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THE IMPACTS OF DEEP GEOTHERMAL FLUID PRODUCTION ON SHALLOW GROUND-WATER SYSTEMS

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ABSTRACT

Geothermal energy is a nationally minor, but regionally significant, potential source of direct heat and electricity in the United States. In developing hydrothermal systems for energy production, it has been necessary in many cases to assess the potential impacts of reservoir drawdown on ground-water discharge points, such as hot springs and seeps, and gaining reaches of surface streams, because many hydrothermal and shallow ground-water reservoirs are hydraulically communicating systems. The extent of interaction between the deep hydrothermal and shallow ground-water reservoirs, however, has often been underestimated during geothermal exploration.

Case studies of hydrothermal exploration and development activities at Coso Hot Springs, California, and Valles Caldera, New Mexico, have indicated that shallow ground-water systems may be affected by geothermal reservoir production. These potential impacts include reduction in quantity and temperature of natural ground-water discharge and water rights and socioreligious issues.

THE IMPACTS OF DEEP GEOTHERMAL FLUID PRODUCTION ON SHALLOW GROUND-WATER SYSTEMS[1,2]

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INTRODUCTION

Geothermal energy is at present a minor but potentially significant source of direct heat and electricity in the United States. There are five currently designated categories of geothermal resource regimes: conduction-dominated; igneous-related; low-temperature [< 90°C (< 194°F)] geothermal; intermediate- to high-temperature [90° - 150°C (194° - 302°F)] to [> 150°C (> 302°F)] hydrothermal convection; and geopressured-geothermal (Muffler and Guffanti 1978). Discussions in this paper will be restricted to the hydrothermal convection systems.

To date, the only on-line electrical production of a geothermal resource in the United States is at The Geysers, a dry steam Known Geothermal Resource Area (KGRA) in California. The Geysers is the world's largest geothermal electrical facility; the power plant units presently have a combined generating capacity of 663 megawatts electrical (MWe) (Brook et al. 1978). There are, however, several thermal test facilities capable of eventually producing up to 10 MWe for short periods of time; one of these is the plant at Niland, in the Imperial Valley (Salton Trough) of California. In addition, a working facility at Cerro Prieto, just across the Mexican Border, has 150 MWe on-line, and several power plants of about 50 MWe have been proposed, particularly in the Imperial Valley of California.

The anticipated electrical production capacity of geothermal resources in this country is expected to increase dramatically during the next decade (Fig. 1), particularly for the hydrothermal resources. Geothermal flash steam power cycle production could produce 10,000 MW of electricity by 1990. This cycle, also referred to as a single-flash once-through cycle, is one in which liquid geothermal fluid or a steam/liquid mixture is allowed to flash either at the wellhead or at satellite separators connecting several production wells to common steam lines that feed a turbine. With new technology, however, advanced hydrothermal power cycles have the potential to result in the production of 20,000 MWe within the same time span. Advanced hydrothermal power

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[2]Publication No. 1451, Environmental Sciences Division, ORNL.

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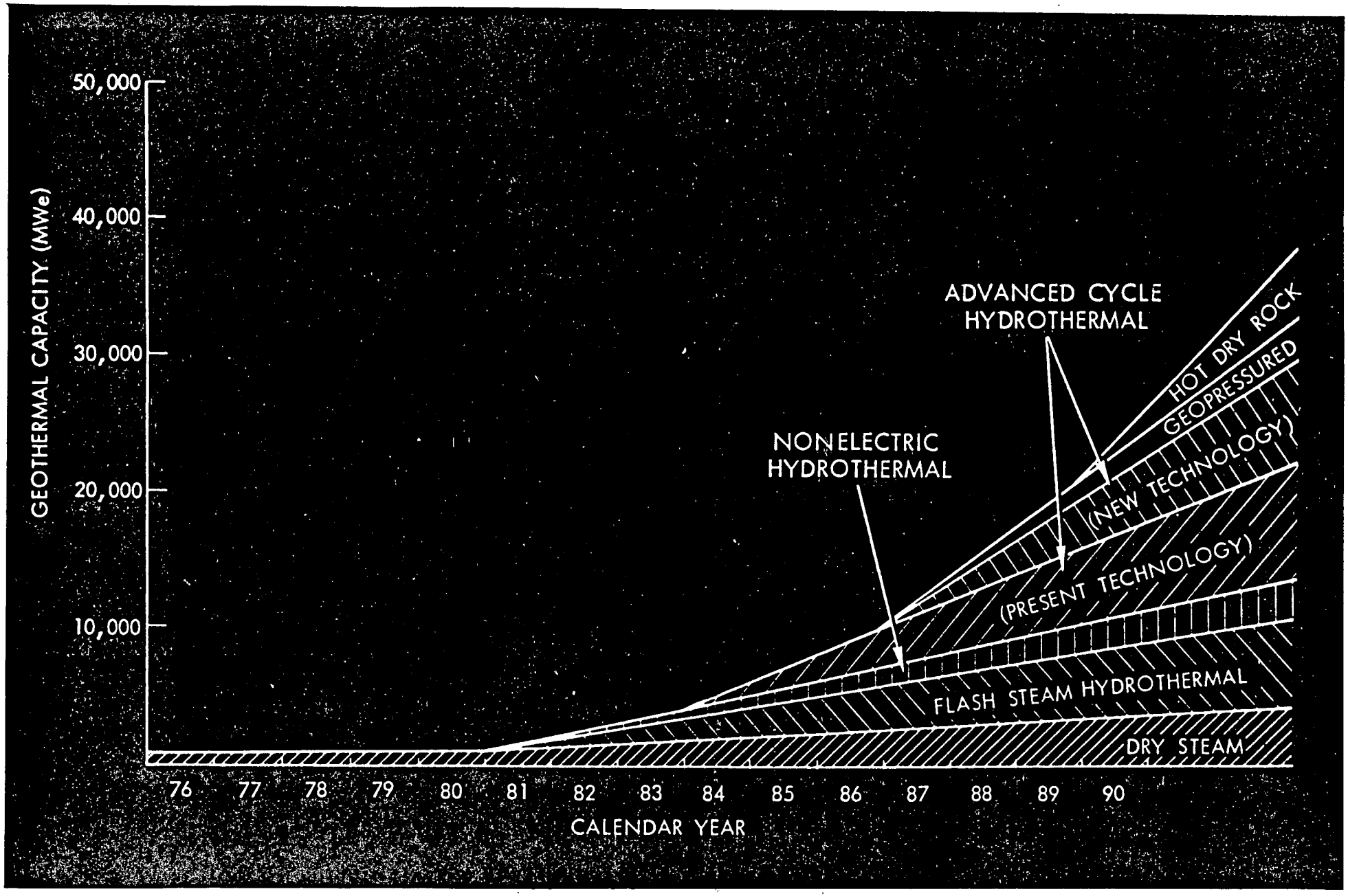
GEOTHERMAL CAPACITY (MWe)
50,000
40,000
30,000
20,000
10,000
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
CALENDAR YEAR
ADVANCED CYCLE HYDROTHERMAL
NONELECTRIC HYDROTHERMAL
HOT DRY ROCK
GEOPRESSURED
(NEW TECHNOLOGY)
(PRESENT TECHNOLOGY)
FLASH STEAM HYDROTHERMAL
DRY STEAM

Fig. 1 Top ↑

cycles include multistage flashing as well as binary cycles; the latter is one in which a lower temperature geothermal fluid is used to boil a working fluid like Freon or isobutane in heat exchangers, with the working fluid expanded through a turbine.

It is obvious that geothermal resource exploration and development are necessary parts of the National Energy Program; what is not immediately apparent is the fact that these activities can negatively impact shallow ground-water systems. Geothermal reservoir drawdown can result in decreased temperature and dissolved solids content of thermal springs and seeps, surface discharge depletion from diversion of a geothermal flow component, and reallocation of water rights.

A hydrothermal resource has three essential features: permeable reservoir material, convectively circulating fluid, and a relatively impermeable caprock. The reservoir rocks usually encountered in this type of geothermal system have secondary (fracture) porosity and permeability, which allows convective circulation of the fluid medium. The caprock ordinarily consists of overlying hydrothermally altered and sealed formations. A typical hydrothermal convection system is shown schematically in Fig. 2.

The traditional industry view of hydrothermal resources is that they are isolated from more shallow ground-water systems. Many hydrothermal and shallow ground-water reservoirs are, however, hydraulically communicating systems that may have common recharge areas. Hydrothermal systems are located in tectonically active regions typified by deep, interconnected fault zones that provide the route by which recharge occurs and hot mineralized fluids from depth can rise and mix with shallow, nonthermal waters. Warm springs and wells exist where shallow ground water is heated by underlying, separate geothermal fluids as shown in Fig. 2. Thermal springs and wells also occur when geothermal fluids leak up along fault zones and mix with shallow nonthermal ground water. In the latter case, the shallow system becomes more mineralized by the input of geothermal fluids. In some cases, mineralized nonthermal waters occur when small amounts of geothermal fluid are highly diluted by shallow aquifer systems (Trainer 1974). The extent of these interactions has often been underestimated.

Geothermal reservoir drawdown (pressure reduction) during and subsequent to production can significantly reduce or even eliminate the geothermal fluid component of ground-water outflow. The consumptive water use in evaporative losses with current technology for a 50-MWe geothermal power plant producing from a liquid-dominated reservoir is slightly more than 100 liters/sec (1600 gal/min) (U.S. DOE 1979a). Provided that all fluids but evaporative losses are injected back into the producing reservoir, the drawdown may still be appreciable depending upon the local flow system characteristics. Regional ground-water discharge containing a geothermal flow component could be correspondingly reduced by decreased geothermal reservoir pressure.

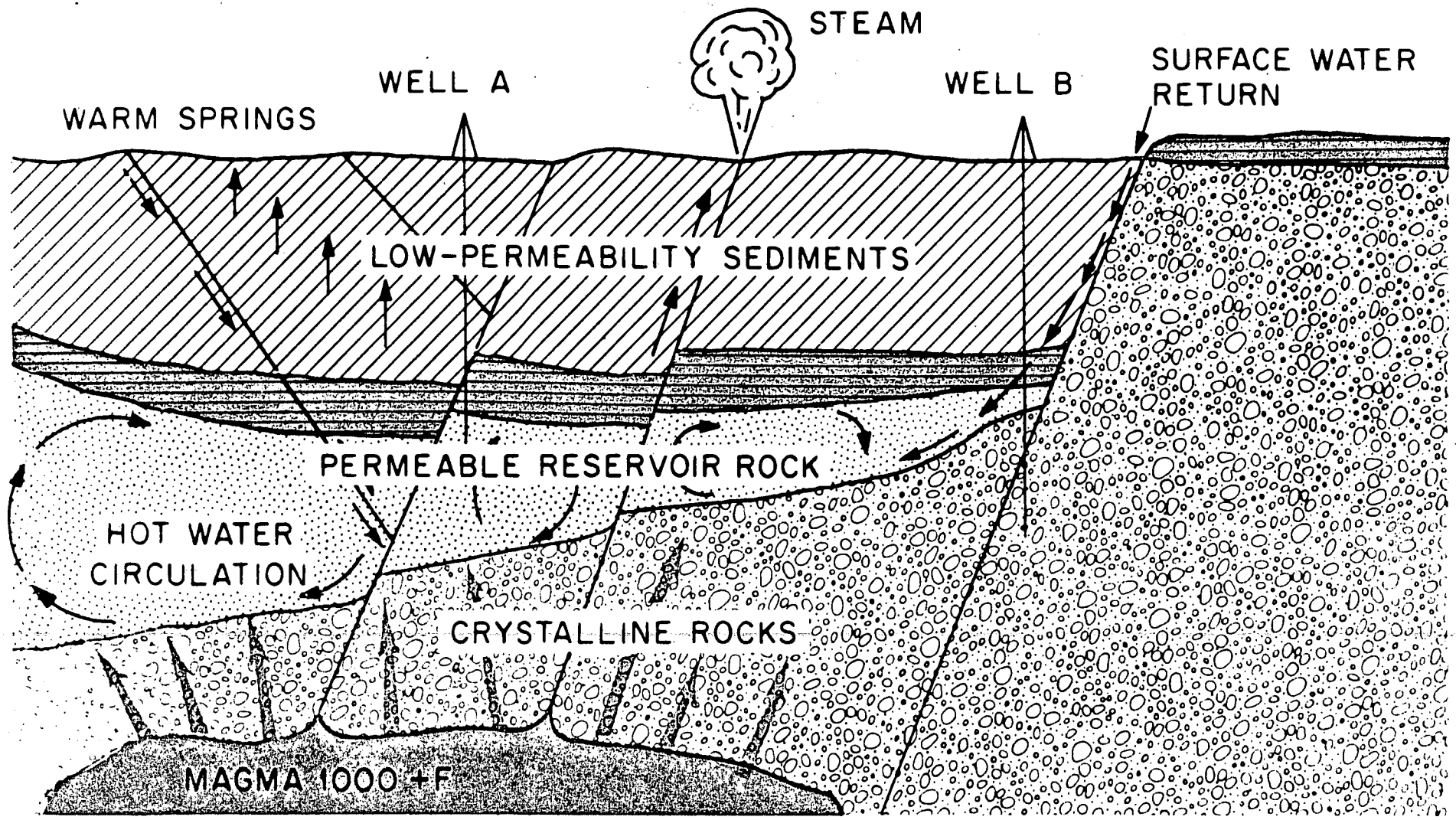
STEAM
WELL A
WELL B
SURFACE WATER RETURN
WARM SPRINGS
LOW-PERMEABILITY SEDIMENTS
PERMEABLE RESERVOIR ROCK
HOT WATER CIRCULATION
CRYSTALLINE ROCKS
MAGMA 1000 +F

Fig. 2 Top ↑

The majority of KGRA's are located in the water-deficient western states. The effects of geothermal fluid withdrawal are therefore important with respect to legal water issues. Water rights must be appropriated to compensate for depletion of surface water flow due to the diversion of a hydrothermal flow component. One way this has been accomplished is for the resource operator or developer to purchase irrigated lands within the watershed and retire them from use (U.S. DOE 1979a).

In addition to better-known water uses, socioreligious interests related to ground-water impacts are also evident, particularly with respect to Native American peoples. Surface manifestations of a geothermal resource are exemplified by hydrothermally altered ground, hot springs, fumaroles, and boiling or bubbling mud pots; these sites are traditionally important or even sacred. Any effects on the hydrothermal and hydraulically connected shallow reservoirs due to geothermal fluid production can be expected to have an adverse impact on the socioreligious values of these sites.

CASE STUDIES

Case studies of hydrothermal exploration and development activities at Coso Hot Springs, California, and Valles Caldera (the Baca Ranch), New Mexico, have indicated that shallow ground-water systems may indeed be affected by geothermal reservoir production. The Coso and Valles Caldera KGRA's will be treated separately in the following discussion.

COSO

The Coso KGRA lies 295 km (183 mi) northeast of Los Angeles, within the China Lake Complex (CLC) of the Naval Weapons Center (Fig. 3). A large elliptic ring fracture system 42 km (26 mi) in diameter is apparently a surface expression of an underlying batholith (Duffield 1975). The geophysical anomalies coincident with the KGRA are centered in an area of silicic volcanic eruptive activity; some 37 rhyolite domes and associated pumice rings overlie a shallow granitic stock (a part of the larger batholith) that acts as the immediate heat source (Austin and Pringle 1970).

The Coso resource is a liquid-dominated system contained within fractured igneous and metamorphic rocks; the mean reservoir volume is approximately 46 km^3 (11 mi^3). The reservoir fluid, which contains 5000 to 6000 mg/liter dissolved solids, has an estimated temperature of 220°C (428 °F). The area is presumably capable of sustaining 650-MWe production for a thirty-year plant life (Brook et al. 1978).

The initial well-test site is located 3 km (1.8 mi) west of the Coso Hot Springs National Historic Place (U.S. DOE 1978). A major concern in flow-testing the Coso Geothermal Exploration Hole No. 1

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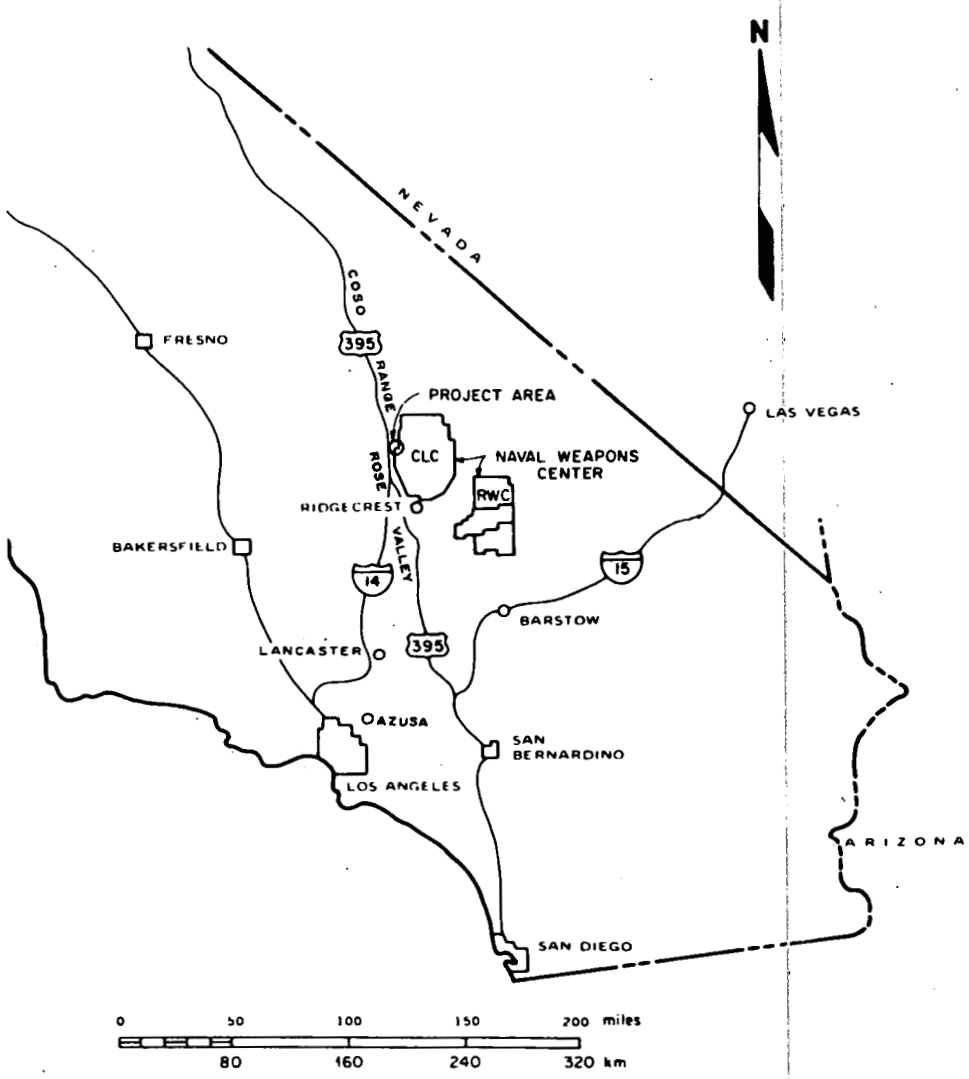

Fig. 3 Top ↑

Moran

(CGEH-1) and in any future development was the effect (if any) that these activities would have on the hot spring area adjacent to the old resort, also within the project area. In addition to the protection afforded by the Historic Preservation Designation, this area holds considerable cultural and religious significance for the Owens Valley Paiute-Shoshone Indian Band (Quesenberry 1978). The Native Americans believe that were the springs and mud pots to dry up, the spirits inhabiting them would cease to exist. In order to address this problem, a hydrogeologic assessment of impact was conducted.

Shallow ground water in the area occurs in discontinuous perched layers in fractured volcanic and intrusive rocks and in permeable alluvium. The system is recharged by local precipitation at an estimated rate of 4.9×10^5 m^3 (390 acre-ft) per year (Spane 1978). Discharge takes place as evaporation in area playas and as some seepage in the vicinity of the old resort. General directions of shallow ground-water movement are to the south and southeast. A deep regional ground-water system is also present; this system derives its recharge from precipitation along the Sierra Nevada front to the west at an estimated annual rate of 3.5×10^6 m^3 (2800 acre-ft.) and it eventually discharges to the floor of Death Valley to the east (Spane 1978). This deep circulation contributes the fluid contained within the Coso reservoir. A portion of the geothermal fluid makes its way to the surface by leakage along the nearly vertical Coso fault at Coso Hot Springs (Fig. 4). The other faults shown in this figure are inferred; if present, they have been apparently sealed by hydrothermal alteration products since no present manifestation of an underlying geothermal resource has been observed in these areas. The deep fluids mix with shallow ground water and then discharge at the surface.

The amount of geothermal fluid consumption during the CGEH-1 flow test was not to exceed 6×10^4 m^3 (50 acre-ft.) (U.S. DOE 1978). Although a hydraulic connection exists between the deep and shallow ground-water systems, hydrothermal activity in old wells, springs, and vents at Coso Hot Springs should be unaffected by the CGEH-1 flow test operations because (1) existing data indicate that this relatively small quantity of deep fluid loss (reservoir drawdown) would not divert any of the flow rising up along the Coso fault, and (2) the thermal wells and springs in the area are supplied primarily by shallow ground water (Spane 1978). The amount of fluid withdrawal associated with future development, however, is significant compared to estimated recharge and could deplete or eliminate the natural geothermal outflow, with the result that spring flows could cease and mud pots dry up during periods of normal low-flow conditions.

VALLES CALDERA

Valles Caldera, the site of DOE's geothermal demonstration power plant, is located in the Jemez Mountains of north-central New Mexico, approximately 97 km (60 mi) north of Albuquerque and 8 km (5 mi) west of

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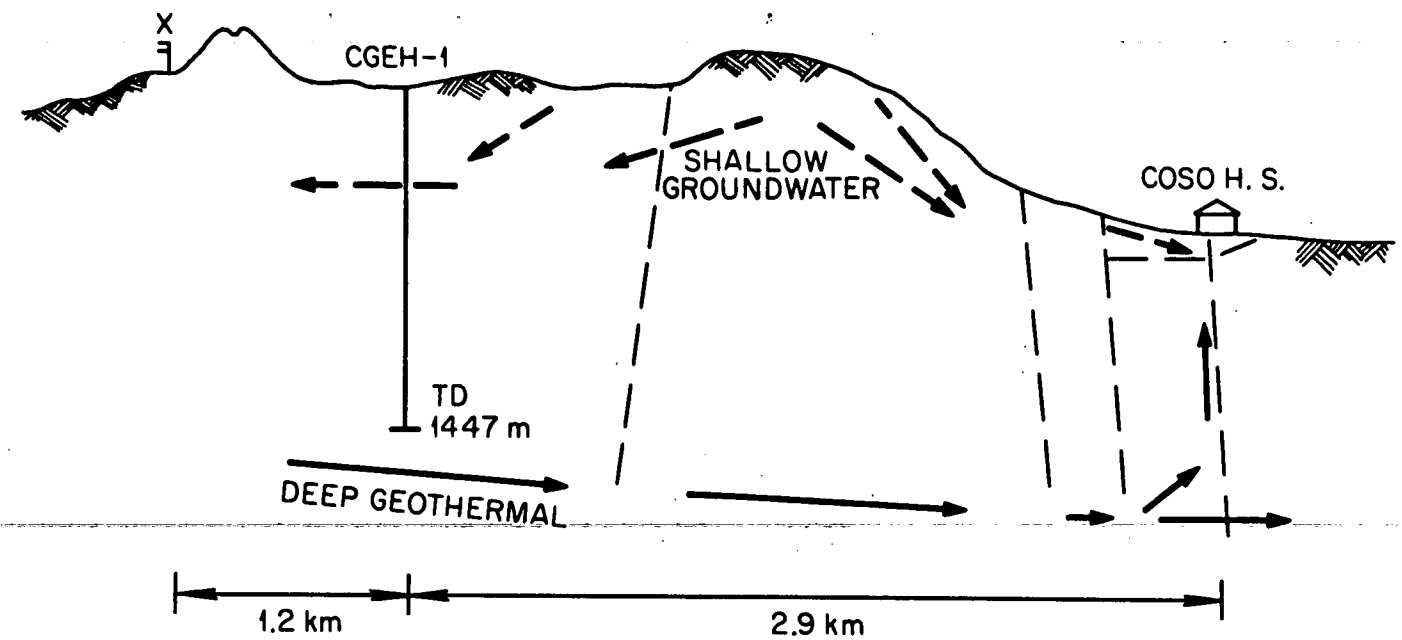

Fig. 4 Top ↑

Los Alamos (Fig. 5). Valles Caldera is a collapsed structural dome superimposed on an extension of the Rocky Mountain belt between the San Juan Basin to the west and the Rio Grande rift zone to the east. The Nacimiento overthrust delineates the east side of the San Juan Basin and the west boundary of the Jemez uplift (West 1973).

The Caldera is a subcircular depression of volcanic origin that ranges from 19 to 24 km (12 to 15 mi) in diameter. Within the structure numerous rhyolite domes divide the area into several valleys, the largest of which is Valle Grande (Dondanville 1978; Conover et al. 1963). The proposed initial 50-MWe power plant will be constructed in Redondo Canyon with development beyond 150 MWe moving into the Sulfur Creek area to the northwest (DOE 1979a) (Fig. 6). An 880-plus-m (2900-plus-ft) thickness of Paleozoic and Cenozoic sedimentary rocks overlies a Precambrian microcline granite basement and underlies up to 3480 m (11,400 ft) of Miocene to Pleistocene volcanics, most notably, the Bandelier Tuff. Caldera fill material has accumulated to depths as great as 600 m (2000 ft). Recent (0.1 to 1.0 million years B.P.) volcanism has occurred along the Caldera ring graben faults (Griggs and Hem 1964; Dondanville 1978; U.S. DOE 1979a).

Surface manifestations of a geothermal resource are present not only within Valles Caldera but also to the southwest, along the Jemez River. Within the Caldera, active or recently active areas of hydrothermal alteration total approximately 39 km^2 (15 mi^2) (Dondanville 1978); the most notable occurrence of hydrothermally altered ground is at the old resort area of Sulfur Springs. The geothermal resource of Valles Caldera has an estimated volume of 125 ± 56 km^3 (30 ± 13 mi^3), and an electrical energy potential of 2700 MW (Brook et al. 1978).

The geothermal resource of Valles Caldera actually consists of two systems. The initial production reservoir is a liquid-dominated system. The reservoir temperature, as calculated from geothermetric data, averages 329°C (624°F) (U.S. DOE 1979a). The primary production-injection zone is within the fractured Bandelier Tuff; the upper part of the formation is very densely welded to form the caprock. The potential source of geothermal fluids is thought to be the underlying Tertiary sands. Fluids migrate to more shallow zones in the Bandelier Tuff by movement through the graben faults of Redondo Canyon (Fig. 7) (U.S. DOE 1979a). The secondary system, a vapor-dominated reservoir not currently designated for near-term production, locally overlies the hot-water reservoir. Several of the Baca test wells have intersected this system; one is completed entirely within it (Brook et al. 1978; U.S. DOE 1979a).

Ground waters in the Valles Caldera area can be classified according to either shallow or deep occurrence. The shallow systems are those in which ground-water circulation takes place close to the land surface. The deep system is that of the geothermal reservoir, which contains deeply circulating hot mineralized fluids and underlies at least a portion of Valles Caldera.

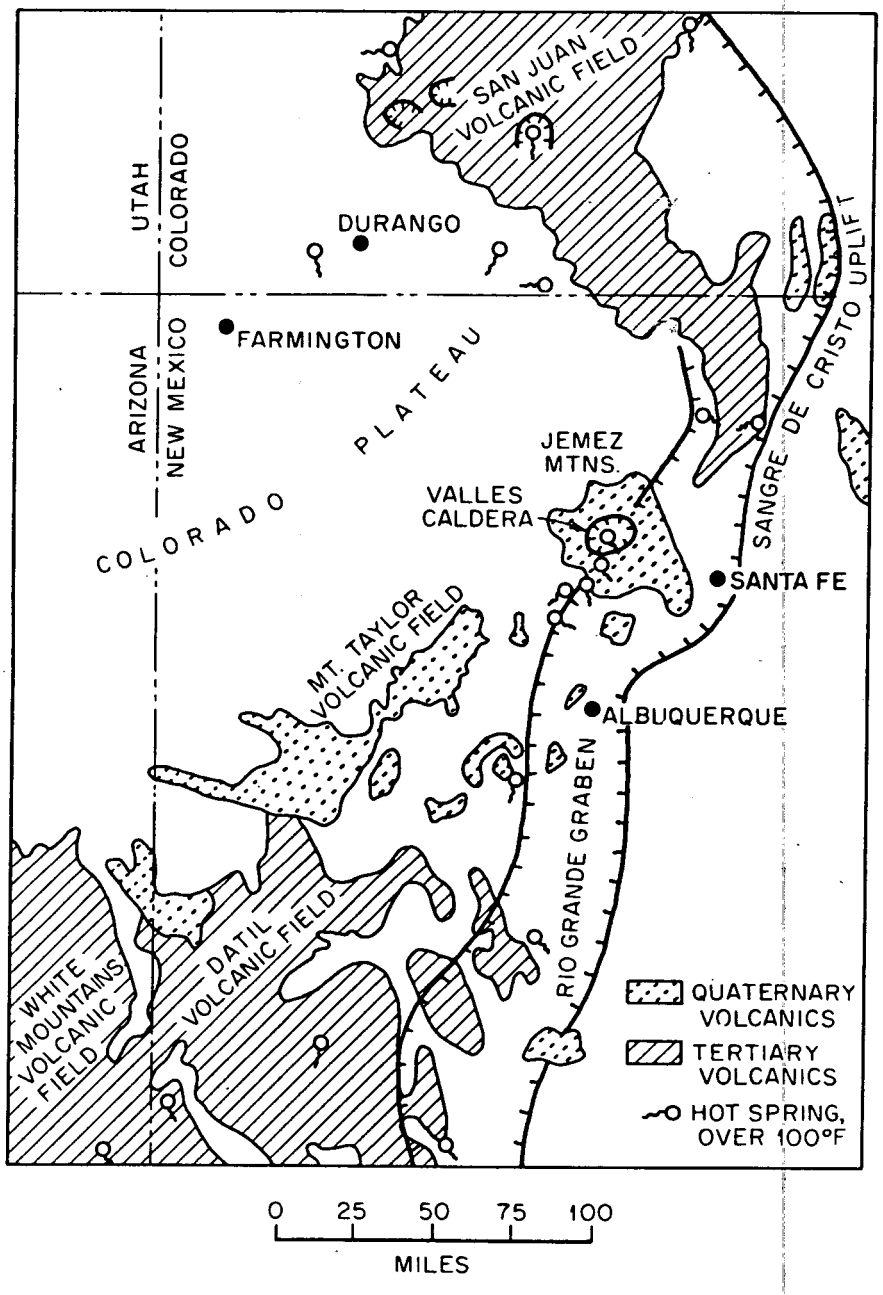
SAN JUAN VOLCANIC FIELD
UTAH
COLORADO
DURANGO
FARMINGTON
ARIZONA
NEW MEXICO
COLORADO PLATEAU
JEMEZ MTNS.
VALLES CALDERA
SANGRE DE CRISTO UPLIFT
SANTA FE
MT. TAYLOR VOLCANIC FIELD
ALBUQUERQUE
RIO GRANDE GRABEN
DATIL VOLCANIC FIELD
WHITE MOUNTAINS VOLCANIC FIELD
QUATERNARY VOLCANICS
TERTIARY VOLCANICS
HOT SPRING, OVER 100°F
0 25 50 75 100
MILES

Fig 5 Top ↑

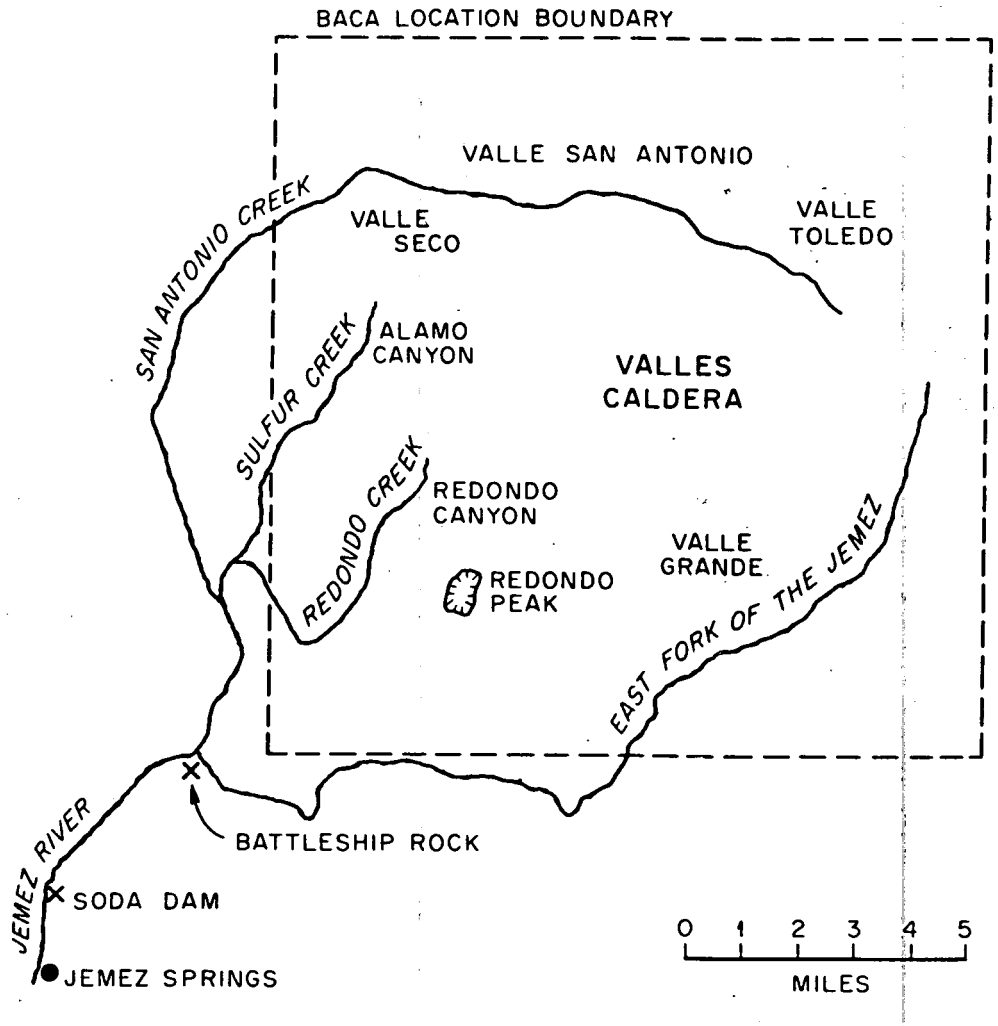
BACA LOCATION BOUNDARY
VALLE SAN ANTONIO
VALLE SECO
VALLE TOLEDO
SAN ANTONIO CREEK
SULFUR CREEK
ALAMO CANYON
VALLES CALDERA
REDONDO CREEK
REDONDO CANYON
VALLE GRANDE
REDONDO PEAK
EAST FORK OF THE JEMEZ
BATTLESHIP ROCK
JEMEZ RIVER
SODA DAM
JEMEZ SPRINGS
0 1 2 3 4 5
MILES

Fig. 6 Top ↑

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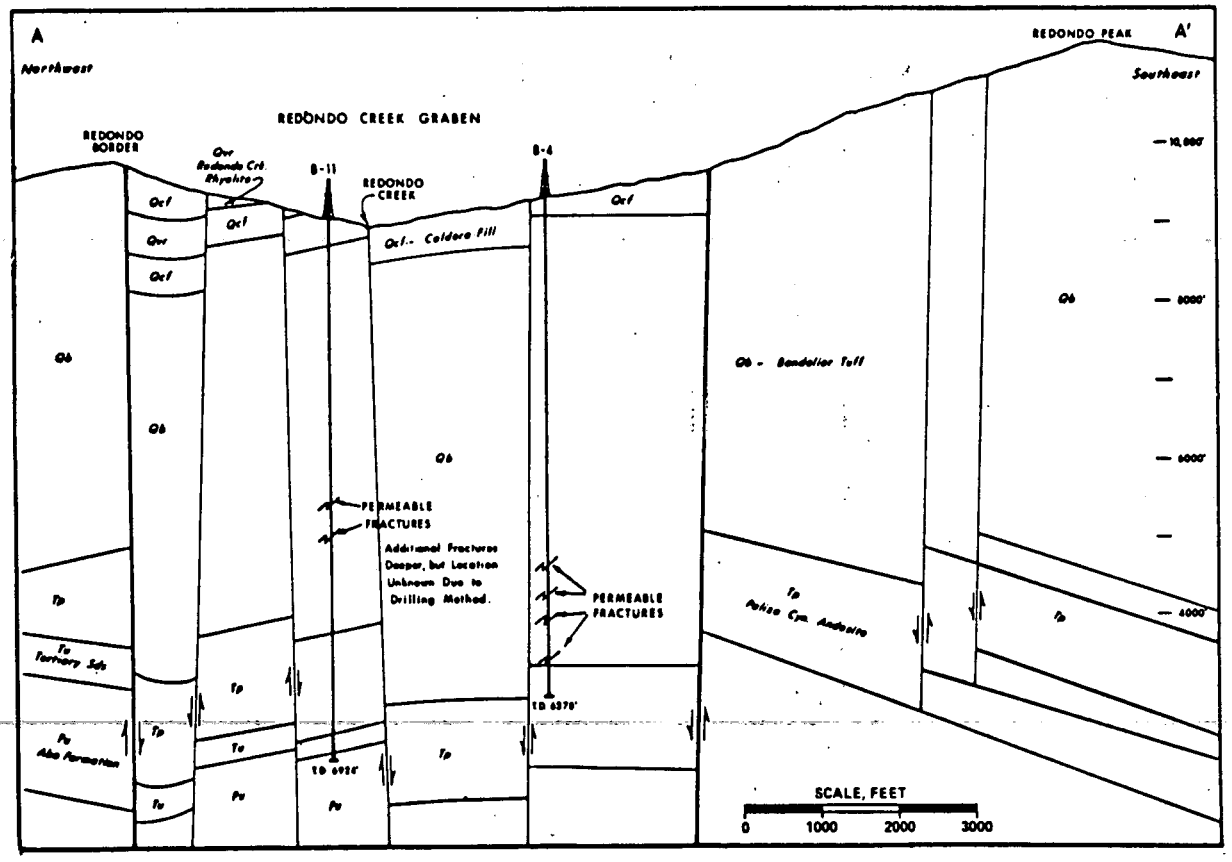

Fig. 7 Top ↑

Shallow aquifers in Valles Caldera are of two types: (1) alluvial fan and terrace deposits and (2) valley (caldera) fill sediments. Igneous rocks generally do not contain any significant aquifers in the area, but they serve as temporary storage reservoirs and are important areas of ground-water recharge (Conover et al. 1963; Griggs and Hem 1964). Pumiceous sand and gravel caldera fill deposits within the intermountain basins comprise the primary aquifer of Valles Caldera. The permeable sand and gravel units may be as much as 270 m (880 ft) thick; these are overlain by, and interfinger with, clay beds. Within Valle Grande, the largest valley of the caldera [5 km (3 mi) wide], the aquifer is confined by a clay zone with the potentiometric surface more than 7.5 m (25 ft) above the land surface. An aquifer test in Valle Grande determined a coefficient of transmissivity (T) of at least 0.21 m^2/min (2.31 ft^2/min); the coefficient of storage was not determined (Conover et al. 1963).

The shallow ground-water reservoirs are recharged primarily by precipitation on the slopes of the interior domes, the inner caldera rim escarpment, and the alluvial fans. Minor recharge occurs on valley floors.

Ground-water outflow in Valle Grande alone is estimated to be 86 liters/sec (2200 acre-ft per year) (Conover et al. 1963). Minor movement of ground water is toward Jaramillo Creek, which may gain as much as 32 liters/sec (500 gal/min) of flow. The East Fork of the Jemez River and Jaramillo Creek, therefore, are major ground-water discharge areas, as are a number of springs within the caldera (Griggs and Hem 1964). An extremely important discharge area of the Valles Caldera aquifer is the main aquifer of the Los Alamos area. This aquifer, which comprises the Puye and Tesuque Formations of the Santa Fe Group, discharges into the Rio Grande. Calculated outflow (and recharge) is 168 to 215 liters/sec (4300 to 5500 acre-ft per year) within an 18.4-km (11.5-mile) gaining reach (Purtymun and Johansen 1974).

Geothermal reservoir properties were determined from preliminary data calculated from pressure-buildup analyses and a six-month reservoir interference test. The "best estimate" of transmissivity used in a reservoir depletion model is 0.001 m^2/min (0.02 ft^2/min); this was based on a static head of 2316.5 m (7600 ft), a porosity of 10%, and a fluid withdrawal rate of 6246.68 m^3/day (2.206×10^5 ft^3/day) (Water Resources Associates 1977).

Ultimate recharge areas for the Valles Caldera geothermal system are probably the same as those for the shallow ground-water system. Isotope data show a meteoric origin of undetermined age (U.S. DOE 1979a). Ground water contained within the Valles Caldera aquifers slowly recharges the geothermal system at depth by leakage through confining layers and by percolation downward through the altered caprock via joints, fractures, and fault zones.

Known natural geothermal fluid discharge occurs at Soda Dam and Jemez Springs, and perhaps several additional areas along the Jemez River, a tributary of the Rio Grande River in San Diego Canyon

(Trainer 1974). The contribution of geothermal fluid at these springs has been calculated to be 10.35 liters/sec (164 gal/min), or one percent of the average mean annual flow of the Jemez River below Soda Dam (Water Resources Associates 1977). San Diego Canyon is a surface expression of the Jemez fault zone, an extension of which is the Redondo Creek graben. This fault zone apparently controls leakage from the geothermal reservoir by providing routes by which deep fluid movement can complement surface-water flow along this reach of the Jemez River.

A stream-flow depletion analysis was conducted for the commercial partners of the project. Results obtained indicated a minimum loss of 0.15 liters/sec (2.4 gal/min) for the Jemez River, with a 50-MWe plant fluid consumption of 100 liters/sec (1600 gal/min) (Water Resources Associates 1977). Because the study was based on arsenic dilution ratios, stream-flow depletion could be underestimated by a factor of 2 to 4. It is to be expected that thermal wells will also be affected by geothermal reservoir drawdown; however, the extent is not known at this time.

Project plans indicate a near-term power plant expansion to 150 MWe, and perhaps to 400 MWe. Depending upon the geometry of the geothermal reservoir and its hydraulic interconnections with shallow ground-water systems, the impacts of accelerated reservoir drawdown can only be conjectured. It is possible that the entire geothermal flow component along the Jemez River in San Diego Canyon can be withdrawn by the increased geothermal production. Areas of traditional cultural and religious significance for several Pueblo lands, as well as public bathing uses in Jemez Springs Village, could be irreparably impacted.

Several Indian Pueblos are located along the Jemez River; these are the Jemez, Zia, and Santa Ana. The Jemez River downstream from Valles Caldera is used by the Native Americans for various medicinal, ceremonial, bathing, and irrigation purposes. Thermal and mineral springs and wells on Pueblo land are used for various purposes, which have not been disclosed. It is of supreme importance to the native Americans that their thermal and mineral water sources not be diverted and that the fully appropriated Jemez River discharge not be decreased by geothermal reservoir drawdown. The Pueblos believe that all ground and surface waters are an inseparable part of Mother Earth and are therefore sacred. If these things are tampered with, their very existence will be threatened in a religious sense as well as physically. These views were expressed very clearly during a Public Hearing held on the Geothermal Demonstration Program (U.S. DOE 1979b).

CONCLUSIONS

The above case studies indicate that ground-water hydrology impacts from geothermal (hydrothermal) resource development are important socio-religious issues to be assessed and dealt with. Nevertheless, they are often underestimated during the early stages of project development, and greater attention should be assigned to this issue in the future.

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BIOGRAPHICAL SKETCH

of

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Mary S. Moran is a research associate with the Environmental Sciences Division at Oak Ridge National Laboratory, Oak Ridge, Tennessee. She received a B.S. degree in Geology from Tennessee Technological University in 1973, and an M.S. degree in Geology from Vanderbilt University in 1977. Her past experience includes working as a hydrologist with the Water Resources Division of the U.S.G.S. from 1974 to 1977. She began employment at ORNL in 1977, where her initial concern was to assess the hydrogeologic environment of various geothermal resource areas and potential hydrogeologic impacts resulting from exploration and development activities. She is presently serving as coordinator of hydrogeologic investigations of shallow land burial of low-level radioactive wastes.

FIGURE CAPTIONS

1. Projected geothermal electrical production capacity.

2. Schematic of a typical hydrothermal convection system.

3. Location of Naval Weapons Center China Lake Complex (CLC).

4. West-to-east cross-section of shallow and deep ground-water movement in the Coso area. (Multiply kilometers by 0.62 to obtain miles.)

5. Regional geologic setting of the Valles Caldera (after Dondanville 1978). (Multiply miles by 1.609 to obtain kilometers.)

6. Surface features of the Valles Caldera area. (Multiply miles by 1.609 to obtain kilometers.)

7. Structure section of Redondo Creek. (Multiply feet by 0.3048 to obtain meters.)