Geotechnical Observations at the Van Norman Complex after the 1994 Northridge Earthquake

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ABSTRACT

The January 17, 1994 Northridge Earthquake severely shook the Van Norman Complex, in the northern San Fernando Valley. Throughout the complex, sand boils, liquefaction induced lateral spreading, and ground cracks were observed. The Upper and Lower San Fernando hydraulic fill dams displayed substantial cracking, settlement and lateral movement. One small dike failed at the San Fernando Tailrace Channel at the northern end of the site. Six rolled fill embankments, including the Los Angeles Reservoir, underwent measurable movement.

INTRODUCTION

The Van Norman Complex is owned and operated by the City of Los Angeles Department of Water and Power. As shown in Fig.1, it is located in the northern San Fernando Valley along Interstate 5 between the 405 and 210 interchanges approximately 7 miles north of the January 17, 1994 Northridge Earthquake epicenter. As shown in Fig.2, the complex includes major water facilities which are critical to the Los Angeles Area, and controls 50 to 75 percent of the cities' annual supply of water. The Northridge Earthquake caused damage to both water and power facilities estimated to exceed $75M.

This paper summarizes the most significant geotechnical observations in the Van Norman Complex after the Northridge Earthquake, especially on the Lower and Upper San Fernando Dams, Los Angeles Reservoir and Power Plane Tailrace. A more complete and comprehensive report of observations, field measurements, and strong motion recordings is in preparation, and will be released in the near future.

SEISMICITY AND STRONG MOTION RECORDING

The Northridge Earthquake occurred at 4:31 AM (PST) on January 17, 1994 with a moment magnitude of 6.7 (Trifunac et al., 1994; USGS and SCEC, 1994). The main release of energy occurred on an unmapped blind thrust segment of the Oak Ridge Fault which dips to the south under the San Fernando Valley. The epicenter was located at 34° 12.53' N; 118° 32.44'W at a depth of 19 km. The duration of strong shaking was 6 to 10 seconds (Porcella et al., 1994; Shakal et al., 1994).

A great number of aftershocks took place below the complex. This is easily seen in the aftershock map in Fig.3, and the cross-sections BB' and CC' in Fig.4 (after Hauksson, 1994). The aftershocks in Fig.3 are so dense that they completely cover the complex which had to be situated by its coordinates. As shown in Fig.4, the aftershocks are located within a narrow band that delineates the fault plane inclined at 35°-40°. The eastern extremity of the fault rupture is just below the Van Norman Complex. As a result, the Van Norman Complex was strongly shaken by the main event, and was continually subjected to numerous, close, and shallow aftershocks.

The Northridge Earthquake produced an unprecedented number of near source seismic recordings. Fig.2 and Table 1 present the site locations and recorded peak ground accelerations of the seismic instruments on and around the Van Norman Complex, which include fourteen accelerographs (1-14) and two seismoscopes (15-16). Fig.5 shows an example of the time history of horizontal and vertical accelerations recorded at the Rinaldi receiving station, located to the southern end of the complex and referred to as No.1 in Fig.2. The horizontal peak acceleration (0.84 g) is observed at about 2.5 second and corresponds to a low-frequency and high-energy pulse, which is noticeable in all the recordings in the complex. The vertical acceleration has a shorter dominant period, but an even larger peak value (0.85 g) than the horizontal components.

The recorded peak accelerations were very large for this earthquake of 6.7 magnitude. In fact, the Van Norman Complex was subjected to some of the largest accelerations ever recorded. In contrast to those large accelerations, relatively low levels of shaking (0.32 g) were also measured near the Los Angeles Reservoir. This provides us with a remarkable example about the rapid variation of ground acceleration intensity over short distances.

Table 1. Location of strong motion recordings in the Van Norman Complex, and peak accelerations recorded during the Northridge earthquake.

Station number	Station name	Owner	Geology/ Foundation	Lat.	Long	Epicentral Distance (km)	Peak acceleration (g)		
							Horiz. 1	Vert.	Horiz. 2
1	Rinaldi receiving station	DWP/Power	Alluvium	34.281	118.478	10	0.84	0.85	0.48
2	LA Dam - West abutment	DWP/Water	Nonmarine deposit	34.294	118.483	11	0.43	0.32	0.32
3	LA Dam foundation	DWP/Water	Nonmarine deposit	34.295	118.479	11	0.32	0.13	0.28
4	LA Dam crest	DWP/Water	Dam fill	34.294	118.481	11	0.56	0.39	0.43
5	LA reservoir	DWP/Water	Concrete structure	34.296	118.478	11	1.34	0.29	1.18
6	North Dike crest	DWP/Water	Dam fill	34.300	118.487	12	0.65	0.38	0.56
7	Generator building	MWD/USGS	Nonmarine deposit	34.313	118.498	12	0.98	0 52	0.56
8	Administration building	MWD/USGS	Alluvium	34.312	118.496	12	0.62	0 40	0.40
9	Reservoir roof	MWD/USGS	concrete structure	34.309	118.499	12	0 84	0.51	0.65
10	Valve group 7	DWP/Power	Alluvium	34.311	118.490	12.5	0.90	0.64	0 61
11	Valve group 7 ground floor	DWP/Power	Alluvium	34.311	118.490	12.5	0.75	0.79	0.60
12	Valve group 16 basement	DWP/Power	Alluvium	34.311	118.490	12.5	0.58	0.53	0.37
13	Free field	DWP/Power	Nonmarine deposit	34.312	118.481	13	0.83	0.38	0.49
14	Valve hall floor	DWP/Power	Nonmarine deposit	34.312	118.481	13	0.79	0.43	0.45
15	Abutment	DWP/Water	Nonmarine deposit	34.294	118.483	11	>0.31	-	-
16	Bypass Reservoir dam crest	DWP/Water	Dam fill	34.292	118.484	11	>0.31	-	-

LOWER SAN FERNANDO DAM

The upstream face of the Lower San Fernando Dam was reconstructed, after it failed during the 1971 San Fernando Earthquake. At the time of the Northridge Earthquake, there was only a small pond of water, a few feet deep, within the upstream basin. Nevertheless, the Lower San Fernando Dam crest and upstream slope substantially cracked and moved. Many sand boils emerged on the upstream face. In addition, a sinkhole occurred at the toe of the dam above the 96 inch drain line which had been crushed laterally.

Fig.6 presents a detailed mapping of the cracks and sand boils observed after the earthquake. Fig.6 also shows the lateral displacements perpendicular to the dam axis. The maximum lateral movement on the upstream slope exceeded 1/2 foot in the upstream direction. Along the crest, the maximum movement was just under 1/2 foot, and was similar to that on the upstream slope. The maximum downstream movement was approximately 3 inches on the downstream slope. Maximum settlement of 8 inches occurred along the crest, while settlement along the upstream slope reached nearly 1/2 foot. The maximum settlement and lateral displacement were measured in the same areas. Settlement along the upstream slope, parallel to the axis, was relatively consistent averaging a little over 4 inches, and increased linearly with the dam height. All settlements and displacements were obtained from the surveys of March 4, 1994 and February 24, 1993.

Earthquake shaking produced extensive cracks along the crest and upstream berm. The cracks were observed to extend across the entire width of the dam. Most cracking occurred in the longitudinal direction. However, there were transverse cracks at the abutments. Some cracks on the berm were observed to have up to 9 inches of vertical displacement. Some small cracking was observed through the grass at the top of the upstream slope. No cracks were observed on the downstream slope which was covered with thick grass. Approximately fifty large sand boils emerged through cracks on the upstream slope of the berm as seen in Fig.6.

A sinkhole approximately 30 feet in diameter and 10 feet deep appeared above the storm basin drain line on the west side of the dam. In addition, a large area subsided over the pipe alignment for a few hundred feet south of the sinkhole. The sinkhole resulted from a loss of material into the 8 foot diameter corrugated metal drain pipe. The earthquake crushed the drain line laterally, over a length of three hundred feet. An additional one hundred feet was severely damaged with lateral buckling up to two feet inward.

UPPER SAN FERNANDO DAM

Water retained behind the Upper San Fernando Dam was limited to a few feet within the backwash ponds (see Fig.2). Similar to the Lower San Fernando Dam, the upper dam also underwent extensive cracking in 1994. Fig.7 presents a detailed mapping of cracks and sand boils observed after the earthquake.

Fig.7 shows the lateral movement at monument locations, and a settlement profile. The movement was obtained by comparing the survey of March 4, 1994 to that of July 29, 1993. Maximum settlement reached nearly 1.5 feet. The maximum settlement curiously corresponds with the minimum lateral movement. After intense shakings, the crest moved laterally a maximum of 7 inches in the upstream direction near the west and east abutments. Settlement was clearly visible by the protruding grout pipes above the outlet line. These pipes were used to grout voids around the outlet line following the 1971 San Fernando Earthquake. Prior to the Northridge earthquake most of the pipes were hidden below the surface, whereas, after the shaking, some of them extended above the surface, as much as six inches.

An extensive network of cracks emerged on the surface of the upper dam, extending from the west abutment across the entire width of the dam and through the spillway on the east side. The majority of cracks were longitudinal to the axis, and became transverse near each abutment. Similar crack patterns were observed in the 1971 San Fernando Earthquake. However, in 1971, settlement reached 3 feet while movement was up to 5 feet in the downstream direction.

Sand boils surfaced at various locations around the Upper San Fernando Dam. Most erupted upstream on the dikes retaining the backwash ponds. Some boils were detected along the eastern upstream toe near the spillway. Others were found downstream of the dam, near piers supporting a 54-inch pipeline.

The 54-inch pipe supported by concrete piers, located below the dam, collapsed as a result of cumulative earthquake damage since the 1971 San Fernando Earthquake. The piers supporting the pipe leaned toward the east, and contributed to the buckling of the ring girders and subsequent pipe collapse. Many large extension cracks were observed along the road in front of the pipe.

LOS ANGELES RESERVOIR

Completed in 1979, the Los Angeles Reservoir is a modern reservoir which provides storage for treated aqueduct water. The water is impounded by two compacted earth fill dams. The Los Angeles Dam, on the south side of the reservoir, is 155 feet high, whereas the North Dike, on the northern side of the reservoir, is 117 feet high. Both embankments are founded on bedrock. Each is zoned with shell material on the upstream and downstream slopes, and contains a chimney drain in the center section made of coarse materials. The Los Angeles Dam also has a clay zone upstream of the chimney drain. The Los Angeles Reservoir is lined with asphalt concrete pavement along all of the interior slopes and perimeter roadways, except for its reservoir floor that is not paved. After the earthquake, the lining on all of the upstream slopes displayed many cracks, in addition to those caused by weathering prior to the earthquake.

The Los Angeles Reservoir is well equipped with modern instruments. The instruments remained functional throughout the earthquake, and were useful to evaluate the safety of the reservoir. Piezometers and observation wells indicated slight increases in pressures in and around the dams immediately after the earthquake, and a rapid return to normal values soon after. However, seepage in the North Dike substantially increased on the west abutment, and still remains high to date. The outlet tower performed extremely well, registering no permanent displacement or noticeable cracking in spite of being subjected to accelerations over 1g. However, the bridge leading to the tower moved significantly. One of the spans hopped out of its bracket supports, and slid more than 1.5 feet.

As shown in Fig.2 and Table 1, there were five seismographs located at the reservoir. Surprisingly, all their recordings were lower than those throughout the complex, which reached record-breaking levels of accelerations. Thus, the reservoir site was subjected to a much lower level of shaking than the surrounding areas.

Movement and settlement measured immediately after the earthquake showed up to 3 1/2 inches of crest settlement, and lateral downstream movement of over 1 inch on the crest. The downstream slope settled a maximum of 3/4 inch, and had lateral displacements in the downstream direction of over 2 inches. Approximately one inch of settlement was observed on the upstream slope around the outlet tower bridge pier. All displacements were measured by comparing the survey results of January 4, 1994 and January 21, 1994.

As shown in Fig.8, the upstream slope displayed a vast array of cracks, the largest cracks occurring at the east abutment. Settlement in this area reached 3.5 inches. These cracks were associated with a wavy and bulging surface. Many of the cracks on the east side were of compressional nature, unlike on the rest of the dam surface. Transverse oriented cracks occurred along the crest road. In many cases the cracks lined up with diagonal cracks extending to the crest on the upstream face. Trenches were excavated across the largest cracks on the crest and upstream slope, and revealed that the cracks died out rapidly with depth. Within the zone encompassed by cracks, three small slump areas were also observed on the upstream face just west of the outlet tower.

POWER PLANT TAILRACE

In the northern part of the complex, substantial damage resulted at the San Fernando Power Plant and Tailrace. The ground surrounding the power plant subsided as much as two feet. Extensional cracking on the surrounding pavement provided evidence of ground spreading toward the tailrace.

Fig.9 shows a detailed mapping of cracks and sand boils around the tailrace. Extensive cracking occurred on both banks of the channel as a result of the lateral spreading induced by liquefaction. Numerous sand boils erupted around the tailrace, mostly on the west bank, although a few were observed on the east bank. A slide over 200 feet wide occurred on the west bank near the south end of the channel. The concrete liner within the channel was pushed over and up five to six feet. The west bank around the slide area settled a few feet, and displayed numerous cracks, most of them having less than 2 inches in width.

The east bank had fewer but larger cracks, which could be better described as scarps and fissures. These cracks were up to 6 inches wide and had over 1 foot vertical offset. A series of cracking patterns followed the old bank of the Upper Van Norman reservoir basin to the southeast of the tailrace. Many cracks extended northwest over to the abutment of the dike. Unfortunately, most cracks around the dike could not be mapped due to the emergency construction activities. Further south, at the site of the California State Northridge observatory, a slide 150 feet wide occurred leaving a scarp 2 1/2 feet high.

The dike retaining the south end of the tailrace channel breached after the earthquake, leaving a breach about 18 feet deep and 45 feet wide. The failure did not occur immediately after the main shock. Disaster response teams did not observe any sign of distress at 9:30 AM the morning of the earthquake. However, by the next morning, the dike had completely failed. Its failure probably resulted from a series of events, related to liquefaction and lateral spreading. The lateral spreading caused subsidence of the slopes into the reservoir basin. Longitudinal cracks propagated into the dike abutments, and possibly into the dike. The large displacements, high pore pressures in the ground, and weakened foundations presented conditions sufficient for piping to occur. It is quite possible that large aftershocks later that day compounded the problem and aided in completing the failure.

In 1971, the Tailrace channel banks completely failed, but the dike withstood the San Fernando Earthquake shaking. Cracking around the tailrace and Upper Van Norman Reservoir had similar patterns for both earthquakes.

CONCLUSION

The Van Norman Complex sustained substantial damage from the 1994 Northridge Earthquake. Sand boils, liquefaction induced lateral spreading, cracks and fissures were observed. The two hydraulic fill dams (Upper and Lower San Fernando) sustained substantial cracking along with settlement and lateral movement. One small dike failed on the San Fernando Tailrace Channel at the northern end of the complex. Six rolled fill embankments, including the Los Angeles Reservoir, sustained measurable movement. Large and moderate levels of shaking coexisted within the site, with the Los Angeles Reservoir receiving a lower level of shaking than that at other nearby locations. The peak accelerations of the 1994 Northridge Earthquake were much higher than those of the 1971 San Fernando Earthquake. Although subjected to stronger shaking, the Van Norman Complex performed much better in 1994 than in 1971.

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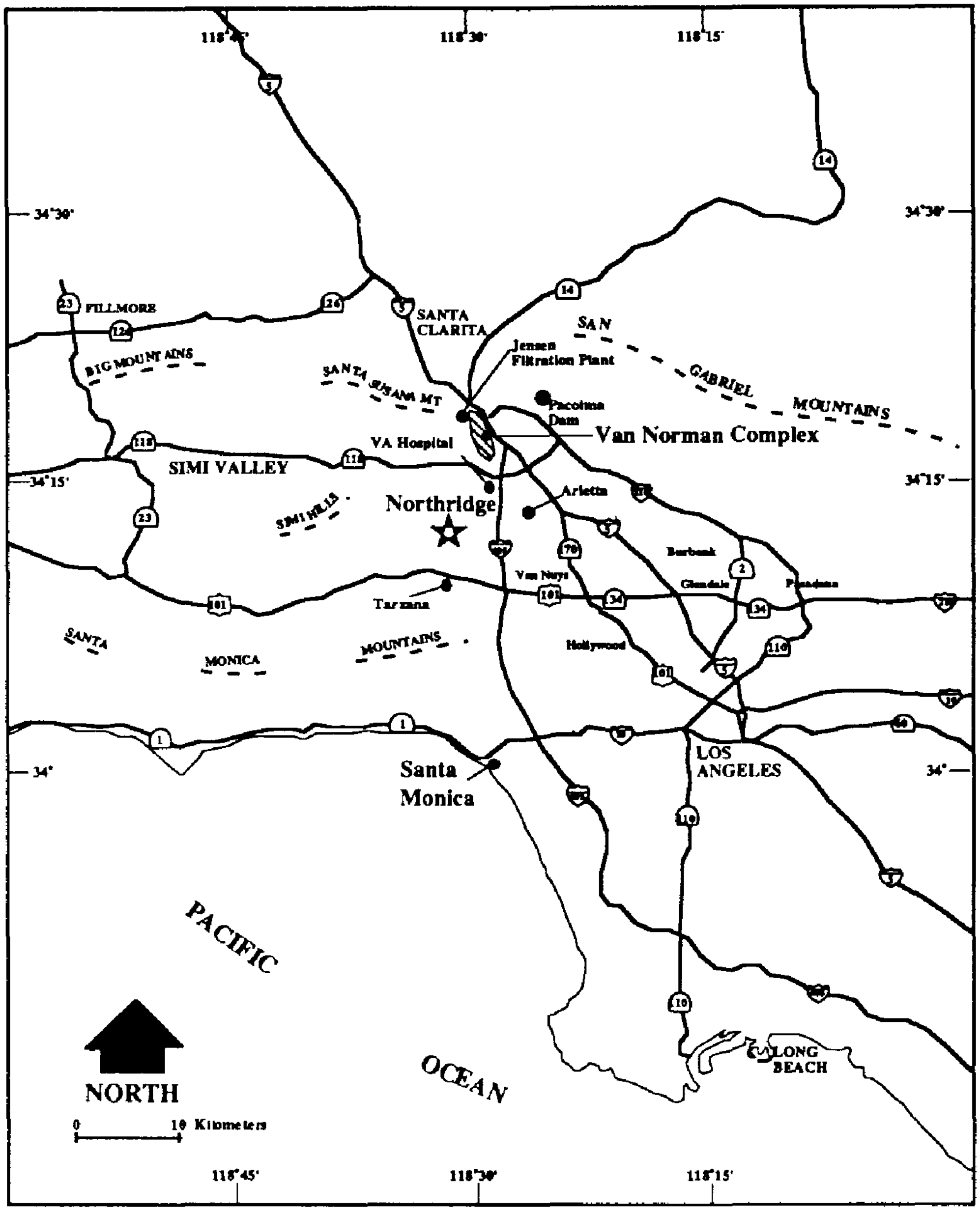

Figure 1. Location of Van Norman Complex in Los Angeles Area.

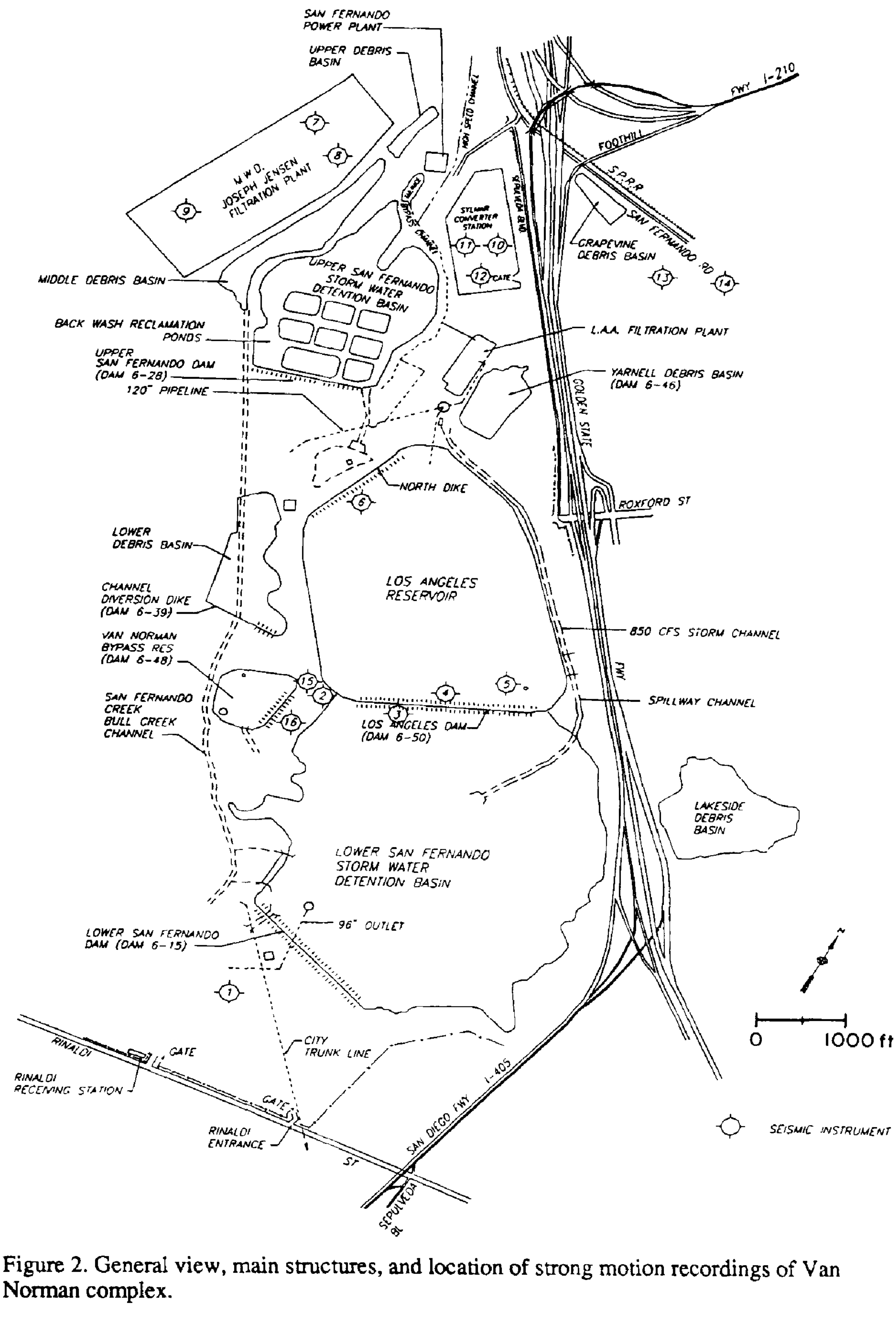

Figure 2. General view, main structures, and location of strong motion recordings of Van Norman complex.

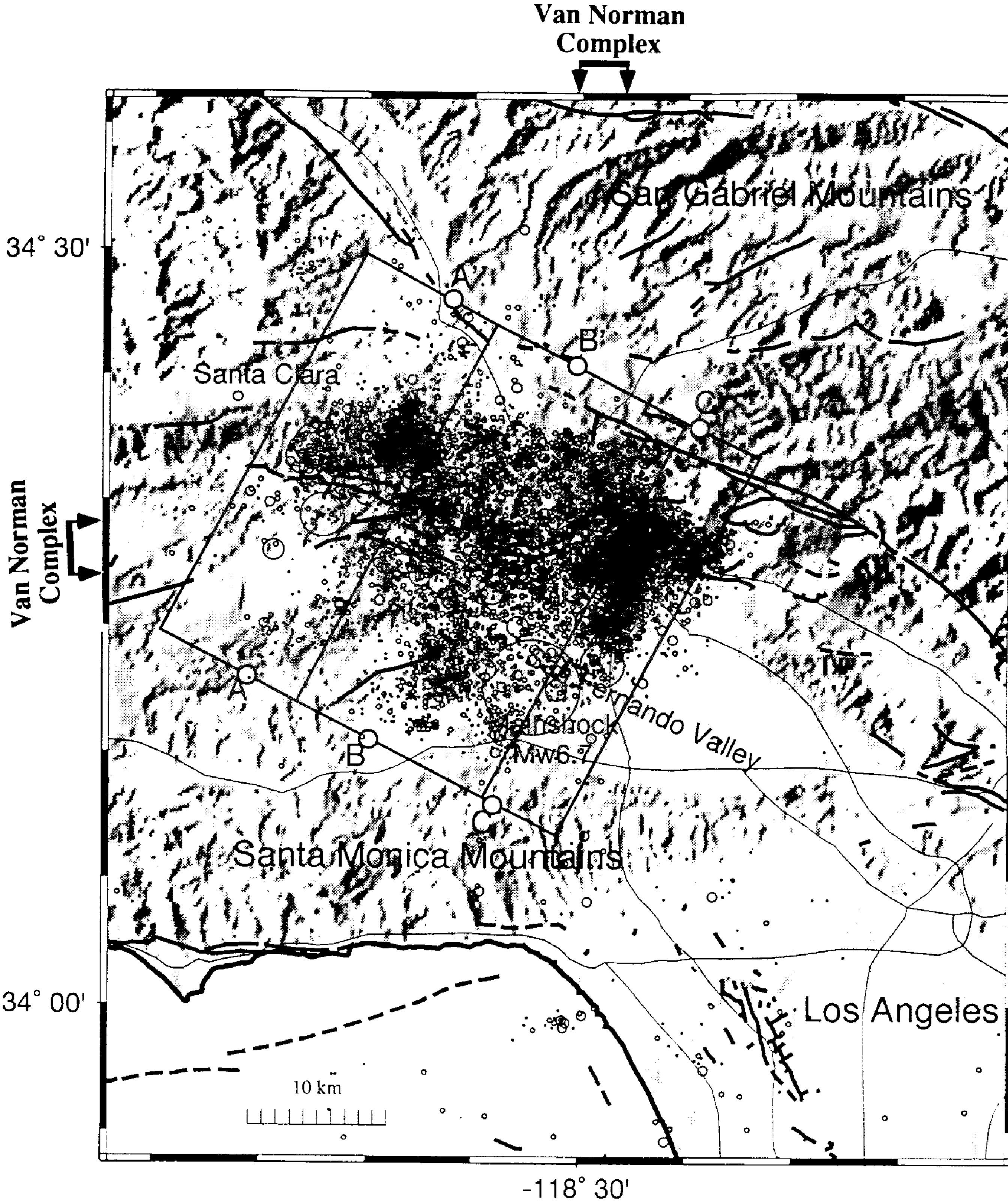

Figure 3. Map of aftershocks after the Northridge earthquake from January to July 1994 (after Hauksson, 1994).

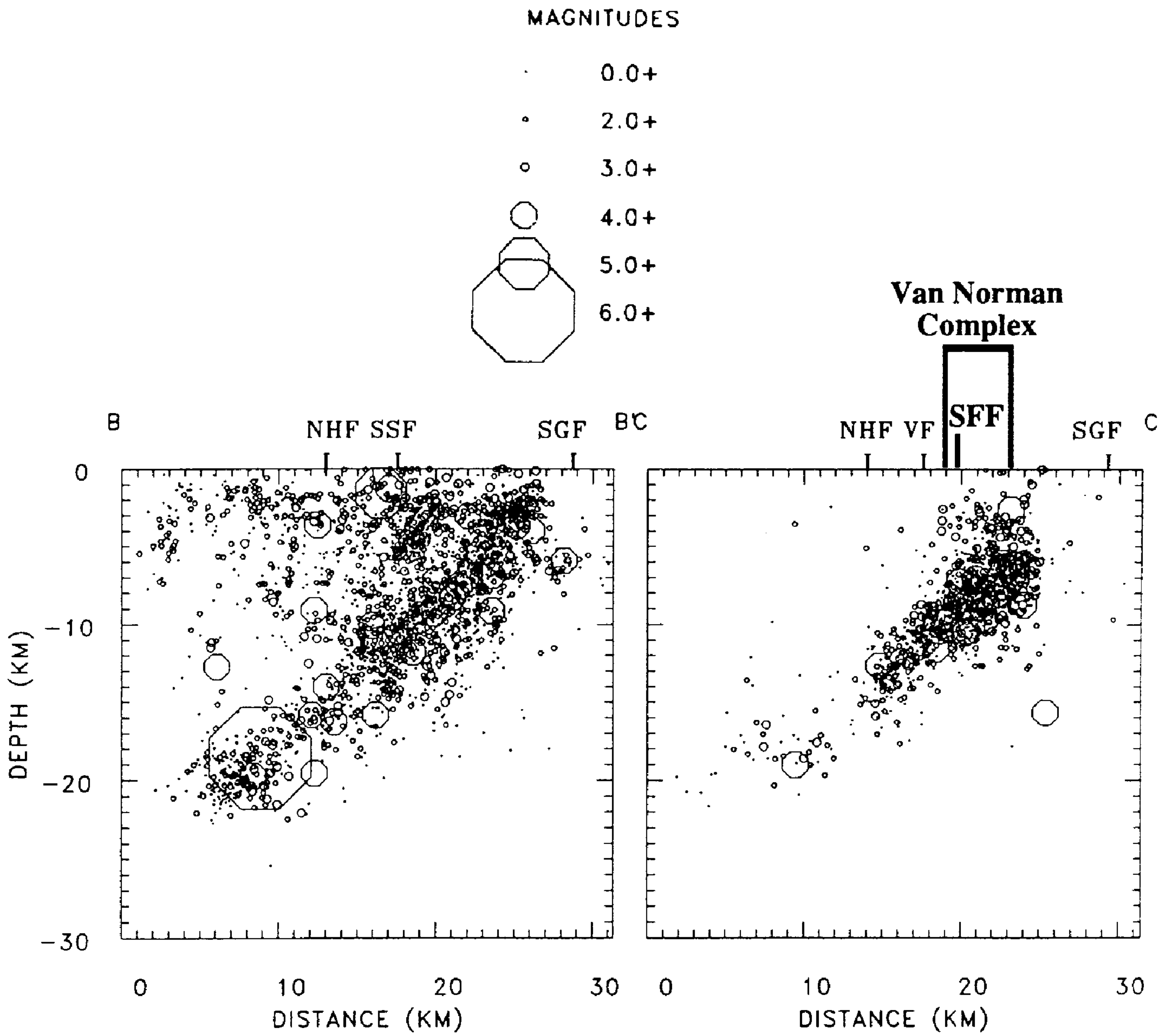

Figure 4. Location and depth of after shocks along sections BB' and CC' of Fig.3 (after Hauksson, 1994).

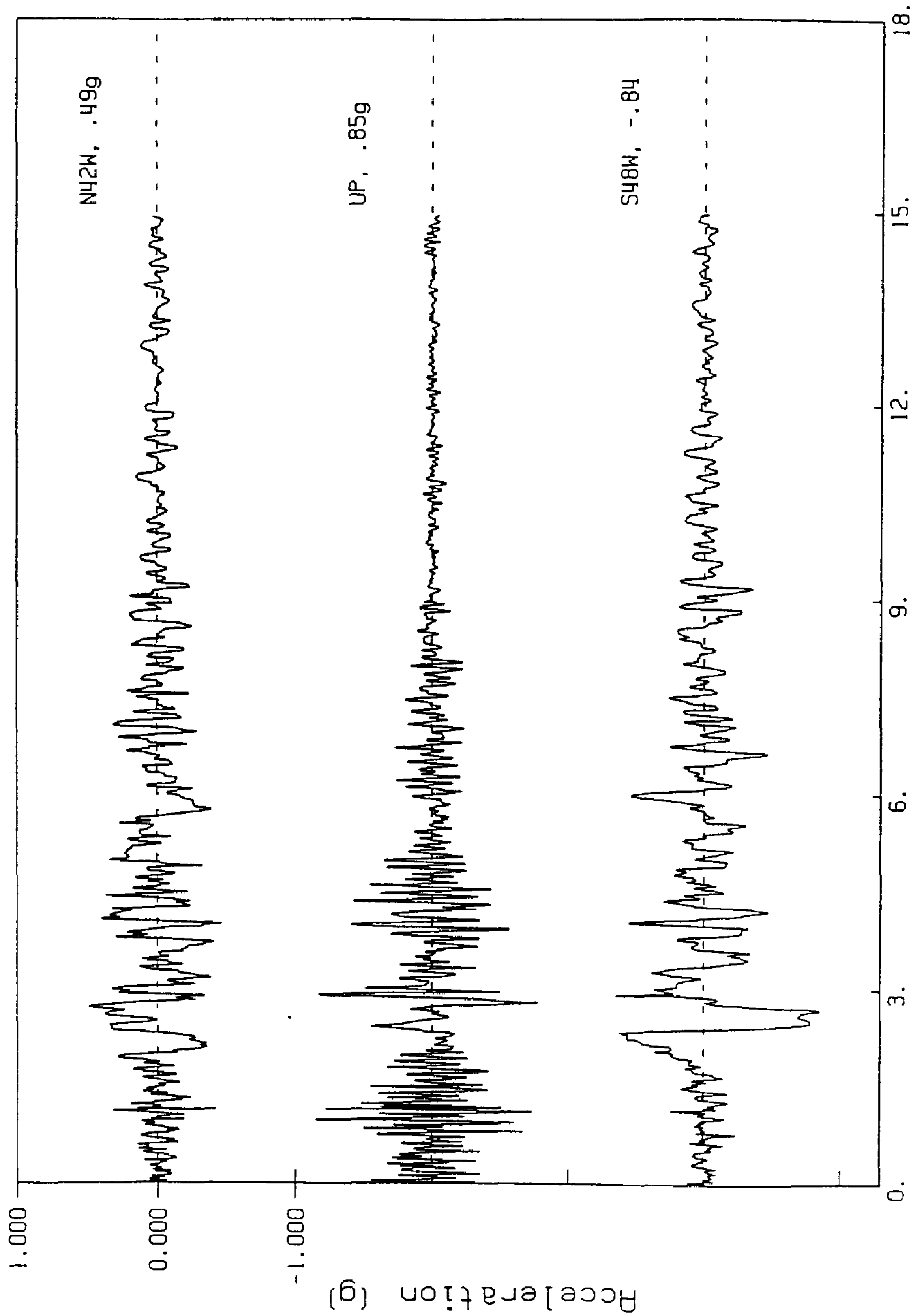

Figure 5. Time history of horizontal and vertical accelerations recorded at Rinaldi receiving station (station No.1 in Fig.2).

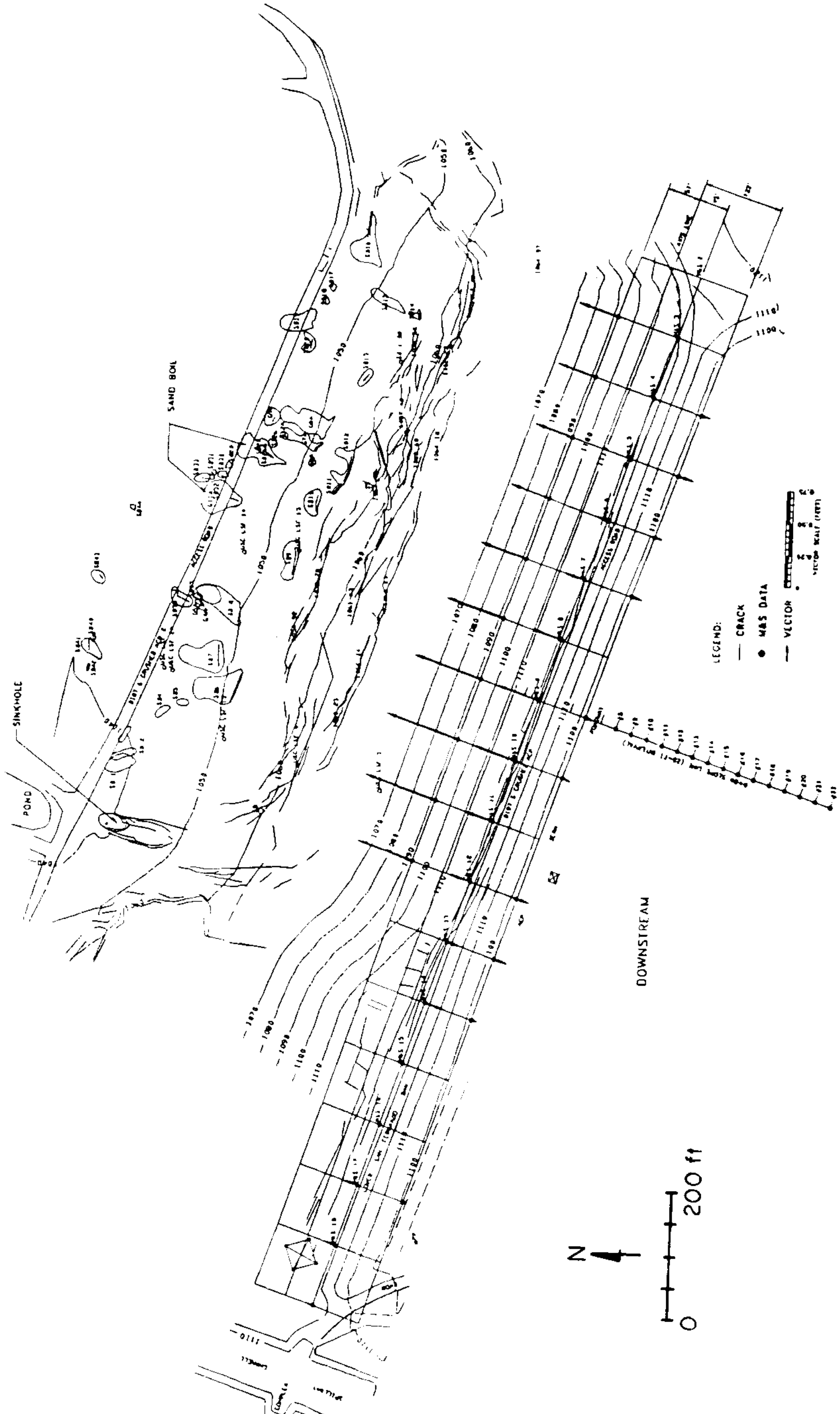

Figure 6. Location of cracks, sand boils, and displacement vectors in Lower San Fernando Dam.

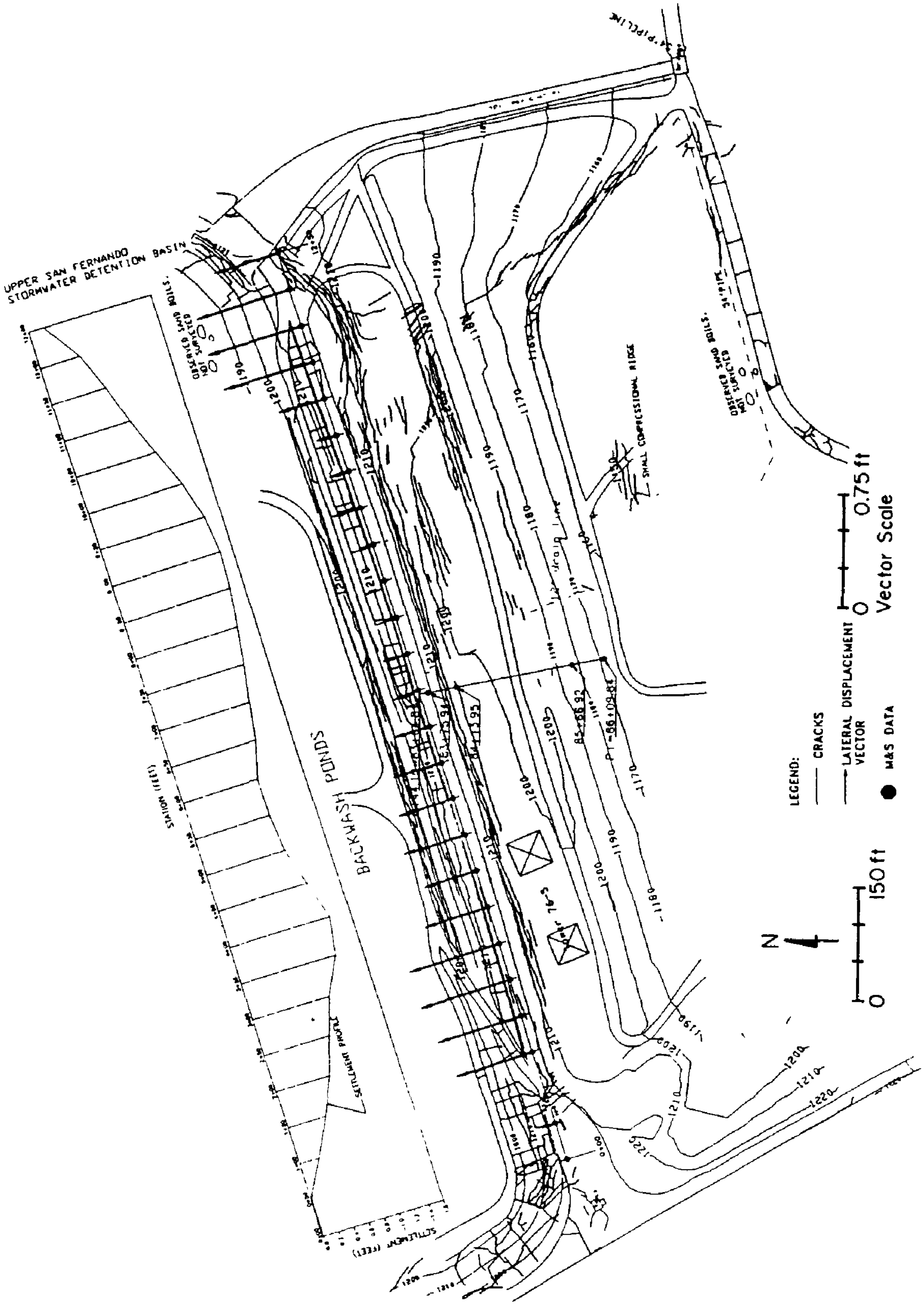

Figure 7. Location of cracks, sand boils, and displacement vectors in Upper San Fernando Dam.

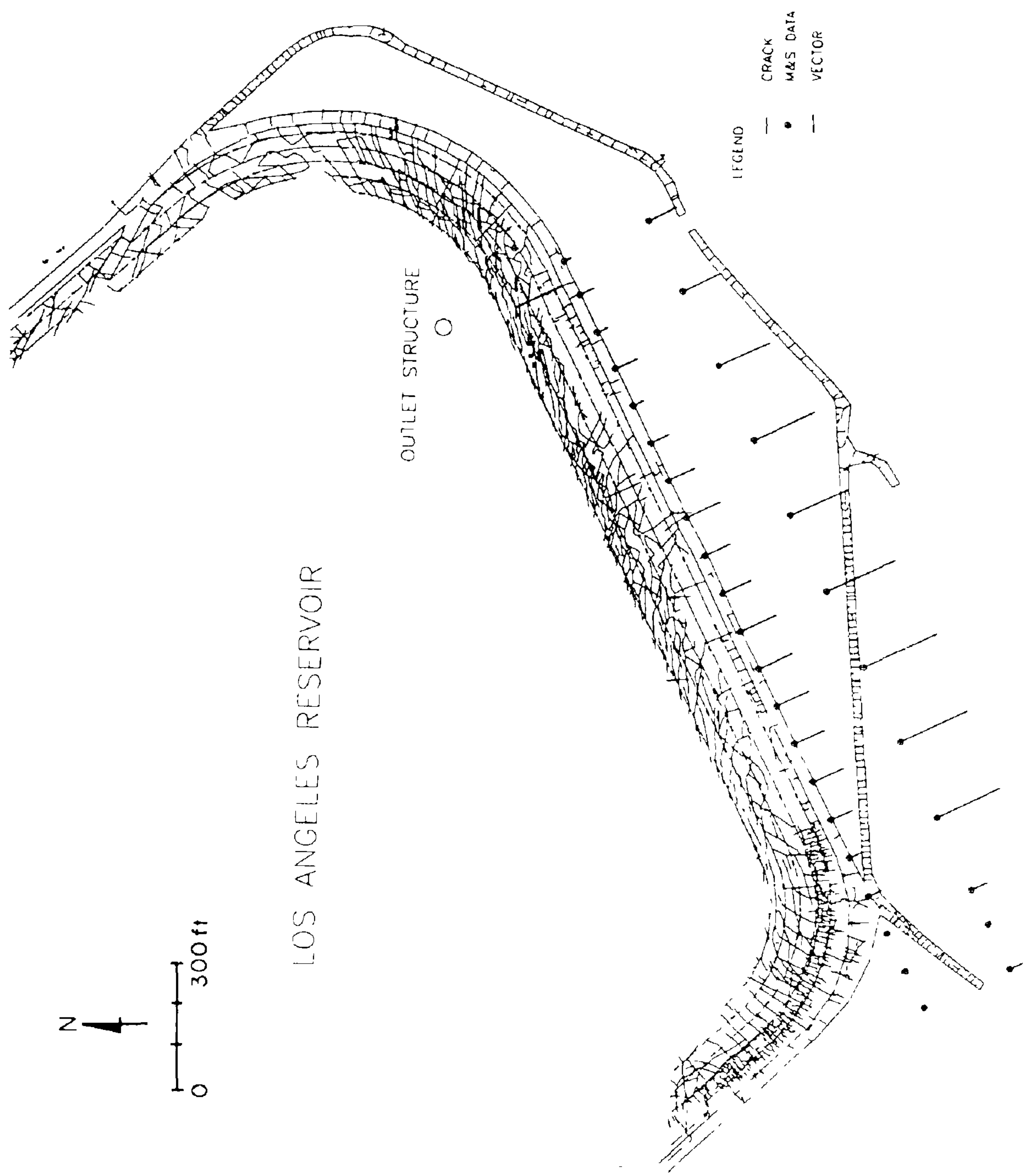

Figure 8. Location of cracks in Los Angeles Resevoir Dam.

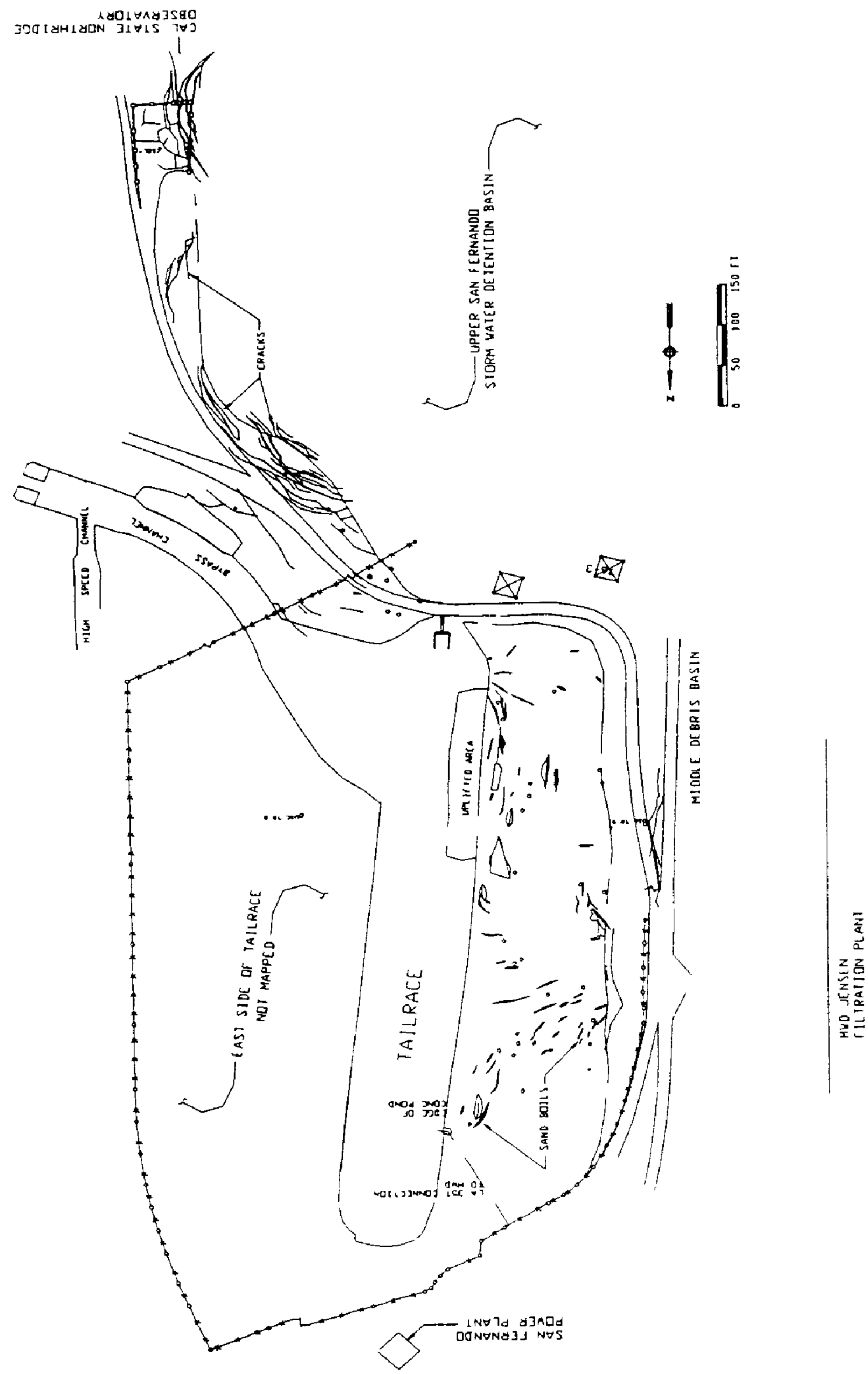

Figure 9. Location of cracks and sand boils in the vicinity of Power Plant Tailrace.