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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

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ABSTRACT

A 1981 earthquake generated liquefaction and other secondary ground effects at many localities within a 150 km^2 area north of Westmorland, California. Surface effects of liquefaction, including sand boils, fissures, slumps, lateral spreads, and ground settlement, spotted fields with sand and disrupted fields, roads, and canals with fissures and scarps. We specifically describe 22 localities where effects or damage were pronounced during the 1981 event. Similar effects were noted within or near this area after earthquakes in 1930, 1950, 1957, and 1979. The 1940 El Centro event also severely shook the area and could have produced ground effects that were unobserved or unreported. Secondary ground effects in this region have developed only in areas of late Holocene sedimentation, primarily areas inundated by 1905-1906 flooding from the New and Alamo Rivers and the concurrent rise of the Salton Sea. Sediment that liquefied during the 1930, 1950, 1957 and 1981 earthquakes are similar in mode of deposition and age to those that have been most susceptible to liquefaction in other parts of the world. All except one of the 1981 liquefaction sites were within a horizontal distance of 7 km from a surface projection of the estimated zone of seismic energy release. The one exception was slight rejuvenation of several sand boils that had previously erupted during the 1979 Imperial Valley earthquake. These sand boils were 12 km from the source zone The distances agree well with similar distances measured in other parts of the world.

INTRODUCTION

On April 26, 1981, a moderate-sized earthquake (M_L = 5.6, M_S = 6.0) struck the northwestern part of the Imperial Valley near Westmorland, California, causing an estimated 1 to 3 million dollars damage, primarily to structures in the towns of Westmorland and Calipatria. The shock generated Modified Mercalli Intensities as great as VII (Barnhard, L. M., 1982) and produced many liquefaction and other secondary ground effects over a 150 km^2 area north of Westmorland. Our field investigation began two days after the earthquake and included ground and low altitude aerial reconnaissance of the area between Brawley and the Salton Sea (figure 1). We drove upon nearly all of the roads in the area and visited all sites of reported damage to canals, roads, and fields. The locations of secondary ground effects were identified, plotted, and documented, and we describe 17 specific sites where effects or damage were particularly pronounced. Though additional ground effects may have been obscured by vegetation in fields and along rivers, enough effects were visible in open areas to provide an adequate basis for determining their type and general distribution. We have conducted additional investigations in which we drilled, sampled, and tested sediments at several sites where liquefaction effects occurred (Bennett and others, 1984).

We collected photographs and available information on secondary ground effects generated by the earthquakes in 1930, 1950, and 1957. We identified and located previous effects caused by liquefaction and compared them with the 1981 effects near the same locations.

GEOLOGIC AND SEISMOLOGIC SETTING

The Imperial Valley lies in the southern part of the Salton Basin, which was formed by the crustal rifting that opened the Gulf of California. Many of these tectonic processes are still very active and generate earthquakes at frequent intervals (Sharp, 1982), making the Imperial Valley one of the most seismically active areas in North America. More than 30 earthquakes with magnitudes greater than 5.0 have shaken the Imperial Valley in the past 50 years.

The area affected by secondary ground effects during the 1981 event as well as the 1930, 1950, and 1957 events lies in the northwestern part of the Imperial Valley between Westmorland and the Salton Sea (figure 1). The area is a former lake bottom which is now shallowly incised by the Alamo and New Rivers. Sporadically throughout Holocene time, flood waters from the Colorado River, which usually flow into the Gulf of California, have flooded the Imperial Valley intermittently forming a large lake and producing sedimentation along the Alamo and New Rivers. During flooding in 1905 and 1906, the Salton Sea formed and rose to the elevation marked on figure 1. During these floods, considerable channel cutting, deposition, and reworking of sediments occurred along the rivers, and a delta formed where the rivers emptied into the developing Salton Sea. The approximate extent of alluvial and deltaic deposition is marked on figure 1.

SECONDARY GROUND EFFECTS AT SPECIFIC SITES

During the 1979 Imperial Valley earthquake, sand boils and ground fissures developed at many locations (Youd and Wieczorek, 1982), including a few sites that are within 20 km of the 1981 epicenter. We examined those sites to determine if rejuvenation of 1979 effects had occurred and found reactivation only at the radio tower site (site 1, figure 1).

River Park Site. During the 1979 earthquake, hundreds of sand boils erupted and several fissures and slumps developed at River Park, near the New River in the southwest part of Brawley, California (Youd and Wieczorek, 1982, p. 231-233). That site is 16 km southeast of the 1981 epicenter and 14.2 km southeast of the nearest boundary of the estimated seismic source zone as mapped on figure 1. We re-examined that area in 1981 and found no rejuvenation of sand boils or fissures.

Wiest Lake Site. In 1979, several sand boils and ground fissures developed near a park and boat ramp on the east shore of Wiest Lake (Youd and Wieczorek, 1982, p. 233). That area is 14.8 km southeast of the 1981 epicenter and 11 km southeast of the estimated source zone. Remnants of the 1979 fissures and sand boils were clearly visible at the time of our visit, but there had been no rejuvenation during the 1981 shock.

Brawley Sewage Treatment Plant Site. During the 1979 event many small fissures developed on the New River flood plain near the Brawley Sewage Treatment Plant 3.5 km north of Brawley (Youd and Wieczorek, 1982, p. 242). That area is 14.0 km southeast of the 1981 epicenter and 11.5 km southeast of the estimated source zone. No fissures developed in that area during the 1981 event.

Site 1. During the 1979 earthquake, several sand boils expelled considerable volumes of water and sand and created a small pond in the New River flood plain about 100 m east of the KROP radio tower. Small fissures developed around that pond, and larger fissures developed at the margin of the river flood plain and locally in the adjacent bluffs (Heaton, and others, 1983, p. 1163; Youd and Wieczorek, 1982, p. 233). That site is 14.2 km southeast of the 1981 epicenter and 12.0 from the estimated source zone. During the 1981 event, small amounts of water and sediment spurted from several 1979-event sand boils, spotting the tops of the old sand-boil deposits with new sediment (figure 2). The slight rejuvenation of these sand boils indicates that shaking intensities were near the threshold for generating liquefaction in the underlying sediment during the 1981 event. Apparently this sediment had been left in a very susceptible condition by the previous occurrence of liquefaction. Because of the shorter distance from the source, peak ground acceleration at this site was probably slightly greater than the 0.18 g recorded at the Brawley instrument station (at Brawley Airport), which is 2.7 km southeast of the radio tower site (Maley and Ethridge, 1981 p. 13).

Site 2. Several fissures developed in dikes and roadway embankments around the northern end of Ramer Lake. These fissures were generally parallel with the road or dike and were characterized by vertical separations as great as 10 cm. The fissures indicate minor slumping toward the lake and a drainage ditch which are parallel to the road along the north edge of the lake. Small fissures were also in the east-west-trending dike that divides the lake into two segments. The largest fissures had openings of about 0.15 m; they were about 11 km east of the epicenter and 7.0 km east of the nearest part of the estimated source zone. Smaller fissures extended as far as 14.2 km from the epicenter and 7.4 km from the source zone and were the most distant fissures noted in this investigation.

Site 3. North of the Alamo River, about 4.5 km south of Calipatria, the pavement of State Highway 111 was slightly disrupted by ground fissures. These fissures produced noticeable roughness to passing traffic, but did not impair use of the road. At the northern margin of the flood plain, a fissure with a 5-cm-high scarp, down to the south, crossed the entire roadway and adjacent shoulders. That fissure was apparently caused by compaction of road fill or flood plain sediment. Another set of fissures were generally parallel to the road and fractured the pavement in the southbound lane and adjacent shoulder for 150 m. These fissures were arcuate in shape, concave to the northwest, with extensional and vertical separations as large as 3 cm. The shapes of these fissures indicate minor northwestward lateral spreading toward the Alamo River.

Several sand boils erupted along the northern edge of the highway shoulder forming deposits as much as 2 m in diameter. Some sand boils developed along fissures while others erupted through undisturbed ground. Additional boils and fissures may have occurred under the thick brush between the highway and the river but were obscured by the thick growth. Many fissures and small scarps developed within a few meters of the river north of the highway bridge (the only section of river we traversed at this site). The fissures, which generally paralleled the river, were as much as 30 cm wide with scarps as high as 20 cm facing the river. The shape and orientation of these features indicate minor slumping into the river channel.

Site 4. Numerous sand boils, fissures, and slumped banks occurred along both sides of a 3-km-long stretch of the Alamo River within the Imperial Wildlife Management Area. Sand boils and fissures extended as far as 100 m from the river but were more concentrated nearer the channel. At several places, segments of bank as wide as 5 m collapsed into the river. Figure 3 shows a vertical cross section exposed by a shallow trench we excavated through one of the sand boil deposits.

One area near several sand boils and a large river bank collapse has been drilled and tested to determine subsurface sediment characteristics and instrumented to monitor ground-motion and pore-water response during future earthquakes. Figure 4 shows a cross section of the sediment layers beneath the site (from Bennett and others, 1984, p. 20). Figure 5 shows the vertical and horizontal layout of the instruments and figure 6 shows the locations of soundings and borings made near the site by the USGS and other institutions to sample and test the sediments. A network of survey points has also been established at the site from which horizontal displacement of the ground surface can be determined after the next earthquake, and a slope-inclinometer casing has been set from which a profile of horizontal displacement versus depth can be determined.

Site 5. Several sand boils with deposits up to 1 m in diameter erupted along a series of cracks about 4 km southwest of Calipatria, about 25 m north of the Vail Canal and 200 m west of the Alamo River. The cracks and sand boils developed on a graded roadway and haystack area that is about 3 m higher in elevation than the fields immediately north of the road. We also searched those fields but found no sand boils or cracks.

Site 6. About 4.6 km southwest of Calipatria, more than 50 sand boils erupted in a field and on Vail Road which bounds the south edge of the field (figure 7). The sand boils were among the largest generated by the earthquake. In some instances, water from sand boils flooded several furrows for more than 100 m, a feat requiring several cubic meters of water. In one place (figure 8), the gush of water from the ground eroded and left open a 20-cm diameter tube, an action requiring many liters per second of flow. Although the amounts of flow were great, the amount of sediment carried to the surface was not particularly large, indicating high water to sediment ratios.

The Vail Canal, which is parallel to Vail Road and is a major water-supply artery for the region, ruptured and washed out near several sand boils at the eastern margin of the sand boil zone (figure 9). The breach diverted the full flow of the concrete-lined canal southward through the embankment and into a drainage ditch parallel to the canal. The washout of the embankment and its rapid repair (within hours of the earthquake) obliterated any evidence of ground failure. A probable cause of failure, however, is vertical or horizontal ground displacement of less than a few tenths of a meter, caused by liquefaction and consequential settlement, slumping, or lateral shifting of the ground. Such displacement could fracture the concrete lining and allow water to penetrate, rapidly flow through the lining, and wash the embankment into the nearby drain.

The sand boils and canal break lie within a zone bounded on the north by the curved line on figure 7. The curved shape of the line suggests that a former stream channel lies below the ground surface and that liquefaction of sediment deposited by that stream produced the sand boils. Further evidence of past fluvial activity at this site is a terrace with a curved scarp at the north end of the field (not visible in photo), which is an erosional feature produced during incision of the New River.

Site 7. A single large sand boil emitted a 20-m diameter deposit of sand and silt west of Calipatria at a locality about 200 m north of Eddins Road and 100 m west of English Road. No other ground effects were observed in the vicinity of this sand boil.

Site 8. Between 3.5 and 4.0 km west of Calipatria, several slumps developed in a steep, 5-m-high bank on the north side of the Alamo River. In one slump, about 10 m^3 of debris collapsed into the river channel. In other failures, arcuate fissures with vertical separations as large as 20 cm marked boundaries of the slumps. At several locations, these failures intersected and obstructed half of an unpaved farm road along the river.

Site 9. About 10 sand boils which left deposits as much as 1 m in diameter erupted on both sides of Brandt Road about 100 m north of the New River. We observed no other ground effects at that locality.

Site 10. Twenty or more sand boils which left deposits as much as 2 m in diameter erupted in the western part of a field bordered on the west by Kalin Road and on the north by Vail Road. This is the same field in which large sand boils erupted during an earthquake in 1930 as described in the next section. Nearly mature wheat growing in this field at the time of the 1981 shock obscured the ground surface and made surface reconnaissance difficult. We walked through part of the field in search of sand boils. At the west end of the field, near Kalin Road, we found the 20 sand boils noted above; none matched the size of those that erupted during the 1930 event. Several of the boils, near Kalin Road lie over a buried drainage ditch and liquefaction of the backfill may have produced those features.

Site 11. About 8 km west of Calipatria, a 500-m-long zone of scattered sand boils stretched across the southern half of a melon field on the south side of Eddins Road between Vail Laterals 3 and 3A. About 75 sand boils erupted in the group, most with diameters of about 1 m. We saw no fissures in this field, nor any sand boils or fissures in adjacent fields.

Site 12. About 20 sand boils erupted along fissures in the south bank of the New River about 200 m west of Gentry Road (Highway 30). The fissures were as wide as 20 cm, and sand boil deposits were as wide as 2 m. These fissures and boils were on a gently sloping flood plain about 0.5 m above river level. Additional fissures were pervasive along both sides of the river throughout this area. These fissures were caused by minor slumping or spreading of river banks toward the channel.

Site 13. Slumps with vertical displacement as great as 2 m were common along the south bank of the New River about 1.5 km west of Gentry Road. At that locality the river has incised about 5 m with steep banks on both sides of the river. We did not inspect the entire length of river bank, but our checks indicate that fissures and slumps with varying sizes were pervasive along the New River between Highway 111 and the Salton Sea.

Site 14. Between Walker Road and the New River, 4.3 - 5.3 km north of Westmorland, three groups of north-northeast-trending discontinuous fissures disrupted Martin Road and concrete-lined canals on both sides of that road (figure 1). The fissures transected alfalfa fields on either side of the road and canals. The mature alfalfa partially obscured the cracks and sand boils and required traverses by foot to trace out these features. The groups which commonly contained two or more parallel fissures formed zones as wide as 50 m and as long as 550 m. Sand boils erupted in several places along the fissures, primarily east of the road, including several that formed a coalesced deposit 4 m wide and 20 m long. The fissures were characterized by vertical and extensional separations as large as 20 cm and 10 cm, respectively. In several instances, the fissures bounded zones of ground settlement. Canal linings were fractured at two locations about 350 m apart where the fissures intersected the road and canals. Removal and replacement of concrete linings were required to repair these canals, but the fissures inflicted no significant damage to the unpaved road.

The lack of a consistent sense of displacement, the eruption of sand boils in some areas, and the generation of some features by ground settlement indicate that the fissures were caused by secondary ground failure rather than faulting. Such secondary features are common in areas underlain by sands that liquefy and compact. The length and linearity of many of the cracks are somewhat unusual for secondary fissures; however, such linearity may occur where the underlying sediment body that produces the secondary effects is also long and linear. In this instance, the fissures are near the New River and a former shoreline of the Salton Sea where channels, deltas, or beaches could have generated long linear bodies of granular sediment.

Several additional small fissures crossed Walker Road about 200 m west of Martin Road and about 300 m south of the fissures described above. These fissures were at most 25 m long and generally trended in a north-northeast direction; however, a few fissures paralleled the road. Most of these fissures were hairline cracks and none was more than 1 cm wide. Sand boils did not erupt at this locality. The localized extent and the parallel trend indicate that these fissures have a secondary origin similar to the larger fissures to the north.

Site 15. About 2.7 km northwest of Westmorland, lateral spreading disrupted the pavement on Lack Road about 100 m south of Bannister Road (figure 10). The spreading resulted in a few tenths of a meter of displacment of the road toward a 5-m-deep drainage ditch. Several arcuate fissures cut across the the bank of the drainage ditch and into the east side of the paved road; the largest of these fissures left an open crack 22 cm wide in the asphalt pavement. A few of the arcuate fissures crossed the road and died out in a wide shiulder to the west. A single linear fissure that extended across the pavement in a south-southwest direction marked the southern margin of the failure zone. The pavement was down 5 cm on the north and slightly buckled across this fissure (figure 10). We observed no other secondary effects, such as sand boils, at this site.

The spreading most likely was caused by soil weakening due to liquefaction. An estimate of ground motions at this site is provided by the strong-motion record made at Westmorland 2.8 km to the southeast; that record has a peak horizontal acceleration of 0.49 g (Maley and Ethridge, 1981). These accelerations are strong enough to produce liquefaction in most moderately susceptible sediments, but they probably were not strong enough nor of sufficient duration to produce the displacements observed here without soil weakening (R.C. Wilson, oral commun., 1981).

Site 16. A hundred or more sand boils erupted in an area centered on Kornbloom Road, 14 km west of Calipatria (figure 1). The sand boils were widely scattered but generally occurred in poorly defined bands. Some boils erupted along short ground fissures, whereas others erupted at random in the field. Sand boil deposits were as much as 15 m in diameter (figure 11). These deposits, being composed of silt and fine sand, are unusually fine-grained. Figure 12 gives grain-size distribution curves for samples from two of the finer of these deposits.

Site 17. About a hundred small sand boils and many small fissures developed in a field in the southwest quadrant of the intersection between Walker and Burchard Roads (7 km northwest of Westmorland). Most of the sand boils and fissures were in a 700-m-long and 300-m-wide zone extending southwestward from Walker Road to the midpoint between Burchard and Baker Roads. Only about 10 of the sand boil deposits in this zone exceeded 1 m in diameter and most had diameters of less than 0.15 m diameter (figure 13). Fissures were as long as 100 m and vertical separations were as large as 10 cm. Most of the fissures trended northwest, but there were many variations from that trend. A second area where fissures and sand boils developed was over a filled drainage ditch that trended north-northwest across the west end of that field. The bounds of the former ditch were marked by two parallel continuous fissures. Displacements across these fissures were consistently downward toward the buried drain, indicating settlement of the fill, with separations as wide as 15 cm. Sand boils with deposits as much as 1 m in diameter erupted sporadically over the buried drain.

Canal damage. In addition to the major break in the Vail Canal at Site 6, fracture and buckling of concrete linings disrupted irrigation canals at the locations marked on figure 1. The probable cause of much of this damage is small differential ground displacements within or beneath the embankments. In a few instances, small open fissures near the canal damage confirmed a ground-failure origin for the damage.

The 1981 damage to canals is similar to canal damage caused by small ground failures during past earthquakes, particularly the 1979 Imperial Valley and 1940 El Centro events (Youd and Wieczorek, 1982; Sylvester, 1979) In nearly all instances the 1940, 1979 and 1981 damage occurred in areas of recent (last 500 years) sedimentation or reworking of sediments, where ground failure is most likely to occur. The 1981 damage occurred almost exclusively in areas inundated during the 1905-06 floods and areas west of Westmorland where remnant rills and washes show on 1937 aerial photographs. This set of photographs is the earliest of the area and predate most of the land-leveling operations that have subsequently obliterated most of these features. The rills and washes were caused by sheet flooding after the evaporation of Lake Cahuilla, possibly during the 1905-06 floods. Lake Cahuilla covered the area between 400 and 1,200 years ago (Van De Kamp, 1973). The high correlation between sites of canal damage and recent sedimentation provides further indication that the canal damage was caused by ground failure.

Other areas investigated. Reconnaissance investigations were made by driving most roads and flying over the entire area extending northward from Highway 86 and westward from Wiest Lake to the Salton Sea. During these excursions, fields and other open areas were visually examined for signs of fissures, sand boils, and other secondary effects. The only secondary features we saw in addition to those noted above were small fissures, generally less than 5 cm wide, which developed parallel to steep banks along roads, canals, drainage ditches, etc. These fissures were pervasive along these steep banks within and near the seismic source zone.

As mentioned previously, crop cover obscured most of the area and possibly many ground effects. We did observe sufficient effects in open fields and along roadways and canals to determine adequately the types of effects generated and their general distribution. It is unlikely that any very large or damaging effects escaped our attention unless they were hidden beneath the southern tip of the Salton Sea.

PAST OCCURRENCES OF LIQUEFACTION

1930 earthquakes. On February 25, 1930, an earthquake centered north of Westmorland produced Rossi-Forel Intensity of VIII over a small area (Neumann and Bodle, 1932). A similarly intense but less widely felt aftershock struck the same area on March 1. The February 25 event generated several large sand boils in the open field shown in figure 14. This same field contains Site 16 where smaller sand boils erupted in 1981. At that time, nearly mature wheat obscured the field and could have hidden many sand boils from our view, but probably none as large as those which erupted in 1930. No other information is given on occurrences or distribution of sand boils or other secondary ground effects of the 1930 event.

1950 earthquakes. Several earthquakes shook the Calipatria-Westmorland area during July and August of 1950. Two of these events generated sand boils and fissures along the Vail Canal southwest of Calipatria (figure 1). For the July 29 event Murphy and Ulrich (1952) reported, "Numerous sand boils were formed, irrigation ditch banks sloughed, and ground settled and cracked 1 to 2 miles (1.6 to 3.2 km) southwest of Calipatria." For the August 1 event they reported, "A few bricks fell and ground fissures opened wider in the vicinity of North End Dam and Vail Canal....Additional earth boils were started in the areas previously affected, mostly at the dam site and along the levees of the Vail Canal." These two events were given respective Rossi-Forel Intesities of VII and VI by Murphy and Ulrich. Photographs and notes collected by the Imperial Irrigation District give locations and show the character of these effects. One of many sand boils generated by this event is shown in figure 15.

1957 earthquake. On April 25, 1957, a magnitude 5.2 event shook the Westmorland-Calipatria area, generating sand boils in an area near the Salton Sea. Notes and photographs taken by the Imperial Irrigation District give locations and show the character of these features (figure 1). C.R. Allen (California Institute of Technology, unpublished notes) described the sand boils as follows: "Ground effects of the April 25th earthquakes were most noticeable about 7 miles west of Calipatria. No throughgoing fractures were formed, but sand boils erupted over an area of about 5 square miles near Pumice Island, the southwesternmost of three obsidian buttes (not now islands) on the south shore of the Salton Sea. The most severe surficial effects appeared to be in Section 4, T. 12 S., R. 13 E. The sand boils were shallow craters, seldom with a relief of over one foot, from which water and sand issued during and shortly after the earthquakes. In many cases, alinenment of the small craters over distances of a few tens of feet suggested fracture control. Although initial press reports indicated that the area was being 'flooded by salt water,' sand covered less than 25% of even the most heavily stricken fields, and the water was no saltier than would be expected at depths of 5 to 10 feet. Sand boils were most abundant in fields that had recently been heavily irrigated. The extent of damage to the young cotton crop is as yet unknown, but the Imperial Irrigation District suffered several thousand dollars worth of damage to irrigation and drainage ditches from slumping of side walls in this same area."

Other earthquakes. Several other earthquakes have shaken the Imperial Valley strongly enough to generate sand boils and fissures, and some effects may have occurred in the Westmorland-Calipatria vicinity but were unobserved or unreported.

The May 18, 1940, El Centro earthquake (M 7.1) is the largest earthquake on record in the Imperial Valley. The seismic energy for that event was generated by a 60-km-long rupture on the Imperial Fault. The northern terminus of the rupture was about 10 km southeast of Westmorland. Very little investigation was made of secondary effects generated by that shock, and no ground effects were reported north of Brawley (Sylvester, 1979). The ground motion should have been sufficiently intense, however, to generate liquefaction in susceptible deposits throughout most of the Imperial Valley, including those in the Westmorland-Calipatria area.

On June 13, 1953, a shock with maximum Modified Mercalli Intensity of VII struck the area south of Westmorland. Murphy and Cloud (1955) reported the following ground effects: "Press reported some damage occurred to the Thistle Lateral Canal (3 miles south of Westmorland) where one of the canal structures was damaged and a half mile of canal bank cracked. Tokay Canal near the Dahm Ranch was cracked and there was considerable settlement of the ground. A landslide along Tamarack Road near the New River Bridge blocked off the road for several hours." No sand boils were reported from that event.

On April 9, 1968, a magnitude 6.4 earthquake struck the Borrego Mountain area, which lies west of the Salton Sea. The earthquake ruptured the Coyote Creek fault northwestward from a point about 35 km west of Westmorland. The shock was felt throughout the Imperial Valley, generating ground settlement in a field 22 km west-northwest of Westmorland and small sand boils along the New River 25 km south of Westmorland (Castle and Youd, 1972). As in the 1979 case, this shock may have generated other minor ground effects in the Westmorland-Calipatria area, but none was reported and no search was made. The October 15, 1979, Imperial Valley earthquake (M_L = 6.5) generated sand boils and ground cracks at several locations along the New and Alamo Rivers north of Brawley (Youd and Wieczorek, 1982). Minor effects may have developed in the Westmorland-Calipatria area, but none was reported and no specific search was made.

DISTRIBUTION OF LIQUEFACTION EFFECTS

Two basic factors control the distribution of liquefaction effects during earthquakes: (1) the distribution of materials susceptibile to liquefaction, and (2) the aerial extent of strong ground shaking.

Materials most susceptible to liquefaction are recently deposited sands and silts that are water saturated. All the liquefaction effects described above occurred in areas of recent sedimentation, including lowland areas near the Alamo and New Rivers and areas inundated in the past few hundred years by the Salton Sea. In most instances, the effects were in areas where fluvial, deltaic, or lacustrine deposition occurred during the floods and lake rise of 1905-06. Thus, many of the sediments that liquefied were probably less than 80 years old and all of them were late Holocene in age. In the epicentral region, surface effects of liquefaction occurred only in a small fraction of the area of recent sedimentation, however, and very few effects were found in the more elevated areas where surficial sediments are a few hundred years older. These sediments apparently are either too compact, cemented, or clay-rich to liquefy and generate surface disturbances under shaking intensities produced by the 1981 earthquake. These results are in agreement with previous findings (Youd and Perkins, 1978; Youd and Wieczorek, 1982).

Intensity of shaking and severity of liquefaction effects are generally greatest near the seismic energy source zone. To estimate the zone of seismic energy release, we plotted epicenters of aftershocks that occurred in the first 6 hours after the main shock and drew a bound around the area containing the greatest concentration of the epicenters (figure 1). The estimated zone also includes a smaller area beneath which a swarm of small earthquakes occurred shortly before the main shock. Twenty minutes after the main shock, a magnitude 4.2 event followed by several smaller aftershocks occurred a few kilometers southwest of the marked zone; also several aftershocks occurred northwest of the marked zone several hours after the main shock. The zone on figure 1 excluded these additional epicenters because they appeared to be appendages of the main zone and probably were outside the main area of seismic disturbance. More detailed analysis of aftershock data and the zone of seismic energy release is beyond the scope of this study. All of the major liquefaction effects developed within 7 km of the estimated source zone, where we define major effects as ground fissures with more than 0.1 m displacement and sand boils with deposits greater than 1 m in diameter. The farthest minor liquefaction effect we observed was the slight rejuvenation of sand boils at Site 1, 12 km from the estimated source zone. These distances agree well with published correlations of distance-to-liquefaction effects versus earthquake magnitude. The datum from the 1981 earthquake is plotted on figure 17 along with data compiled by Youd and Perkins (1978) where it agrees well with the expected maximum distance for M_S = 6 event.

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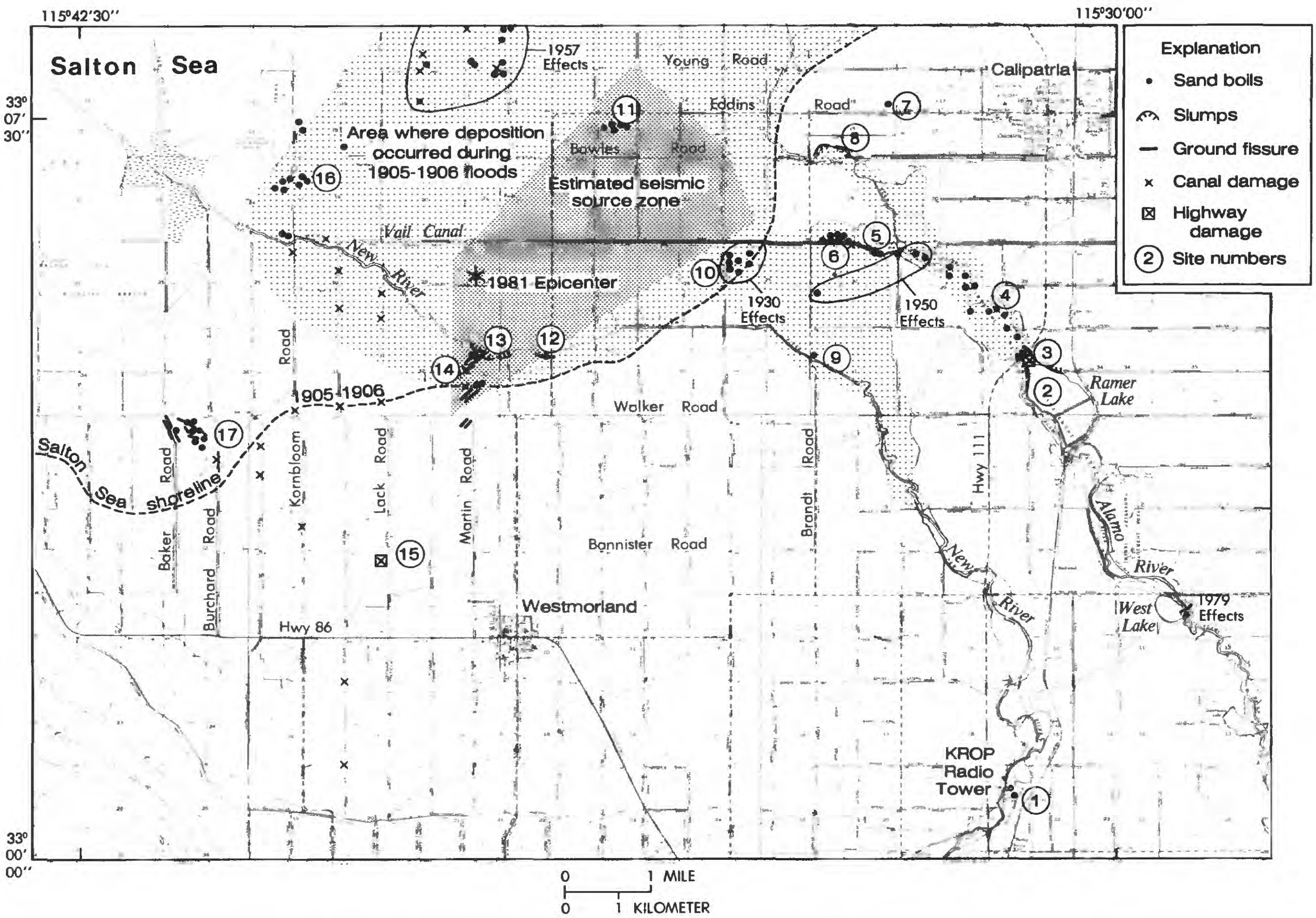

Figure 1. Map of epicentral area showing place names, localities of sites described and localities of other damage, areas of 1905-06 flooding, and the seismic source zone we estimated from aftershock locations.

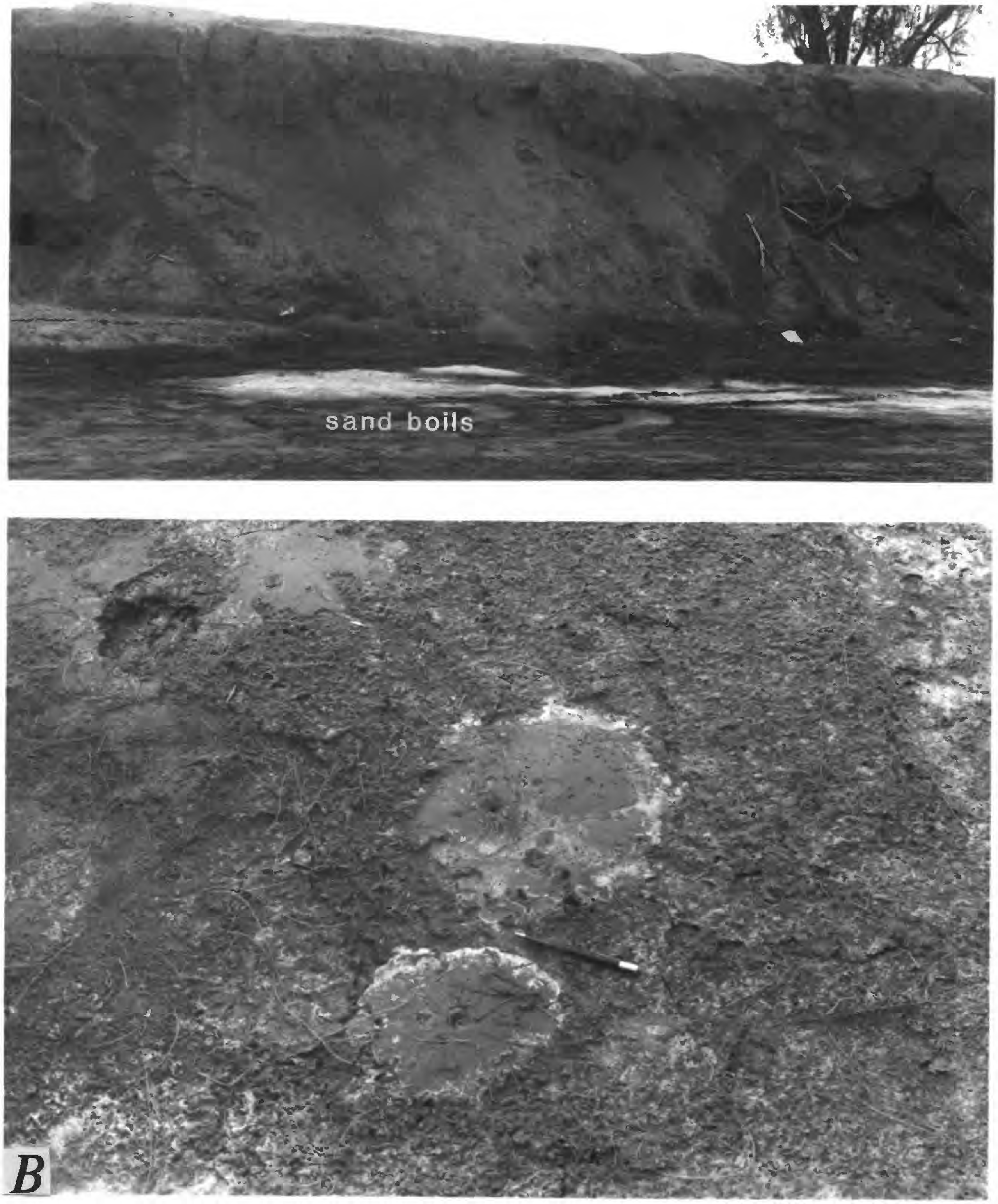

Figure 2. (A) Sand boils (white patches on photo) generated by 1979 Imperial Valley earthquake which (B) slightly reactivated and spotted the ground surface with water during the 1981 earthquake (site 1). Pencil is 13.7 cm long.

Figure 3. Vertical section through sand boil in Imperial Wildlife Managmemnt Area showing horizontal layers of sand boil deposit and funnel-shaped spout through which sediment was ejected. (Photograph by M. J. Bennett).

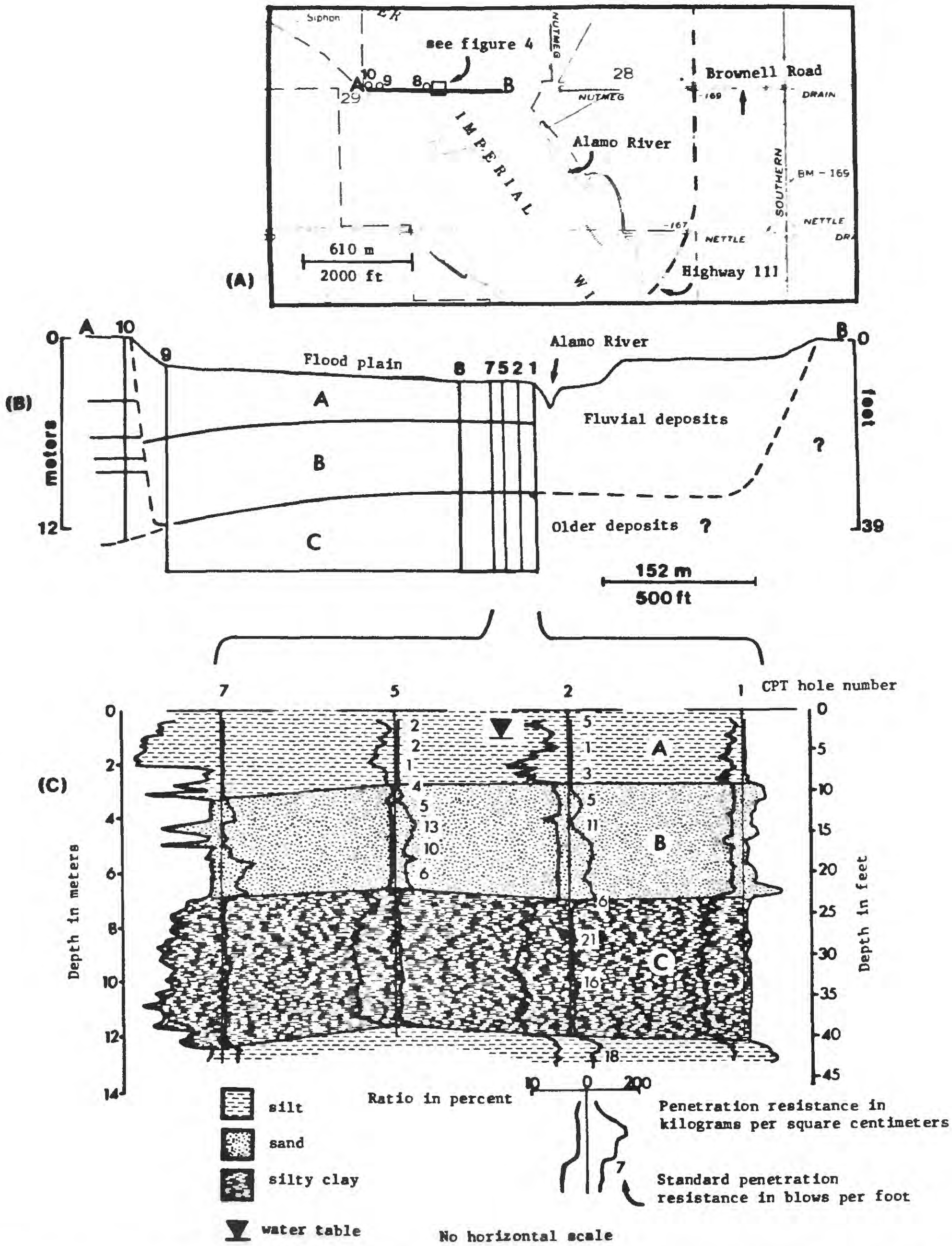

Figure 4. Map and cross section showing location and sediment layers at Wildlife instrument site (site 4, figure 1). (A) shows the location of the site within the flood plain fo the Alamo River. (B) shows a general cross section across the flood plain. The dashed line represents the approximate boundary between fluvial and the pre-channel deposits. (C) shows a detailed cross section in the area of the instrument station. (After Bennett and others, 1984).

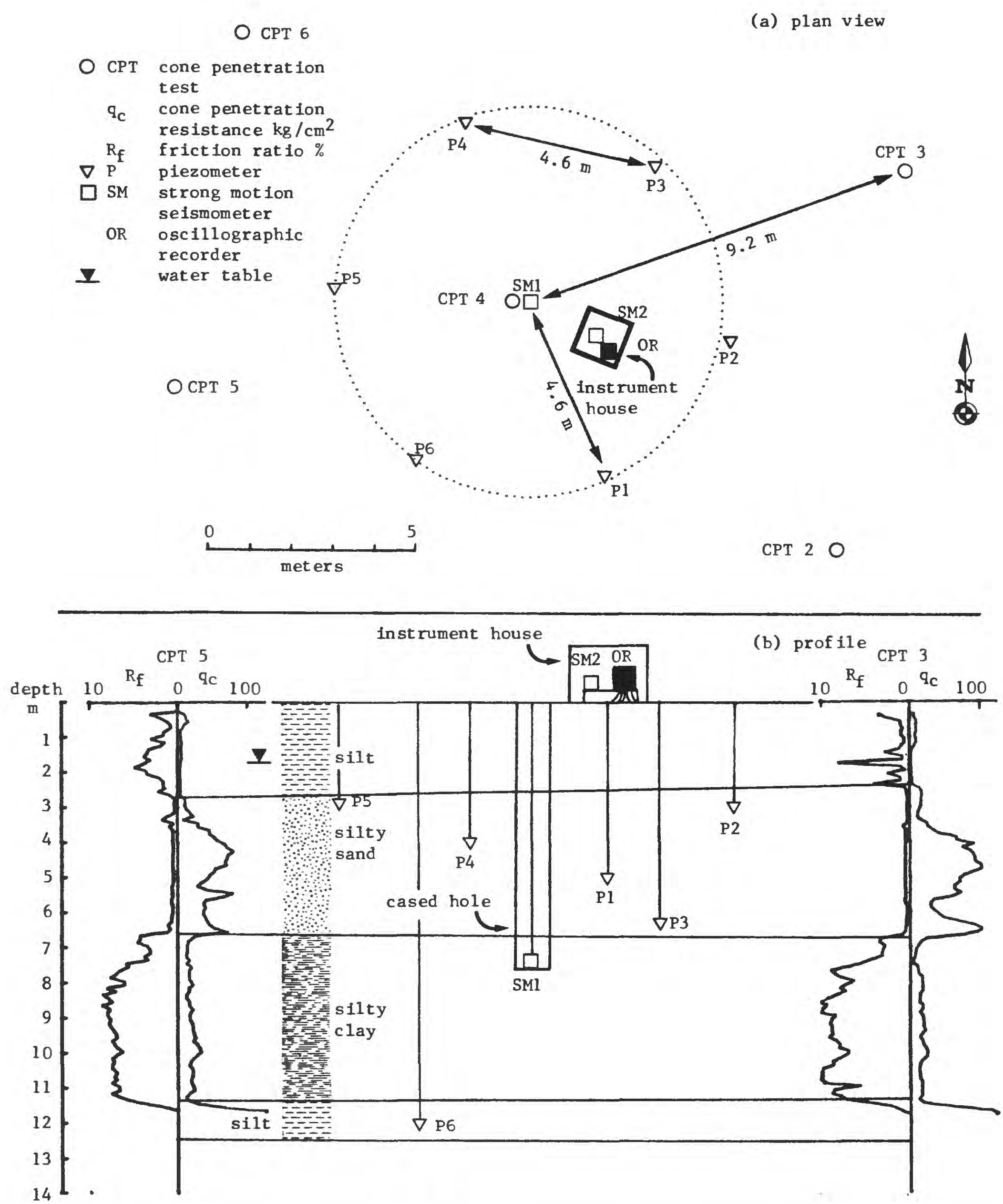

Figure 5. Map and cross section at Wildlife site (site 4, figure 1) showing location of instruments set to measure ground and pore-water response during future earthquakes. (After Bennett and others, 1984).

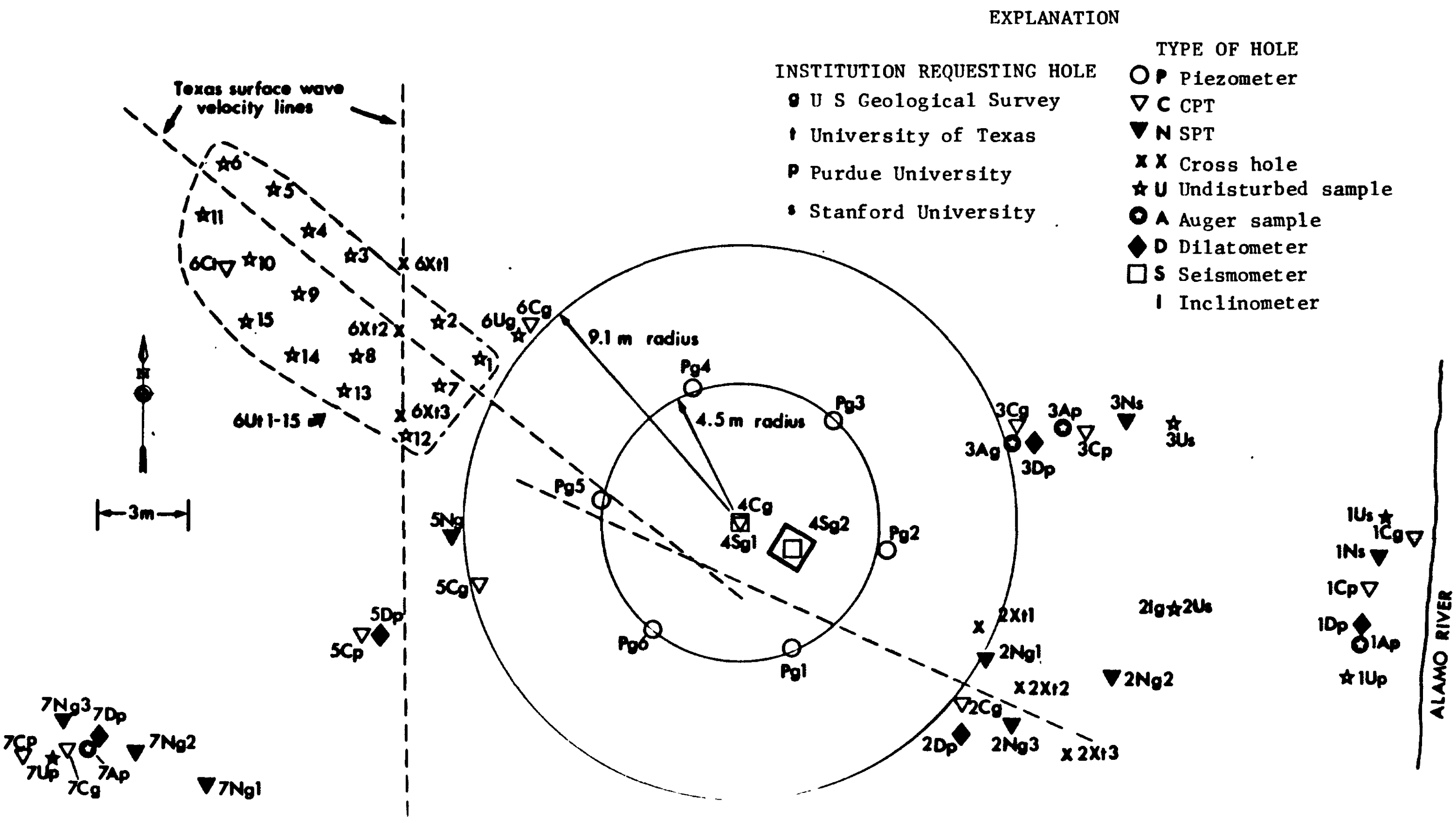

Figure 6. Map showing arrangement of Wildlife site and sounding and drilling locations occupied by various investigators during 1982 and 1983. (After Bennett and others, 1984).

Figure 7. South-southeast view showing sand boils, some of which discharged large quantities of water, and location of breach in Vail Canal (Site 6). The dashed line indicates approximate bound of zone within which sand boils erupted.

Figure 8. Sand boil near Vail Canal (Site 6) that discharged a gusher of water and eroded a 20-cm diameter tube. The small amount of deposited sediment here indicates that the water-to-sediment ratio for this sand boil was very high.

Figure 9. Photograph taken shortly after the 1981 earthquake showing washout in Vail Canal at Site 6. (Photograph courtesy of Imperial Valley Press).

Figure 10. View of Lack Road showing fissures that disrupted pavement (Site 15). The disturbance was caused by lateral spreading toward drainage canal at left edge of photo.

FIGURE 11. View of a 10- to 15-m diameter sand boil deposit about 100 m east of Kornbloom Road (Site 15); this is one of the largest sand boils that erupted during the 1981 event. (Photograph by John Sarmiento.)

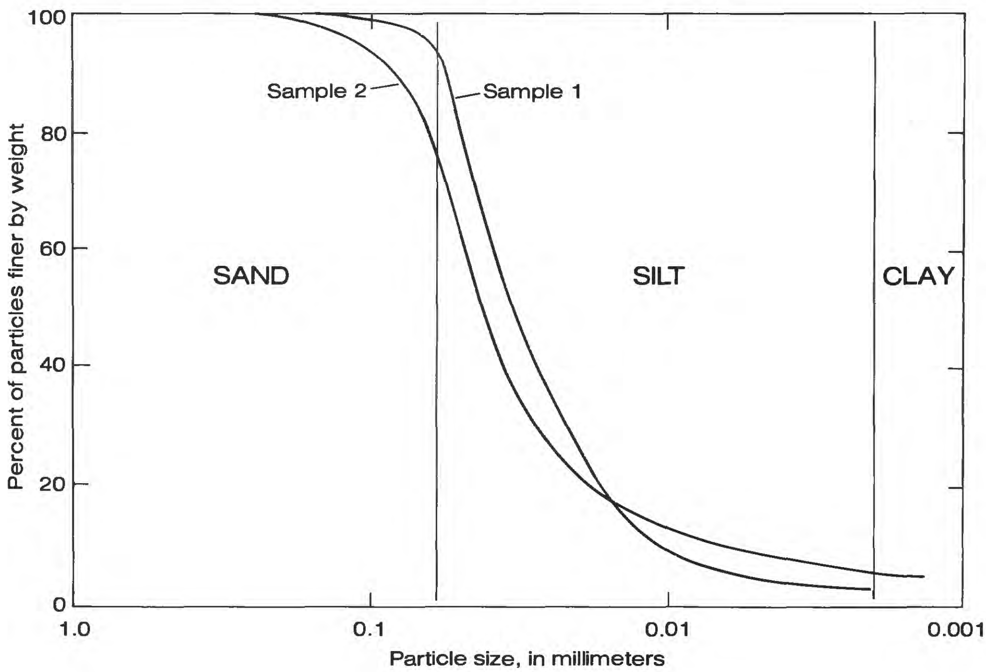

Figure 12. Grain size distribution curves for samples taken from two sand boil deposits near Kornbloom Road.

Figure 13. View of small sand boils that erupted in a field near the west end of Walker Road (Site 16). About 100 small sand boils erupted in that field.

Figure 14. Sand boils that erupted during earthquake of February 25, 1930, near Site 8. Other than near the far west end, where some 1-m diameter sand boils erupted, crop cover prevented reconnaissance of this field in 1981. (Photograph from files of Imperial Valley Irrigation District.)

Figure 15. Sand boils that erupted during earthquake of July 29, 1950, between Sites 4 and 5. (Photograph from files of Imperial Valley Irrigation District.)

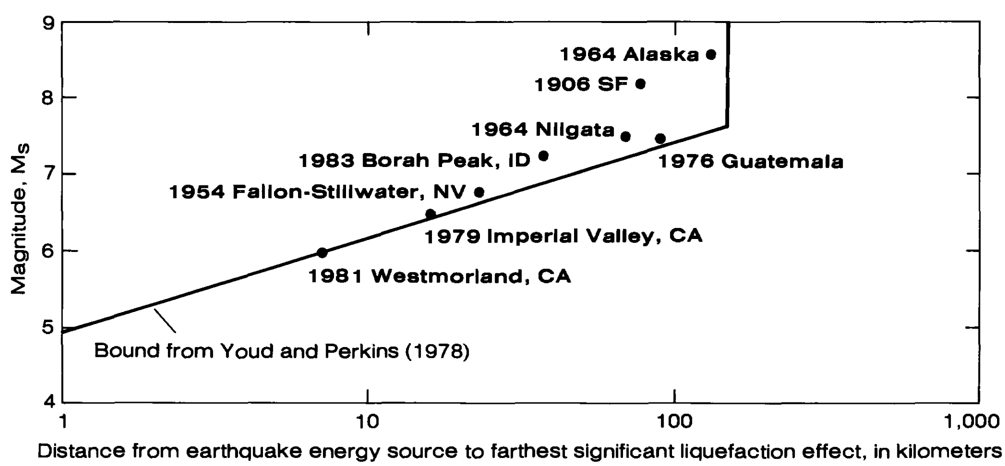

Figure 16. Distance from seismic energy source to farthest significant effect of liquefaction versus earthquake magnitude (M_S) for several past earthquakes and the 1981 event.