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Hydrologic effects associated with the June 28, 1992 Landers, California, earthquake sequence

By

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ABSTRACT

This report compiles hydrologic observations in southern California and elsewhere associated with the 1992 M_L = 7.3 Landers, California earthquake sequence. In southern California, the largest ground-water-level changes were a rise of 3 meters at Lucerne Valley and a drop of 5 m at Pinon Flat. Most of the steplike water-level changes recorded in the hours following the Landers and Big Bear earthquakes agreed in direction with the sign of the calculated coseismic volume strain field. In the Pinon Flat area, however, two wells measured on June 28, after both these earthquakes, displayed water-level rises of 9 cm above the reading made two days before. A spring discharge increase in Millard Canyon was reported to have preceded the earthquake by several days. Outside of southern California, water-level changes were also observed, but are not consistent in sign or size with the static strain field of the earthquake sequence. At Parkfield, California, water-level changes took place in three wells at the time of the earthquake, and recovered over periods as long as 30 days. At Long Valley, California, observed water-level changes generally returned to normal after minutes to hours, consistent with their having been caused by the passage of surface waves. Water levels in one well at Long Valley and in a well near Grants Pass, Oregon, remained low for at least two days following the earthquake. Water-level oscillations took place in two wells in eastern Nevada. Phenomena accompanying the Landers earthquake that were of practical significance include the Tapo Canyon oil seep, which polluted part of the Santa Clara River; gas bubbles in San Bernardino city water supply wells, which clogged filters; and a coseismic discharge increase in Millard Creek, which added to the water supply.

INTRODUCTION

The Landers, California earthquake (M_L=7.3, M_s=7.5) was the largest earthquake in California in 40 years (Hauksson et al., 1993). Like other earthquakes of comparable size, the Landers earthquake affected ground water and surface water not only in its immediate vicinity, but also at distances of hundreds of kilometers. Some of these hydrologic observations are consistent with our present understanding of the response of well-aquifer systems to strain. Other observations, however, are unexplained at this time. Observations of distant hydrologic effects may be particularly significant because the Landers earthquake triggered seismicity at a number of locations many hundreds of kilometers distant from the epicenter (Hill et al., 1993).

This purpose of this report is to collect hydrologic observations related to the Landers earthquake sequence. Although an attempt has been made to locate and include data from as many sources as possible, the report should not be viewed as exhaustive. Where appropriate, the observations are compared with observations from other earthquakes and with the present understanding of earthquake-related hydrologic phenomena.

For further information about the data described here, the reader is referred to the Appendix, which lists the authors' addresses and field study areas.

THE LANDERS EARTHQUAKE SEQUENCE

The Landers earthquake sequence actually began with the magnitude 6.1 Joshua Tree earthquake on April 23, 1992. The Landers earthquake itself took place on June 28, 1992 and was followed about three hours later by the magnitude 6.2 Big Bear earthquake, 30 to 40 kilometers to the west (Hauksson et al., 1993) and on a separate fault. Table 1 lists the times, magnitudes, and locations of these earthquakes. Figure 1 is a map showing the Landers and Big Bear epicenters and the observation sites referred to in this report.

Table 1. Earthquakes larger than magnitude 6 in the Landers sequence (Hauksson et al., 1993).

Earthquake	Date (UT)	Time (UT)	Magnitude	Latitude	Longitude	Depth (km)
Joshua Tree	23 April 92	04:50	M_L=6.1	33° 57.33′	116° 17.97′	14
Landers	28 June 92	11:57	M_L=7.3	34° 12.13′	116° 25.95′	3
Big Bear	28 June 92	15:05	M_L=6.2	34° 9.94′	116° 49.35′	13

Most of the hydrologic phenomena reported here are in response to the Landers earthquake (M_L=7.3), which was significantly larger than either the Joshua Tree or Big Bear events. The Landers earthquake ruptured several separate fault segments with a total length of 85 km, and the epicenters of its aftershocks extend throughout an area 180 km long (Hauksson et al., 1993).

The Landers earthquake triggered seismic activity at a number of locations in the western United States (Hill et al., 1993). In California, seismicity was triggered at the White Mountains, Long Valley, and Mount Lassen. Outside of California, seismicity was triggered at Cedar City, Utah; Cascade, Idaho; and possibly at Yellowstone, Wyoming. The mechanism of the triggering is not understood, but it is likely the Landers earthquake induced dynamic stresses significantly larger at these locations than other recent California earthquakes because rupture in the Landers event propagated unilaterally to the north (Wald and Heaton, 1994).

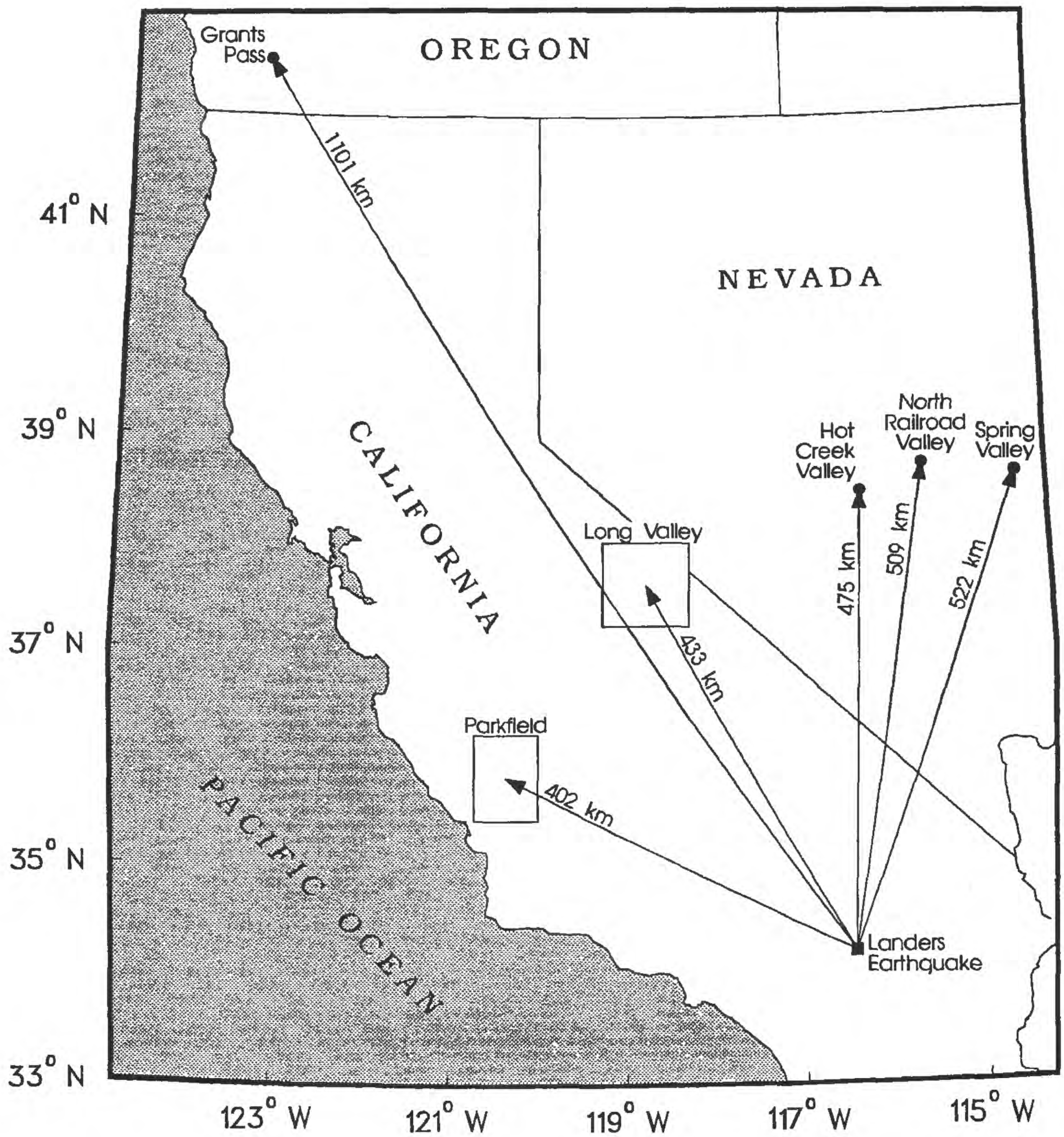

Figure 1. Map showing location of Landers earthquake and general locations of hydrologic observations outside of southern California.

PRESENT UNDERSTANDING OF EARTHQUAKE-RELATED HYDROLOGIC PHENOMENA

This section provides a brief description of the types of hydrologic phenomena caused by earthquakes and their causes, when known.

Coseismic Water-level Steps

An earthquake subjects the earth's crust in its immediate vicinity to stress and strain. These stresses and strains are applied in seconds or tens of seconds as the earthquake rupture progresses, and they remain after the earthquake shaking has ceased. In porous elastic aquifers, fluid pressure generally changes when the aquifer undergoes volumetric strain. Consequently, a steplike change in well water level would be expected when the earthquake occurs.

If the fault orientation and the amount and direction of slip are known, then the amount of volumetric strain can be computed using a program such as the one given by Okada (1992). For a well that responds to earth tides, the relationship between well water-level change and strain can be determined. Typically, water levels in wells completed in confined aquifers change tens of centimeters in response to one part per million (ppm) volumetric strain. Unconfined aquifers are much less sensitive to strain. A quantitative comparison can sometimes be made between the size of a coseismic step and the expected response to the earthquake's volume strain field.

Recovery of Coseismic Water-level Steps

In a perfectly confined aquifer, a coseismic water-level change that is due to the earthquake's static strain field should persist indefinitely. In practice, most aquifers are not perfectly confined, so that recovery to the pre-earthquake water level takes place via flow to or from the water table over a period of time. This period of time can be so short that no change will be detected if the water level is sampled every 15 minutes, or it may be as long as months. Seasonal hydrologic fluctuations often mask the recovery of small coseismic steps, making it difficult to establish exactly how long they persist.

Coseismic Water-level Oscillations

In addition to imposing a static strain field, an earthquake radiates several types of seismic waves. Compressional (P) waves and Rayleigh waves both involve volumetric strain and are therefore expected to change aquifer pressure. If the aquifer is highly conductive and the well is favorably completed, it is possible for the water column's motion to resonate at periods of several tens of seconds, amplifying the aquifer pressure changes by an order of magnitude or more (Cooper et al., 1965; Liu et al., 1989). In the few cases where the oscillations have been recorded on a sufficient time scale, they resemble long-period seismograms. Theory predicts that these oscillations should last as long as the surface wave train of the earthquake, which is on the order of ten minutes for an event the size of Landers. After the wave amplitudes have diminished sufficiently, the water level should return to its pre-earthquake level.

Surface-water Effects

Effects of earthquakes on surface water are not quantitatively understood, but often include discharge increases following the earthquake. These increases seem to reflect permeability increases caused by the earthquake (Rojstaczer and Wolf, 1992; Rojstaczer and Hickman, 1994), but it has also been suggested that they reflect fracture conductance changes caused by the earthquake's static strain field (Muir-Wood and King, 1993). Appearance of new springs, particularly in landslide areas, and turbidity in streams are also common.

HYDROLOGIC OBSERVATIONS IN SOUTHERN CALIFORNIA

Ground Water

Water-level changes in wells within 150 km of the Landers epicenter can plausibly be caused by the static strain field of the earthquake. Murray and others (1993) used geodetic data to determine the amounts of strike-slip displacement over 10 separate fault segments that ruptured in the Landers-Big Bear sequence. Eight of these fault segments are along the main Landers rupture; one represents the Big Bear earthquake; and one represents the Eureka Peak fault, which was the site of aftershock activity to the south of the main Landers rupture. Subsurface slip on these fault segments, as adjusted to fit the geodetic measurements, ranged from 0.1 m left lateral on the Johnson Valley north segment to 9.2 m right-lateral on the Kickapoo segment. This "dislocation model" of the earthquake sequence was used to calculate the volumetric strain produced by the earthquake, which is plotted in Figure 2.

Information about wells being monitored is listed in Table 2 and their locations are shown in Figure 2. Although many additional wells are monitored in southern California, the data are often not suitable for detecting earthquake-related changes because they are measured too infrequently or because artificial effects obscure the natural aquifer response. Precipitation was negligible in southern California during June, 1992 (National Climatologic Data Center, 1992).

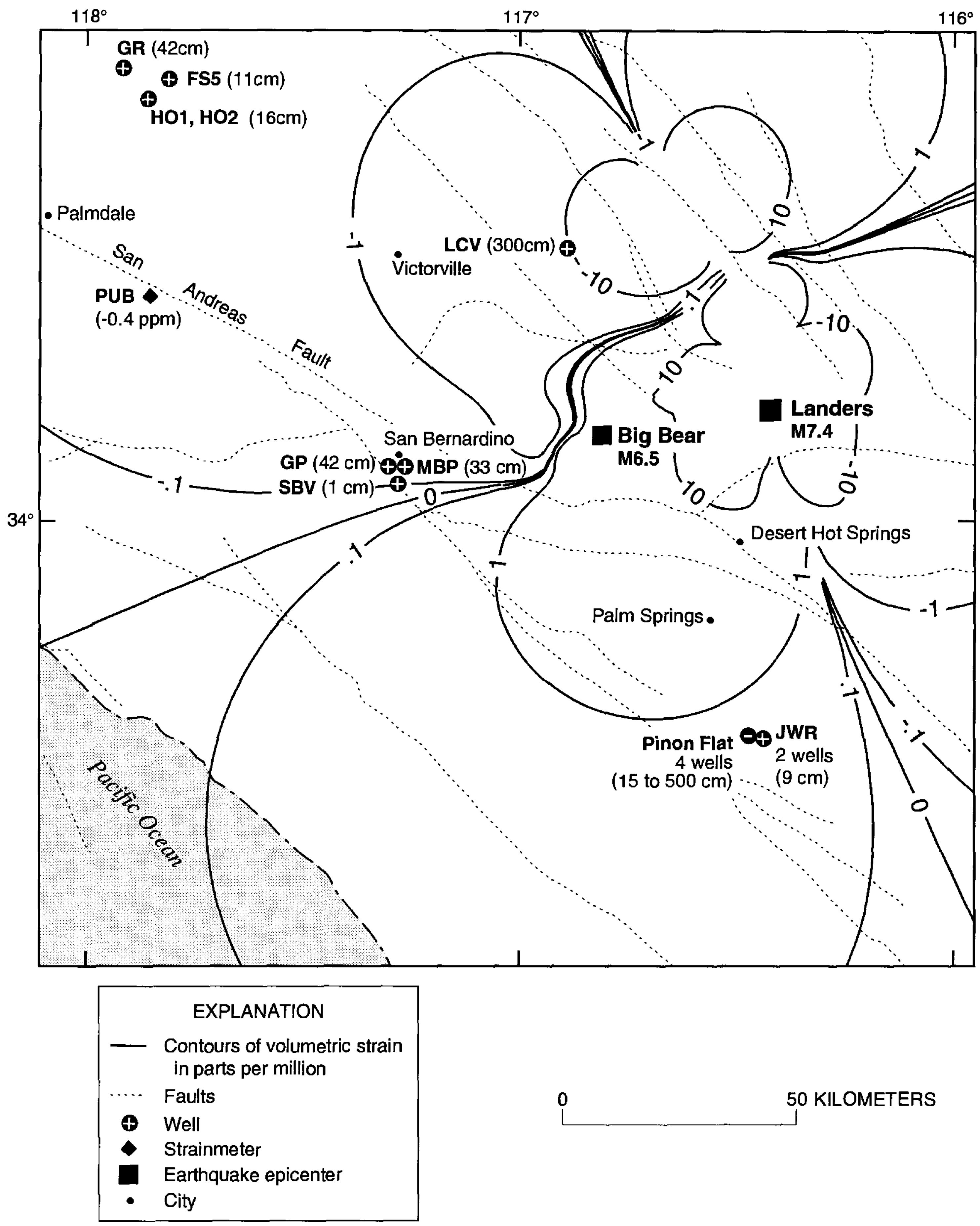

Figure 2. Location of observation wells in southern California where a response to the Landers earthquake was documented, with contours indicating computed volumetric strain caused by the earthquake.

Table 2. Wells in Southern California.

Site Name	Map Symbol	Latitude	Longitude	Total Depth (meters)	Screened Interval (meters)	Landers Earthquake Response
Graham Ranch	GR2	34° 52′ 12″	117° 56′ 18″	198	151-172	Step +42 cm
Fissure	FS5	34° 50′ 56″	117° 50′ 14″	32	12-18	Step +11 cm
Holly	HO1	34° 48′ 35″	117° 53′ 13″	328	299-309	Step +16 cm
	HO2			337	184-194	Step +16 cm
Lucerne Valley	LCV	34° 31′ 53″	116° 54′ 23″			+300 cm[1]
San Bernardino Municipal Water District	SBV	34° 4′ 39″	117° 17′ 39″	61	49-61	+0.3 cm
Meadowbrook Park	MBP	34° 6′ 15″	117° 17′ 9″	37	30-37	Step +33 cm
Garner Park	GP	34° 6′ 55″	117° 18′ 40″	78	73-78	Step +42 cm
J. Wellman Ranch	JWR	33° 35′ 30″	116° 27′ 30″	11	unknown	+9 cm[1]
				22	unknown	+9 cm[1]

1. Includes response to Big Bear earthquake.

Edwards Air Force Base. At the time of the Landers earthquake, wells were monitored by the U.S. Geological Survey (USGS) Water Resources Division at Edwards Airforce Base (Galloway, 1993). Data are shown in Figures 3 through 6. Data are instantaneous hourly measurements from H-300 Hydronet 5 psi transducers. Data precision is approximately 1 mm of water.

Water levels increased in each of the wells by 11 to 51 cm after the Landers earthquake. No preseismic signals were observed in these records. The one-hour sampling interval does not permit the recording of any possible water-level oscillations caused by surface waves.

The Graham Ranch and the deeper Holly water-levels respond to earth tides. A least-squares analysis of *M2*, *N2*, and *O1* tidal constituents of Graham Ranch water-level data results in an estimate of the tidal response of 0.62 meters per part-per-million (m/ppm). Consequently, the 51 cm coseismic water-level rise in this well would correspond to volumetric strain of 0.82 ppm compression, in approximate agreement with the calculated strain field shown in Figure 2.

In addition to earth tides, water-level data from the Holly site also display frequent transient changes due to pumping which complicates the task of obtaining well-constrained tidal response estimates from water-level data at this site. Pumping near the GR2 well also influences the water-level records. A new pumping well that came on line near GR2 on July 6 masks the recovery of water-level data after the coseismic offset due to the Landers earthquake.

The steplike water-level changes in these wells are consistent with the expected effects of the earthquake's static strain field. Each hydrograph exhibits an exponential decay of the coseismic water level rise over a period of days to a week. The recovery of the steps presumably reflects the dissipation of the strain-induced pressure by flow to the water table. In particular, these hydrographs cannot be interpreted as the time history of the strain caused by the Landers earthquake.

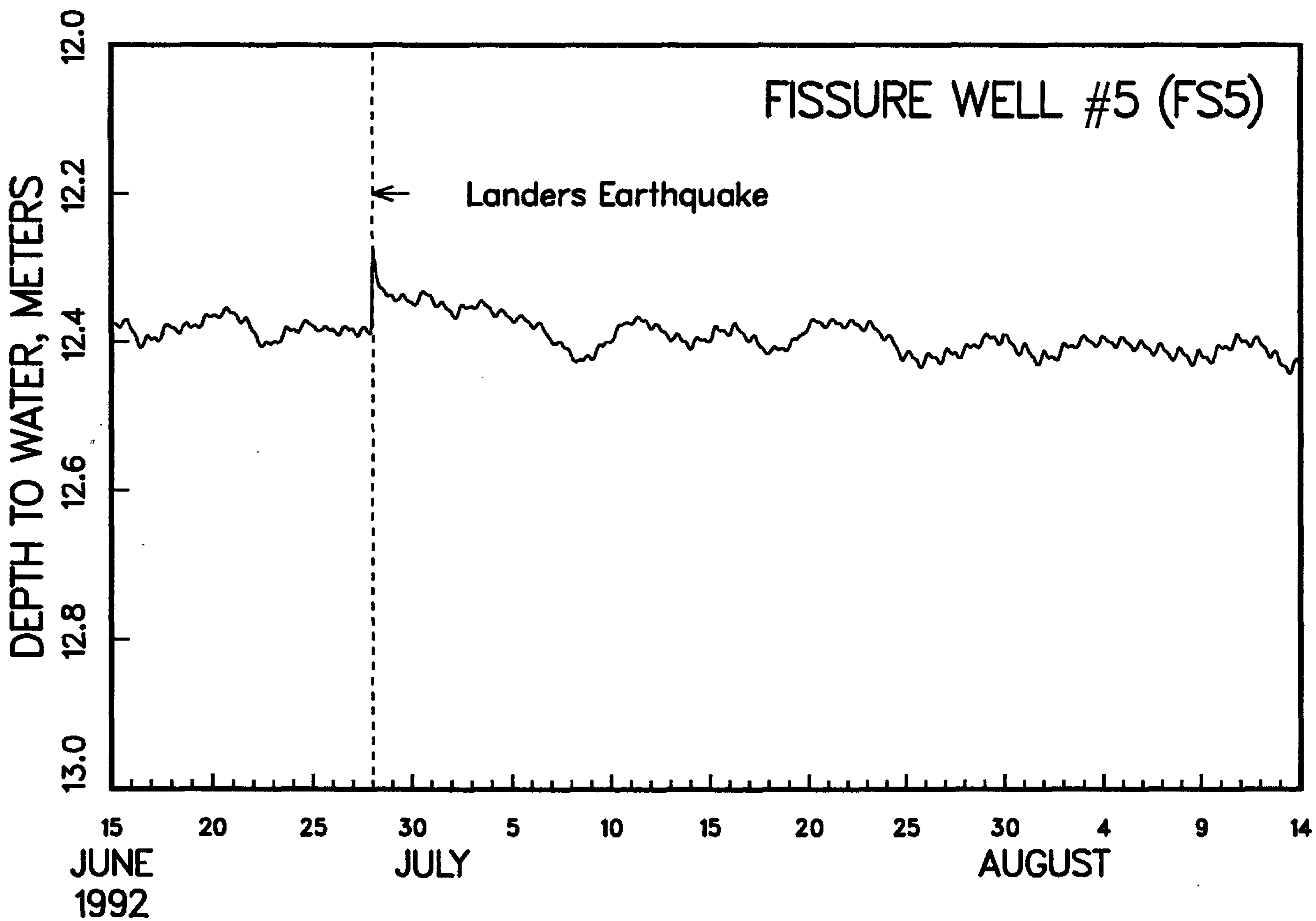

Figure 3. Water level in Fissure #5 well, Edwards Airforce Base, California. (a) June 15 to August 15, 1992.

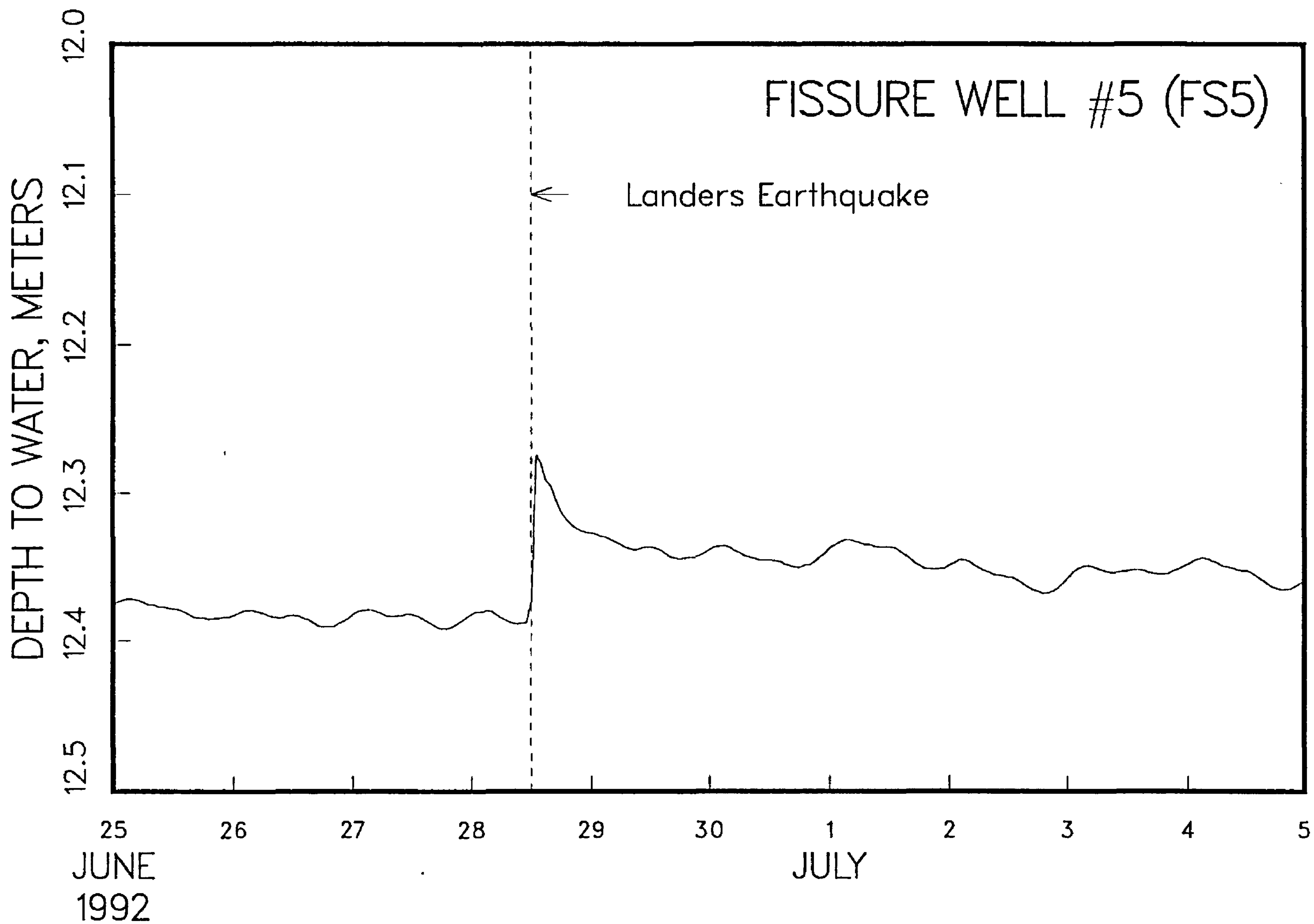

Figure 3, continued. Water level in Fissure #5 well, Edwards Airforce Base, California. (b) June 25 to July 5, 1992.

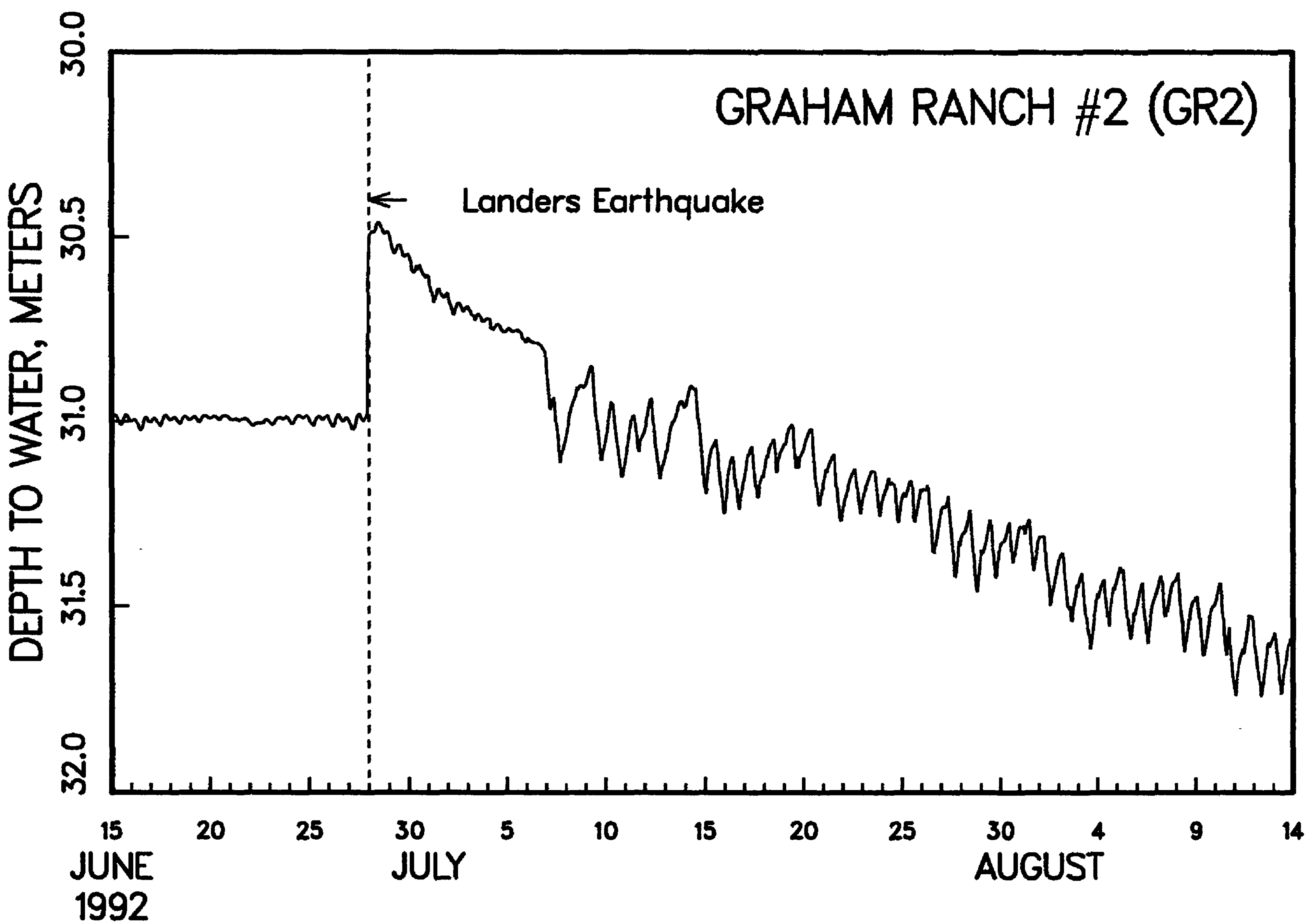

Figure 4. Water level in Graham Ranch #2 well, Edwards Airforce Base, California. (a) June 15 to August 15, 1992.

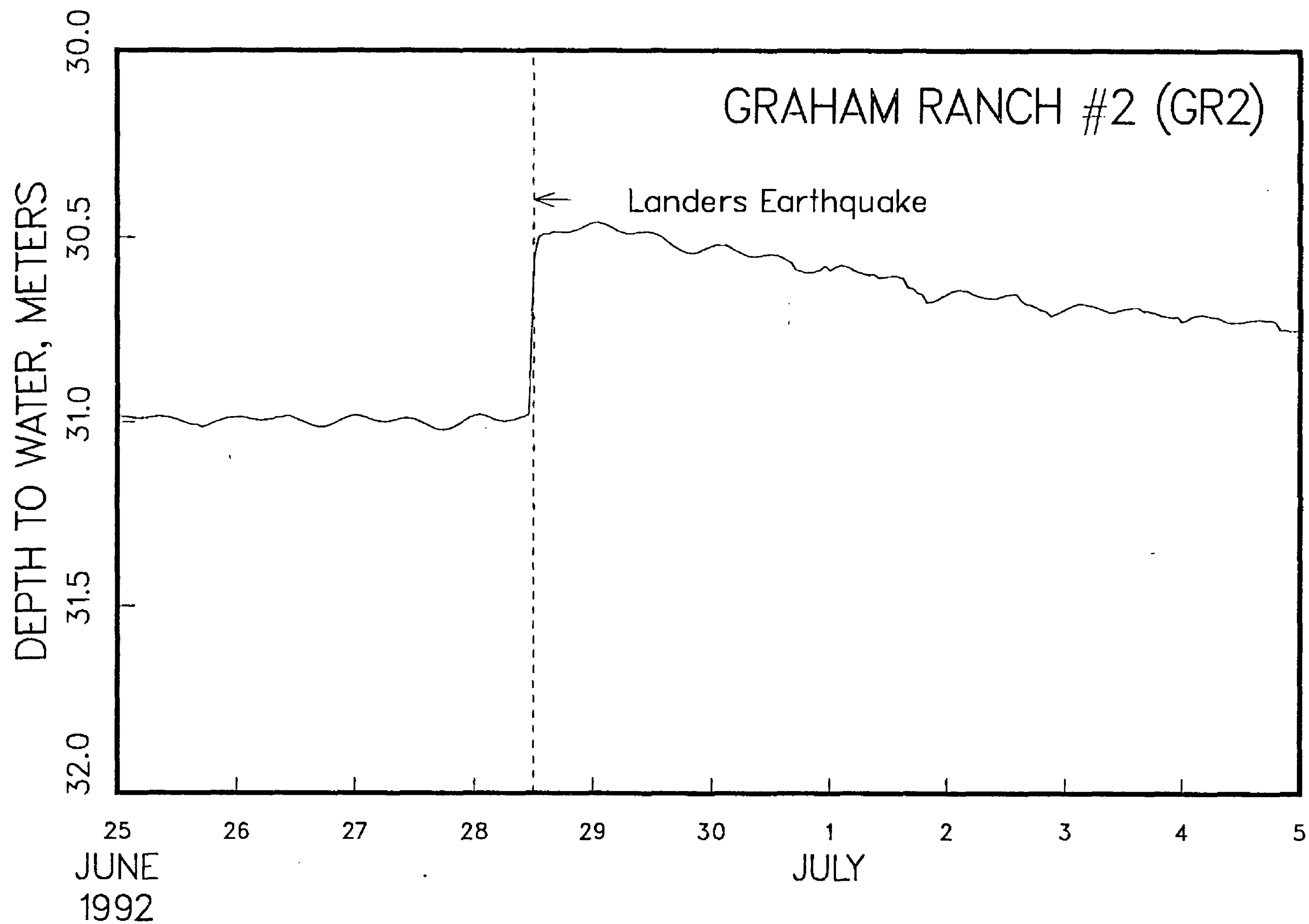

Figure 4, continued. Water level in Graham Ranch #2 well, Edwards Airforce Base, California. (b) June 25 to July 5, 1992.

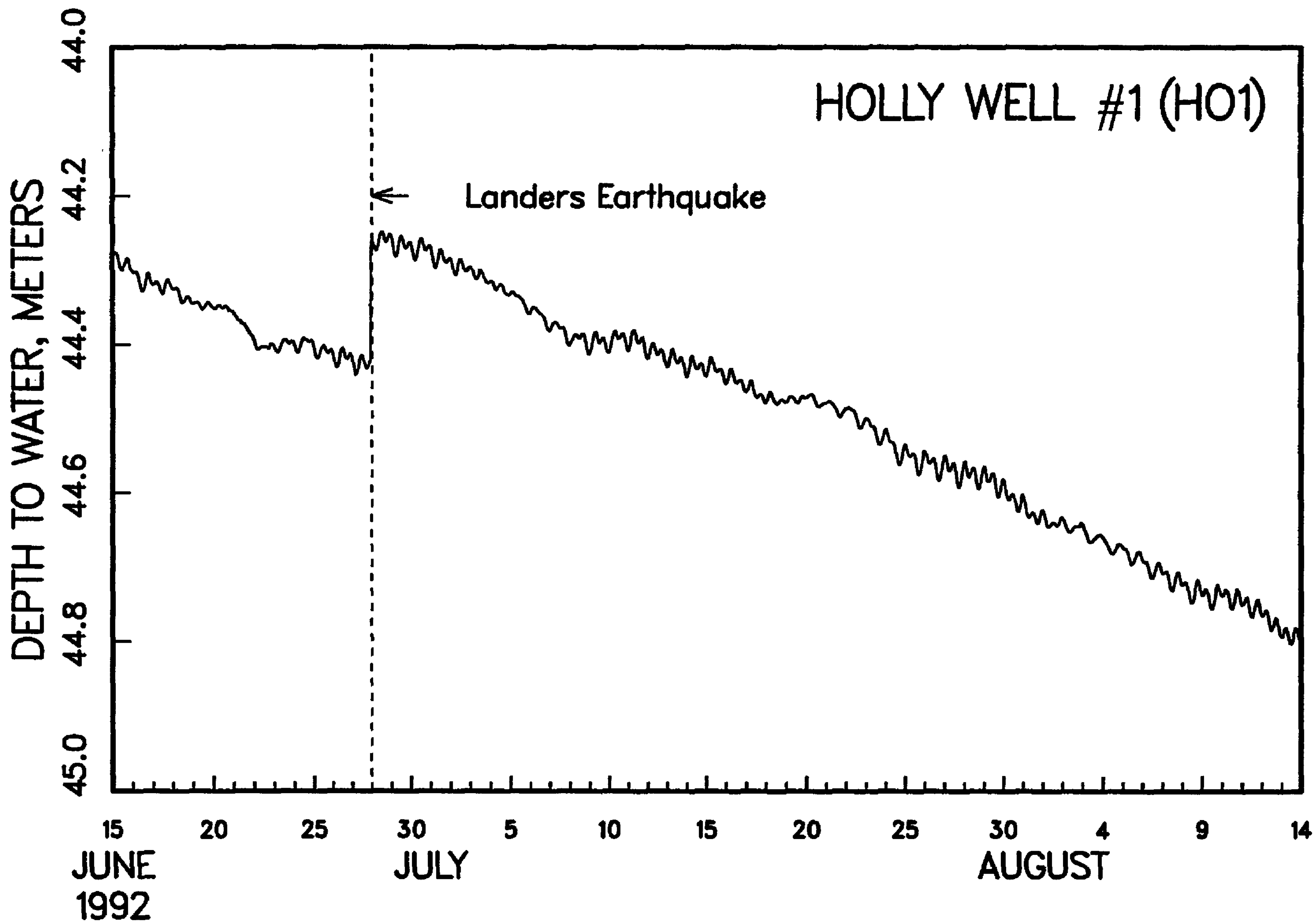

Figure 5. Water level in Holly well #1, Edwards Airforce Base, California. (a) June 15 to August 15, 1992.

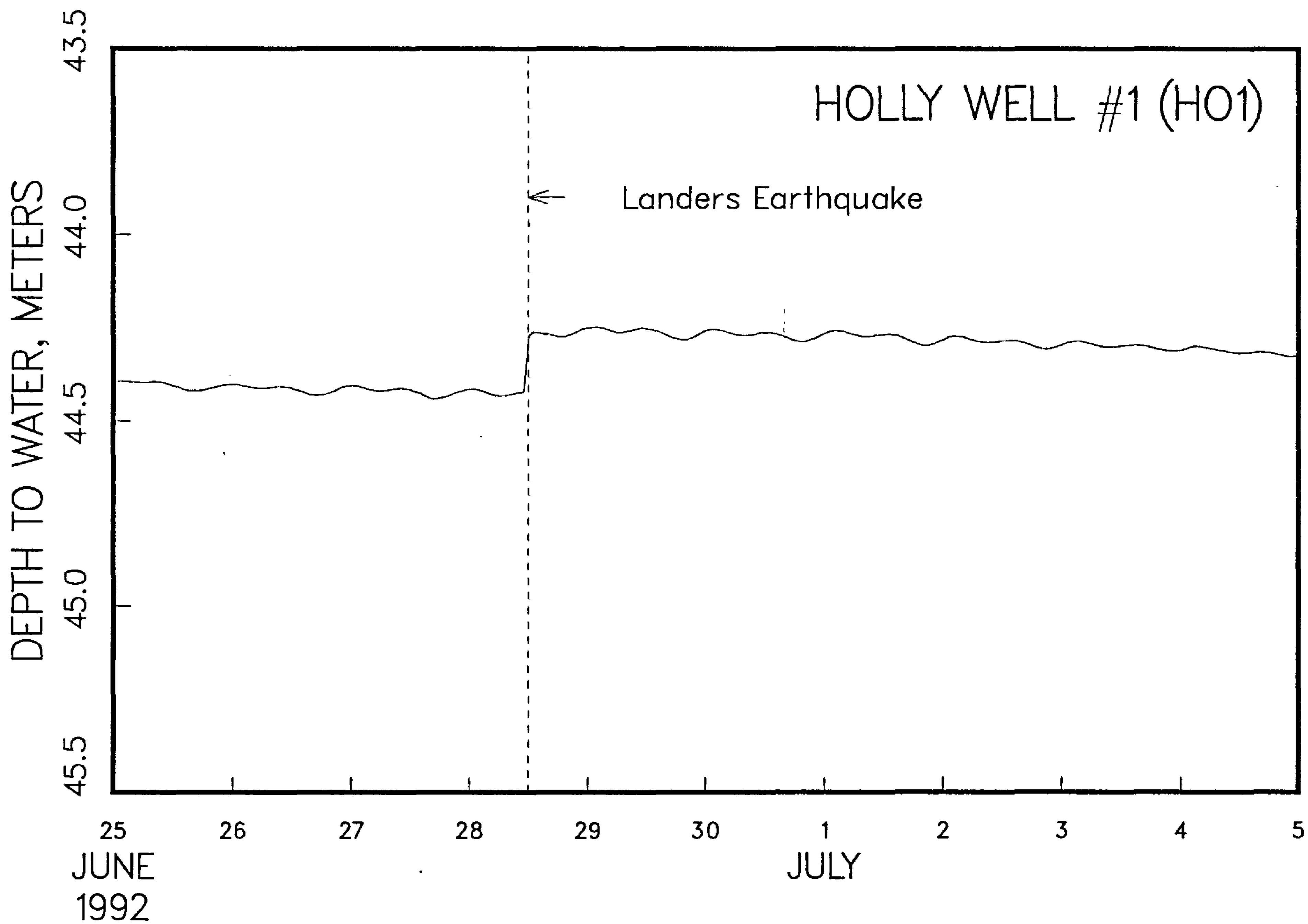

Figure 5, continued. Water level in Holly well #1, Edwards Airforce Base, California. (b) June 25 to July 5, 1992.

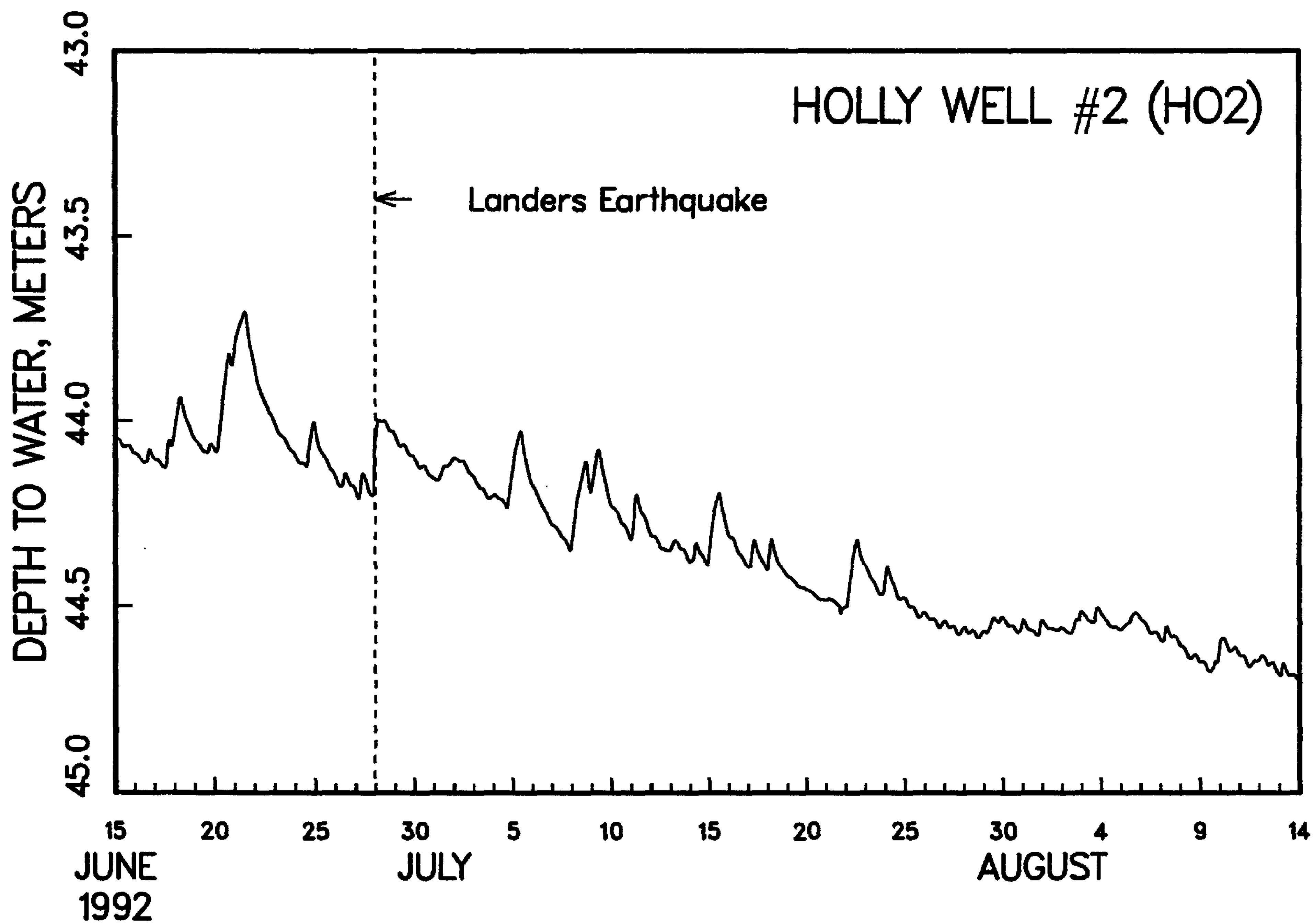

Figure 6. Water level in Holly well #2, Edwards Airforce Base, California. (a) June 15 to August 15, 1992.

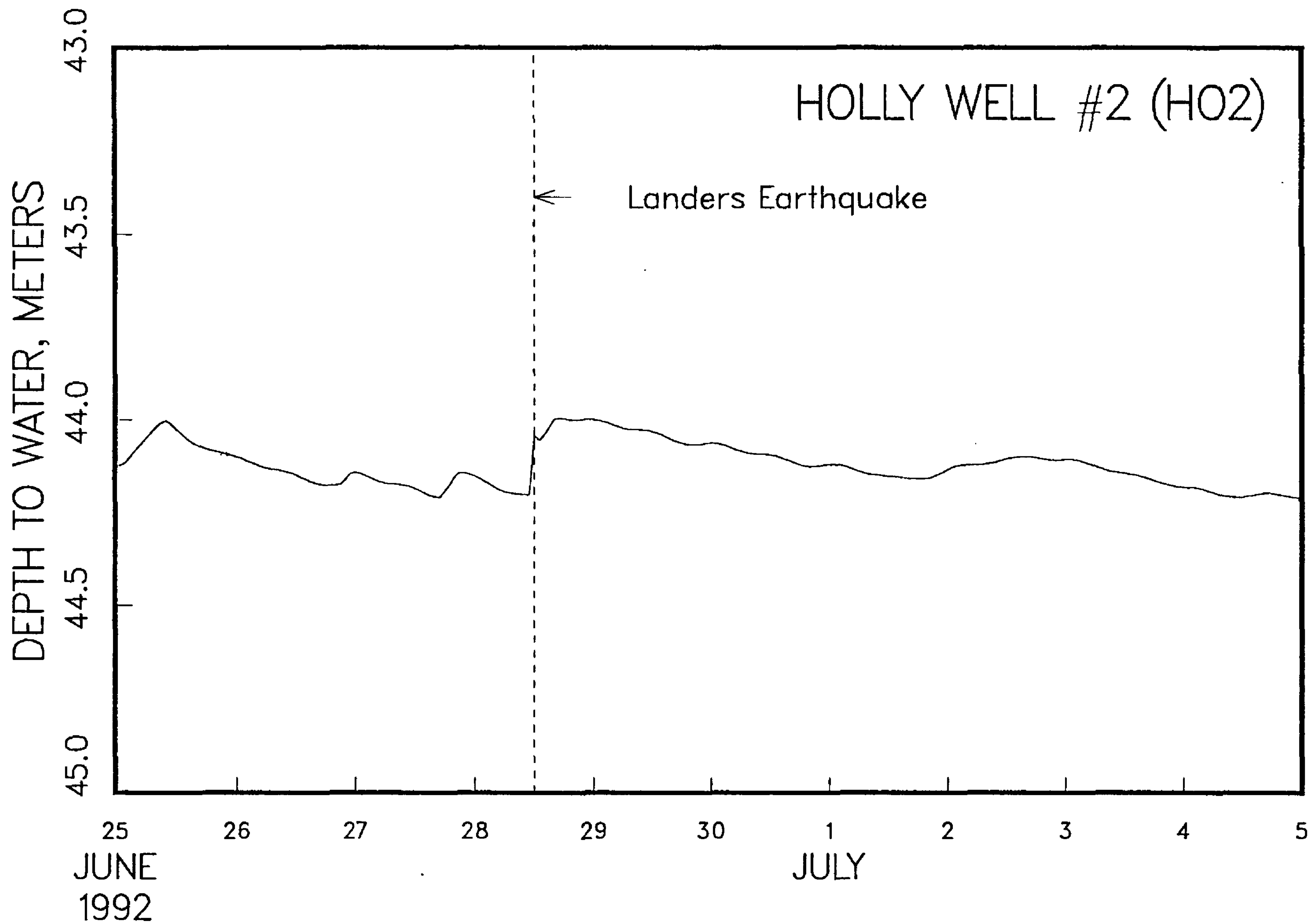

Figure 6, continued. Water level in Holly well #2, Edwards Airforce Base, California. (b) June 25 to July 5, 1992.

San Bernardino. Water level is being monitored in wells at several depths in alluvial aquifers in the San Bernardino area. In a group of wells about 60 meters from the San Jacinto fault (SBV in Figure 2), measurements are made once every 15 minutes with a resolution of at least 0.3 cm of water. Water-level changes generally less than 1 cm were observed in response to the Landers earthquake sequence.

Hourly measurements are made in wells in Garner (Encanto) Park and in Meadowbrook Park (GP and MBP in Figure 2, respectively). In Meadowbrook Park, water level is measured at depths of 207-213 m, 91-98 m, and 30-37 m. No earthquake response was observed in the two deeper intervals. In the shallowest depth interval, water level rose 33 cm in response to the Landers earthquake, with a further rise of 12 cm in response to the Big Bear event (Figure 7). Water level gradually returned to the pre-earthquake level in about 30 days.

In Garner Park, three aquifer levels are monitored. No response was observed in the depth intervals 49-53 m or 163-168 m. In the intermediate depth interval 73-78 m, water level rose 42 cm in response to the Landers earthquake, with a further rise of 13 cm in response to the Big Bear event (Figure 8). Post-earthquake recovery of the water level is masked by water-level changes due to pumping.

Neither the Meadowbrook Park nor Garner Park hydrographs exhibit fluctuations caused by earth tides, so no quantitative comparison can be made between the sizes of the water-level changes and the calculated volumetric strain fields of the Landers and Big Bear earthquakes.

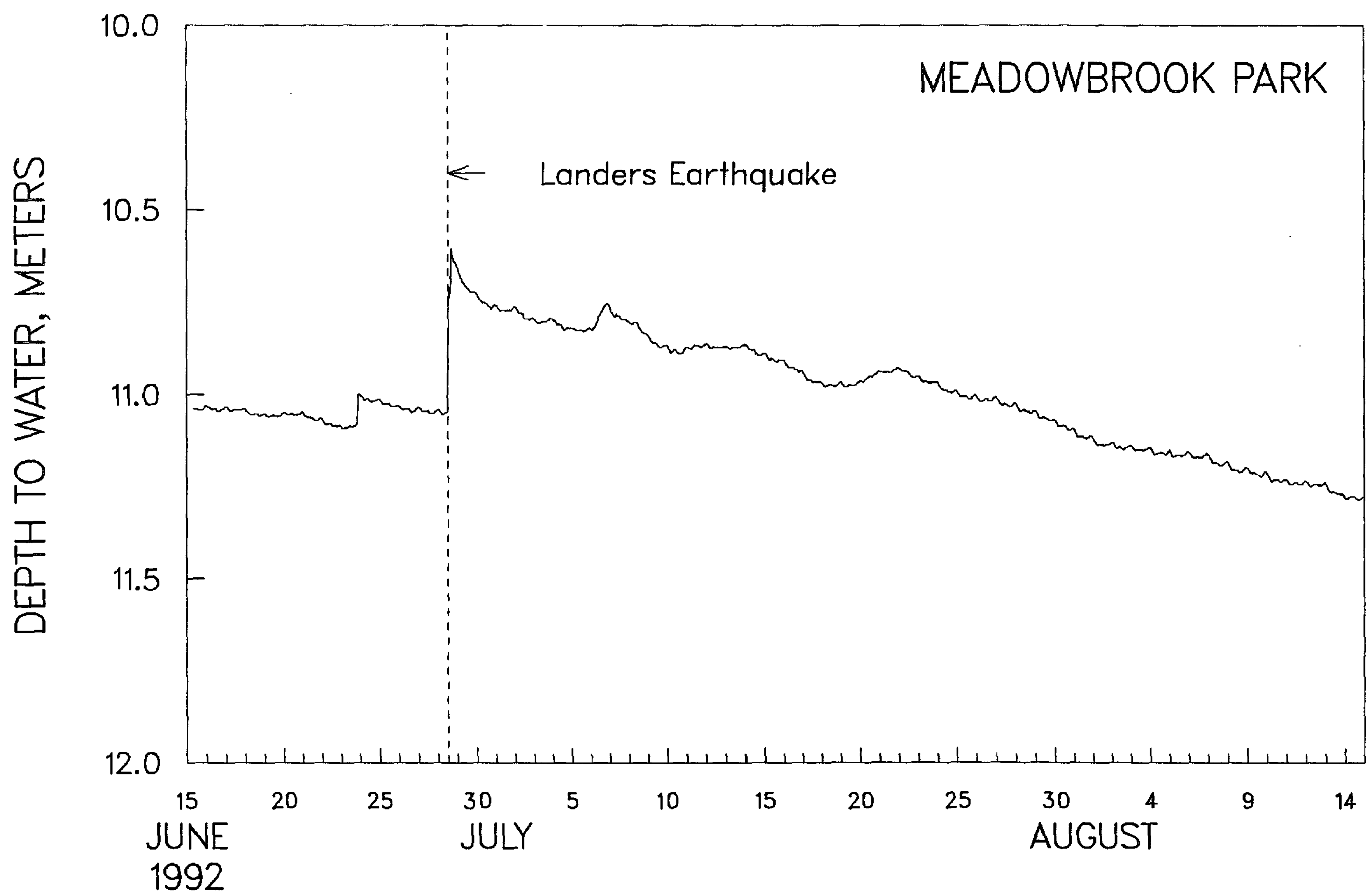

Figure 7. Water level in Meadowbrook Park, near San Bernardino, California. Data are from the depth interval 30-37 m. (a) June 15 to August 15, 1992.

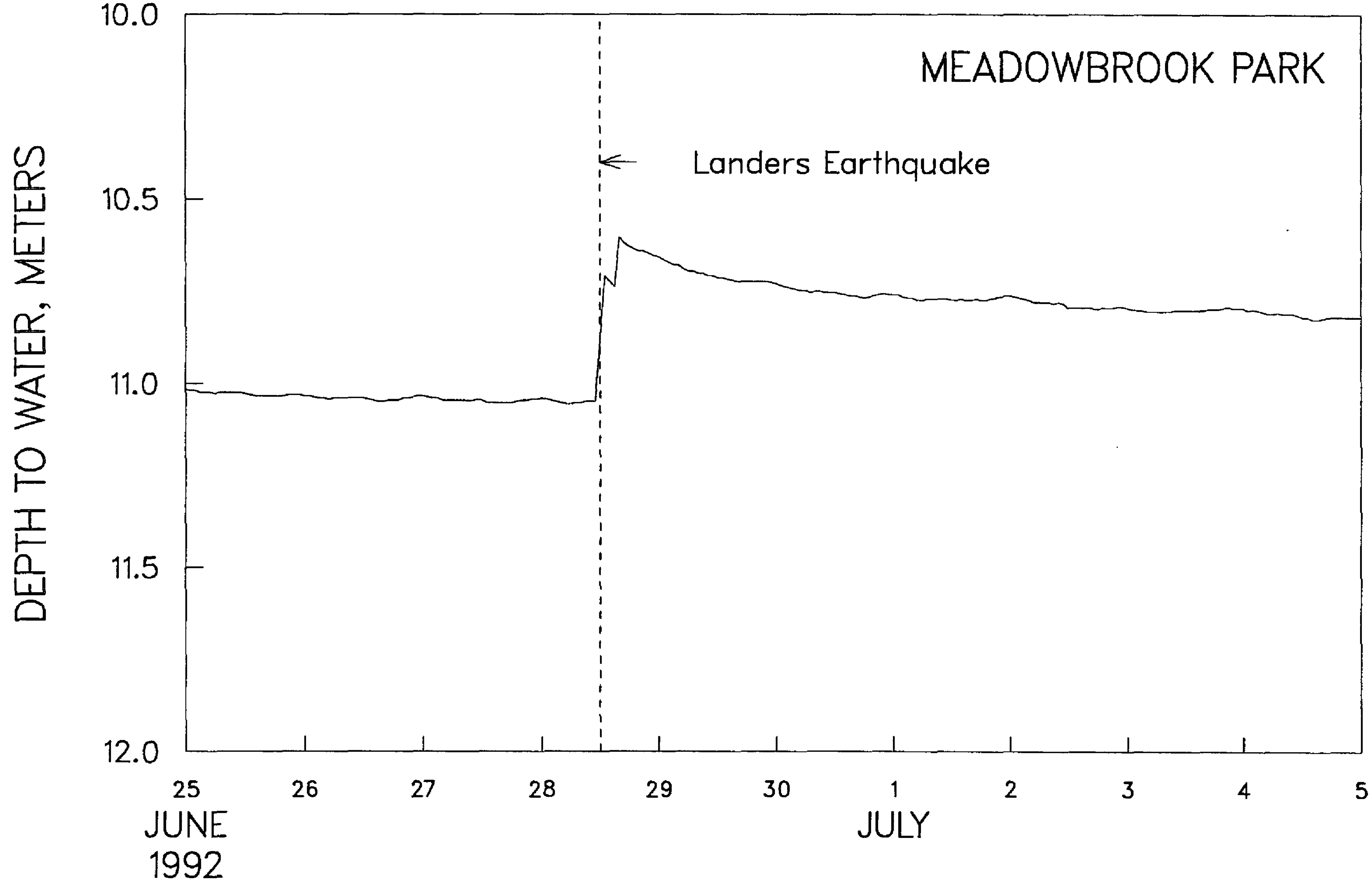

Figure 7, continued. Water level in Meadowbrook Park, near San Bernardino, California. Data are from the depth interval 30-37 m. (b) June 25 to July 5, 1992.

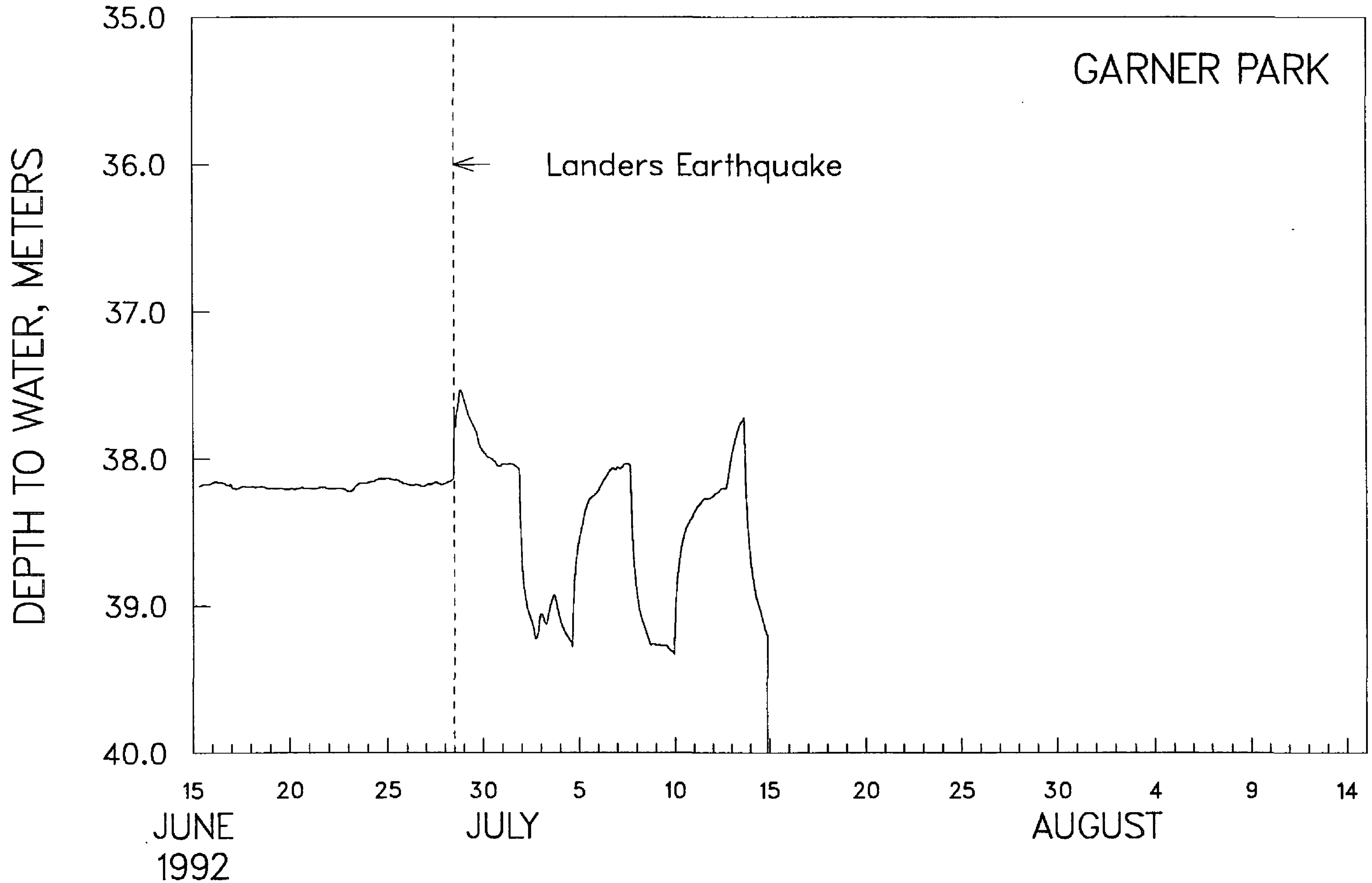

Figure 8. Water level in Garner Park, near San Bernardino, California. Data are from the depth interval 74-78 m. (a) June 15 to August 15, 1992.

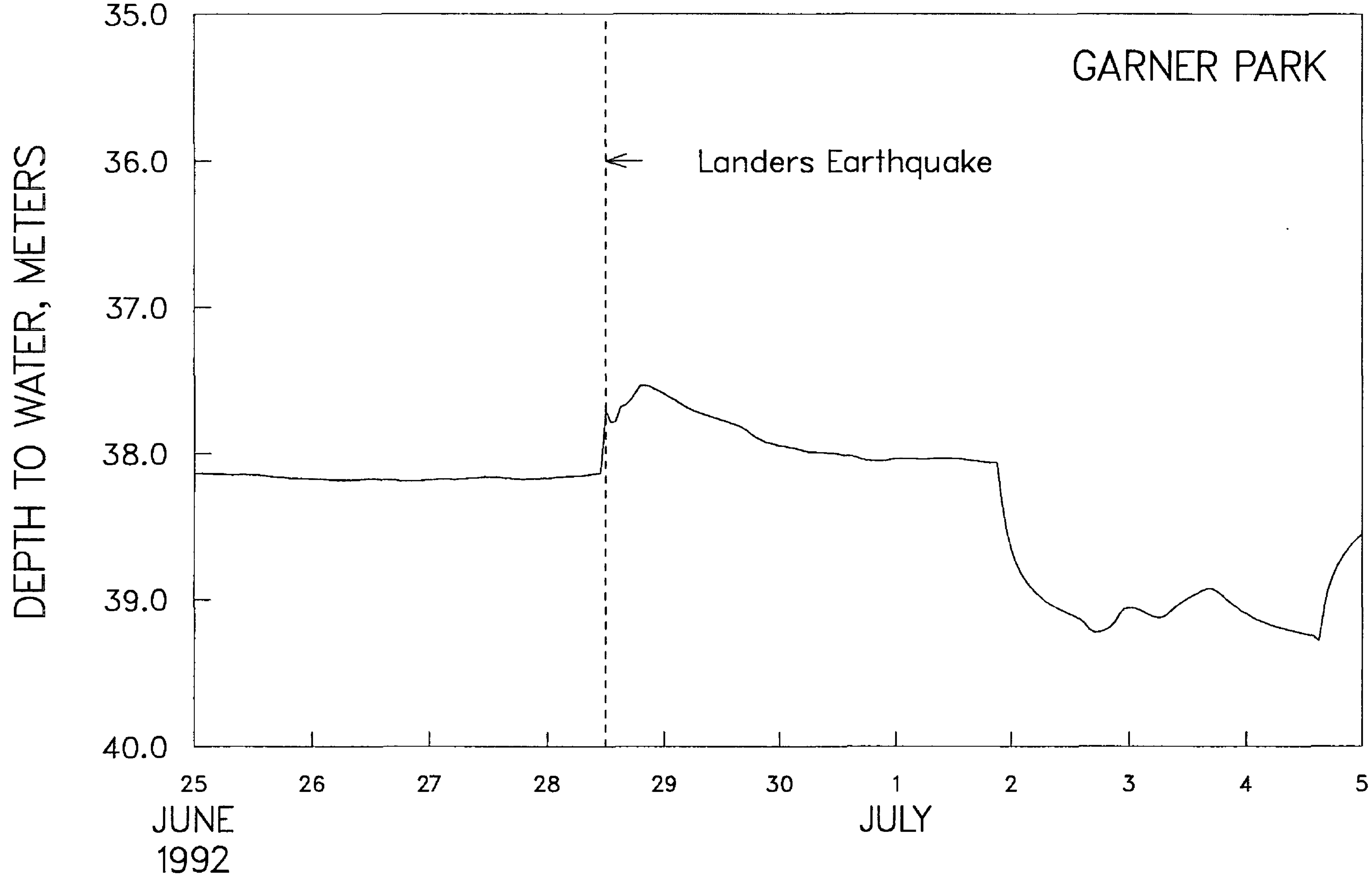

Figure 8, continued. Water level in Garner Park, near San Bernardino, California. Data are from the depth interval 74-78 m. (b) June 25 to July 5, 1992.

Other Sites. At Pinon Flat, water levels are monitored continuously in four boreholes (Wyatt et al., 1994). At the time of the Landers earthquake, water levels in three of these wells dropped 15 to 30 cm; water level in the fourth well dropped 500 cm. A variety of longer-term changes took place following the earthquake. In particular, water level in one of the wells recovered in several days following the coseismic drop, and then continued to rise for at least 60 days to a level above the pre-earthquake level. The data are shown in Wyatt et al. (1994).

Water levels in two unused wells in the Pinon Flats area have been measured using a water-level indicator on a rather regular basis since December 22, 1991. The two wells are located 5 m apart, near the ruins of the old Jim Wellman ranch (JWR in Figure 2). No information is available on the drilling or completion of these wells, but they probably date to the 1930's or early 1940's. In 1992, water levels had been measured 14 times between January 1 and April 26, but no measurements were made between April 26 and June 24, 1992. Measurements from June 24 to August 15 are shown in Figure 9. In both wells, the water level measured on June 28, 1992, after the Landers and Big Bear earthquakes, was 9 cm higher than the previous measurement on June 24. These water-level changes are in the opposite direction from the intial water level changes recorded by Wyatt et al. (1994).

A borehole volumetric strainmeter is operated by the U.S. Geological Survey in southern California (PUB in Figure 2). This strainmeter recorded compressional strain of 0.4 ppm at the time of the Landers earthquake, in general agreement with the computed volumetric strain field shown in Figure 2.

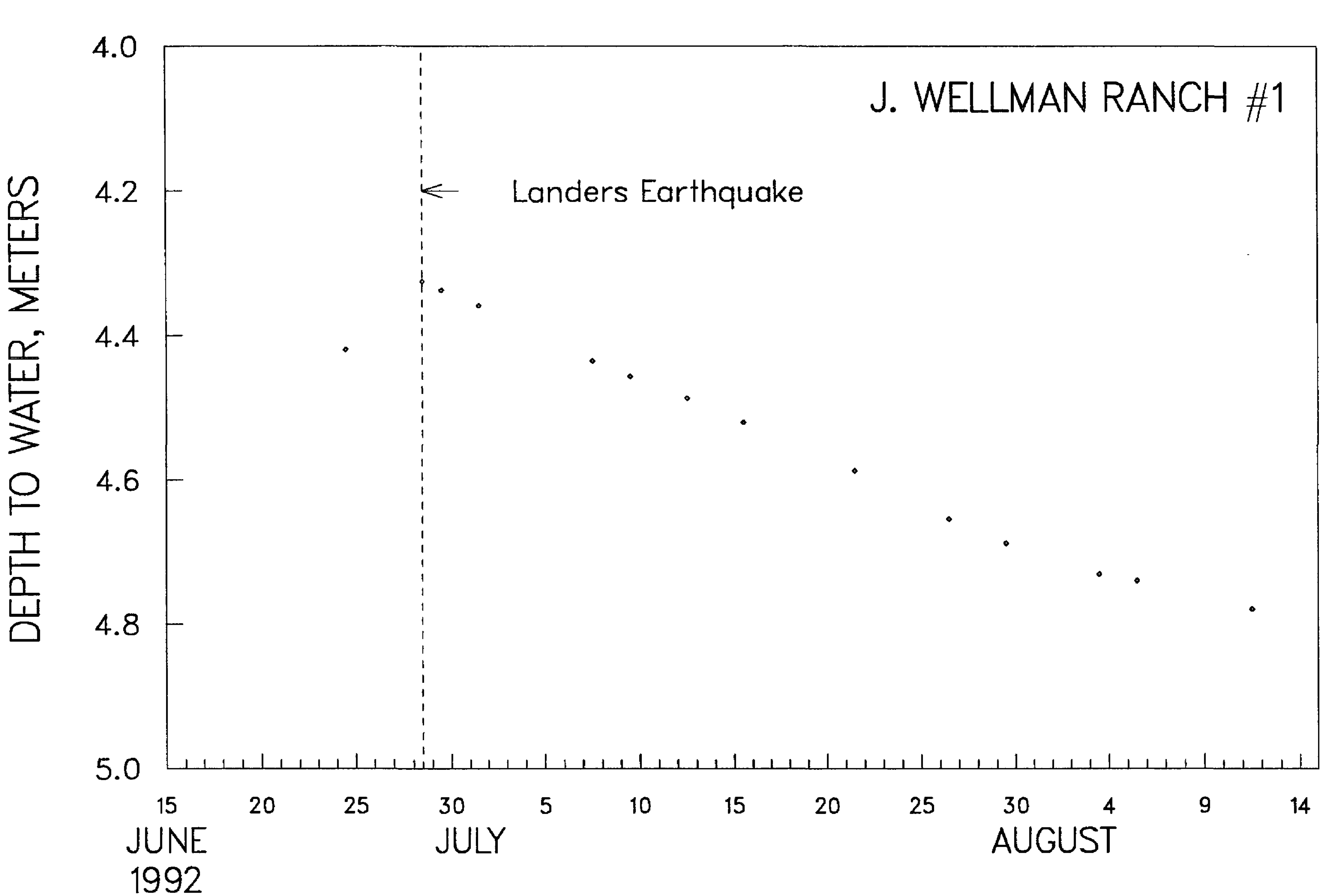

Figure 9. Water levels in two unused wells at the old Wellman Ranch near Pinon Flat, California, June 15 to August 15, 1992. (a) #1 (11 m deep).

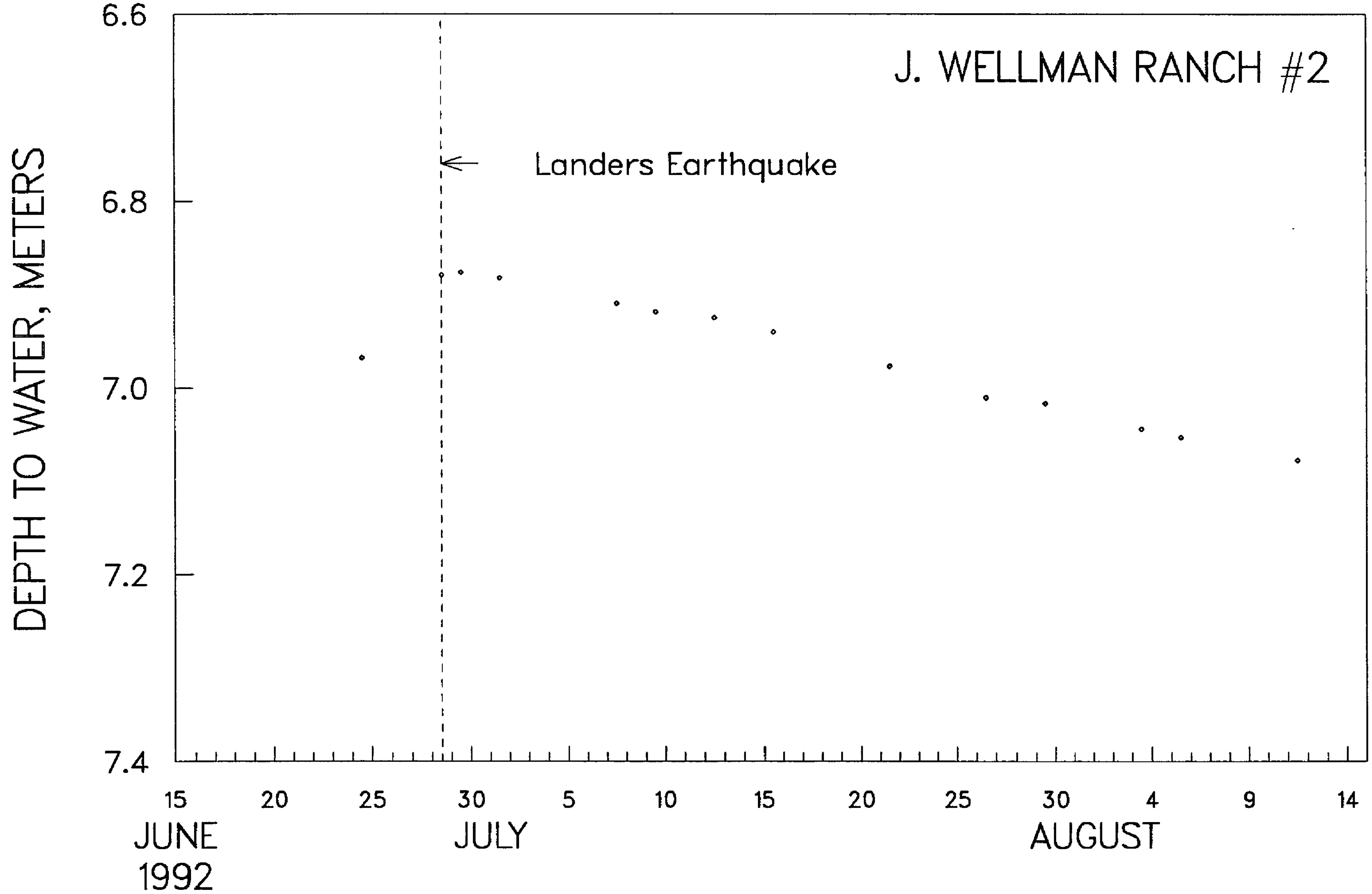

Figure 9, continued. Water levels in two unused wells at the old Wellman Ranch near Pinon Flat, California, June 15 to August 15, 1992. (b) #2 (22 m deep).

Summary of Ground-water Level Changes Within 150 km of Epicenter. Except for the two Wellman ranch wells near Pinon Flat, the signs of the initial water-level changes at all sites shown in Figure 2 agree with the calculated volumetric strain field. With the exception of the one 500 cm drop at Pinon Flat, the sizes of the water-level changes are in approximate relation to the calculated volumetric strains. This consistency would be expected if all of the observation wells were in formations that could be characterized as "porous", rather than fractured. Analysis of longer records of data from these sites would be necessary to establish which wells consistently respond to volumetric strain.

After the earthquake, the water level at some sites recovered to the pre-earthquake level on a time scale consistent with flow to the water table. One well at Pinon Flat displayed a longer-term increase in water level.

Surface Water

USGS Gaging Stations. The U.S. Geological Survey maintains 80 stream gaging stations within 125 km of the Landers epicenter (Figure 10). In at least 23 of these, flow is artificially controlled, either partially or completely. Daily average discharge from all 80 gaging stations was examined to identify possible earthquake-related changes. At all stations except for the Santa Ana River near Mentone, any effect of the earthquake on discharge was below the resolution and/or background variation level of the data.

In the Santa Ana River near Mentone, discharge increased by approximately 50 cubic feet per second (cfs) on the day of the Landers earthquake because earthquake damage to a power plant water intake reduced the amount of flow that could be diverted to the plant (C. Fessler, Southern California Edison Co., written communication, 1994).

Pinon Flat Area. Following the Landers-Big Bear earthquake sequence, increased flow was reported by hikers and by Bureau of Land Management personnel in Palm Canyon, Martinez Canyon, and Horsethief Canyon, approximately 20-40 km to the NW, E, and SE of Pinon Flat, respectively.

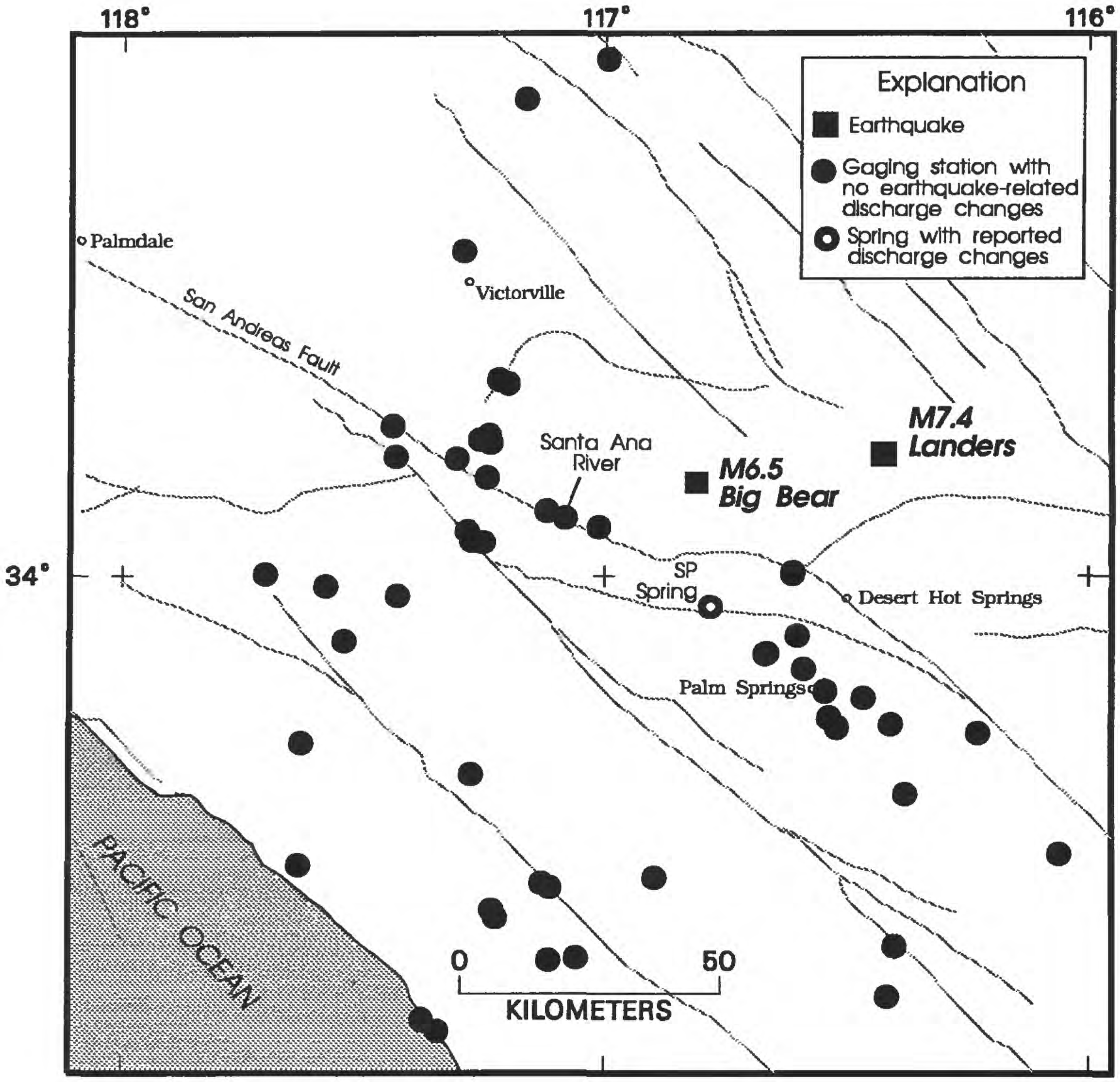

Figure 10. Map showing locations of USGS gaging stations and the Southern Pacific (SP) Spring.

Millard Creek. Rick Hall, a technician with the Cabazon County Water District (CCWD), reported that flow from a spring that they use as a water source had increased before and after the Landers earthquake. The spring is located in Millard Canyon, within the Morongo Indian Reservation, about 130 kilometers east of Los Angeles and near the town of Cabazon (Figures 10 and 11). The Southern Pacific (SP) spring is associated with, and probably in, a strand of the San Andreas fault system, as mapped by Matti et al. (1992) and Matti (unpublished map, 1994).

The spring, which is in the bed of Millard Creek, has been "developed" for use as a water source by excavating its vent to a depth of 3 meters, over a roughly elliptical area 12 m wide and 37 m long, and backfilling with gravel. Spring discharge enters a perforated pipe in this "infiltration gallery" and from there enters an older system of piping belonging to the CCWD. The CCWD has adjudicated rights to 224 gpm (0.5 cfs) from this spring, which they take through the pipes down to tanks at the valley floor near Interstate 10. When spring discharge exceeds this rate, a valve about 100 m downstream from the infiltration gallery is used to reduce the flow rate. When the valve is sufficiently closed down or the natural spring discharge is sufficiently high, excess flow emerges from one or both of two bypasses in the pipe between the infiltration gallery and the valve. When natural spring discharge is below 224 gpm, the valve is fully opened. There is no provision for measurement of the spring discharge upstream of the valve, but there is a flowmeter at the tank site at the valley floor, which is read every few days by Rick Hall.

Because of the valve and the excess flow bypasses, natural spring discharge can be read at the flowmeter only when the valve is open and the flow is less than about 275 gpm. This was the situation in March, April, and May 1992, before the Landers earthquake. At 5:30 PM on June 26, Mr. Hall noticed flow emerging from one of the bypass outlets near the SP spring. He noted on June 27 that the situation was the same as the previous day. At 9 AM on June 29, after the earthquake, he read the flowmeter and found the flow to be 410 gpm. At this time he closed the valve somewhat to decrease the flow rate; subsequent readings do not accurately reflect the spring's discharge but confirm that the discharge remained high for at least several months following the Landers event.

There have been many reports worldwide of hydrologic changes that precede earthquakes, but to date there is no conclusive evidence that such changes consistently take place. Roeloffs and Quilty (1995) reported small ground-water-level and strain changes preceding the 1985 Kettleman Hills, California earthquake (M5.8). The changes were observed at sites 30 to 40 km from the epicenter and began 3 days before the earthquake. Roeloffs (1993) describes a stream discharge increase observed by a hiker about one hour prior to the 1989 Loma Prieta, California earthquake (M7.1), which qualitatively resembles the report regarding the SP spring prior to the Landers earthquake.

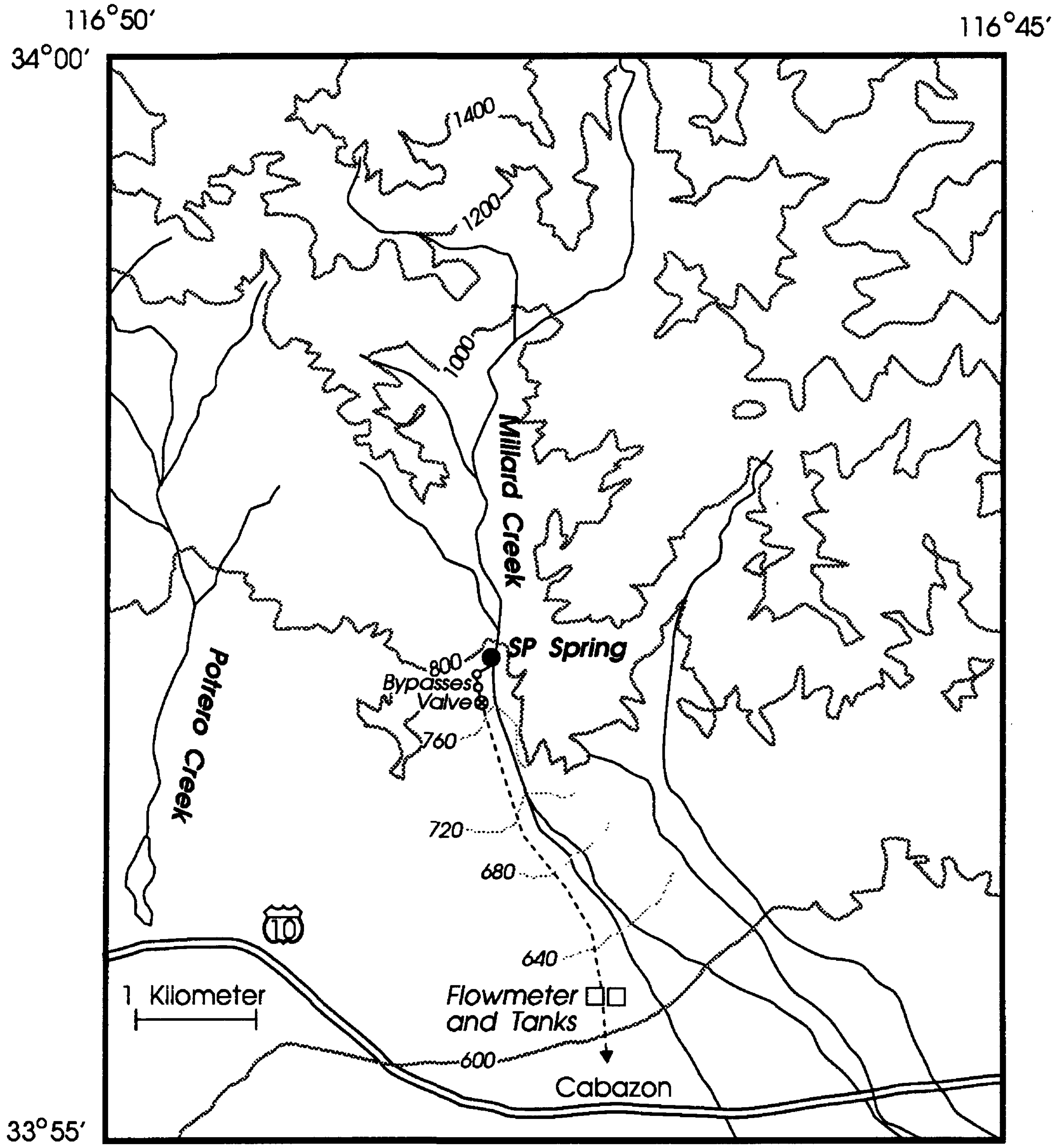

Figure 11. Map showing the area of the SP spring in Millard Canyon.

Summary of Surface Water Effects. Of 80 gaging stations, none recorded a postseismic discharge change of natural origin. A discharge increase, reported to have begun before the earthquake, took place at the SP Spring in Millard Canyon, near active strands of the San Andreas fault system.

Ground-water discharge at a seep or spring can increase because of either an increase of spring vent conductance, or an increase of subsurface fluid pressure in the formation feeding the spring. The SP Spring is in an area where coseismic volumetric strains were 0.1 to 10 ppm extension. Available ground-water observations suggest that the initial response to the earthquake was for subsurface fluid pressure to rise in areas that were volumetrically compressed, and fall in most areas that were volumetrically extended. The observation of increased discharge in an area where coseismic volumetric extension should have lowered subsurface fluid pressure suggests that the increased discharge may be due to increased spring vent conductance. It is plausible that volumetric extension would increase spring vent conductance, although it is also likely that other components of the strain field would be better predictors of spring vent conductance.

Other Phenomena

Tapo Canyon Oil Seep. A pre-existing oil and natural gas seep at Tapo Canyon in the Santa Clara River drainage east of Ventura (Figure 12) became more active after the earthquakes. Information about the seep was obtained from W. Lewis of the Environmental Protection Agency and J. Calloway of the Minerals Management Service.

The increased seepage was not noticed until 8 July when it reached the Santa Clara River. Although earthquake shaking may have been a factor in the increased seepage, hot weather that lowered the oil's viscosity near the surface, and heavy rains that raised the water table may also have played roles.

These seeps are at locations marked as oil seeps on maps as early as 1900. The material seeping from them was approximately 19 parts water to one part oil. The seepage is from the Modelo formation. At least one of the seeps was described as "roiling", and smelled as though hydrogen sulfide and methane were being emitted.

The oil seep contaminated the Santa Clara River, with possible effects on endangered fish and bird species as well as other river life.

Gas Bubbles in San Bernardino Wells. Five wells that are part of the water supply system for the City of San Bernardino (Figure 12) began to produce relatively large amounts of a clear, odorless, non-flammable gas on July 21, 1992. This phenomenon has not been observed before in the city water supply wells. Gas samples were taken from two of the wells on July 30, and analysis in the Gas Geochemistry Lab at the USGS in Vancouver showed the samples to consist of air somewhat enriched with CO_2.

The gas bubbles posed a practical problem in that the water containing the gas could not pass through the filtering system. The bubbling was still in progress as of July 19, 1994.

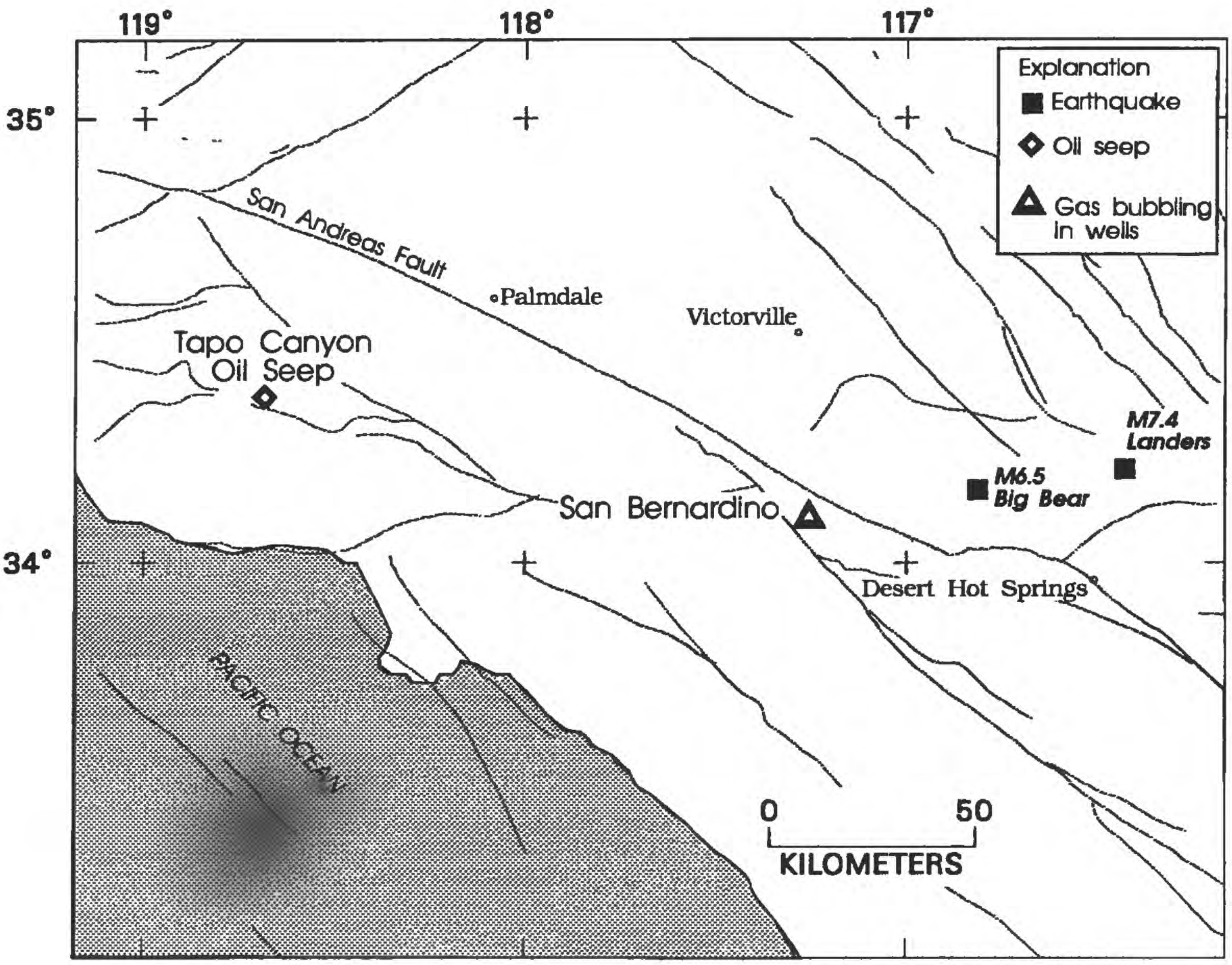

Figure 12. Map showing locations of Tapo Canyon oil seep and San Bernardino, where gas bubbling in water supply wells followed the Landers earthquake.

HYDROLOGIC OBSERVATIONS OUTSIDE OF SOUTHERN CALIFORNIA

Parkfield, California

Three observation wells in the Parkfield water-level network (Figures 1 and 13) displayed coseismic responses to the Landers earthquake. Well information is listed in Table 3, and Figures 14 through 17 show barometric pressure, rainfall, and hydrographs. All wells near Parkfield are monitored using transducers with a resolution of approximately 1 mm of water. Data are sampled at intervals of either 10 or 15 minutes.

The Bourdieu Shallow (BS) well displayed a 34 cm water-level rise following the Landers earthquake (Figures 14 and 15). This behavior is similar to the response of this well to the Loma Prieta earthquake of October 18, 1989, the Parkfield M 4.7 earthquake of October 20, 1992, and the Parkfield M 4.8 earthquake of November 14, 1993 (Figure 14). A small amount of rainfall fell in the Parkfield area on June 30, but is judged unlikely to have contributed significantly to the water-level rise, which began before the rainfall. Moreover, additional rainfall in the second week of July did not produce a comparable water-level rise. After the coseismic water-level rise associated with the Landers earthquake the long term hydrological decline characteristic of summer months at this well site was re-established.

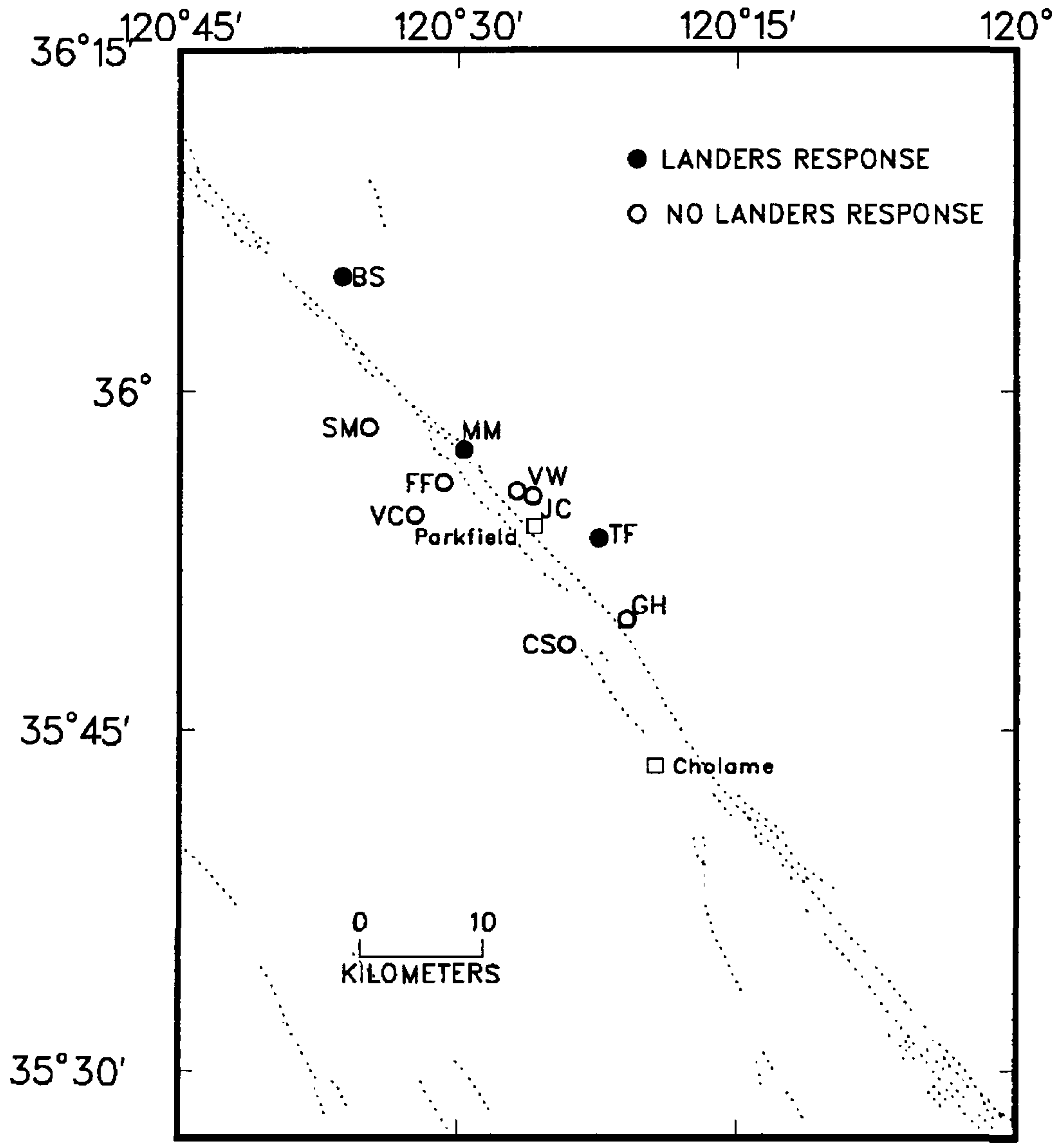

Figure 13. Map of the water level monitoring network near Parkfield, California. Faults are shown as dotted lines.

Table 3. Wells in Parkfield, California

Site Name	Map Symbol	Latitude	Longitude	Depth Monitored (meters)	Landers Response	Tidal Sensitivity (cm/ppm)	Barometric Efficiency
Turkey Flat	TF	35° 53′ 30″	120° 22′ 25″	177	Step +4 cm	53	-0.4
Middle Mountain	MM	35° 57′ 23″	120° 29′ 41″	247	Step -3 cm	53	-0.1
Bourdieu Shallow	BS	36° 5′ 4″	120° 36′ 15″	30	Step +34 cm		-0.6

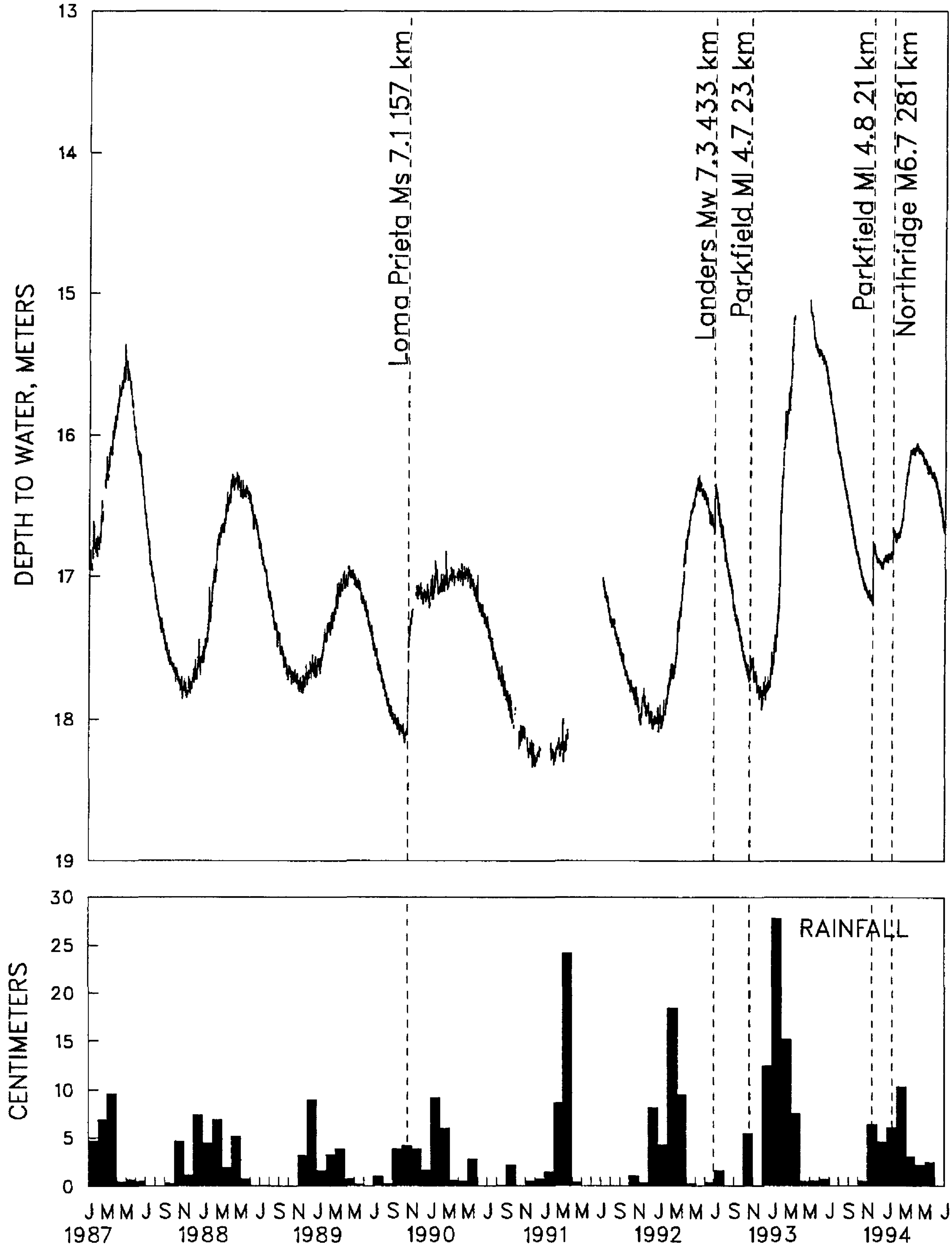

Figure 14. Long-term hydrograph and monthly rainfall for Bourdieu Shallow well near Parkfield, California (BS in Figure 13).

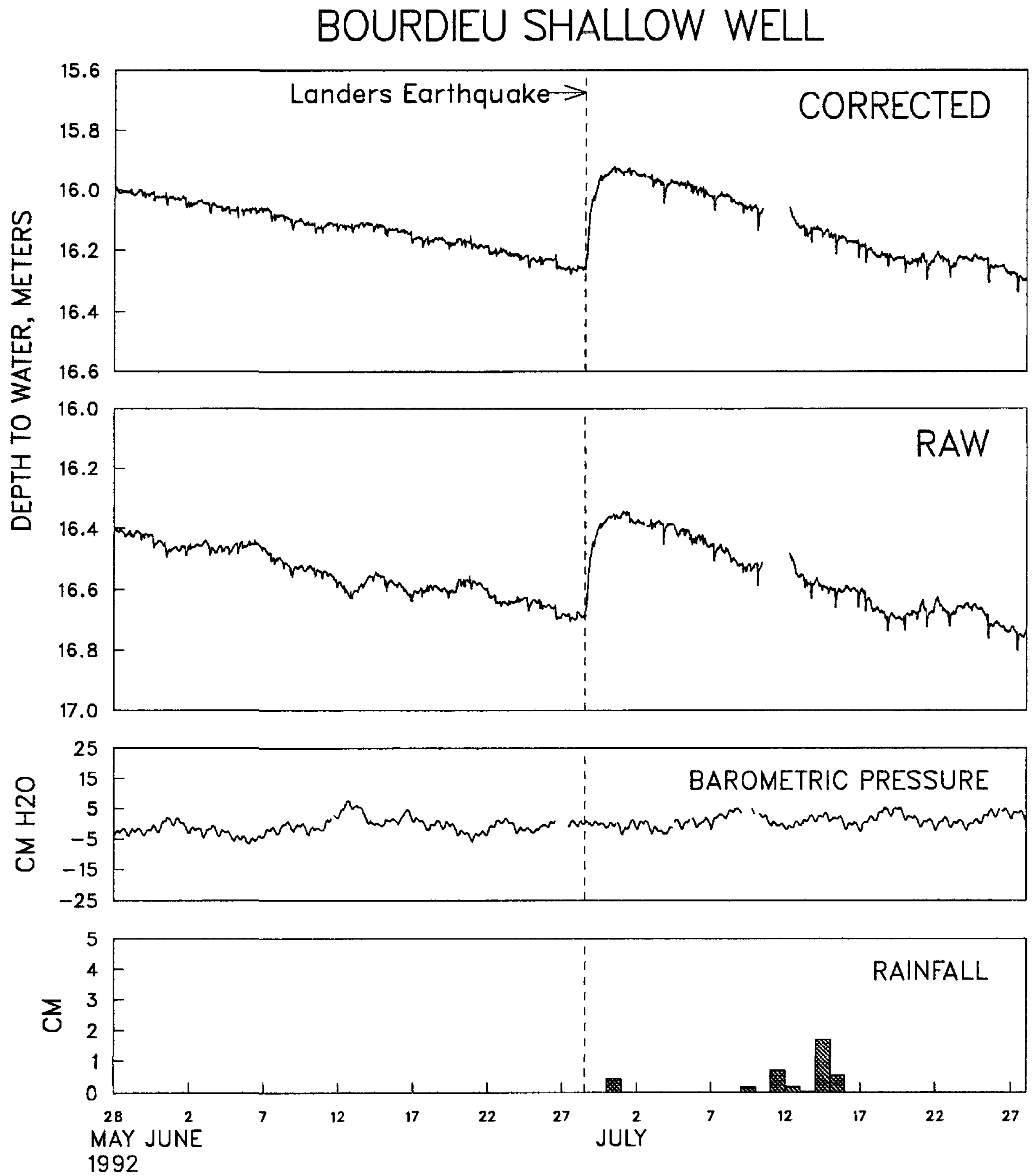

Figure 15. Water level in the Bourdieu Shallow well, barometric pressure, and rainfall. "Corrected" data have been prepared by multiplying the barometric pressure record by a scalar barometric efficiency and subtracting the result from the "Raw" data. (a) May 28 to July 28, 1992.

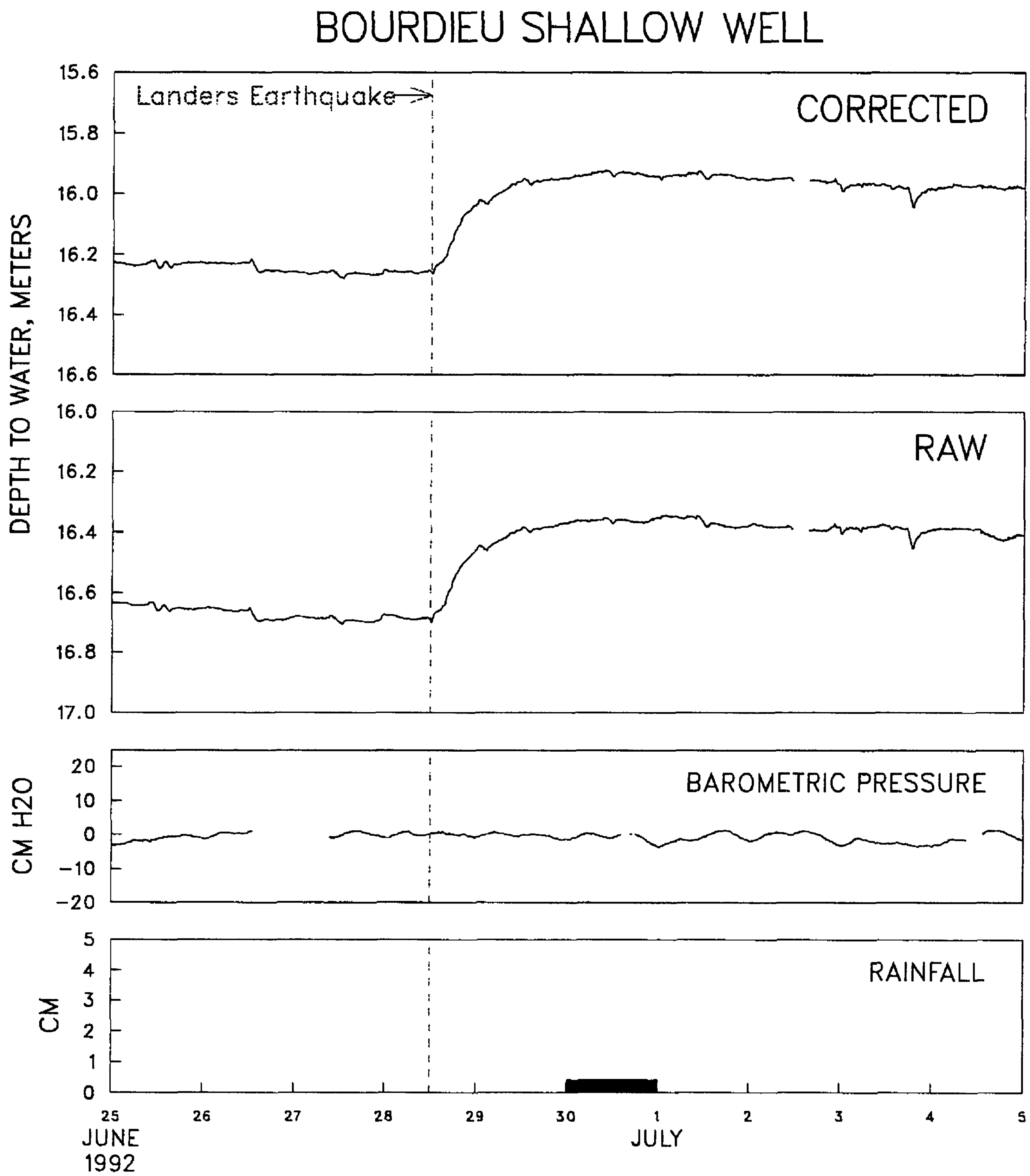

Figure 15, continued. Water level in the Bourdieu Shallow well, barometric pressure, and rainfall. "Corrected" data have been prepared by multiplying the barometric pressure record by a scalar barometric efficiency and subtracting the result from the "Raw" data. (b) June 25 to July 5, 1992.

The coseismic responses of water level in the wells located at Middle Mountain and Turkey Flat were much smaller and are not clearly distinguishable until earth tide and barometric pressure signals are removed from both water-level data sets (Figures 16 and 17). The slow recovery of water level in the Middle Mountain well after the coseismic drop is very similar to water-level recovery at this site following large water-level drops that coincide with nearby creep events on the San Andreas fault (Roeloffs et al., 1989). Small water-level rises in the corrected Middle Mountain data on June 2 and July 14 coincide with small creep events. The Landers earthquake itself triggered about 0.5 mm of right-lateral slip on the San Andreas fault near the Middle Mountain well (K. Breckenridge, unpublished data), which may have in turn influenced the response of well water level.

The Middle Mountain and Turkey Flat wells exhibit earth tidal signals, with strain sensitivities of 53 cm/ppm. At this distance from the epicenter, however, the static strain field of the Landers sequence would not be expected to produce measureable water-level changes in these wells. The Bourdieu Shallow well does not respond to earth tides. In general, it seems unlikely that a static strain change could produce the water-level changes observed in the Parkfield wells.

At Middle Mountain, the slow recovery of water level is characteristic of a confined aquifer. The slow recovery of water level in the filtered data from the Turkey Flat well after the coseismic rise cannot be so readily accounted for since various investigators (Rojstaczer,1988; Quilty and Roeloffs,1991) have established by means of cross-spectral analysis that the aquifer at this site is poorly confined. In a poorly confined aquifer, water-level changes due to volume strain would be expected to recover quickly via upward flow to the water table. Water-level changes in poorly confined aquifers that do not recover quickly might be explained by flow of fluid into or out of the region around the wells but cannot be explained by elastic response to static or dynamic earthquake strain fields.

Other types of data are available from Parkfield. Spudich and others (1995) used data from a dense seismograph array to measure the transient stresses induced by the Landers earthquake. They found that, at the earth's surface, transient strain of 7 ppm and stress of 0.035 Mpa occurred with periods of 2 to 15 seconds, with peak stresses inferred to increase to 0.12 Mpa at depths of 2 to 14 km. The amplitude of the transient strain is thus more than sufficient to account for the amplitude of the observed water-level changes in the Turkey Flat and Middle Mountain wells, but offers no explanation for their persistence.

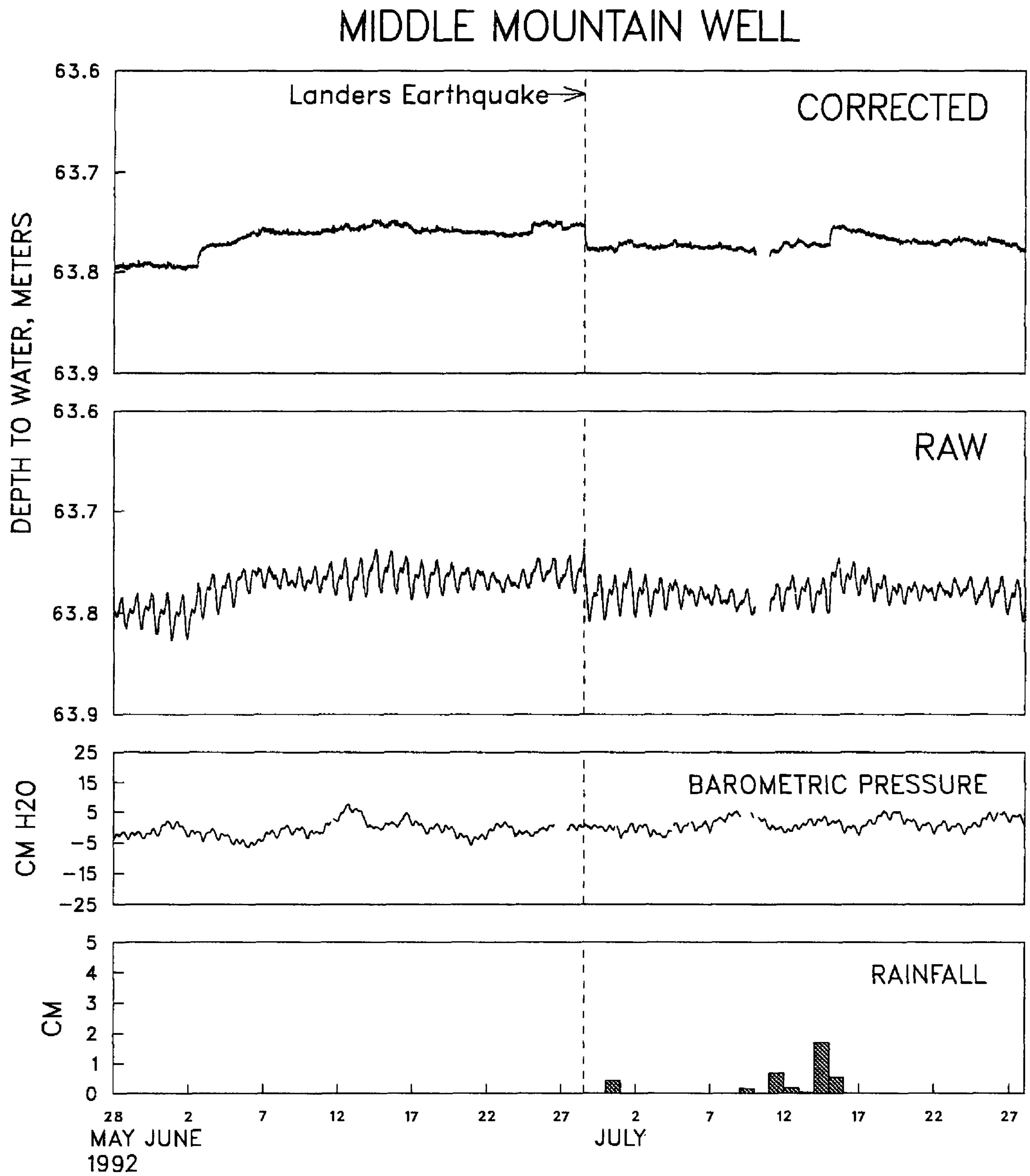

Figure 16. Water level in the Middle Mountain well, barometric pressure, and rainfall. Earth tidal and barometric fluctuations have been subtracted from the "Corrected" data. (a) May 28 to July 28, 1992.

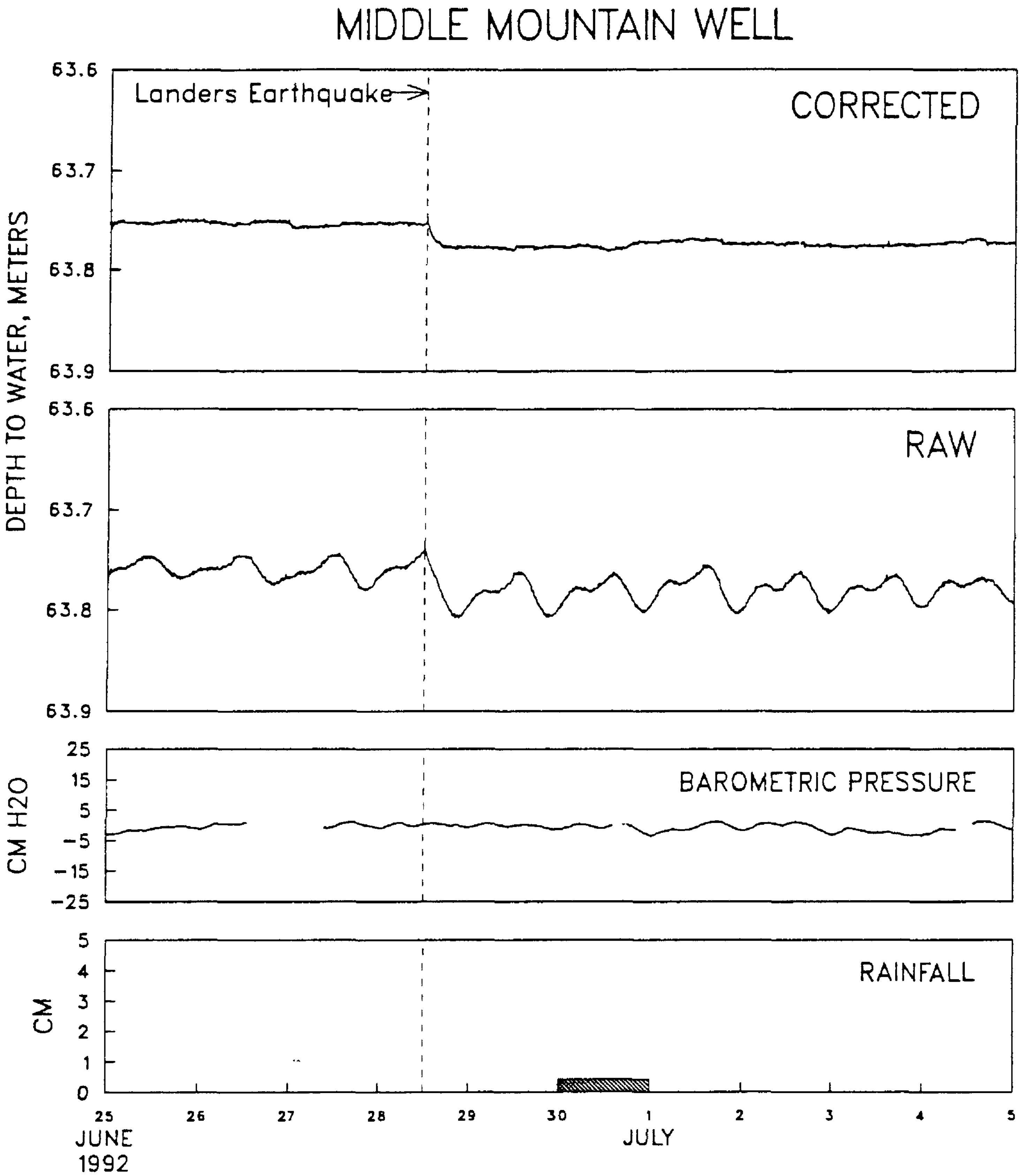

Figure 16, continued. Water level in the Middle Mountain well, barometric pressure, and rainfall. Earth tidal and barometric fluctuations have been subtracted from the "Corrected" data. (b) June 25 to July 5, 1992.

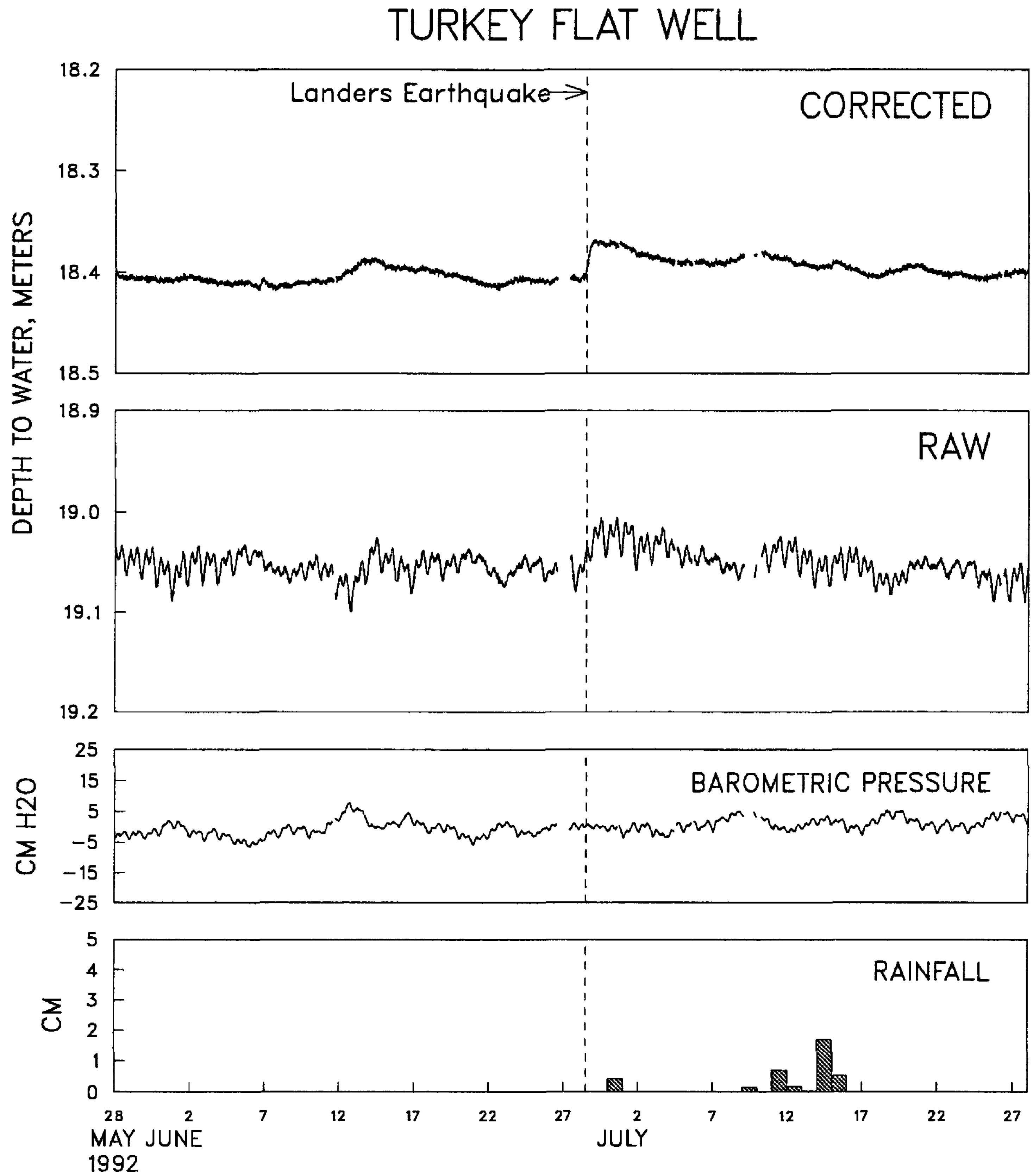

Figure 17. Water level in the Turkey Flat well, barometric pressure, and rainfall. Earth tidal and barometric fluctuations have been subtracted from the "Corrected" data. (a) May 28 to July 28, 1992.

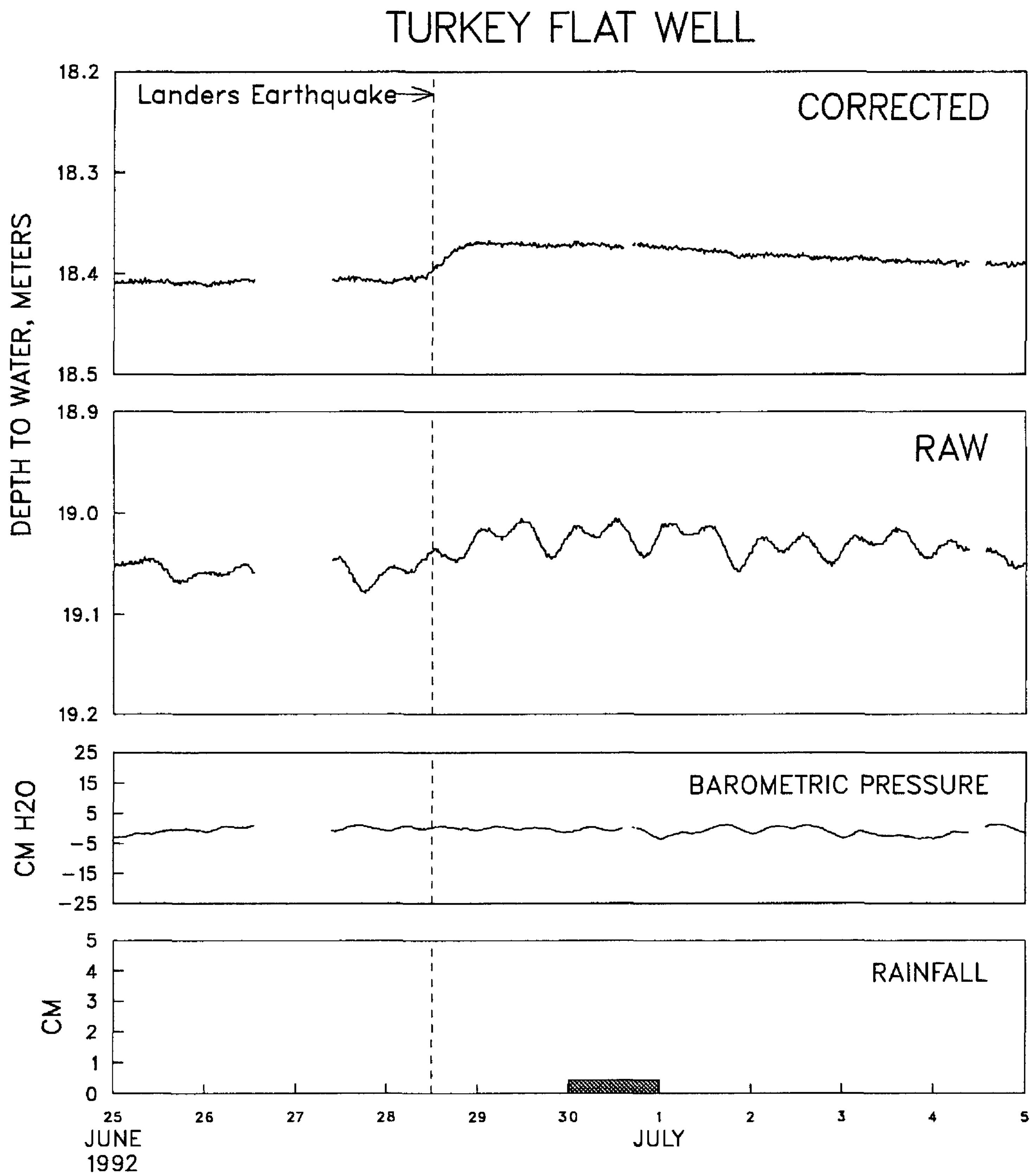

Figure 17, continued. Water level in the Turkey Flat well, barometric pressure, and rainfall. Earth tidal and barometric fluctuations have been subtracted from the "Corrected" data. (b) June 25 to July 5, 1992.

Long Valley, California

The Long Valley area is shown in Figure 1 and the site locations are shown in Figure 18. Table 4 lists the Long Valley sites and their responses. Records of water level or pressure change for three wells with digital recorders and two wells with chart recorders showed coseismic changes of 1.5 to 180 cm (Figures 19 through 22). For two other wells with digital recorders (CH-1 and CM-2), slight rises at the time of the Landers earthquake were comparable to the resolution of the measurement and therefore may be insignificant. In addition to water-level changes in wells, the water level in the Hot Bubbling Pool (HBP) dropped about 4 cm (Figure 23). Hot Bubbling Pool is a thermal (80° C) spring pool approximately 20 m in diameter with no surface discharge point.

At all the Long Valley sites, low frequency (< 1 cycle per day) water-level changes were taking place prior to the Landers earthquake and continued afterwards. These water-level changes included both long-term trends (with periods of 1 year or more) and seasonal fluctuations. In addition, water levels were changing at RDO-8 and probably at HBP, CW-3, and CM-2 due to well field testing in the geothermal field at Casa Diablo. In particular, water level was changing in well RDO-8 before the Landers earthquake in response to a partial shutdown of the geothermal plants at Casa Diablo, beginning at 19:15 local time on June 26, 1992. Because this well is hydraulically connected to the injection zone, its response to the shutdown was a drop in water level. Water levels in wells LKT and CH10-B showed no response to the well field testing because of their distance from the well field.

The recorded water-level changes are in part a function of measurement frequency. The hydrograph from CW-3 (Figure 19) which is equipped with a chart recorder, exhibits vertical lines at the times of the Landers and Big Bear earthquakes. These lines most likely represent an oscillatory response to the earthquake surface waves. Although the time resolution does not allow individual oscillations to be discerned, the maximum amplitude should be accurately recorded because of the continuous nature of the record. Well MW-5 (data not shown) is also monitored using a chart recorder, and appears to have exhibited smaller amplitude fluctuations at the time of the Landers earthquake.

The other three Long Valley wells that responded (CH10-B, LKT, and RDO-8) probably also oscillated in response to the earthquake surface waves, but because the sampling interval of 15 or 30 minutes is long compared to surface wave periods of tens of seconds, the maximum recorded amplitude is probably not equal to the maximum amplitude of the oscillations.

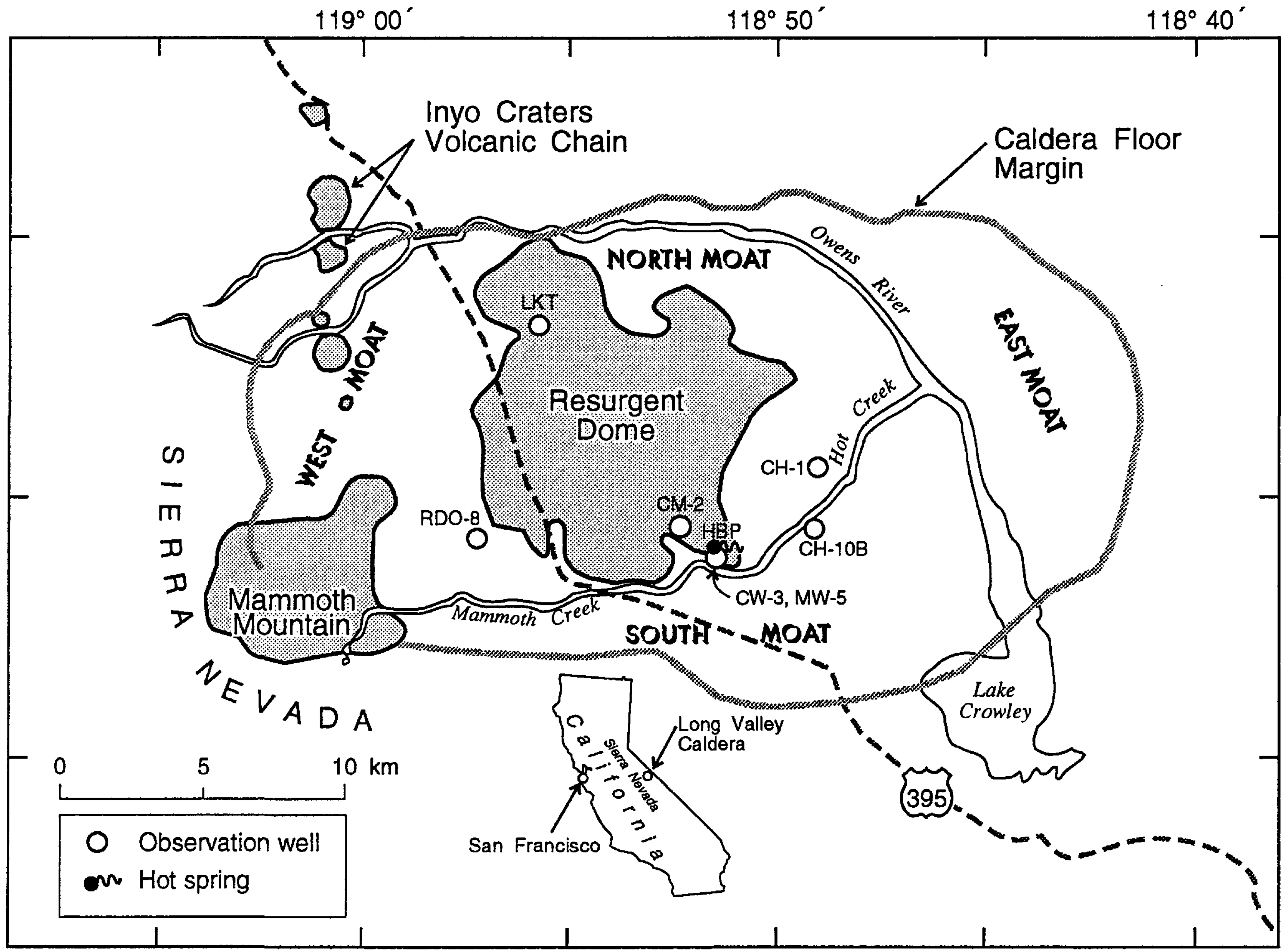

Figure 18. Map showing sites in Long Valley, California.

Table 4. Sites in Long Valley.

Map Symbol	Latitude	Longitude	Depth (meters)	How Measured	Earthquake Response
CH-1	37° 40′ 45″	118° 49′ 10″	143-145	Transducer 15 min. sampling	Questionable- +0.3 cm change at time of earthquake comparable to measurement precision
CH10-B	37° 39′ 30″	118° 49′ 16″	91-96	Gas Bubbler 15 min. samples 20 min. equilibration	Drop -180 cm Rise 0.3 cm Drop 1.8 cm
CM-2	37° 39′ 06″	118° 52′ 23″	46	Transducer 15 min. sampling	Questionable- +0.3 cm change at time of earthquake comparable to measurement precision
CW-3	37° 38′ 49″	118° 51′ 30″	128-280 accessible depth 267 m	Stevens Recorder Time Res. 0.025 in/hour	Landers:41.8 cm peak-to-peak Recovery in < 1 hour Big Bear:3 cm peak-to-peak
LKT	37° 43′ 00″	118° 55′ 44″	152-1,067 Bridged at 302 m	Transducer 30 min. sampling	7.7 cm peak-to-peak
MW-5	37° 38′ 41″	118° 51′ 29″	140-151 Accessible Depth 101 m	Stevens Recorder Time Res. 0.025 in/hour	1.5 cm peak-to-peak
RDO-8	37° 39′ 24″	118° 57′ 12″	338-341 Accessible Depth 390 m	Transducer 15 min. sampling	Drop -35.1 cm 12 cm drop persists at least two days

Notes. Unless otherwise indicated, depths are those of the open intervals of the wells. "Step" means, an abrupt rise or fall at the time of the earthquake. Responses are at time of Landers earthquake, unless otherwise noted.

The transducer in well LKT, which is designated as a strain-indicator well, malfunctioned during the initial coseismic compressional change. Thus, it is not possible to determine the full extent of the compressional change, or whether a postseismic extensional change occurred, as was observed after the Chalfant and Loma Prieta earthquakes.

Aside from well CH10-B, the magnitude of the coseismic response in the wells is less than a maximum of 37 cm, and in each case the seismically induced changes were considerably smaller than fluctuations occurring during that general time period as a result of the shut-down of the geothermal well field at Casa Diablo and normal seasonal hydrologic processes. The coseismic change observed in well CH10-B, located near the Hot Creek gorge, was anomalous in magnitude and duration. Its response is due in part to the characteristics of the nitrogen bubbler-tube system used to detect changes in water level, and possibly to its proximity to the thermal water discharge area in Hot Creek gorge.

Except for RDO-8, water levels in all wells returned to their pre-earthquake levels within an hour or two, consistent with the hypothesis that the coseismic changes were oscillations in response to elastic strain induced in the aquifers by the passage of surface waves. At RDO-8, however, a decrease of about 12 cm relative to the pre-earthquake water level persisted for about two days. It is not known when the water level at well LKT returned to its pre-earthquake level, because the transducer failed.

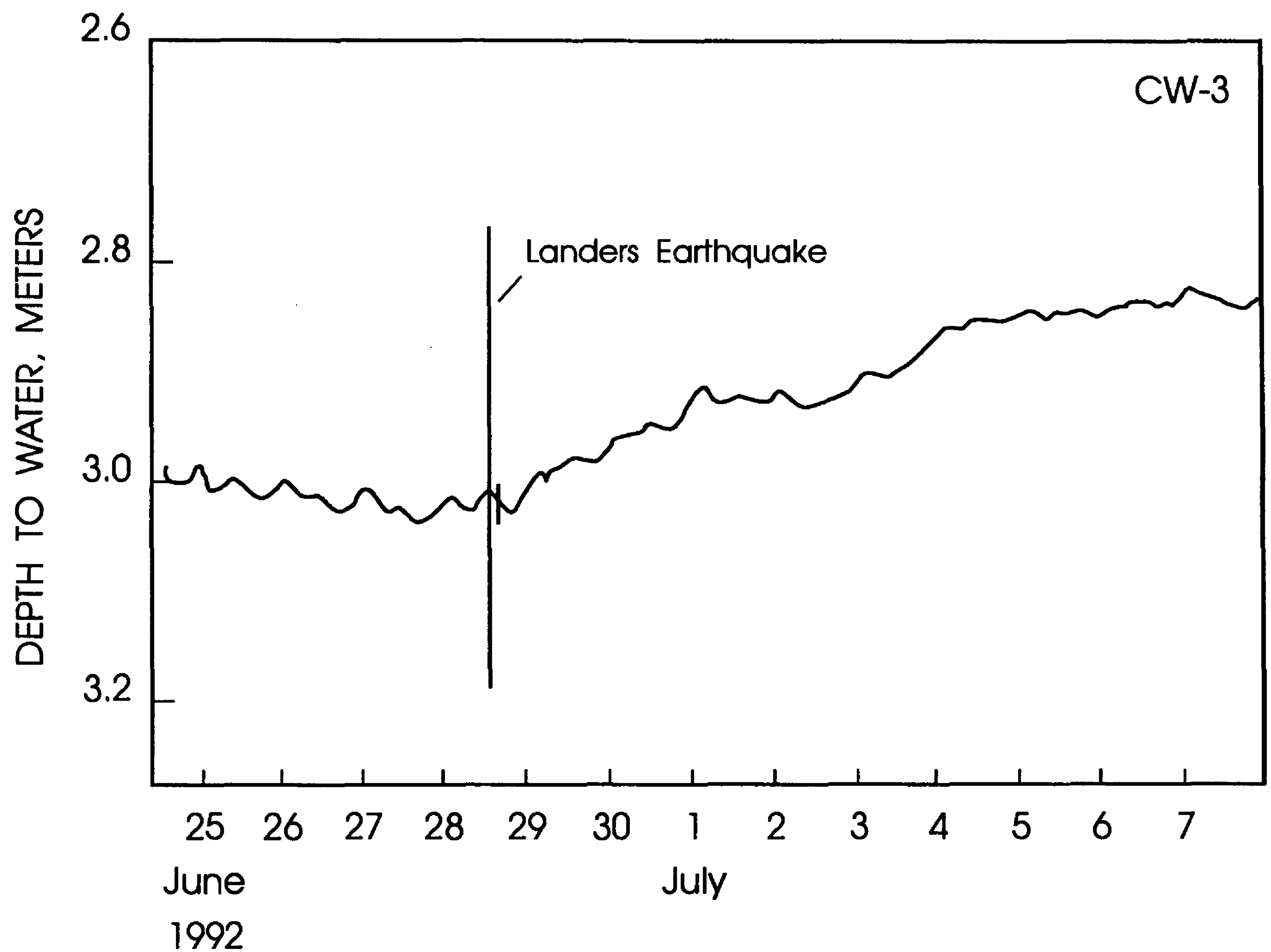

Figure 19. Chart record from well CW-3, Long Valley, California.

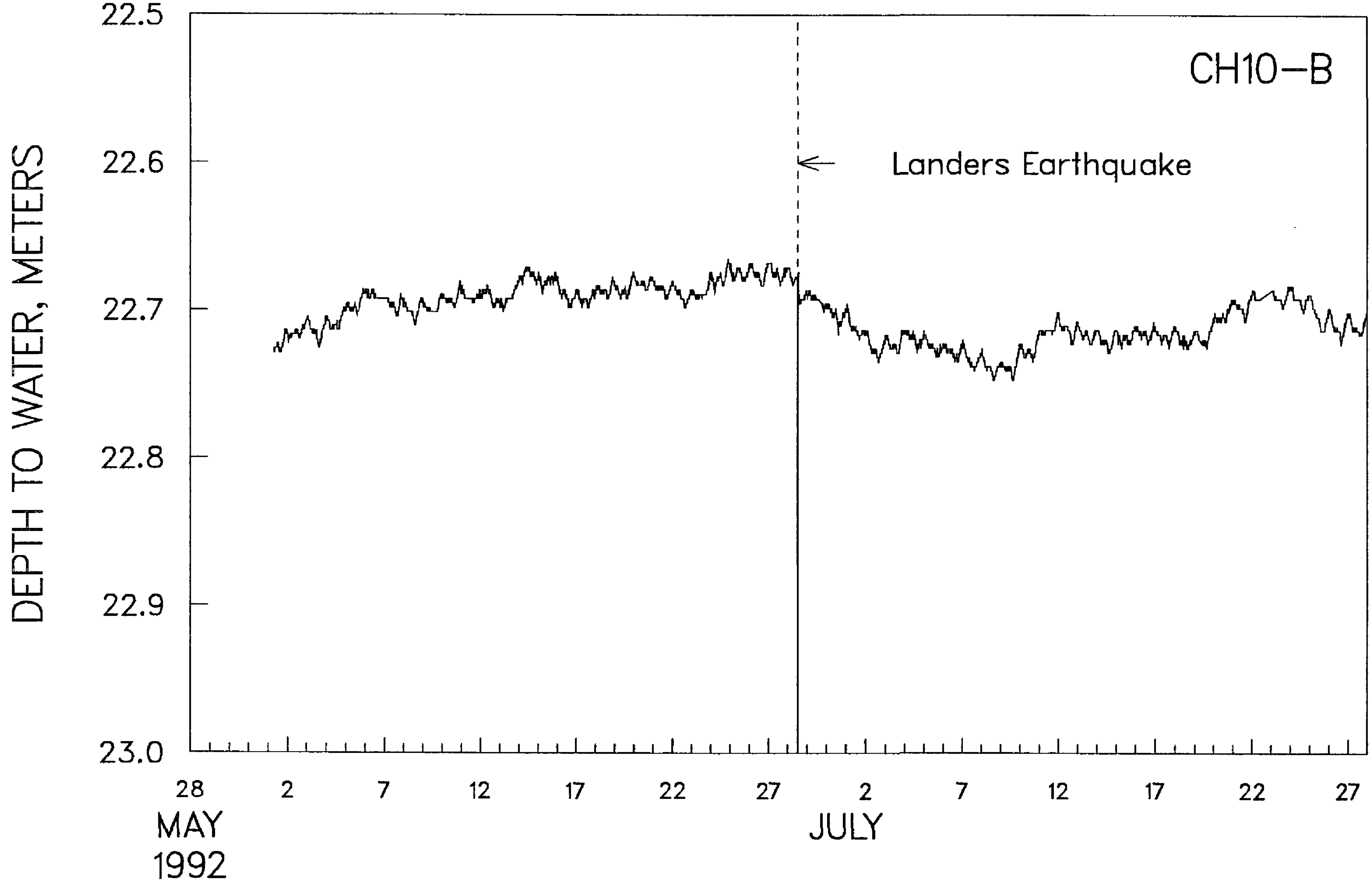

Figure 20. Water level in well CH10-B, Long Valley, California. (a) May 28 to July 28, 1992.

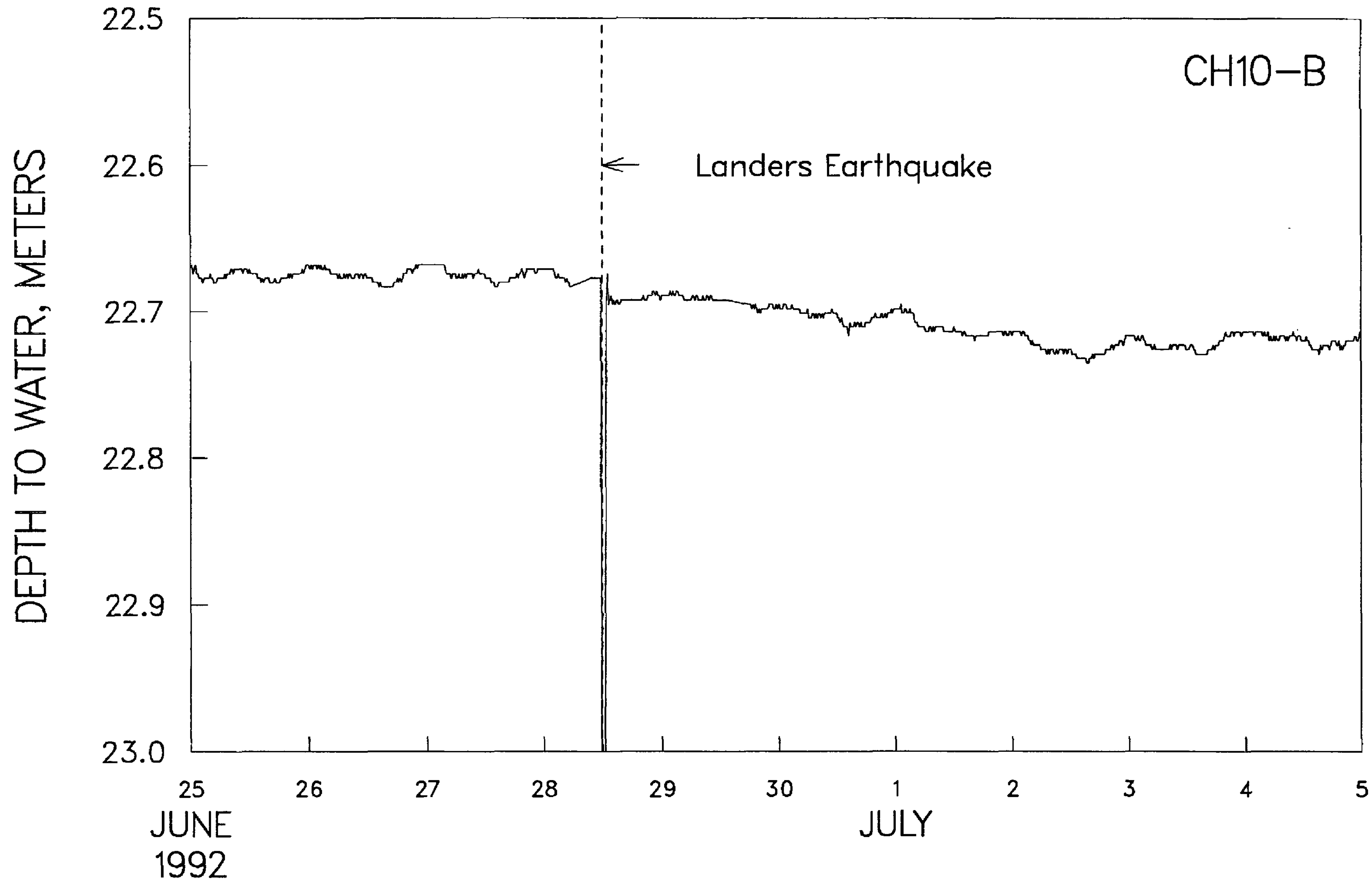

Figure 20, continued. Water level in well CH10-B, Long Valley, California. (b) June 25 to July 5, 1992.

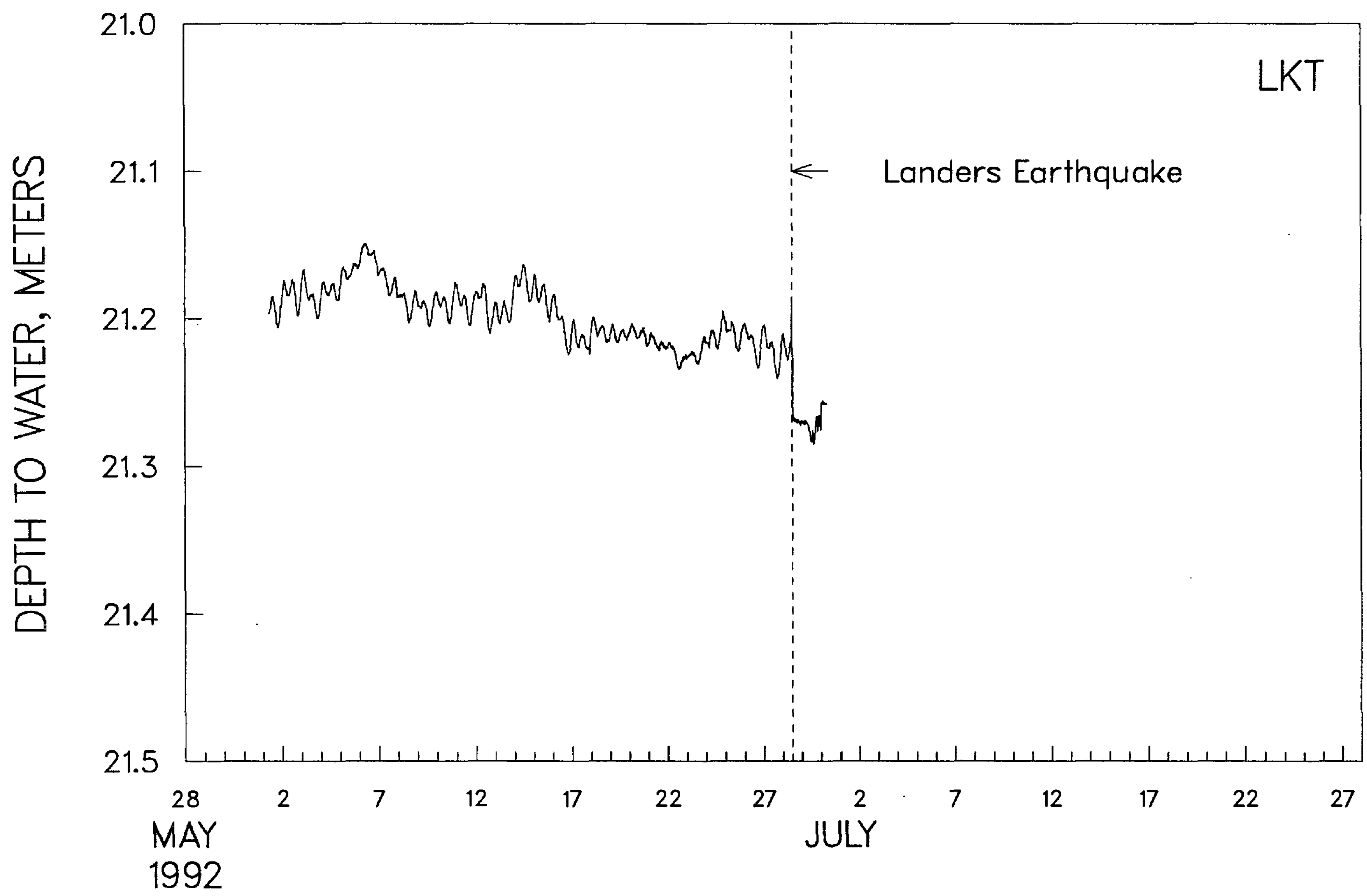

Figure 21. Water level in well LKT, Long Valley, California. (a) May 28 to July 28, 1992.

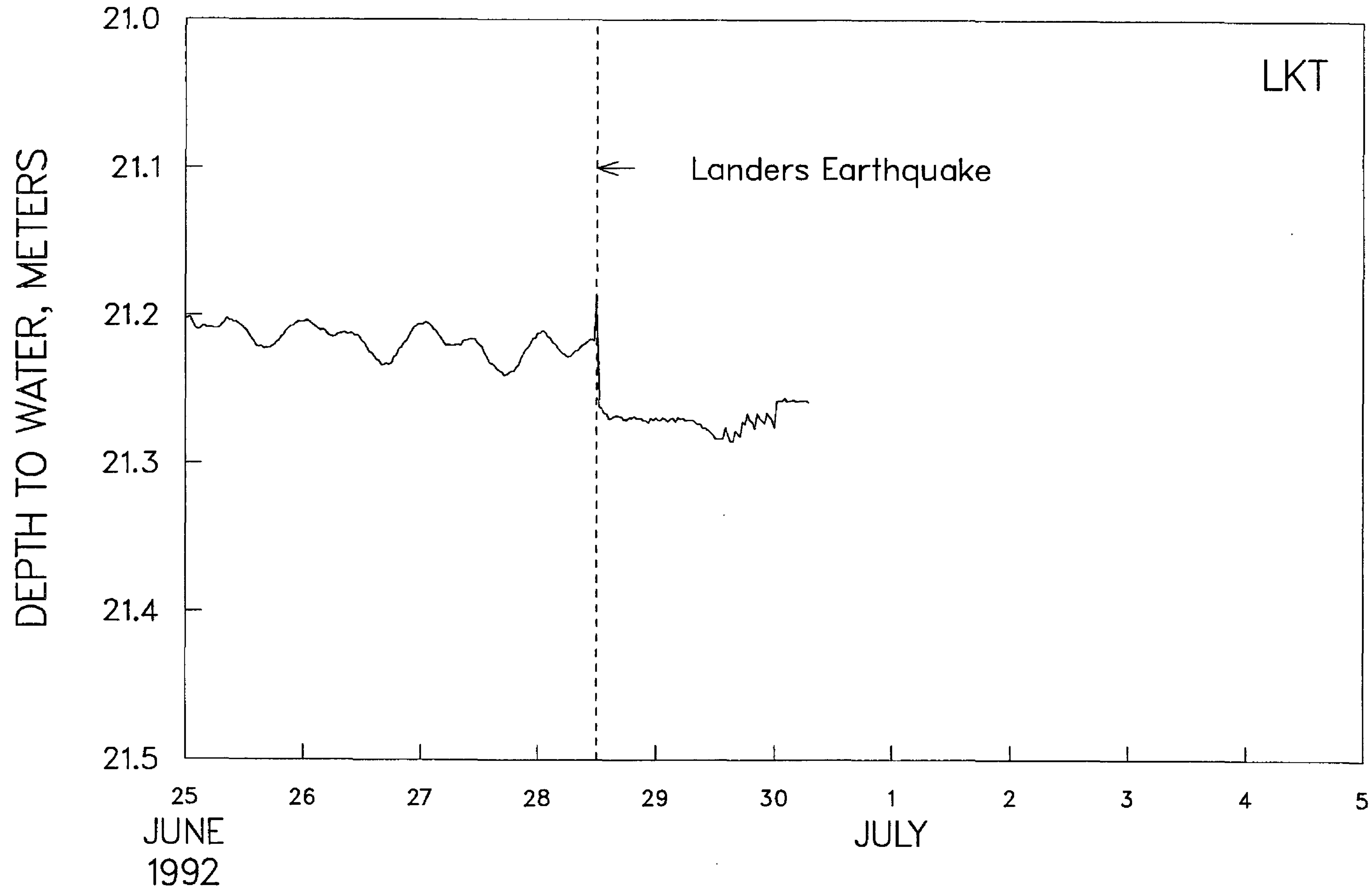

Figure 21, continued. Water level in well LKT, Long Valley, California. (b) June 25 to July 5, 1992.

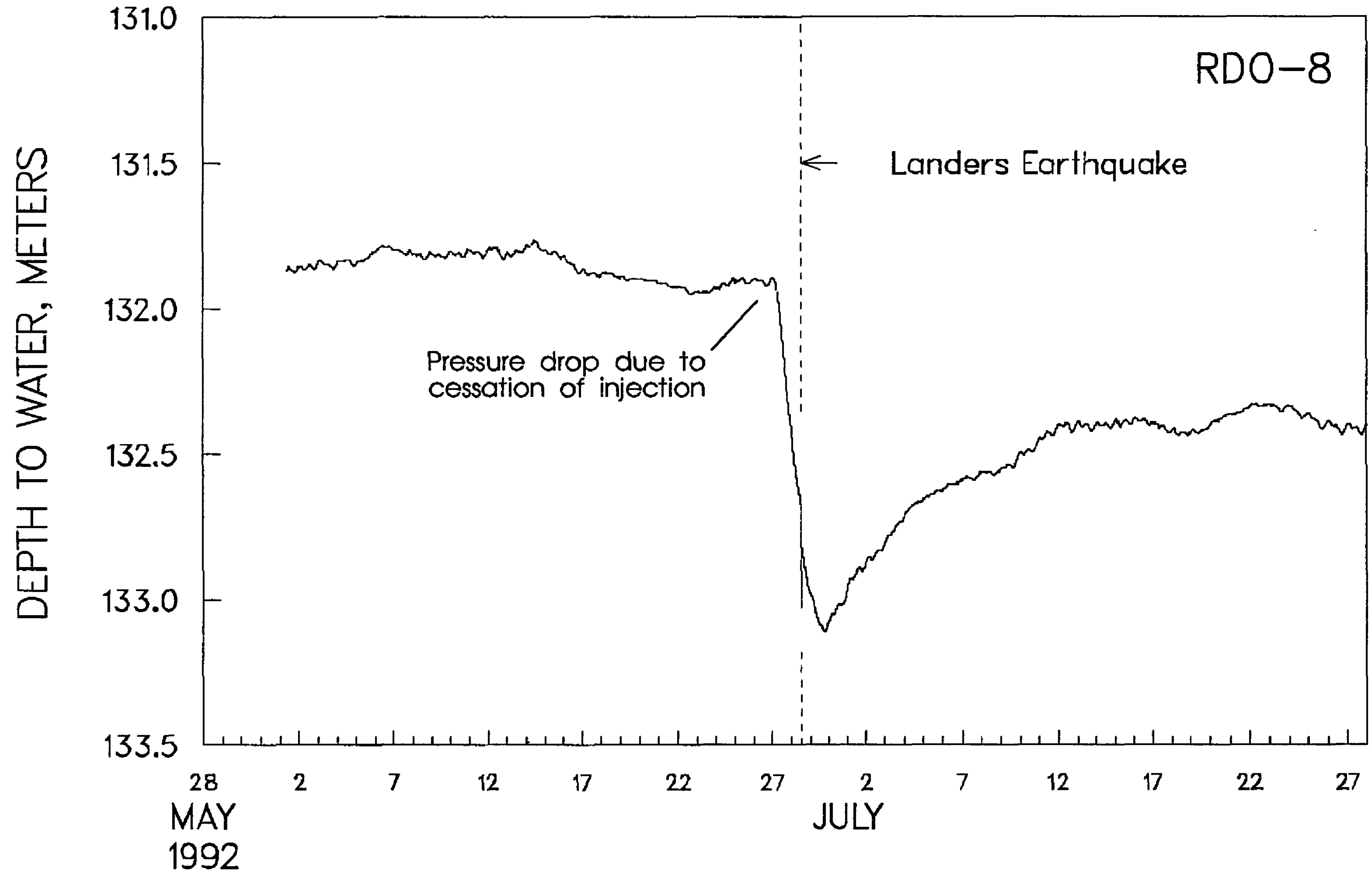

Figure 22. Water level in well RDO-8, Long Valley, California. (a) May 28 to July 28, 1992.

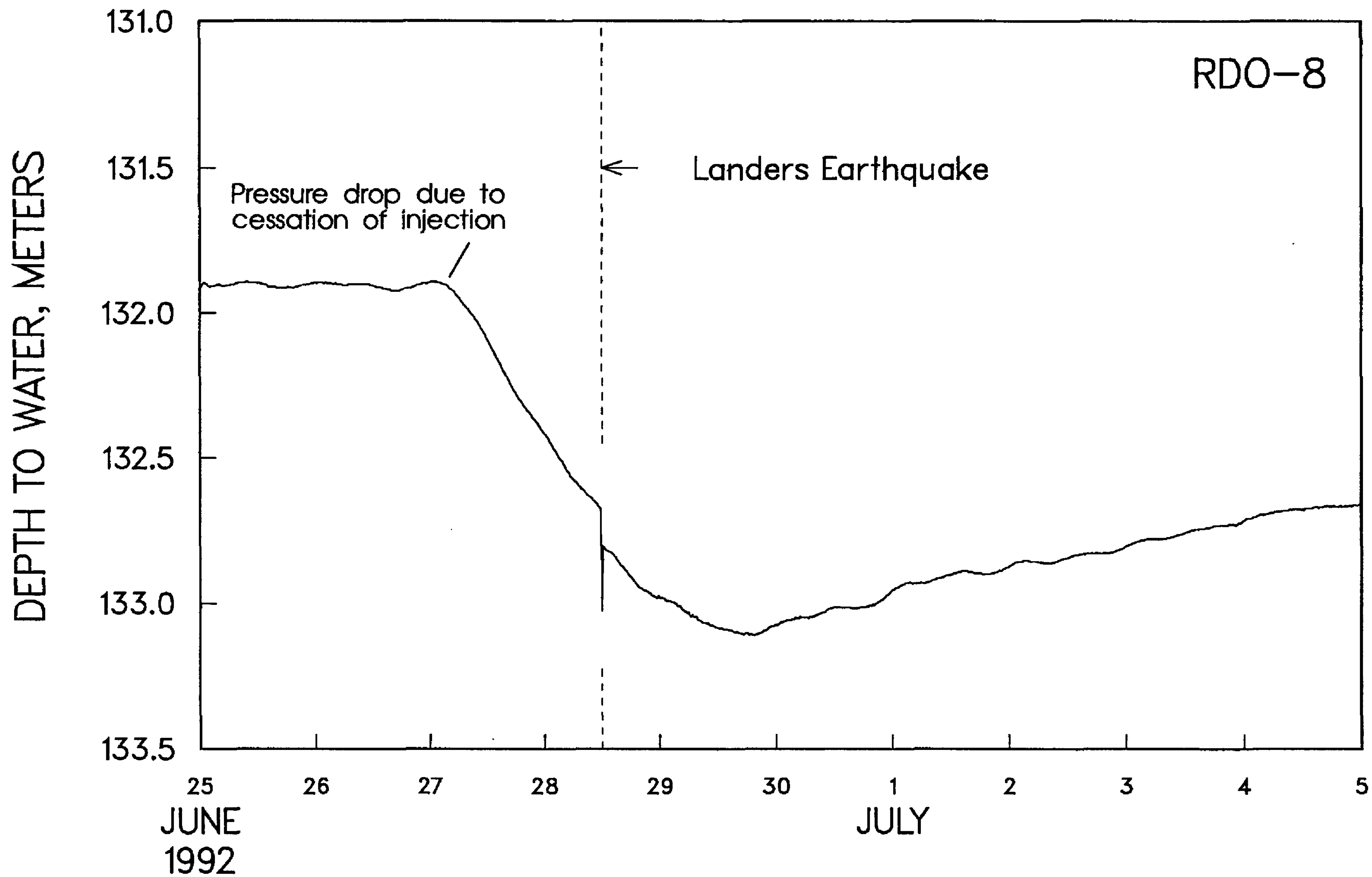

Figure 22, continued. Water level in well RDO-8, Long Valley, California. (b) June 25 to July 5, 1992.

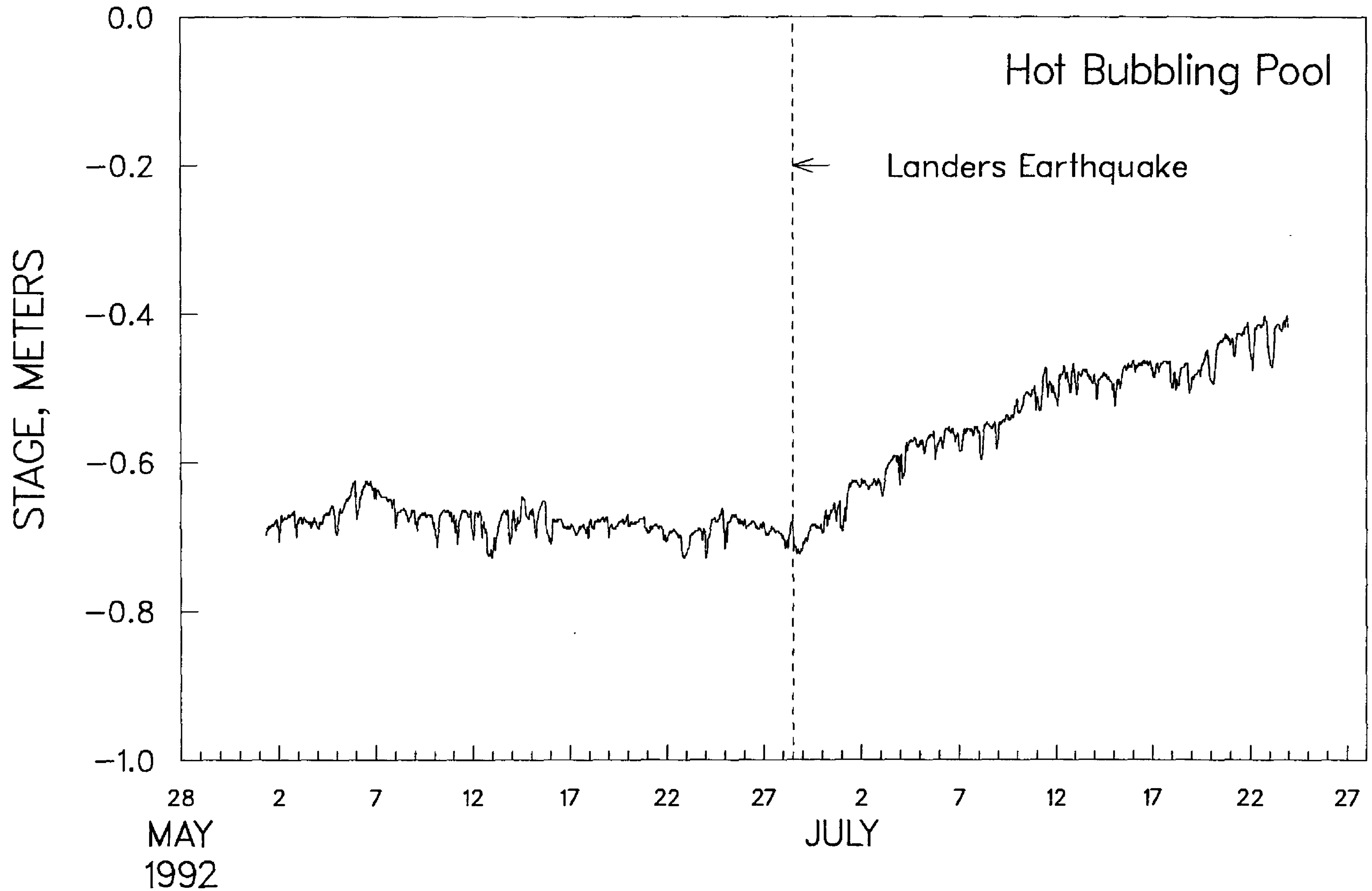

Figure 23. Stage in Hot Bubbling Pool, Long Valley, California. (a) May 28 to July 28, 1992.

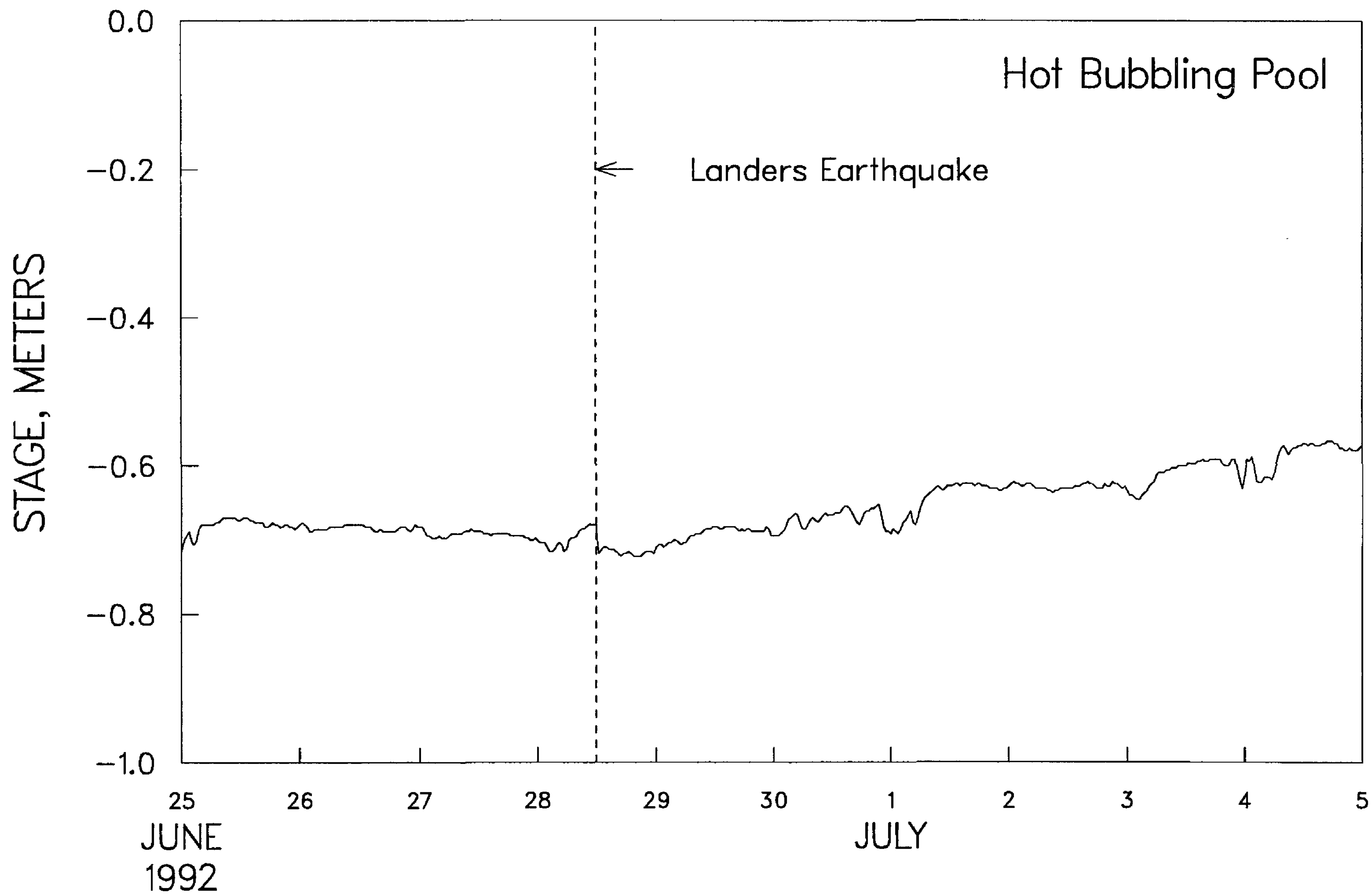

Figure 23, continued. Stage in Hot Bubbling Pool, Long Valley, California. (b) June 25 to July 5, 1992.

Eastern Nevada

Water-level fluctuations were recorded in two wells in eastern Nevada (Figure 1; Table 5), 509 and 522 km from the Landers epicenter. Both wells are completed in unconsolidated alluvium. The wells are instrumented with 20 psi transducers, and maximum, minimum, and average water levels are logged every six hours (Figure 24). The data are consistent with the occurrence of seismic oscillations, with water level returning to the pre-earthquake level within one six-hour sampling interval.

Table 5. Wells in Eastern Nevada

Site Name	Latitude	Longitude	Depth (meters)
Spring Valley	38° 37′ 04″	114° 22′ 50″	213
North Railroad Valley	38° 43′ 48″	115° 28′ 37″	178

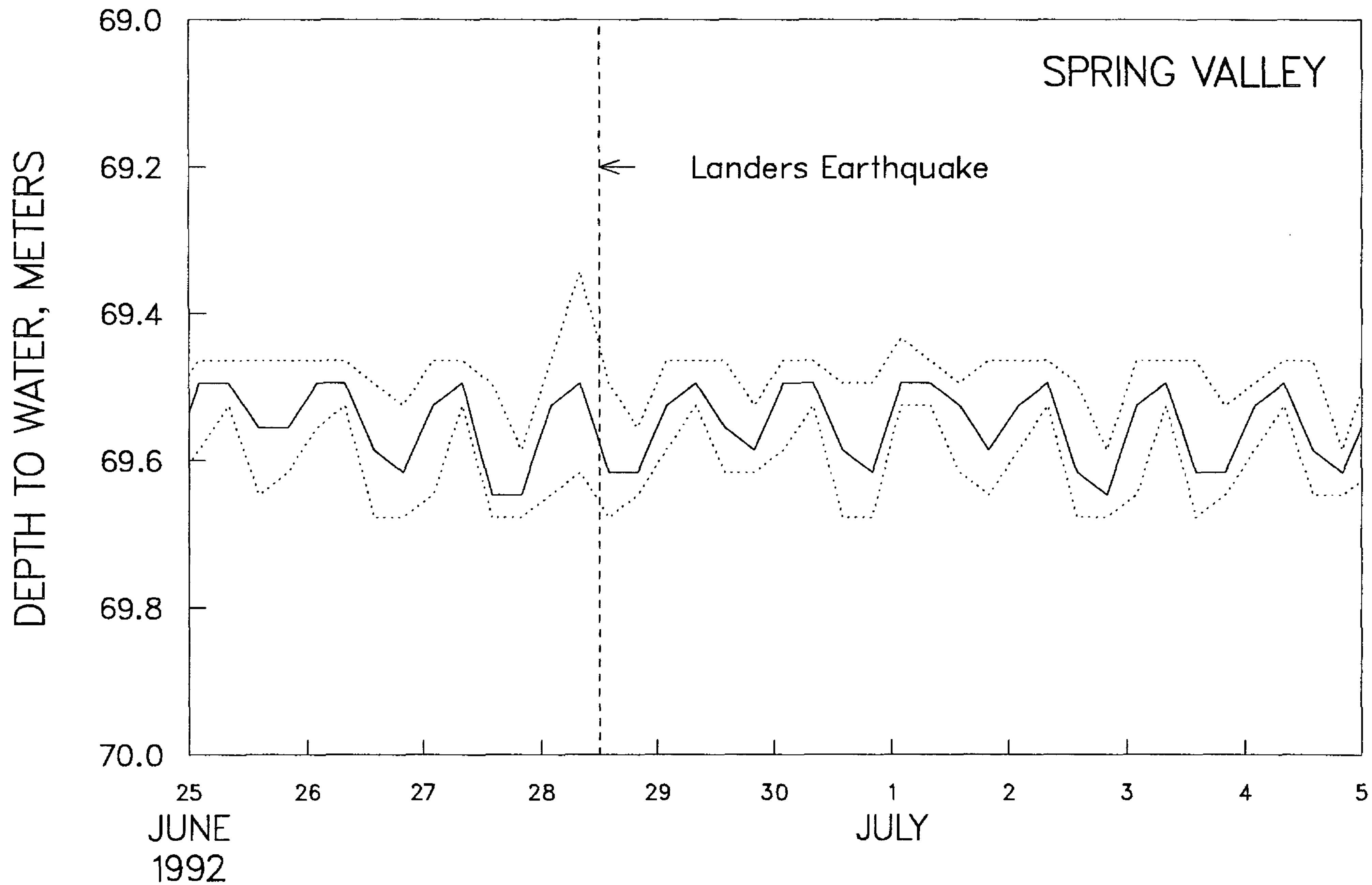

Figure 24. Water levels in wells in eastern Nevada, June 25 to July 5, 1992. Average, maximum, and minimum values are recorded every 6 hours and are shown as the solid curve and the upper and lower dotted curves, respectively. (a) Spring Valley.

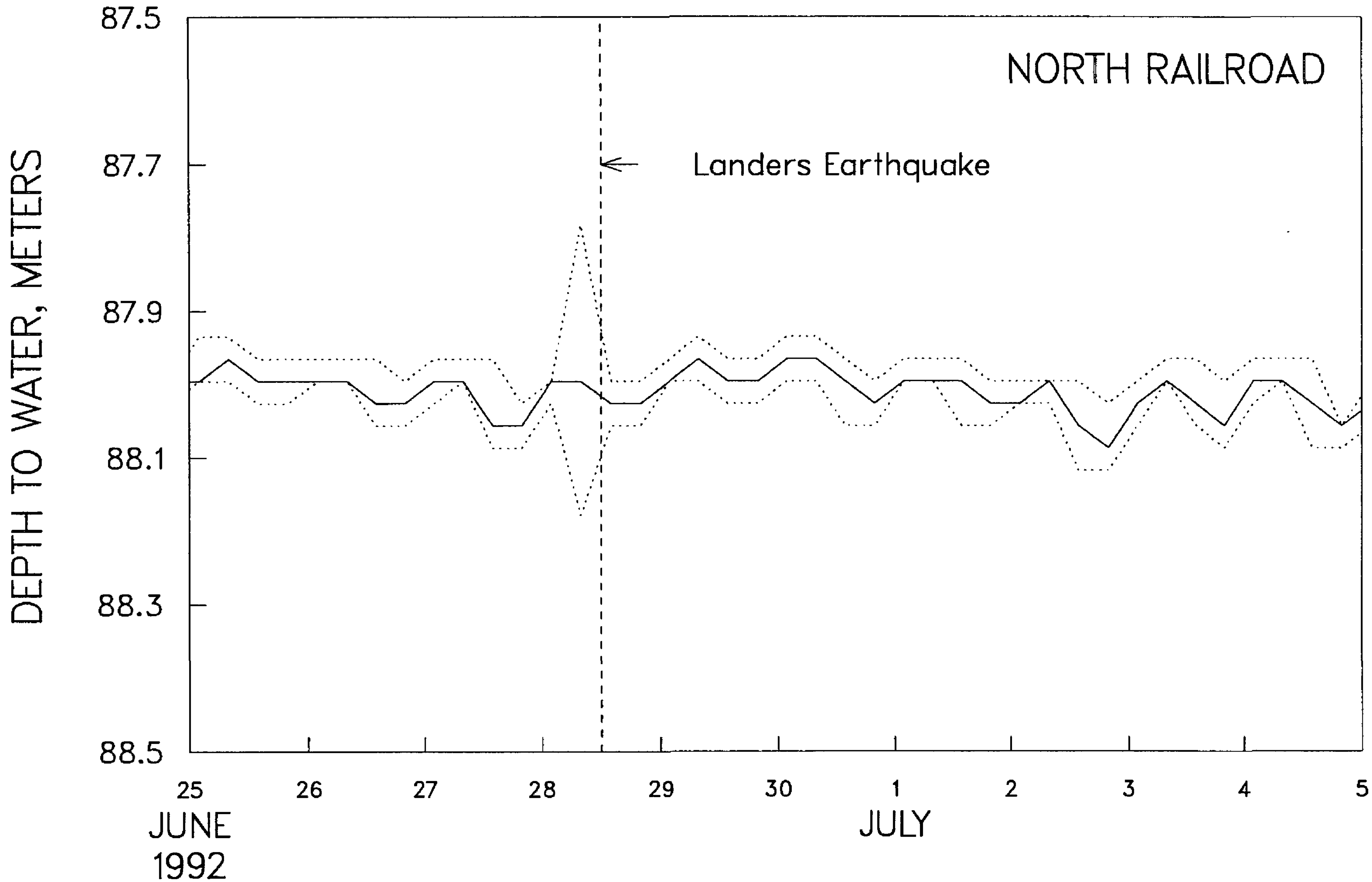

Figure 24, continued. Water levels in wells in eastern Nevada, June 25 to July 5, 1992. Average, maximum, and minimum values are recorded every 6 hours and are shown as the solid curve and the upper and lower dotted curves, respectively. (b) North Railroad Valley.

Grants Pass, Oregon

Water-level oscillations were recorded in the North Valley Industrial Park (NVIP) well in Grants Pass, Oregon. The well is 91 meters deep, cased to a depth of 51 meters, and developed in fractured granodiorite and crystalline metamorphic rock. The well has been monitored since 1984 with a Stevens chart recorder.

The NVIP well has displayed many oscillations in response to earthquakes. Some of these oscillations correspond to earthquakes of magnitude 7 or larger at teleseismic distances. The largest oscillations measured 114 cm peak to peak, and were recorded on April 25, 1992, corresponding to the magnitude 7.1 Cape Mendocino earthquake. The oscillations corresponding to the Landers earthquake, with an amplitude of 78 cm peak to peak, were the second largest to have been recorded in the NVIP well. The chart record was digitized and is plotted as Figure 25.

Seismic water-level oscillations in the NVIP well that are larger than 30 cm peak to peak have been accompanied by water-level drops that persist for a period of days after the earthquake. For the Landers earthquake, the occurrence of a persistent water level change is suggested by comparing the tidal troughs for the three days following the earthquake with those for the three days before. Following the coseismic water-level oscillation, the water level appears to have fallen by about 3 cm and returned to the pre-earthquake level 5 to 6 days later. Barometric pressure effects probably obscure the recovery to the pre-earthquake water level, because a storm accompanied by 3.2 cm of rain took place on June 28 and 29, 1992.

The coseismic oscillations in the NVIP well are probably due to resonant movement of the water column in the well, as described by Cooper et al. (1965) and Liu et al. (1989). The reason why water-level changes sometimes persist for several days after earthquakes is not yet understood.

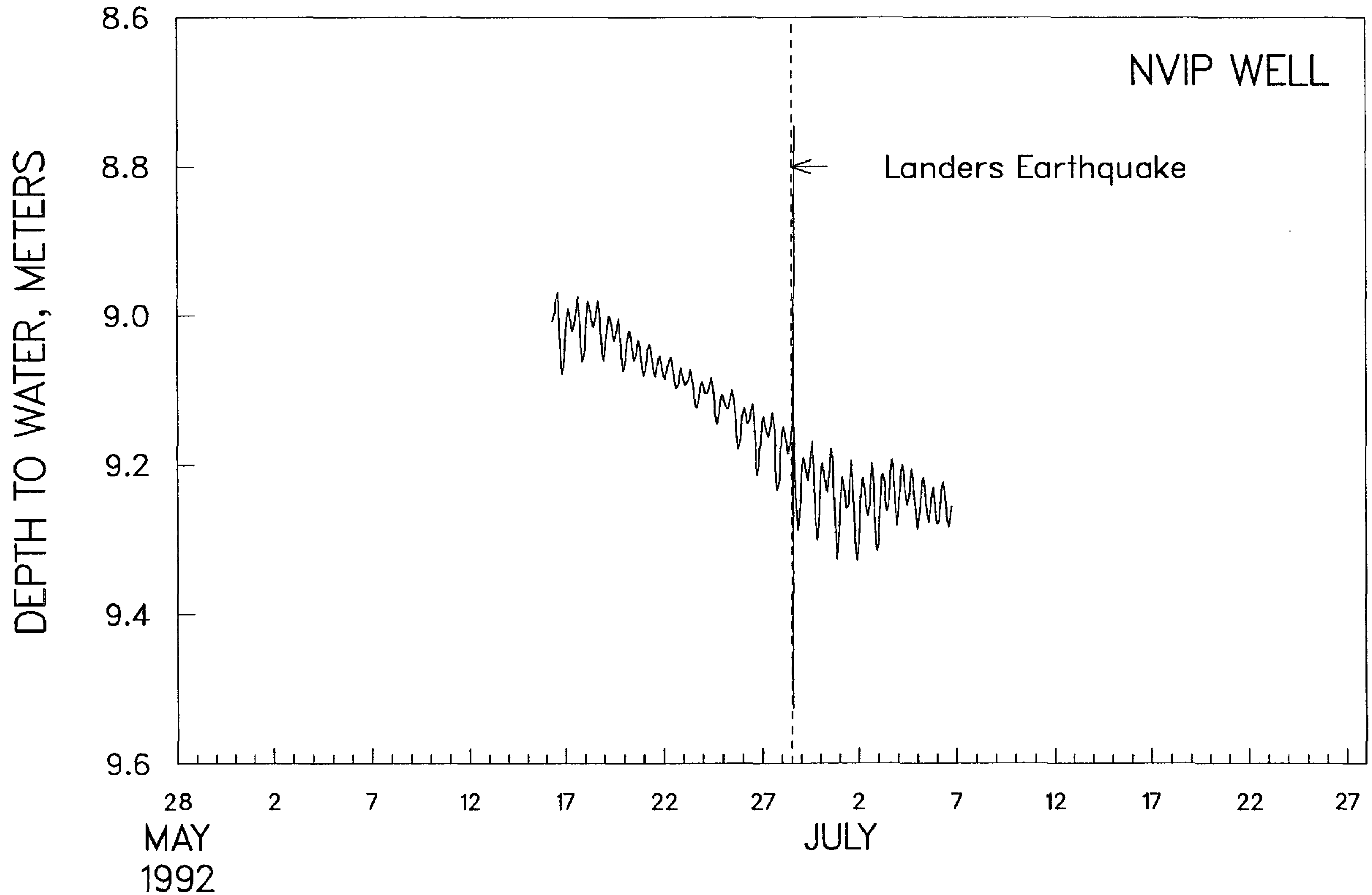

Figure 25. Graph of digitized Stevens chart record from the North Valley Industrial Park well in Grants Pass, Oregon.

SUMMARY

Ground-water level changes in southern California recorded in the hours following the Landers and Big Bear earthquakes agreed in direction with the sign of the calculated coseismic volume strain field. In two shallow wells at the old Wellman ranch near Pinon Flat, however, measurements on June 28 after both the Landers and Big Bear earthquakes showed that water levels had risen 9 cm. The largest ground-water level changes were a rise of 3 meters at Lucerne Valley and a drop of 5 m at Pinon Flat.

A spring discharge increase in Millard Canyon was observed by a technician, who reported that the change preceded the earthquake by several days. This discharge increase was in an area where the earthquake produced extensional volumetric strain, which presumably decreased subsurface fluid pressure. The discharge increase may therefore represent an increase of spring vent conductance caused by the earthquake's static strain field.

At Parkfield, California, water-level changes took place in three wells at the time of the earthquake, and recovered over periods as long as 30 days. At Long Valley, California, observed water-level changes generally returned to normal after minutes to hours, consistent with their having been caused by the passage of surface waves. However, water level in one well at Long Valley and in the NVIP well near Grants Pass, Oregon, remained low for at least two days following the earthquake. Water-level oscillations were observed in two wells in eastern Nevada.

Some of the hydrologic phenomena accompanying the Landers earthquake were of practical significance. The Tapo Canyon oil seep polluted part of the Santa Clara River. Gas bubbles in San Bernardino city water supply wells rendered those wells temporarily unusable. The coseismic discharge increase in Millard Creek was a welcome addition to the water supply.

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Michael Lowe, Joseph Stejskal and Shirley Cismowski of the City of San Bernardino Water Department provided information and samples of the gas bubbles in some of their wells. Mark Iven at USGS/CVO analyzed these gases. Rick Hall and Richard Dinges of the Cabazon County Water District provided information about the spring discharge changes in Millard Canyon. Byron Aldrich of USGS/WRD Menlo Park compiled discharge data for stations in the vicinity of the Landers earthquake. Jeff Agajanian of the USGS/WRD Santee Field Office provided useful background information about the Santa Ana River discharge data. Carl Fessler of Southern California Edison Co. checked on power plant diversions from the Santa Ana River at the time of the Landers sequence.

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