Title
RESULTS OF INTERFERENCE TESTS FROM TWO GEOTHERMAL RESERVOIRS

Author
Witherspoon, Paul A.

Publication Date
1976-09-07

LBL-4484

RESULTS OF INTERFERENCE TESTS FROM TWO GEOTHERMAL RESERVOIRS

Paul A. Witherspoon

Society of Petroleum Engineers of AIME
6200 North Central Expressway
Dallas, Texas 75206

PAPER
NUMBER 6052

RESULTS OF INTERFERENCE TESTS FROM TWO GEOTHERMAL RESERVOIRS

by

Paul A. Witherspoon, Member, SPE-AIME
Lawrence Berkeley Laboratory
and
Department of Material Science and Engineering
University of California, Berkeley, California 94720

T. N. Narasimhan and D. G. McEdwards
Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720

INTRODUCTION

An important facet in the problem of geothermal energy development is that of assessing the productivity and size of the geothermal reservoir. Modern techniques of well test analysis (pressure draw-down buildup and interference tests) developed in the fields of petroleum engineering hydrogeology have been successfully applied to two liquid dominated geothermal reservoirs in the United States: one in the Raft River Valley, Idaho and the other at East Mesa, in the Imperial Valley, California. These tests provided reasonable estimates of the permeability and storage parameters for these reservoirs. In addition, they also illustrate the type of instrumentation that can be used in testing geothermal wells as well as the nature of the data that can be collected while testing geothermal reservoirs.

References and illustrations at end of paper.

A large body of literature is available on well testing in both fields of petroleum engineering and hydrogeology. Ramey[1] has recently summarized the practical aspects of modern well test analysis.

The purpose of this paper is to review the results of interference tests performed with a very sensitive pressure measuring device on these two geothermal reservoirs. A brief discussion of the geologic setting for each reservoir will be given and a discussion of the instrumentation will be presented. Some unusual features of the data will be discussed followed by the methods of interpretation that were utilized.

DESCRIPTION OF THE GEOTHERMAL RESERVOIRS

The Raft River Valley Geothermal Field, Idaho

The Raft River Valley geothermal field (Figure 1) is located on a graben filled with

Prepared for the U.S. Energy Research and Development Administration under Contract W-7405-ENG-48.

Tertiary and Pleistocene sediments and volcanics, with an aggregate thickness of about 5000 feet. The sediments rest on a basement of quartzites, schists, and quartz monzonites of Precambrian age.

Two wells, RRGE 1 and RRGE 2, drilled during 1975, successfully produced hot water at approximately 295°F from a geothermal reservoir occurring at the base of the sediments, at depths of 3500 to 5000 feet below the land surface. The wells are separated by 4000 feet with RRGE 2 being northeast of RRGE 1. Both are artesian wells with well head pressures of about 150 psi when shut in. During construction, both wells indicated free flows of about 400 gpm. The completion details for the two wells are summarized in Table 1.

Subsurface correlations of borehole data suggest that the sediments dip toward RRGE 2 with north-easterly apparent dips increasing from about 3 degrees in the upper portion to about 7 degrees toward the bottom. It is also known that RRGE 1 pierced a fault zone between 3800 and 4500 feet. Apparently, RRGE 2 did not intercept any faults.

The East Mesa Geothermal Field, California

The East Mesa geothermal field (Figure 2) is located on the eastern part of the Salton Trough in the Imperial Valley of California. The Salton Trough is a young and geologically active sedimentary basin filled with over 10,000 feet (?) of sediments comprised of sandstones, siltstones and clays. Structurally the sediments of the East Mesa field are considerably faulted and three intersecting faults (Figure 2) have so far been mapped. Five wells, varying in depth between 6000 and 8000 feet have been drilled to date at East Mesa by the U. S. Bureau of Reclamation. The bottom hole temperatures from these wells were distinctly higher than in the Raft River field and varied between 309 and 399°F. In addition, other geothermal wells have also been drilled on neighboring leases by private companies. Of these private wells we will be concerned with only one well (RG38-30), which was used during the interference tests. This well is owned by the Republic Geothermal Company. As at Raft River, the East Mesa wells are also artesian, but with smaller shut-in well head pressures of about 70 psi. The completion data for the East Mesa wells is summarized in Table 2.

RESERVOIR TESTS AND INSTRUMENTATION

Both interference tests and production well tests were conducted during these studies. The interference tests provided relatively more important information on the reservoir conditions and are the only tests that will be discussed here.

In all, three interference tests were conducted during the current studies: one at Raft River and two at East Mesa. The Raft River test was of the longest duration, with RRGE 2 flowing at the rate about 400 gpm (13,700 bbl/day) for nearly 26 days. During this production period and the subsequent buildup, pressure changes were monitored in RRGE 1, which acted as the observation well. The two interference tests at East Mesa (EM) were of relatively shorter duration, with production lasting for only ten to eleven days. The first test consisted in producing EM 6-2 at a near constant flow rate of about 90 gpm (3100 bbl/day) for 11 days and monitoring pressure change at the observation wells EM 6-1 (1500 feet away) and EM 8-1 (2300 feet away). The second interference test was conducted in the northern part of the field, with well EM 31-1 producing at approximately 130 gpm (4450 bbl/day) for ten days and the Republic Geothermal well RG 38-30 acting as the observation well. Since all the pressure observations were being made on shutin wells with positive well head pressures and since for well test analysis only the pressure differentials are critical, it was not necessary to obtain pressure transient data opposite the reservoir itself. Instead, it was feasible to collect such data from any convenient intermediate depth. During the present studies pressures were monitored in the observation wells at depths of 1000 and 1500 feet. In addition, in the Raft River test, accurate pressure monitoring was also simultaneously carried out at the well head. The data pertaining to the individual tests are summarized in Table 3.

Instrumentation

A key piece of equipment used in the interference tests was a very sensitive downhole quartz pressure gage capable of measuring in situ absolute pressures with an accuracy of 0.01 psi over a range of 0 to 10,000 psi. This instrument can tolerate temperatures up to 300°F over prolonged periods of time and is capable of yielding pressure data at intervals as small as one second. Thus, the instrument is ideally suited for monitoring pressures in shut-in observation wells in geothermal reservoirs, especially when these wells have positive well head pressures, as at the Raft River field and at East Mesa. However, the present 300°F limit for the temperature tolerance renders this instrument unsuitable in measuring downhole pressures in most geothermal reservoirs where temperatures exceed this value. Hence, we are at present limited in our ability to use this instrument in producing wells. Thus, for example, at the Raft River field where the reservoir temperature is only about 295°F, we were able to set the instrument opposite the reservoir in the production well and obtain pressure drawdown and buildup data. On the other hand, at the East Mesa field we attempted to use the instrument in one well opposite the reservoir at a temperature of about 318°F and the instrument failed after about 40 hours of operation.

During the interference test in the Raft River field, we also tested the utility of another quartz crystal pressure device that is capable of measuring only well-head pressures. With this surface pressure gage in position and with the downhole gage at 1000 feet, simultaneous pressure measurements were made during the interference test and the data collected showed that the pressure differentials sensed by the two instruments agreed very closely with each other, except for the fact that the surface instrument tended to accentuate pressure peaks during early afternoons, probably due to the thermal expansion of the air-column buffer that was used to protect the crystal from well fluids. It would appear that this could easily be avoided by using a buffer of an inert oil such as silicone oil, instead of air.

NATURE OF DATA COLLECTED

The small magnitude of pressure transient effects that generally manifest themselves in observation wells far removed from the producing well, coupled with the high resolution of the pressure data collected during the interference tests brought to light the important fact that in testing geothermal reservoirs the raw data may often be masked by small but significant extraneous effects. Appropriate corrections have to be made to these effects before a meaningful interpretation of the reservoir parameters can be achieved.

The data collected from the Raft River field showed that the reservoir pressures respond systematically to the earth tides. Figure 3 presents the observed variation of pressure in observation well RRGE 1 as well as the computed changes in the earth's gravitational field for the period September 28 to October 6, 1975. It is clearly seen from this figure that superposed on the overall pressure decline caused by interference due to the producing well are the periodic pressure changes caused by the earth tide effects. A cross spectral analysis of the gravity and the pressure waves indicated that the crests and the troughs of the pressure wave appear to lead those of the gravity wave by approximately 30 minutes. The maximum perturbation induced by the earth tides is approximately 0.1 psi about the mean or a total crest to trough amplitude of about 0.2 psi. Similar earth tide effects were noticed by Stobel et al.[2] in a dry gas reservoir. It is interesting to note that the total amplitude observed in the gas reservoir is only about 0.03 psi or about a tenth of the amplitude observed at Raft River. The influence of earth tide effects on groundwater reservoirs has been documented by many workers in the field of hydrogeology. In a recent work, Marine[3] reports the response of water levels in some deep wells in crystalline rock to earth tides in South Carolina. His study indicates a maximum tidal amplitude of about 0.15 psi. A theoretical study of the response of a well-aquifer system to earth tides has been carried out by Bredehoeft[4].

Since the pressure data is almost in phase with gravity variation, it is relatively simple to eliminate the effect of earth tides; one needs to consider only those pressure data corresponding to those instants of time at which the computed change in gravity is zero. The dashed line in Figure 3 has been drawn in this fashion.

In contrast to the Idaho experience, the raw data collected at East Mesa has been characterized by considerable noise (Figure 4). The noise level in the data showed a total variability of about 0.5 psi. The source of the noise is not yet clearly understood. It is known that the Salton Trough, of which East Mesa forms a part, is seismically active and this seismic activity could be a possible cause of the noise. At the same time, it is also possible that the noise may be generated by the instrument-cable system. It was essential to extract the mean trend from the noisy data before attempting an interpretation of reservoir performance. For this purpose, a non-linear regression technique was used. The line connecting the solid dots in Figure 4 is a segment of the regression line so calculated.

Although the overall noise present in the East Mesa may not be due to microseisms, there is evidence to show that the reservoir is indeed seismically active and that the seismic activity does affect water pressures in wells. Figure 5 presents the pressure history observed in shut-in wells EM 6-1 and EM 8-1 during the morning hours of February 13, 1976. It is seen from this figure that commencing at about 0310 hours, the fluid pressure in EM 8-1 rose rapidly, reaching a peak of about 3 psi above the mean at about 0347 hours. After this, the pressure dissipated gradually, with the occurrence of a few minor peaks. Fortunately, the Bureau of Reclamation also maintains a microseismic network at the East Mesa site. Examination of the seismographic records pertaining to the period in Figure 5 showed that between 0312 and 0347 hours some 14 minor seismic events occurred in the area, with the epicenters apparently located two to four miles east and north east of EM 8-1. These events were picked up by a geophone located about a mile south east of EM 8-1. Another geophone, located about a mile and a half north of EM 6-1 picked up the same events slightly later and the signals appeared to have attenuated significantly before reaching that geophone. It is of considerable interest to note from Figure 5 that EM 6-1 does not show any of the pressure peaks sensed by well EM 8-1. This difference in the seismic response of these two East Mesa wells is not yet fully understood, but it is believed that this may have significant implications in understanding the structure of the geothermal reservoir at East Mesa.

INTERPRETATION

The flow rates associated with each of the three tests conducted during this study were so chosen as to prevent flashing of the hot water within the well. Thus, the reservoir-well system was filled with a single fluid and it was possible to use, for interpretation, the conventional techniques of well testing used in the fields of petroleum engineering and hydrogeology. Although both drawdown and buildup data were analyzed, major emphasis was placed on the interpretation of the drawdown data in so far as the observation well data was concerned. The drawdown data was analyzed both by matching the data with type-curves and by using the asymptotic solution. These techniques enabled the determination of the parameters kH and ϕcH and permitted inferences regarding the presence of boundaries.

Interference Test, Raft River Valley Field, Idaho

A log-log plot of drawdown versus time is presented in Figure 6 and a semilog plot of the same data is given in Figure 7. The data points correspond to instants of zero gravitational effect and thus avoid the perturbations caused by earth tides. The log-log plot yielded a kH of 228,000 millidarcy feet and a ϕcH of 1.19 x 10^{3} feet/psi while the semilog plot yielded a kH of 228,000 millidarcy feet and a ϕcH of 9.38 x 10^{-4} feet/psi. Both Figures 6 and 7 clearly show the effects of the presence of a barrier boundary. The distance from the observation well to the image well was computed to be about 12,000 feet. With only two wells available for testing, it is not possible to locate the exact position of the barrier boundary.

Although we are not concerned here with the details of the production well tests, it is of interest here to briefly present the pressure buildup data obtained from well RRGE 2 after a short-term production test, during which the well was produced for 15 hours at a rate of 225 gpm (7,700 bbl/day) and then shut in. The total drawdown at the end of 15 hours was 37.5 psi. Analysis of the drawdown data suggested a formation kH of about 50,000 millidarcy feet.

The buildup observed in this well is presented in Figure 8. Note that because of the sophistication of the available instrumentation, buildup data could be collected commencing within two seconds after shut in. Qualitatively, the most interesting feature of Figure 8 is the lack of the presence of either a unit slope or a half-slope in the observed data within the first ten seconds of observation. Thus, we were not able to detect well bore storage and apparently the reservoir is not dominated by a fracture close to the well.

Interference Test No. 1, East Mesa, California

During this interference test, well EM 6-2 was produced and wells EM 6-1 and EM 8-1 acted as observation wells (Table 3). However, only well EM 6-1 showed noticeable pressure declines directly as a consequence of the production at EM 6-2, while EM 8-1 did not show any pressure drop at all. Interpretation of the pressure drawdown observed in well EM 6-1 is presented in Figure 9. The data used in the interpretation correspond to the mean values obtained with the non-linear regression fit. Type curve matching of the early drawdown data suggest a kH of 11,200 millidarcy feet and a ϕcH of 5.7 x 10^{-3} feet/psi. It is also seen from Figure 9 that the observed data departs from the type curve after about 100 hours suggesting the possible presence of a leaky boundary some distance away from EM 6-1. Calculations indicate that such a boundary may exist between 200 and 1700 feet from well EM 6-1. As can be seen from Figure 2, the reservoir is considerably faulted in the vicinity of wells EM 6-2, EM 6-1 and EM 8-1, and there are indications that faults may be intersecting each other in this part of the reservoir. It seems possible that the leaky boundary suggested by Figure 9 may be indicative of an intersecting fault system.

At the same time it should also be pointed out that there is a difficulty in interpreting the data in Figure 9 with certainty. An examination of Table 2 shows that well EM 6-2 produces from the interval 4800 to 6000 feet while the producing interval extends from 6200-8000 feet. There is thus a 200 feet break between the bottom of well EM 6-2 and the top of well EM 6-1, although they may both be tapping the same production zone. It is therefore not immediately clear whether the observed departure from the type curve in Figure 9 can be attributed to a leaky boundary or to the effect of the different depth intervals that are open in the two wells.

Interference Test No. 2, East Mesa, California

During this test, EM 31-1 was produced (Table 3) and the Republic Geothermal RG 38-30 was used as an observation well. The interpretation of the drawdown data is presented in Figure 10. Type-curve matching of the early drawdown data has indicated a kH of 29,500 millidarcy feet, which is nearly three times the value obtained for the region between EM 6-2 and EM 6-1. The ϕcH value is about 2.1 x 10^{-3} feet/psi. Unlike Test No. 1 at East Mesa, this test indicates the presence of a barrier boundary, which exists between 1100 and 2400 feet from RG 38-30.

CONCLUSIONS

The experience gained in testing geothermal reservoirs in Idaho and in California has shown that the availability of sophisticated pressure measuring devices has greatly increased our ability to conduct sensitive pumping tests. We are now in a position to measure very weak pulses over a long period of time even in the presence of extraneous noises and masking effects, and are able, therefore, to apply to geothermal reservoirs the repertoire of well testing techniques that have successfully been developed over a long period of time in the fields of petroleum engineering and hydrogeology.

Theoretical work such as that of Bredehoeft[4] suggest that depending on their elastic properties, different reservoirs may respond differently to earth tides and that by studying the coherence between earth tide and fluid pressure changes it may be possible to estimate the gross elastic properties of the reservoir. Also, differing responses of different wells in a given well field to known seismic events may also give clues about reservoir geometry. These facts point to the interesting possibility that by passively monitoring reservoir pressures over prolonged periods of time one may be able to arrive at overall long-range estimates of reservoir parameters and geometry.

NOMENCLATURE

c = compressibility, psi^{-1}

H = reservoir thickness, feet

k = permeability, millidarcy

ϕ = porosity

ACKNOWLEDGEMENTS

We would like to thank Dr. Jay Kunze of the Idaho National Engineering Laboratory and Mr. Kenneth Fulcher of the U. S. Bureau of Reclamation for rendering us all facilities during our present studies and permitting us to publish our findings. We are also thankful to Dr. R. Rex of Republic Geothermal Company for letting us make use of well RG 38-30 as an observation well during one of our interference tests. We also thank Mr. Kenneth Mathias of the Bureau of Reclamation who provided us with the East Mesa seismographic records and Mr. Ernest Majors, Department of Geology, University of California, who interpreted the seismic data. Our thanks are also due to Dr. Howard Oliver of the U. S. Geological Survey who computed the earth tides for the Raft River field and to Ms. Jeanette Mullaney of the University of California, who provided us with considerable help in processing field data from Idaho and California.

This work was done with support from the U.S. Energy Research and Development Administration.

REFERENCES

1. Ramey, H. J. Jr., "Practical Use of Modern Well Test Analysis," Paper SPE 5878, to be presented at the 51st Annual Fall Meeting of SPE of AIME, New Orleans, Lousiana, October 3-6, 1976.

2. Strobel, C. J., Gulati, M. S. and Ramey, H. J. Jr., "Reservoir Limit Tests in a Naturally Fractured Reservoir - A Field Case Study Using Type Curves," Paper SPE 5595, presented at the 50th Fall Meeting of the SPE of AIME, Dallas, Texas, September 28-October 1, 1975.

3. Marine, I. W., "Water Level Fluctuations Due to Earth Tides in a Well Pumping from Slightly Fractured Crystalline Rock," Water Resources Research (1975), 11, No. 1, 165.

4. Bredehoeft, J. D., "Response of Well-aquifer System to Earth Tides," Journal of Geophysical Research, (1975), 72, No. 12, 3075.

5. Mathias, K. E., "The Mesa Geothermal Field A Preliminary Evaluation of Five Geothermal Wells," Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 19-29, 1975.

TABLE 1

Completion Data for the Raft River Valley Geothermal Wells

Well No.	Total Depth		Bottom Hole Temp.		Production Interval		Casing		Well head Pressure psi
	Feet	Meters	°F	°C	Feet	Meters	O.D.	Depth	
RRGE 1	4,989	1,521	294	146	3,620 to 4,200	1,105 to 1,280	13 3/8" (34 cm) Uncased	G.L. to 3,620 ft. (1,105 m) to bottom	150
RRGE 2	5,988	1,826	294	146	4,230 to 5,000 (?)	1,290 to 1,520 (?)	13 3/8" (34 cm) Uncased	G.L. to 4,230 ft. (1,290 m) to bottom	150

TABLE 2

Completion Data for East Mesa Geothermal Wells
(after Mathias,[5] 1975)

Well No.	Total Depth		Bottom Hole Temp.		Production Interval		Lower Casing*		Well head Pressure psi
	Feet	Meters	°F	°C	Feet	Meters	O.D.	Depth	
EM 6-1	8,015	2,443	399	204	6,201 - 7,982	1,890 - 2,433	7"	To bottom	66
EM 6-2	5,958	1,816	340	188	4,790 - 5,959	1,460 - 1,816	7 5/8"	To bottom	110 (?)
EM 5-1	6,004	1,829	315	157	5,007 - 6,004	1,526 - 1,830	7 5/8"	To bottom	68
EM 8-1	6,001	1,829	354	179	4,948 - 6,001	1,508 1,829	7 5/8"	To bottom	71
EM 31-1	6,175	1,882	309	154	5,420 - 6,175	1,652 - 1,882	7 5/8"	To bottom	65
RG 38-30	8,890	2,710	N/A	N/A	6,383†- 7,022	1,945†- 2,140	7"	To 7,020' (2,140 m)	N/A

*Casing includes blank, perforated and slotted sections.

†Casing partly filled in.

TABLE 3

Summary of Interference Tests, Raft River and East Mesa Geothermal Fields

Field	Interference Test No.	Producing Well			Observation Well 1					Observation Well 2				
		No.	Rate gpm (bbl/day)	Duration hrs.	No.	Distance feet	Pressure Gage Setting ft.	Static Pressure psia	Maximum Drawdown psi	No.	Distance feet	Pressure Gage Setting ft.	Static Pressure psi	Maximum Drawdown psi
Raft River Idaho	1	RRGE 2	400 (13,708)	615.5	RRGE 1	4,000	i) 1,000 ii) at surface	575.0 150.0	3.6					
East Mesa California	1	EM 6-2	90 (3084)	273	EM 6-1	1,480	1,100	553.8	0.7	EM 8-1	2,320	1,500	709.60	0.0
	2	EM 31-1	130 (4450)	237	RG38-30	1,250	1,500	726.18	0.46					

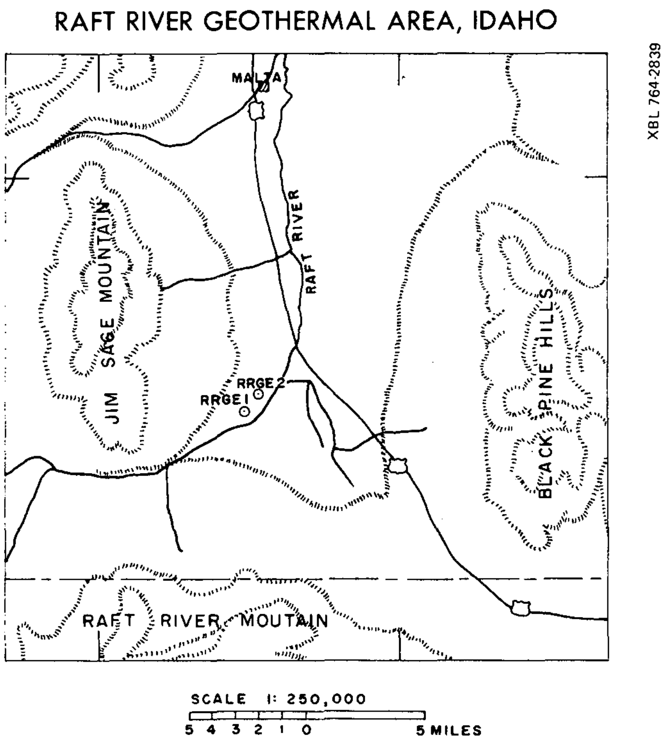

Figure 1. Location map of the Raft River Valley Geothermal Field, Idaho.

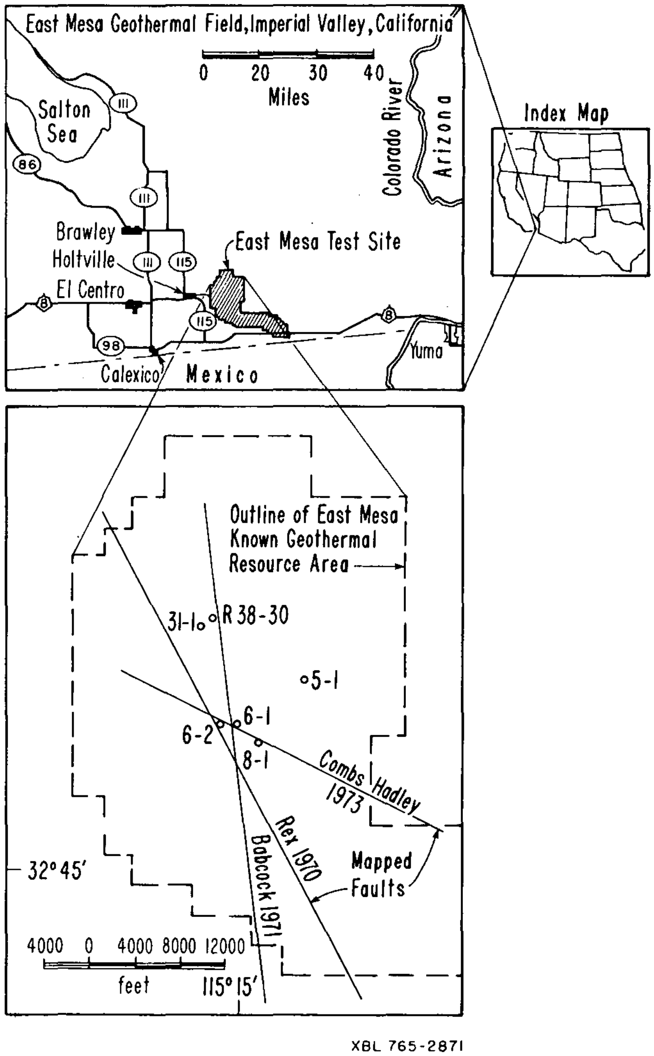

Figure 2. Location map of the East Mesa Geothermal Field, California.

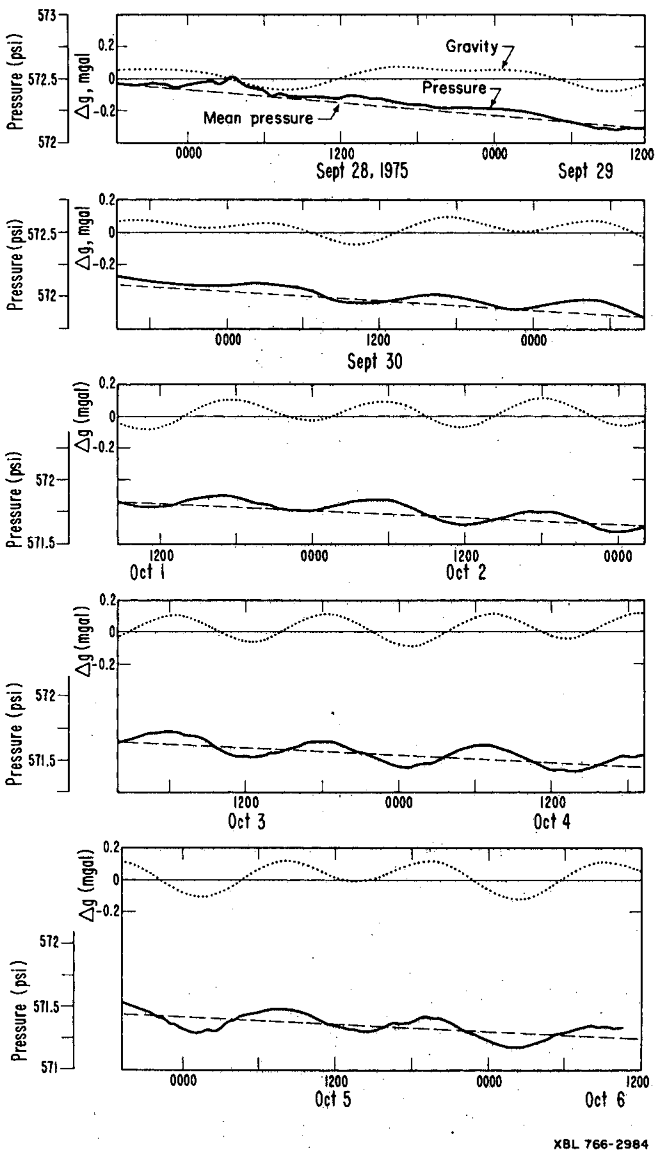

Figure 3. Correlation between variation in the earth's gravitational field and water pressure in RRGE 1 during the interference test.

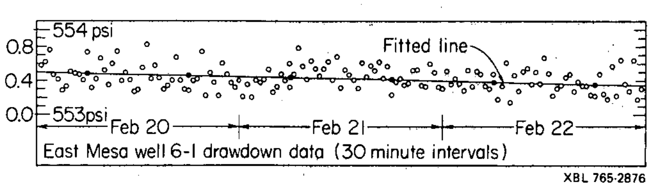

Figure 4. Comparison of the pressure data recorded in EM 6-1 during the first interference test and the fitted line used for analysis.

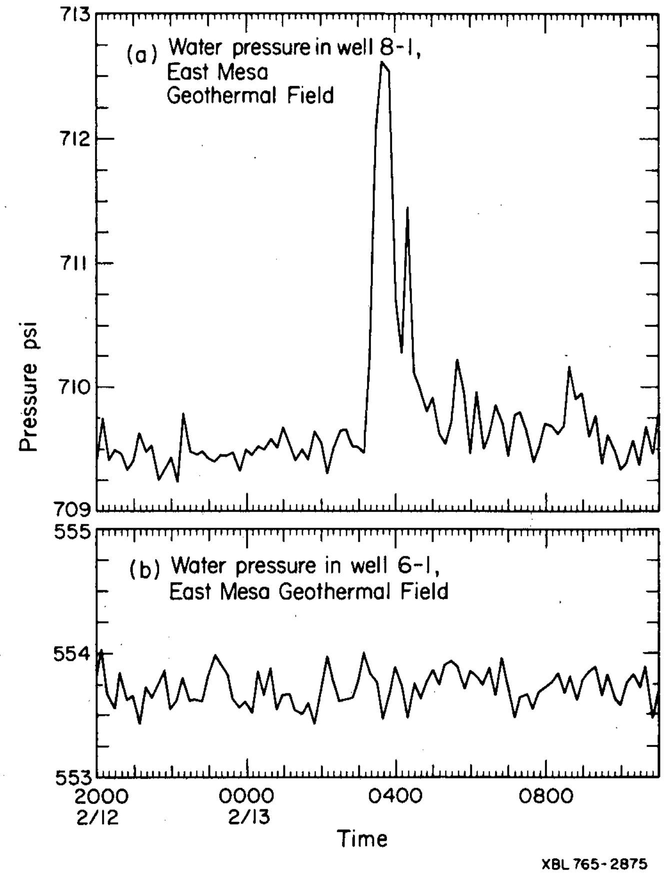

Figure 5. Comparison of water pressure fluctuations in EM 8-1 and EM 6-1 recorded before the start of the first interference test.

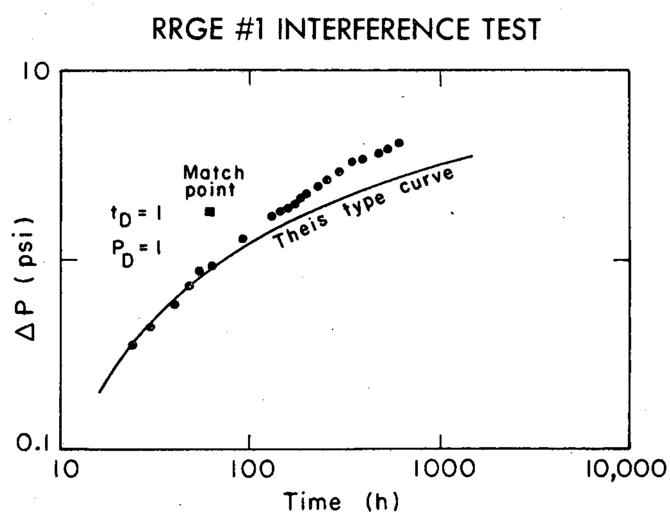

Figure 6. Interference test, RRGE 1: Log-log plot of time versus drawdown.

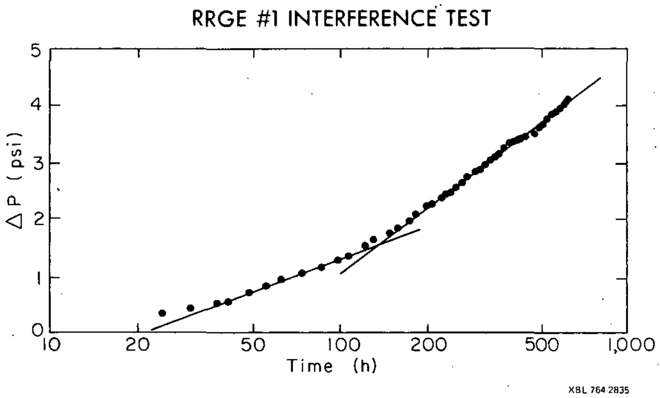

Figure 7. Interference test, RRGE 1: Semi-log plot of time versus drawdown.

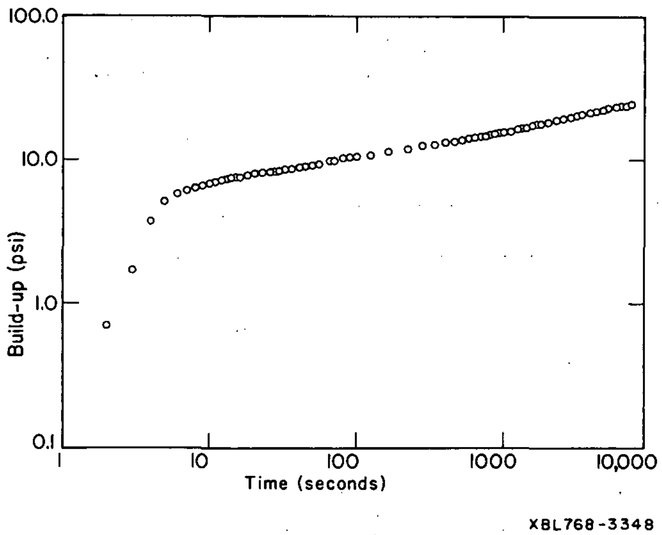

Figure 8. Short term production test, RRGE 2: Log-log plot of buildup versus time.

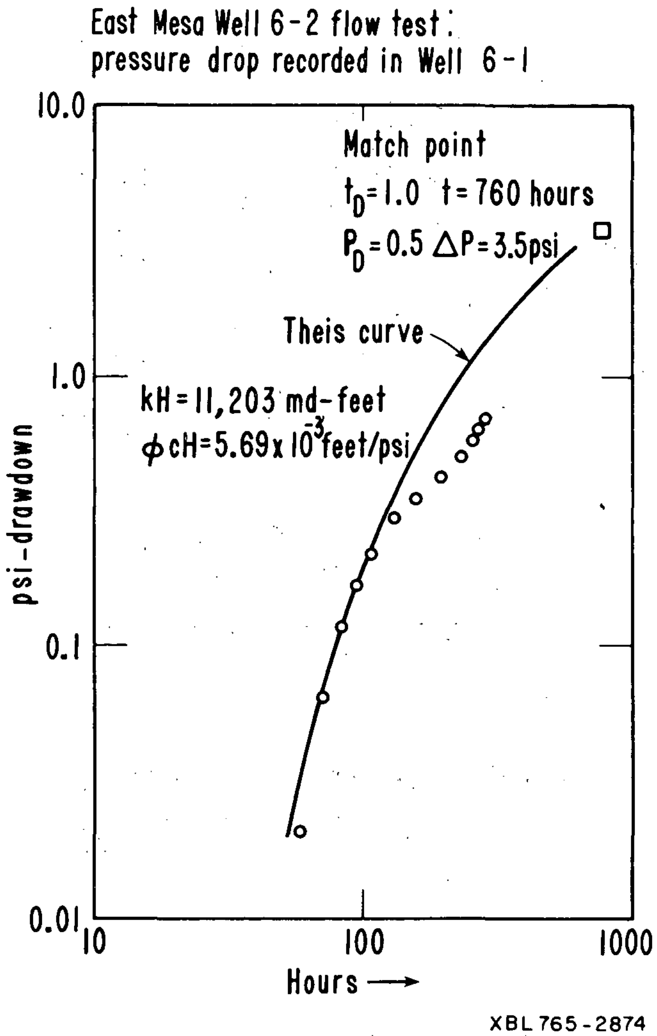

Figure 9. Interference test, EM 6-1: Log-log plot of time versus drawdown.

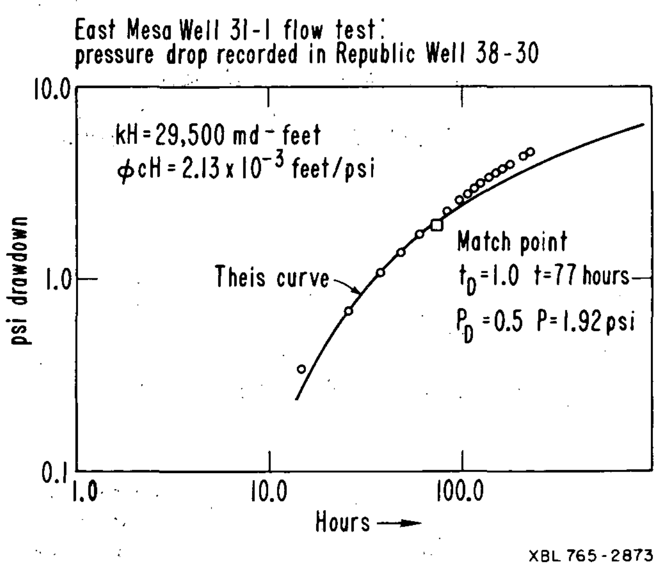

Figure 10. Interference test, RG 38-30: Log-log plot of time versus drawdown.

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