RESULTS OF THE FLOWMETER-INJECTION TEST IN THE LONG VALLEY EXPLORATORY WELL (PHASE II), LONG VALLEY, CALIFORNIA

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CONVERSION FACTORS

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
centimeter per second (cm/s)	0.3937	inch per second
centimeter per minute (cm/min)	0.3937	inch per minute
meter (m)	3.281	foot
meter per minute (m/min)	3.281	foot per minute
liter (L)	0.2642	gallon
liter per minute (L/min)	0.2642	gallons per minute

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°C = 5/9\ (°F-32).$$

Permeability, in darcies, may be converted to hydraulic conductivity, in cm/s, by the following equation, assuming the permeant fluid is water at 20°C:

$$\text{cm/s} = (0.966 \times 10^{-3})\ (\text{darcies}).$$

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By R.H. Morin, M.L. Sorey, *and* R.D. Jacobson

ABSTRACT

The Long Valley Exploratory Well is being drilled in the Long Valley caldera in east-central California to investigate active magmatic intrusion processes. In an effort to obtain hydrologic information concerning deep hydrothermal circulation beneath the caldera floor, a flowmeter-injection test was performed in the well. The test was designed to determine the vertical distribution of hydraulic conductivity in the lowermost section of the borehole left uncased after completion of Phase-II drilling. Total depth of the well in May 1992 was 2,313 meters, with the lower 215 meters being open hole. A total of approximately 30,000 liters of water was injected into the well over 22 hours while water levels in the inner Ocean Drilling Program drill pipe and the outer-casing annulus were independently monitored and measurements of vertical fluid flow were recorded as a function of depth. Flowmeter measurements obtained in the open hole indicate no detectable fluid movement, and volumetric calculations indicate that all of the water introduced into the well can be accounted for by the attendant increases in water levels. Temperature logs obtained immediately before and after injection support the hypothesis that injected fluid simply shunted the open hole directly below the Ocean Drilling Program drill pipe and subsequently filled the outer-casing annulus above. The low hydraulic conductivity of the open hole is also manifested in the chemical analysis of fluid samples that show no evidence of formation fluids in the well.

The hydraulic conductivity of the lowermost section of the Long Valley Exploratory Well after Phase-II drilling proved to be too low to quantify accurately by means of the flowmeter-injection field technique. Hydraulic communication between fluid within the inner Ocean Drilling Program drill pipe and fluid filling the outer-casing annulus further complicated the situation and introduced additional uncertainties. Nevertheless, the field data and a record of falling water levels for 6 months enable the permeability of the open hole to be constrained. An upper bound on the permeability of the formation between 2,098 and 2,313 meters is estimated to be in the microdarcy range.

INTRODUCTION

The Long Valley Exploratory Well (LVEW) is being drilled in the Long Valley caldera in east-central California to substantiate the hypothesis of active magma intrusion to relatively shallow depth beneath the caldera floor (Long Valley Science Panel, 1991). The well is located on the resurgent dome and intrusion is hypothesized to occur in the central to south-central part of the caldera (Rundle and Hill, 1988). The physiographic setting of the Long Valley caldera and the location of the LVEW drill site are shown in figure 1. Phase-I drilling of this four-phase drilling project was completed to a total depth of 780 m in October, 1989. Phase-II drilling was completed in the fall of 1991 to a depth of 2,313 m, with the lower 215 m being open hole. A diagram of the LVEW construction after Phase-II drilling is shown in figure 2.

The LVEW project has been motivated by several fundamental scientific objectives related to understanding the thermal and lithostratigraphic structure of an active silicic caldera and the magmatic intrusion processes that create it. One of the primary goals of the LVEW project is the characterization of the hydrologic system beneath the caldera fill, where hydrothermal circulation in a series of permeable reservoirs is thought to be extensive (Sorey and others, 1991). As part of this hydrologic theme, a flowmeter-injection test was performed in the LVEW to determine the transmissivity of the lowermost section of the well left uncased after the completion of Phase-II drilling.

Purpose and Scope

This report presents the results of a flowmeter-injection test and interprets these data with respect to the local hydrologic system underlying the Long Valley caldera. Also included in this report are the results of other related activities that complement and extend the interpretations developed from the injection experiment. This supporting information consists of chemical analyses of fluid and drilling-mud samples, and water levels in the LVEW recorded for 6 months prior

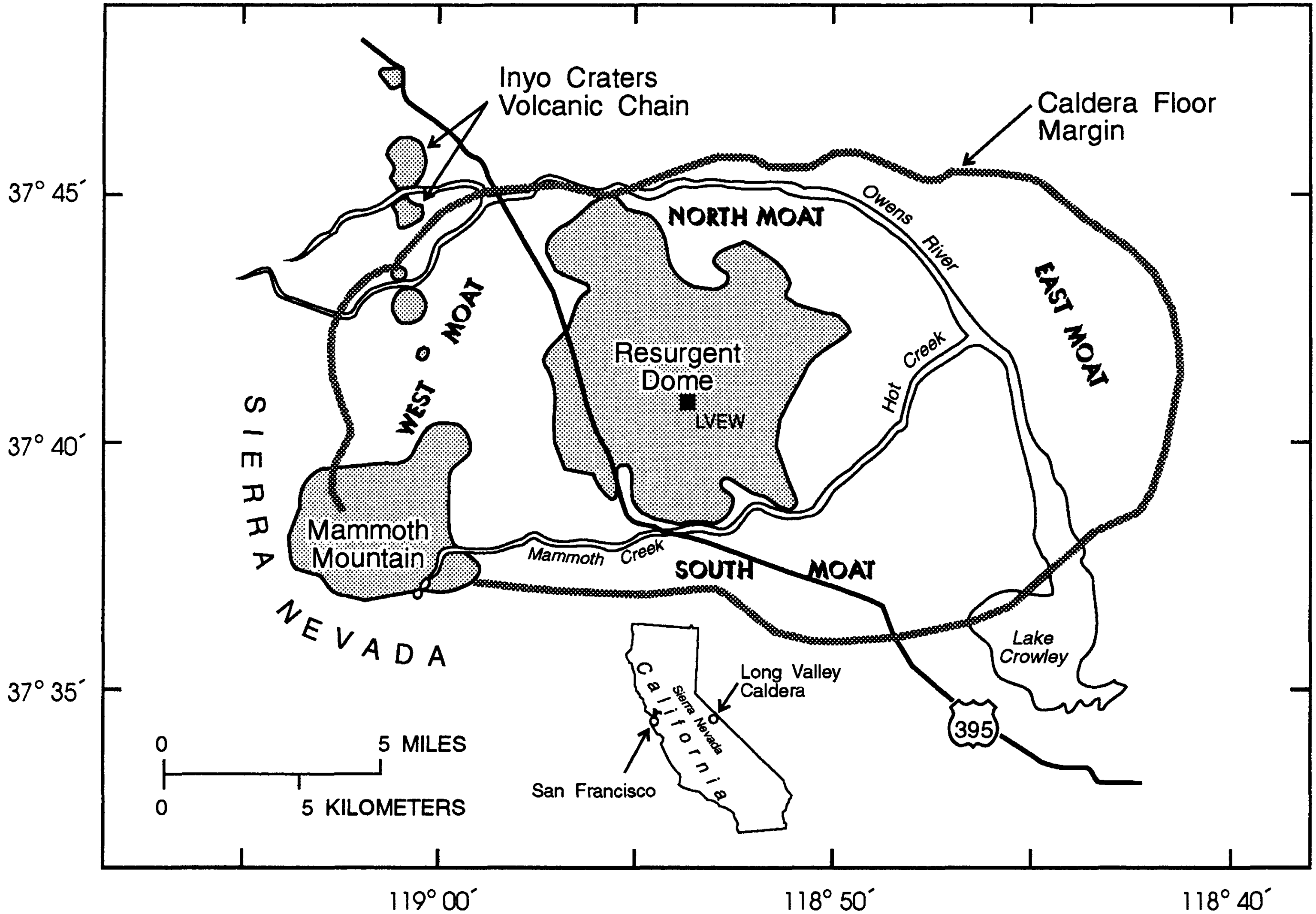

Figure 1. Physiographic setting of the Long Valley caldera and location of the Long Valley Exploratory Well (LVEW) drill site. Outlines of Mammoth Mountain, Resurgent Dome, and Inyo Craters Volcanic Chain encompass the limits of quartz latite, early rhyolite, and 550-650 year-old rhyolite, respectively (modified from Bailey, 1989).

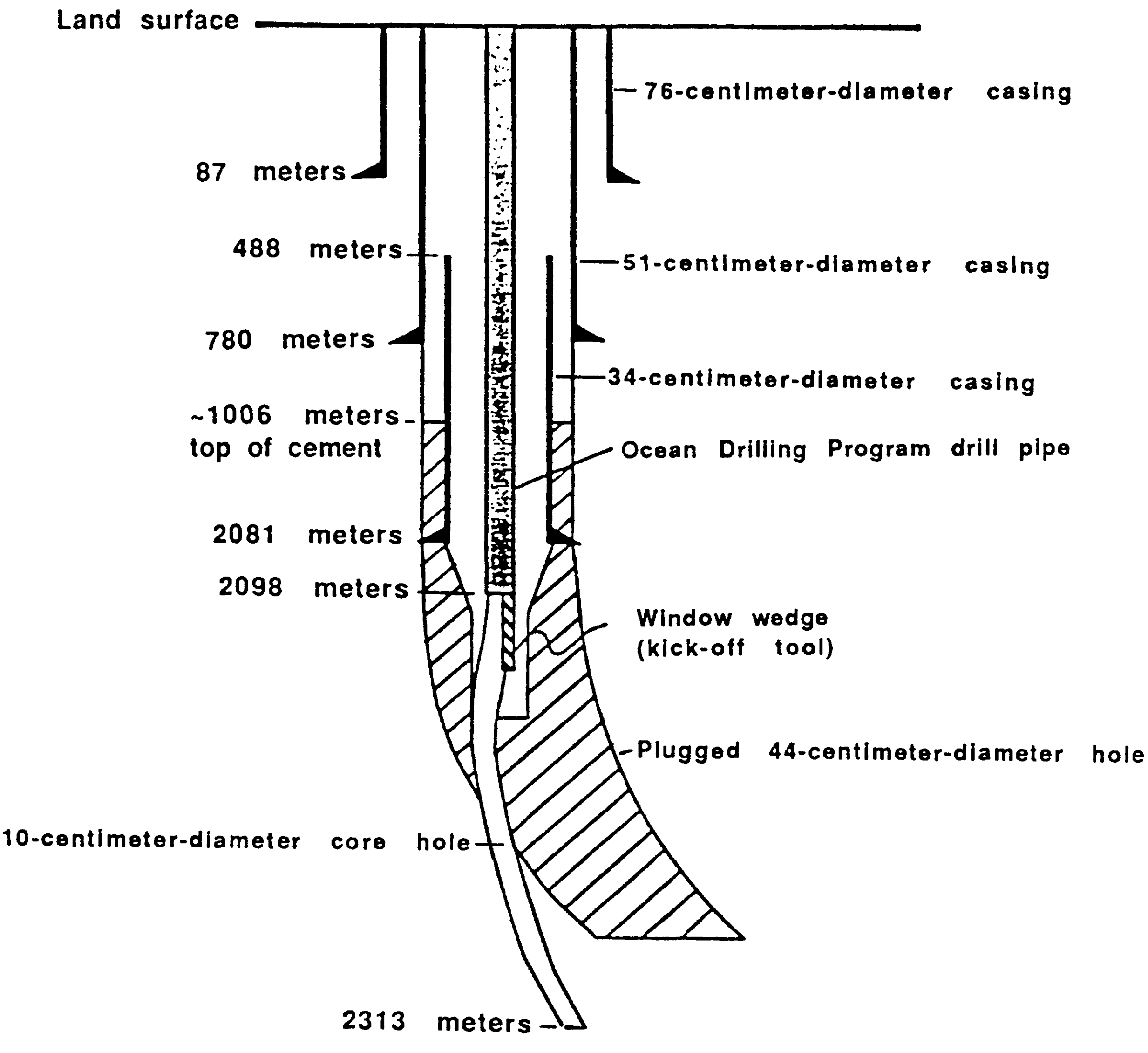

Figure 2. Schematic diagram showing casing configuration in the Long Valley Exploratory Well (modified from Finger and Jacobson, 1992). Hole deviation is highly exaggerated; actual angle between the core hole and the plugged hole is approximately 1.5 degrees.

to the injection test. Hydrologic interpretations based on these field observations are limited to the lowermost 215 m of the hole that was left uncased.

Acknowledgments

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FIELD METHOD

A flowmeter-injection test was attempted in the LVEW on May 26-27, 1992, to determine the vertical distribution of hydraulic conductivity in the open-hole section. This field test was originally proposed by Hufschmied (1984); it combines the concepts of pumping to investigate bulk aquifer properties (transmissivity) and in-situ hydraulic measurements at specified depths to monitor fine-scale variability in hydraulic conductivity. This field method has been evaluated and refined at several sites (Morin and others, 1988; Hess, 1989), and a comparison of permeability values estimated from this test to those values determined from other standard, established field methods has been excellent (Molz and others, 1989).

In this method, fluid is injected into a well at a constant rate, and the accompanying increase in hydraulic head is monitored. When the water level stabilizes and reaches a quasi-steady state, the vertical distributions of fluid flow and pressure in the well are measured by means of wireline logging. These data then are analyzed in terms of changes in head and resulting flows to yield quantitative estimates of permeability across arbitrary depth intervals with a vertical resolution dictated by the frequency of measurements. Details of this analysis are presented by Morin (1988).

The U.S. Geological Survey has access to two different types of flowmeters that measure vertical fluid movement in wells: (1) A standard impeller meter that is capable of measuring mid-range velocities of 0.5 to 20 m/min and (2) a heat-pulse flowmeter (Hess, 1986) that is designed to measure slow velocities in the range of 0.02 to 2 m/min. This latter instrument, with its improved resolution, enables the delineation of low-permeability zones that are typically characterized by small amounts of fluid exchange between the formation and the open hole. The relatively high temperatures measured in the lower part of this well (>100 °C) could have precluded the use of the heat-pulse flowmeter, which is not capable of withstanding temperatures greater than approximately 60 °C. The possibility remained, however, that transmissivities in the open hole could be high enough to produce substantial cooling of the wellbore during the injection operation, thus permitting the use of this tool. The impeller was initially deployed and the higher-resolution flowmeter was kept ready if conditions became favorable.

Water was pumped from a nearby water-supply well and injected directly into the LVEW. Injection rates were measured using a digital volumetric flow gage at the surface. Injection began at 9 am on May 26, 1992, and continued for approximately 22 hours. A wireline pressure transducer was lowered to 2,134 m in the open-hole section of the well to continuously monitor head build-up during injection. The initial injection rate was 19 L/min, and this rate was adjusted as the test progressed to achieve a stable water level by the end of the day. The injection schedule that evolved during this field experiment is listed in table 1.

Table 1. Schedule of injection rates maintained during the flowmeter-injection test

Time	Injection rate (liters per minute)
0900-1100 [May 26, 1992]	19
1100-1140	76
1140-1230	114
1230-1250	57
1250-1310	38
1310-1845	30
1845-0630 [May 27, 1992]	10

Because of the unusual construction of the LVEW (fig. 2), fluid flow down the inner Ocean Drilling Program (ODP) drill pipe did not necessarily translate into an equivalent loss of fluid into the formation. The annulus between the ODP drill pipe and the cement plug at 2,098 m was not sealed effectively and permitted water to flow around the ODP inner liner and up into the casing. Moreover, if this fluid continued moving upward above the top of the 34-cm-diameter casing at 488 m, it then could flow down along the outer annulus between the 51-cm-diameter casing and the 34-cm casing, possibly entering the open formation exposed between the bottom of the 51-cm casing at 780 m and the top of the cement at about 1,006 m (fig. 2).

To understand the unique fluid dynamics produced during the injection operation by the hydraulic communication among the inner well (inside the ODP drill pipe), the outer annulus, and two different sections of open hole, water levels were monitored both in the ODP liner and in the outer annulus. Water levels in the annulus were measured periodically using an acoustic echometer; the analog chart record showing a sequence of reflectors associated with casing collars above the water table was converted to rising water level since fewer casing collars could be detected as injection proceeded. Water levels in the ODP drill pipe were monitored continuously using a wireline pressure transducer connected to a 4-conductor cable and operated from a logging truck at the surface.

Prior to the field test, well clean-out operations involving repeated trips with a bailer were conducted for several days, and a downhole fluid sample was subsequently collected for chemical analysis from a depth of 2,215 m. Water levels at the start of the injection test were 263 m in the ODP liner and 211 m in the annulus between the ODP drill pipe and the 51-cm casing. The discrepancy in water levels was probably due to the preceding well clean-out operations that disturbed the reference water levels. A plot of water-level variations as a function of time after the onset of injection is presented in figure 3. Changes in the slopes of these curves reflect the changes in injection rates controlled from the surface (table 1).

After injection had proceeded for approximately 500 minutes and water levels in the ODP drill pipe and the outer-casing annulus had reached a slow and predictable rate of increase, the wireline pressure transducer was recovered from the well and an impeller flowmeter was deployed. Injection from the surface continued at 30 L/min, but no measurable fluid velocity could be detected once the impeller was lowered below the ODP pipe and into the open hole. Further calculations supported this observation by confirming that the cumulative volume of injected water was equal to that required to fill the ODP pipe and the outer-casing annulus to their new water levels. Thus, there was a negligible loss of fluid to the open hole, even with a maximum increase in hydraulic head of 263 m.

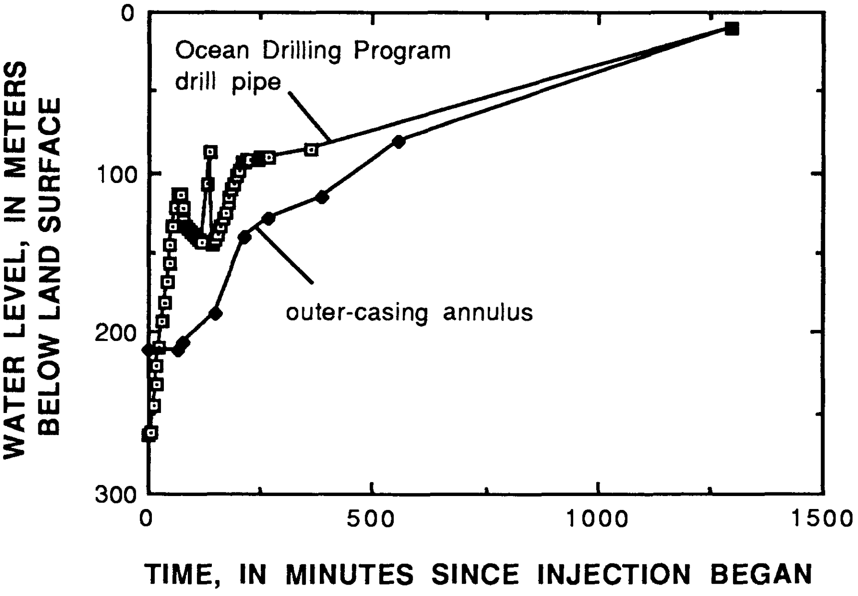


Figure 3. Water levels recorded in the Ocean Drilling Program drill pipe and in the outer-casing annulus during injection into the Long Valley Exploratory Well on May 26, 1992.

TEST RESULTS

The fluid sample obtained from the LVEW prior to the injection test was determined to have a sodium concentration and a specific-conductance value similar to those of the drilling mud that was sampled in November 1991 (table 2). A sample collected from the 270-m-deep water-supply well adjacent to the drill site contained relatively dilute concentrations. These comparisons indicate that the bailing operations failed to induce water to flow into the core hole from the surrounding formation.

A total of approximately 30,000 L of water was injected into the LVEW during the test. Volumetric calculations indicate that all of this fluid simply shunted the open hole directly below the ODP drill pipe and filled the casing annulus above. This observation is supported by the temperature logs obtained in this well before and after injection (fig. 4). An expanded view of these temperature profiles for the bottom 500 m of the LVEW (fig. 5) indicates that cooling is localized above 2,100 m, a depth that corresponds to the bottom of the ODP inner liner and marks the lowermost extent of any perturbation in temperature. The open core hole has undergone no change in temperature due to fluid injection. The bottom-hole temperature of 102 °C also validates the decision not to deploy the heat-pulse flowmeter in this well without clear evidence of substantial fluid loss into the open hole.

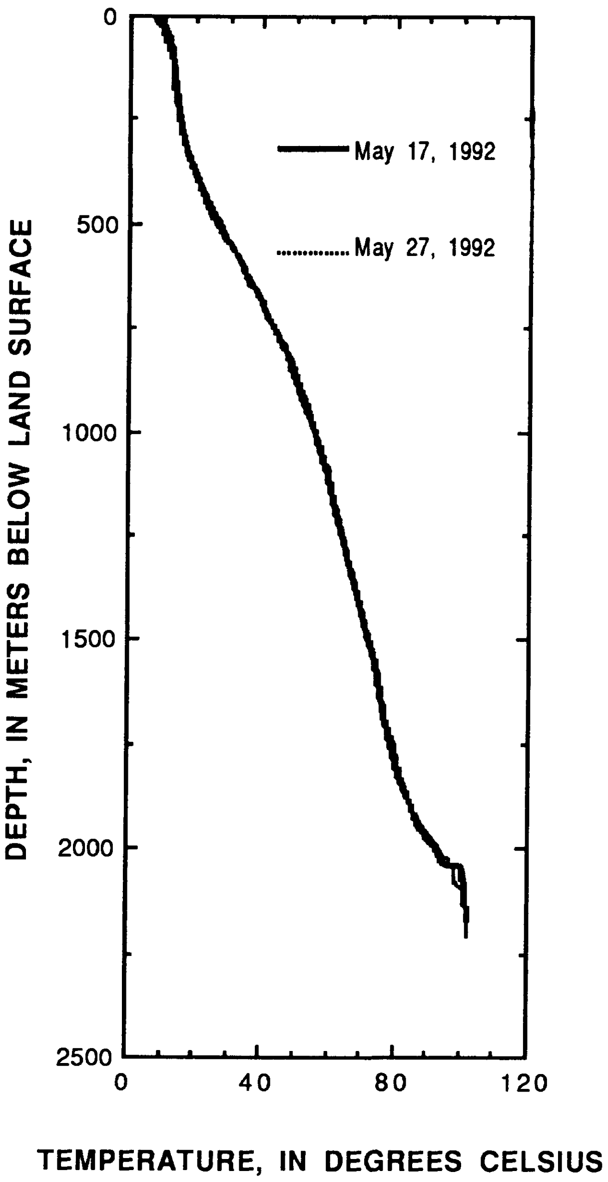
Given these results, the transmissivity of the open-hole section (2,098-2,313 m) cannot be quantified. However, an upper bound may be placed on the value of hydraulic conductivity above which flow would have been measurable during this experiment. If a minimum velocity resolution for the impeller flowmeter of 0.5 m/min (~ 4 L/min) and if a formation exposed to a hydraulic-head differential of 263 m are assumed, a maximum value of hydraulic conductivity can be computed from expressions derived by Cooper and Jacob (1946) and by Hvorslev (1949). This maximum hydraulic conductivity is on the order of 10^{-7} cm/s (permeability ~ 10^{-4} darcies). This maximum value could have been reduced considerably had the heat-pulse flowmeter been used to measure fluid flow. Had this tool, with its velocity resolution of a few centimeters per minute, detected no flow in the open hole, the upper bound on hydraulic conductivity would have been reduced by more than an order of magnitude.

The maximum hydraulic conductivity of the open hole also may be derived from water levels recorded in the well during the 6 months immediately following the completion of Phase-II drilling in late 1991 and early 1992. By applying a falling-head analysis (Hvorslev, 1949) to the data plotted in figure 6, hydraulic conductivity can be estimated. Again, because of the unusual well construction, it is not known if the water moving down the ODP drill pipe entered the formation below or bypassed the open hole to fill the casing annulus. However, the falling-head data present another opportunity to place an upper limit on the permeability of the formation by assuming that all of the mass exchange associated with the falling water level in the ODP drill pipe was into the open hole below 2,098 m. This situation defines a maximum value of hydraulic conductivity that is on the order of 10^{-9} cm/s (permeability ~ 10^{-6} darcies); a lower hydraulic conductivity would require some fluid to shunt the open hole and move up into the casing annulus. This upper limit on hydraulic conductivity is two orders of magnitude less than that derived from the injection test and overrides that previous estimate.

Table 2. Concentrations of selected ions in water samples from the Long Valley Exploratory Well, from an adjacent supply well, and from drilling mud used in the Long Valley Exploratory Well

Source	Depth (meters)	Date	Ions (milligrams per liter)			Specific conductance (microsiemens per centimeter at 25 degrees Celsius)
			Sodium	Sulfate	Chlorine	
LVEW	2,215	05-25-92	626	298	140	2,700
Supply well	270	05-25-92	14.5	4.4	3.4	125
Drilling mud	*	11-21-91	450	98	124	2,350

*representative sample taken at surface



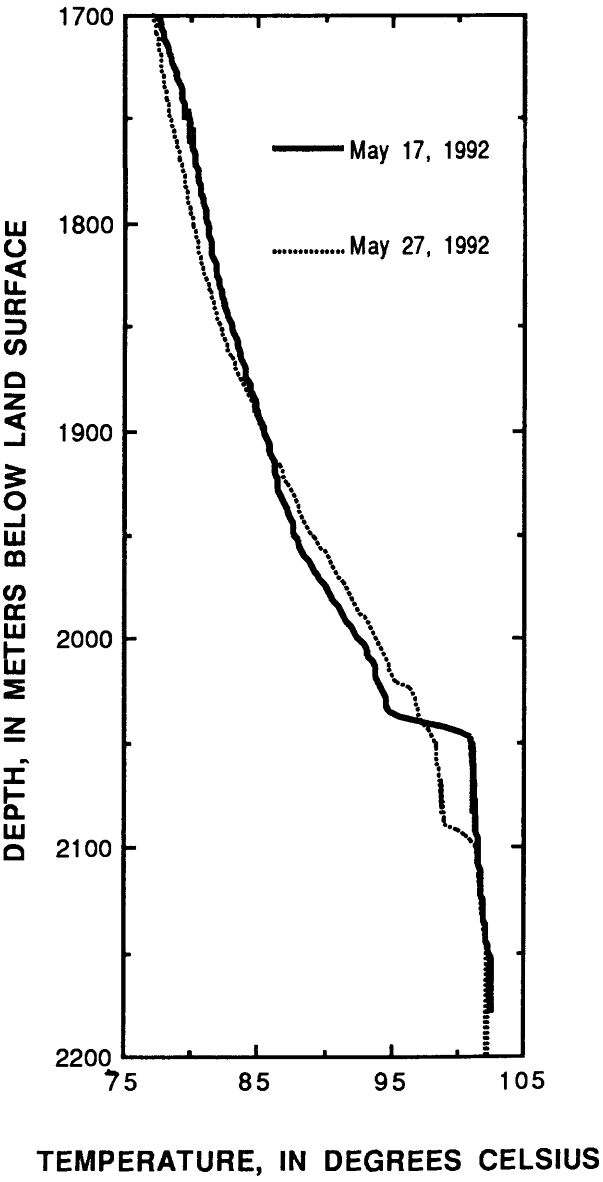


Figure 4. Temperature logs obtained in the Long Valley Exploratory Well before and after the injection test.

Figure 5. Expanded view of temperature profiles from figure 4 for lower 500 meters of bore hole.

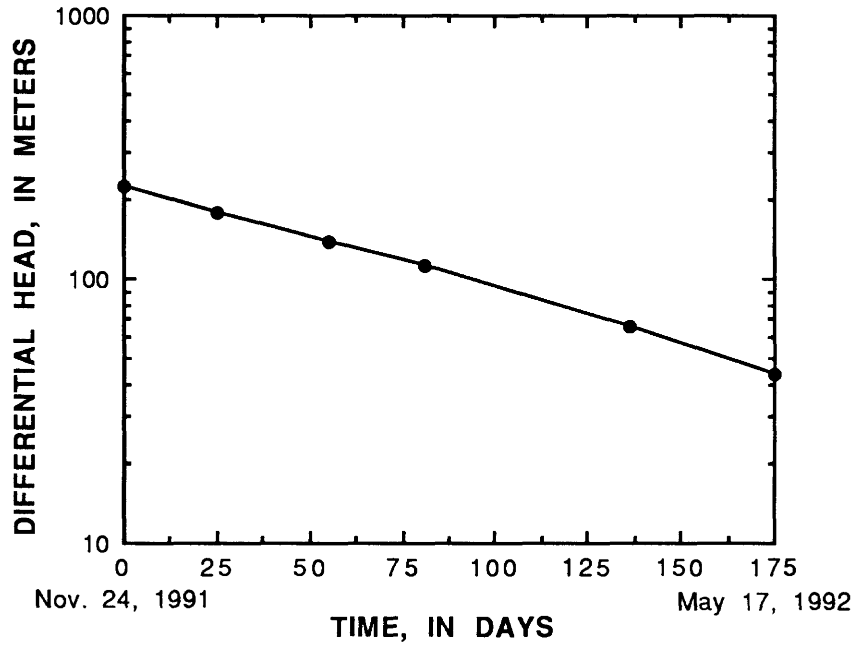


Figure 6. Falling-head data recorded in the Long Valley Exploratory Well during the 6 months prior to the injection test.

SUMMARY AND CONCLUSIONS

The hydraulic conductivity of the open-hole section (2,098-2,313 m) of the Long Valley Exploratory Well after Phase-II drilling proved to be too low to measure accurately by means of the flowmeter-injection field technique. Hydraulic communication between fluid within the ODP drill pipe and fluid within the outer-casing annulus further complicated the situation and introduced additional uncertainties. Temperature logs obtained before and after injection of approximately 30,000 L of water and complementary comparisons of injected volumes to volumes associated with rising water levels indicate that all detectable flow bypassed the open core hole and simply filled the outer annulus between the casing and the ODP drill pipe. Nevertheless, these results and a record of falling water levels for 6 months permit the permeability of the open hole to be constrained. An upper bound on the permeability of the formation between 2,098 and 2,313 m is estimated to be near the low end of the microdarcy range.

This very low estimate of permeability needs to be considered in light of the core descriptions and the geophysical logs obtained in the open-hole section of the LVEW. The electrical resistivity logs presented by Nelson and others (1992) indicated that variations in resistivity as a function of depth reflected changes in mineralogy rather than in fracture porosity, with high-resistivity spikes corresponding to the appearances of metaquartzite and marble. Moreover, Nelson and others (1992) were unable to extract a clear and reliable correlation between the neutron log and the rubble zones, as designated by McConnell and others (1992), from examination of cores. Therefore, these sections of fragmented core may represent localized, drilling-induced damage rather than a genuine hydrostratigraphic marker. The lack of distinct fracture zones and the very low values of apparent porosity (near zero) obtained in the metaquartzite sections of the metasediments support the conclusion that transmissivity in the open-hole section is very low.

The analyses and interpretations described in this report are based on results from field measurements that probed only the lower 215 m of the LVEW. This circumscribed set of data reflects the limited understanding of the hydrogeologic system underlying the caldera.

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