EARTHQUAKE-INDUCED WATER-LEVEL FLUCTUATIONS AT YUCCA MOUNTAIN, NEVADA, JUNE 1992

By GRADY M. O'BRIEN

U.S. GEOLOGICAL SURVEY

Open-File Report 93-73

Prepared in cooperation with the
NEVADA FIELD OFFICE,
U.S. DEPARTMENT OF ENERGY, under
Interagency Agreement DE-A108-92NV10874

Denver, Colorado
1993

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

The use of trade, product, industry, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

For additional information write to:

Chief, Hydrologic Investigations Program
Yucca Mountain Project Branch
U.S. Geological Survey
Box 25046, Mail Stop 421
Federal Center
Denver, CO 80225-0046

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Box 25425, Mail Stop 517
Federal Center
Denver, CO 80225-0425

CONTENTS

FIGURES

TABLE

CONVERSION FACTORS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
pounds per square inch (psi)	703.1	kilograms per square meter

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Earthquake-Induced Water-Level Fluctuations at Yucca Mountain, Nevada, June 1992

By Grady M. O'Brien

Abstract

This report presents earthquake-induced water-level and fluid-pressure data for wells in the Yucca Mountain area, Nevada, during June 1992. Three earthquakes occurred which caused significant water-level and fluid-pressure responses in wells. Wells USW H-5 and USW H-6 are continuously monitored to detect short-term responses caused by earthquakes. Two wells, monitored hourly, had significant, longer-term responses in water level following the earthquakes. On June 28, 1992, a 7.5-magnitude earthquake occurred near Landers, California causing an estimated maximum water-level change of 90 centimeters in well USW H-5. Three hours later a 6.6-magnitude earthquake occurred near Big Bear Lake, California; the maximum water-level fluctuation was 20 centimeters in well USW H-5. A 5.6-magnitude earthquake occurred at Little Skull Mountain, Nevada, on June 29, approximately 23 kilometers from Yucca Mountain. The maximum estimated short-term water-level fluctuation from the Little Skull Mountain earthquake was 40 centimeters in well USW H-5. The water level in well UE-25p #1, monitored hourly, decreased approximately 50 centimeters over 3 days following the Little Skull Mountain earthquake. The water level in UE-25p #1 returned to pre-earthquake levels in approximately 6 months. The water level in the lower interval of well USW H-3 increased 28 centimeters following the Little Skull Mountain earthquake. The Landers and Little Skull Mountain earthquakes caused responses in 17 intervals of 14 hourly monitored wells, however, most responses were small and of short duration. For several days following the major earthquakes, many smaller magnitude aftershocks occurred causing measurable responses in the continuously monitored wells.

INTRODUCTION

The Yucca Mountain area in southern Nevada is being studied by the U.S. Department of Energy as a potential site for an underground high-level nuclear-waste repository (U.S. Department. of Energy, 1988). As part of this study, the U.S. Geological Survey monitors water levels in 29 wells to define the potentiometric surface, determine long-term and seasonal water-level changes, and estimate hydraulic properties using short-term water-level fluctuations. Frequency of monitoring ranges from quarterly to continuous with most measurements being done either monthly or hourly. Monthly measurements are sufficient to detect long-term and seasonal changes, whereas hourly measurements are required to detect changes induced by barometric-pressure fluctuations and earth tides. Generally, only continuous measurements are capable of detecting short-term, seismically-induced water-level fluctuations. Data collected from wells showing significant fluctuations caused by earthquakes in June 1992, are presented in this report.

During late June 1992, earthquakes in California and Nevada (fig. 1) caused water levels to fluctuate throughout the Yucca Mountain area. Continuous water-level measurements made in wells USW H-5 and USW H-6 recorded the fluctuations caused by the earthquakes. Hourly water-level measurements in several wells at Yucca Mountain detected changes caused by the earthquakes. The Landers earthquake (fig. 1) occurred approximately three minutes before the hourly measurements were taken, at which time the water level was fluctuating rapidly due to the passing seismic waves. Hourly measurements represent an instantaneous sample of the water level during fluctuations that lasted for over one hour. The Little Skull Mountain earthquake occurred approximately 23 km from Yucca Mountain. Water level and fluid pressure in continuously monitored wells rose sharply and then receded, over a period of several hours, to pre-earthquake levels. Small amplitude, short-term water-level rises in hourly monitored wells were detected. The water-level rise in hourly monitored wells was on the order of centimeters and indistinguishable after two hours.

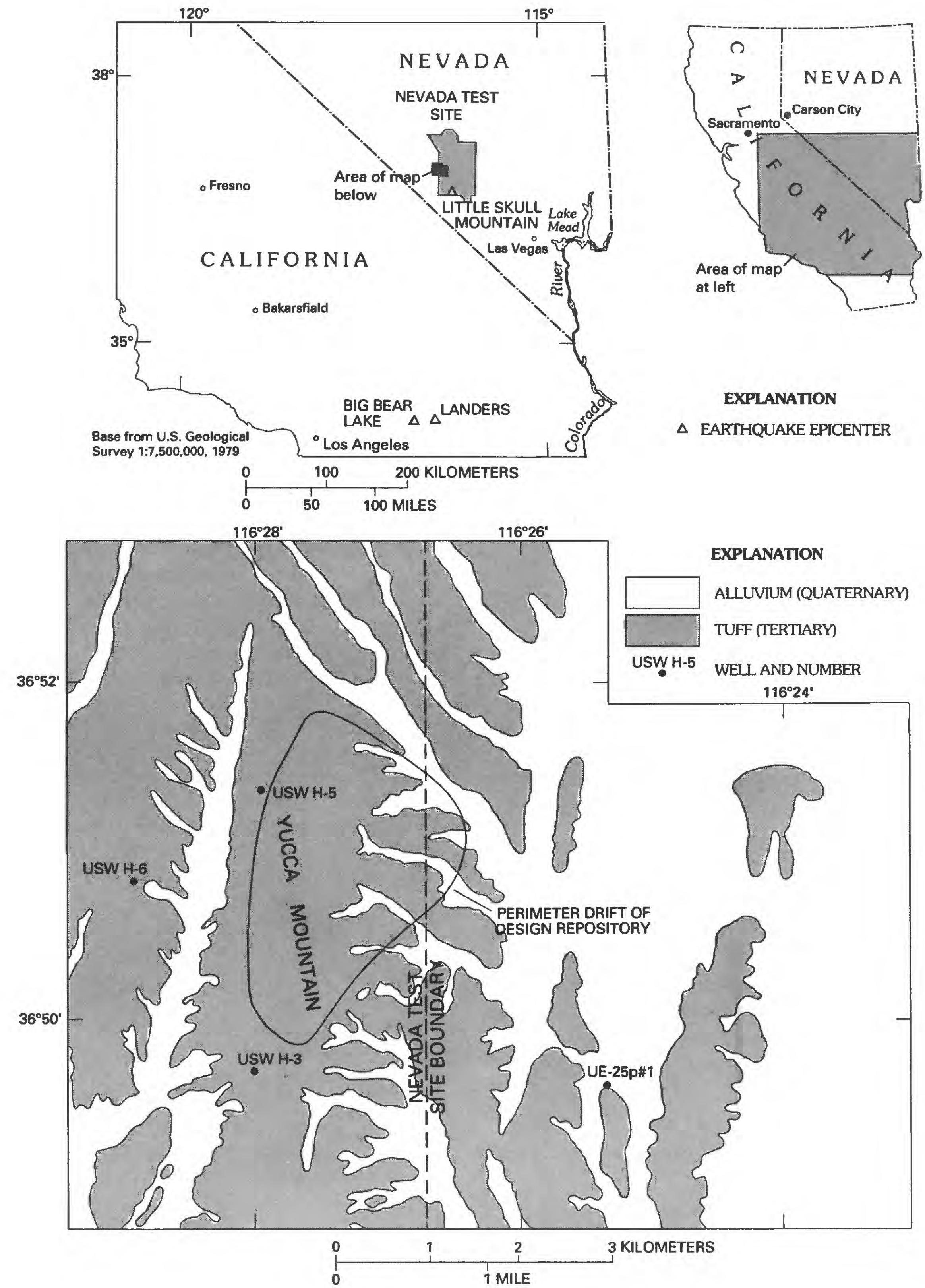

Figure 1. Map showing geographic locations of wells and earthquake epicenters.

Hydroseisms, or water-level fluctuations in response to earthquakes, are relatively common phenomena observed in wells penetrating confined aquifers (Todd, 1980, p. 250-252). For example, the Anchorage, Alaska, earthquake of 1964, magnitude 9.2, the largest North American earthquake thus far in the 20th century, caused water-level fluctuations throughout the world; the largest recorded peak-to-trough range was about 7.0 m (meters) in a well in South Dakota (Vorhis, 1967, p. 32). Hydroseisms are more commonly in the centimeters-to-meter range and typically are observed for minutes to tens of minutes. Hydroseisms roughly resemble damped oscillation curves but are somewhat more complicated because several different types of seismic waves participate in the phenomena. Relatively small dilatational (P) and shear (S) body waves are followed by long-period surface waves. Earthquakes several hundred kilometers away generating long-period surface waves can produce water-level fluctuations somewhat larger than aquifer-pressure changes. During local seismic events, short-period body waves probably predominate and produce water-level fluctuations that are smaller than aquifer-pressure changes. Rayleigh surface waves, from earthquakes with depths less than 15 km (kilometers), produce the largest water-level fluctuations in wells several hundred kilometers from the earthquake epicenter (Eaton and Takasaki, 1959, p. 227-229).

The author would like to thank Darrell Baldwin, Terry Campbell, and Rafael Valentin, of Foothills Engineering Consultants, Inc., for their assistance in collecting the data. Conversion of hourly data to water levels was done by Douglas Burkhardt. Earthquake information was obtained from the U.S. Geological Survey National Earthquake Information Center in Golden, Colorado.

DESCRIPTION OF WELLS

Well USW H-5 (lat 36°51'22"N., long 116°27'55"W.) is located on the crest of Yucca Mountain (fig. 1). The well was drilled to a depth of 1,219 m, and cased to a depth of 788 m, with perforations from 707-782 m. The well penetrates various volcanic units of Tertiary age (Robison and Craig, 1988). The well contains two intervals separated by a packer located at a depth of 1,091 m. Approximate depth-to-water, in both intervals, is 703 m, and the water-level altitude in this well is approximately 775 m above sea level. The upper interval is a free-water surface and is used to monitor the water level in the Bullfrog and Tram Members of the Crater Flat Tuff and a lower lava flow. The lower interval of the well is used to monitor the fluid pressure in an unnamed lava flow beneath the Crater Flat Tuff (Robison and others, 1988). The major water-producing zones in the well, as determined by borehole-flow surveys, occur in the upper interval at the contact between the Tram Member and the lower lava (8 percent of total flow) and in the Bullfrog Member (90 percent of total flow). Because water yield is not uniformly distributed through the stratigraphic units, fractures are believed to be the primary source of water (Robison and Craig, 1988).

Well USW H-6 (lat 36°50'49"N., long 116°28'55"W.) is located to the west of Yucca Mountain (fig. 1). The well was drilled to a depth of 1,220 m, and cased to a depth of 581 m, with perforations from 530-572 m. The well penetrates Tertiary volcanic rocks that are predominately ash-flow tuffs, with an unnamed lava from 877 to 1126 m (Craig and Reed, 1989). The well contains two intervals separated by a packer located at a depth of 752 m. Approximate depth-to-water, in both intervals, is 526 m, and the water-level altitude in this well is approximately 776 m above sea level. The upper interval is a free-water surface and is used to monitor the composite water level in the Prow Pass, Bullfrog, and Tram Members of the Crater Flat Tuff. The lower interval of the well is used to monitor the fluid pressure in the Tram Member and a lower unnamed lava flow of the Crater Flat Tuff and Lithic Ridge Tuff. Two major water-producing zones exist in the well, as determined by borehole-flow surveys (Craig and others, 1983). In the upper interval, a 15-m section produced approximately 60 percent of the total flow. In the lower interval, an 11-m section produced approximately 32 percent of the total flow. The two major water-producing zones are believed to be due to fractures (Craig and Reed, 1989).

Well UE-25p #1 (lat 36°49'38"N., long 116°25'21"W.) is located on the east side of Yucca Mountain (fig. 1). The well was drilled to a depth of 1,805 m, and cased to a depth of 1,297 m. The well penetrates various Tertiary volcanic units and Paleozoic carbonate rocks (Craig and Robison, 1984). Approximate depth-to-water is 362 m, and the water-level altitude is approximately 752 m above sea level. The well is constructed so that the hydraulic head in the Silurian and Devonian Lone Mountain Dolomite and Roberts Mountains Formation are measured (Craig and Johnson, 1984). The major water-producing zones in the Paleozoic section occur in the Lone Mountain Dolomite; a 190-m interval produced 30 percent of the total flow, and an interval less than 10-m thick produced more than 50 percent of the total flow (Craig and Robison, 1984).

Well USW H-3 (lat 36°49'42"N., long 116°28'00"W.) is located on the crest of Yucca Mountain (fig. 1). The well was drilled to a depth of 1,219 m, and cased to a depth of 792 m, with perforations from a depth of 754 to 792 m. The well penetrates various volcanic units of Tertiary age (Thordarson and others, 1984). The well contains two intervals separated by a packer located at a depth of 1,057 m. In the upper interval the approximate depth-to-water is 751 m, and the water-level altitude is approximately 732 m above sea level. In the lower interval the approximate depth-to-water is 728 m, and the water-level altitude is approximately 755 m. The packer separating the well into two intervals was placed in its present position in December 1990. The water level in the lower interval has been rising towards a static hydraulic head since that time. The upper interval is used to monitor the Tram Member of the Crater Flat Tuff. The lower interval is used to monitor the lower part of the Tram Member, a bedded tuff, and the Lithic Ridge Tuff. Two major water-producing zones exist in the well, as determined by a borehole-flow survey (Thordarson and others, 1984). In the upper interval of the well, at a depth of 809 to 841 m, the upper part of the Tram Member received 63 percent of the flow. In the lower interval of the well, at a depth of 1060 to 1120 m, the lower part of the Tram Member and the Lithic Ridge Tuff received 30 percent of the flow. Non-uniform distribution of watet yield in the stratigraphic units indicates fractures could be the primary source of water.

Instrumentation of Wells USW H-5 and USW H-6

Wells USW H-5 and USW H-6 are instrumented in the same manner for continuous water-level monitoring. The water levels in the upper intervals are open to the atmosphere and fluctuate in perforated casing and open borehole. The lower interval is separated from the upper interval by an inflatable packer attached to a 62-mm inside diameter access tube. Inside the lower interval access tube is an air-inflatable small-diameter packer which allows fluid pressure (rather than free-water surface) to be measured. The packer configuration in the lower interval eliminates well storage as well as viscosity and inertia effects that retard the movement of water as it flows to and from the well. The result is increased sensitivity in detecting pressure changes in the aquifer. Fluid-pressure measurements in the lower interval detect rapidly changing aquifer pressure induced by short-period earthquake waves. Due to the time required for water to move into and out of the well a free-water surface can not respond efficiently to short-period seismic waves (Leggette and Taylor, 1935).

To detect seismically induced water-level fluctuations, continuous monitoring of wells is required. Wells USW H-5 and USW H-6 have been equipped to monitor seismic events since March 17, and April 30, 1992. The data-collection system in the upper and lower intervals of each well consists of gauge pressure transducers with 5 pounds per square inch pressure ranges. The pressure transducers are continuously powered, and the output is recorded on an analog chart recorder. The chart recorder prints the transducer output and grid simultaneously so that no signal distortion or chart drift occurs. Chart speed is 1 millimeter per minute, and the full-scale range for each interval is approximately 0.52 m.

Instrumentation of Wells UE-25p #1 and USW H-3

Water levels in wells UE-25p #1 and USW H-3 are monitored hourly. Data collection platforms are used to sample pressure transducers and transmit the data via satellite to computers every 4 hours, resulting in near real-time data. The wells are equipped with gauge pressure transducers with 2.5 psi (UE-25p #1) and 5 psi (USW H-3) pressure ranges. UE-25p #1 is constructed so that only the hydraulic head in the lower carbonate rocks is monitored; the water level is open to the atmosphere. The packer configuration in USW H-3 allows water-level fluctuations to be measured in two intervals. Instrumentation is designed to detect water-level fluctuations caused by barometric-pressure changes and earth tides. Only significant and persistent water-levels changes caused by earthquakes can be detected in these wells.

EARTHQUAKE-INDUCED WATER-LEVEL FLUCTUATIONS

Two major earthquakes in southern California and one earthquake near Yucca Mountain during late June 1992, produced measurable water-level and fluid-pressure fluctuations in wells USW H-5 and USW H-6. Sections of the analog chart that recorded the effects of the earthquakes are shown in figures 2-5. Earthquake information and hydrologic responses to the earthquakes are summarized in table 1. The major earthquakes caused fluctuations that exceeded the range of the recording equipment. Maximum double amplitude values have been estimated to place an approximate limit on the fluctuations. Estimates were determined by graphically reconstructing the response past the limits of the analog chart. The accuracy of the estimates is approximately ±50 percent. Earthquakes at

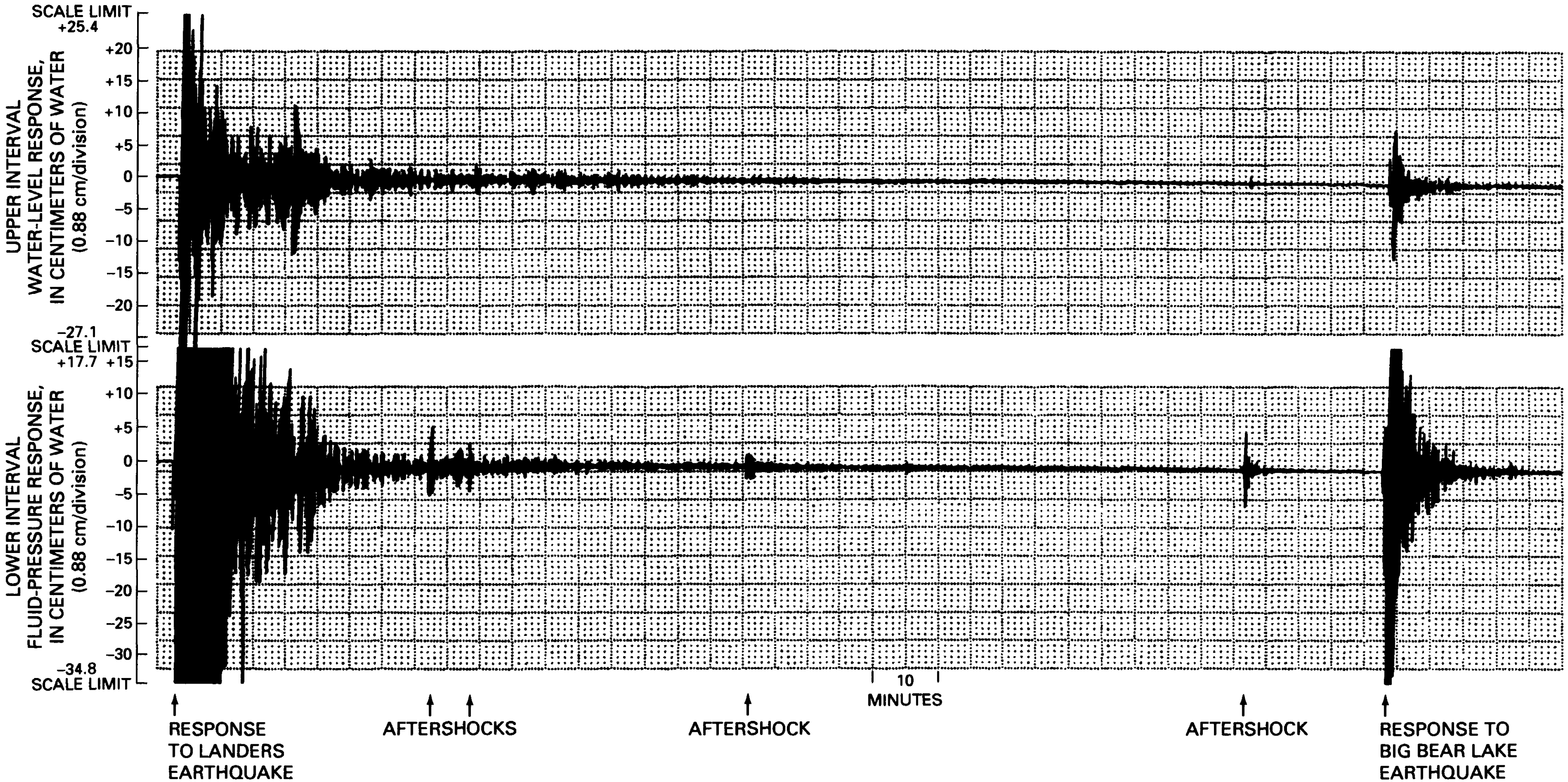

Figure 2. Well USW H-5 response to earthquakes near Landers (11:57:34 UTC) and Big Bear Lake (15:05:30 UTC), California, on June 28, 1992.

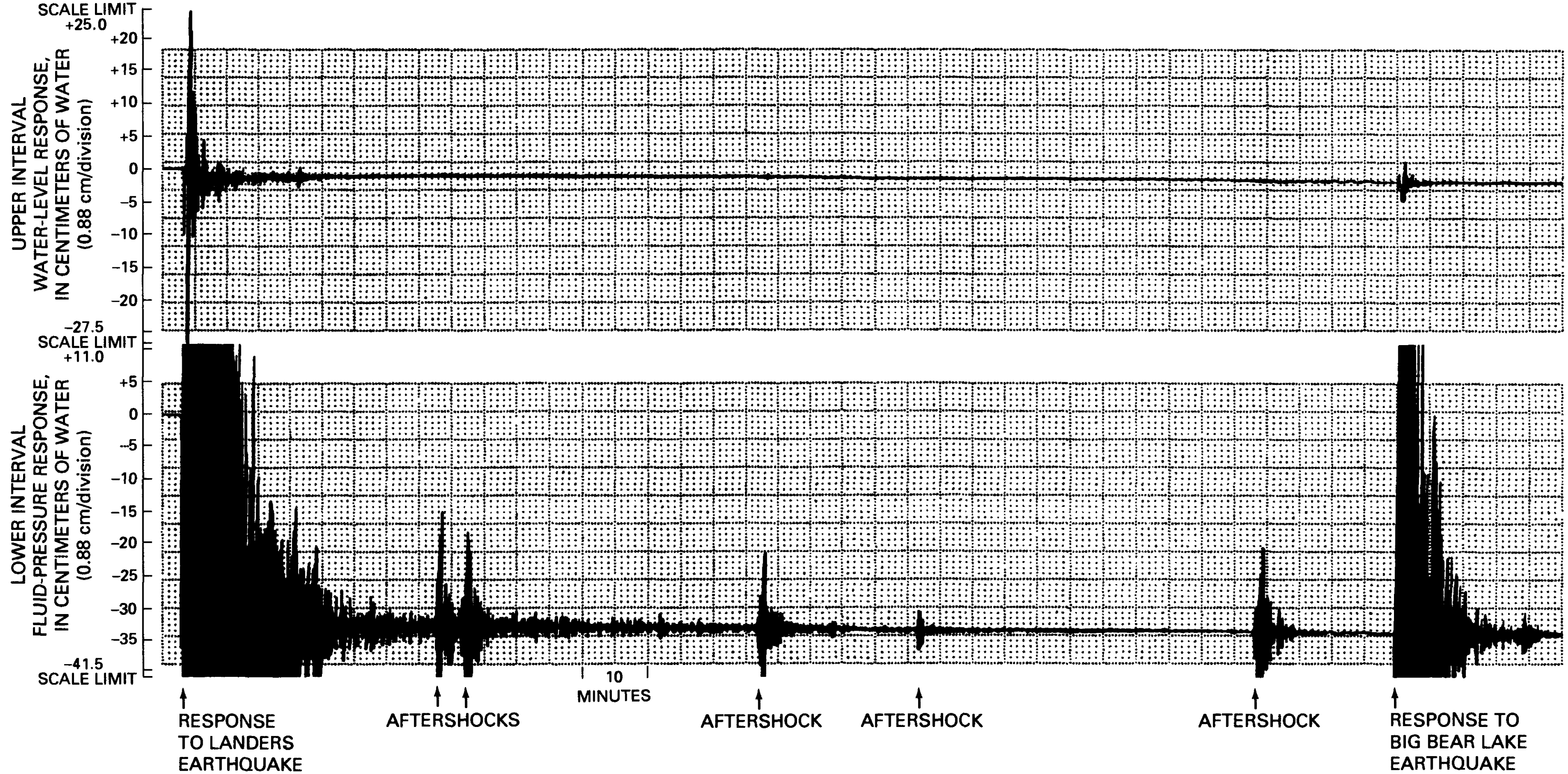

Figure 3. Well USW H-6 response to earthquakes near Landers (11:57:34 UTC) and Big Bear Lake (15:05:30 UTC), California, on June 28, 1992.

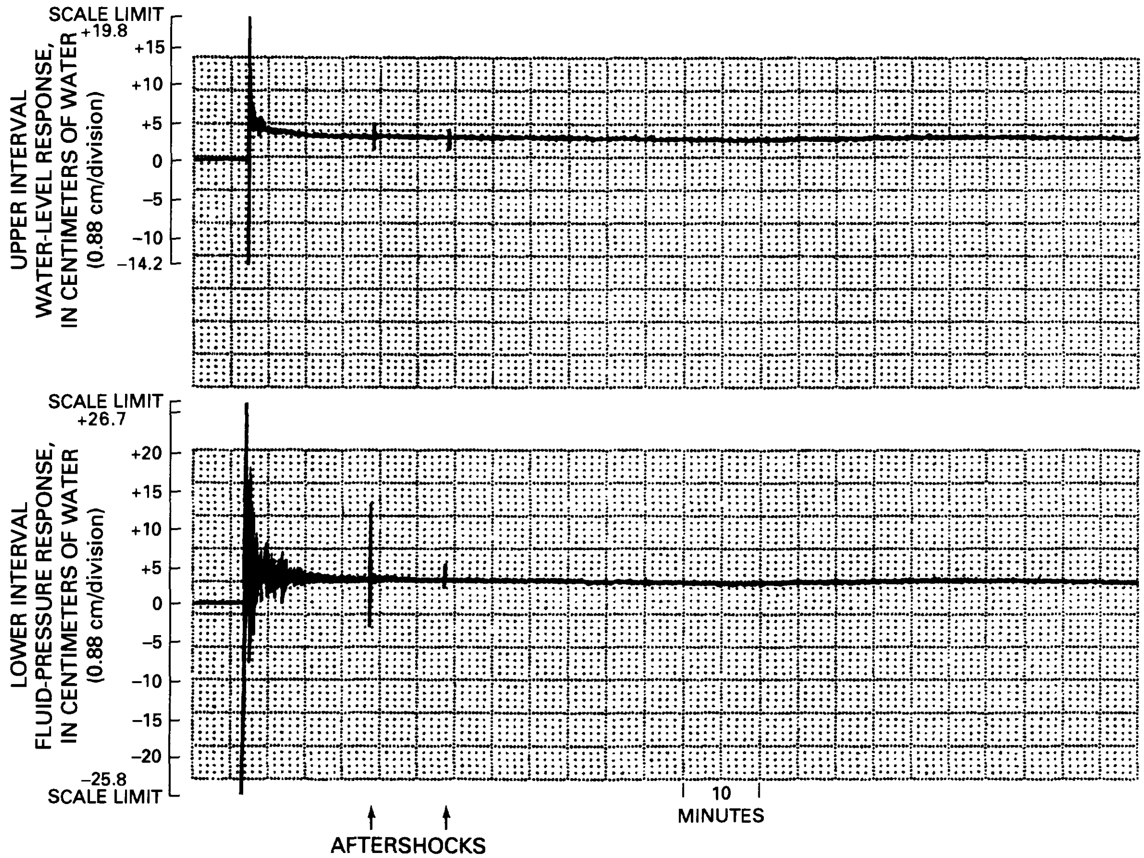

Figure 4. Well USW H-5 response to earthquake at Little Skull Mountain, Nevada, occurring at 10:14:22 UTC, on June 29, 1992.

similar distances from the well produce similar fluctuations. The double amplitude refers to the full range of fluctuation--maximum decrease to maximum increase in water level or fluid pressure.

The continuous water-level and fluid-pressure responses to an earthquake near Landers, California (fig. 1), at 11:57:34 Universal Time (UTC), June 28, 1992 (UTC minus 8 hours equals Pacific Standard Time) are shown in figures 2-3. The 7.5-magnitude earthquake occurred at lat 34°10'55" N., long 116°28'12" W. One person was killed, 400 people were reportedly injured, and significant damage occurred in the Landers area as a result of the earthquake. Surface faulting occurred along a series of faults that extended north and northwest from Landers for over 70 km, vertical scarps of 1.5 m were seen, and 4-5 m offsets were common on the northern part of the fault (Mori and others, 1992). The earthquake was reportedly felt in much of southern California, southern Nevada, southern Utah, and western Arizona. The earthquake occurred on a right-lateral strike-slip fault (Mori and others, 1992), at a distance of approximately 293 km from Yucca Mountain. Water-level fluctuations caused by the arrival of P-waves and Rayleigh waves are difficult to distinguish in figures 2-3, due to the relatively short distance to the earthquake epicenter and the compressed time scale. The peak water-level double amplitude in the upper interval of USW H-5 was off scale and estimated to be 90 cm. The fluctuations damped to 1 cm in about 90 minutes. The peak fluid-pressure double amplitude in the lower interval was off scale and estimated to be 1.5 m. The fluctuations damped to 1 cm in about 100 minutes. The peak water-level double amplitude in the upper interval of USW H-6 was off scale and estimated to be 60 cm. The fluctuations damped to 1 cm in about 19 minutes. The peak fluid-pressure double amplitude in the lower interval was off scale and estimated to be 2.2 m. The fluctuations damped to 1 cm in about 90 minutes. Several aftershocks caused smaller amplitude responses in USW H-5 and USW H-6, which can be seen in figures 2-5.

An apparent offset of the water level in the lower interval of USW H-6 after the Landers earthquake is due to the small-diameter packer moving upward as a result of the high pressure caused by the seismic waves. Moving the transducer upward in the water column resulted in a decrease of pressure and thus, an apparent

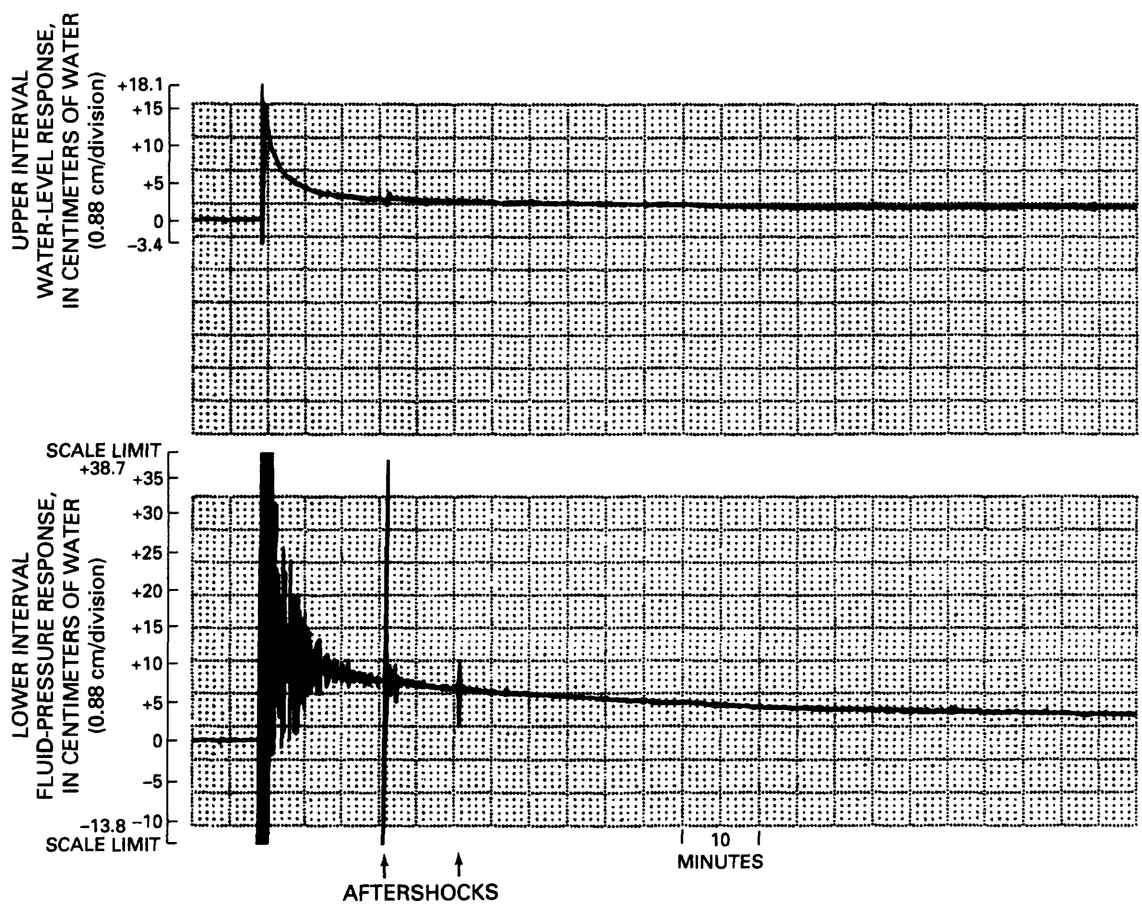

Figure 5. Well USW H-6 response to earthquake at Little Skull Mountain, Nevada, occurring at 10:14:22 UTC, on June 29, 1992.

Table 1. Summary of earthquake information and hydrologic responses to earthquakes

Earthquake location	Earthquake magnitude	Distance to earthquake from well (kilometers)	Well name	Water-level response[1] (meters)	Fluid-pressure response[1] (meters)
Landers, CA	7.5	296	USW H-5	0.9 (E)	1.5 (E)
Landers, CA	7.5	295	USW H-6	0.6 (E)	2.2 (E)
Big Bear Lake, CA	6.6	299	USW H-5	0.2	1.0 (E)
Big Bear Lake, CA	6.6	298	USW H-6	0.06	1.4 (E)
Little Skull Mountain, NV	5.6	25.5	USW H-5	0.4 (E)	0.6 (E)
Little Skull Mountain, NV	5.6	25.9	USW H-6	0.22	1.1 (E)

(E) = estimated value

[1]Responses are observed or estimated double-amplitude fluctuations (maximum increase to maximum decrease).

decrease in water level. A water-level measurement one day later confirmed that no persistent change in water level occurred. After repositioning the transducer and packer at the original position, the transducer output returned to its normal level. Calibrations before and after the earthquake indicated that no damage occurred to the transducer as a result of the seismic waves.

Seismic waves produced larger amplitude water-level fluctuations in the upper interval of USW H-5 than in the upper interval of USW H-6. The upper interval of USW H-5 produces a larger percentage of total borehole flow than the upper interval of USW H-6, probably because the upper interval of USW H-5 contains more fractures than the upper interval of USW H-6. The upper interval of USW H-5 is, therefore, more responsive to seismic waves than the upper interval of USW H-6. The lower interval of well USW H-6 had greater sensitivity to seismic waves than the lower interval of well USW H-5. The major difference between the intervals is that no significant flow occurs in the lower interval of USW H-5, whereas, the lower interval of USW H-6 contains a major producing flow zone. Orientation of fractures relative to the direction of seismic wave propagation could also affect the sensitivity and amplitude of the well response. Fractures oriented perpendicular to seismic waves could potentially have dilation and compression of the aperture resulting in increased fluid flow to and from the well which could cause large-amplitude water-level fluctuations. The amount of dilation or compression of fractures oriented parallel to seismic waves would be smaller, resulting in less fluid flow to the well and smaller amplitude water-level fluctuations.

Hourly monitored wells were sampling 3 minutes after the Landers earthquake, during a time when the seismic waves were causing rapid, short-term changes in the water levels. UE-25p #1 and USW H-3, lower interval, were the only hourly monitored wells to detect a water-level change 1 hour after the earthquake. The long-term effect of the Landers earthquake on the water level in UE-25p #1 is difficult to determine because of the strong earth-tide influence on the water level (fig. 6). USW H-3 had a decrease in water level of approximately 14 cm 1 hour after the earthquake (fig. 7).

A major earthquake near Big Bear Lake, California (fig. 1), occurred at 15:05:30 UTC, June 28, 1992, 3 hours after the Landers mainshock. The 6.6-magnitude earthquake occurred at lat 34°10'12" N., long 116°47'13" W. The earthquake occurred on a northeast trending left-lateral strike-slip fault (Mori and others, 1992), at a distance of approximately 296 km from Yucca Mountain. Damage to structures and landslides were reported in the Big Bear Lake area. The earthquake was felt in large parts of southern California, southern Nevada, and western Arizona. The water-level and fluid-pressure response to the Big Bear Lake earthquake is shown in figures 2-3. The peak water-level double amplitude in the upper interval of USW H-5 was 20 cm. The fluctuations damped to 1 cm in about 12 minutes. The peak fluid-pressure double amplitude in the lower interval was off scale and estimated to be 1 m. The fluctuations damped to 1 cm in about 21 minutes. The peak water-level double amplitude in the upper interval of USW H-6 was 6 cm. The fluctuations damped to 1 cm in about 5 minutes. The peak fluid-pressure double amplitude in the lower interval was off scale and estimated to be 1.4 m. The fluctuations damped to 1 cm in about 24 minutes. Hourly monitored wells did not detect any water-level changes as a result of the Big Bear Lake earthquake.

A 5.6-magnitude earthquake occurred at Little Skull Mountain, Nevada, at 10:14:22 UTC, June 29, 1992. The earthquake, located at lat 36°40'59"N., long 116°16'34"W., was approximately 23 km from Yucca Mountain. It is the largest recorded earthquake within the boundary of the Nevada Test Site. The tectonic region, at the western edge of the Basin and Range, in general, has a mixture

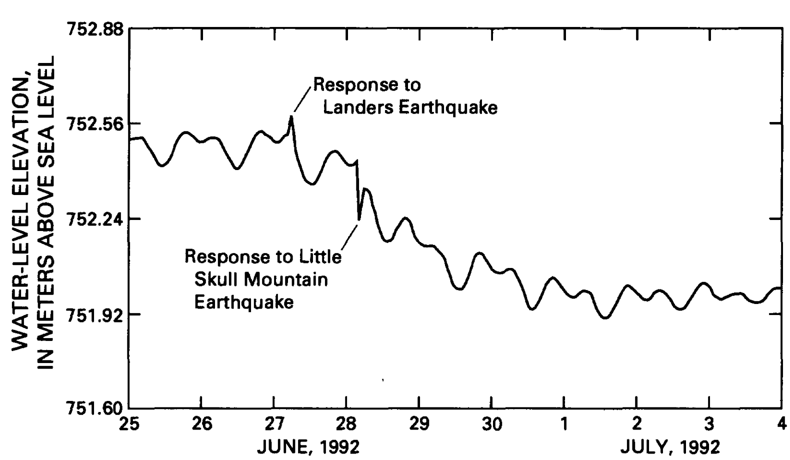

Figure 6. Well UE-25p #1 water-level response to Landers and Little Skull Mountain earthquakes.

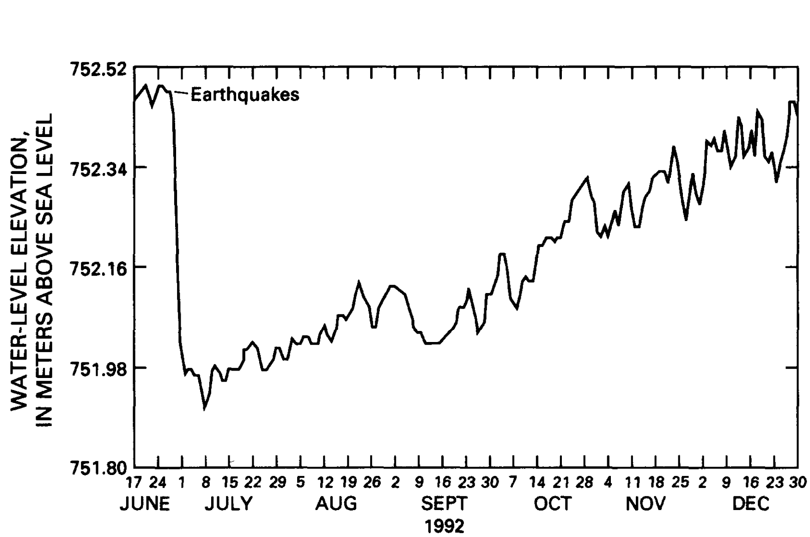

Figure 7. Recovery of mean-daily water level in well UE-25p #1 following Landers and Little Skull Mountain earthquakes.

of north-trending normal faults, as well as northwest and northeast-trending strike-slip faults. The earthquake occurred on a northeast-trending normal fault dipping to the southeast (Professor James Brune, University of Nevada, Reno, Seismological Laboratory, written commun., 1992). No surface rupture occurred and no mapped surface faults have been correlated to the earthquake. Several aftershocks with both normal faulting and strike slip faulting occurred in the area, suggesting a complex stress-release pattern (Professor James Brune, written commun., 1992).

The continuous water-level and fluid-pressure responses to the Little Skull Mountain earthquake are shown in figures 4-5. The responses are unique when compared to other earthquake-induced fluctuations recorded at wells USW H-5 and USW H-6. Changes in the regional strain field may have occurred in the area close to the earthquake epicenter (Joan Gomberg, U.S. Geological Survey, oral commun., 1992). The change in the strain field may have compressed the aquifer which could cause the water levels to temporarily rise. Water-level and fluid-pressure responses at Yucca Mountain may be due to both seismic waves and the change in the regional strain field.

Peak water-level double amplitude in the upper interval of USW H-5 was off scale and estimated to be 40 cm. Peak fluid-pressure double amplitude in the lower interval was off scale and estimated to be 64 cm. Water and fluid pressure had returned to within 2 cm of pre-earthquake conditions 440 minutes after the earthquake. Peak water-level double amplitude in the upper interval of USW H-6 was 22 cm, and the water level returned to pre-earthquake level in about 286 minutes. Peak fluid-pressure double amplitude in the lower interval was off scale and estimated to be 1.1 m; fluid pressure returned to pre-earthquake conditions in about 447 minutes.

Only two hourly monitored wells showed significant water-level changes following the Little Skull Mountain earthquake. The water level in UE-25p #1 decreased for about 3 days following the earthquake (fig. 6). The total change of approximately 50 cm was confirmed by water-level measurement on July 7, 1992. UE-25p #1 is the only well at Yucca Mountain that monitors the water level in the deep carbonate aquifer, therefore, it is not possible to correlate the water-level change with other wells. However, the water level in Devil's Hole, a ground-water filled fault in the carbonate aquifer, about 47 km to the southeast, decreased less than 25 cm following the period of earthquake activity on June 28-29, 1992 (Timothy Coonan, National Park Service, written commun., 1992). The Landers earthquake occurred less than 23 hours before the Little Skull Mountain earthquake, making it difficult to determine which earthquake had the greatest effect on the water level in UE-25p #1. The hydraulic head in UE-25p #1 returned to its pre-earthquake level (fig. 7) in approximately 6 months.

The water level in the lower interval of USW H-3 increased a total of 28 cm from the hour before to the hour after the Little Skull Mountain earthquake (fig. 8). The total change can probably be attrib-

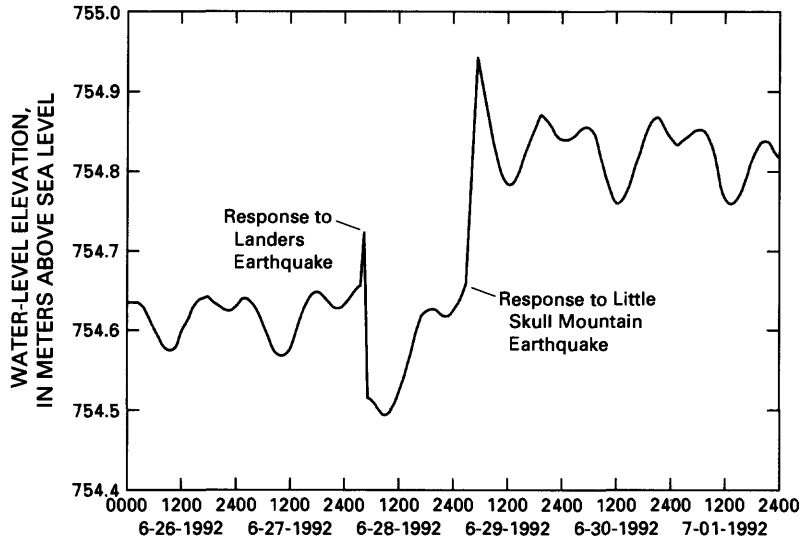

Figure 8. Well USW H-3, lower interval, water-level response to Landers and Little Skull Mountain earthquakes.

uted to the earthquake because the normal fluctuation due to earth tides was beginning a downward trend. Water level in this interval has been rising toward a static hydraulic head since the packer was installed in December 1990. The upper interval of USW H-3 did not show any significant changes that could be attributed to the earthquakes.

SUMMARY

Three earthquakes caused measurable changes in water level and fluid pressure at Yucca Mountain during June 28-29, 1992. The Landers earthquake caused the largest responses, the maximum water-level double amplitudes were estimated to be 90 cm in USW H-5 and 60 cm in USW H-6; maximum fluid-pressure double amplitudes were estimated to be 1.5 m in USW H-5 and 2.2 m in USW H-6. Fluctuations caused by the earthquakes, however, were typically of short duration and of small amplitude. Water-level fluctuations caused by the Landers and Big Bear Lake earthquakes were due to seismic waves. The Little Skull Mountain earthquake caused responses that were probably not due solely to seismic waves, but may have been a result of a change in the regional strain field. Wells UE-25p #1 and USW H-3, lower interval, were the only wells with persistent changes in water levels observed as a result of the earthquakes. The water level in UE-25p #1 recovered from the effect of the earthquakes in approximately 6 months. The water level in USW H-3 was offset due to the earthquakes, but is following the same, pre-earthquake trend toward a static water level.

REFERENCES

Craig, R.W., Reed, R.L., and Spengler, R.W., 1983, Geohydrologic data for test well USW H-6, Yucca Mountain Area, Nye County, Nevada: U.S. Geological Survey Open-File Report 83-856, 35 p. (NNA.870406.0058)

Craig, R.W., and Johnson, K.A., 1984, Geohydrologic data for test well UE-25p #1, Yucca Mountain Area, Nye County, Nevada: U.S. Geological Survey Open-File Report 84-450, 63 p. (NNA.870406.0256)

Craig, R.W., and Robison, J.H., 1984, Geohydrology of rocks penetrated by test well UE-25p #1, Yucca Mountain, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigation Report 84-4248, 57 p. (HQS.880517.1133)

Craig, R.W., and Reed, R.L., 1989, Geohydrology of rocks penetrated by test well USW H-6, Yucca Mountain, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigation Report 89-4025, 40 p. (NNA.900615.0030)

Eaton, J.P., and Takasaki, K.J., 1959, Seismological interpretation of earthquake-induced water-level fluctuations in wells: Seismological Society of America Bulletin, v. 49, no. 3, p. 227-245. (NNA.920529.0052)

Leggette, R.M., and Taylor G.H., 1935, Earthquakes instrumentally recorded in artesian wells: Seismological Society of America Bulletin, v. 25, no. 2, p. 169-175. (NNA.920605.0069)

Mori, J., Hudnut, K., Jones, L., Hauksson E., and Hutton K., 1992, Rapid scientific response to Landers quake: Eos, Transactions, American Geophysical Union, v. 73, number 39, September 29, 1992, p. 417-418.

Robison, J.H., and Craig, R.W., 1988, Geohydrology of rocks penetrated by test well USW H-5, Yucca Mountain, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigation Report 88-4168, 44 p. (NNA.900110.0400)

Robison, J.H., Stephens, D.M., Luckey, R.R., and Baldwin, D.A., 1988, Water levels in periodically measured wells in the Yucca Mountain area, Nevada, 1981-87: U.S. Geological Survey Open-File Report 88-468, 132 p. (NAA.890306.0113)

Thordarson, William, Rush, F.E., and Waddell, S.J., 1984, Geohydrology of test well USW H-3, Yucca Mountain, Nye County, Nevada: U.S. Geological Survey Water-Resources Investigations Report 84-4272, 38 p. (HQS.880517.1852)

Todd, D.K., 1980, Groundwater hydrology, (2d ed.): New York, Wiley, 535 p. (NNA.920529.0056)

U.S. Department of Energy, 1988, Site characterization plan, Yucca Mountain site, Nevada research and development area, Nevada: U.S. Department of Energy Report DOE RW/0199, 9 v., various pagination. (HQO.881201.0002)

Vorhis, R.C., 1967, Hydrologic effects of the earthquake of March 27, 1964, outside Alaska, *with sections on* Hydroseismograms from the Nunn-Bush Shoe Co. well, Wisconsin, by E.E. Rexin and R.C. Vorhis, *and* Alaska earthquake effects on ground water in Iowa, by R.W. Cable: U.S. Geological Survey Professional Paper 544-C, 54 p. (NNA.920529.0057)

NOTE: Parenthesized numbers following each cited reference are for U.S. Department of Energy OCRWM Records Management purposes only and should not be used when ordering the publication.

*U.S. GOVERNMENT PRINTING OFFICE: 1993-774-207/60043