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# Hydrologic effects associated with the January 17, 1994 Northridge, California, earthquake

By

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## ABSTRACT

This report compiles hydrologic observations in southern California associated with the 1994 $M_W$ = 6.7 Northridge, California earthquake. In southern California, the largest ground water level change was a drop of 52 cm at Crystalaire. Most of the steplike water-level changes recorded following the Northridge earthquake agreed in direction with the sign of the calculated coseismic volume strain field. A spring discharge increase at Southern Pacific Springs 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.

## INTRODUCTION

On January 17, 1994 an $M_W$ 6.7 earthquake occurred in a northern suburb of Los Angeles, California at 1230 Greenwich Mean Time (GMT), the first earthquake since 1933 to strike directly under an urban area of the United States (Jones et al., 1994). Like other earthquakes of comparable size, the Northridge 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. This purpose of this report is to present hydrologic observations related to the Northridge earthquake. 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. Many of the sites described here also responded to the $M_L$=7.3 Landers earthquake on June 28, 1992 (Roeloffs et al., 1995).

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 NORTHRIDGE EARTHQUAKE

Table 1 lists the time, magnitude, and location of the Northridge earthquake and the largest aftershock. Figure 1 is a map showing the Northridge epicenter and the observation sites referred to in this report.

Table 1. Northridge earthquake parameters (Jones et al., 1994).

| Earthquake | Date (UT) | Time (UT) | Magnitude | Latitude | Longitude | Depth (km) |
|---|---|---|---|---|---|---|
| Northridge Mainshock | 17 January 94 | 12:30 | $M_W$=6.7 | 34° 12.53' | 118° 32.44' | 19 |
| Northridge Aftershock | 17 January 94 | 23:33 | $M_W$=5.6 | 34° 19.58' | 118° 41.90' | 11 |

Most of the hydrologic phenomena reported here are in response to the Northridge mainshock. One site, however, appears to have responded to the largest of the 3000 aftershocks recorded three weeks after the Northridge mainshock.

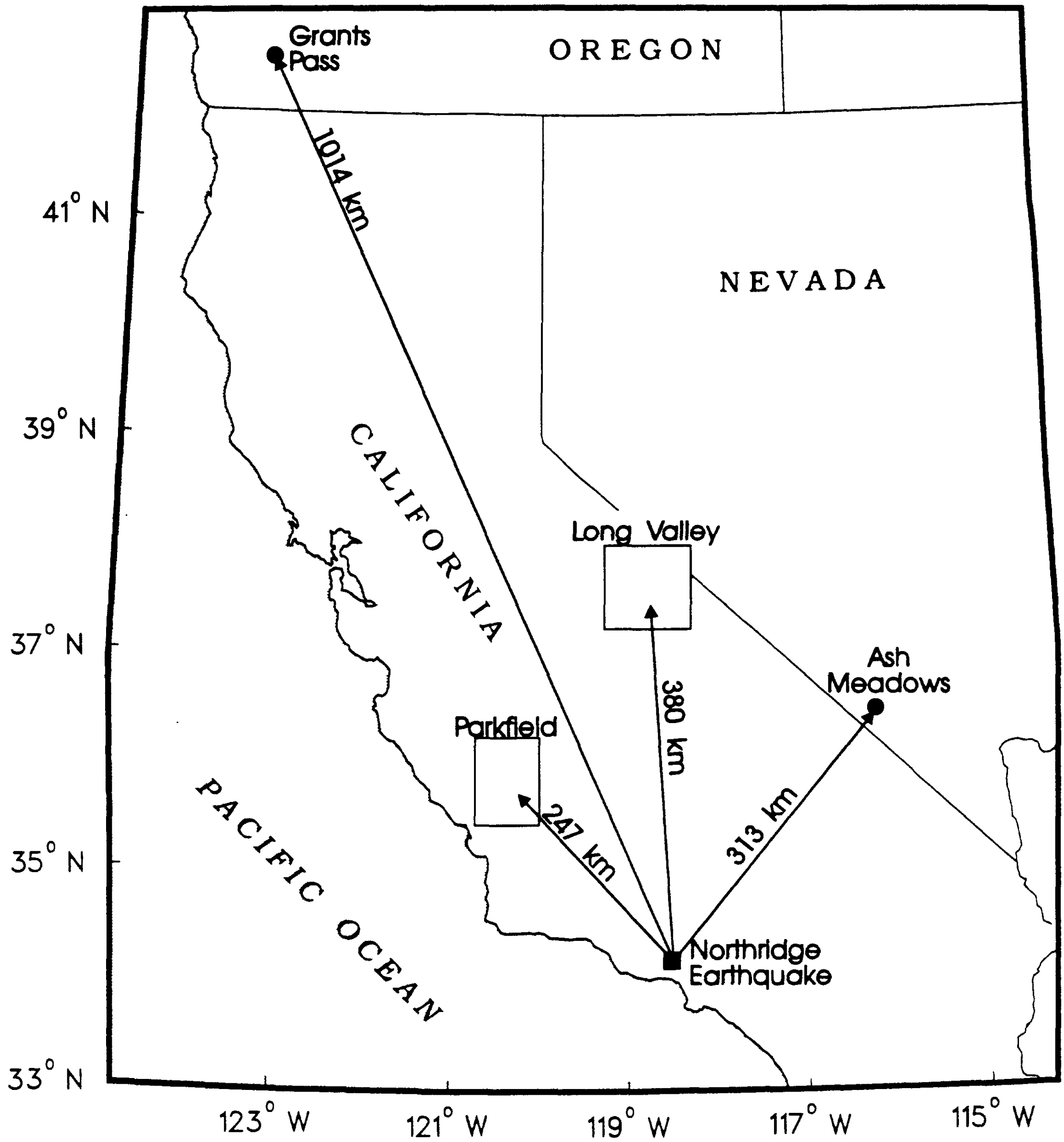


Figure 1. Map showing location of the Northridge earthquake and general locations of hydrologic observations outside of southern California.

## 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 that of 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 in well water level 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 with a high enough time resolution, they resemble long-period seismograms. Theory predicts that these oscillations should last as long as the surface wave train of the earthquake. 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 100 km of the Northridge epicenter can plausibly be caused by the static strain field of the Northridge earthquake. Wald and Heaton (1994) estimated fault location, orientation, and slip based on strong ground motion data and teleseismic data (earthquake signals recorded at stations distant from the epicenter). For purposes of comparison with water level and continous strain measurements, we assumed that the Northridge earthquake represented 1.2 m of primary and reverse slip over an 18 km by 20.9 km fault striking 122 degrees and dipping 42 degrees to the Southwest. The top of the fault is 7 km below the surface. This slip distribution, which is consistent with, but simpler than, that derived by Wald and Heaton (1994), was used to calculate the volumetric strain plotted in Figure 2.

A borehole volumetric strainmeter is operated by the U.S. Geological Survey in southern California (PUB in Figure 2). This strainmeter recorded extensional strain of 0.03 ppm at the time of the Northridge earthquake, in general agreement with the computed volumetric strain field.

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 infrequently or because artificial effects such as pumping obscure the natural aquifer response.

**Edwards Air Force Base**. At the time of the Northridge earthquake, wells were monitored by the U.S. Geological Survey (USGS) Water Resources Division at Edwards Airforce Base. Those wells located on Edwards Airforce base are denoted on Figure 2 as FS1 (Fissure well) and SS1 (Survival School well). Data are shown in Figures 3(a,b) through 4(a,b). Figures 3(a) and 4(a) show water level data for the month of January 1994 in order to display long term trends and possible recovery from coseismic water level changes. Figures 3(b) and 4(b) show ten days of data centered on the time of the Northridge earthquake of January 17 to better display coseismic changes and precursors, if any. Data are instantaneous hourly measurements from H-300 Hydronet 5 psi transducers. Data precision is approximately 1 mm of water.

Water levels decreased by 1.7 cm in FS1 and 2.5 cm in SS1 after the Northridge 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.

Water levels in the Fissure well and Survival School well respond to earth tides. A least-squares analysis of the $M_2$ tidal constituent of Fissure Well water-level data results in an estimate of the tidal response of 33 centimeters per part-per-million volumetric strain (cm/ppm). Consequently, the 1.7 cm coseismic water-level drop in this well would correspond to volumetric strain of 0.05 ppm dilatation. A similar analysis of the tidal response of the Survival School well shows a volumetric strain of 0.06 ppm dilatation for a water level drop of 2.5 cm. These values are in approximate agreement with the calculated strain field shown in Figure 2.

Table 2. Wells in Southern California.

| Site Name | Map Symbol | Latitude | Longitude | Depth Monitored (meters) | Northridge Response | Tidal Sensitivity (cm/ppm) | Barometric Efficiency |
|---|---|---|---|---|---|---|---|
| Fissure | FS1 | 34° 50′ 56″ | 117° 50′ 14″ | 221-232 | Step -1.7 cm | 33 | -0.37 |
| Survival School | SS1 | 34° 49′ 32″ | 117° 52′ 54″ | 270-278 | Step -2.5 cm | 38 | -0.41 |
| Crystalaire | XTA | 34° 28′ 8″ | 117° 46′ 23″ | 71-869 | Step -52.2 cm | 122 | -0.67 |

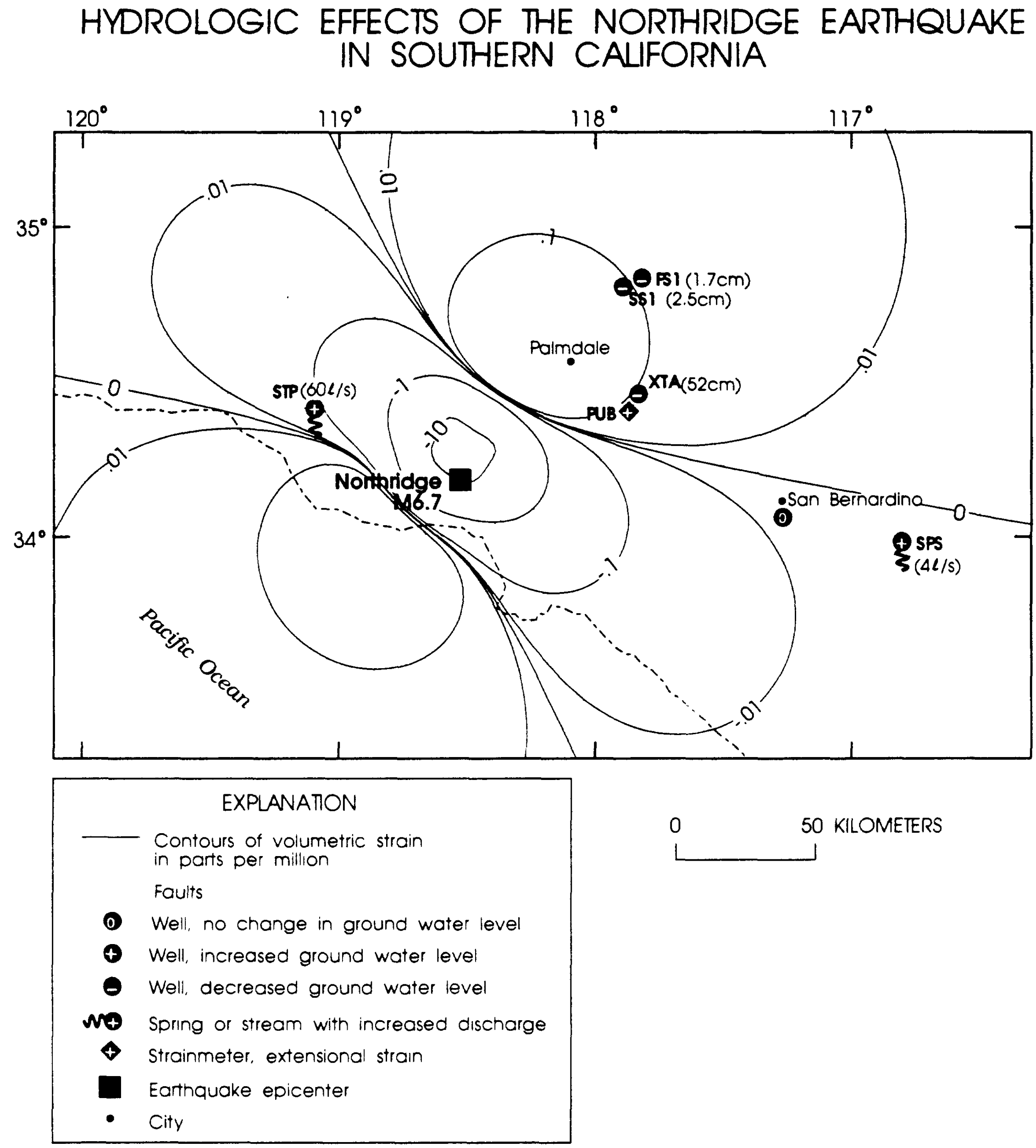


Figure 2. Location of observation wells in southern California where a response to the Northridge earthquake was documented.

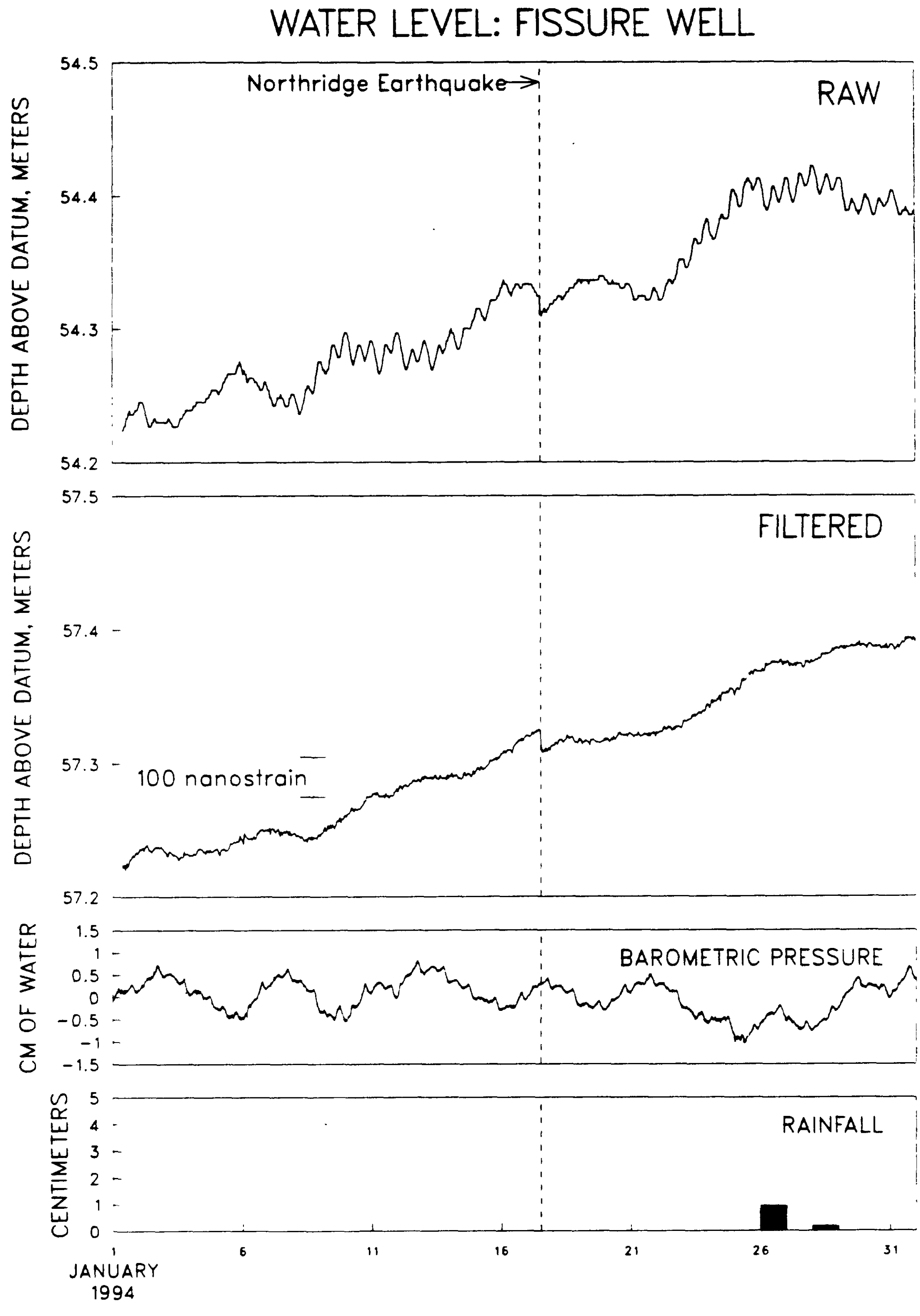


Figure 3. Water level, barometric pressure and rainfall at Fissure well (FS1), Edwards Airforce Base, California. Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (a) January 1 to February 1, 1994.

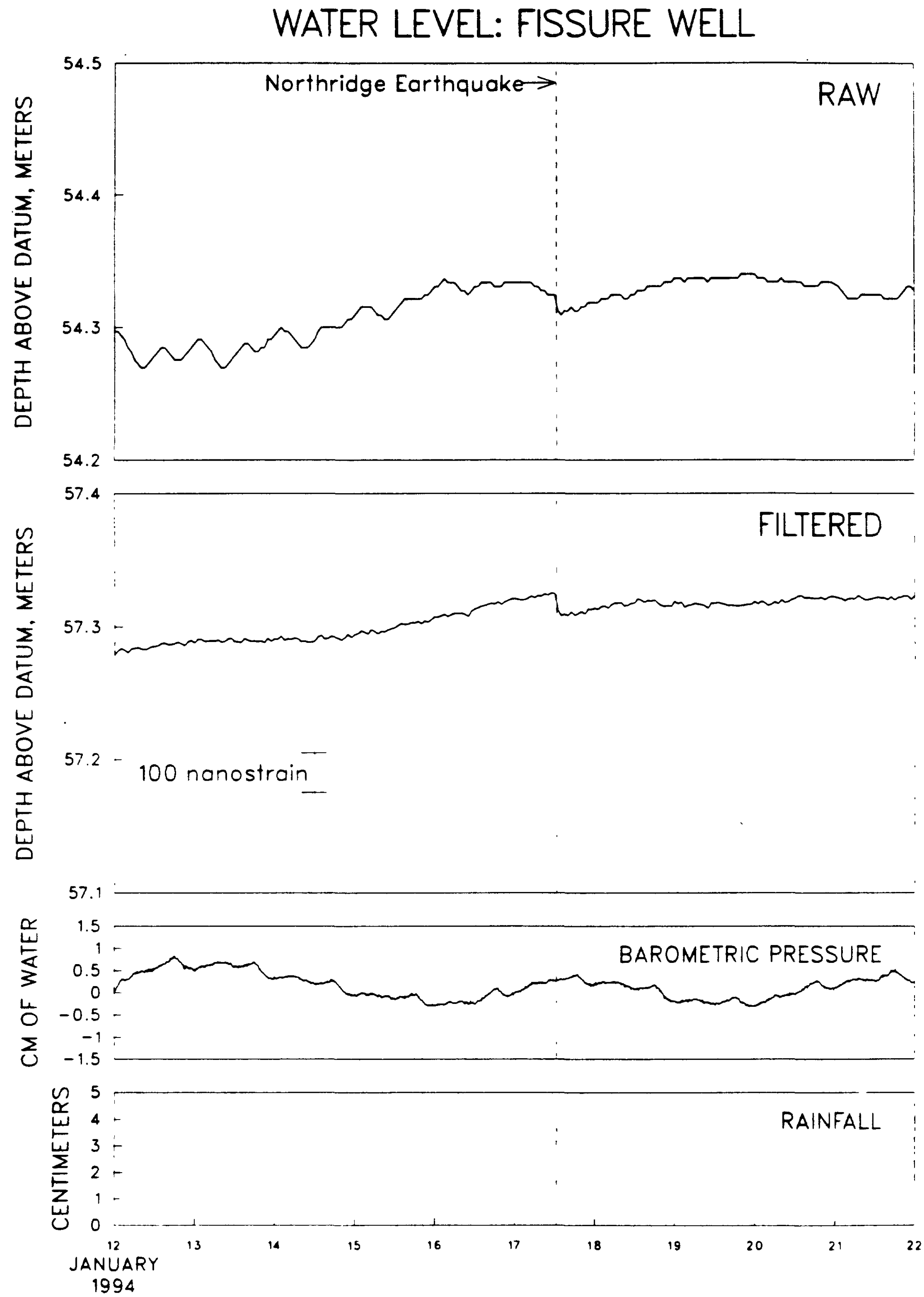


Figure 3, continued. Water level, barometric pressure and rainfall at Fissure well (FS1), Edwards Airforce Base, California. Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (b) January 12 to January 22, 1994.

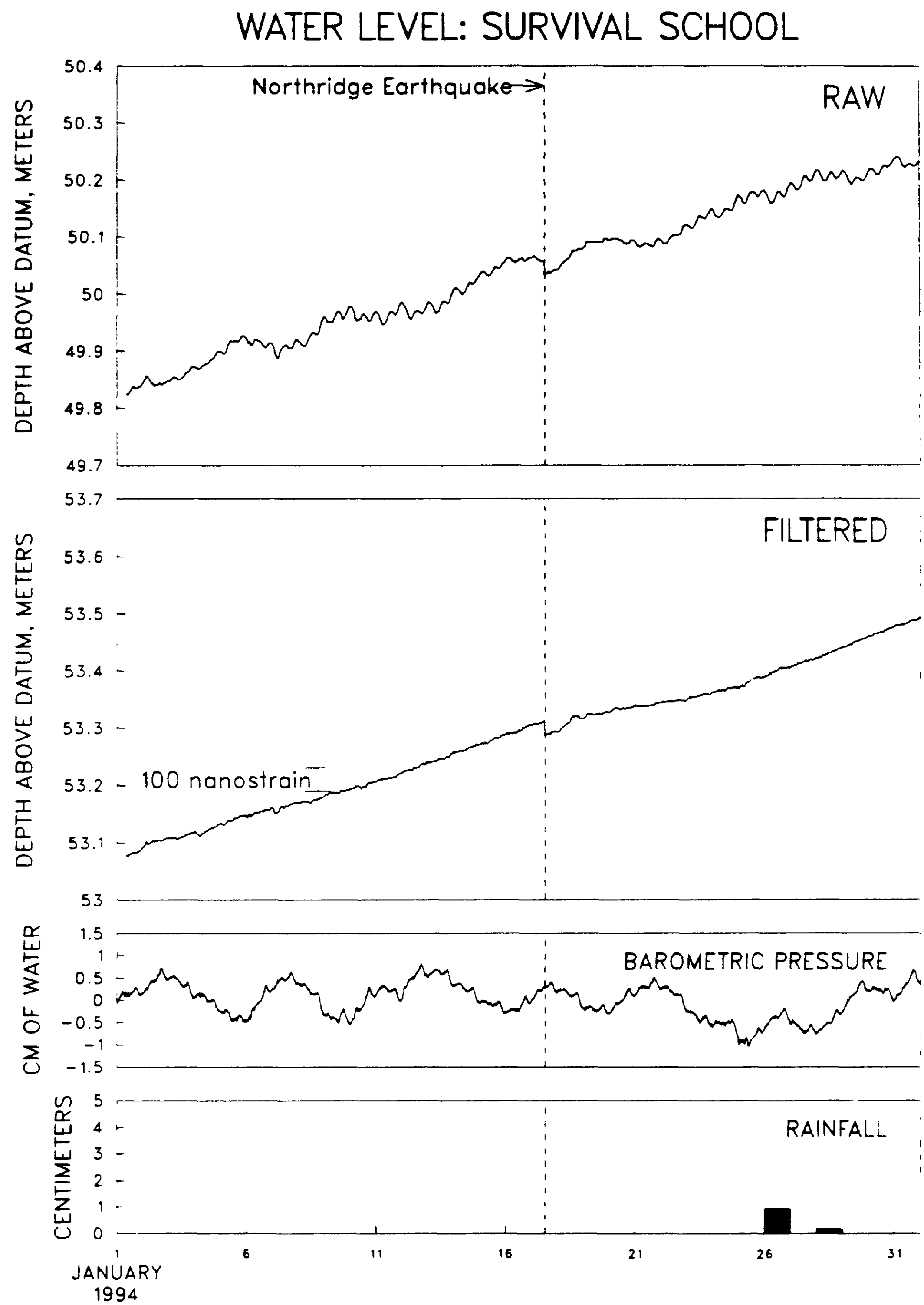


Figure 4. Water level, barometric pressure and rainfall at Survival School well (SS1), Edwards Airforce Base, California. Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (a) January 1 to February 1, 1994.

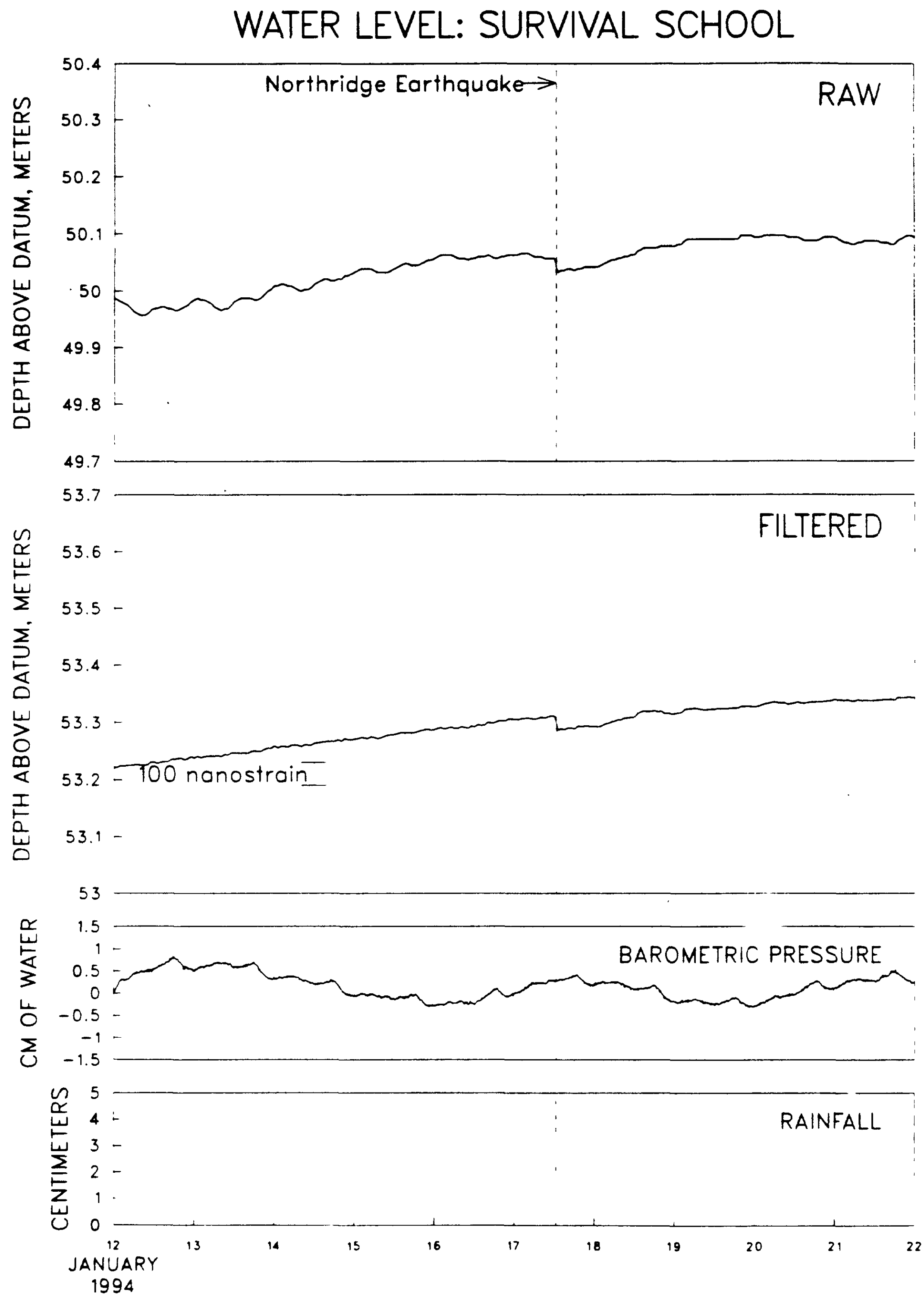


Figure 4, continued. Water level, barometric pressure and rainfall at Survival School well (SS1), Edwards Airforce Base, California. Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (b) January 12 to January 22, 1994.

**Crystalaire well.** At the time of the Northridge earthquake, a well (XTA in Figure 2) was monitored by the USGS southeast of Palmdale, California. Data from this well are sampled every 10 minutes with a resolution of approximately 1 mm of water.

An estimate of the $M_2$ tidal response of this well shows a water-level change of 122 centimeters corresponds to a volumetric strain change of one part per million. The 52 cm drop of water level at this site in response to the Northridge earthquake corresponds to an extensional strain of 0.43 ppm, somewhat larger than the strain computed using the dislocation model. Data from this well site are shown in Figures 5a and 5b. In addition to the response to the Northridge mainshock, a response to an $M_W$ 5.6 aftershock which occurred at 23:33 UT on January 17, whose focal mechanism was similar to the mainshock, can be clearly seen in the filtered data in Figure 5(b). No water level changes that could have been precursors to the Northridge earthquake were observed in the Crystalaire well.

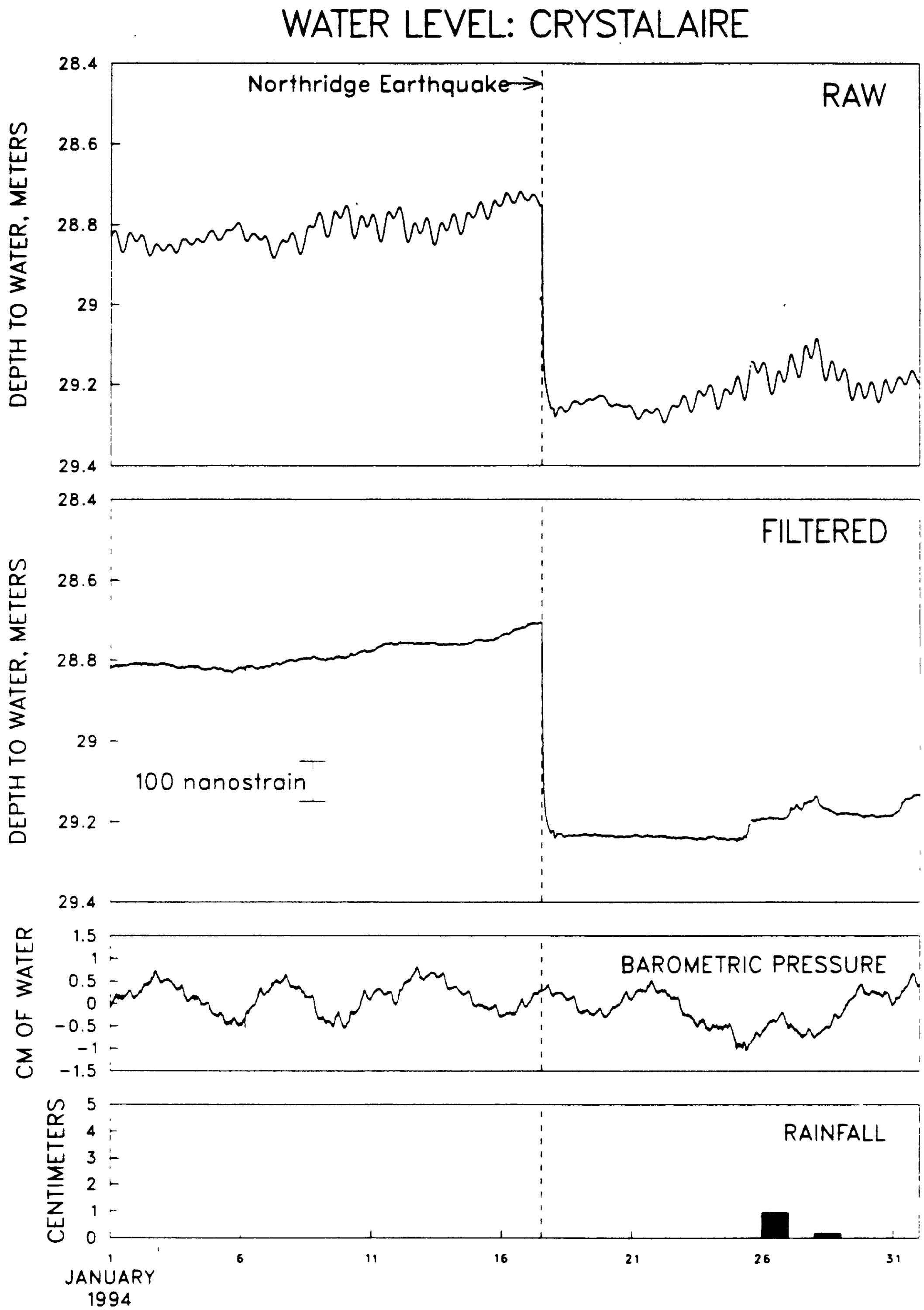


Figure 5. Water level, barometric pressure and rainfall at Crystalaire well (XTA). Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (a) January 1 to February 1, 1994.

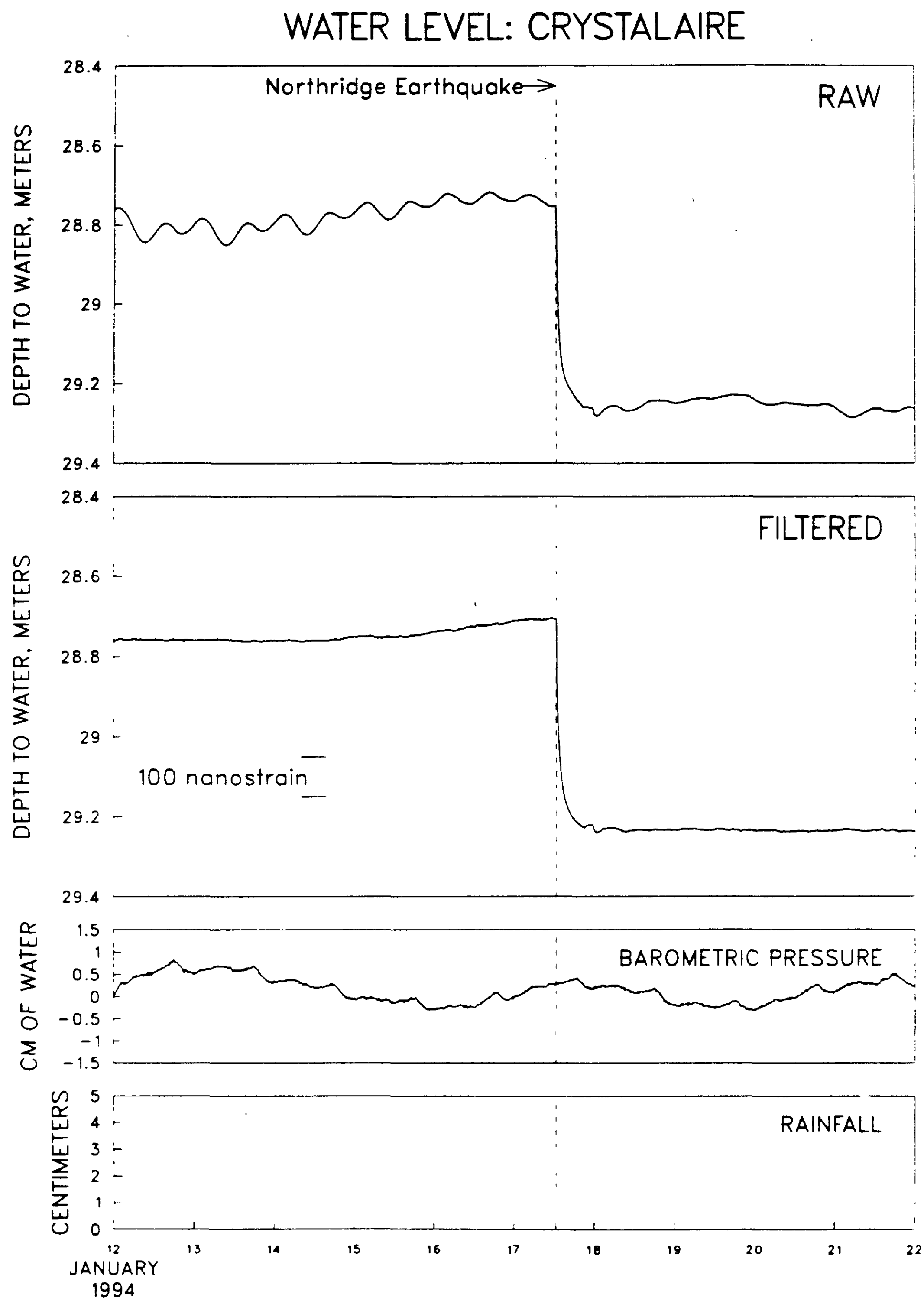


Figure 5, continued. Water level, barometric pressure and rainfall at Crystalaire well (XTA). Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (b) January 12 to January 22, 1994.

### Summary of water level changes in Southern California.

The steplike water-level changes in these wells are consistent with the expected effects of the earthquake's static strain field. The hydrographs of SS1 and FS1 exhibit a decay of the coseismic water level drop over a period of days. Subsequent analysis of data collected at XTA suggest an extremely well confined aquifer whose expected recovery from the large coseismic drop would have been on the order of several weeks. Since the transducer monitoring this site failed shortly after the Northridge earthquake, data showing the complete recovery of water level are not available. The recovery of the steps presumably reflects the dissipation of the strain-induced pressure by flow to the water table rather than the time history of the strain caused by the Northridge earthquake. This phenomena can be clearly seen in the contrasting recovery histories of simultaneous drops in the deep and shallow intervals of the Middle Mountain well near Parkfield, California. These drops are caused by aseismic slip on the nearby San Andreas fault as recorded by creepmeters on Middle Mountain(Roeloffs et.al.,1989). meter.

### Other Sites.

Water level is being monitored in wells at several depths in alluvial aquifers in the San Bernardino area by the U.S. Geological Survey. In contrast to the Landers earthquake sequence where water level changes were seen in two wells at shallow depth intervals, the Northridge earthquake did not produce a response at any well site in the San Bernardino area.

**Santa Paula Creek.**

A coseismic discharge increase of 60 liters/second was recorded in Santa Paula creek, 55 km WNW of the epicenter in an area subject to coseismic volumetric contraction as computed by the dislocation model (STP in Figure 2). The Santa Paula Creek is monitored by the Santa Paula Water Works using a chart recorder on a rectangular weir. A plot of values digitized from the chart record is shown in Figure 6.

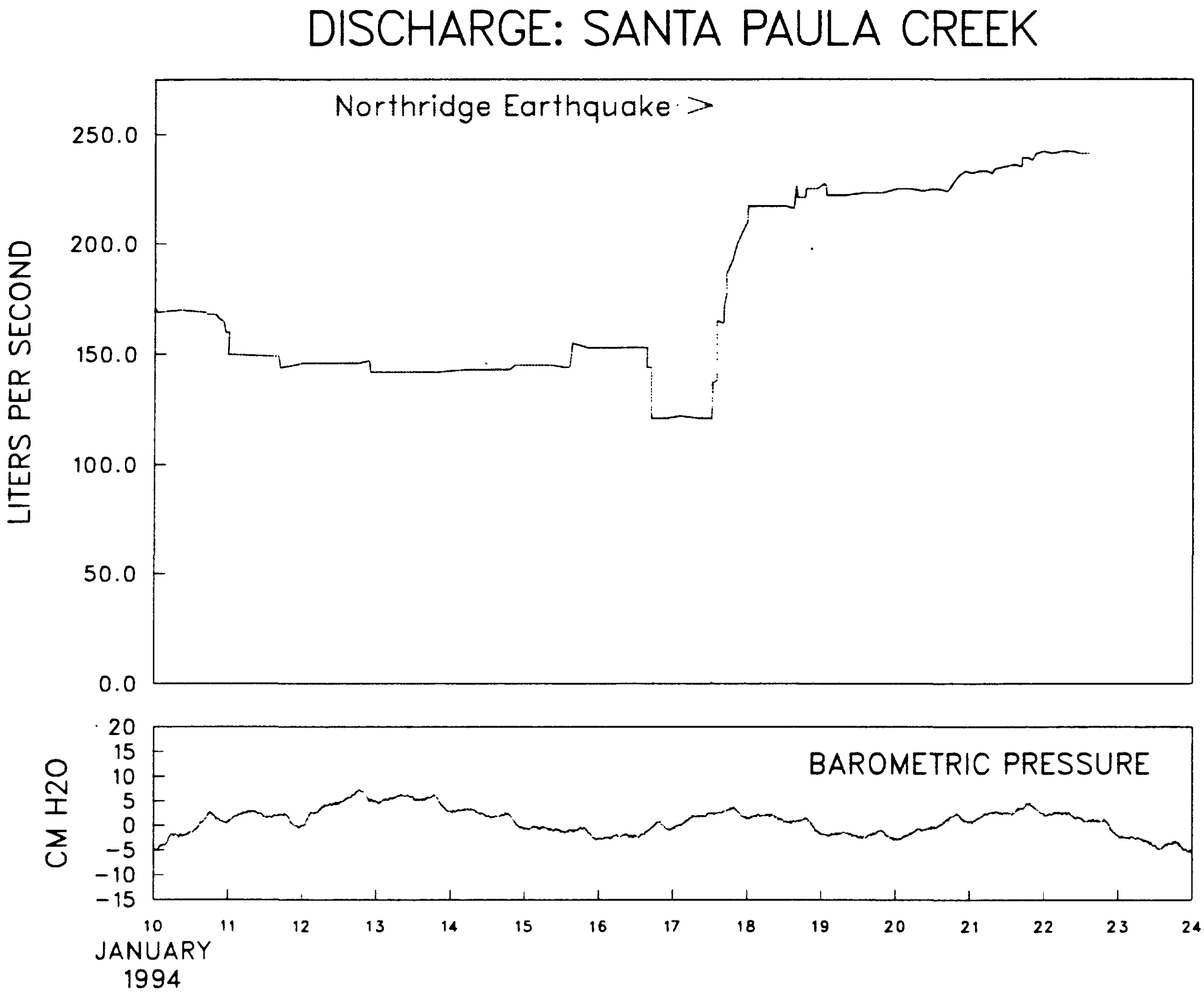


Figure 6. Coseismic discharge increase recorded at the Santa Paula creek shortly after the Northridge earthquake.

**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 Northridge 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 (Figure 7). The Southern Pacific (SPS) 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 total amount of increase in flow before the Northridge earthquake was estimated to be approximately 1.0 *l/s*. Following the Northridge earthquake, an additional increase of 4.4 *l/s* took place. Prior to the earthquake flow had been about 32 *l/s*. Several days after the earthquake flow from the spring was 30 to 37 *l/s*. Water quality remained unchanged after the Northridge earthquake and turbidity remained low

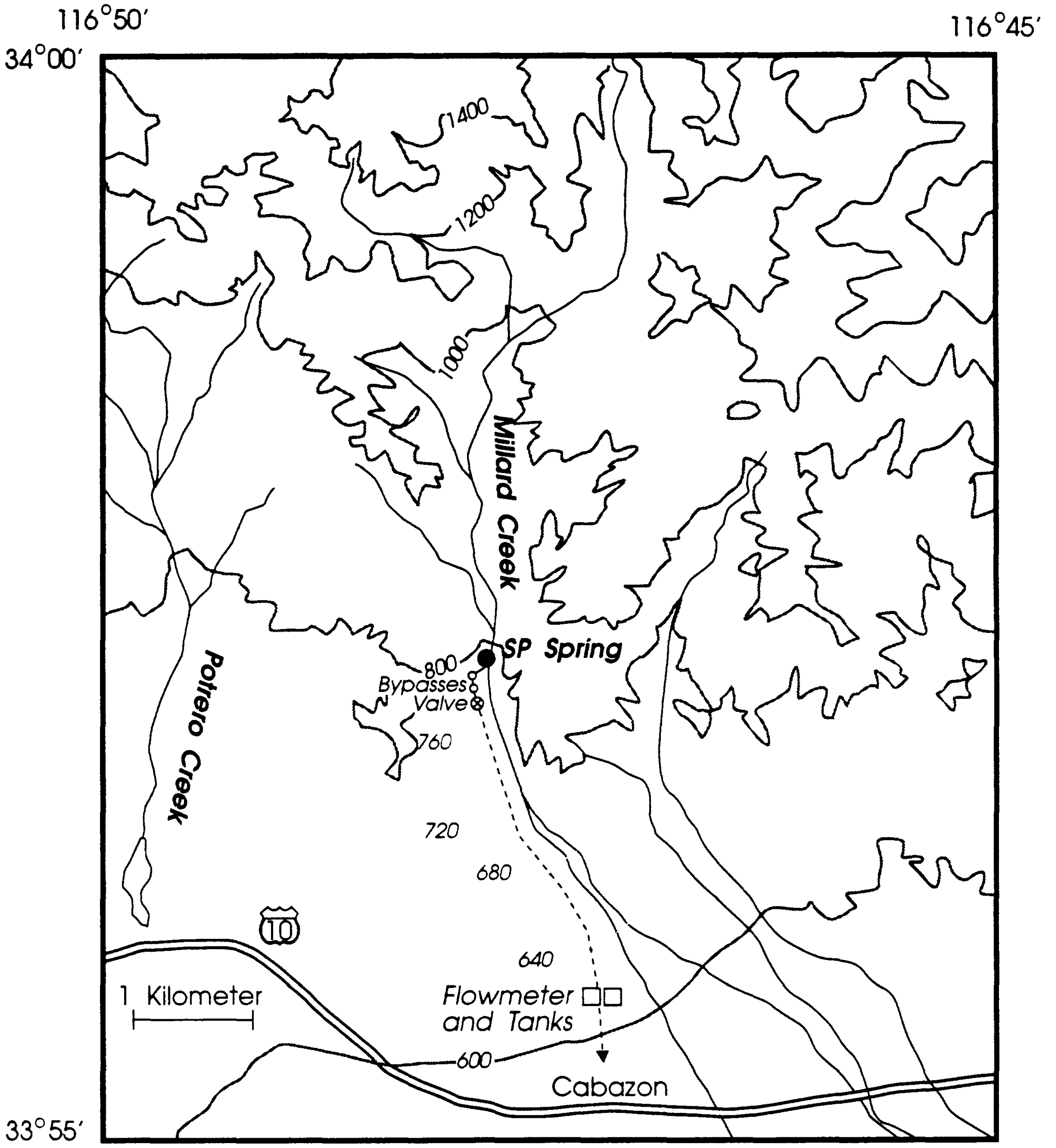


Figure 2. Map of the area surrounding the SP spring. 100 m elevation contours are shown.

Figure 7. Map showing the area of the SP spring in Millard Canyon.

### Summary of Surface Water Effects.

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. A co-seismic discharge increase was recorded in Santa Paula Creek in an area subject to co-seismic volume strain.

Ground-water discharge to a stream at a seep or springs can increase because of either an increase of spring or seep vent conductance, or an increase of subsurface fluid pressure in the formation feeding the springs. 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.

## HYDROLOGIC OBSERVATIONS OUTSIDE OF SOUTHERN CALIFORNIA

### Parkfield, California

One observation well in the Parkfield water-level network (Figures 1 and 8) displayed a coseismic response to the Northridge earthquake. Well information is listed in Table 3, and Figure 9 shows water level and barometric pressure. 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 15 cm water-level rise following the Northridge earthquake (Figure 9). This behavior is similar to the response of this well to the $M_s 7.1$ Loma Prieta earthquake of October 18, 1989, the $M_L 7.3$ Landers earthquake of June 28, 1992, the $M4.7$ Parkfield earthquake of October 20, 1992, the $M4.8$ Parkfield earthquake of November 14, 1993 and the $M5.0$ Parkfield event of December 20, 1994(Figure 10). After the coseismic water-level rise associated with the Northridge earthquake, water level began recovering to its earlier depth until it was interrupted by a long term hydrological recharge characteristic of this well during winter and early spring.

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 Bourdieu well. It has been suggested that the passage of seismic waves temporarily increases aquifer permeability by driving off gases lodged in the aquifer near the open interval of the well bore. In support of this speculation, the frequent transient drops seen in the water level signal from this site are probably due to gas bubbling. Such a temporary increase in permeability would account for the water level rise following even comparatively distant seismic events.

Table 3. Wells in Parkfield, California

| Site Name | Map Symbol | Latitude | Longitude | Depth Monitored (meters) | Northridge Response | Tidal Sensitivity (cm/ppm) | Barometric Efficiency |
|---|---|---|---|---|---|---|---|
| Bourdieu Shallow | BS | 36° 5′ 4″ | 120° 36′ 15″ | 30 | Step +15.2 cm | | -0.6 |

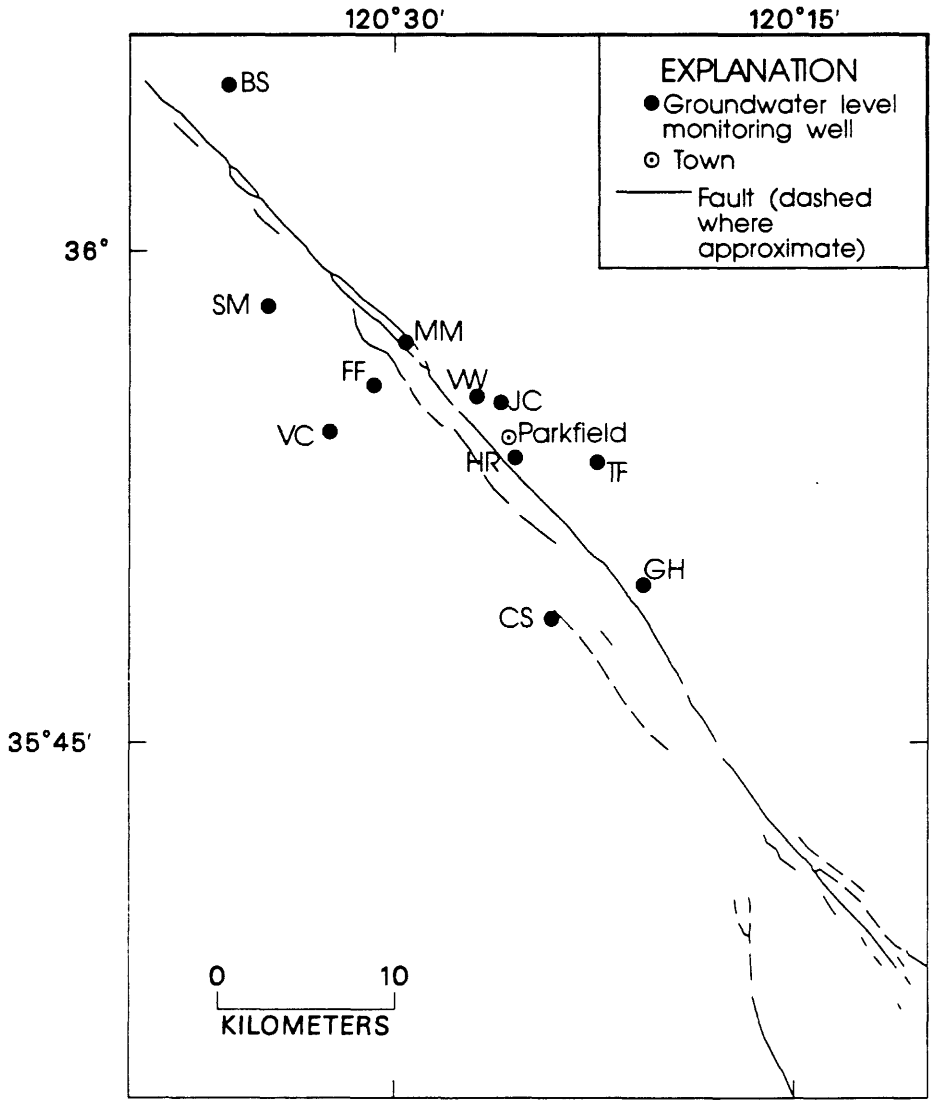


Figure 8. Map of the water level monitoring network near Parkfield, California. Faults are shown as dotted lines.

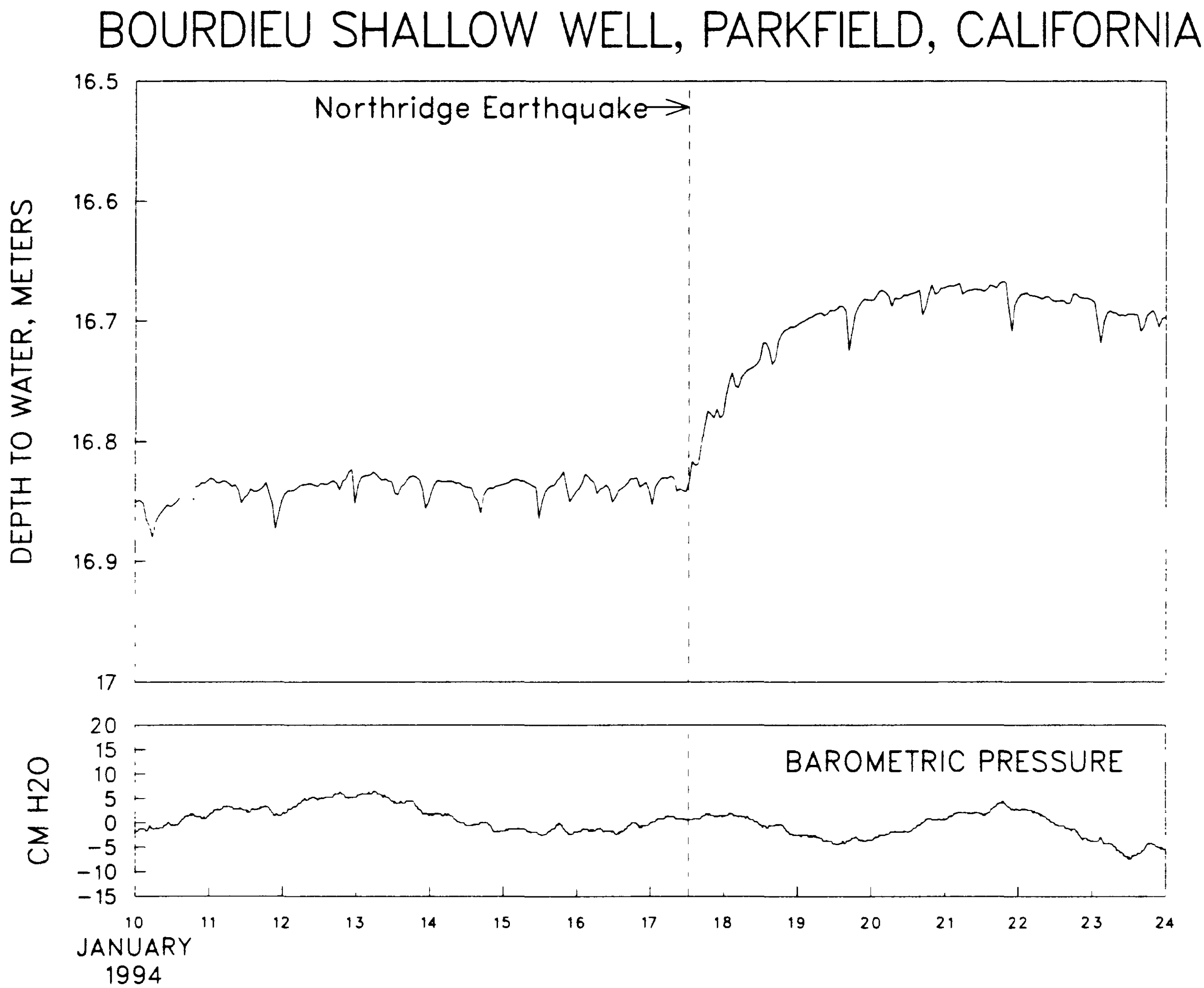


Figure 9. Water level and barometric pressure at the Bourdieu Shallow well.

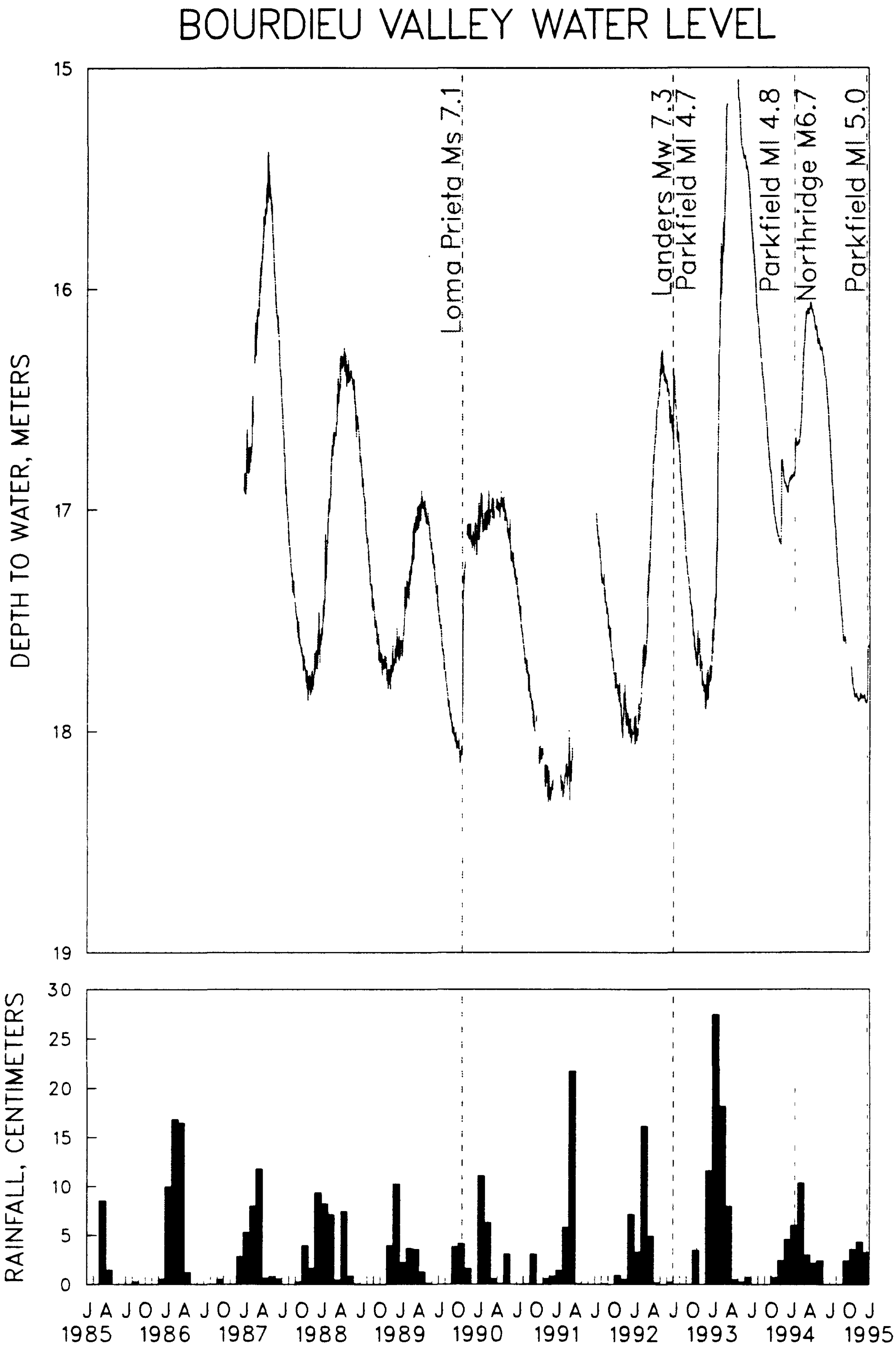


Figure 10. Long-term hydrograph and monthly rainfall for Bourdieu Shallow well near Parkfield, California (BS in Figure 8).

## Long Valley, California

The Long Valley area is shown in Figure 1 and the location of the RDO8 well is shown in Figure 11. Table 4 lists the response of RDO8 to the Northridge earthquake as well as the barometric pressure response and the depth interval monitored by the transducer at this site. At all the Long Valley sites, low frequency (< 1 cycle per day) water-level changes were taking place prior to the Northridge earthquake and continued afterwards. These water-level changes included both long-term trends (with periods of 1 year or more) and seasonal fluctuations. RDO8 probably also oscillated in response to the earthquake surface waves, but because the sampling interval of 15 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. Water level response at RDO8 to the Northridge earthquake is shown in Figures 12a and 12b.

Table 4. Sites in Long Valley.

| Site Name | Map Symbol | Latitude | Longitude | Depth Monitored (meters) | Northridge Response | Tidal Sensitivity (cm/ppm) | Barometric Efficiency |
|---|---|---|---|---|---|---|---|
| Resurgent Dome | RDO8 | 37° 39′ 24″ | 118° 57′ 12″ | 338-341 | Step -1.5 cm | 42 | -0.58 |

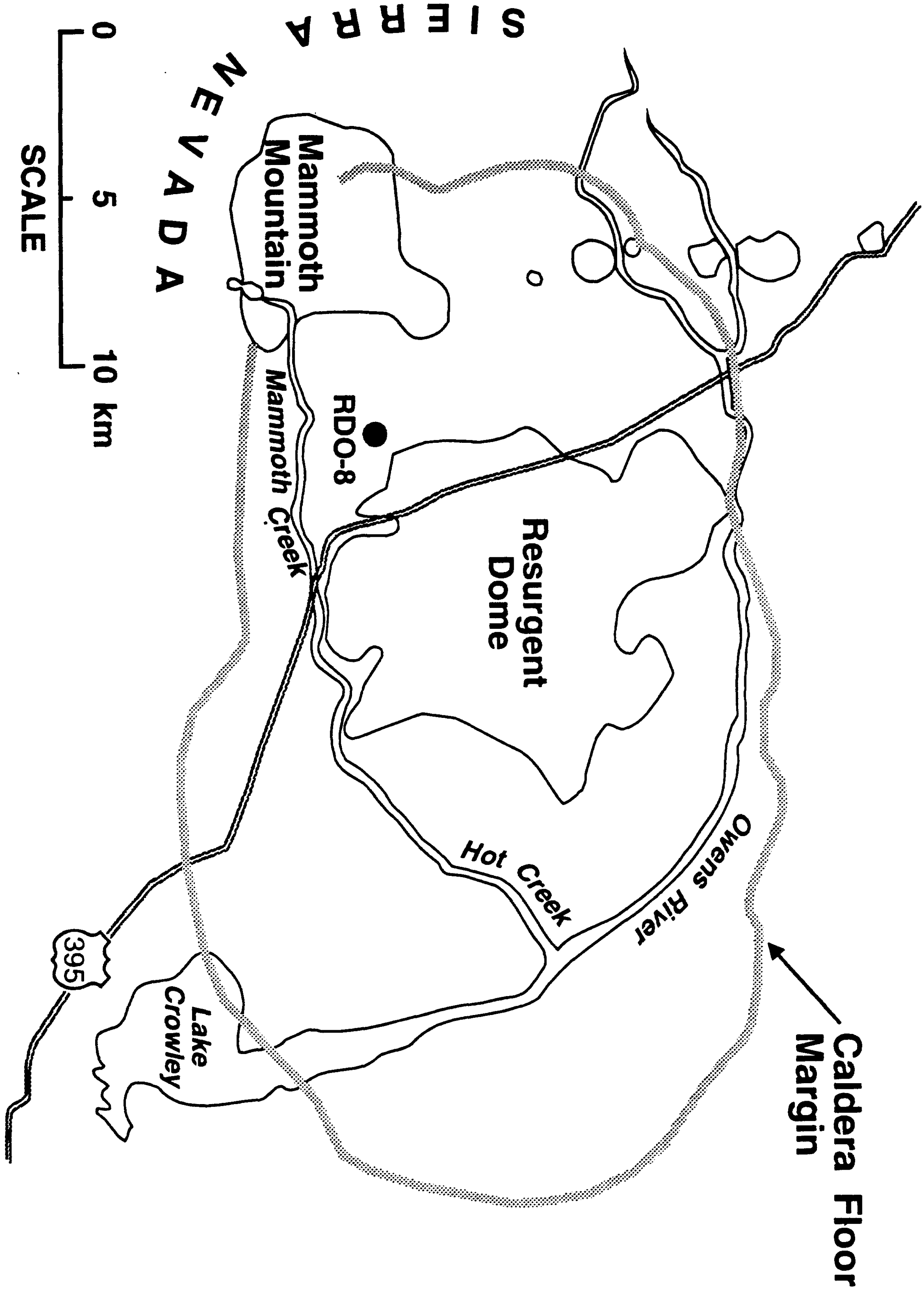


Figure 11 Map showing sites in Long Valley, California.

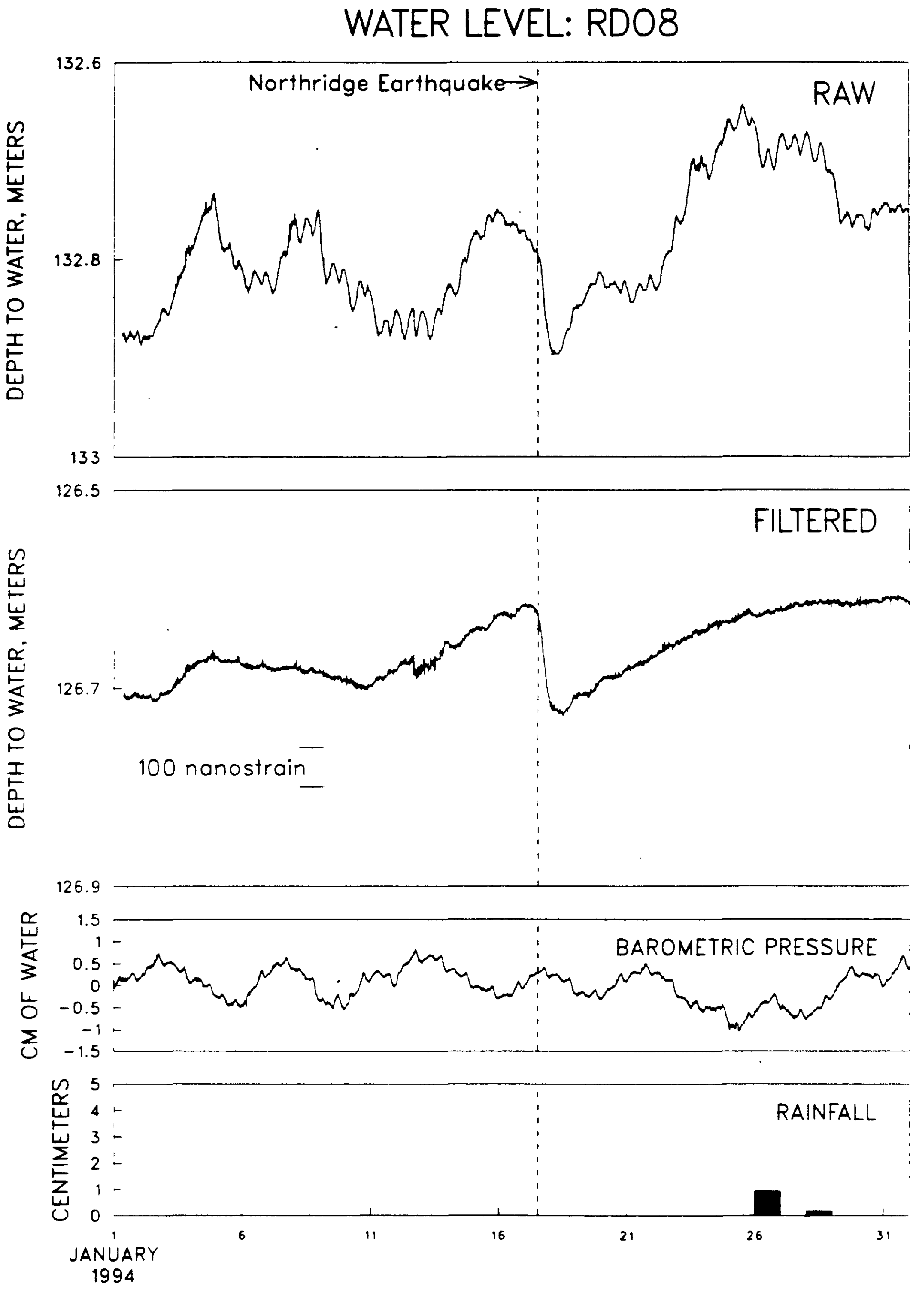


Figure 12. Water level in well RDO8, Long Valley, California. Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (a) January 1 to February 1, 1994.

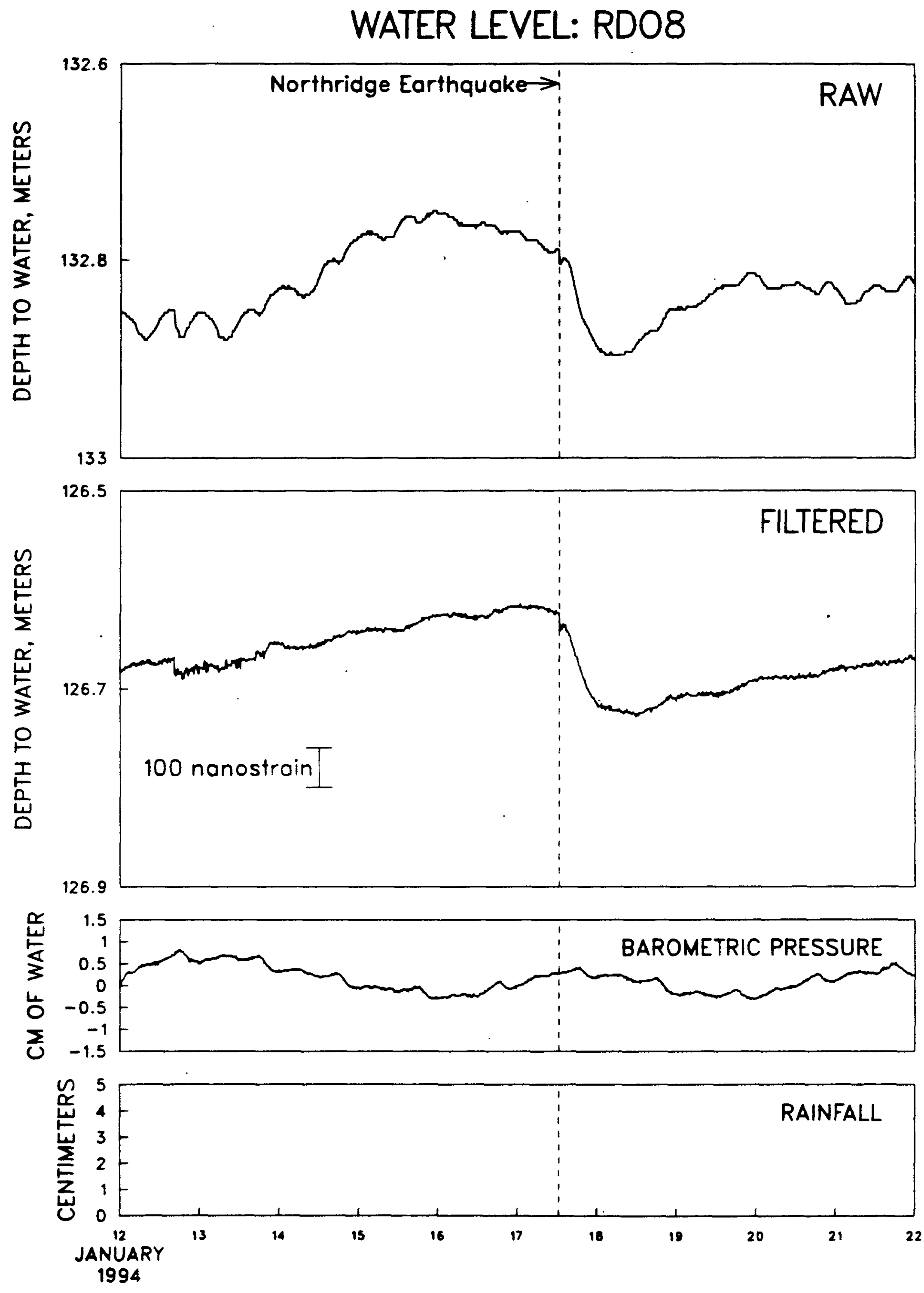


Figure 12, continued. Water level in well RDO8, Long Valley, California. Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (b) January 12 to January 22, 1994.

## Grants Pass, Oregon

Water-level oscillations were recorded in the North Valley Industrial Park (NVIP) well in Grants Pass, Oregon (Woodcock and Roeloffs, 1995). The well is 91 meters deep, cased to a depth of 51 meters, and developed in fractured granodiorite and crystalline metamorphic rock. The well was monitored from 1984 until November 1993 with a Stevens chart recorder and since November 1993 with a UNIDATA digital shaft encoder, data logger and barometric transducer. The data logger records water level change at one second intervals during rapid water level movement and at 15 minute intervals between events.

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 Northridge earthquake had an amplitude of 22 cm peak to peak.

Figure 13 displays the responses recorded at NVIP to the Northridge earthquake and largest aftershock, and two unrelated events. The oscillations corresponding to the Northridge mainshock and aftershock had respective peak-to-peak amplitudes of 22 cm and 1.5 cm. Although coseismic step changes have been previously recorded at NVIP, no offset is apparent in response to the Northridge event.

The coseismic oscillations in the NVIP well are probably due to resonant movement of the water column in the well bore responding to the vertical oscillations of passing seismic wave trains, as described by Cooper et al. (1965) and Liu et al. (1989).

Figure 14 shows the digital data record for the Northridge earthquake. For comparison, the vertical component broadband seismogram from the station operated at Yreka, California by the University of California at Berkeley is shown. The water level fluctuations resemble a version of the seismogram that has been filtered so that only frequencies at or near .05 cycles per second - the resonant frequency of the well water column in this well - remain in the data record.

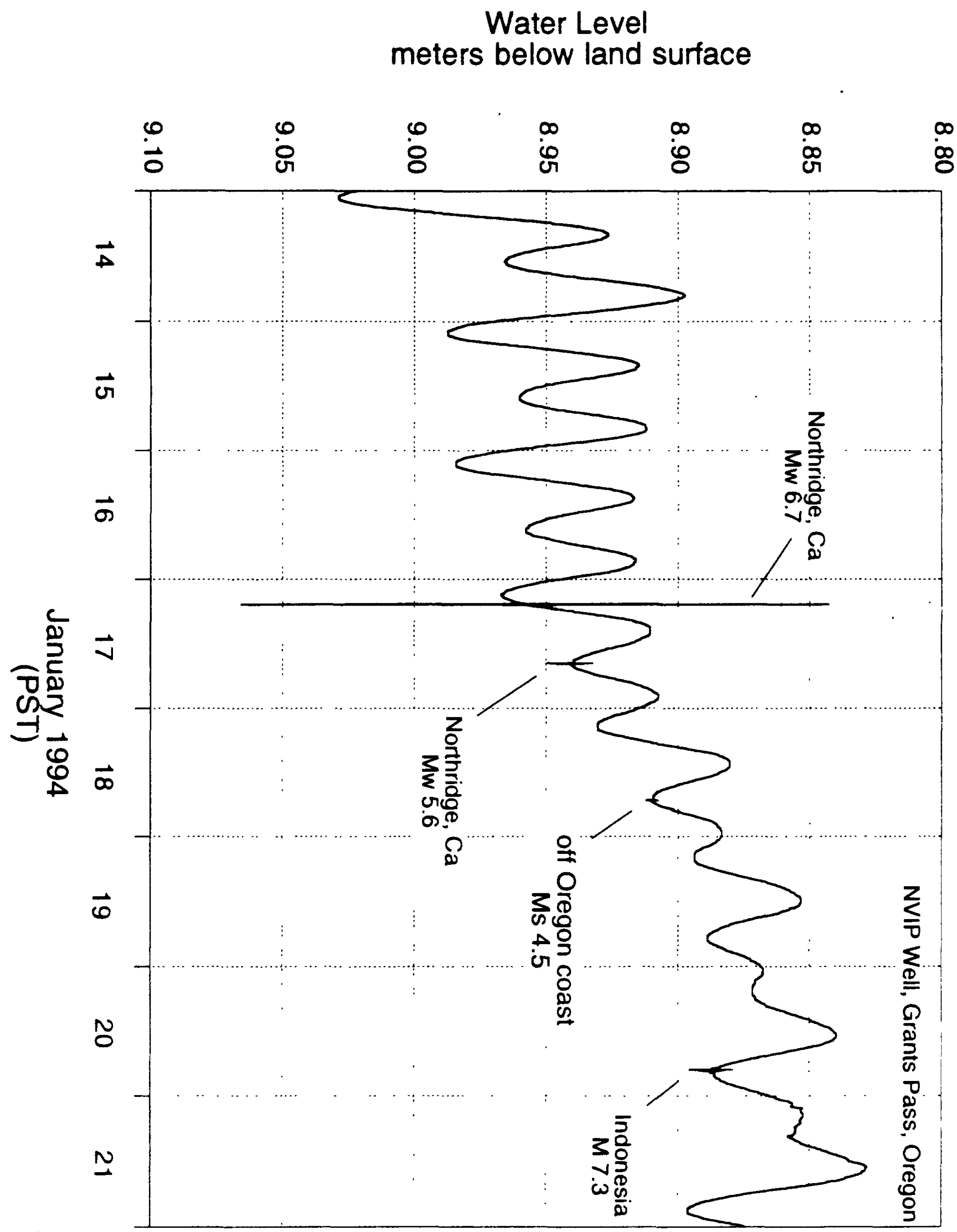


Figure 13. Water level in the North Valley Industrial Park well recorded from January 14 to January 22, 1994.

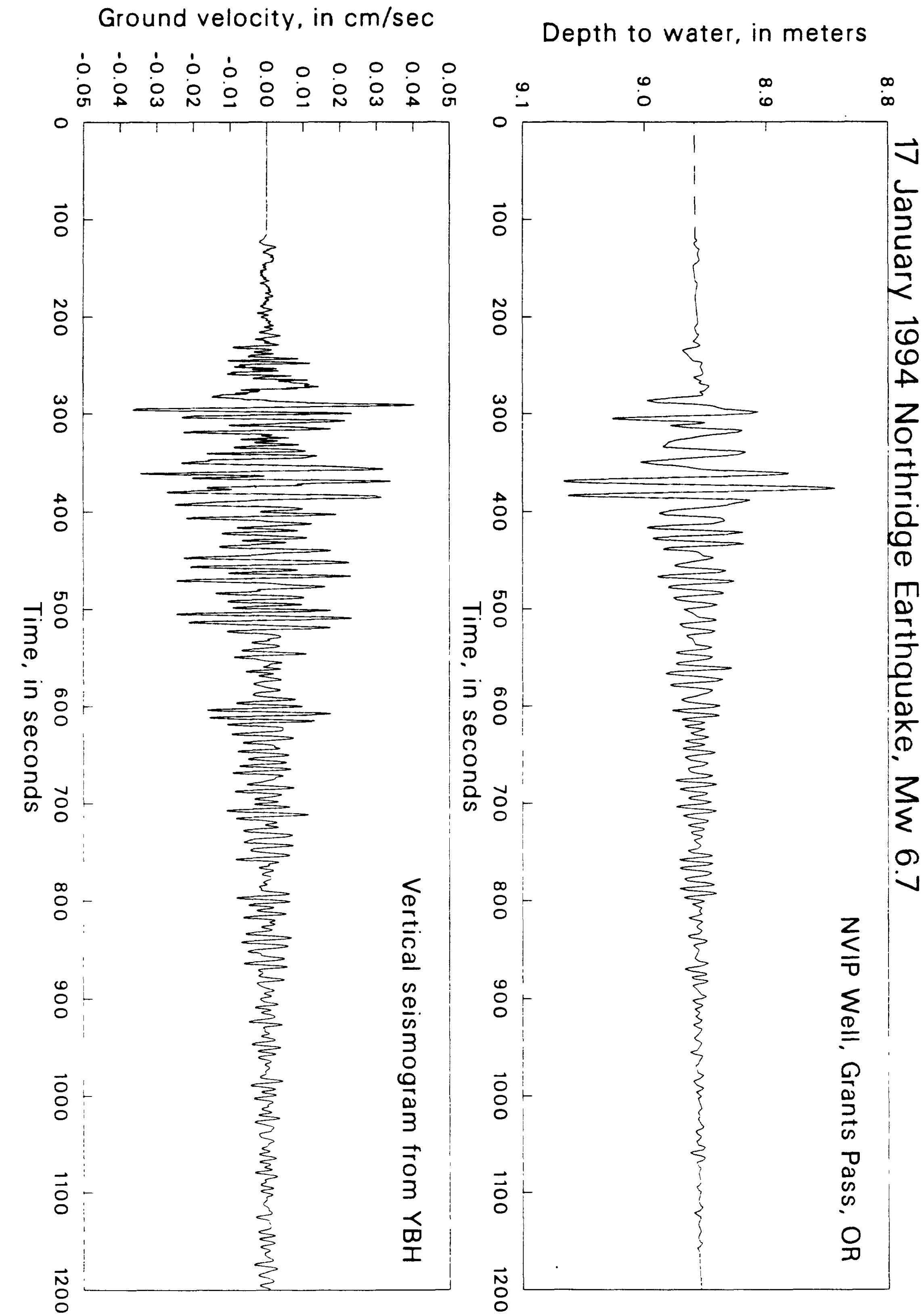


Figure 14. Digital data record from the North Valley Industrial Park well in Grants Pass, Oregon and filtered vertical component seismogram data recorded at a station near Yreka, California.

## Ash Meadows, Nevada

A water level rise of 19 cm was recorded at the Point of Rocks - South well in Ash Meadows, Nevada. The water level at this site was monitored by an R200 low resolution transducer developed by the USGS/WRD Hydrologic Instrumentation Facility, which sampled data hourly. Since this well is 313 km from the Northridge epicenter, the observed water level rise is too large and of the opposite sense to be a response to co-seismic poroelastic dilatation. However the sense of the response could be explained by stress applied to a deformable fracture nearby or by a concentration of regional earthquake strains on a nearby fault(Galloway et. al., 1994) This water level rise is followed by a slow decay plotted in Figures 15a and 15b as water level begins to re-equilibrate to its earlier depth over a period of weeks.

Table 5. Sites in Southwestern Nevada.

| Site Name | Map Symbol | Latitude | Longitude | Depth Monitored (meters) | Northridge Response | Tidal Sensitivity (cm/ppm) | Barometric Efficiency |
|---|---|---|---|---|---|---|---|
| Point of Rocks South | PORS | 36° 24′ 20″ | 116° 16′ 37″ | 40-249 | Step +18.5 cm | 24 | -0.14 |

**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 Northridge earthquake, unless otherwise noted.

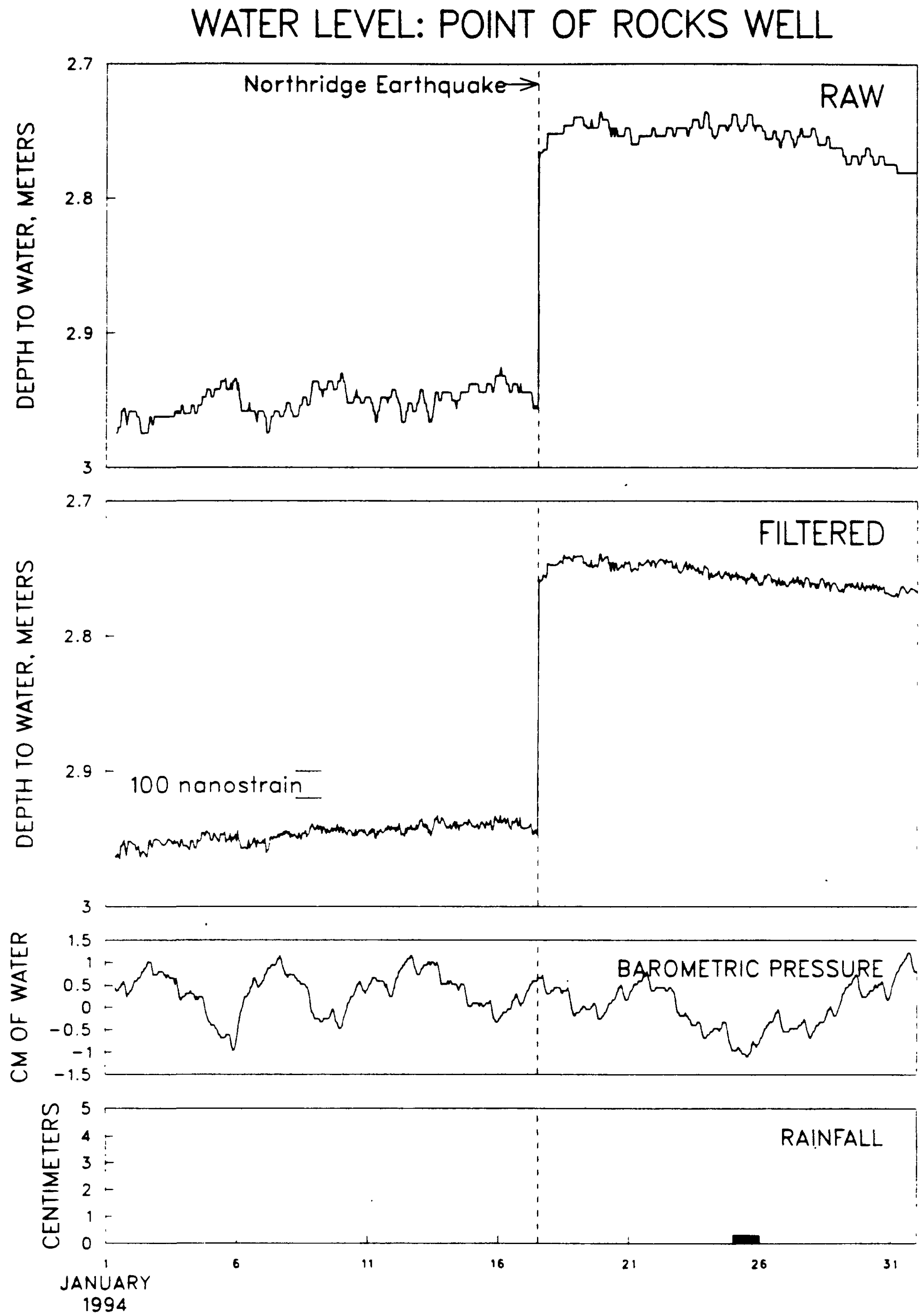


Figure 15. Water level in well PORS, Ash Meadows, Nevada. Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (a) January 1 to February 1, 1994.

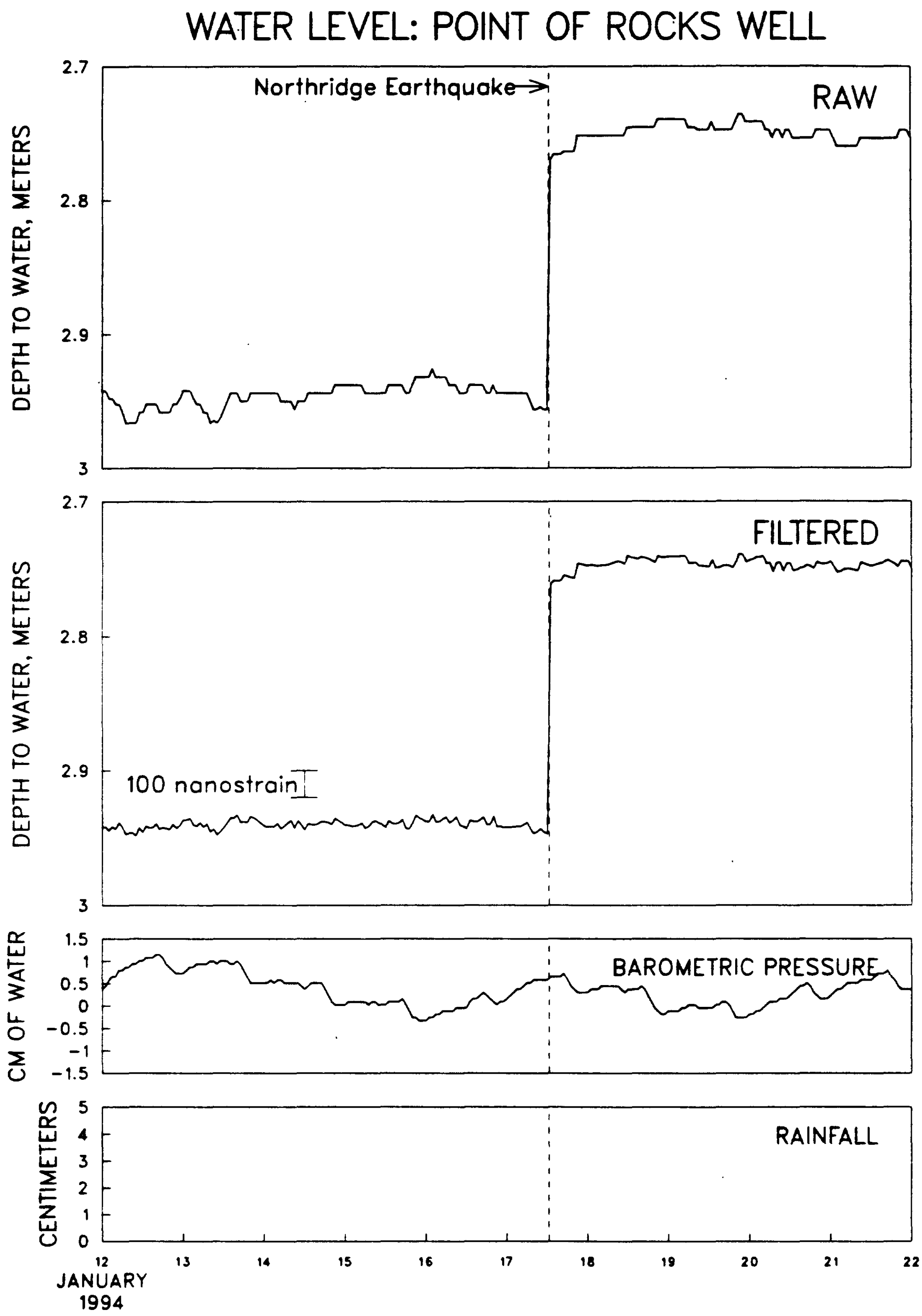


Figure 15, continued. Water level in well PORS, Ash Meadows, Nevada. Earth tidal and barometric fluctuations have been subtracted from the "Filtered" data. (b) January 12 to January 22, 1994.

## SUMMARY

Ground-water level changes in southern California recorded in the hours following the Northridge earthquake agreed in direction with the sign of the calculated coseismic volume strain field. The largest ground-water level change was a drop of 52 cm at the Crystalaire well. Two spring discharge increases were also observed in Southern California.

At Parkfield, California, a water-level change took place in one well at the time of the earthquake. At Long Valley, California, one water-level change was observed, which returned to normal after a few hours, consistent with having been caused by the passage of surface waves.

In general many water wells can reliably record crustal strain signals and for wells in the near field of an earthquake can help constrain earthquake dislocation models.

## ACKNOWLEDGMENTS

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