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# Water Level Observations in the East San Francisco Bay Area, California

by

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**Introduction**

This report summarizes water level data from five wells in the east San Francisco Bay area, with respect to their response to crustal strain. Water level changes in wells at distances up to several hundred kilometers from an earthquake epicenter have been interpreted as possible earthquake precursors by various investigators (Roeloffs, 1988). In order to rule out non-tectonic hydrologic anomalies and to measure fluid pressure (well water level) changes resulting from crustal strain, we seek well sites that respond to crustal strain induced by earth tides. Because many well aquifer systems also respond to barometric pressure changes and to rainfall, water level data should be supplemented with barometric pressure and rainfall data before we can begin to identify water level changes with precursory crustal strain changes. In this report we display water level data collected at five existing observation well boreholes drilled at various depths at three sites in the East San Francisco Bay area as well as local barometric and rainfall data. We next briefly describe the lithologies at each site taken from well drilling reports. We conclude that well bores which penetrate only the unconsolidated deposits in the East Bay plain are unlikely to display measureable earth tides and are therefore poor candidate wells for observing any possible water level changes that can be unambigously ascribed to tectonic processes.

**Lithology of the East Bay plain**

The East Bay plain consists of two general geologic units - (1) unconsolidated deposits up to four hundred meters deep overlying (2) consolidated bedrock of the Jurassic, Cretaceous and Tertiary age. These unconsolidated deposits in turn consist of sand and gravel aquifers embedded in clay and silt aquicludes. Lithologic data from numerous well drilling logs suggest that there are no thick continous aquifers beneath the East Bay plain and that the ratio of aquiclude to aquifer in the region is on the order of four to one (Muir, 1993). A general lithologic cross section of the East Bay plain is shown in Figure 1. For purposes of further hydrologic study the East Bay plain has been subdivided into five areas as shown in Figure 2. Two well sites lie in the area designated the San Lorenzo cone. A typical lithologic cross section of the San Lorenzo cone derived from well drilling logs is shown in Figure 3. The remaining well site lies in the Niles cone; no lithologic cross section for this area is shown.

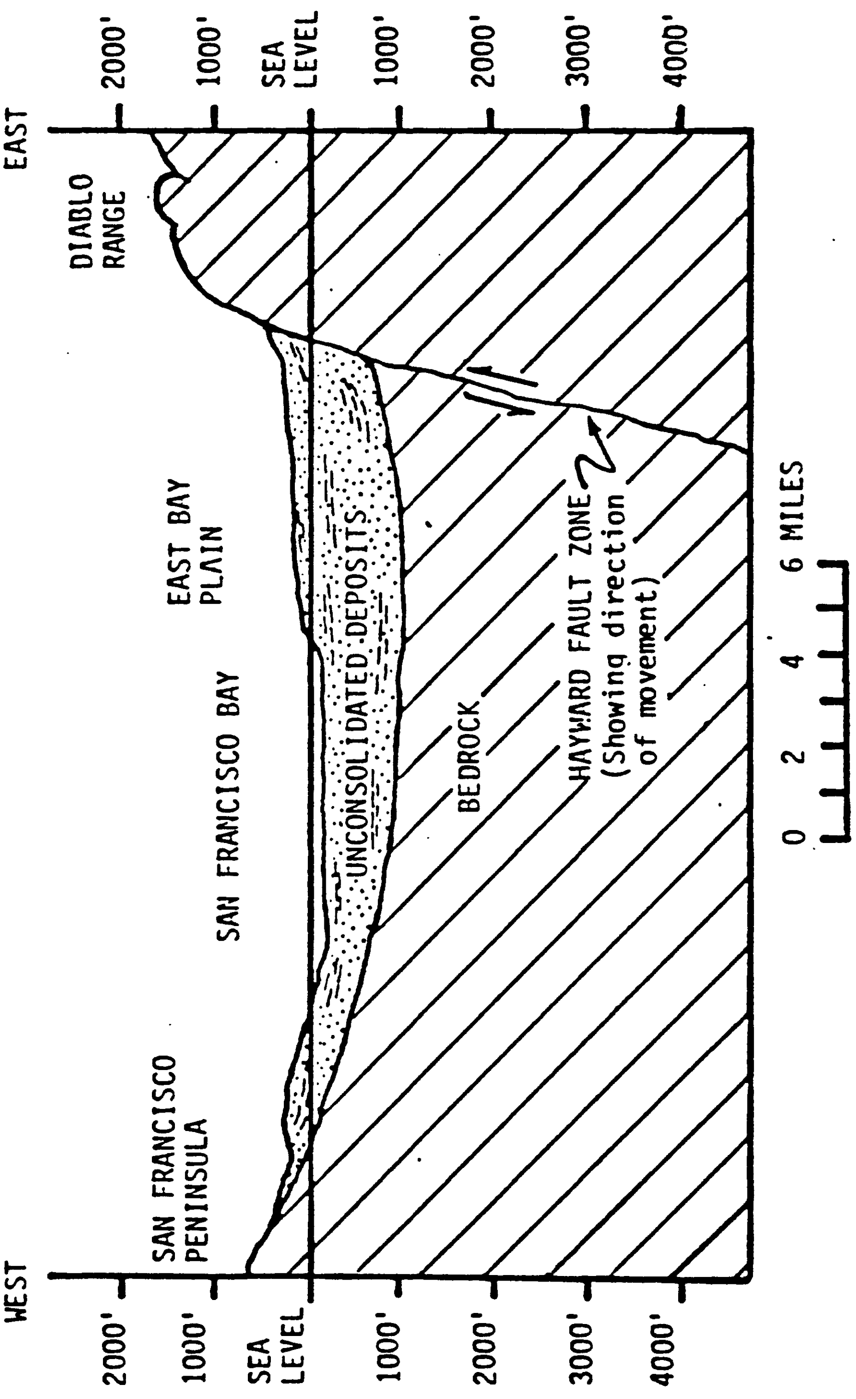


Figure 1. A generalized lithologic cross section of the San Francisco bay area. Typical depths of unconsolidated deposits and the underlying bedrock are shown. The Hayward fault is more vertical than shown in this figure [Lienkamper, oral communication, 1994]. Refer to Figure 3. Reprinted from K. S. Muir [1993].

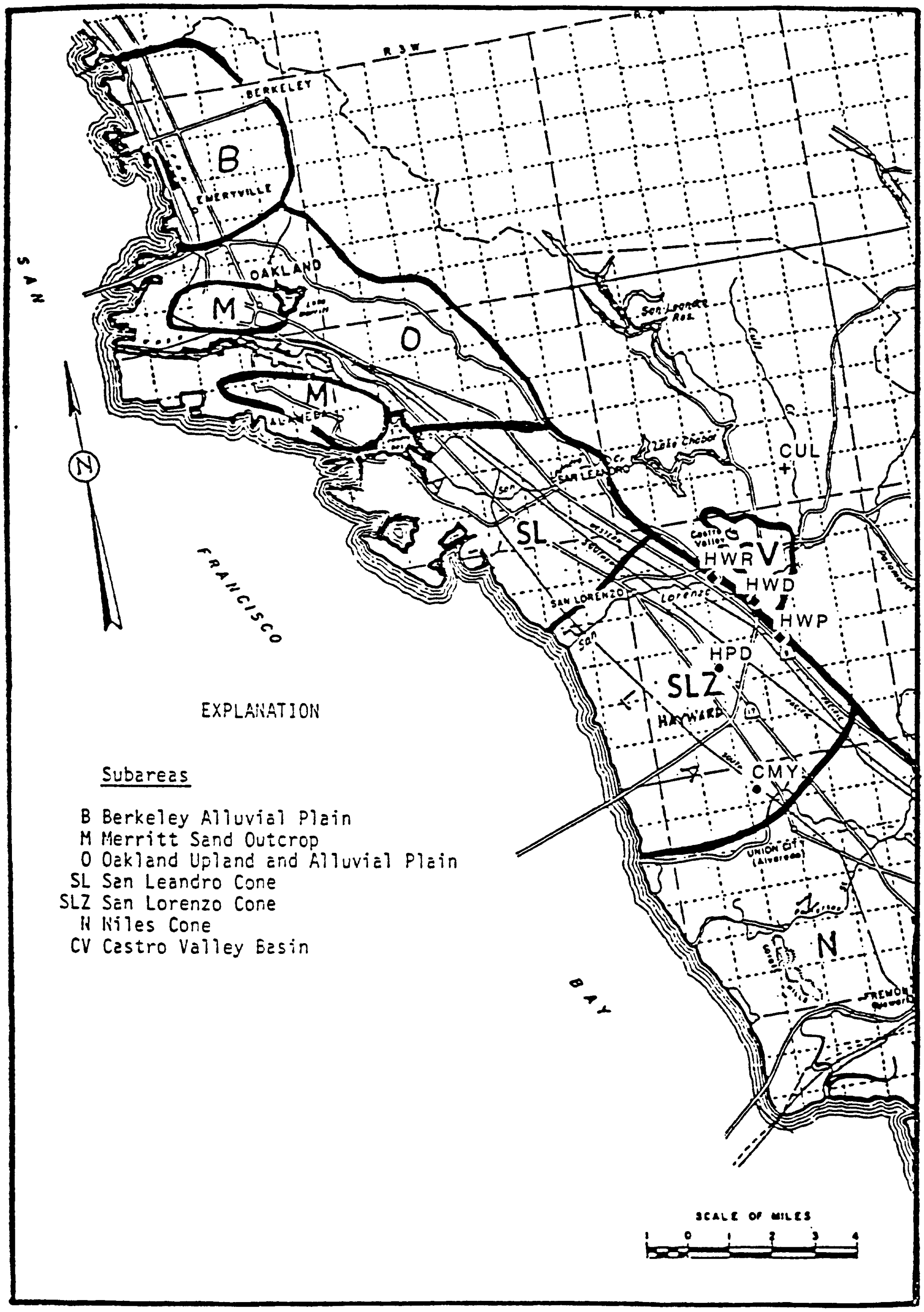


Figure 2. Groundwater subareas of the East Bay plain. Reprinted from K. S. Muir [1993].

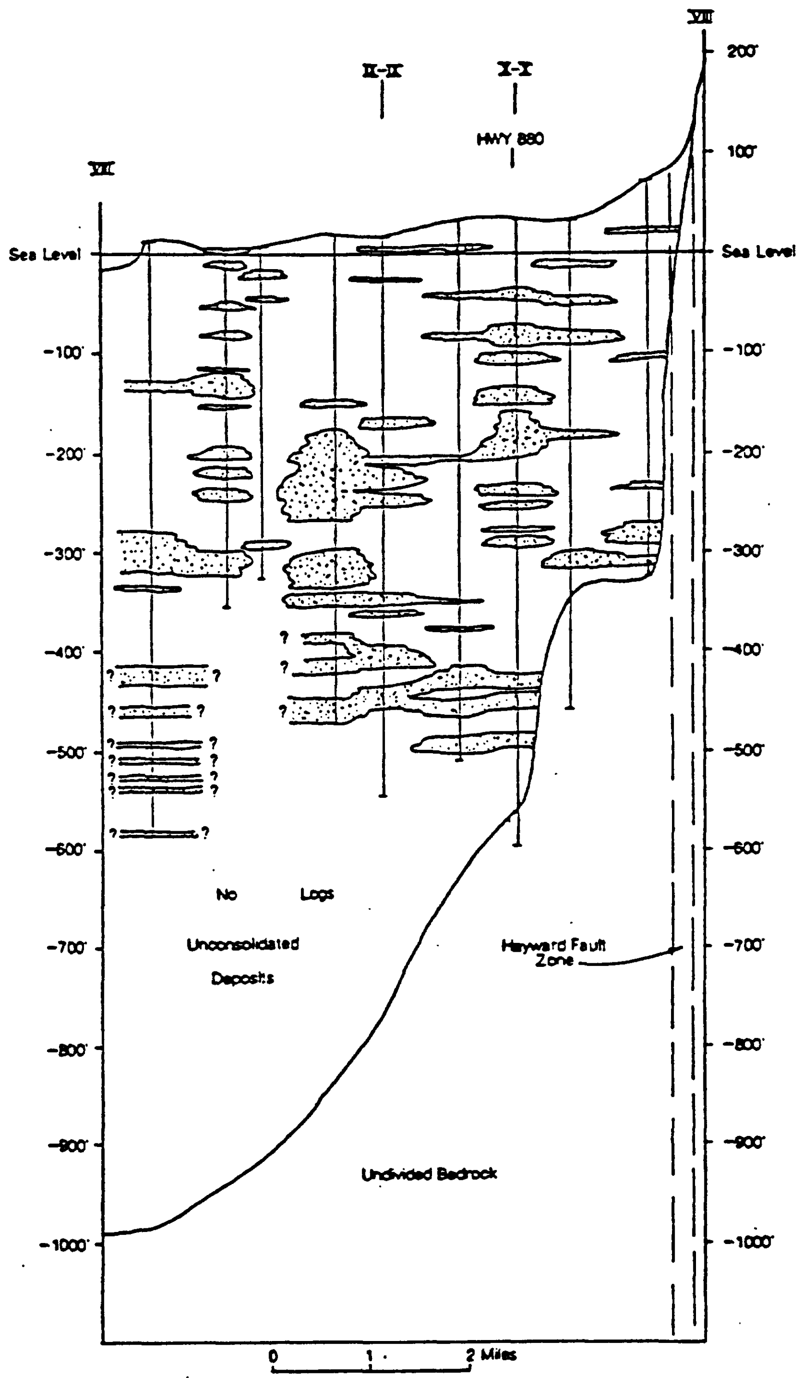


Figure 3. Aquifer-aquiclude cross section of the San Lorenzo cone (SLZ) groundwater subarea shown in Figure 2. Reprinted from K. S. Muir [1993].

### East Bay Site Locations

Three locations with existing well bores were instrumented using on-site data loggers and water-level pressure transducers. Site locations are shown in Figure 4. The filled diamonds show the water level site locations, the open diamonds show three creepmeter locations and the crosses show the location of two borehole volumetric strainmeters. Barometric data was collected at the borehole volumetric strainmeter site designated GA in Figure 4 beginning in 1993. Rainfall was recorded using a tipping bucket rain gauge owned by the Alameda County Flood Control District in a location within 500 meters of the well site denoted HPD in Figure 4.

### County Maintenance Yard (CMY) water level data

There are three adjacent well bores at the site denoted by CMY in Figure 4. Figure 5 shows the well completion diagram at this site. The reader should note perforations where each well bore casing is open to the various water bearing gravel layers (aquifers) as well as the comparatively thick clay or sand-and-clay confining aquicludes. Water level data collected from the shallow(p1), middle(p2) and deep(p3) boreholes are shown in Figure 6. The three large water level rises in the shallow borehole are believed to be caused by interruption of pumping in a nearby well. Small offsets in the water level data from the middle borehole can be seen during the transient episodes logged in the shallow borehole. In the deepest borehole, water level transients lasting from one to several days were recorded, but do not correlate with earth tides, barometric pressure, or the pumping transients observed in the shallow well. Both the shallow and middle borehole casings are open to shallow aquifer layers while the deep borehole is only open to the deepest aquifer layer shown in the well completion diagram. This may explain why water level data from the deep borehole does not respond to water level changes in the shallower boreholes. We further note that there were no earthquakes of magnitude 3.0 or greater within 15.0 *km* of any of our observation well sites in the East San Francisco Bay area during the periods they were monitored by us.

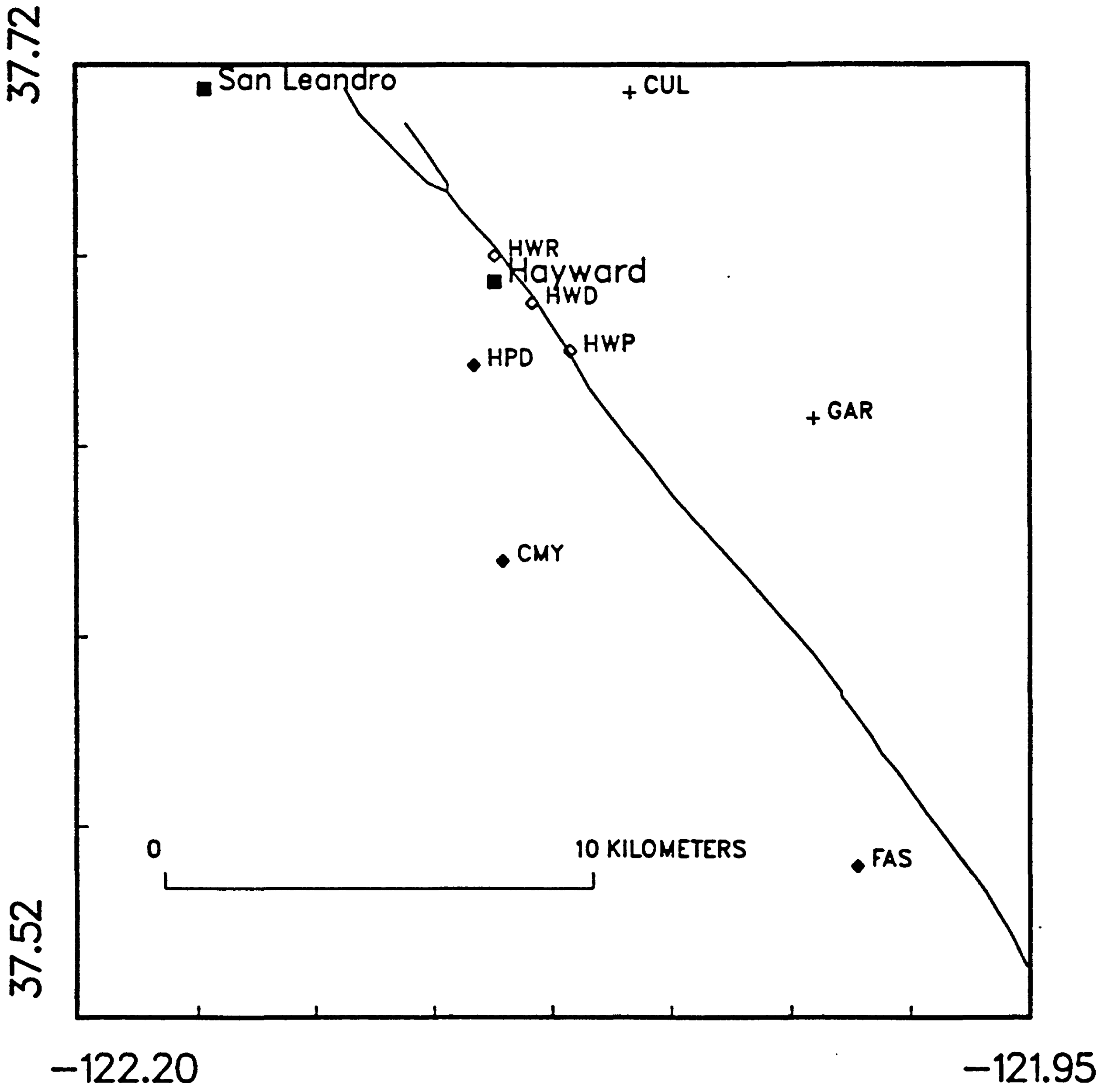


Figure 4. Map showing water wells (HPD, CMY, FAS) in the east San Francisco Bay area in which water levels have been monitored. Creepmeters (HWR, HWD, HWP) and borehole strainmeters (CUL, GAR) are also shown.

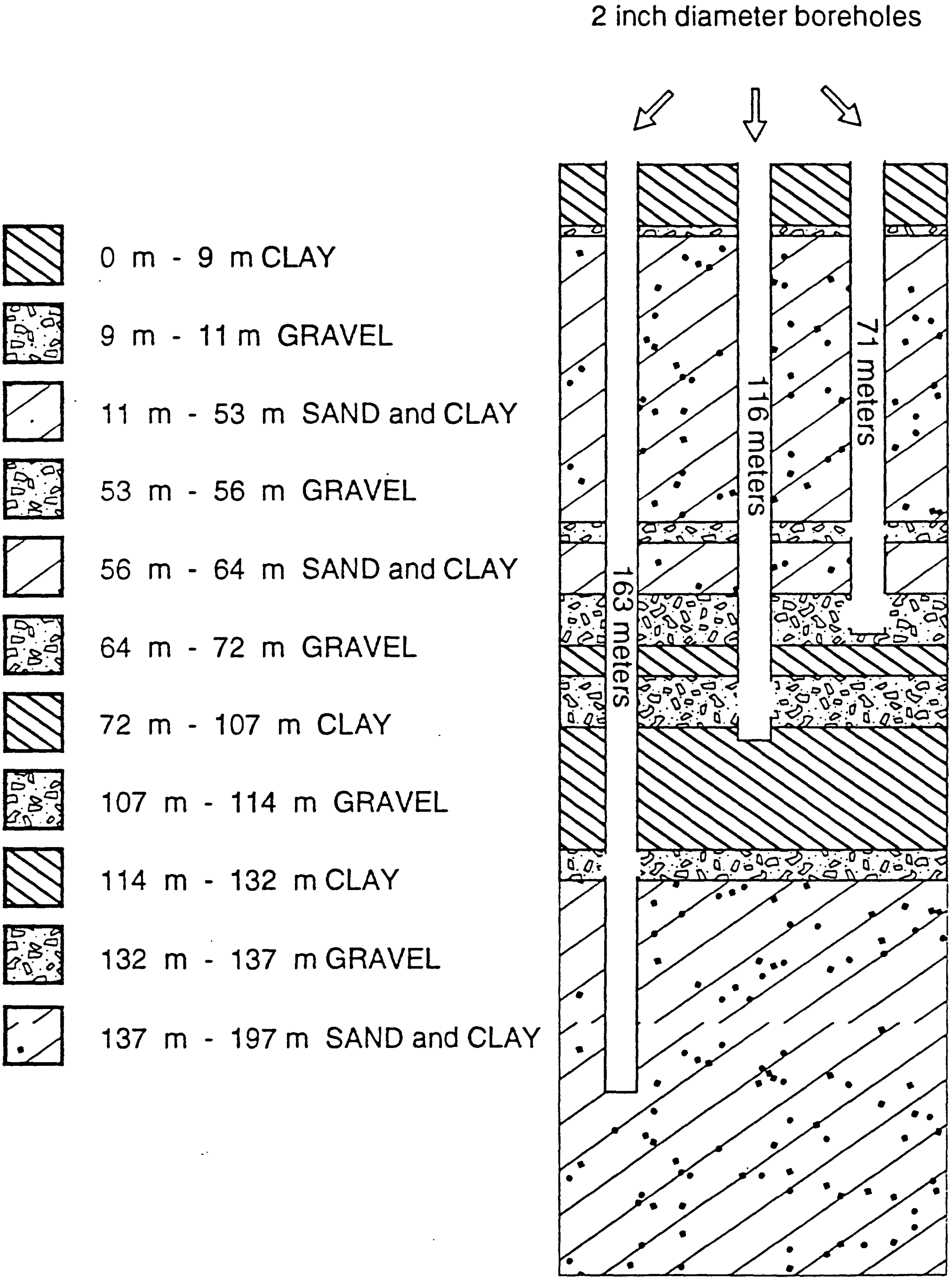


Figure 5. Well completion diagram for the well site designated CMY in Figure 4. Borehole depths, surrounding lithologies and the open intervals of each borehole are shown.

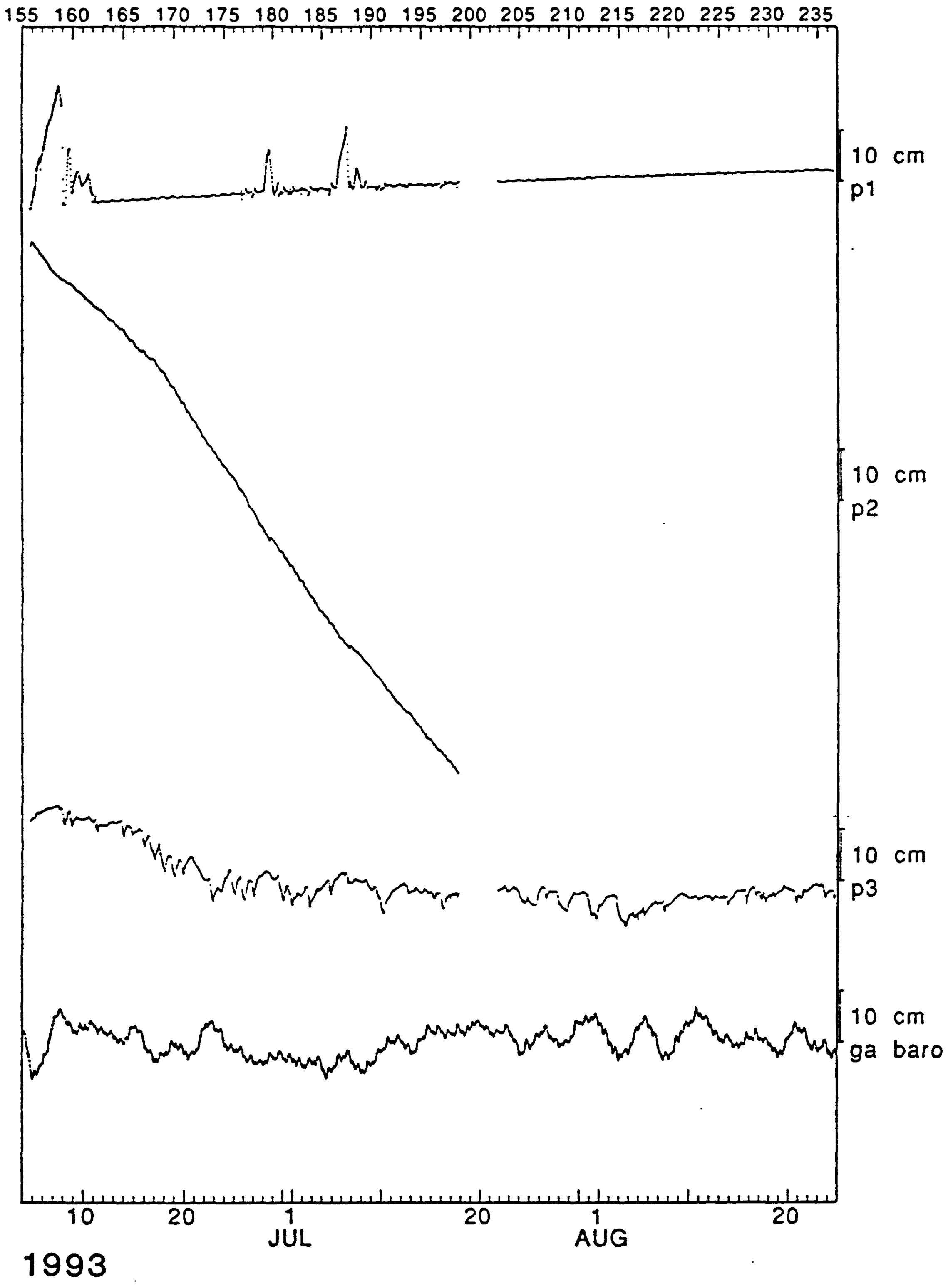


Figure 6. Water level, barometric pressure, and rainfall records from the site denoted CMY in Figure 4. Hourly values are plotted for water level and barometric pressure. Water level is in centimeters above an arbitrary datum. Barometric pressure is in centimeters of water with respect to an arbitrary datum. Bars indicate total rainfall in a 24-hour period. Site names are indicated at right. Julian day number is given on top axis.

**Hayward Police Department (HPD) water level data**

Water level data was recorded at the site denoted by HPD in Figure 4. Figure 7 shows the well completion diagram for the single borehole at this site. As at the CMY site there are relatively narrow aquifer bands embedded in sand-and-clay aquicludes. Water level data from this site is shown in Figure 8. The water level data shows no response to earth tides, barometric pressure changes or recent rainfall.

A small transient in the data can be seen on December 2, 1993. We generated a family of curves using the Theis equation for water level response to pumping transients as presented in Freeze and Cherry [1979]. Assuming low values for transmissivity and storativity appropriate to the narrow aquifer bands at this site and for various distances of a pump from the borehole, we attempted to match the transient in the water level data with a range of possible drawdown and recovery curves assuming pumping ceased around the time of the lowest point of the transient. The results can be seen in Figure 9. Clearly the data do not support our assumption of a sudden shutoff of pumpage, but absent any information about pumping in the immediate area we cannot rule out the possibility that this transient in the water level record was caused by pumpage drawdown. This site and the site denoted CMY lie in an area with a well density of over twenty wells per square mile according to a well density map prepared by the Alameda County Flood Control and Water Conservation District (Hickenbottom and Muir, 1988).

**Fremont Animal Shelter (FAS) water level data**

Water level data was recorded during spring and summer of 1991 at the site denoted FAS in Figure 4. Figure 10 shows the well completion diagram at this site. Unlike the two previous sites the water bearing gravel layers are thicker than the overlying clay aquicludes in the depth interval where the well is open to the formation. Figure 11 shows water level and rainfall data collected during this period. No barometric pressure data in the East Bay was recorded by the U.S.G.S. during this time. The transients in the water level record do not correlate with earth tide strain changes; the drop and recovery seen are probably not the result of barometric pressure fluctuations since observed barometric pressure signals almost never fluctuate so rapidly. These water level transients may be caused by pumpage drawdown since the well bore is open to a shallow aquifer as shown in Figure 10. No information on well density is available for this area.

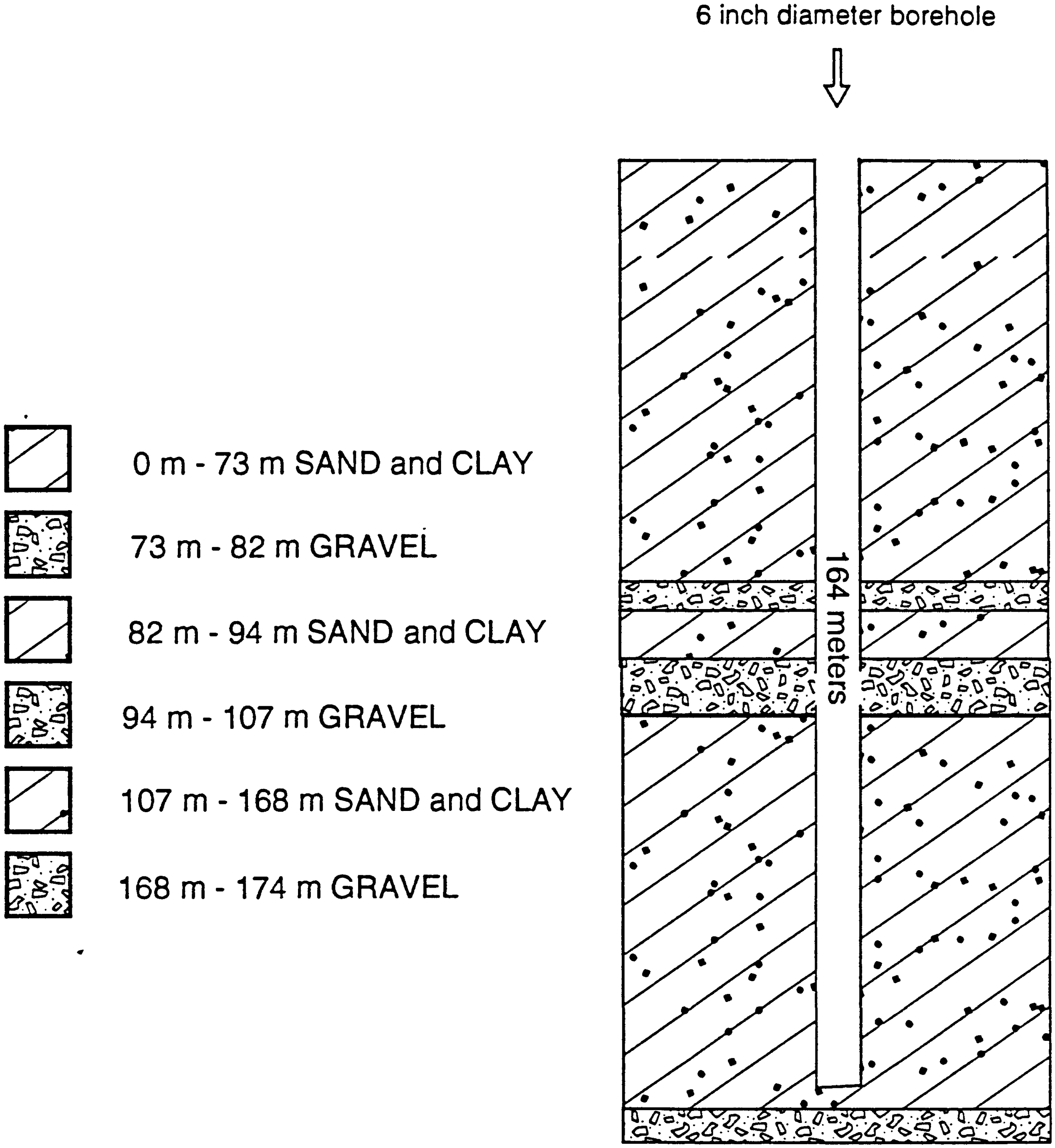


Figure 7. Well completion diagram from the site denoted HPD in Figure 4 plotted as in Figure 5.

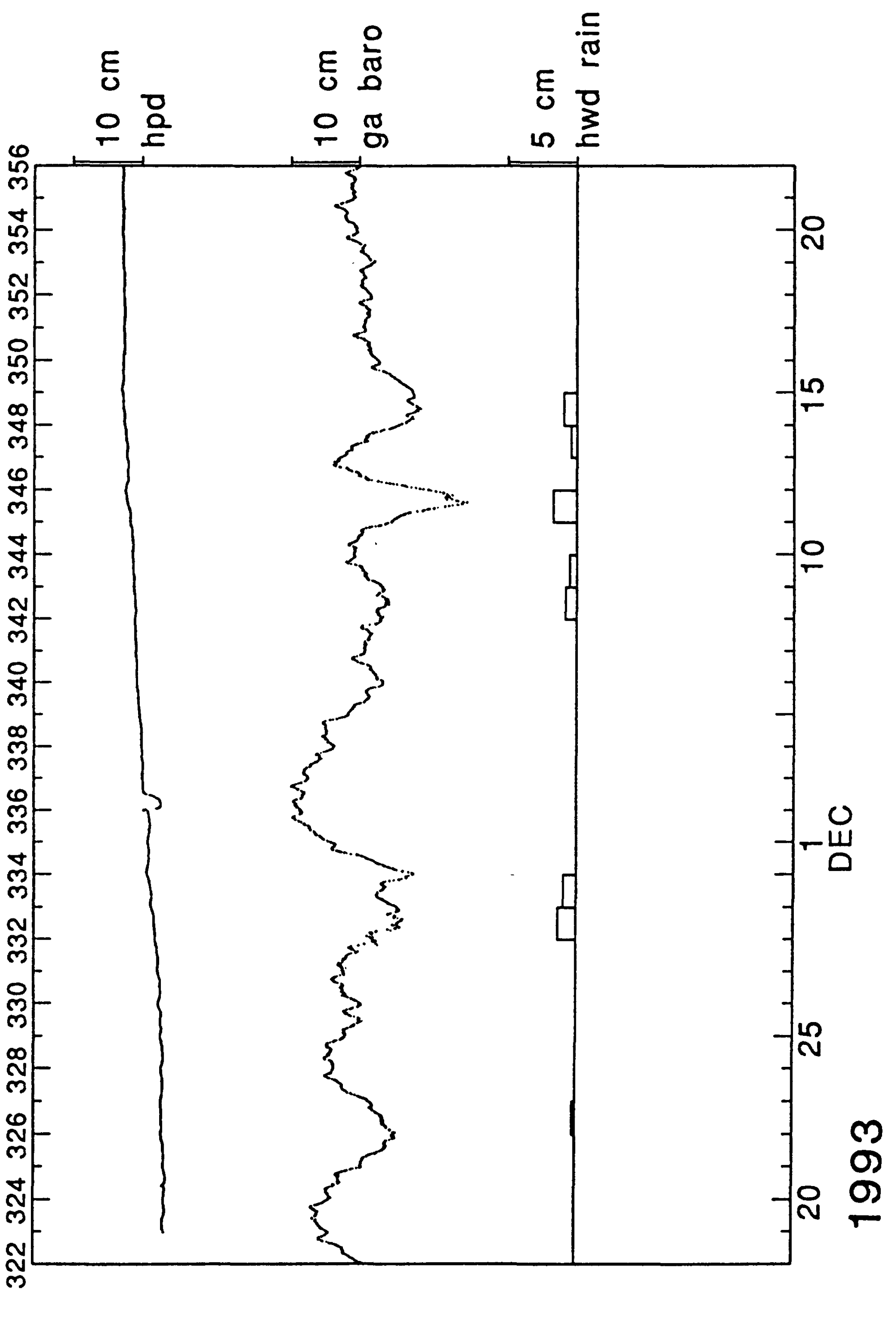


Figure 8. Water level records from the site denoted HPD in Figure 4 plotted as in Figure 6.

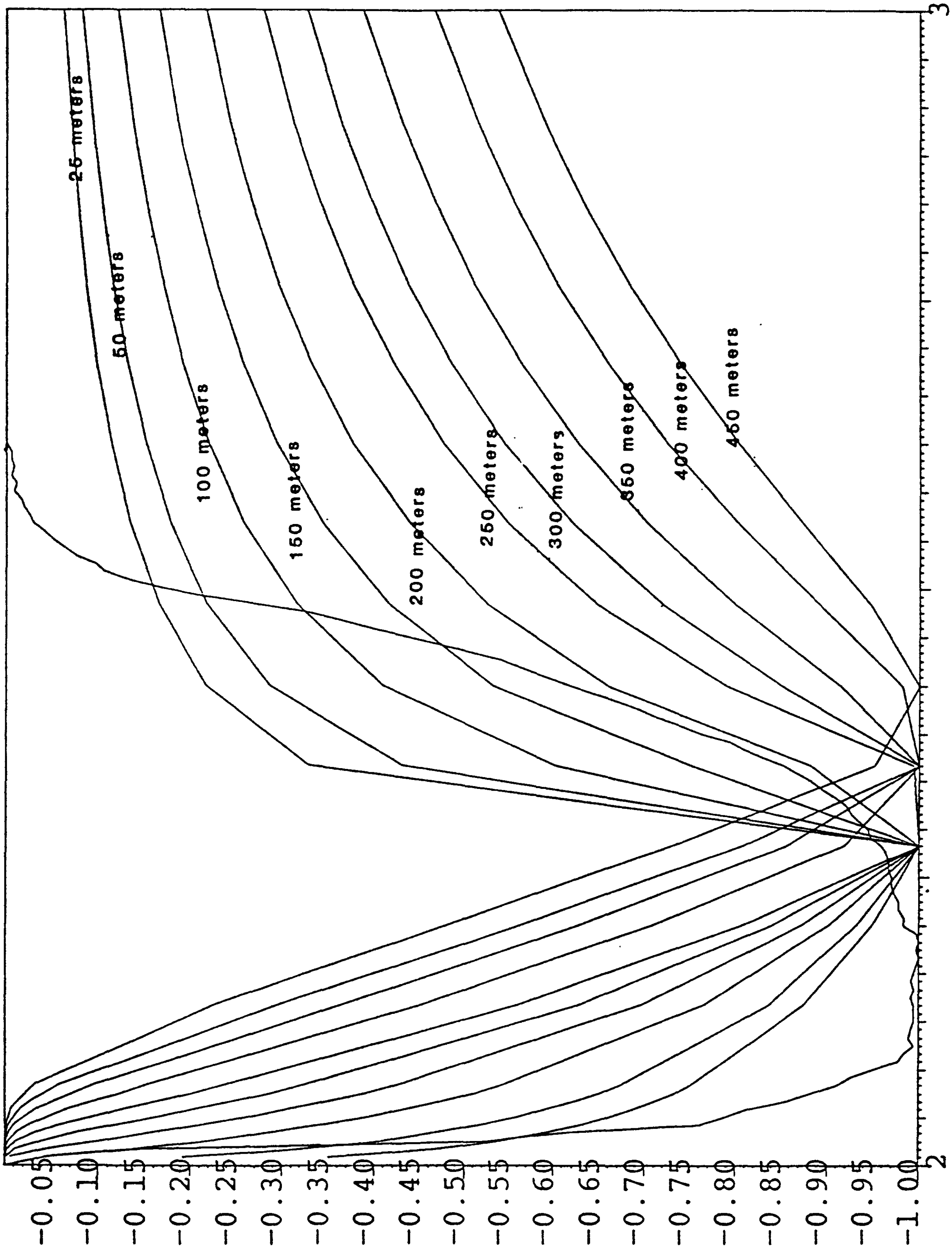


Figure 9. Normalized type curves generated by the Theis equation and the normalized transient seen in the water level record plotted in Figure 8. A transmissivity of $0.015 m^2/s$ and a storativity of 0.005 was used to generate the type curves. We assumed a drawdown rate of $4.0 l/s$ while the pump was operating. Each type curve is identified with the distance from the pump to the associated well bore.

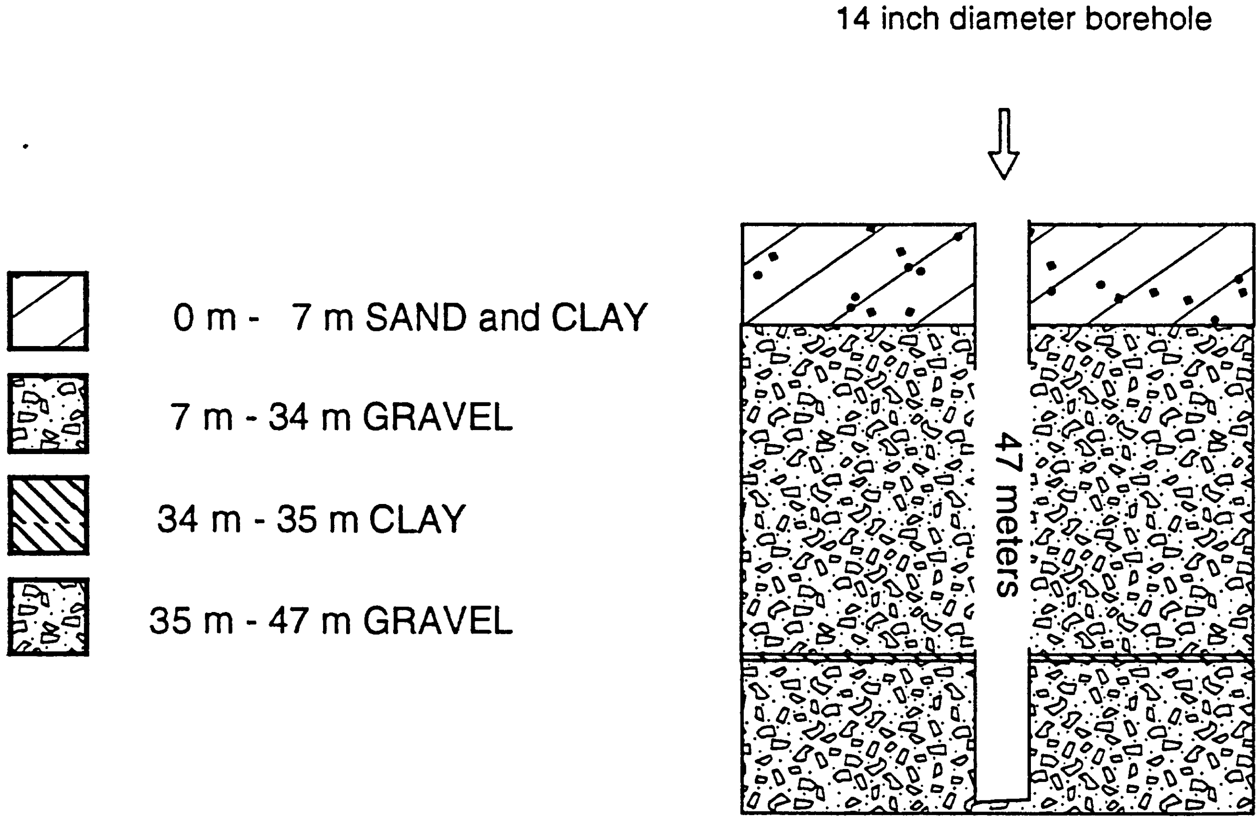


Figure 10. Well completion diagram from the site denoted FAS in Figure 4 plotted as in Figure 5.

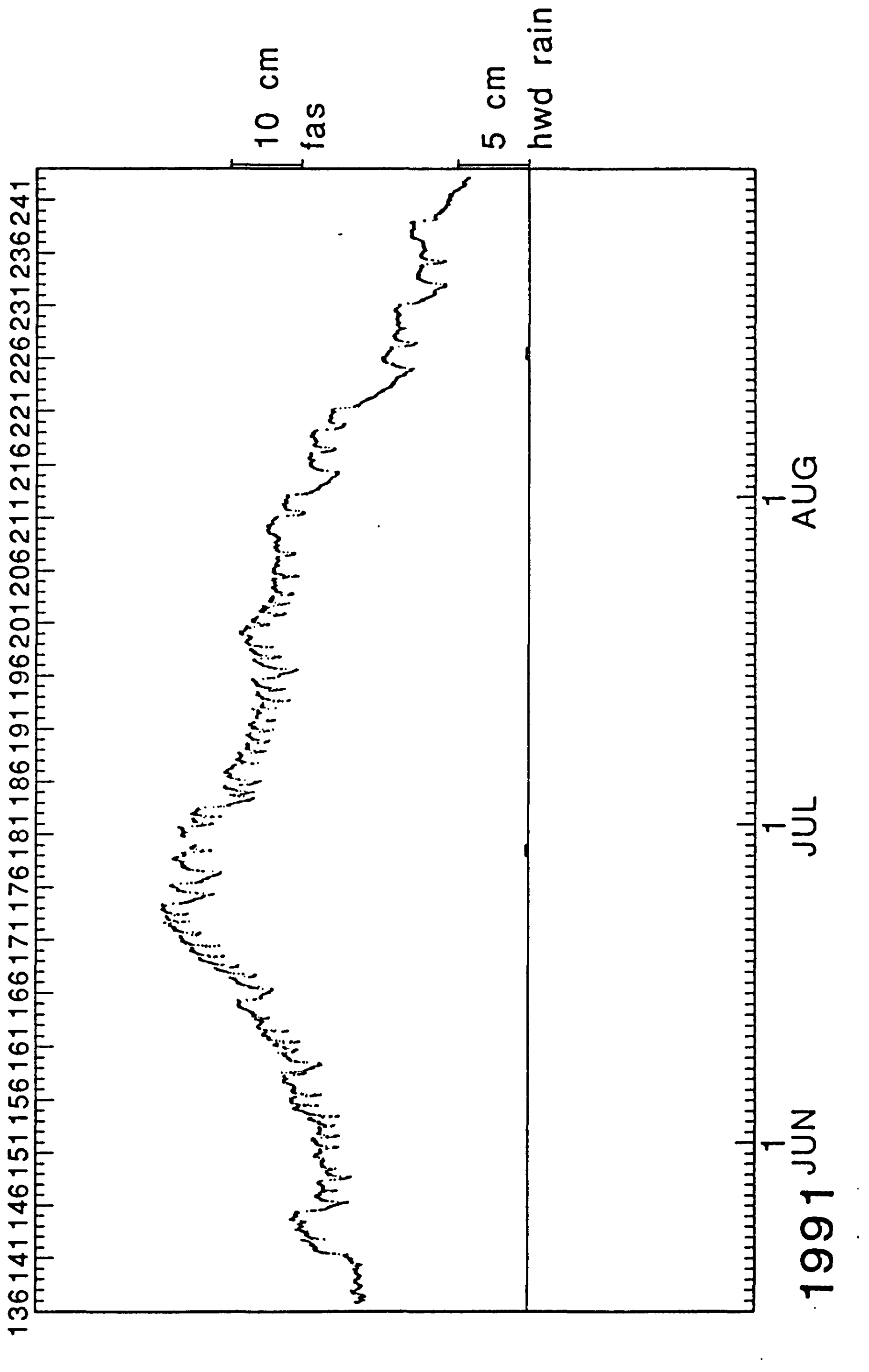


Figure 11. Water level records from the site denoted FAS in Figure 4 plotted as in Figure 6.

## Conclusion

All five boreholes in this study lie completely within the unconsolidated deposits of the East Bay plain. None tap the underlying bedrock. The clay matrix of the unconsolidated upper geologic layer has a compressibilty two to three orders of magnitude larger than sound or fractured rock and one to two orders of magnitude greater than the water bearing gravel layers (Freeze and Cherry, 1979). When gravel aquifers are embedded in a clay matrix and the aquifer- aquiclude complex is deformed by earth tide stresses, most of the deformation is taken up by the clay confining layers since clay is much more compressible than gravel (Weeks, 1979); (Nur and Byerlee, 1971). If the gravel aquifers had been embedded in a rock matrix, most of the deformation induced would appear in the aquifer layers since gravel is more compressible than either sound or jointed rock. Therefore earth tide stresses would be expected to force very little pore fluid out of aquifers embedded in a clay matrix compared with aquifers embedded in a rock matrix. Water levels in well bores open to aquifers respond to lateral pore fluid movement due to stress on the aquifer. This perhaps explains why no earth tides can be seen in the water level data records from all five boreholes in the area. By contrast observation wells drilled even in highly fractured rock matrices often display large earth tide signals. This suggests that any well in the San Francisco East Bay that is likely to display precursory water level changes must be located nearer the Hayward Fault zone so as to readily tap the comparatively shallow underlying bedrock in the vicinity.

**Acknowledgments**

Andreas Godfrey of the Alameda County Public Works Agency provided us with a great deal of written material on the lithology of the East Bay from which this report draws heavily. He also promptly responded to our requests for rainfall data during 1991 and 1993 recorded in the region. Mark Wang of the City of Hayward Department of Public Works provided us with drillers logs from both well sites located in Hayward and arranged access to the County Maintenance Yard well site. Our U.S.G.S. colleague Robert Mueller located two of the well sites we later instrumented and made several helpful suggestions on how to use a CR10 data logger to gain sufficient resolution from our pressure transducers to detect tidal signals if any were to be found. As always our co-worker David Campbell provided invaluable assistance to us in site preparation and site instrumentation. Argy Mena, a former employee of the U.S.G.S., located the Fremont Animal Shelter well site and retrieved water level data recorded on site by a CR10 data logger which she helped install.

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