LBL-17084
Preprint c.2

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

RECEIVED
LAWRENCE
BERKELEY LABORATORY
MAR 14 1984
LIBRARY AND
DOCUMENTS SECTION

EARTH SCIENCES DIVISION

Submitted to the Geothermal Resources Council Bulletin

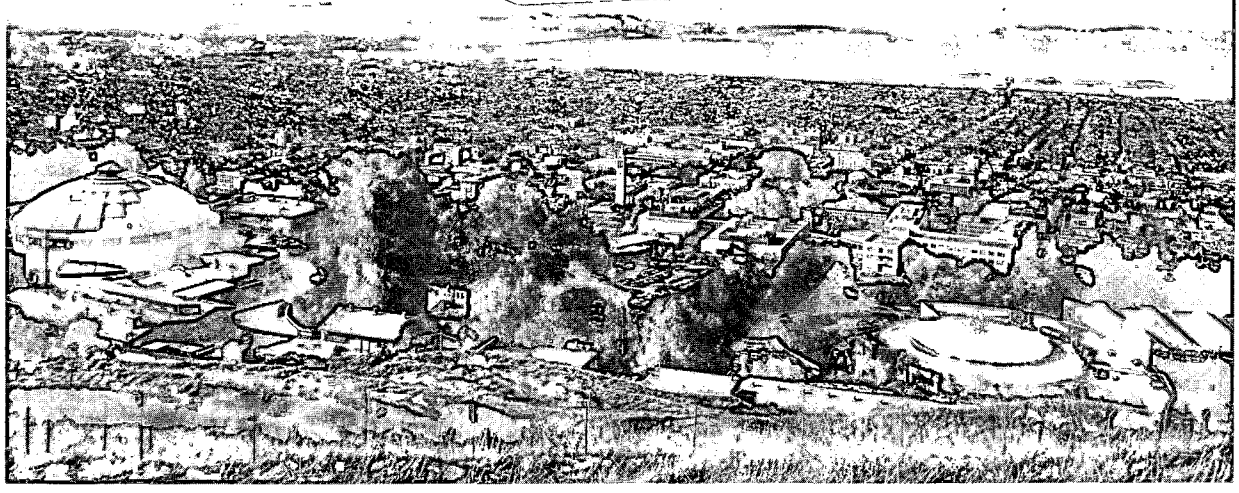
A REVIEW OF LESSONS LEARNED FROM THE DOE/UNION BACA GEOTHERMAL PROJECT AND THEIR APPLICATION TO CSDP DRILLING IN THE VALLES CALDERA, NEW MEXICO

N.E. Goldstein and C.F. Tsang

November 1983

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 6782.



LBL-17084 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-17084

A REVIEW OF LESSONS LEARNED FROM THE DOE/UNION BACA GEOTHERMAL PROJECT AND THEIR APPLICATION TO CSDP DRILLING IN THE VALLES CALDERA, NEW MEXICO

N.E. Goldstein
C.F. Tsang

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA. 94720

November 1983

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Division of Engineering, Mathematics and Geosciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

INTRODUCTION

Geothermal trade papers and the general press have called attention to the Baca Project--a joint project of the U.S. DOE, Union Geothermal Company of New Mexico, and Public Service of New Mexico--and particularly to the lack of sufficient steam that caused cancellation of the planned 50 MWe demonstration plant. The authors of this paper, together with other scientists from DOE offices and laboratories, universities and industry, were empaneled to advise DOE when it became apparent in 1981 that Union was encountering difficulty in developing the expected steam from its new production wells. The Baca Reservoir Definition Review Team closely followed activities until the principal parties mutually agreed in January 1982 to terminate the project. The review team was issued its final report later that year (Goldstein et al., 1982).

In contrast to the negative outcome of the project, the less newsworthy but beneficial scientific aspects of the project may have been largely ignored except by interested specialists in industry and research. Some of the lessons and information coming out of the project have been noted by members of the Thermal Regimes Panel of the National Academy of Sciences Continental Scientific Drilling Committee (CSDC) and particularly by scientists investigating the Valles Caldera as a site for deep drilling into an active hydrothermal-magmatic system (Reicker, 1983). It is significant and interesting that the Mexican national utility, Comisión Federal de Electricidad (CFE), is currently drilling a geothermal system in the La Primavera Caldera, which is geologically similar to the Valles Caldera. While no two systems are totally alike, preliminary indications from Mexico are that CFE may be experiencing some of the same problems encountered by Union Geothermal at the Baca Project site (Domínguez and Lippmann, 1983).

Space does not allow us to review the regional geology and exploration activities in the Jemez Mountains and the Valles Caldera. That material is contained in several excellent papers (Smith and Bailey, 1966, 1968; Doell et al., 1968; Bailey et al., 1969; Dondanville, 1978; Laughlin, 1981). In this paper we first review the more significant lessons for geothermal

developers. Next we discuss the implications of the Baca project to the intermediate to deep drilling proposed in the Valles Caldera for scientific purposes under the Continental Scientific Drilling Program (CSDP).

Lessons for Geothermal Developers

Drilling in the Redondo Creek area revealed that a surprisingly large thickness, as much as 1.8 km, of Bandelier Tuff (ignimbrite) fills the medial graben on the flank of the resurgent dome. Because of the low permeablility of the tuff, major graben-bounding and low-angle faults and their intersections within the tuff were considered to be the principal controls on fluid flow (Behrman and Knapp, 1980). Recognition of a three-dimensional fault pattern was believed to be the key to finding hot water entries and developing a viable reservoir. According to a later analysis, the pattern of normal faults mapped in detail at the surface (Behrman and Knapp, 1980) and fracture orientations obtained from dipmeter logs in Redondo Creek wells were considered to be unreliable guides to hot fluid entries at depth for two principal reasons (Hulen, 1982; Hulen and Nielson, 1982):

1. Some faults predicted by surface mapping and subsequently intersected by drill holes were found to be non-productive, presumably sealed by hydrothermal minerals.
2. Some of the fluid entries, initially believed to be steeply dipping faults, are actually discontinuous, permeable stratigraphic zones of tuffaceous sandstones and non-welded tuffs within the Bandelier Tuff.

Despite the 23 well completions, together with information from geological and geophysical logs and well tests, the conceptual model for the reservoir and its geological controls remains a point of debate. Union Geothermal (Union, 1983) believes that neither the steeply dipping faults of Behrman and Knapp (1980) nor the stratigraphic zones identified by Hulen (1982) and Hulen and Nielson (1982; 1983) are the features primarily responsible for high-temperature, hot-water production. Instead, they attribute production to a discontinuous, permeable contact zone at the base of the Bandelier Tuff and at the top of the Paliza Canyon Formation; this zone has been dislocated by faulting into separate cells that communicate hydraulically only weakly.

Regardless of which interpretation is correct, one conclusion seems inescapable: despite the number of holes drilled, logged and tested, geologists and reservoir engineers have not established a complete and verifiable geological explanation for the reservoir. Whether the bulk of the reservoir permeability is in a coarse fracture network (Garg and Riney, 1982) or in a confined stratigraphic contact zone (Union, 1983) has not been conclusively determined. If there are geological lessons to be learned from the development activities in the Bandelier Tuff, they might include the following:

1. The tuff was far thicker and much lower in permeability than one might have surmised from studies on outcrops outside the caldera.

2. Detailed studies of volcanic stratigraphy based on well cuttings were important for understanding the structure within the project area and for indentifying higher-permeability stratigraphic zones.

In addition, the work seems to reinforce the argument that better high-temperature well-logging instrumentation, well-log analyses and well-testing techniques are needed.

Secondary (i.e., deeper) reservoir targets below the Bandelier Tuff proved equally difficult to find and develop for various geological reasons. The only productive intervals that could be developed in rocks older than the Bandelier Tuff were in the underlying Paliza Canyon Andesite (Pliocene). In addition to the contact zone, fluid entries may include faults and fractures.

Stratigraphically below the Paliza Canyon Andesite are sandstones logged as the Abiquiu Formation (Oligocene) and the Santa Fe Sandstone (Miocene). Both units are regarded to be too unconsolidated to support production (Behrman and Knapp, 1980).

Disconformably below the Abiquiu/Santa Fe is the Abo Formation (Permian "red beds" of interbedded arkosic siltstones and sandstones). While this formation may be a good aquifer, it presented severe lost-circulation

problems and yielded no fluids. Formation damage due to drilling muds is one explanation for the lack of fluid extracted from the Abo.

Finally, the underlying Madera Limestone (Pennsylvanian) and Precambrian granite proved to be too tight where intersected by two deep wells at ~ 2.7 km below surface. Since the probability of finding permeable rocks tends to decline with increasing rock age and depth of burial, the findings from the deep wells cannot be considered unexpected.

How much more could have been learned or anticipated about low-permeability conditions prior to and during drilling from detailed surface geophysical investigations may never be known. While adequate geophysics (gravity, magnetics, electrical/electromagnetic) was performed in the exploration stages, little detailed geophysical follow-up was done in the Redondo Creek project area. There seem to be two reasons for this decision: (1) access within the topographically steep project area is limited, and (2) the early drilling results were so encouraging that additional expenditures for geophysics did not seem prudent or necessary. If exploration and development were starting today in Redondo Creek, it is likely that additional methods such as self-potential and controlled-source EM methods would be tried to help find areas of fluid convection and higher porosity (Wilt et al., 1982). The EM is particularly intriguing because magnetotelluric (MT) sounding interpretations (Wilt et al., 1982) revealed several interesting features that correlated with drilling results; namely, (1) the generally high resistivities (100-200 ohm-m) obtained for the Bandelier Tuff are characteristic of low-porosity, low-salinity conditions; (2) a low-resistivity zone (70 ohm-m) within the Bandelier Tuff correlated with the concentration of known hot-water entries; and (3) the presence of a steeply dipping electrical discontinuity may indicate a reservoir boundary. Even though we now possess better methods of data acquisition and interpretation, the Valles Caldera experience reinforces the fact that industry still lacks downhole geophysical techniques and instruments that can be used in high-temperature environments to help map major fracture zones.

Geochemistry of produced fluids provided useful information. The data not only indicated local boiling around the wells but verified the existence

of a broader two-phase zone of interest to reservoir engineers. Geothermometer temperatures based on the Na-K-Ca method (Fournier and Truesdell, 1973) applied to well fluids were substantiated by means of direct downhole measurements. More important, the chloride-enthalpy relationship showed that there was little fluid convection within the reservoir rocks and that these rocks are conductively heated from below (Delany and Truesdell, 1982).

Drilling problems were more numerous than at other geothermal areas for which comparable data are available (The Geysers-Clear Lake and Imperial Valley). These problems added to well costs (Kelsey, 1983) and detracted from the acquisition of potentially useful geologic information. The problems, tabulated by Pye (1981), Molloy and Laughlin (1982), and Union (1983), were due to lost circulation, lost fish and stuck pipe. Although these problems occur in all geothermal areas, the severity of the problems at Baca can be attributed to specific geological conditions, mainly lost circulation. Because they encountered many lost-circulation zones and underpressured reservoir conditions, Union initially used aerated water as a drilling fluid. This severely accelerated corrosion of drill pipe and casings, increasing the likelihood of stuck pipe and twist-offs. The corrosion rate was substantially reduced by adding caustic, Unisteam and ammonium hydroxide to keep the pH above 10.5 (Pye, 1981; Molloy and Laughlin, 1982). Union also found it necessary to cement off many lost-circulation zones. Not only is this process costly but various factors make it difficult to carry off successfully (Pye, 1981). However, cementing casing and liners was found to be a relatively simple procedure. Drilling problems also arose because Union sidetracked five of the 24 wells in the hope of finding better fluid entries and bypassing lost fish. It was in drilling the deviated legs that problems frequently occurred. Additional mechanical stresses on the drill pipe, together with thermal stresses and stress corrosion cracking, contributed to the twist-offs and lost fish. Directional drilling was done with mud motors and turbines. Both approaches had notable success and failure. Union concluded that the difference between success and failure is more a function of the organization doing the drilling than the equipment (Pye, 1981).

Large hydraulic fracturing treatments were carried out in two wells. In each well a previously non-productive interval with a shut-in temperature of about 500°F was fractured (Morris et al., 1982). Although the hydraulic fractures did not intersect any major zones of natural permeability, and hence did not result in high productivity, the work demonstrated that hydraulic fracturing can be done under high-temperature conditions.

At the time Union and DOE initiated the Baca project, the state of the art in geothermal reservoir assessment consisted of two approaches. On the one hand, because the early success of geothermal power production at The Geysers, Wairakei, Cerro Prieto and Larderello, the common practice was to apply conventional petroleum engineering methods for estimating geothermal reservoir productivity. Methods included single-phase well-testing analyses, even though a system might be two phase (steam and water). There was also the implied belief that all in-place hot fluids could be produced. On the other hand, modeling techniques that accurately accounted for two-phase reservoir conditions had been developed for porous media. These newer techniques were in an early stage of development and use, and were being extended to fractured, low-permeability rocks. The Baca project provided the first practical opportunity to put these numerical methods to a stringent test. Many lessons were brought to light as a result (Bodvarsson et al., 1982).

1. The importance of a careful, non-isothermal, two-phase well-testing program was emphasized. Because the fluid in a petroleum reservoir has a high energy density, the tolerable margin of uncertainty can be relatively large. This is not the case for a geothermal reservoir, where one must make a careful determination of the transmissivity and the storativity, as well as boundaries. Recent developments in two-phase flow in fractures also provided the basis for new well-test methodologies.

2. The conventional method of equating hot fluid in place with the resource potential was found not applicable, especially in a low-permeability, fracture-controlled reservoir system, such as Baca. Up to the time of the Baca project, the producing capacity was

usually estimated by what is known as the lumped parameter model, in which the reservoir is represented by a rock volume of uniform pressure, temperature and liquid water saturation. This assumption is safe so long as there is a very high permeability within the volume. The reservoir engineering study of the Baca project focused on the necessity to use a "distributed parameter model" in which the above-named parameters vary over the reservoir region. The sharp drop in the pressure of the two-phase fluid near the well field turned out to be a controlling factor in the producing capacity of the Baca geothermal field.

3. The usefulness of modeling geothermal reservoirs numerically was also demonstrated by the Baca project. A conventional view was that if detailed reservoir information is sparse, a detailed numerical modeling study is not justified. The Baca example showed that because of the strong non-linearity of two-phase phenomena, even a simple case with only a few reservoir parameters given (usually by well testing) requires the use of detailed numerical modeling investigations. Some very crucial information can be obtained only in this way.

4. The Baca project also provided impetus for an accelerated study of fracture flow phenomena. The importance of fracture and channel flow is clearly noted in the Baca reservoir. Considerable progress has been made recently in the well testing and modeling of fractured reservoirs, ranging from new understanding of heat and fluid flows in discrete fractures to the recent development of the MINC (Multiple Interacting Continua) representation of fractured-porous media (Pruess and Narasimhan, 1982).

Implications for CSDP Drilling

Although the Baca project wells were concentrated in a relatively small area (Redondo Creek) of the Valles Caldera, the information gained can be applied to the siting and drilling of additional intermediate to deep drill holes within the caldera.

The wealth of temperature data from shallow and deep Union wells have been re-examined and reprocessed recently by Swanberg and Li (1982). Their analysis indicates a component of heat from a cooling magma body, but the most they can say about the depth of such a body is that it could be "shallow." The consensus of other geophysical data indicates that there is a good possibility for magma at < 12 km depth (Reicker, 1983) and perhaps as shallow as 8 to 10 km. The Redondo Creek area appears to have the highest near-surface temperatures encountered within the caldera. Temperature gradients in the deeper sections of the Union wells indicate that at 10,000 feet (~ 3 km) the subsurface temperatures should be < 350-375°C; i.e., roughly at the limit of the depth-temperature conditions presently considered drillable at reasonable costs (Kelsey, 1983, personal communication). Assuming one were available, reopening and deepening an existing Union well in Redondo Creek to 10,000 feet might be a feasible CSDP endeavor, but it might not yield much new scientific information. A better course of action is to drill dedicated holes in a "cooler" part of the caldera. This would provide geologic and thermal information in another part of the hydrothermal system and reduce temperature-related drilling and logging problems. Because of its smaller diameter, a CSDP hole should be inherently faster and cheaper to drill than a geothermal production well. However, the CSDP hole might also be subject to potential problems associated with lost circulation zones as encountered by Union in Redondo Creek. Union's drilling and cementing experience could help reduce costs and risks. Perhaps, and more importantly, a hole sited away from the underpressured and badly faulted conditions within the medial graben might encounter fewer and less serious lost-circulation zones. However, drilling experience by the Comisión Federal de Electricidad in the La Primavera Caldera showed lost circulation to be a serious problem in the Tala Tuff both near the center of the caldera and within the ring fracture zone bounding the caldera (Domínguez and Lippmann, 1983). This suggests that careful geophysical surveys should be conducted prior to drilling to help assess subsurface conditions.

In addition to the standard geological, geophysical and geochemical measurements that would be made in a CSDP well, various thermal, chemical and hydraulic tests should be made both during and after drilling. It is

expected that at greater depths, the permeability will be low and probably fracture controlled. On the basis of lessons learned in studying the Redondo Creek wells and other geothermal sites, a number of tests can be designed to obtain key parameters, such as fluid enthalpy, fracture permeability and chemical characteristics. Discussions of some possible tests for CSDP wells are recently summarized in a report by Witherspoon et al. (1983).

Acknowledgements

Much of the work described in this report was supported by the Assistant Secretary for conservation and Renewable Energy, Office of Renewable Energy, Division of Geothermal Energy and Hydropower Technologies of the U.S. Department of Energy. The preparation of this report and the discussions herein was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Division of Engineering, Mathematics and Geosciences of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

Bailey, R.A., Smith, R.L., and Ross, C.S., 1969, Stratigraphic nomenclature of the volcanic rocks in the Jemez Mountains, New Mexico: U.S.G.S. Bull. 1274-P, 19 p.

Behrman, P.G., and Knapp, R.B., 1980, Structure of the Redondo Creek area, Baca Project, New Mexico--Implications concerning the nature of permeability and production and recommendations for future drilling: Union Oil Co., Geoth. Div., Internal Report.

Bodvarsson, G.S., Vonder Haar, S.P., Wilt, M.J., and Tsang, C.F., 1982, Preliminary estimation of the reservoir capacity and the longevity of the Baca geothermal field, New Mexico: Water Res. J., v. 1B, p. 1713-1723.

Delaney, J.M., and Truesdell, A.H., 1982, Geochemical indications of reservoir conditions, in Goldstein, N.E., Holman, W.R., and Molloy, M.W., eds., Final Report of the Department of Energy Reservoir Definition Review Team for the Baca Geothermal Demonstration Project: Lawrence Berkeley Laboratory, LBL-14132, p. 18-21.

Doell, R.R., Dalrymple, G.B., Smith, R.L., and Bailey, R.A., 1968, Paleomagnetism, potassium-argon ages and geology of rhyolites and associated rocks of Valles Caldera, New Mexico: Geol. Soc. Am., Memoir 116, p. 211-248.

Domínguez, B.L., and Lippmann, M.J., 1983, Some comments on the La Primavera geothermal field: Lawrence Berkeley Laboratory, LBL-16706 (also in the Proceedings of the Ninth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, December 1983).

Dondanville, R.F., 1978, Geologic characteristics of the Valles Caldera geothermal system, New Mexico: Geoth. Resour. Council, Trans., v. 2, p. 157-160.

Fournier, R.O., and Truesdell, A.H., 1973, An empirical Na-K-Ca geothermometer for natural waters: Geochim. Cosmochim. Acta, v. 37, p. 1255-1275.

Garg, S., and Riney, T.D., 1982, Reservoir definition and conceptual model, in Goldstein, N.E., Holman, W.R., and Molloy, M.W., eds., Final report of the Department of Energy Reservoir Definition Review Team for the Baca Geothermal Demonstration Project: Lawrence Berkeley Laboratory, LBL-14132, p. 31-35.

Goldstein, N.E., Holman, W.R., and Molloy, M.W., 1982, Final report of the Department of Energy Reservoir Definition Review Team for the Baca Geothermal Demonstration Project: Lawrence Berkeley Laboratory, LBL-14132.

Hulen, J.B., 1982, Structure, stratigraphy and permeability in the Redondo Creek project area, in Goldstein, N.E., Holman, W.R., and Molloy, M.W., eds., Final Report of the Department of Energy Reservoir Definition Review Team for the Baca Geothermal Demonstration Project: Lawrence Berkeley Laboratory, LBL-14132, p. 7-14.

Hulen, J.B., and Nielson, D.L., 1982, Stratigraphic permeability in the Baca geothermal system, Redondo Creek area, Valles Caldera, New Mexico: Geoth. Resour. Council, Trans., v. 6, p. 27-30.

_____, 1983, Stratigraphy of the Bandelier Tuff and characterization of high-level clay alteration in borehole B-20, Redondo Creek area, Valles Caldera, New Mexico: Geoth. Resour. Council, Trans., v. 7, p. 163-168.

Kelsey, J.R., 1983, Geothermal Technology Development Program Annual Progress Report, October 1981-September 1982: Sandia National Laboratory, Sandia Report SAND82-2690, 259 p.

Laughlin, A.W., 1981, The geothermal system of the Jemez Mountains, New Mexico and its exploration, in Rybach, L., and Muffler, L.J.P., eds., Geothermal Systems: Principles and Case Histories: John Wiley & Sons, Ltd., p. 295-320.

Molloy, M.W., and Laughlin, A.W., 1982, Drilling problems, in Goldstein, N.E., Holman, W.R., and Molloy, M.W., eds., Final Report of the Department of Energy Reservoir Definition Review Team for the Baca Geothermal Demonstration Project: Lawrence Berkeley Laboratory, LBL-14132, p. 22-25.

Morris, C.W., Hanold, R.J., and Pearson, C.F., 1982, Fracture stimulation experiments, in Goldstein, N.E., Holman, W.R., and Molloy, M.W., eds., Final Report of the Department of Energy Reservoir Definition Review Team for the Baca Geothermal Demonstration Project: Lawrence Berkeley Laboratory, LBL-14132, p. 26-30.

Pruess, K., and Narasimhan, T.N., 1982, On fluid reserves and the production of superheated steam from fractured, vapor-dominated geothermal reservoirs: J. Geophy. Res., v. 87, no. B11, p. 9329-9339.

Pye, S., 1981, Drilling, completing and maintaining geothermal wells in Baca, New Mexico: Proceedings, International Conference on Geothermal Drilling and Completion Techniques, Albuquerque, NM, Jan 21-23: Sandia National Laboratory, SAND81-0036C.

Reicker, R.E., 1983, Valles Caldera Workshop: EOS, Trans. Am. Geophys. Union, June 28, p. 434-435.

Smith, R.L., and Bailey, R.A., 1966, The Bandelier Tuff: A study of ashflow eruption cycles from zoned magma chambers: Bull. Volcanol., v. 29, p. 83-104.

_____, 1968, Resurgent cauldrons, in Coats, R.R., Hay, R.L., and Anderson, C.A., eds., Studies in volcanology: Geol. Soc. Am., Memoir 116, p. 613-662.

Swanberg, C.A., and Li, T.M.C., 1982, Wave number filtering of thermal data from the Valles Caldera, New Mexico: Trans. Geoth. Resour. Council, v. 6, p. 181-184.

Union, 1983, Baca Project Geothermal Demonstration Power Plant, Final Report: Union Oil Company of California, Union Geothermal Division.

Wilt, M., Goldstein, N.E., and Vonder Haar, S., 1982, Geophysics, in Goldstein, N.E., Holman, W.R., and Molloy, M.W., eds., Final Report of the Department of Energy Reservoir Definition Review Team for the Baca Geothermal Demonstration Project: Lawrence Berkeley Laboratory, LBL-14132, p. 15-17.

Witherspoon, P.A., ed., 1983, Proposed scientific activities for the Salton Sea Scientific Drilling Project--Report of the Experiments Panel: Lawrence Berkeley Laboratory, in press, 134 p.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720