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SALTON SEA SCIENTIFIC DRILLING PROJECT: SCIENTIFIC PROGRAM

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ABSTRACT

State 2-14, the Salton Sea Scientific Drilling Project, was spudded on October 24, 1985, and reached a total depth of 10,564 ft (3.2 km) on March 17, 1986. There followed a period of logging, a flow test, and downhole scientific measurements. The scientific goals were integrated smoothly with the engineering and economic objectives of the program and the ideal of "science driving the drill" in continental scientific drilling projects was achieved in large measure. The principal scientific goals of the project were to study the physical and chemical processes involved in an active, magmatically driven hydrothermal system. To facilitate these studies we attached high priority to four areas of sample and data collection, namely: (1) core and cuttings, (2) formation fluids, (3) geophysical logging, and (4) downhole physical measurements, particularly temperatures and pressures. In all four areas, the results obtained were sufficient to meet the stated scientific goals.

INTRODUCTION

The first deep well of the U.S. Continental Scientific Drilling program was drilled to a depth of 3.22 km in the Salton Sea Geothermal Field of the Imperial Valley near Calipatria, California (Figure 1). The well is located near the southeast end of the Salton Sea (Figure 1) in the Salton Trough, a tectonic depression within the transition zone between the spreading centers of the Gulf of California and the San Andreas transform fault (Elders et al., 1972). The trough is a fluvial sedimentary basin with associated evaporitic and lacustrine deposits. Within the trough and adjacent crystalline basement, heat flow is very high, averaging about 140 mW m^{-2} (Lachenbruch et al., 1985). Within the region of high heat flow are zones of extraordinarily high heat flow like the Salton Sea Geothermal Field, where heat flow averages about 400 mW m^{-2} (Sass et al., 1984) and temperatures as high as 370°C have been encountered at only 2 km depth. The Salton Sea Field is also characterized by brines with total dissolved solids in excess of 200,000 ppm (Muffler and White, 1969).

The well was drilled using standard oilfield technology, modified to take account of the high temperatures; however, the philosophy was quite different from that employed in conventional exploration drilling, chiefly in that scientific objectives had priority over economic and engineering concerns where safety and well integrity were not compromised. This was accomplished through a unique grouping of specialists termed the "Site Coordination Committee" consisting of the site manager, drilling supervisor, toolpusher, DOE technical representative, on-site science manager, and chief scientist, with input from coring engineers, mud chemists, and others as deemed appropriate.

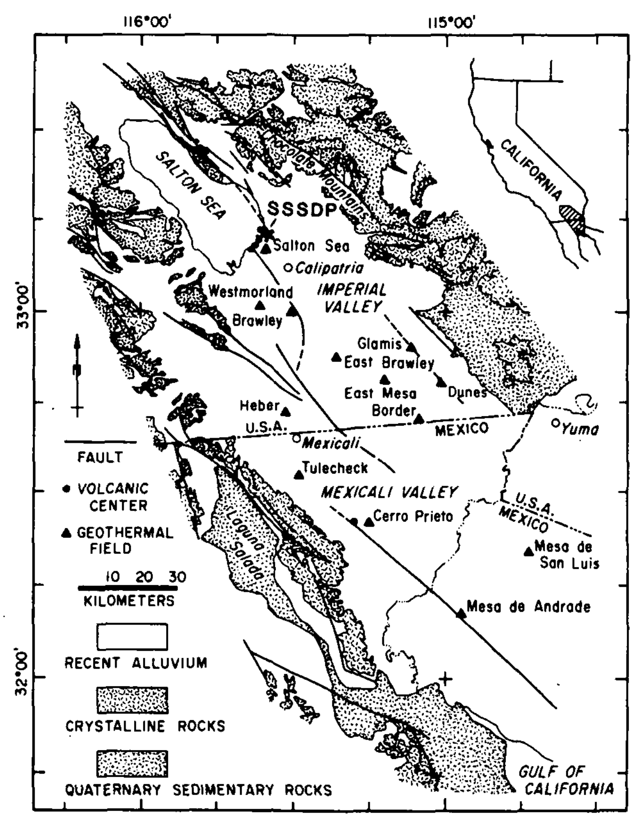

Figure 1. Major faults and geothermal fields of the Salton Trough.

The primary scientific goals of the Salton Sea Scientific Drilling Project (SSSDP) were to study active physical and chemical processes in a magmatically driven hydrothermal system. As the well is twice as deep as typical production wells in the field, the temperatures, pressures, salinities, and flow rates encountered also provided an opportunity for a preliminary study of the deeper reservoir characteristics and geothermal energy potential.

Forty proposals were approved by the Science Coordinating Committee of the SSSDP. Of these, nearly half were concerned with geochemical studies of rock, fluid, and gas including the organic chemistry of fluids. Twenty-five percent of the proposals involved petrologic and geophysical studies of core and cuttings. The remaining proposals were concerned with downhole sampling, geophysical logging, other geophysical measurements, and technology development involving the downhole deployment of geophysical instruments like seismometers, temperature-pressure sensors, flowmeters, and gravimeters.

Given this program, the recovery of core, cuttings, fluid, and gas samples had the highest priority. To maximize the interpretation of data obtained from these samples, and to allow interpretation in zones where samples could not be obtained, high priority was also assigned to the collection of an integrated set of downhole data including geophysical logs, temperature measurements, and downhole fluid samples. A time-depth plot (Figure 2) summarizes the amount of time devoted to the various scientific and engineering activities. A preliminary progress report of these activities by the USGS on-site science management team (which coordinated and supervised all science activities during the drilling phase) has been published (Sass et al., 1986).

CORE AND CUTTINGS

At least 1 kg of cuttings was retained at 6- to 9-m intervals to about 900 m and at 3-m intervals below that depth. Each sample consisted of one 500 mL cup of washed sample and three cups of unwashed samples containing drilling mud and additives as well as rock cuttings. Cuttings were not recovered in zones of complete loss of drilling fluid between 2022 and 2097 m, 2616 and 2682 m, 2719 and 2750 m, and between 3193 and 3220 m (total depth). In some zones of partial fluid loss, cuttings samples were contaminated by

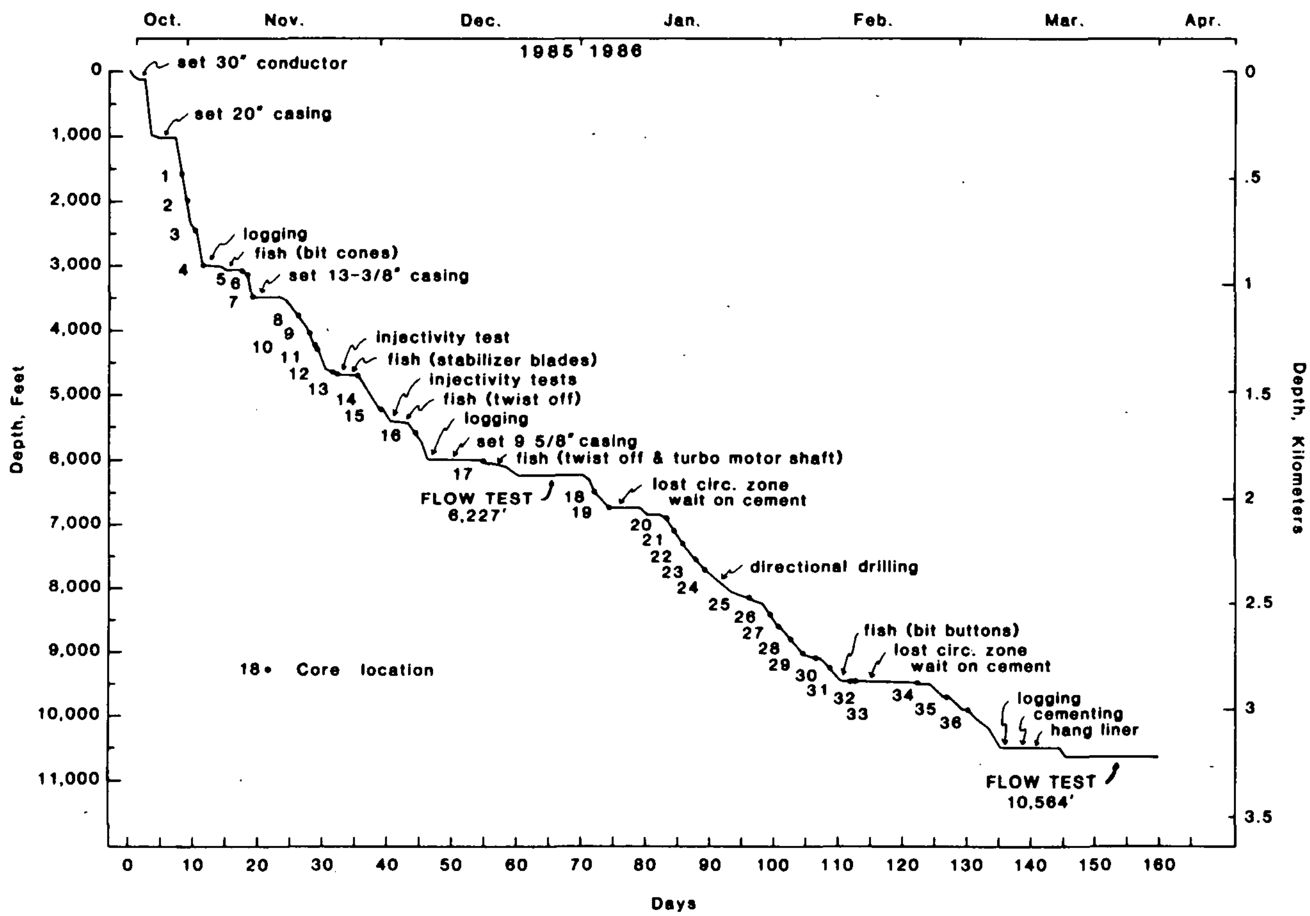

Figure 2. SSSDP depth/progress chart. Core numbers correspond to those in Table 1.

lost circulation material and rock material flowing back into the well from partially plugged lost circulation zones above the bit.

The coring plan developed before drilling envisaged 43 coring attempts between 1700 and 10,000 ft (518 and 3048 m) with an average interval of 200 ft between cores in the depth range 3,000 to 10,000 ft. We hoped to recover 1,200 to 1,500 ft (366 to 460 m), depending on the number of 30-ft core runs as opposed to 60-ft runs. A total of 36 cores were attempted, of which 2 (marked "N/A" in the footage/recovery columns of Table 1) were obtained in junk baskets or junk subs during fishing operations. Percentage recovery was reasonable over the entire depth, but the footage drilled declined precipitously below 5,000 ft (1,500 m) primarily because the rock was fractured either in situ or by the release of stress by the core bit with the result that the barrel jammed frequently, often after only a few feet had been cored. In addition, some cores were drilled "blind" (no circulation) which made coring even more difficult.

Table 1. History of coring attempts and recovery, SSSDP

Date	Core	Ft. drilled	Marked core interval	% recovery
10/31/85	1	25	1553-1577.6	98.4
11/01/85	2	30	1983-2012.2	97.3
11/02/85	3	30	2448-2478.0	100.0
11/04/85	4	60	2970-3028.4	97.3
11/08-09/85	5	N/A	3083-3087.0	N/A
11/11/85	6	60	3107-3161.7	91.2
11/12/85	7	35	3470-3504.0	97.1
11/19/85	8	60	3790-3846.6	94.3
11/20/85	9	60	4007-4069.9	100.0
11/21/85	10	40	4241-4300.4	99.0
11/22/85	11	36	4301-4338.6	100.0
11/25/85	12	38	4643-4680.5	98.6
11/26/85	13	5	4681-4683.0	40.0
11/27-28/85	14	N/A	4718-4718.5	N/A
12/02/85	15	30	5188-5219.2	100.0
12/07/85	16	17.5	5574-5591.5	100.0
12/19/85	17	18	6026-6040.8	82.2
01/03/86	18	11	6506-6517.0	100.0
01/06/86	19	13	6758-6766.0	61.5
01/14/86	20	9	6880-6889.0	100.0
01/16/86	21	9	7100-7107.0	77.7
01/18/86	22	13	7300-7311.5	88.5
01/19/86	23	30	7547-7574.5	91.6
01/20/86	24	30	7708-7738.0	100.0
01/28/86	25	29	8133-8161.0	96.5
01/31/86	26	6	8395-8400.0	83.3
02/01/86	27	19	8585-8597.0	63.2
02/03/86	28	7	8800-8804.5	64.3
02/05/86	29	23	9004-9009.5	23.9
02/07/86	30	3	9095-9098.0	100.0
02/10/86	31	6	9248-9251.5	58.3
02/13/86	32	5	9453-9455.3	46.0
02/14/86	33	15	9458-9463.0	33.3
02/23/86	34	4	9473-9475.0	50.0
02/28/86	35	4	9694-9697.5	87.5
03/02/86	36	5	9907-9908.0	20.0

Even though there were problems, we are satisified with the total recovery of about 730 ft (224 m) in terms of its utility in characterizing the stratigraphy of the well and in satisfying the requirements of the principal investigators interested in physical properties, petrology, and geochemistry of solid rock samples. In view of the difficulties experienced here using the best in off-the-shelf technolgy and experienced coring personnel, it would seem that coring in ultra-deep and/or ultra-hot wells will require considerable research and redesign of conventional coring hardware.

FLOW TESTS

The fluid sampling plan envisaged two or even three discrete flow tests at shallow (1 km), intermediate (2 km), and total depth to allow estimates of salinity and other concentration gradients within the brines. Only one minor (15 bbl/hr) loss zone was encountered above 1 km. Injectivity tests were performed at depths of 4,684 and 5,418 ft (1,428 and 1,651 m), but no significant potential for flow was detected. At that stage, it was decided not to attempt a shallow flow test and 9 5/8" casing was set at 6,000 ft (1,829 m) (Figure 3). A loss zone associated with abundant epidote was encountered slighly below the casing (6,119 to 6,135 ft), and the first flow test was run in late December of 1985 (Figure 2). Only a few hundred barrels of fluid had been lost to the formation, and the fluids cleaned up very rapidly, resulting in very satisfactory samples and confident estimates of total dissolved solids, temperature, enthalpy, and other important parameters. The observed flow rate and enthalpy demonstrated the commercial potential of this well.

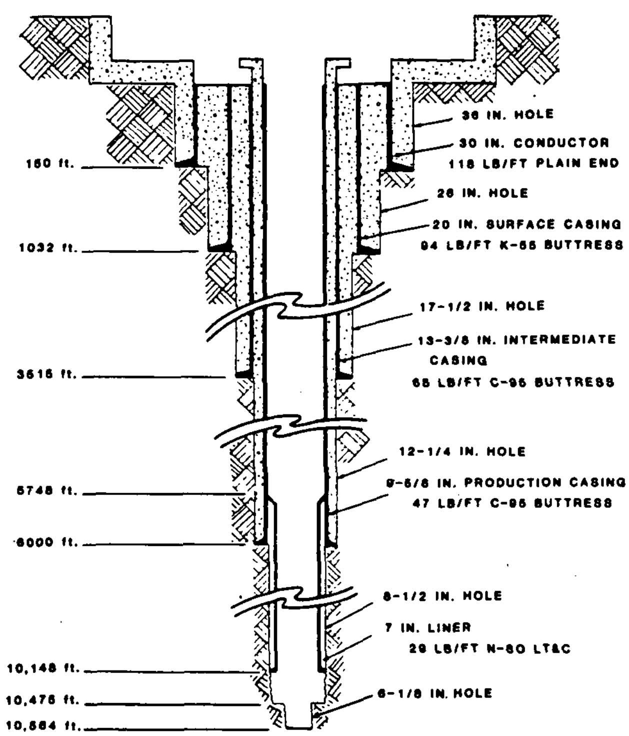

Figure 3. Casing configuration, SSSDP.

From 6,637 to 9,500 ft (2 to 2.9 km), a succession of loss zones (reflecting fracture permeability) was encountered. Enormous quantities of fluid (several tens of thousands of barrels) were lost and a large amount of lost circulation material and cement were used to regain circulation and control losses. When circulation was again lost near total depth (10,475 ft), temperature logs indicated that fluid loss was occurring at the bottom of the well. The zone was then plugged off with cement, a liner was set (but not cemented) at 10,135 ft (3,089 m), the cement plug was drilled out, and an additional 89 ft of hole was drilled with no returns. Following this, the well was flowed, but the brine produced was contaminated, not only by the fluid lost in the bottom zone but probably by inflow around the liner from a depth of about 8,600 ft (2,621 m); the results were considerably less satisfactory than those obtained during the first flow test. The duration of the flow test was limited by the 36,000-bbl (5.7×10^6 L) capacity of the brine pond.

GEOPHYSICAL LOGGING

No open-hole geophysical logs were attempted in the 26-inch (0.66 m)-diameter hole, which was 1,032 ft deep (Figure 3) and into which the 20-inch (0.51 m)-diameter surface casing was set. Because of the large hole diameter, we thought that record quality would be poor, and that if open-hole data in the upper 300 m were needed, a slim hole could be drilled to this depth easily and inexpensively. Complementary and, in some cases, redundant sets of logs were run at the 3,000 to 3,500 ft casing point and 6,000 ft casing point (Figure 3) by both Schlumberger and USGS Water Resources Division's Research Logging Unit (Tables 2 and 3). The Schlumberger logs allowed a comparison and correlation with commercial logs from other wells in the Salton Sea Field. The USGS logs provided both a comparison and confirmation of such things as depth registration (gamma-ray logs) and an extension of the commercial logs. Lawrence Livermore National Laboratory (LLNL) provided at the site a system capable of reading and displaying digital data from both USGS and commercial logs. This proved useful for real-time analysis and interpretation. A second commercial company ((Dialog) carried out a casing caliper log on March 30, 1986, to assess the condition of the 9 5/8-inch casing (Figure 3). Several attempts were made by the USGS (Table 3) to obtain televiewer logs, particularly in loss zones and flow zones. At the 6,000-ft casing point (Figure 3) the televiewers were bedeviled by mechanical and electrical problems. Below 6,000 ft, televiewer records were obtained, but because of deleterious effects of viscous mud, lost circulation material, and cement, a large percentage of the energy was absorbed, resulting in poor record quality. The same comment applies to the acoustic logs made by both Schlumberger and USGS, although useful data were obtained in both cases.

Table 2. Dates, intervals, and types of Schlumberger logs, SSSDP

Date	Logged Interval (ft.)	Logs*
11/04/85	1,032 to 3,008	1-6
11/13/85	2,900 to 3,525	1-6
11/17/85	30-3,523	7
12/09/85	3,520 to 5,988	1-6
12/18/85	50-5,670	8
12/18/85	190-5,696	7
03/10/86	6,020-8,813	9

*
1) Dual Induction
2) Compensated Neutron-Formation Density
3) Borehole Compensated Sonic
4) Sonic Waveforms
5) Gamma Ray
6) 4-arm Caliper
7) Cement bond
8) Temperature
9) Deep induction

Table 3. History of USGS geophysical logs, SSSDP.

Date	Log	Interval (ft.)	Comments/Results
11/05/85	Temp	100-2,998	Before circulation.
11/05/85	Nat Gamma	9-3,000	Two second time constant.
11/06/85	Temp/Caliper	100-2,998	After circulation.
11/06/85	Televiewer	N/A	No useful logs due to mud density & problems with tools.
11/06/85	Temp	100-3,000	Many stationary readings.
11/06/85	Caliper	943-2,950	
11/06/85	Acoustic DT	1,000-2,950	2 and 3 ft. spacing.
11/07/85	Waveform		2 microsecond sampling.
11/07/85	Temp	2,500-3,000	Stationary readings temperature vs. time.
11/07/85	Nat Gamma	1,000-2,980	
11/07/85	Gamma Spec	1,000-2,980	
11/07/85	Temp	2,500-2,998	Stationary readings at bottom.
12/04/85	Temp		Stationary readings at bottom.
12/09/85	Temp	2,700-5,984	Build up, stationary readings on bottom.
12/10/85	Temp/Caliper	3,375-6,000	
12/10/85	Televiewer		Both televiewers failed.
12/11/85	Nat Gamma	3,400-6,000	Tool did not work.
12/11/85	Gamma Spec		Analyzer failed after one spectrum.
12/11/85	Single Point Resistivity		Burned up tool.
12/11/85	Acoustic DT		Data marginal due to mud density.
12/11/85	Acoustic Full Wave		Total waveforms.
12/11/85	Temp/Caliper	3,400-5,120	Tool hung up.
12/12/85	Caliper	3,500-6,000	
12/12/85	Neutron	2,900-5,980	
12/23-24/85	Temp	3,500-6,230	
12/28/85	Temp	300-6,240	
02/15/86	Temp	6,000-10,400	
03/08/86	Temp	0-10,500	Pre-flow test.
03/12/86	Temp	0-10,500	Pre-flow test.
03/12/86	Televiewer	6,000-6,500	Log through first flow zone, marginal pictures.
03/13/86	Sonic	6,000-8,000	Several passes.
03/27/86	Temp	0-10,220	After 1st phase of reinjection.
03/29-30/86	Gamma Ray	5,690-10,000	
03/29-30/86	Neutron	5,770-10,000	
03/31-04/1	Temp	0-10,200	
04/07/86	Temp	0-9,660	Insulation resistance declining. Run terminated.

Because of financial constraints, the commercial loggers could only be brought in on specific occasions like casing points. On the other hand, the USGS Water Resources Division committed its geothermal research logging truck for the duration of the period from 3,000 ft to total depth. This gave us the flexibility to run logs, particularly temperature logs, when drilling was suspended (e.g., while waiting for fishing tools). This capability was enhanced by the fact that the on-site science managers were trained in running the logging unit and could do so literally on a moment's notice.

Apart from the lack of useful televiewer data and sonic data of questionable quality, the chief gap in the SSSDP logging program was caused by the failure of a motor in the USGS high-temperature 3-arm caliper. Because of repeated trips below 6,000 ft (Figure 2), the wellbore was doubtless over bit gauge over much of that interval, contributing to the loss of acoustic energy from both the televiewer and sonic velocity tools. Although records of excellent quality were obtained to nearly total depth with both passive gamma and neutron tools, their interpretation will be hampered by the lack of a caliper log. The time series of temperature logs is continuing throughout the six-month shut-in period. By the date of this meeting, a joint USGS/LLNL report is expected to be released, including hard copies of all geophysical logs, comparisons of USGS and Schlumberger logs, and some interpretive comments on the logs. A separate report will be issued on the post-drilling temperature logs.

DOWNHOLE EXPERIMENTS

Other downhole experiments included temperature-pressure measurements during and after flow and an attempt at measuring differential flow rates using a spinner-flow meter (Table 4). These measurements were made with developmental "slickline" type tools commissioned by Sandia Corporation (see C. C. Carson, this volume) and assembled by the Kuster Company. They were essentially conventional slickline tools with modified transducers and with recorders housed in dewars with a design operating period of 10 to 12 hours at 400°C. With the exception of the spinner, these tools functioned well and produced useful data on temperature and pressure. An electronic slickline tool which measures both temperature and pressure was built by Service Systems Engineering and is being used primarily for the time series of temperature logs to establish formation temperature over the entire length of the well.

Another category or downhole experiment involved fluid sampling. This proved exceptionally difficult under the hostile conditions encountered in the well. In fact, out of a total of 11 attempts using three different samplers only one was completely successful and an additional run obtained a liquid sample but no gas (Table 4). An attempt to retrieve fluid inclusions by annealing fractured quartz crystals in the brine within the lowermost producing zone was frustrated when the wireline broke because of corrosion, leaving the sample buried in fill near the bottom of the well.

Other experiments involving downhole instruments included a vertical seismic profile experiment using both shear- and compressional-wave vibrators and a downhole gravity experiment (Table 4). Both experiments yielded useful data.

Table 4. Downhole Experiments, SSSDP.

Date	Depth (ft)	Experiment	Comments/Results
a) 1st Flow Test - 6,220 ft.			
12/30/85	6200	Kuster T/P	Log during flow and buildup after shutin. Well bottom hole temp. (BHT) 305 ±5°C.
12/31/85	6200	LANL/Sandia downhole fluid sampler	Two attempts: 1st failed due to brine flashing upon entry into sample bottle and clogging port. 2nd failed due to malfunction of battery system.
(b) 2nd Flow Test - 10,564 ft.			
03/21/86	0-5,000	Kuster spinner/ pressure	Spinner failed at 5,000 ft.
03/21/86	0-10,000	Kuster T/P	Baseline error on temp chart.
03/22/86	0-10,400	Kuster T/P	BHT 350 ±10°C.
03/22-23/86	10,400	1st LANL downhole fluid sampler	No sample due to seal failure causing motor to flood and short out.
03/23/86	10,400	2nd LANL	No sample due to seal failure.
03/23/86	10,400	1st Leutert downhole fluid sampler	Failure due to LCM clogging bullnose.
03/23/86	10,200	2nd Leutert	Clock stopped so canister did not close.
03/23/86	10,200	3rd Leutert	O-rings on sampler bottle failed.
03/23-24/86		USGS Bethke fluid inclusion	Wireline broke leaving tool in bottom of hole. One fishing attempt with no recovery.
03/25/86	10,200	3rd LANL	Sample bottle returns empty.
03/25/86	10,200	4th LANL	Recovered 1.5 liters liquid and .5 liter gas sample.
03/25/86	10,200	5th LANL	Bottle did not open.
03/25/86	10,200	LBL fluid sampler	Recovered 1 liter unpressurized fluid.
03/27-29/86	50-5,650	LBL- Vertical Seismic Profile	Two good data sets with vibrators on drill pad and 1/2 mile off pad. 3rd data set with tool in liner produced too much noise. 4th run tool shorted out.
03/30-31/86	6,000	LLNL downhole gravity	Recovered good data with gravimeter ascending hole from 6000'.
(c) Shut In Period, April-September, 1986			
04/08/86	10,080	Digital T/P	Calibration off on temp tool.
04/22/86	10,080	Kuster T	Stops at 2,016, 4,032, 6,048, 8,064, 10,080.
04/22/86	10,080	Digital T/P	Same stops as above.

*T, temperature; P, pressure

SUMMARY AND CONCLUSIONS

The SSSDP well exceeded target depth, and a comprehensive set of cuttings, cores, and downhole logs was obtained. Two flow tests of different depth were successfully completed, although interferences between different producing horizons will make the data from the second test difficult to interpret. Temperature logging to establish the equilibrium profile will be completed by September 1986. A proposal for further long-term flow tests and to deepen the well a further 1,000 m is now under consideration. If successful, these activities would greatly increase the scientific yield of the SSSDP.

In an early memo (March 8, 1985), the Science Experiments Committee stated that "The SSSDP will be a success if we obtain and release to the public domain drill cuttings, cores, fluid samples, temperature measurements, and a limited suite of wireline logs from a temperature regime that has not previously been adequately sampled and tested." There is a wealth of data and samples, in some instances exceeding our early expectations, and by the standards enunciated in March of 1985, the SSSDP has been a resounding success.

ACKNOWLEDGMENTS

The work described herein could not have been accomplished without the wholehearted cooperation and dedication of all the scientific investigators involved. We thank the management, technical, and drilling staff for their conscientiousness and their sensitivity to the needs of the scientific program. James Mehegan and his assistants at U.C. Riverside played a valuable role in logging, cataloging, and describing core and cuttings samples.

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