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A Core Hole in the Southwestern Moat of the Long Valley Caldera: Early Results

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A continuously cored hole penetrated 715 m into the southwestern moat of the Long Valley caldera. Temperatures in the postcaldera deposits increased rapidly with depth over the upper 335 m to 202°C, then remained nearly isothermal into the Bishop Tuff to the bottom of the hole. The depth to the Bishop Tuff is the shallowest, and the temperatures observed are among the highest in holes drilled in the caldera. The hole identifies a potential geothermal resource for the community of Mammoth Lakes, constrains the position of the principal heat source for the caldera's hydrothermal system, and serves as access for monitoring changes in water level, temperatures, and fluid chemistry.

Introduction

Intensive investigations in the Long Valley caldera (Figure 1) have considered the caldera's volcanic petrology, seismic and volcanic hazards, and geothermal energy potential. With respect to the latter consideration, attention has focused on the area underlain by the resurgent dome [*Rundle et al.*, 1986]. However, the western and southwestern portions of the caldera are both the most volcanically active and the least explored areas within the caldera. An understanding of the hydrothermal regime of the western moat may be the key to understanding the origin of and circulation within the present-day hydrothermal system in the Long Valley caldera.

Concepts of the Long Valley hydrothermal circulation system have most recently been described by *Sorey* [1985] and *Blackwell* [1985]. On the basis of temperature reversals in wells, there appear to be one or more zones of hot water flowing eastward beneath the south moat from Casa Diablo (CD on Figure 1) at an altitude of approximately 2100 m. The flow is in aquifers within and above the welded Bishop Tuff. The temperature in this region decreases from about 170°C in wells that supply the geothermal electric power plant at Casa Diablo Hot Springs to less than 70°C near Lake Crowley. Test drilling on and around the resurgent dome and to the east of the dome to depths of 2100 m has failed to encounter temperatures as high as those measured in the shallow aquifer at Casa Diablo. Prior to the drilling of the core hole described in this report, the only direct public domain evidence of hot water reservoirs beneath the western moat was the high temperature gradient in the bottom part of the 716-m-deep PLV-1 well. However, the analyses by *Sorey* [1985] and *Blackwell* [1985], along with reservoir temperature estimates based on chemical geothermometer calculations applied to thermal water from Casa Diablo, indicated that a reservoir at temperatures above 200°C existed beneath the western moat and was the source of thermal fluids at Casa Diablo and to the east. A suggested heat source for the postulated west moat reservoir was hot intrusive rocks associated with the southern extension of the 600-yr-old Inyo volcanic chain of phreatic craters and with the lava flows described by *Miller* [1985].

Drill hole information indicates that zones of deep fluid circulation no longer exist beneath the resurgent dome and that hot springs and fumaroles on or around the dome are fed from relatively shallow aquifers connected by lateral flow to a source reservoir within the Bishop Tuff beneath the western moat. Therefore, if a residual magma chamber is in place beneath the central part of the caldera, it does not represent a significant heat source for the present-day hydrothermal system, and if magma is present at depths as shallow as 4–5 km beneath the resurgent dome, it has not been in place long enough to influence the overlying groundwater system. The resurgent dome is made up primarily of rocks that were extruded 630,000 to 680,000 years ago, and the last eruptions near the dome were ~300,000 years ago [*Bailey and Koeppen*, 1977]. In contrast, evidence of magmatic activity along the Inyo volcanic chain as recently as 600 years ago lends support to the inference that the heat source for the present-day hydrothermal system is magma associated with this chain beneath the western moat. A southern projection of the Inyo-Mono system terminates at Mammoth Mountain, a large, andesite-dacite volcano that is 200,000 to 50,000 years old [*Bailey and Koeppen*, 1977] on the caldera's southwestern rim. Phreatic explosion craters on the north and northeast flanks of Mammoth Mountain may be contemporaneous with the most recent Inyo volcanic chain eruptions [*Miller*, 1985].

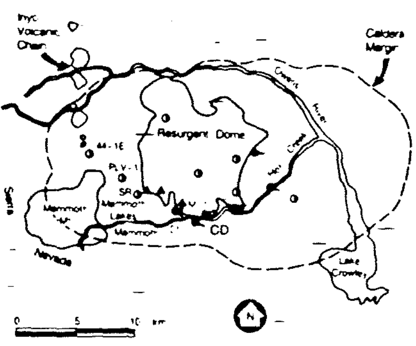

Fig. 1 Map of Long Valley caldera, showing locations of deep test wells (half-filled circles) and active thermal features on or around the resurgent dome. Hot springs are shown as solid circles with "tails," while fumaroles are shown as solid triangles. The Shady Rest core hole described in this report is designated SR. The area around well M-1 is labelled CD ("Casa Diablo Hot Springs"). (Geologic base from *Bailey and Koeppen* [1977]).

Given this setting, it was evident that one or more new drill holes were needed in the caldera's western moat to provide confirmation of the models of the present-day hydrothermal system. Researchers therefore proposed to drill a hole near the Shady Rest Campground to provide information on the presence of a hot water reservoir within the Bishop Tuff beneath the southwestern moat. The high temperature gradient in well PLV-1, which is located 2.5 km to the northwest of Shady Rest (Figure 1), suggested that such a reservoir might exist. Data from a 155-m test hole drilled in 1984 near Shady Rest for the Mammoth County Water District [*Guacci and McCann*, 1984] suggested that shallow zones of thermal water occur above the Bishop Tuff. This water could provide energy for space heating in Mammoth Lakes. For this reason, Mono County and the California Energy Commission contributed financially to the Shady Rest drilling effort. Industry interest was also focused on the western moat. Unocal Geothermal was actively exploring the Inyo Craters area, ~6 km northwest of Shady Rest, and drilled a ~1800-m-deep test hole (number 44–16) in late fall 1985. This hole intersected a hot zone with temperatures up to 218°C in the Bishop Tuff at depths of 915–1175 m. The hot zone is immediately underlain by a much cooler zone in precaldera volcanic rocks [*Suemnicht*, 1987].

Coring and Related Activities

The Shady Rest hole was spudded in on May 5, 1986, and completed on June 17. Its

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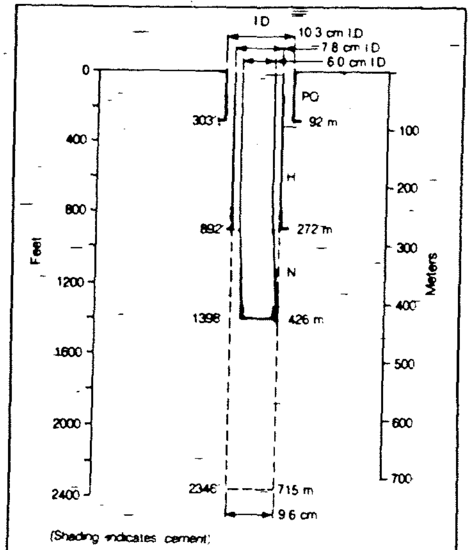

Fig. 2 Completion diagram of the Shady Rest hole.

configuration is shown in Figure 2. The hole was rotary drilled to 92 m, and a 12.7-cm-diameter surface casing installed. The hole was then cored at 9.6-cm diameter to a total depth of 715 m. Core recovery exceeded 90%. The core is now at the Department of Energy (DOE) repository at Grand Junction, Colo.

Difficulties were encountered in completing the hole: Sloughing, squeezing, and lost circulation prevented installation of casing over the full 715 m depth. Attempts to redrill and recover the portion of the hole below 245 m resulted in a "new" hole, diverging from the original at 241 m (Figure 2). The new hole was cored to a depth of 426 m, where N-sized casing (which has a 6-cm inner diameter) was cemented in and filled with water.

After repeated temperature surveys to determine an equilibrium profile, a ~3-m section of the casing at a depth of 340 m within the high-temperature zone was perforated in mid-October 1986. This provided access for fluid sampling of the hot aquifer. Immediately upon perforation, ~2000 L of cold water were pumped into the hole to prevent flashing, in case communication with the formation caused excessive drawdown of the hole's water column, and to assess the permeability of the perforated zone. Flashing did not occur, as the water level rapidly fell to a depth of 146 m and then gradually rose to stabilize at 134 m. In mid-November 1986, another temperature survey was made, and the fluid in the hole was bailed to ensure the presence of formation water. Then, in collaboration with scientists at the Sandia National Laboratory (Albuquerque, N.Mex.) and Los Alamos National Laboratory (Los Alamos, N.Mex.), the research team obtained fluid samples at perforation depth with a downhole sampler and from a depth of approximately 150 m with the bailer.

Early Results

Lithologic units that were encountered are shown in Figure 3, and a provisional geologic section is displayed in Figure 4. The upper glacial till is underlain by rhyolitic white to light gray pumiceous tuff, the Moat Rhyolite of *Bailey and Koeppen* [1977]. The Moat Rhyolite overlies harder gray, flow-banded Early Rhyolite, which contains a zone of lacustrine volcaniclastic deposits. The lower portion of the hole is in predominantly welded ash flow tuff (the Bishop Tuff). Numerous steeply dipping open fractures, lined by quartz and calcite covering sulfide minerals (Figure 5), are preserved in core from the lower ~400-m portion of hole, that is, the high-temperature zone. The depth to the top of the Bishop Tuff is the shallowest encountered in holes in the caldera.

An equilibrium temperature profile, together with projected bottom hole temperatures measured during drilling, is plotted in Figure 3. The temperature increases fairly regularly, interrupted by two cooler zones at 120 and 245 m, to ~160°C at a depth of ~330 m. Temperatures then rise abruptly to 202°C at 335 m, where a lost circulation zone in the fractured, silicified Early Rhyolite was encountered. Below this zone the projected bottom hole temperatures indicate a nearly isothermal pattern, mostly between 190 and 200°C, that extends into the Bishop Tuff and to the bottom of the hole.

The relative position of the Shady Rest thermal profile with respect to those of PLV-1 and the deep test hole at Casa Diablo Hot Springs is shown in Figure 6. When the upper part of the high-temperature zone at Shady Rest is plotted on the same elevation scale, we see that it is at nearly the same elevation as the upper high-temperature zone at

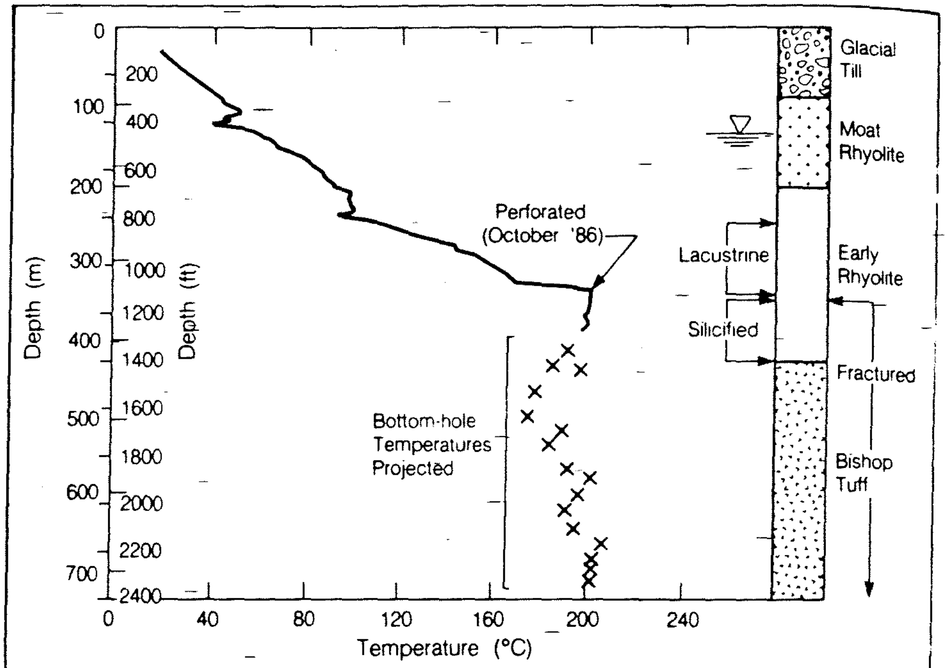

Fig. 3 Equilibrium temperature profile (July 7, 1986) with projected temperatures from bottom hole measurements made during coring, together with a lithologic diagram of the Shady Rest hole.

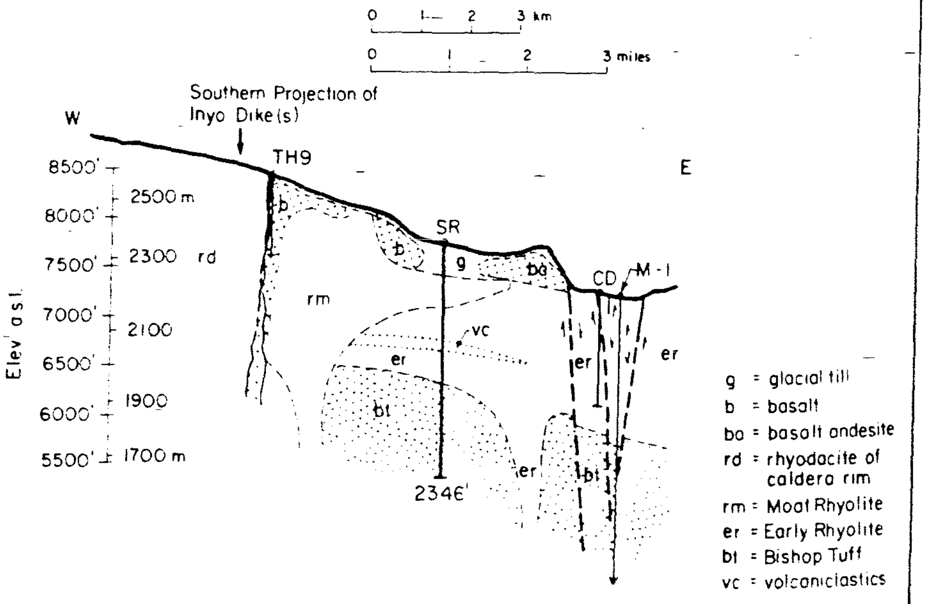

Fig. 4 Geologic section from the eastern flank of Mammoth Mountain, through Shady Rest, to Casa Diablo Hot Springs. TH-9 is a water supply test well drilled by the Mammoth County Water District.

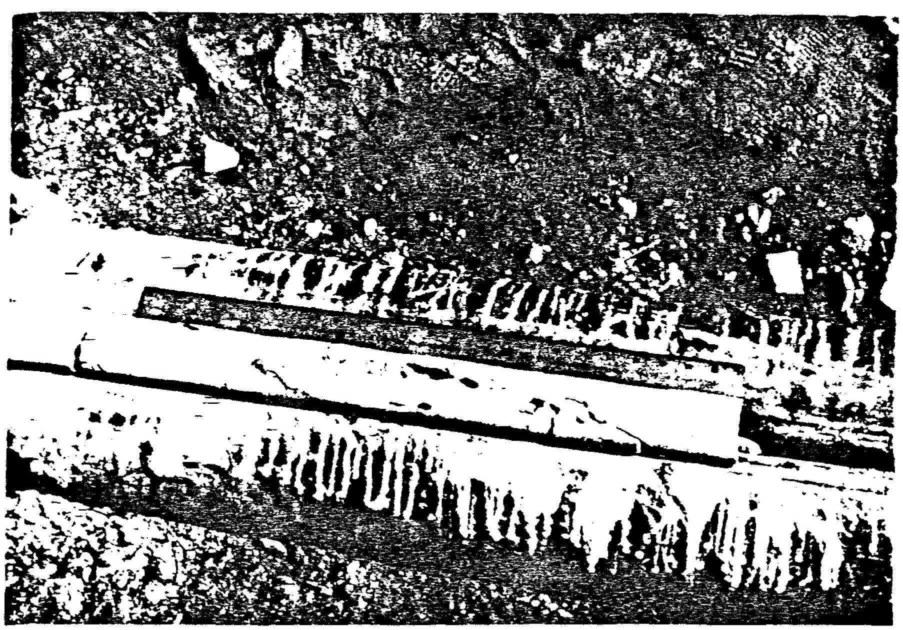

Fig. 5 Core from Bishop Tuff section, showing an open fracture lined by calcite-quartz (light), rimmed by a darker zone of sulfide minerals.

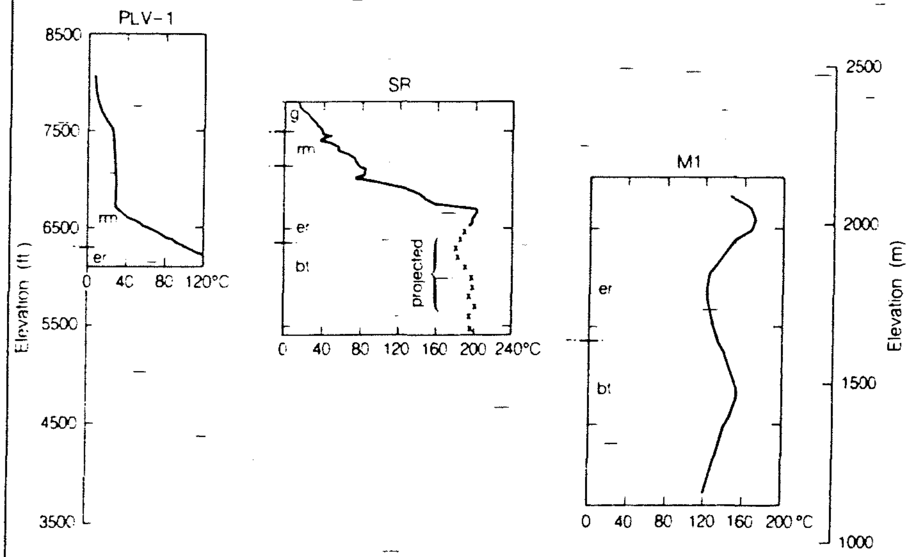

Fig. 6 Comparison of thermal profiles at PLV-1, Shady Rest; and the Casa Diablo deep test hole (M-1). Lithologic abbreviations are defined in Figure 4.

Casa Diablo, while the zone of increasing temperature near the bottom of hole PLV-1 is at a somewhat lower elevation. The similarity in the elevations of the high-temperature portions of the Shady Rest and Casa Diablo profiles and the difference in water level elevation between these two areas suggest that hot water is moving southeastwardly from Shady Rest to Casa Diablo through the Early Rhyolite section. However, as indicated on the geologic section (Figure 4), the flow path may be interrupted by one or more faults. The lower zone of thermal water flow in well M-1 within the Bishop Tuff may also be fed by lateral flow from the Shady Rest area.

Preliminary chemical analyses and calculated geothermometer temperatures from a fluid sample are compared with analyses of a Casa Diablo geothermal well fluid in Table 1. The similarities in most of the chemical concentrations and in ionic ratios suggest that the Shady Rest fluids supply the Casa Diablo geothermal field. The higher calcium concentration at Shady Rest is probably caused by the abundant calcite that lines the open fractures of the high-temperature zone (Figure 5). Calculated Na/K/Ca chemical geothermometer temperatures for the Shady Rest and Casa Diablo well samples are higher than those measured downhole but are similar to the temperature measured at Unocal's 44-16 hole (218°C).

Future Activities

The core has been described in detail. Planned investigations of the core include alteration mineralogy, $^{87/86}$Sr and $^{12/13}$C measurements on fracture calcite, and $^{18/16}$O and H/D determinations on fracture minerals and whole rock specimens. Uranium series disequilibrium will be investigated in intervals indicated by gamma ray logs. Major and trace chemical constituents of fluid and gases will be analyzed, and measurements of fluid inclusion temperature will be attempted.

TABLE 1. Preliminary Chemical Analyses and Geothermometer Temperatures of Shady Rest Fluids, Compared With Fluids From a Casa Diablo Well

Constituent, mg/L	Shady Rest*	Casa Diablo†
Na	369	350
K	43	36
Ca	7.4	1.2
Li	2.8	2.6
Cl	280	270
SO_4	159	120
B	12	11
SiO_2	250	250
$\delta^{18}O$	−14.3	−14.8
Na/K/Ca geothermometer temperature, °C	214	224

*Bailed sample, analysis by USGS.

†Well MBP 3, sampled July 12, 1985; analysis by USGS.

As was the case with the fluids sampled at Casa Diablo Hot Springs, chemical geothermometer temperatures derived from major element concentrations suggest that still hotter conditions will be encountered at depth to the west of Shady Rest. This expectation provides a good rationale for siting a deeper hole that would penetrate through caldera fill and into Sierra Nevada basement rock to investigate the source of heat for the hot fluids. The high temperature encountered in the Bishop Tuff in the aforementioned Unocal hole (44-16), together with the immediately underlying relatively cold zone, suggest that stratified hydrothermal conditions occur west of Shady Rest. The hot water at 44-16 could be moving northward from the vicinity of Mammoth Mountain through fractured Bishop Tuff, while colder water, recharged from the Sierra Nevada, moves more easterly in the underlying precaldera Tertiary volcanic and Paleozoic metamorphic rocks. In this respect the Mammoth Mountain area remains as one primary location for the next hydrothermal drilling target. Alternatively, hot water could be moving both eastward and westward from a source area between Shady Rest and 44-16, suggesting that a deep (1.5-2-km) hole in this location should also be considered. A hole will be cored in the summer of 1987 to intersect the dike(s) of the Inyo Chain, ~1 km west of 44-16 (John Eichelberger, Sandia Natinal Laboratory, personal communication, 1987). Temperature measurements and fluid samples from this hole will also be valuable in determining the hydrothermal setting of this part of the western moat.

It was the consensus of participants at recent Long Valley hydrothermal workshops [*Sorey et al.*, 1984, 1987] that a 1-2-km-deep hole should be drilled to resolve the critical question of the flow paths in the hydrothermal system of the western moat area and the location of the associated heat source. In this respect, the Shady Rest hole described here can be considered a "step out" west of Casa Diablo, to test the rationale for the deeper hole. Although the Shady Rest hole does not penetrate deeply enough to delineate the characteristics of the hydrothermal system in the western moat satisfactorily, it does confirm the presence of 200°+ water and provides access to hydrologic and geochemical information otherwise unobtainable until a deeper hole is drilled. Such information will prove invaluable in siting and determining the depth of the deeper hole.

Acknowledgments

The Shady Rest project was sponsored by the U.S. Department of Energy's Office of Basic Energy Sciences, the California Energy Commission, Mono County, and the U.S. Geological Survey. Drilling, coring, and hole completion were ably accomplished by the Tonto Drilling Company, supervised by personnel of DOE's Geosciences Research Drilling Office at Sandia National Laboratories. Transportation and curation of core were coordinated by DOE's curatorial office at Grand Junction, Colo. Lawrence Berkeley Laboratory (Berkeley, Calif.) activities were conducted under U.S. Department of Energy Contract DE-AC03-76SF 00098.

References

Bailey, R. A., and R. P. Koeppen, Preliminary geologic map of Long Valley Caldera, Mono County, California, *U.S. Geol. Surv. Open File Map 77-468*, 1977.

Blackwell, D. D., A transient model of the geothermal system of the Long Valley Caldera, California, *J. Geophys. Res.*, *90*, 11,229, 1985.

Guacci, G., and D. L. McCann, Exploratory drilling, vicinity of Mammoth Lakes, California for Mammoth County Water District, internal report prepared by LeRoy Crandall and Assoc., Los Angeles, Calif., 1984.

Miller, C. D., Holocene eruptions at the Inyo volcanic chain, California: Implications for possible eruptions in Long Valley Caldera, *Geology*, *13*, 14, 1985.

Rundle, J. B., C. R. Carrigan, H. C. Hardee, and W. C. Luth, Deep drilling to the magmatic environment in Long Valley Caldera, *Eos, Trans. AGU*, *67*, 490, 1986.

Sorey, M. L., Evolution and present state of the hydrothermal system in Long Valley Caldera, *J. Geophys. Res.*, *90*, 11,219, 1985.

Sorey, M. L., C. D. Farrar, and H. A. Wollenberg (Eds.), Proceedings of the workshop on hydrologic and geochemical monitoring in the Long Valley Caldera, *Rep. LBL 20020*, Lawrence Berkeley Lab., Berkeley, Calif., 1984.

Sorey, M. L., C. D. Farrar, and H. A. Wollenberg (Eds.), Proceedings of the second workshop on hydrologic and geochemical monitoring in the Long Valley caldera, *Rep LBL 22852*, Lawrence Berkeley Lab., Berkeley, Calif., 1987.

Suemnicht, G., *Results of Deep Drilling in the Western Moat of Long Valley California: Proceedings, Twelfth Workshop, Geothermal Reservoir Engineering*, Stanford University, Stanford, Calif., 1987.

News

Peer Review and the Pork Barrel

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Unless and until Congress establishes a large-scale program to improve academic research facilities, researchers (or groups that represent them) should try to convince Congress that some sort of merit review should be applied to the "pork barrel" system of research facilities funding now in operation, according to a working committee set up last fall by the Association of American Universities (AAU) and five other higher education groups. In recent years, an increasing number of colleges and universities have sought and received direct congressional appropriations earmarked for their research facilities without conventional merit review, against the objections of groups like AAU.

One member of this working committee, however, prepared a dissenting statement to this report, to the effect that it would harm the "long-range interests of science and higher education" for the research community to show any acquiescence at all to the pork barrel or "earmarking" system. If the working committee's proposals are adopted, "political influence will remain the final determinant of funding. This will fuel the growing perception of higher education as another special interest group," wrote Arthur M. Sussman of the University of Chicago (Chicago, Ill.).

Federal science agencies have not had programs for funding the "bricks and mortar" for research facilities since the mid-1960s, according to the "Report of the Working Committee on Principles, Policies, and Procedures in the Award of Federal Funds for University Research Facilities and Research Projects." Other recent reports, such as the 1986 "Report of the White House Science Council Panel on the Health of U.S. College and Universities," have called for federal programs to improve academic research facilities. Large-scale facilities programs have been proposed but not passed in Congress. According to the working committee's report, "the proper role of the federal government in support of university facilities, as compared with the roles of state governments or private sources, remains an open question."

In its report, the working committee recommended that its sponsoring associations and other professional groups intensify their efforts to persuade the current Congress to initiate traditional, competitive programs to fund research facilities, preferably by establishing separate programs in each of the six major research funding agencies (National Science Foundation, National Institutes of Health, U.S. Department of Agriculture, National Aeronautics and Space Administration, Department of Defense, and Department of Energy). Such programs should be two-tiered, they said, with proposals from established research universities considered separately from those of "developing institutions." They also recommended that the research community drop its insistence that facilities funds not be taken from what would have been the research budget. Congress is skeptical about that demand, they said, because "insistence on incremental funding is tantamount to an assertion that *all* research projects . . . are more important than *any* research facility candidate." Instead, they said, the research community should argue for "reasonable floors and ceilings" on facilities budgets or for a portion of research budget increases after inflation to be used for facilities.

Until Congress initiates this sort of large-scale program, requests for earmarked facilities funds are bound to increase, the working committee said, and the research community should try to persuade the Congress to let the existing research agencies judge the proposals' scientific merit. The committee added, however, that the university associations should recognize that nonscientific forms of merit also deserve consideration when judging the overall worth of large-scale facilities projects. Nonscientific merit is already a factor in National Science Foundation research grants aimed at goals such as increasing the participation of women and minorities in science or distributing resources to a wider selection of institutions, the committee noted. The working committee stressed that its views were not necessarily shared by its sponsoring associations.

In his dissent, Sussman argued that the development of a congressional funding system for research facilities could lead to a similar system for project funding. "What persuasive arguments would distinguish the facilities from the project funding?" he asked. Even with modifications, the congressional earmarking system "will continue to be divisive," Sussman said.—*JAK*

1985 Magnetic Models for the United States

PAGE 530

The U.S. Geological Survey (USGS) has developed new mathematical models of the magnetic field in the United States. The models describe the direction and intensity of the field at the beginning of 1985 and the rate of change expected during the next few years. They were derived from several tens of thousands of original field measurements from land, marine, and aerial surveys; from values synthesized from the Magsat-based International Geomagnetic Reference Field (IGRF) model for 1985; and from recent data from magnetic observations and repeat stations. The models will serve as the basis for a new set of magnetic charts, now in preparation. Figure 1 is a simplified small-scale version of the chart of declination.

The new models are in the form of spherical harmonic series representing the scalar magnetic potential, from which all the field