THE SALTON SEA SCIENTIFIC DRILLING PROJECT, CALIFORNIA, U. S. A.: AN INVESTIGATION OF A HIGH-TEMPERATURE GEOTHERMAL SYSTEM IN SEDIMENTARY ROCKS

ELDERS, W. A., Institute of Geophysics and Planetary Physics, University of California, Riverside, CA 92521 U. S. A.
SASS, J. H., U. S. Geological Survey, Office of Earthquakes, Volcanoes & Engineering, Tectonophysics Branch, 2255 N. Gemini Drive, Flagstaff, AZ 86001

INTRODUCTION

In March 1986, a research borehole, called the "State 2-14", reached a depth of 3.22 km in the Salton Sea Geothermal System (SSGS), on the delta of the Colorado River, in Southern California (Figure 1). This was part of the Salton Sea Scientific Drilling Project (SSSDP), the first major (i.e., multi-million U. S. dollar) research drilling project in the Continental Scientific Drilling Program of the U. S. A. The principal goals of the SSSDP were to investigate the physical and chemical processes going on in a high-temperature, high-salinity, hydrothermal system. The borehole encountered temperatures of up to 355°C and produced metal-rich, alkali chloride brines containing 25 weight per cent of total dissolved solids. The rocks penetrated exhibit a progressive transition from unconsolidated lacustrine and deltaic sediments to hornfelses, with lower amphibolite facies mineralogy, accompanied by pervasive copper, lead, zinc, and iron ore mineral. The SSSDP included an intensive program of rock and fluid sampling, flow testing, and downhole logging and scientific measurement (Elders and Sass, 1988). The purpose of this paper is to describe briefly the background of the project and the drilling and testing of the borehole, and to summarize some of the important scientific results.

BACKGROUND TO THE SSSDP

The concept of drilling the continental crust of the U. S. A. for scientific purposes has been actively discussed for many years. Among the prime targets selected for drilling into magma-hydrothermal regimes was the SSGS, for numerous reasons (U. S. Geodynamics Committee, 1979). Many students of water-rock interactions are familiar with the SSGS through the pioneering publications of White, and others (1963), and Helgeson (1968). This hydrothermal system is one of a number of geothermal fields within the Salton Trough at the head of the Gulf of California. The high heat flow and volcanic activity associated with this structural setting give rise to numerous high-intensity geothermal fields within the Trough (Lachenbruch and others, 1985).

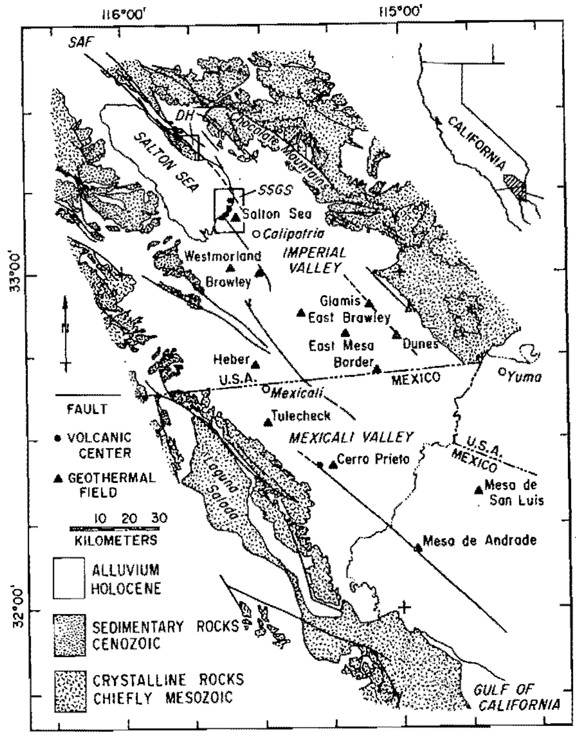

Figure 1. Geology of the Salton Trough and location of its geothermal fields. The Salton Sea Geothermal System (SSGS) is the largest and most saline high-temperature system in the Trough. The rectangle marked "SSGS" shows the location of Figure 2.

The Salton Sea field is the largest, hottest and most saline geothermal field in the Trough. In spite of its size, the pace of commercial development has been slow due to the difficulty of handling hypersaline brines. As well as being a locus of high heat flow, high temperatures and high salinity, the field is also associated with positive gravity, magnetic and seismic velocity anomalies, low electrical resistivity, and high microseismicity. Typically temperatures in the central part of field exceed 320°C at 2 km depth with the highest reported temperature being 365°C at 2,200 m in the Elmore No. 1 borehole. Similarly heat flow in the field exceeds 400 mWm^{-2}. New wells drilled to the northeast of the main part of the field, on the other hand, reached 3,000 m before encountering 300°C (Figures 1 and 2).

Unfortunately much of the information obtained by drilling of commercial wells is kept proprietary for competitive reasons. This situation lead us to renew the proposal for scientific drilling in this field and in 1983 to make a direct approach to the U. S. Congress for funds. In 1984 the necessary funds for drilling a borehole 3.2 km deep (10,000 ft) were given to the U. S. Department of Energy. Eventually the budget for engineering and management of the SSSDP grew to be U. S. $6.7 million. A further U. S. $2.65 million was funded by government agencies for scientific studies. In all, some 40 different science and technology development projects were involved (Sass and Elders, 1986). Our aims in the SSSDP were to probe the roots of a very hot geothermal system, a unique hypersaline, high-temperature environment never before thoroughly investigated scientifically. The current drilling for new commercial developments also presents the opportunity to extend the results of the SSSDP over the whole geothermal field.

THE WELL STATE 2-14

The well was drilled to a depth of 3.22 km (10,564 ft) between 24 October 1985 and 17 March 1986. The well was designated the State 2-14 because it lies on lands owned by the State of California. The specific location of the borehole (Figure 1) is in a zone where horizontal temperature gradients are highest. Thus the site is potentially able to yield information on horizontal fluid circulation. It is about 50% deeper than typical production wells in the center of the field. High priority was given to obtaining: 1) core and cuttings, 2) formation fluids, 3) geophysical logs, and 4) downhole physical measurements, especially temperatures and pressures (Sass and Elders, 1986). The well was drilled using standard oil field technology so cost considerations precluded continuous coring, but extensive collections of drill cuttings were obtained except in zones of total loss of circulation. A total of 36 core runs were attempted which recovered an aggregate length of 224 m of wide diameter core. These samples demonstrate a sequence of unconsolidated lake mud and deltaic sediments being progressively transformed into hornfels. A highly altered silicic volcanic tuff and two partly altered diabase (dolerite) sills were also penetrated.

No significant permeability was encountered between the first casing point at 1,071 m (3,515 ft) and the second at 1,829 m (6,000 ft). However a major loss zone associated with abundant vein-filling epidote was encountered between 1,865 and 1,870 m. A flow test of this zone was successful in obtaining very satisfactory fluid samples. A resource temperature 305°C was measured downhole and the pre-flash total dissolved solids content was 24.8 wt%, with an enthalpy of 930 kJ/kg. Drilling then continued.

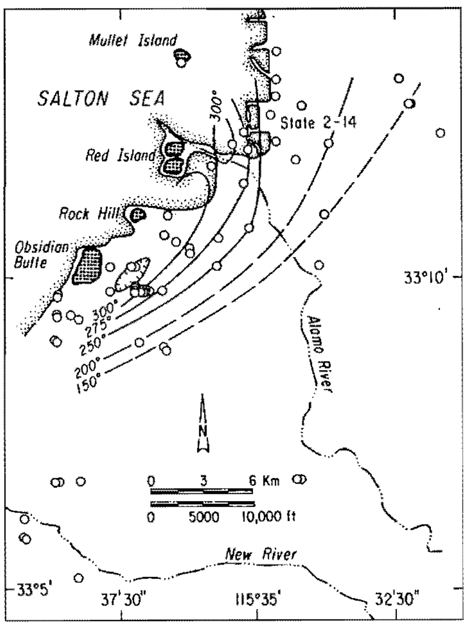

Figure 2. Location of the research borehole "State 2-14" (star), and other nearby geothermal wells (open circles). Cross-hatched areas are Holocene or Quaternary rhyolite domes. The contours are isotherms, in degrees centigrade, measured in the geothermal wells at 914 m (3,000 ft) depth.

From 2,022 to 2,805 m a succession of five zones of total loss of circulation were encountered. Hundreds of thousands of litres of drilling fluid were lost. We therefore cemented off these zones before continuing. When circulation was again lost near total depth (3,193 m), the loss zone was cemented and a 17.8 cm (7 inch) liner was set (but not cemented) to a depth of 3,089 m. The well was then deepened to a total depth of 3,220 m without regaining circulation.

A second flow test was then carried out, its duration being limited by the capacity of the available storage pond (5.7 x 10^6 litres). Flow rates as high as 265 tonnes/hr with enthalpies of 1,260 kJ/kg were observed. However, the brines produced during this test however were contaminated due to flow from behind the liner, from the 2,620 m level. A temperature of 355°C was measured at the bottom of the liner shortly after the flow ended. Attempts to obtain samples using a downhole sampler after both of the flow tests proved difficult. Out of a total of 12 attempts, using three different samplers, only one was completely successful and four partially successful.

More than 450 hours of rig-time were devoted to downhole logging and measurement. Commercial wireline logs were attempted at each casing point. However, at temperatures greater than 300°C, problems were severe. The only log which was successful below 1,829 m was provided by the deep induction tool. A United States Geological Survey logging truck with special tools and a TFE-insulated, MP35N-armored, seven-conductor cable, rated to 315°C, was stationed continuously at the site, so that logs could be run during interuptions of drilling. These included temperature, 3-arm caliper, natural gamma, gamma spectral, epithermal neutron, acoustic velocity, fullwave form, and acoustic televiewer (Paillet and Morin, 1988). Above 300°C, the best results were obtained from passive gamma and neutron tools, but the sonic and borehole televiewer logs were of poor quality and the caliper tool failed. A new continuously recording, digital pressure-temperature tool, built around a dewared, downhole, electronic memory, was also deployed, which has considerable advantages over the mechanical systems previously used above 300°C (Carson, 1986).

After the second flow test the borehole was shut in and a series of temperature profiles were measured to monitor the return to thermal equilibrium. By the end of May 1986 it was found that the 7 inch liner had corroded and parted at 1,883 m preventing logging below that depth. In August 1986 when the nine joints (82 m, i.e. 270 ft) of liner which remained suspended were removed, the collars on these joints were found to be moderately to severely cracked due to stress corrosion. Remedial work was delayed until August 1987 when it was found that the fallen liner could not be retrieved. The borehole was therefore plugged at 1,860 m and redrilling commenced, using downhole turbine motors to sidetrack past the old liner. Numerous technical difficulties caused this drilling to be abandoned at only 2,188 m. In June of 1988 the redrilled borehole was flowed for 19 days through a full flow separator to an injection well. The purpose of this reservoir engineering test was to obtain step-rate flow data for resource and well assessment. The well was flowed at rates of up to 350 tonnes/hr of steam and brine.

THE SCIENCE PROGRAM

A total of 40 different science projects were part of the SSSDP. Of these, nearly half were concerned with geochemical studies of rock, fluid, and gas, including organic chemistry of the fluids. These projects include major, minor and trace element chemistry, fluid inclusions, light stable isotopes, and radioactive isotopes, among others. Some ten projects involve various aspects of mineralogy and petrology and physical properties of core and cuttings. The remainder concern downhole sampling, geophysical logging, and other geophysical measurements, and technology development. The SSSDP will be the subject of a special issue of the Journal of Geophysical Research in 1988.

The lithostratigraphy of the rocks penetrated by the State 2-14 borehole consist of Pleistocene to Pliocene lacustrine mudstones and siltstones, and minor amounts of sandstones, deposited as lake margin, channel-fill, and freshwater lacustrine-delta environments (Herzig and others, 1988). A silicic tuff from 1,704 m depth appears to be correlative with a widely-dispersed tephra in Southern California, the Bishop Tuff, erupted 720,000 years ago (Herzig and Elders, 1988).

The occurrence of diabase sills in the State 2-14 is at first sight inconsistent with the occurrence of rhyolitic Quaternary volcanoes in the field (Figure 2). However such mafic rocks present a much more likely source of the high gravity and magnetic anomalies than does rhyolite. A conceptual model emerges of cold evaporitic brines sinking through a sedimentary pile being intruded from below by a sheeted dike or sill complex of basaltic composition. Thus hydrothermal circulation in this system may be as much controlled by salinity gradients as by temperature gradients (Williams, 1988; McKibben and others, 1988a).

With increasing depth the sediments become progressively metamorphosed and develop hornfelsic textures. The metamorphic zones observed include a chlorite-calcite zone (610-2,480 m); a biotite zone (2,480-3,000 m); and a clinopyroxene zone (3,000-3,180 m). Authigenic epidote, quartz and albite are abiquitous below 900 m. The coexistence of actinolite, hornblende, and oligoclase in the clinopyroxene zone demonstrates the transition from greenschist to amphibolite facies (Cho and others, 1988; Shearer and others, 1988).

Studies of the drill cores provide direct physical evidence for the origin of the salt in the SSGS brines. Recrystallized, metamorphosed bedded anhydrite and anhydrite-cemented shale breccias, which appear to have formed by solution-collapse are apparently the residues from the dissolution of non-marine evaporites. Fluid inclusions within some of these anhydrites contain halite, sylvite, and carbonates in a Na-Ca-K-Cl brine, and have homogenization temperatures of 300°C (McKibben and others, 1988b). Apparently halite-saturated brines were trapped during dissolution of evaporites by hydrothermal fluids. Comparison of the data on brine chemistry of the State 2-14 with that from other wells in the SSGS suggest a sharp interface exists between a cooler, shallow, metal-poor fluid of <12%TDS and a deeper, hotter, fluid containing 25% TDS (Williams, 1988). An intense zone of mineralization and ore genesis occurs in the zone of mixing these two fluids. An earlier mineralized vein system contains epidote, adularia, ankerite, and calcite with sphalerite, pyrite, chalcopyrite, galena and pyrrhotite. A later, more open, vein set contains epidote, quartz, chlorite, chalcopyrite, pyrite, hematite, with sphalerite and galena. These mineral veins record a complex history of fracturing and infiltration by the two different brine types which differed in salinity, temperature and oxidation state (McKibben and others, 1988a).

CONCLUSIONS

In spite of technical difficulties the SSSDP met or exceeded almost all of its initial objectives. We showed that although the rocks in the SSGS become indurated with depth, the permeability increases due to fracturing. Another lesson learned is the difficulty of dealing with zones of massive loss of circulation if it is necessary to drill deeper. We also learned that it is important to obtain as much core as possible. The results of logging above 300°C were disappointing. However better coring systems are needed to make coring of very hot wells economically feasible. Our experience with the SSSDP has convinced us of the importance of broadly based scientific study of hot deep wells to probe the roots of magma-hydrothermal systems.

ACKNOWLEDGEMENTS

The SSSDP was funded by the United States Department of Energy, United States Geological Survey and National Science Foundation. Numerous individuals worked hard to make the project successful. I am particularly grateful to John H. Sass of the U. S. G. S. who served as on-site science manager. The Chief Scientist position of the SSSDP was funded by NSF grants EAR 8303557 and EAR 8502402. This is IGPP/UCR Report No. 88/33.

REFERENCES

Carson, C.C, 1986, Development of downhole instruments for use in the Salton Sea Scientific Drilling Project: Trans. Geothermal Resources Council, 10, 449-454.

Cho, M., Liou, J.F., and Bird, D.K., 1988, Progrock phase relations in the State 2-14 Well metasandstones, Salton Sea geothermal field, California: Journal of Geophysical Research, 1988, in press.

Elders, W.A., and Sass, J.H., 1988, The Salton Sea Scientific Drilling Project: Journal of Geophysical Research, in press.

Helgeson, H.C., 1968, Geologic and thermodynamic characteristics of the Salton Sea geothermal system: Amer. Jour. Sci., 226, No. 3, 129-166.

Herzig, C.T., and Elders, W.A. 1988, Igneous Rocks in the State 2-14 Research Borehole: The Salton Sea Scientific Drilling Project, California, U.S.A.: Journal of Geophysical Research, in press.

Herzig, C.T., Mehegan, J.M., and Stelting, C.E., 1988, Lithostratigraphy of an active pull-apart basin: Salton Sea Scientific Drilling Project: Journal of Geophysical Research, in press.

Lachenbruch, A.H., Sass, J.H., and Galanis, Jr., S.P., 1985, Heat flow in southern most California and the origin of the Salton Trough: Journal of Geophysical Research, 90, NO. B7, 6709-6736.

McKibben, M.A., Andes, Jr., J.P, and Williams, A.E., 1988a, Active ore formation at a brine interface in metamorphosed deltaic lacustrine sediments: The Salton Sea Geothermal System, California: Economic Geology, 83, 511-523.

McKibben, M.A., Williams, A.E., and Okubo, S., 1988b, Metamorphosed Plio-Pleistocene evaporites and the origins of hypersaline brines in the Salton Sea Geothermal System, California, U.S.A.: Geochim. Cosmochim. Acta, 52, 1047-1056.

Paillet, F.L., and Morin, R.H., 1988, Analysis of geophysical well logs obtained in the State 2-14 borehole, Salton Sea geothermal area, California: Journal of Geophysical Research, in press.

Sass, J.H., and Elders, W.A., 1986, Salton Sea Scientific Drilling Project: Scientific Program: Geothermal Resources Council, Transactions, 10.

Shearer, C.K., Papike, J.J., Simon, S.B., Davis, B.L., and Rich, F.J., 1988, Mineral Reactions in Altered Sediments from California State 2-14 Well: Variations in the Modal Mineralogy, Mineral Chemistry and Bulk Composition of the SSSDP core: Journal of Geophysical Research, in press.

U. S. Geodynamics Committee, 1979, Continental Scientific Drilling Program: National Academy of Sciences, 150 pp.

White, D.E., Anderson, E.T., and Grubbs, D.K., 1963, Geothermal brine well: mile deep hole may top ore-bearing magmatic water and rocks undergoing metamorphism: Science, 139, 919-922.

Williams, A.E., 1988, Delineation of a brine interface in the Salton Sea Geothermal System, Calfornia: Transactions, Geothermal Resources Council, 12, in press.