HYDROLOGIC RESPONSES TO EARTHQUAKES, JUNE 28-29, 1992 AT YUCCA MOUNTAIN, NEVADA

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ABSTRACT

Yucca Mountain in southern Nevada is being studied as a potential site for an underground, high-level, nuclear-waste repository. Concern that earthquakes might cause the water table to rise more than 145 meters to the proposed repository level has increased interest in seismically-induced water-level fluctuations. Two wells are each instrumented to continuously monitor both water-table fluctuations and fluid-pressure changes in a deeper, isolated interval; other wells are monitored hourly or monthly. The responses to earthquakes closely resemble seismograms and can be used to determine rock strain and aquifer properties. Fluid-pressure responses are more sensitive to seismic waves than are water-level responses because no water flows into or out of the well, eliminating well storage, viscosity, and inertia effects that retard the movement of water.

On June 28, 1992, two major earthquakes occurred in southern California, both approximately 300 kilometers from Yucca Mountain. A 7.5-magnitude earthquake near Landers caused an estimated maximum water-level fluctuation of 0.9 meters, and an estimated maximum fluid-pressure fluctuation of 2.2 meters. Three hours later, a 6.6-magnitude earthquake near Big Bear Lake caused a maximum water-level fluctuation of 0.2 meters, and an estimated maximum fluid-pressure fluctuation of 1.4 meters. On June 29, 1992, a 5.6-magnitude earthquake at Little Skull Mountain, Nevada, approximately 23 kilometers from Yucca Mountain, caused an estimated maximum short-term water-level fluctuation of 0.4 meters, and an estimated maximum fluid-pressure fluctuation of 1.1 meters. Several maximum fluctuations had to be estimated because the peak response exceeded the scale of the recording equipment. A well monitoring water levels in the carbonate aquifer beneath Yucca Mountain on an hourly basis was one of only two wells that showed a persistent change in water-level altitude following the earthquake sequence. The decrease of about 0.5 meters in the water level in that well corresponds to a water-level decrease of less than 0.25 meters long-term over 3 days in Devil's Hole, a ground-water filled fault in the carbonate aquifer, about 47 kilometers to the southeast of Yucca Mountain.

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 (1). As part of that 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. The frequency of measurement ranges from quarterly to continuous, and most measurements are obtained either monthly or hourly. Generally, only continuous measurements are capable of detecting short-term, seismically-induced water-level fluctuations.

During late June 1992, earthquakes in California and Nevada (Fig. 1) caused water levels to fluctuate throughout the Yucca Mountain area. The two wells that continuously monitor water levels and fluid pressures, USW H-5 and USW H-6 (Fig. 1), detected high-frequency fluctuations caused by the earthquakes. Hourly water-level measurements in several wells in the Yucca Mountain area also detected short-term fluctuations caused by the earthquakes. The Landers, California, 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. The Little Skull Mountain, Nevada, earthquake occurred approximately 23 km (kilometers) 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 the hourly monitored wells also were detected for the Little Skull Mountain earthquake. The water-level rise in the hourly monitored wells was on the order of centimeters and was indistinguishable after two hours. Data collected from wells showing fluctuations caused by earthquakes in June, 1992, are presented in this paper.

Hydroseisms, or water-level fluctuations in response to seismic waves, are relatively common phenomena observed in wells penetrating confined aquifers (2). For example, the Anchorage, Alaska earthquake of 1964, magnitude 9.2, is the largest North American earthquake thus far in the 20th century, and 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 (3). Hydroseisms are more commonly less than one meter, and typically are observed for periods ranging from 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 short-period dilatational (P) and shear (S) body waves are followed by long-period surface waves. Distant earthquakes generating long-period surface waves can produce water-level fluctuations somewhat larger than aquifer fluid-pressure changes. However, short-period body waves, which probably predominate during local seismic events, produce aquifer fluid-pressure changes much larger than water-level fluctuations. Rayleigh surface waves, from earthquakes of depths less than 15 km, produce the largest water-level fluctuations in wells

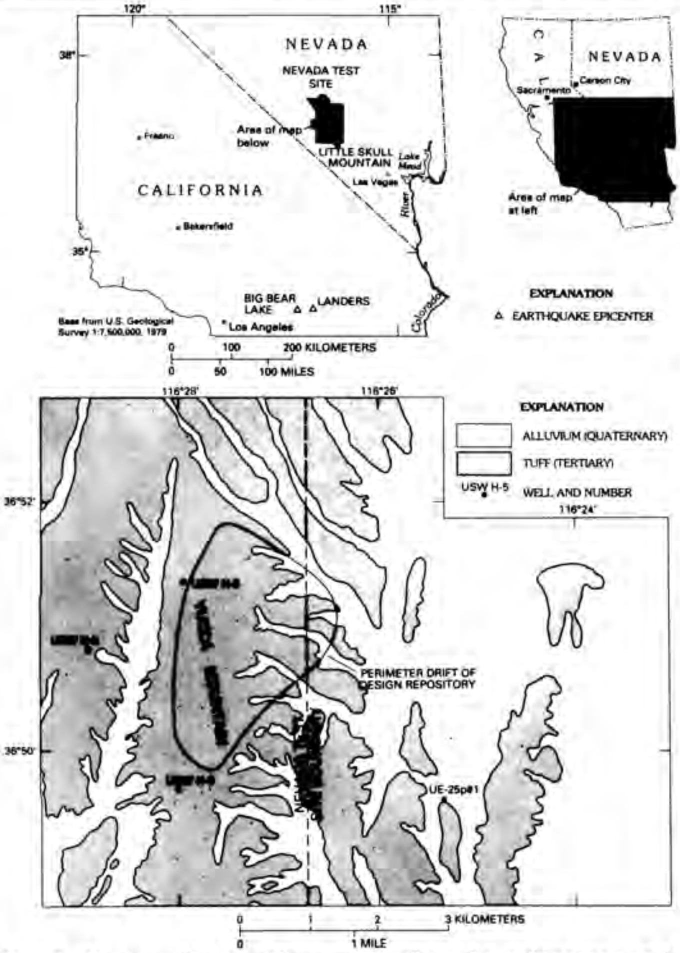

Fig. 1. Geographic locations of earthquake epicenters and monitoring wells.

several hundred kilometers from the earthquake epicenter (4).

DESCRIPTION OF WELLS

Well USW H-5 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 Tertiary volcanic units (5), and the approximate depth to water in both intervals is 703 m. Well USW H-5 contains two intervals separated by a packer located at a depth of 1,091 m. The upper interval contains a free-water surface and monitors the water level in the upper, more productive part of the aquifer. The lower interval of the well monitors fluid pressure in the lower, less productive part of the aquifer. Borehole-flow surveys indicated that 98 percent of the water flowing to the well occurs in two zones in the upper interval of the well (6). Because water-yield is not uniformly distributed through the stratigraphic units, fractures are believed to be the primary source of water to the well (5).

Well USW H-6 is located about 1 km 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 unit from 877 to 1126 m (7), and the approximate depth to water in both intervals is 526 m. Well USW H-6 contains two intervals separated by a packer located at a depth of 752 m. The upper interval contains a free-water surface and monitors the water level in the upper, more productive part of the aquifer. The lower interval of the well is used to monitor the fluid pressure in the lower, less productive part of the aquifer. Borehole-flow surveys indicated that two major water-producing zones exist in the well (8). 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 30 percent of the total flow. The two major water-producing zones are believed to be due to fractures in those zones (7).

Wells USW H-5 and USW H-6 are similarly instrumented for continuous water-level monitoring. Both intervals of each well contain continuously powered gauge pressure transducers. Transducer 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. Data are also collected hourly using data-collection platforms that transmit the data via satellite to project computers.

Well UE-25p #1 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. Well UE-25p #1 penetrates various Tertiary volcanic units and Paleozoic carbonate rocks (9), and the approximate depth to water is 362 m. The well is constructed so that only the hydraulic head in the Paleozoic carbonate rocks are measured (10). Two major water-producing zones occur in the Paleozoic section; 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 (9).

Well USW H-3 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. Well USW H-3 penetrates various Tertiary volcanic units (11), and is separated into two intervals by a packer located at a depth of 1,057 m. In the upper interval the approximate depth to water is 751 m, and in the lower interval the approximate depth to water is 728 m. The packer separating the well into two intervals was placed in its present position in December, 1990, and the water level in the lower interval has been rising towards a static hydraulic head since that time. A borehole-flow survey indicated that two major water-producing zones are present in the well (11). In the upper interval of the well, a zone between 809 and 841 m, produced about 60 percent of the flow. In the lower interval of the well, a zone between 1060 and 1120 m, produced 30 percent of the flow.

Water levels in wells UE-25p #1 and USW H-3 are monitored hourly, using gauge pressure transducers. Data collection platforms are used to sample the transducers and transmit the data via satellite to project computers every 4 hours, resulting in near real-time data collection. Instrumentation is designed to detect water-level fluctuations caused by barometric-pressure changes and earth tides. Only significant (above background) and persistent water-levels changes caused by earthquakes can be detected in these wells.

HYDROLOGIC RESPONSES TO EARTHQUAKES

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 Figs. 2-5. Earthquake information and hydrologic responses to the earthquakes are summarized in Table I. The major earthquakes caused fluctuations that exceeded the range of the recording equipment, and maximum double-amplitude values have been estimated to place an approximate limit on the fluctuations. The double amplitude refers to the full range of fluctuation, maximum decrease to maximum increase in water level or fluid pressure. Estimates were determined by graphically reconstructing the response beyond the limits of the analog chart. This method of estimation is considered valid because smaller magnitude earthquakes at similar distances from the well produce fluctuations that are similar in shape but smaller in magnitude.

The continuous water-level and fluid-pressure responses to a magnitude 7.5 earthquake near Landers, California, at 11:57:34 Universal Time (UTC), June 28, 1992 (UTC minus 8 hours equals Pacific Standard Time) are shown in Figs. 2-3. 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 (12). The earthquake was felt in much of southern California, southern Nevada, southern Utah, and western Arizona. The earthquake occurred on a right-lateral strike-slip fault (12), at a distance of approximately 293 km from Yucca Mountain. The peak water-level double amplitude in the upper interval of USW H-5 was off scale and is estimated to be 90 cm (centimeters). Fluctuations damped to 1 cm in about 90 minutes. Peak fluid-pressure double amplitude in the lower interval was off scale and is estimated to be 1.5 m. Fluctuations damped to 1 cm in about 100 minutes. The peak water-level double amplitude in the

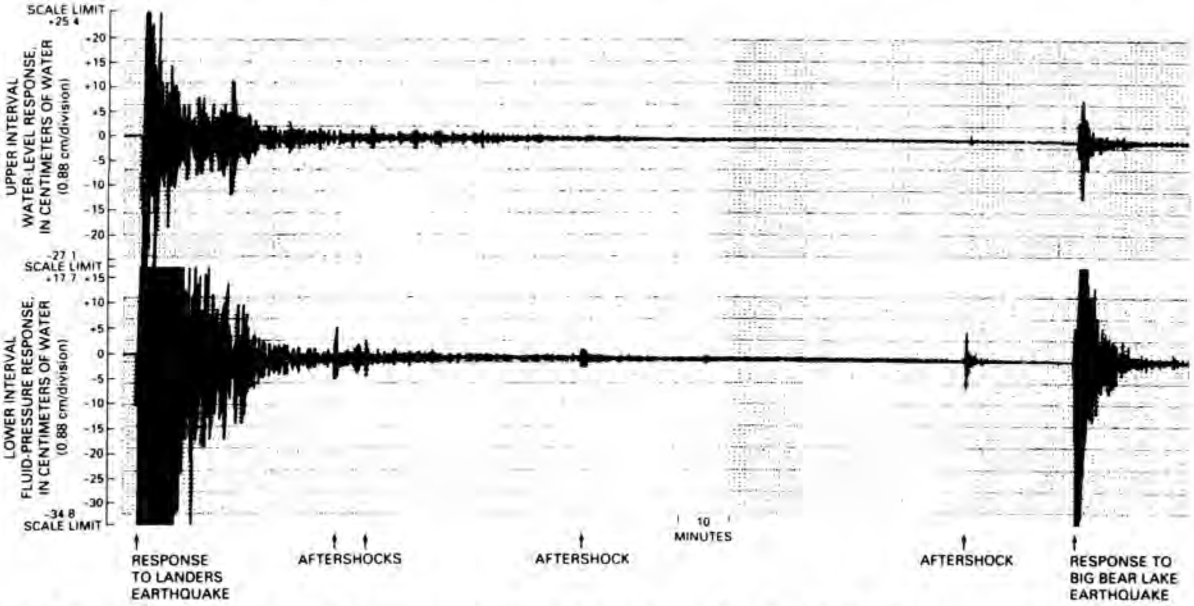

Fig. 2. Well USW H-5 response to earthquakes near Landers and Big Bear Lake, California, on June 28, 1992.

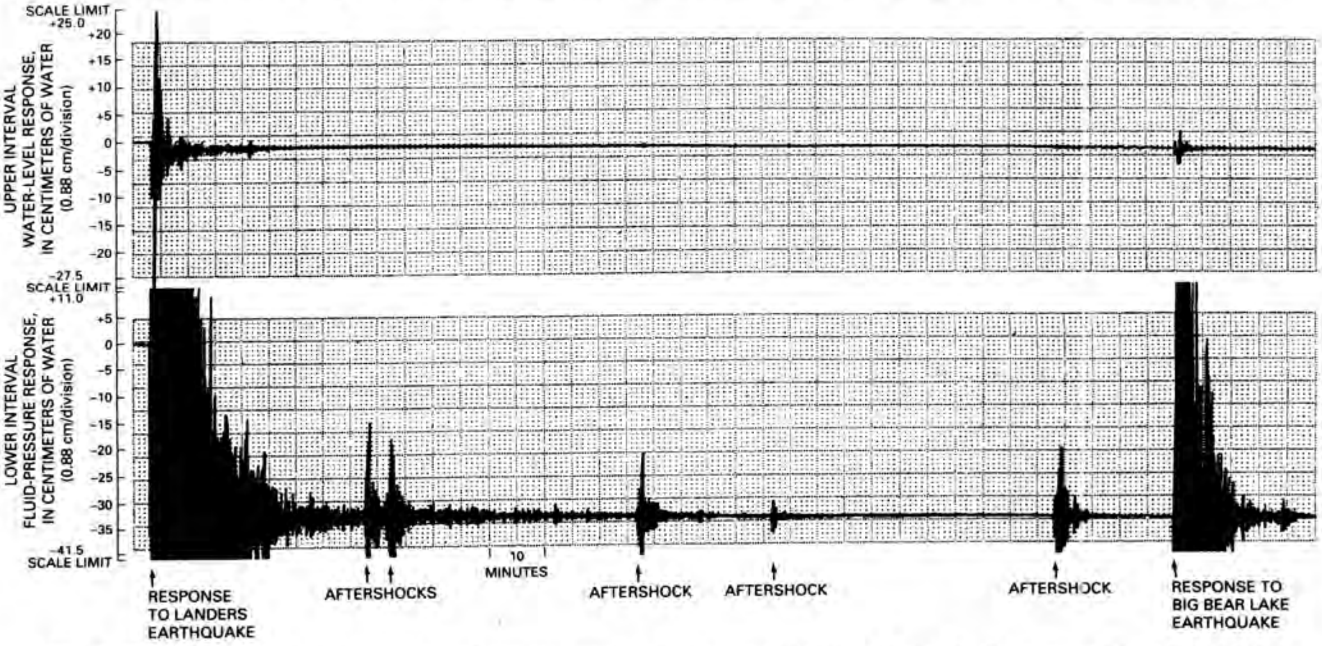

Fig. 3. Well USW H-6 response to earthquakes near Landers and Big Bear Lake, California, on June 28, 1992.

upper interval of USW H-6 was also off scale and is estimated to be 60 cm. The fluctuations damped to 1 cm in about 20 minutes. Peak fluid-pressure double amplitude in the lower interval was off scale and is estimated to be 2.2 m. Fluctuations damped to 1 cm in about 90 minutes. Several aftershocks caused smaller amplitude responses in both USW H-5 and USW H-6 (Figs. 2-5).

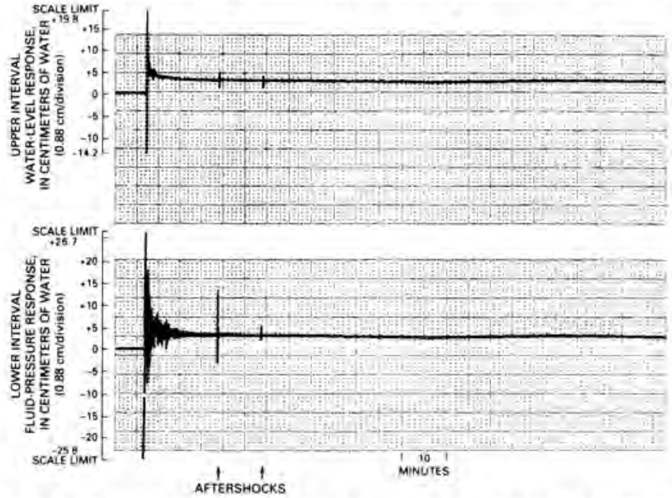

Fig. 4. Well USW H-5 response to earthquake at Little Skull Mountain, Nevada, on June 29, 1992.

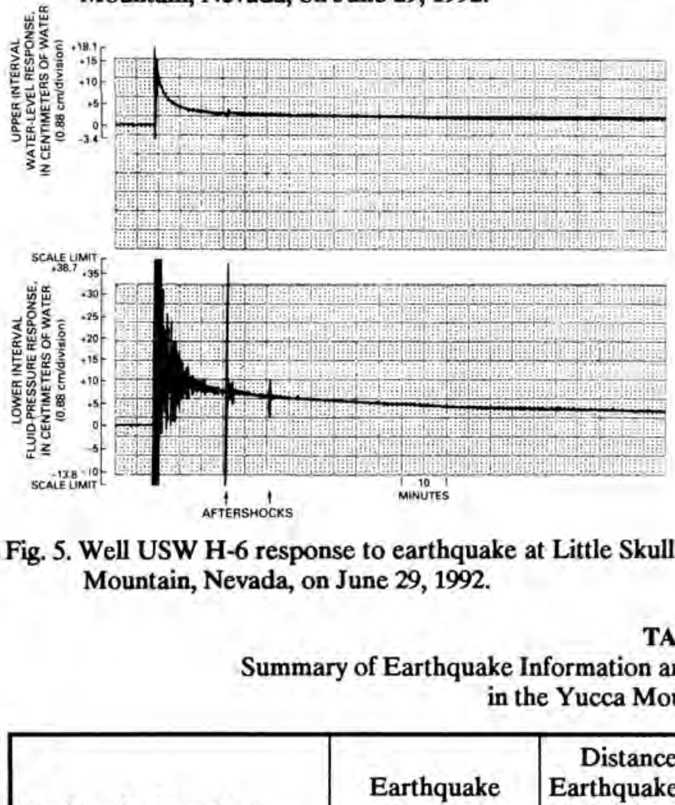

Fig. 5. Well USW H-6 response to earthquake at Little Skull Mountain, Nevada, on June 29, 1992.

An apparent offset of the water level in the lower interval of USW H-6 after the Landers earthquake is due to a small-diameter packer, used to completely confine the lower interval moving upward as a result of the high pressure caused by the seismic waves. Movement of the transducer upward in the water column resulted in a decrease of pressure and thus, an apparent decrease in water level. A water-level measurement one day later confirmed that no persistent change in water level from the pre-earthquake level occurred.

The earthquakes 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 the total flow to the well 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 a greater sensitivity to the earthquake 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 effect 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. Water-level and fluid-pressure changes were detected in several wells immediately following the earthquake; however, wells UE-25p #1 and USW H-3, lower interval, were the only wells to detect changes one hour or more after the Landers

TABLE I

Summary of Earthquake Information and Hydrologic Responses to Earthquakes, in the Yucca Mountain Area, Nevada

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).

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) and the effects of subsequent earthquakes. USW H-3 appeared to have a decrease in water level of approximately 14 cm one hour after the earthquake (Fig. 7). Water levels in USW H-3 appear to remain lowered, although fluctuating in response to earth tides, until the following day when levels increased in response to another earthquake (Fig. 7).

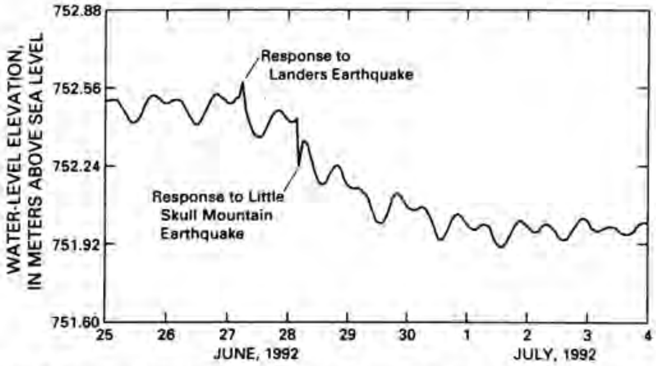

Fig. 6. Water-level response in well UE-25 p#1 to Landers and Little Skull Mountain earthquakes.

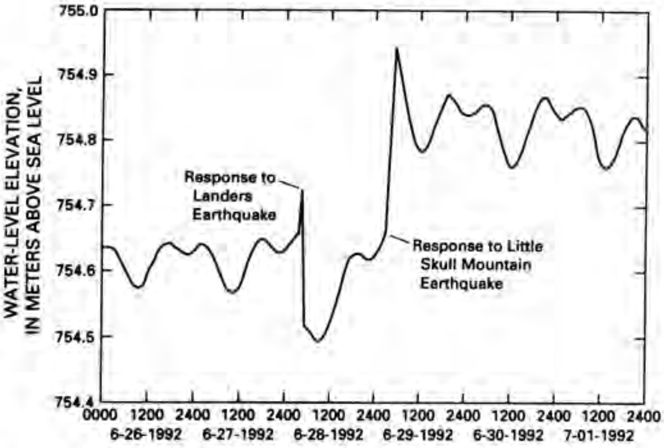

Fig. 7. Water-level response in well USW H-3 to Landers and Little Skull Mountain earthquakes.

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 on a northeast trending left-lateral strike-slip fault (12), at a distance of approximately 296 km from Yucca Mountain. The earthquake was felt in large parts of southern California, southern Nevada, and western Arizona. The water-level and fluid-pressure responses to the Big Bear Lake earthquake are shown in Figs. 2-3, and are summarized in Table I. The peak water-level double amplitude in the upper interval of USW H-5 was 20 cm, and the fluctuations damped to 1 cm in about 10 minutes. Peak fluid-pressure double amplitude in the lower interval was off scale and is estimated to be 1 m. Fluctuations damped to 1 cm in about 20 minutes. Peak water-level double amplitude in the upper interval of USW H-6 was 6 cm, and fluctuations damped to 1 cm in about 5 minutes. The peak fluid-pressure double amplitude in the lower interval was off scale and is estimated to be 1.4 m. Fluctuations damped to 1 cm in about 25 minutes. Hourly monitored wells did not detect any water-level or fluid-pressure changes as a result of the Big Bear Lake earthquake, because water levels and fluid pressures in those wells had returned to their pre-earthquake levels before the next sampling time (16:00:00 UTC).

A 5.6-magnitude earthquake occurred at Little Skull Mountain, Nevada, at 10:14:22 UTC, June 29, 1992. The earthquake epicenter was approximately 23 km from Yucca Mountain, and it was the largest recorded earthquake within the boundary of the Nevada Test Site. 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). Several aftershocks with both normal faulting and strike slip faulting occurred in the area, suggesting a complex stress release pattern (Professor James Brune, University of Nevada, Reno, Seismological Laboratory, written commun., 1992).

The continuous water-level and fluid-pressure responses to the Little Skull Mountain earthquake are shown in Figs. 4-5, and are summarized in Table I. 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). Water-level and fluid-pressure responses at Yucca Mountain indicate that the area may have undergone compression as a result of the earthquake. The sudden water-level increase, caused by compression of the aquifer that forced water into the well, was followed by a slow recession of the water level to the pre-earthquake level.

Peak water-level double amplitude in the upper interval of USW H-5 for the Little Skull Mountain earthquake was off scale and is estimated to be 40 cm. Peak fluid-pressure double amplitude in the lower interval was also off scale and is estimated to be 64 cm. Water and fluid pressure had returned to within 2 cm of pre-earthquake conditions about 7 hours 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 5 hours. Peak fluid-pressure double amplitude in the lower interval was off scale and is estimated to be 1.1 m. Fluid pressure returned to pre-earthquake conditions in about 8 hours.

Water level and fluid pressure in several wells have been monitored during underground nuclear explosions (UNE's) within 50 km of Yucca Mountain. High frequency energy, or seismic waves, predominates in the areas close to earthquakes and UNE's; however, UNE's have not caused the same type of water-level response at Yucca Mountain as the Little Skull Mountain earthquake. The responses to UNE's are similar to responses from more distant earthquakes. Water-level and fluid-pressure responses to the Little Skull Mountain earthquake at USW H-5 and USW H-6 may, therefore, be due to both seismic waves and a change in the regional strain field.

Only two hourly monitored wells showed persistent long-term 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 appropriate 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 (Tim 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 returned to its pre-earthquake level in approximately 6 months (Fig. 8).

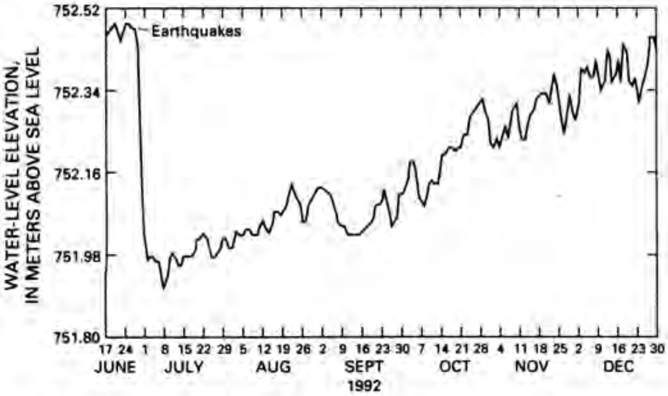

Fig. 8. Recovery of mean-daily water level in well UE-25 p#1 following earthquakes at Landers and Little Skull Mountain.

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. 7). The total change can probably be attributed to the earthquake because the normal fluctuation due to earth tides was beginning a downward trend. A small amount of water may have been released from storage from fractures in the vicinity of USW H-3, causing this increase in water level. Water level in this interval has been rising toward a static hydraulic head since the packer was installed in December, 1990. No change in the rate of this water-level recovery from the pre-earthquake rate are apparent subsequent to the earthquake. The upper interval of USW H-3 did not show any significant changes that could be attributed to the earthquakes.

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