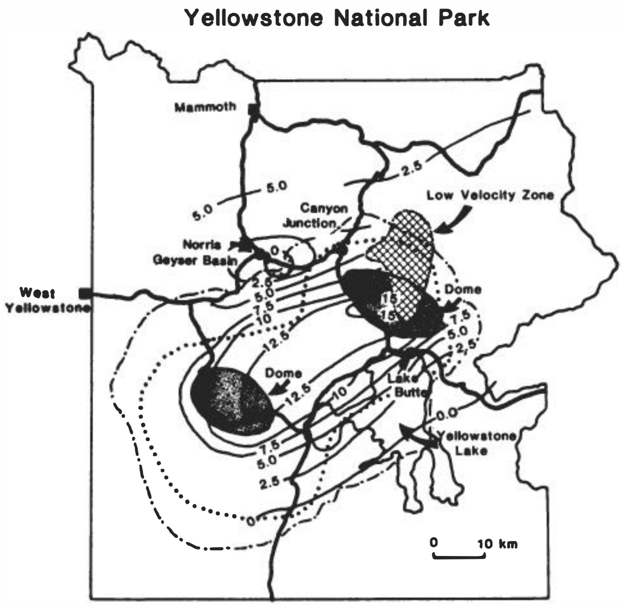

FIGURE 5 Yellowstone Caldera (dot-dashed line), showing location of outer edge of main ring fracture system (dotted line), two resurgent domes, low-velocity zone, contours of relative uplift rates in millimeters/year, and the present road system (heavy lines). Modified from Smith and Braile (1984).

tectonic strain parameters for the Yellowstone area and fault plane solutions of small earthquakes within the caldera. The injection of basalt into the crust at a depth greater than about 10 km is the simplest and most likely explanation for the inflation because this process seems to have been important over a long period of time, furnishing the energy to form the silicic magmas and maintain the long-lived, bimodal, basalt-rhyolite volcanic system (Christiansen, 1984). Crystallization of an amount of magma sufficient to furnish the heat discharged by the advecting hydrothermal system could produce enough evolved magmatic gas, accumulated at lithostatic pressure, to account for the uplift (discussed later). Episodic leakage, by hydrofracturing, of lithostatically pressured fluid into the hydrostatically pressured convecting hydrothermal system might contribute to rapid deflation of the caldera (Fournier, in press). This mechanism is very speculative.

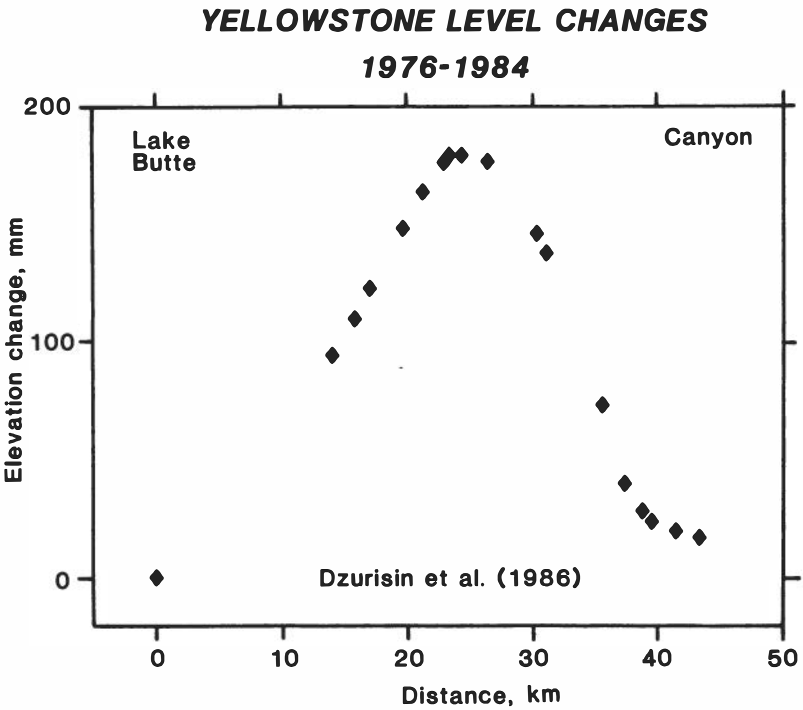

FIGURE 6 Elevation changes at Yellowstone caldera during 1976-1984 measured along the road from Canyon Junction to Lake Butte. From Dzurisin and Yamashita (1986) and Dzurisin *et al.* (1986).

EVIDENCE FOR LONG-TERM COUPLING OF THE YELLOWSTONE SYSTEM TO PROCESSES OF THE EARTH'S MANTLE

Geologic mapping, regional stratigraphy, and K/Ar dating show that a series of voluminous rhyolitic caldera systems formed sequentially, beginning about 15 m.y.B.P. in the region of southwestern Idaho, and were localized successively northeastward along the axis of the eastern Snake River Plain (Armstrong *et al.*, 1975; Christiansen and McKee, 1978). The Yellowstone magmatic system, which itself has a 2-m.y. history (Christiansen, 1984), is the youngest and still active member of this long-lived series of such systems. About 6000 km^3 of rhyolitic magma have erupted from the Yellowstone system over the last 2 m.y., and more than 1000

km^3 in about the past 150,000 years. It appears to be sustained by a more or less continued input of basaltic magma from the upper mantle that partially melts lower crustal material producing silicic magma (Christiansen, 1984).

Morgan (1972) identified Yellowstone as one of a group of "hot spots" that define a framework fixed to the sublithospheric mantle, relative to the moving lithospheric plates. Smith and Sbar (1974) calculated the relative motion of Yellowstone with respect to a mantle reference frame and found a direction of movement of the North American Plate across Yellowstone the same as that of the orientation of the Snake River Plain with a rate of motion of approximately 4 cm/yr. This finding is consistent with the hypothesis that the Yellowstone-Snake River Plain system represents the track of a mantle "hot spot." This propagation must have left in its wake a buried sequence of granitic plutons of batholithic dimensions. It should be emphasized, however, that this propagating system was not represented by a smoothly migrating point source of volcanism but by a series of long-lived voluminous magmatic systems having lifetimes of 2-4 m.y., each succeeding member of which was localized northeast of its predecessors.

Geophysical data, particularly studies of teleseismic P-wave delays (Iyer *et al.*, 1981) and long-wavelength gravity anomalies (Evoy, 1977), indicate that anomalously low velocities and low densities associated with the Yellowstone system may extend to a depth of about 250 km. The upper-crustal seismic velocity structure beneath Yellowstone has been determined using seismic refraction techniques (Lehman *et al.*, 1982; Brokaw, 1985) and inversion of earthquake and refraction data (Benz and Smith, 1981, 1984). According to Brokaw (1985), who interpreted refraction data obtained both in 1978 and 1980, there is a broad region with velocities of 5.4-5.6 km/sec between Island Park and Old Faithful, and much of the region beneath the Yellowstone caldera has a velocity of ~5.4 km/sec. The Brokaw (1985) model is generally in good agreement with the velocity model of Benz and Smith (1981, 1984) and is slightly different in some respects from the model of Lehman *et al.* (1982), who used only the 1978 refraction data in their interpretation.

Lehman *et al.* (1982) show a velocity of 5.7 km/sec beneath much of the Yellowstone caldera and two sharply bounded zones with low velocities of 4.0 km/sec, one at the northeast side of the caldera and the other at the southwest side. However, in their interpretation extensive extrapolation was required in the development of a velocity model for the region in the southwest part of the caldera because there were no recording stations off roads between Old Faithful and shot points to the east of Island Park. The possibility that the southwest low-velocity zone might be fictive, the result of an attenuation problem in which very weak first arrivals were not detected, was discussed by Lehman *et al.* (1982). The 1980 seismic experiment was carried out with recording stations placed in remote areas (inaccessible in 1978) along a profile from Island Park to the Old Faithful area in order to obtain better velocity data for that region. The combined old and new seismic data now clearly show that a 4.0 km/sec low-velocity zone is not present in the southwest part of the caldera, and the northeast low-velocity zone is slightly smaller than reported by Lehman *et al.* (1982) with a velocity of ~4.8 km/sec instead of 4.0 km/sec (Brokaw, 1985). This northeast low-velocity zone, Figure 5, coincides with a local (−20 mgal) gravity low, and these geophysical data are consistent with partial melt, hot dry rock, or a large vapor-dominated system from about 3 to 10 km beneath a limited area of the Yellowstone caldera (Lehman *et al.*, 1982).

Isotopic data on Yellowstone's volcanic rocks and on gases and other hydrothermal fluids also illuminate the deep origins of the magmatic system. The high ratio of $^{3}He/^{4}He$—as much as 16 times the atmospheric ratio (Craig *et al.*, 1978)—directly points to a mantle source region that is undepleted in volatile constituents relative to mid-oceanic ridge systems. This conclusion is confirmed and amplified by data on isotopic ratios of other noble-gas elements (Kennedy *et al.*, 1985). Isotopic ratios of Nd from basalts of Yellowstone and the eastern Snake River Plain also point to origins in relatively undepleted mantle materials, but radiogenic isotopes of Pb and Sr in basalt and rhyolite are interpreted as reflecting a long-term coupling of the mantle source region to ancient North American lithosphere (Doe *et al.*, 1982; Leeman, 1982).

THE YELLOWSTONE HYDROTHERMAL-MAGMATIC SYSTEM

The major feature besides size and volume of volcanic materials that distinguishes Yellowstone from the other large active silicic centers in the United States, Long Valley and Valles calderas, is the extent of its high-temperature hydrothermal system (White *et* *al.*, 1975; Fournier *et al.*, 1976). The heat naturally discharged by this hydrothermal system, about 4×10^{16} cal/yr (5.5×10^{9} watts), makes it by far the largest in North America, with the most intense surface expression of hydrothermal activity of any system in the world. The area of Yellowstone caldera is about 2,500 km^2, so the average thermal energy flux that results just from advection of the hot-spring water is about 1800 mW/m^2, about 30 times greater than the average continental heat flow. If the assumption is made that thermal energy is transferred uniformly by conduction from magma across a 2500 km^2 surface, through hot dry rock to the base of circulation of the hydrothermal system, a thermal gradient of about 700° to 1000°C/km is required to sustain the average convective thermal output (Morgan *et al.*, 1977; Fournier and Pitt, 1985).

Mixing model and mineral deposition considerations suggest that the maximum temperature attained by meteoric water circulating at hydrostatic pressure is about 350°C, and physical chemical considerations indicate a maximum temperature of 400-430°C (Fournier *et al.*, 1976; Truesdell and Fournier, 1976; Fournier and Pitt, 1985). If the maximum temperature attained by that convecting hydrothermal water is just 350°C and the magmatic heat source has a temperature of 850°C, the circulating water must come within about 0.5 to 0.7 km of the magma to maintain the calculated advective thermal flux, no matter how deep the magma is situated.

The depth of circulation of convecting water of meteoric origin probably is limited to the depth at which frequent seismic activity maintains permeability by reopening fractures that become clogged by mineral deposition and by squeezing together of the channel walls by quasi-plastic flow. Because few earthquakes occur at depths greater than about 4 km beneath the Yellowstone caldera (Figure 3), it is unlikely that there is sufficient permeability below about 4-5 km for significant convective hydrothermal circulation to occur at hydrostatic pressure (Fournier and Pitt, 1985). Thus, to account for both the large advective heat flux and lack of earthquakes below about 4-5 km, it is likely that magmatic temperatures are attained beneath some portions of the caldera at depths as shallow as about 4.5-5.5 km.

If the heat carried in the advective flow of water from the system was supplied entirely by the latent heat of crystallization of dry rhyolite magma, about 5×10^{11} kg/yr of magma (about

0.2 km^3/yr) would be required to furnish that heat (Fournier and Pitt, 1985). It is possible that all or most of the thermal energy carried by the advecting hot-spring water is derived from hot but already crystalline rocks that are being cooled by the circulating meteoric waters. Cooling of hot crystalline rock, however, should lead to thermal contraction of the rocks through which the waters circulate, so the uplift reported by Pelton and Smith (1979, 1982), Dzurisin and Yamashita (1986), and Dzurisin *et al.* (1986) would have to be explained by injection of magma at much greater depths and/or horizontal compressive strain (Meertens and Levine, 1985). However, the very large and long-sustained flux of thermal energy from the caldera coupled with the apparently shallow penetration (limited by depth of seismic activity) of hydrostatic water into the top of the system suggest that the latent heat of crystallizing magma is an important source of energy.

The calculated total volume change associated with the crystallization of a given amount of rhyolitic magma is strongly influenced by the amount of water that is assumed to be liberated during that crystallization, the salinity of that water, and the temperature and fluid pressure. The presence of fayalite and a lack of water-bearing minerals in the rhyolite erupted at Yellowstone are evidence that the initial magma contained not more than 1 to 2 wt. % dissolved water (Hildreth *et al.*, 1984), and the minimum range in salinity of an aqueous magmatic fluid evolved during crystallization of that magma is likely to be 10-25 wt. % (Fournier and Pitt, 1985). For a crystallization temperature of 800°C at 150 MPa (lithostatic fluid pressure at about 5 km depth), the total volume change that would result from the crystallization of 0.20 km^3/yr of rhyolite with the liberation of 2 wt. % dissolved water as a 10 wt. % NaCl solution would be about +0.035 km^3/yr. (Fournier, in press). The calculated average rate of volume increase determined from the measured rate of uplift at Yellowstone is about 0.012 km^3/yr (Dzurisin *et al.*, 1986). Therefore, the volumetric change associated with crystallization of an amount of magma that could supply the heat discharged by the hydrothermal system is within the range of the volume of the uplift. These calculations do not demonstrate conclusively a causal relationship between the uplift and liberation of fluid from crystallizing magma. However, the calculations do show that the volumetric effects of liberating a magmatic fluid could be important if the latent heat of crystallization of magma is an important source of energy for the hydrothermal system.

At this time the most plausible model for the Yellowstone magma-hydrothermal system is one in which the thermal energy carried to the surface by the advecting hot-spring water comes in part from crystallizing magma and in part from cooling already crystalline rock. It is likely that crystallization and cooling are occurring at some levels while new magma accumulates at others.

PREVIOUS SCIENTIFIC DRILLING TO INVESTIGATE THE YELLOWSTONE HYDROTHERMAL SYSTEMS

Previous scientific drilling at Yellowstone provided temperature, pressure, fluid chemistry, stratigraphic, and hydrothermal alteration data for the shallow outflow parts of vigorous hydrothermal systems, an environment generally neglected by commercial exploration and production drilling (Fenner, 1936; Honda and Muffler, 1970; White *et al.*, 1975; Keith *et al.*, 1978; Bargar and Beeson, 1981; Bargar and Muffler, 1982; Bargar *et al.*, 1985). Knowledge of processes occurring within this environment is of special importance in the development of theories of epithermal ore deposition (White *et al.*, 1971; Fournier, 1983, 1985b). The drilling also provided a wealth of information that was of great value in the development and verification of chemical geothermometers and mixing models that are now widely used throughout the world in the exploration for geothermal resources and the assessment of reservoir responses to production (Fournier, 1973, 1977, 1979, 1981; Fournier and Truesdell, 1970, 1973; Truesdell and Fournier, 1976, 1977).

The first drilling to investigate Yellowstone hydrothermal systems was carried out by the Carnegie Institution at Washington in 1929-1930. One hole was drilled at Upper Geyser Basin and another at Norris Geyser Basin (Fenner, 1936). The Upper Basin hole attained a depth of 123.8 m with a bottom temperature of 180°C, and the Norris Basin hole attained a depth of 75 m with a bottom temperature of 205°C. In 1967-1968 thirteen research holes were drilled by the U.S. Geological Survey (USGS) to investigate shallow hydrothermal conditions in widely scattered thermal areas of the Park (White *et al.*, 1975). USGS drilling was carried out using a truck-mounted diamond-bit coring rig equipped with a wire line for core retrieval; conventional equipment in common use by the mining industry for mineral exploration and assessment at relatively shallow depths. A total of 2074 m were cored. The holes ranged in depth from 65.5 m to 331.7 m, and the highest recorded temperature was 237.5°C at Norris Basin. Most of the holes attained a depth of about 150 m and a temperature near 200°C.

Above the first aquifer, at depths less than 30 m to more than 75 m, the holes show a near linear conductive thermal gradient. Many rocks in this zone were initially highly permeable but lost their permeability because of hydrothermal alteration and deposition of silica and silicate minerals (White *et al.*, 1975). As drilling progressed every hole showed an increase in static water level and, at the termination of coring, every hole but one (Y-7) had a positive wellhead pressure with water filling the hole. The self-sealed rock at and near the surface serves as an effective cap, allowing thermoartesian pressure (Studt, 1958; White *et al.*, 1975) to develop underground. Bottom-hole pressures measured in most static, shut-in wells corresponded to pressures that would be exerted by a column of cold water extending up to about the ground surface (Fournier, 1983). In order for a hot column of water in thermal equilibrium with the adjacent rock to exert the same pressure at equivalent depths, that column of water would have to extend above ground level (as in a pipe sticking vertically out of the ground). Temperature-depth profiles below the first aquifer in wells drilled within zones of hydrothermal upflow generally followed boiling-point curves appropriate for the measured static overpressures.

The high temperatures and positive wellhead pressures encountered at relatively shallow depths within the main parts of the hot-spring systems caused considerable drilling difficulties, particularly during the early stages before drilling equipment and procedures were modified to cope with the extreme conditions. Wells drilled at the cooler margins of hydrothermal upflow zones, such as Y-4, Y-6, and Y-7, were relatively easy to control and presented few drilling problems (White *et al.*, 1975).

Eight of the wells drilled in 1967-68 were within a few tens of meters of boiling hot springs. In the course of drilling, four of these wells appear to have caused an increase in supply of water and thermal energy to nearby springs that resulted in increased flow and/or geysering activity. After these wells were cased to greater depth or completely filled with cement the activity of the springs returned to the pre-drilling states. A total of six of the USGS wells have been filled with cement, either because of high wellhead gas pressures or relatively high H_2S contents that posed a threat of corroding the wellhead valves. By 1980 two additional wells had completely self-sealed (gas-tight) by silica and carbonate deposition at gas-water interfaces at the bottoms of the casings. All the remaining holes, except Y-7, accumulate gas within the casing while shut in, and it is likely that they too will self-seal in the near future, if they have not already done so.

Environmentally, only the Carnegie hole at Norris appears to have produced a lasting effect upon the local hydrothermal system, but the causal relationship is equivocal. A boiling hot spring with a small flow of water has been active since about 1968 at the site of that well, drilled in 1929-1930. The appearance (by natural build-up of underground pressure) and disappearance (by self-sealing) of hydrothermal features in Norris is common, and small hydrothermal explosions have occurred repeatedly in the general region near the drill site, both before and after the drilling. The Carnegie hole was sited on unstable hot ground in a very acid-altered area dotted with many hot springs of acid or mixed (acid-chloride-sulfate) type and one large spring of mixed water (Fenner, 1936). Only about 12 m of casing were cemented in place (in highly altered rock), and about 25 m of casing were later hung in place without cementing. During the course of drilling, very high steam pressures were encountered in the well, and from time to time steam burst through the surrounding ground in jets. After attaining a depth of just 75 m, and with a wellhead pressure of 297.5 psig (20.2 bars), drilling was terminated and 5 tons of cement were pumped into the hole. The hole appears to have intersected a major fracture that channels water and steam to the many nearby active springs, and their continued activity after the hole was filled shows that the natural channel was not completely closed by the cement. The weakening and fracturing of the ground during drilling may have allowed a spring to emerge right at the drill site that would have emerged by natural processes a few meters away.

3
Objectives for Continental Scientific Drilling in Yellowstone National Park

The objectives or rationale for scientific drilling in Yellowstone National Park are both generic and specific. The generic objectives are those presented in the CSDC Thermal Regimes Panel Report (CSDC, 1984) for scientific drilling of active hydrothermal systems in silicic caldera complexes, and the specific objectives would be to provide information about the evolution of the Yellowstone volcanic complex, an apparent "hot spot" that is presently active in the continental crust with accompanying hydrothermal activity that is the most intense in the world.

BROAD OBJECTIVES FOR SCIENTIFIC DEEP DRILLING INTO THE ACTIVE HYDROTHERMAL SYSTEM AT YELLOWSTONE

The main goal stated in the Thermal Regimes Panel Report for drilling into an active silicic caldera complex is to ". . . understand the dynamic evolution in space and time of actively coupled hydrothermal-magma systems in sufficient detail to choose among predictive physical models of this phenomenon" (CSDC, 1984, p. 19). An understanding of the processes controlling the intrusion of magma into the upper crust, the release of heat and volatiles from the intrusions, and the development of associated hydrothermal systems is central to understanding the evolution of continental crust and its resources (Luth and Hardee, 1980; U.S. Geodynamics Committee, 1979; Varnado and Colp, 1978; Shoemaker, 1975).

The above-cited reports also concluded that, at present, practically everything one needs to know about the deeper portions of hydrothermal systems is based on inference. Because the crust is normally saturated with water, the process of magma cooling is not simply a question of thermal conduction but involves a complex pattern of meteoric water circulation combined to an uncertain degree with water and volatiles released from the magma. Data from (a) experimental studies in the laboratory, (b) field and laboratory studies of exhumed "fossil" hydrothermal-magma systems, (c) theoretical modeling of heat flow, convection, and fluid flow in and around magma bodies, (d) geophysical studies of present-day volcanic areas, and (e) drilling to depths of 2 to 4 km and to temperatures of 300°-400°C in certain hydrothermal systems, together with limited drill-core sampling and measurement of downhole geophysical parameters, have allowed development of several plausible models for hydrothermal-magma systems. However, no model has yet been confirmed because of the lack of critical information on the intensive parameters in the hydrothermal-magma transition zone, their spatial relations, and their correlations with fluid and rock properties. This essential information can be determined only through measurements and investigations in drill holes that penetrate the hydrothermal-magma interface in an active system.

The active silicic magma-hydrothermal system at Yellowstone is an ideal location from a scientific point of view to address the goals of scientific drilling enumerated by the CSDC (1984). The crustal hot-spot environment that typifies the Yellowstone system is of major geologic importance. The kinds of processes currently active at Yellowstone are likely to have produced plutonic rocks throughout a broad zone hundreds of miles long beneath the Snake River Plain (a batholith). Magmatic temperatures are likely to be attained at a depth of about 5 km throughout a broad region beneath the Yellowstone caldera, and the hydrothermal system that would be encountered above the igneous heat source is mature and vigorous.

SPECIFIC OBJECTIVES FOR SCIENTIFIC DEEP DRILLING INTO THE ACTIVE HYDROTHERMAL SYSTEM AT YELLOWSTONE

(1) *Interactions of the local stress field (created by a persistent and large magmatic system) with the regional tectonic stress field.* At Yellowstone, drilling to about 5-6 km could provide data over the entire seismogenic column to depths exceeding the hypothesized brittle fracture/quasi-plastic flow transition. Deep drilling for scientific purposes would be designed to evaluate stress, pore properties, seismic velocities, temperature, and rock compositions with depth. These are the important parameters to assess tectonic models for crustal magmatic systems.

While direct data on the mechanism of uplift at Yellowstone is unlikely to be sampled, vertical stress gradients and inferred directions of stresses determined from deformation of the well bore and from fractures and veins in core, coupled with surface measurements of crustal deformation (e.g., tilt, vertical and horizontal strain) and gravity changes, can provide crucial information on the depth, shape, and stress-state of the magmatic system.

(2) *Heat transfer in a coupled hydrothermal-magma system.* A major objective of deep research drilling in an active silicic caldera complex is to resolve uncertainties in the mechanism (or mechanisms) by which heat is transferred from magma to the overlying hydrothermal system. Mechanisms that have been proposed include: (a) conduction; (b) transfer of heat by movement of water and volatiles out of the magma; and (c) circulation of meteoric water into a thin zone of thermal cracking that migrates inward toward the magma with time as the rocks are cooled (Figure 7). Several recent investigations (Lister, 1974, 1980, 1983; Hardee, 1980, 1982; Hermance and Colp, 1982; Sleep, 1983) have focussed upon the likely significance of this last mechanism, but major aspects are poorly understood. Among these are the thickness of the cracking zone, the temperature gradient from the magma to the thermal cracking front (line DB in Figure 7b), the temperatures at which thermal cracking occurs (perhaps 350° to 450°C), and the chemical consequences of water-rock interaction in that zone. Yellowstone would be an outstanding place to investigate mechanisms of heat and mass transfer from magma to a hydrothermal system in a crustal environment for two reasons: (1) the hydrothermal system is huge and mature, and (2) magmatic temperatures are likely

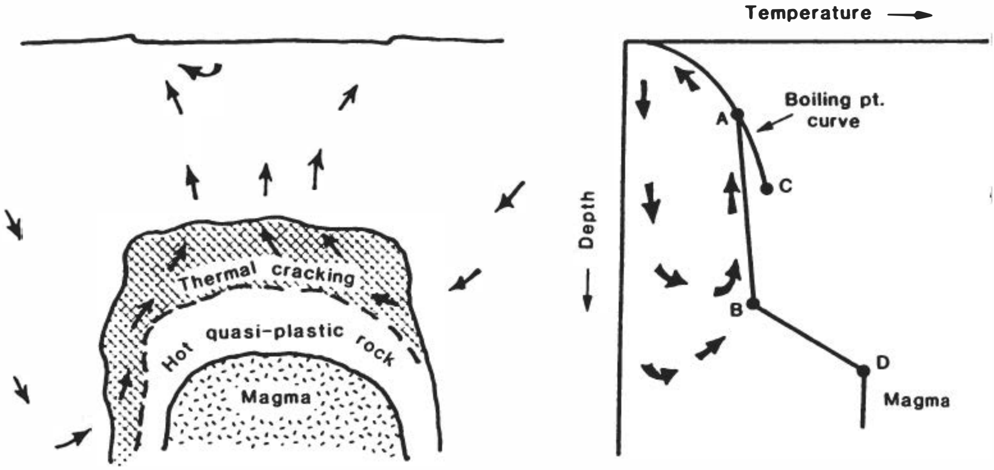

FIGURE 7 (a) Schematic diagram showing inward crystallisation and subsequent cooling of a magmatic body beneath a silicic caldera. (b) Schematic depth-temperature profile for conditions shown in Figure 7(a).

to be encountered at a variety of relatively shallow depths, ranging from 3 to 10 km, depending on where one drills. Oxide-insulated electrical cables for use with thermocouples and thermisters are presently available on special order that will allow measurement of the maximum temperatures expected in a deep hole at Yellowstone.

(3) *Depth of meteoric water circulation and evolution of salinity.* An objective related to heat transfer is to determine the depth to which meteoric water can circulate in a hydrothermal-magma system and mechanisms by which salinity is generated in convecting fluids (Fournier, 1985a, 1987). It is not known if dilute meteoric water circulates directly to and into the magma, if there are stacked circulation systems of differing salinity within and overlying igneous bodies (Figure 8), or if deeper and separate circulation cells have significant components of magmatic fluids. It is important to learn whether pressures deep in hydrothermal systems increase abruptly from hydrostatic to greater than hydrostatic and if there is convective flow of fluids in "overpressured" regions. The maximum fluid pressure that is likely to be attained

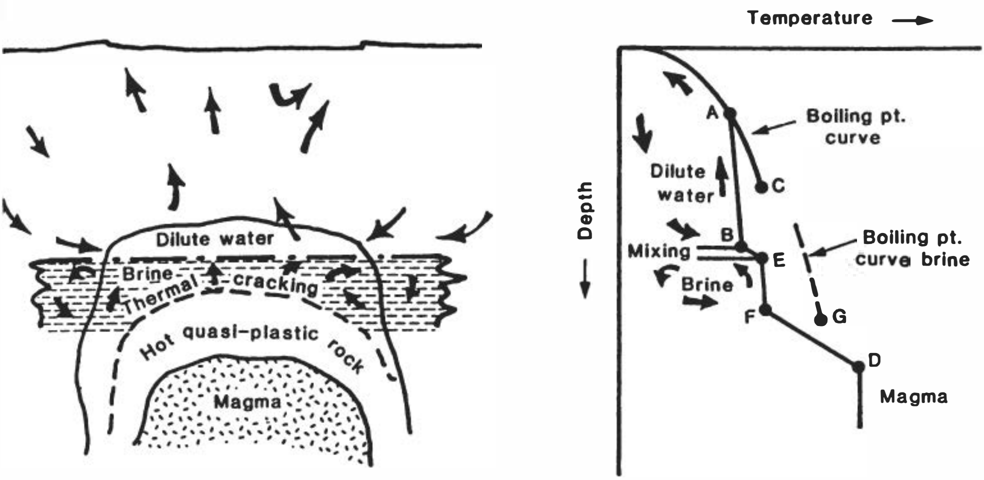

FIGURE 8 (a) Schematic diagram showing inward crystallisation and subsequent cooling of a magmatic body beneath a silicic caldera. Brine that forms by condensation of superheated fluids, partly of meteoric origin and partly of magmatic convecting meteoric water. (b) Schematic depth-temperature profile for conditions shown in Figure 8(a).

is equal to the least principal stress in the rock, which may be about equal to the lithostatic load.

Yellowstone would be an excellent place to investigate the deep limits of hydrothermal circulation because the lack of seismic activity deeper than about 4 km suggests that significant fracture permeability does not extend much below that depth. Therefore, the lower limit of present hydrothermal circulation at hydrostatic pressure should be about 4 km, a depth that is well within the range of present drilling technology. However, deeper circulation of water may have taken place in the past. Hildreth *et al.* (1984) present ^{18}O data that strongly suggest that large amounts of isotopically light (presumably meteoric) water interacted directly with magma immediately after major ash-flow eruptions and caldera subsidence. Earliest post-collapse lavas are 3 to 6 per mil lighter than the preceding ash-flow sheets. The ^{18}O depletions were short-lived events that immediately followed caldera subsidence. Sequences of post-caldera lavas record partial recovery toward precaldera ^{18}O values. Although some contamination by foundering roof rocks seems to be required, water was probably the predominant contaminant. Even if roof rocks had been strongly depleted in ^{18}O before engulfment, their assimilation into a silicic magma of relatively large volume would have been far from sufficient to account for the large ^{18}O shift. The amount of ^{18}O depletion of the magma requires exchange with a mass of low-^{18}O water greatly exceeding the solubility limits. Apparently recurrent explosive activity was required to sustain access and mixing of water with magma, coupled with relatively rapid convection of the magma reservoir, or diffusion of water through magma, to prevent local saturation. Studies of the oxygen isotopic composition of core and cuttings from below the zone of deepest present hydrothermal circulation would give information about possible deeper circulation in the past.

Yellowstone is also a good place to study the possibility of increasing salinity with depth that may come from magmatic sources. The thermal water in the deepest part of the known hydrothermal system contains only about 400 mg/kg chloride (Fournier *et al.*, 1976), and there are virtually no known salt deposits in the host rock. Therefore, increasing salinity at depth should be the result of processes related to the silicic volcanism. It was previously noted that crystallization of about 0.2 km^3/yr of rhyolitic magma containing 1 to 2 wt. % water could furnish all the heat advected to the surface by the hot-spring waters and associated steam in one year. The amount of water that would be liberated by crystallizing the above amount of magma is about 5 to 9 percent of the total flow from the deep part of the hydrothermal system (Fournier and Pitt, 1985). However, when the chloride that is likely to be evolved with that magmatic water also is considered, it appears that only a small fraction of magmatic water can reach the dilute hydrothermal system.

The minimum quantity of chloride liberated upon crystallizing 0.2 km^3/yr of rhyolitic magma at Yellowstone is about 7×10^8 kg/yr (Fournier and Pitt, 1985). In contrast, the calculated amount of chloride discharged by the hot-spring activity is only about 0.4×10^8 kg/yr. Therefore, if all the heat supplied to the hydrothermal system is derived from the latent heat of crystallization of magma plus the heat carried in the evolved water, only about 5 to 6 wt. % of the co-evolved chloride becomes incorporated in the dilute hot-spring system.

One explanation for the above is that all or most of the thermal energy carried by the advecting hot-spring waters is derived from hot but already crystalline rocks that are being cooled by the circulating meteoric waters. However, to account for the observed uplift, the restriction of seismic activity to a depth less than about 4 km, and the long-sustained hydrothermal activity, it is likely that the thermal energy carried to the surface by the advecting hot-spring water comes in part from crystallizing magma and in part from cooling already crystalline rock, and that brine is accumulating at depth. Therefore, Yellowstone would be an excellent place to investigate the evolution and behavior of brines in silicic volcanic systems.

(4) *The source of fluids and solutes deep in hydrothermal systems—A search for magmatic components.* In any geothermal region, one of the objectives in its scientific exploration is to understand the origin and history of those fluids that reach the surface naturally. The fluids are usually mixtures of a small number of source fluids or components, and it is important to determine the elemental and isotopic proportions within each of the different source fluids in the mixtures. In addition to mixing that takes place underground, compositions of fluids sampled at the surface are also affected by other processes that occur during upward movement, such as evaporation, condensation, and dissolving or precipitation of solids.

Some hydrothermal systems should contain significant amounts of waters and solutes derived by expulsion from crystallizing magmas. However, magmatic water has not been recognized in presently active systems, except as steam evolved from volcanoes (and much of this steam may be vaporized meteoric water). Thus far, the solutes found in geothermal waters appear to have been leached by deeply circulating meteoric or connate waters from partly cooled and fractured magmatic rocks, or from other types of country rock under the influence of elevated temperatures. However, $^{3}He/^{4}He$ ratios measured in gases obtained from some geothermal systems indicate that a subcrustal or magmatic component is present in those gases (Craig, 1963), particularly at Yellowstone (Craig *et al.*, 1978; Kennedy *et al.*, 1985). Ratios of $^{3}He/^{4}He$ as high as 15 to 16 times the atmospheric value have been found at Yellowstone, similar to helium values found in gases from Iceland and Kilauea (Craig *et al.*, 1978), and substantially higher than the ratios found in gases from Long Valley (4.3, according to Craig *et al.*, 1979) and Valles (3.9 to 4.8, according to Smith and Kennedy, 1985). Because ^3He is a definitive tracer for mantle and/or magmatic components, it can be used to identify other (non-noble gas) chemical and isotopic species of subcrustal origin surfacing in the hydrothermal system, and also may be tied to convective heat flux.

In establishing limits on the composition of this magmatic or subcrustal component, it is important to obtain concentrations per kilogram total fluid of the various noble-gas components. This is not possible for surface samples where there has been gas-liquid separation during boiling. Deep drilling to the base of the hydrothermal system is essential for any attempts at quantifying convective fluxes of the gases within and from a geothermal reservoir, as well as the influx of meteoric water into the system. Samples of both rocks and fluids deep in the Yellowstone hydrothermal system could provide chemical and isotopic data on materials that have undergone minimal interactions with meteoric fluids. Also, as discussed previously, there is a chance that deep drilling at Yellowstone would intersect brine with significant magmatic components.

(5) *Hydrothermal activity and ore deposition*. A major objective of deep scientific drilling into an active hydrothermal system in a silicic caldera complex is to determine how the processes enumerated above relate to ore deposition. Concentrations of many metals in hydrothermal solutions increase with an increase in dissolved chloride (Helgeson, 1969; Barnes, 1979; Bischoff *et al.*, 1981). Therefore, in developing models of transport and deposition of hydrothermal ore deposits it is important to take account of the conditions that promote the formation of hydrothermal fluids that are rich in chloride. The possibility that highly saline brines may underlie more dilute, circulating thermal waters is of great significance for models of ore deposition. Metals in deep highly saline brines may scavenge most of the reduced sulfur that is evolved from crystallizing magma so that relatively little reduced sulfur reaches high levels in the hydrothermal system. Therefore, different kinds of ore minerals may deposit at different places, perhaps controlled by individual circulation cells with different characteristic temperatures and salinities. Again, Yellowstone appears to be an ideal place from a scientific point of view to carry out deep

drilling to investigate ore-forming processes related to the evolution of magmatic waters and the formation of brines (Fournier and Pitt, 1985).

(6) *Acquisition of three-dimensional information about the Yellowstone volcanic and hydrothermal system.* The Yellowstone system has been the subject of a wide variety of excellent geological, geophysical, and geochemical studies, enumerated previously. Those studies have shown that the Yellowstone silicic caldera complex ranks among the largest recognized in the Quaternary geologic record, and the associated active hydrothermal system appears to be the largest in the world. Although many research wells have been drilled in the Park, the deepest to date is only 332 m (White *et al.*, 1975). Therefore, the present three-dimensional picture of the system has been formulated mainly from the interpretation of geophysical data and by geologic inference. It would be scientifically very rewarding to calibrate those interpretations and inferences with direct information about actual rock and fluid properties at depth.

(7) *The use of a drill hole for long-term observations.* The use of a drill hole for long-term observations of conditions 2-5 km deep in the Yellowstone caldera would be a desirable part of a scientific drilling program. However, a decision whether or not to use a deep well for long-term observations would depend on several factors, such as obtaining on-going funding for that purpose, the state of the well at the termination of drilling, the potential for scaling and corrosion that could affect the long-term integrity of the well, the potential for leakage of fluids from one aquifer to another or to the surface, possible adverse impacts upon the ecology by long-term human occupation of the well, possible conflicts with other scientific objectives, such as sampling fluids from specific depths in the hole (discussed later), and the availability of monitoring instruments that can withstand the temperatures and chemical environment encountered in the deep hole. At this time thermocouples and thermisters are available that could be used to monitor temperatures in the deepest and hottest parts of a research hole, but other presently available measuring instruments would be restricted to shallower and cooler levels. Cables are presently available that can be used to conduct electrical signals to and from the monitoring instruments at the highest anticipated temperatures. These cables consist of wire conductors insulated

by oxides encased within sheaths of stainless steel or some other corrosive resistant material.

A scientific drill hole in Yellowstone National Park could provide opportunities for long-term monitoring of phenomena that bear on the local as well as the regional geophysical setting. Because of the location of the drill hole within a national park, there would be no industry drilling or production from the hydrothermal system that could interfere with measuring naturally occurring changes. The present rapid rate of uplift (Pelton and Smith, 1979, 1982; Dzurisin *et al.*, 1986), abundant seismic activity (Pitt, 1981), and the long history of violent and voluminous volcanism (Christiansen and Blank, 1972; Christiansen, 1984) underscore the need to keep a close watch on changes occurring within the Yellowstone caldera that may signal a renewal of volcanic activity. Temperature, gas emissions, fluid pressure, rock strength (at low strain rates), local seismicity, and temporal variations in seismic travel times would be important parameters to monitor over a long time scale.

If the fluid encountered in the well is too corrosive and/or pore-fluid pressures are too high to safely maintain a deep, open well for monitoring purposes, there are various alternatives that might be adopted to obtain long-term information. Tubing, sealed shut at the bottom, could be lowered to the bottom of the hole and then cemented in place so that geophysical instruments could be lowered and withdrawn, as required, for calibration or replacement. This would preclude chemical and pressure monitoring. For particularly adverse conditions, geophysical instruments, such as thermocouples and thermisters, could be cemented in place at various levels in the hole. In this event the duration of monitoring would be limited to the life of the instruments.

4
A Strategy for Scientific Drilling at Yellowstone

If the previously stated objectives are to be realized, scientific drilling at Yellowstone must be designed to do the following:

(1) To achieve many of the scientific objectives enumerated below, (particularly objectives stated in items 9, 10, and 11), drilling must be conducted by a method that will provide nearly continuous core from the top to the bottom of the well. Intermittent or spot coring is an unsatisfactory strategy for studying active hydrothermal systems because hydrothermally altered zones are often narrow and unpredictable in their distribution. By the time that cuttings reach the surface indicating that an interesting zone is present that should be cored, the drill bit is likely to have already passed the zone. Also, many of the most interesting veins and hydrothermally altered rocks correspond with zones of highest permeability where drilling fluid circulation tends to be lost. Thus, just as these interesting features are approached, cuttings are not brought to the surface, so all solid sample information is lost. Core drilling allows retrieval of vital solid samples even when lost circulation occurs. In the high-temperature environment expected in a deep hole at Yellowstone, little reliance can be placed on well logging to provide information about portions of a hole from which cuttings were not retrieved. Side-hole coring in a completed hole is useful for obtaining stratigraphic information, but it is not

effective for studying chemical, isotopic, and mineralogic changes that may extend tens of meters away from veins and fractures.

(2) Determine the temperature profile, from the top to the bottom of the well, that was present prior to drilling. After all "open hole" experiments have been completed, casing must be set to the bottom of the well in some medium that will prevent fluid circulation between the annulus of the casing and the wall rock. Then, repeated temperature measurements must be made as the well heats up until an equilibrium temperature profile is attained.

(3) Determine variations in salinity and gas content with depth. Liquids and gases must be sampled for complete chemical and isotopic analyses from specific levels at several depths within the well, including near the top and bottom. Perforation of the casing may be necessary to obtain fluid samples from specific depths. A likely strategy would be to perforate the deepest level first, and then sample fluid just from that depth. Perforating and sampling would then be conducted at successively higher elevations with a packer used to isolate the last and highest perforated zone from all the lower perforated zones. If temperatures are too high for use of a packer, it may be necessary to incrementally fill the hole with cement to above the level of the previously perforated zone and just below the next level that is to be perforated. In this case the hole would not be available for other experiments or long-term monitoring at the conclusion of the fluid sampling. It is likely that an intermediate-depth fluid disposal well will be required so that enough fluid can be produced from the research well to overcome contamination by drilling fluids.

(4) Determine pore fluid pressures at many depths within the well. Particular attention must be given to determining whether there are sudden and sharp increases in fluid pressure that might be the result of self-sealing or a change from hydrostatic to almost lithostatic conditions, with a maximum possible fluid pressure equal to the least principal stress in the rock.

(5) Determine the chemical and isotopic compositions of the major and rare gases from deep in the system to assess subcrustal contributions that might result from "hot-spot" activity.

(6) Look for other magmatic contributions to the deep hydrothermal system using chemical and isotopic information.

(7) Determine the maximum depth of fluid circulation in the present hydrothermal system at the drill site, and whether more

than one fluid convection cell is present (from information provided by the temperature, pressure, and salinity profiles).

(8) Determine the present state of stress at depth through studies of deformation of the drill hole and relaxation deformation of core. It is likely that direct determination of stress by hydrofracturing may not be possible in a deep drill hole at Yellowstone because the temperature may be too high for the successful operation of packers.

(9) Determine how both the state of stress in the rock and fluid circulation patterns have varied with depth and time through study of the distribution, orientation, and cross-cutting relations of veins and fractures exhibited within the core. This will also provide information about how the porosity and permeability have changed with time.

(10) Determine previous temperatures and salinities at given depths through studies of fluid inclusions in minerals that formed by hydrothermal processes (mostly vein minerals).

(11) Estimate the amount of water that has interacted with the rock at progressively deeper levels through study of the amount of isotopic exchange and amount of hydrothermal alteration that has occurred.

(12) Obtain information about magmatic processes that may include melting of wall rocks, diffusion of water into magma, physical mixing of magmas of different compositions, and fractional crystallization from the major element, trace element, and isotopic variations in rocks deep in the caldera.

(13) Use variations in metal and sulfur concentrations in the hydrothermal fluids and surrounding rocks to develop models to account for the origin of the ore components, how they are transported, and conditions which caused deposition.

(14) Obtain geophysical logs in cooled parts of the well and perform appropriate downhole experiments to determine the state of stress at different depths in the well and to calibrate geophysical data obtained at the surface.

(15) Determine physical properties of representative rocks (core) from various depths in the well.

5
Special Considerations Applied to Research Drilling in Yellowstone National Park

There are a number of limitations and/or constraints on a deep drilling project in Yellowstone that may have impact on the scientific activities (data collection) and limit hypotheses that can be tested. These can be subdivided into two categories:

1. Administrative and social-political.
2. Environmental, both in terms of mitigating or avoiding any impacts on resources and of placing limitations on field operations and data collection.

ADMINISTRATIVE AND SOCIAL-POLITICAL CONSTRAINTS

(1) *Possible conflicts with legislation.* A deep drilling project in Yellowstone has the potential of conflicting with the National Park Service Organic Act, the Yellowstone National Park Enabling Act, and the Threatened and Endangered Species Act. The National Park enabling legislation has, to some extent, created conflicting goals that the National Park Service Administration must keep in perspective. On the one hand Yellowstone is to be preserved unspoiled and on the other it is to be a "pleasuring place" for the people. Within this framework it has been the policy of the National Park Service to foster scientific research, in part to provide

information about how to better preserve Yellowstone unspoiled and in part to better interpret the Park to the public and to protect the public from natural hazards.

Many thousands of people visit Yellowstone each year, and it is an impossible task to keep all of Yellowstone completely unspoiled and yet satisfy the material needs and desires of the public who wish to see and experience all that Yellowstone has to offer. For the past several years a particularly difficult problem that the Park Service has been addressing is that of a diminishing bear population owing to human intrusion upon bear habitat and intrusion of bear into campgrounds and other areas now used extensively by people. Current policy is to keep people and bear as separated as possible and to encourage bear to live off the land rather than human refuse. In some places in the Park (actually developed areas) people are given priority over bear and in other places (designated remote areas) bear are given priority over people. Between these two extremes are "gray" areas, where roads and trails cross bear habitat and where developed areas are scheduled to be returned as nearly as possible to their natural condition. A drilling program would be looked at, administratively, within this framework of designated land usage and possible impact upon animal populations, including the endangered species (grizzly, bald eagle, whooping crane, peregrine falcon, and grey wolf), and habitat displacement of other wildlife.

The Park Administration also must be satisfied that there would be no possibility (even remote) that the hot springs and geysers of Yellowstone would be affected by deep scientific drilling. Processes that might affect the hydrothermal activity are accidental loss of a well that results in uncontrolled discharge of fluids and thermal energy to the atmosphere, well testing that draws water and thermal energy to the bore to the extent that adverse effects are induced in natural thermal features, and "short-circuiting" of the geothermal system by movement of water from one permeable zone to another in uncased portions of the well. In addition, there will be concern that there be no adverse effects of discharged liquids, gases, and drilling fluids upon the nearby flora and fauna. These dangers were brought out in the *Continental Scientific Drilling Program* (U.S. Geodynamics Committee, 1979, page 98, par. 2).

(2) ***A politically controversial environmental impact statement.*** A rather substantial and expensive environmental impact statement would be required before deep scientific drilling in Yellowstone could be initiated, and it can be assumed that this document would be politically controversial. The politically controversial aspects of drilling in Yellowstone have great importance, and cannot be neglected by any group that presents a formal and specific proposal to conduct scientific drilling in the Park. However, political realities and considerations continuously change, and it is not appropriate for this report to do more than acknowledge their existence and importance. The best way to address these issues will be to present a very realistic and complete environmental impact report and to design a drilling program that would have little short-term and no long-term environmental impact. In effect, this means drilling far from geyser basins and away from bear habitat, near an existing paved road, and preferably at a site that has already suffered environmental degradation, such as a dump or quarry. The environmental impact statement would have to address all the possible effects of achieving both the short-term goals of the drilling project and long-term goals (e.g., follow-up studies, monitoring, final abandonment of the well). If it were proposed that the well be used as a semipermanent or permanent installation for long-term testing and monitoring activities, the sensitivity of this aspect would need to be addressed.

(3) ***Any drilling in Yellowstone may be viewed as a threat by some segments of society.*** Even though the borehole would be drilled using public funds and dedicated for scientific purposes, the project is likely to be viewed in some segments of society as an industry-supported internal threat (geothermal development) and/or external threat (philosophically linked to the Island Park Known Geothermal Area) to the National Park (this too has been discussed in *Continental Scientific Drilling Program*, U.S. Geodynamics Committee, 1979, pages 120-121). On the other hand, the lack of any possibility of future industry-funded drilling to intermediate depths in the hydrothermal system makes Yellowstone a less desirable location than some other localities in terms of developing a three-dimensional picture.

Although industry-funded geothermal energy exploration drilling could take place at some future time in the Island Park area, the 1.2 m.y. caldera that is present in that region is not a good candidate for dedicated scientific drilling to study presently active, or even fossil, hydrothermal systems. There are no indications that surface thermal manifestations have ever been present there, and results of recent geophysical studies suggest that the area is underlain by relatively impermeable rock that includes a still hot, crystalline pluton (Hoover *et al.*, 1985). The Island Park region might be drilled at some time in the future to evaluate a potential hot dry rock resource, but this type of resource does not appear to be economically viable at present (within the United States there is no private industry interest in exploiting the energy in hot dry rocks at this time).

(4) *Possible conflicts with tourism.* The drilling operation would have to be conducted in a manner that would minimize inconveniencing the large number of tourists that visit the Park each year. Large vehicles associated with the drilling operation that might cause traffic congestion might have to travel during periods when there normally is little tourist traffic. The drilling operation would have to be conducted as quietly as possible, and preferably distant from campgrounds and hotels. Also, there could be seasonal restrictions on drilling. During the winter, snow is allowed to accumulate on the roads and tourists travel through the Park using over-snow vehicles. The plowing of snow from roads to bring supplies and equipment to an active drill site could conflict with winter tourist activity.

ENVIRONMENTAL CONSTRAINTS AND TECHNOLOGICAL CONSIDERATIONS

Wherever continental scientific drilling is carried out, it must be planned and conducted with the utmost regard for safety and for protection of the environment. The factors that distinguish Yellowstone from other possible drill sites are the greater potential for adverse environmental impacts and very close scrutiny by the National Park Service and a host of environmental groups that will insist that there be absolutely no change in the environment brought about by drilling.

(1) *Restricted drill sites.* Because Yellowstone is designated as a Natural Area the number of drill holes and their precise locations may be more limited at Yellowstone than at alternative locations. Drilling in the Park would have to be carried out (a) near an existing major road in order not to have an impact on currently undeveloped regions, (b) away from areas devoted to preservation

of endangered and diminishing species, and (c) distant from major thermal features. In addition the drill site must be large enough to accommodate the entire drilling operation, including mud pit, pipe storage, and contractor's and scientist's trailers, without excessive cutting of trees or movement of earth. Also, if a drill hole is to be used for long-term observations, it must be situated at a site that is environmentally compatible with long-term human access. Thus, less than optimal sites for drilling may be all that are available for the investigation of some phenomena. If deep drilling at Yellowstone is considered *as an alternative* to drilling elsewhere, it will be necessary to weigh the disadvantages (information or data "loss" that may occur because of limitations in the siting of the drill rig or of carrying out the drilling and testing program) against the advantages that the Yellowstone system might offer, and compare these with the advantages of a possibly less restricted drilling program at other locations.

(2) *Use of proven technology in a Yellowstone drilling project.* Separate and apart from the scientific merits of a deep drill hole in Yellowstone is the question of whether the Park is an appropriate place to develop the technology of drilling in young, silicic magma systems. Because of the sensitive nature of this kind of project in a National Park, the Task Group realizes that the National Park Service would require proven and tested drilling methods, therefore it recommends that deep scientific drilling in Yellowstone be conducted only at such time as a proven technology becomes available. Techniques for deep drilling and core retrieval in high-temperature systems should be worked out in other sites such as Valles, New Mexico; Long Valley, California; and in the Salton Trough, California.

(3) *Environmental and safety considerations in the drilling process.* The Task Group is concerned with environmental and safety aspects of drilling and logging technology, as articulated in the *Continental Scientific Drilling Program* (U.S. Geodynamics Committee, 1979, Appendix E (II) pars. 2, 3, p. 149).

The detailed operational mechanics of drilling in Yellowstone may have greater liabilities compared to drilling at other localities with regard to the time of year drilling is done, safety factors in well design, disposal of drilling muds, source and disposal of cooling waters, and environmental constraints with reference to equipment and testing procedures.

6
Potential Drill Sites in Yellowstone

The primary, though not necessarily the most important, ecologic or environmental factor that limits the sites that might be acceptable for deep scientific drilling in Yellowstone National Park is the requirement that drilling be conducted close to an existing major road. Figure 9 shows the major road system in Yellowstone in relationship to the caldera rim, the outer edge of the main ring-fracture zone, hydrothermal features, and the two resurgent domes. Figure 5 shows the major road system in relationship to the seismic low-velocity zone and contours of uplift, as well as the outline of the caldera. Roads do not come close to the northeast low-density and low-seismic-velocity zone that may have magma at the shallowest levels beneath the surface at Yellowstone. That zone also is within an ecologically sensitive region, and there is no possibility in the forseeable future to conduct deep scientific drilling to investigate the cause of the seismic and gravity anomalies found there. However, the major road system does give access to many places within the Yellowstone caldera where deep scientific drilling would provide a wealth of data about coupled hydrothermal-magma systems in general, and the Yellowstone system in particular.

The outer edge of the main ring-fracture zone is an attractive drilling target for investigating hydrothermal processes within a structure that appears to control a major part of the upward hydrothermal convection within the caldera. It is crossed by major roads in four places. However, one of these crossings is by the road that extends from Old Faithful to Madison Junction. Localities in that region were not given serious consideration as potential sites for deep scientific drilling, because they are close to major geysers that might be jeopardized in the event of substantial in-hole fluid flow or an unexpectedly large discharge of fluid from the drill hole. If, on the basis of scientific merit, the main ring-fracture zone were chosen as a target for deep scientific drilling in Yellowstone, it is likely that a drill site could be found close to the road from Norris Geyser Basin to Canyon Junction, which follows along that fracture zone for several miles (Figures 5 and 9).

The road from Canyon to Fishing Bridge crosses the main axis of maximum current uplift that also coincides with the region where the highest $^3He/^4He$ ratios in Yellowstone have been found, but most of this region is within an ecologically and politically sensitive grizzly bear habitat, and the likelihood of obtaining permission to drill there is low. However, there are several potential drill sites well within the caldera on the flank of the currently uplifted area that may be administratively and ecologically acceptable. For example, several potential drill sites are adjacent to the road that extends from the outlet of Yellowstone Lake (at Fishing Bridge) to West Thumb that may satisfy both the scientific objectives and the ecologic, social, and political constraints. There are no known hydrothermal features within about 7 km of that region. It is far from the politically sensitive Island Park where geothermal lease sales are contemplated, and is about 15 km from the nearest major geyser area (West Thumb) and 32 km from Old Faithful. The average rate of uplift there has been about 1.0 cm/yr, compared to a maximum rate of uplift of about 1.5 to 2.5 cm/yr along the central axis of the caldera. High heat-flow values (500 to 600 mW/m^2) have been measured nearby beneath Yellowstone Lake (Morgan *et al.*, 1977), and there is a linear zone of extremely high heat flow (over 3000 mW/m^2) just east of Stevenson Island and aligned with seismic activity that occurs along a north-south trend (D. Blackwell, Southern Methodist University, unpublished data). The general area has been one of the most seismically active in the Park and focal depths are relatively shallow. There is a good probability that the transition from brittle

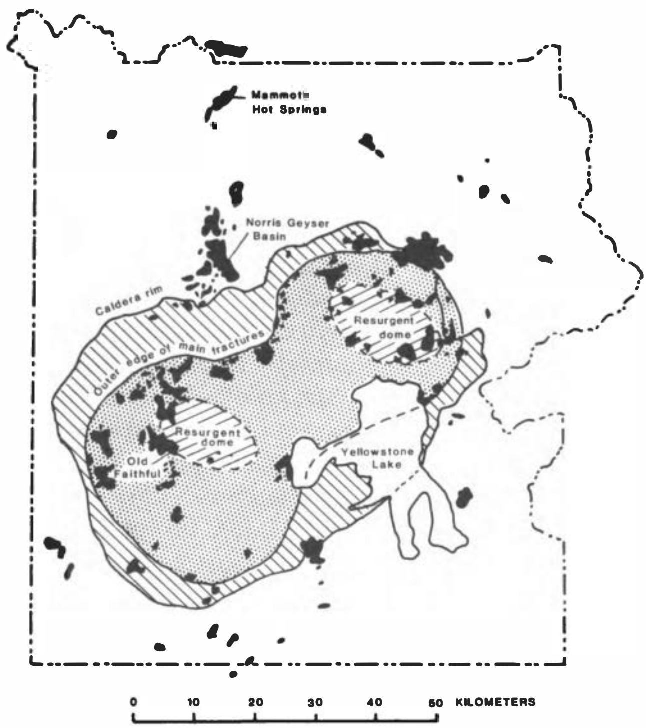

FIGURE 9 Yellowstone caldera, showing region bounded by outer edge of main ring-fracture system, active and recently active hydrothermal features, resurgent domes, and the present road system. Modified from Christiansen (1984).

fracture to quasi-plastic ductile deformation could be penetrated at a depth of 4 to 5 km.

The western resurgent dome is traversed by the road that extends from Old Faithful to Yellowstone Lake. This section of road also crosses the crest of the west end of the elongate zone defined by Pelton and Smith (1979, 1982) that is currently undergoing uplift (Figure 5).

7
Studies Prior to a Drilling Decision

Although a large information base exists that supports the desirability of a deep drilling project in Yellowstone, additional studies should be carried out before a decision is reached to proceed with an initiative to secure funding for such a project. These studies should form the foundation for preliminary planning and later design of the proposed drilling program, location selection (including a justification of the choice of Yellowstone National Park, rather than or in addition to drilling elsewhere), and site definition (if within the Park). These studies (including deep drilling in other thermal systems) would be designed to provide the standard of proof to the National Park Service of a safe and tested drilling technology and "No Effect" to the unique geothermal resources of Yellowstone as part of the environmental and management decision process within the Service. We should not underemphasize the need for these studies, and should begin now if we are to plan for an orderly national deep drilling experiment in a 10-year time frame.

We should not lose sight of the fact that the Yellowstone thermal area is there, and that it is in a pristine state; therefore we do not need to rush into less than an optimally conceived experiment.

ADDITIONAL SCIENTIFIC INVESTIGATIONS THAT COULD BE DONE NOW TO REFINE MODELS OF THE YELLOWSTONE HYDROTHERMAL-MAGMA SYSTEMS

(1) *Earthquake monitoring and focal-depth determinations.* The present program of seismic monitoring in the Park should be continued, with increased attention given to the determination of precise locations and focal depths of seismic events. Additional seismograph recorders should be installed and maintained, as required, to give detailed information in the vicinity of potential drill sites. This would provide information about local faults that might serve as conduits for thermal waters and gases, and about the probable depth to the brittle-ductile transition, a major target for scientific drilling in Yellowstone.

(2) *Seismic velocity and attenuation studies.* Equipment and techniques are now available to carry out detailed P- and S-wave studies using controlled sources as well as natural earthquakes as sources. P-waves travel relatively slowly through silicic magma compared to crystalline rocks of equivalent composition. The size of the region surveyed and the depth of penetration using a controlled source depends mostly on the amount of energy that can be put into the ground at reasonable cost. With present equipment, a region about 12 km in diameter can be covered with a depth of penetration of several kilometers. The resulting data can be inverted to obtain a three-dimensional P-velocity model with a spatial resolution of about 1 km.

(3) *Seismic reflection profiling.* A series of detailed seismic reflection profiles in the vicinities of potential drill sites would provide a great amount of information about local underground structures.

(4) *Detailed electromagnetic soundings.* Electrical resistivity profiles determined from active electromagnetic and passive magnetotelluric surveys would provide valuable information to help constrain models of the Yellowstone system that have been developed mainly from seismic profiles plus gravity and magnetic data. Concordances between electromagnetic and seismic profiles would lend weight to choices of drilling targets inferred from geophysical data.

(5) *Heat flow.* Detailed heat-flow measurements should be carried out in northern parts of Yellowstone Lake in order to obtain a more complete picture of the thermal regime in that

region. These measurements should help define zones of convective upflow of thermal waters and gases. Also, holes should be drilled to measure temperature gradients and thermal conductivities of rocks from the surface to a depth of about 100-200 m at potential sites for deep drilling.

(6) *Active deformation studies*. The ground deformation within the caldera should continue to be closely monitored to determine whether the distribution and rate of deformation are remaining constant or changing.

(7) *Shallow (1 km) to intermediate (1-3 km) depth drilling*. The equipment and technology are presently available to drill by diamond core methods to about 3 km in hydrothermal environments, and such drilling is now common in the geothermal energy industry using conventional rotary methods. Shallow to intermediate drilling at Yellowstone would provide a wealth of information about subsurface temperatures, pressures, fluid compositions, stratigraphic data, and rock properties (for calibration of geophysical techniques). It is a worthy endeavor in its own right, and an important intermediate step in the decision process before the final siting and drilling of a deep research hole. In addition to the above-mentioned information, a previously drilled intermediate-depth hole at a deep drilling site would (1) provide vital information for the design of a casing program for a deep hole, (2) free the deep drilling of the necessity to take expensive core through the depth range that already has been drilled and sampled, and (3) serve as a disposal well for liquids produced from the deep hole just before and during fluid sampling.

8
Comparison of Yellowstone with Other Silicic Caldera Complexes

To varying degrees it is likely that political, social, environmental, and site availability constraints will be present at any locality that is suggested for deep scientific drilling into an active hydrothermal system. The assumption within the scientific community seems to be that these constraints can be successfully dealt with once the scientific rationale for drilling at a specific locality is clearly established. However, Yellowstone clearly will be more constrained than other localities in these regards. No matter what site or sites are eventually selected for deep scientific drilling, the continental scientific drilling program must be planned and conducted with the utmost concern for safety and non-pollution of the environment.

Although the presence of magma at a relatively shallow depth is not an absolute prerequisite for drilling to investigate magmatic-hydrothermal processes, an estimate of the depth at which temperatures in excess of 500° to 600°C are likely to be attained is very important because of the influence of temperature on the models that were previously discussed, on the rock and fluid properties that are likely to be encountered, and on the design of the drilling program. The surest way to confirm the minimum depth required to attain temperatures in excess of 500° to 600°C is to demonstrate that molten or partly molten material is present at a given depth.

The geophysical evidence for the locations, sizes, and depths to magma chambers in the crust has been reviewed recently by Iyer (1984b). He showed that gravity, magnetic, electromagnetic, and a variety of seismic techniques, including the absence of earthquakes within a seismically active region, can be usefully employed in the search for shallow magma chambers. Surveys of these parameters are presently underway, most intensively at Long Valley, and evaluation of their usefulness at that caldera will be applicable to investigations of other calderas. The interpretations based on these methods are most convincing when different techniques all give the same result. Geologic inference and geophysical data indicate that crustal magma chambers exist beneath many regions of Quaternary volcanism, including several in the United States. A comparative assessment of five of the most promising of these—the Rio Grande Rift (including the Valles caldera), New Mexico; Roosevelt, Utah; the Salton Trough, California; Long Valley, California; and The Geysers-Clear Lake, California—has been made by the Department of Energy (Goff and Waters, 1980; Kasameyer, 1980; Luth and Hardee, 1980). Of these, only the Valles and Long Valley systems (Smith and Bailey, 1966, 1968; Bailey *et al.*, 1976) are large silicic caldera complexes. Parameters common to the Yellowstone, Long Valley, and Valles calderas are compared in Table 2.

VALLES CALDERA

Volcanic activity in the Valles, New Mexico, region began ~13 m.y.B.P. and culminated during formation of the Toledo (1.45 m.y.) and Valles (1.12 m.y.) calderas (Doell *et al.*, 1968; Bailey *et al.*, 1969; Gardner and Goff, 1984). Approximately 300+ km^3 of rhyolitic ash-flow tuffs (Bandelier Tuff) were erupted during each caldera event (Smith and Bailey, 1966). Valles caldera is 22 km in diameter. Subsequent to caldera formation and collapse, tumescence of the magma chamber caused uplift of a central resurgent (structural) dome (Smith and Bailey, 1968). Resurgence was followed by eruption of flows, tuffs, a single ash flow, and a ring of 12 rhyolitic domes, all ranging in age from 1.04 to 0.13 m.y. (Doell *et al.*, 1968; Marvin and Dobson, 1979) with the most recent activity

TABLE 2 Comparisons of Different Measures of the Intensity of Hydrothermal Activity at Several Young Silicic Calderas. (From Sorey et al., 1985)

Caldera (age)	Fluid Discharge[a] (kg/s)	Heat Discharge[b] (10^8 W)	Heat Flux[c] (mW/m^2)
Yellowstone[d] (0.6 m.y.)	3000	42.0	~2000
Long Valley[e] (0.7 m.y.)	250	2.9	630
Valles[f] (1.1 m.y.)	35	0.75	500

[a] Discharge of high-chloride thermal water in hot springs and river seepage.
[b] For Yellowstone caldera, heat discharge represents convective heat flow in deep reservoirs from which thermal water discharges at the land surface with in part of the caldera draining east of the Continental Divide. For Long Valley caldera, heat discharge represents the surficial discharge of heat by conduction and convection within the caldera area. For Valles caldera, heat discharge represents the sum of conductive and convective heat flow within the caldera and convective heat flow in subsurface outflow of thermal water that discharges in springs and river seepage outside the caldera.
[c] Calculated as heat discharge divided by caldera area (2,023 km^2 for Yellowstone, 450 km^2 for Long Valley, and 150 km^2 for Valles).
[d] Data from Fournier et al. (1976).
[e] Data from Sorey et al. (1978).
[f] Data from Faust et al. (1984) and Goff and Sayer (1980).

concentrated in the southwestern sector of the caldera. Present-day thermal manifestations include acid-sulfate hot springs and associated fumaroles on the western and central resurgent dome (Goff *et al.*, 1985), neutral-chloride hot springs along the Jemez fault zone southwest of the caldera (Goff *et al.*, 1981), and thermal meteoric hot springs in the western moat zone of the caldera (Goff and Grigsby, 1982).

Because of relatively young volcanic activity and active surface manifestations, Valles caldera has long been an attractive target for geothermal exploration and has become the most thoroughly drilled silicic caldera in the United States. Over 35 geothermal wells have been drilled deeper than 1 km both inside and just outside the caldera. Maximum bottom-hole temperatures are 341°C at 3.2 km beneath the resurgent dome (Nielson and Hulen, 1984) and 325°C at 4.5 km on the western flank of the caldera (Heiken and Goff, 1983). As a result of this drilling, the subsurface structure and stratigraphy of the caldera are relatively well-known, including the depth to pre-caldera volcanics, Paleozoic sedimentary rocks, and Precambrian basement (Nielson and Hulen, 1984; Goff *et al.*, 1985). The drilling data in combination with recent field work has revised previous concepts about resurgence in Valles caldera (Goff, 1983; Nielson and Hulen, 1984), and the location of the earlier Toledo caldera (Goff *et al.*, 1984; Heiken *et al.*, 1986; Self *et al.*, 1986).

Geothermal drilling has also revealed much about the hydrodynamics of the geothermal reservoir beneath the resurgent dome (Baca geothermal field). A hydrothermal system at temperatures of 220°C to at least 300°C or greater circulates at depths of 600 to 2000 m, primarily in fractured Bandelier Tuff and pre-caldera volcanics (Dondanville, 1978; Hulen and Nielson, 1982). The neutral-chloride fluids range from 5000 to 7000 total dissolved solids, and several recent studies indicate that the hydrothermal system contains at least two types of deep fluids (White *et al.*, 1984; Smith and Kennedy, 1985; Truesdell and Janik, 1986). Stable isotope data show that recharge to the geothermal system occurs from precipitation on the caldera depression and surrounding heights (Vuataz and Goff, 1986). The ratio of $^3He/^4He$ in the geothermal gas is about 4-5, indicating a significant mantle component of He (Smith and Kennedy, 1985). A vapor zone 500 to 600 m thick overlies the hydrothermal system in local areas (Goff *et al.*, 1986), and a lateral outflow plume discharges from the hydrothermal system to the southwest (Goff *et al.*, 1981; Trainer, 1984).

The Jemez volcanic zone, which includes the Valles system, is ringed by moderate earthquake activity in the upper 20 km of the crust but is notably aseismic in a large elliptical area (50 × 100 km) centered on the Valles caldera. This suggests that hot rock (350°C) may be present at a shallow level beneath much of the caldera region. Geophysical studies of the caldera have been varied but poorly integrated. A gravity study by Segar (1974) shows a −30 mgal gravity anomaly over the eastern side of the caldera attributed mostly to asymmetric caldera collapse. Heat-flow studies by Reiter *et al.* (1976) show that convective heat flow exceeds 10 HFU while thermal gradients exceed 50°C/km in the shallow system (Swanberg, 1983). A conductive thermal gradient of 80°C/km was measured in metamorphosed Paleozoic limestone and Precambrian granite in the bottom portion of the deepest hole (3.2 km) drilled in the caldera (Hulen and Nielson, 1986). Seismic studies by Ankeny *et al.* (1986) and Olsen *et al.*

(1986) show that a low-velocity body (6.0 to 5.6 km/s) having a diameter of 15 km occurs beneath Valles caldera at a depth of 5 to 10 km. This is interpreted as a hot crystallized pluton that may still have pockets of residual melt. Nielson and Hulen (1984) modeled the resurgent dome of the caldera as a brittle plate deformed by a laccolithic intrusion and estimated the depth to the top of the crystallized pluton at 4.7 km. With the assumptions that the measured thermal gradient in the lower portion of the deepest well drilled within the caldera is conductive and that convective hydrothermal flow does not occur beneath that well, the temperature expected at the interface of Precambrian granite and the young pluton is 500°C.

Although hydrothermally altered rocks abound in the older volcanics of the Valles caldera wall and an Au-, Ag-quartz vein deposit is documented in the Cochiti Mining District in pre-caldera volcanics at 6 m.y., few studies of the altered older rocks have been made (Wronkiewicz *et al.*, 1984). Hulen and Nielson (1986) documented the zonation of hydrothermal alteration in the Valles hydrothermal system, which ranges from argillitic to propylitic to phyllitic grade. Fractured zones contain abundant pyrite with high Ag values. Charles *et al.* (1986) characterized the argillitic to advanced argillitic alterations in the acid-sulfate zones of the resurgent dome. The first CSDP core hole in Valles caldera (VC-1) drilled to 856 m in the southwestern moat zone penetrated hydrothermally altered Paleozoic carbonates, sandstones, and shales displaying argillitic to phyllitic alteration (Goff *et al.*, 1986). Ore minerals identified in core and cuttings from the many holes drilled at Valles include chalcopyrite, sphalerite, galena, and molybdenite as well as ubiquitous pyrite. Clearly, the ore minerals and alteration assemblages of the Valles hydrothermal system are representative of epithermal base-metal deposits of the Creede and perhaps Questa types (Bethke and Rye, 1979).

A program of scientific drilling has been initiated at Valles, and additional scientific drilling has been proposed. The first of the new holes would investigate the vapor cap associated with the hydrothermal system at Sulphur Springs in the southwestern part of the caldera where a hole 500 to 600 m deep should penetrate the steam zone and bottom in the liquid-dominated system in fractured Bandelier Tuff. There are also plans to reenter and deepen an abandoned geothermal test well (Baca-12) that presently bottoms in Precambrian granite at a depth of 3242 m and at a temperature of 341°C. The intent is to drill into the crystallized pluton beneath the Valles caldera that produced the resurgent doming. The top of that pluton is thought to be at a depth of about 4700 to 4900 m or approximately 1500 to 1700 m beneath the bottom of Baca-12.

LONG VALLEY

Volcanism in the Long Valley/Mono Craters Volcanic Complex is the most recent (~550 yr.B.P.) of the three major silicic caldera complexes. Moreover, high seismicity (including swarms of spasmodic tremor), uplift of the resurgent dome, and renewed fumarolic activity, along with evidence for recent volcanism, caused the USGS to issue a "Notice of Potential Volcanic Hazard" for Long Valley in May 1982.

The Long Valley caldera, 17 km wide by 32 km long, is located on the eastern front of the Sierra Nevada. The volcanic rocks that fill the caldera are underlain by metamorphosed Paleozoic sedimentary rocks and granitic rocks of the Sierra Nevada batholith. According to Bailey *et al.* (1976), the oldest volcanic rocks in the caldera are rhyolitic and basaltic flows 3.2 m.y.B.P. Volcanism related to the present Long Valley caldera began about 1.9 m.y.B.P., and the caldera formed 0.7 m.y.B.P. There were extensive intracaldera rhyolite eruptions and the formation of a resurgent dome 0.68 to 0.64 m.y.B.P., rhyolitic volcanism from peripheral vents 0.5 to 0.1 m.y.B.P., and dacite erupted from the outer ring fracture 0.2 to 0.05 m.y.B.P. In the Inyo chain, just north of the caldera, rhyolitic domes were emplaced 1500 to 600 yr.B.P. (Miller, 1984), and a phreatic eruption occurred within the caldera just 450 yr.B.P.

The thermal character of the Long Valley caldera has been discussed by Lachenbruch *et al.* (1976), Sorey *et al.* (1978), Sorey (1985), and Blackwell (1985). The convective heat flow has been estimated by Sorey and Lewis (1976) and Fournier *et al.* (1979). Heat discharge by convection and conduction is 2.9×10^8 W, resulting in the overall average heat loss for the caldera of approximately 630 mW/m^2, or a factor of ~3 less than that of Yellowstone.

Earthquake activity began to increase in Long Valley in 1978, and in 1980 seismic swarms occurred about 10 days before the occurrence of four earthquakes of Richter magnitude 6 (Miller *et al.*, 1982; Cramer and Toppozada, 1980). The M6 earthquakes all had epicenters in the Sierra Nevada block and occurred within a 48-hour period. Since then a continued high level of seismic activity and an uplift of 25 cm, possibly within 2 years, suggest that magma is being intruded to a more shallow position beneath the resurgent dome (Miller *et al.*, 1982; Savage and Clark, 1982).

The location and boundaries of what appears to be a magma body currently existing within the caldera have been delineated by several recent experiments (Muffler and Williams, 1976; Hermance, 1983; Hill *et al.*, 1984, 1985; Iyer, 1984b; Kissling *et al.*, 1984). Seismic reflections indicated a low-velocity region 5 to 8 km wide at a depth of 7 to 8 km beneath the western section of the caldera; a gravity low was interpreted as indicating a low-density body of uncertain size at 8 to 16 km depth; and teleseismic data were interpreted as indicating a low-velocity body 8 to 10 km wide at a depth of 7 to 12 km. Recent shear wave attenuation data suggest that melt zones may exist at depths as shallow as 5 km beneath the resurgent dome (Sanders, 1984). Temperature data obtained in three moderately deep (1550 to 2100 m) holes drilled east and south of the main resurgent dome, to the east of where the main magma body is likely to reside, indicate that shallow magma is probably not present under the eastern part of the caldera. The temperatures at the bottoms of these holes all were much lower than would be the case if molten rock is at a depth of just 7 km. If the conductively controlled thermal gradient in the eastern part of the caldera is maintained at depth, the 600°C isotherm would be deeper than 15 km. In contrast, a linear temperature gradient of about 650°C/km was measured in the lowest 157 m of a hole (PLV-1) recently drilled to a depth of 715 m in the *western* moat of the caldera (Benoit, 1984). However, the bottom temperature was only 124°C, and temperature-depth profiles in Blackwell (1985) and Sorey (1985) show that the steep conductive gradient in PLV-1 projects to an aquifer within the Bishop Tuff. There is a high probability that there will be a temperature inversion below that aquifer. A second hole drilled to a depth of 640 m in the western moat of the caldera, about 3 km north of hole PLV-1, had isothermal temperatures in the lowest 61 m of the hole and a bottom temperature of only 46°C (Benoit, 1984). However, this hole did not penetrate deep enough to intersect the high gradient observed in hole PLV-1. The isotopic composition of helium at Long Valley, prior to the onset of increased seismic activity in 1978 and subsequent uplift, showed only a slightly larger amount of a mantle component than is present at Valles. New collections and analyses of helium show a trend of increasing $^3He/^4He$ and He/CO_2 between 1978 and 1983 (Rison *et al.*, 1983). A decrease in $^3He/^4He$ was observed between 1983 and 1984.

If magma is currently being intruded to a shallow level beneath the resurgent dome or the western moat, the rise to the present level may be too recent to have allowed the development of a mature convecting hydrothermal system. Temperature profiles measured in wells in Long Valley have been interpreted by Blackwell (1985) to be the result of a complex history in which waning hydrothermal activity was rejuvenated about 3000 yr.B.P. and again 200-700 yr.B.P.

CONCLUSION

The silicic calderas at Yellowstone, Valles, and Long Valley present different targets for continental scientific drilling. Different evolutionary stages of hydrothermal activity appear to be present within these three systems. Valles appears to contain a very mature hydrothermal system that is associated with a heat source that may now be entirely crystalline. The critical geophysical measurements at Valles that might confirm the existence of a magma body and determine its probable size and depth have not been done. Deep drilling at Valles would intersect a well-developed vapor-dominated cap, its underlying hot-water zone, and the alteration associated with a long-lived, possibly waning hydrothermal system. The present hydrothermal system probably bottoms at about 2.5 km at a temperature close to 300°C, but it could extend into a crystalline pluton at depths greater than 4-5 km. There is a good chance that fluid circulation is restricted to relatively shallow levels because there is a lack of seismic activity within the caldera that would serve to reopen fractures that self-seal at temperatures in excess of 350°C. Even though the magmatic heat source at depth beneath Valles may now be entirely crystalline, it is still very hot and presents a good target for investigating plutonic processes and associated ore deposits in what is now a relatively aseismic environment.

Drilling at Long Valley offers the opportunity of investigating a magmatic heat source at a depth possibly as shallow as 5 km and a dike (or dikes) that have been injected at an even shallower depth. The associated evolving hydrothermal system may be very young and relatively immature. There is no evidence that there ever was high-temperature hydrothermal activity in the eastern part of the caldera, and the present hydrothermal activity in the western part of the caldera may date from two pulses of recent volcanic activity, one about 3000 yr.B.P. and the other 200-700 yr.B.P. The nature of and depth to "basement" rock forming the heat conductor between the present or crystallized magma chambers at Long Valley has been thoroughly studied using a wide variety of geophysical techniques.

By comparison to both the Valles and Long Valley calderas, Yellowstone presents a larger and more vigorous present-day hydrothermal-magma system (Table 2). Yellowstone offers an especially attractive target for attaining magmatic temperatures *with* associated well-developed and long-lived (>10,000 years) hydrothermal activity at depths of 5 to 6 km. At present, it appears that Yellowstone offers an outstanding target to investigate the nature of the transition from brittle fracture to quasi-plastic deformation, an environment that is very important in regard to geophysical and hydrologic models. Yellowstone also offers an outstanding opportunity to investigate a system that is evolving as a result of "hot-spot" activity within the continental crust.

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