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QUATERNARY FAULTS AT SAN DIEGO BAY, CALIFORNIA

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Work done in cooperation with Scripps Institution of Oceanography

Abstract.—Acoustic-reflection profiles of subbottom strata reveal numerous faults that cut Quaternary deposits within and directly outside of San Diego Bay. These faults, together with previously mapped onshore faults, constitute the Rose Canyon fault zone that forms the local west boundary of the Santa Ana tectonic block, which is bounded on the east by the Elsinore fault zone. The minor earthquakes that have been felt in San Diego during historic time and accurately recorded during the past 41 yr are too infrequent to explain the observed rate of slip. The principal faulting is inferred to take place during moderate earthquakes similar to previous ones recorded along the west side of the Santa Ana block in 1933 at Long Beach, Calif., and in 1956 at San Miguel, Baja California. The known magnitudes of these previous events suggest that earthquakes in San Diego could attain a magnitude of approximately 6.5. An offset of the coast at Point La Jolla, when divided by the offset associated with previously studied earthquakes of magnitude 6.5, suggests that such events occur there at an average of approximately once every 600 yr.

The San Diego embayment contains Cretaceous, Tertiary, and Quaternary strata (Kennedy and Moore, 1971). These strata are generally nearly flat lying but are locally folded and cut by normal and right-lateral faults within a deformed belt that parallels the northwest-trending axis of San Diego Bay. This deformed belt, called the Rose Canyon fault zone, is exposed southeast of San Diego Bay in California and Baja California beside the delta of the Tijuana River (Ziony, 1973) and is especially well exposed in hilly terrain northwest of the bay (Kennedy, 1969).

In the present investigation, acoustic-reflection methods were used aboard a Scripps Institution of Oceanography vessel to map the faults under San Diego Bay and under the adjacent bight outside Silver Strand barrier beach. Navigational fixes, by horizontal sextant angles, had a maximum error of 100 m within the bay and 300 m outside the bay. The sound source for the survey was a spark array with 60 electrodes that reached a subbottom penetration of about 200 m. Discharge of 5 J at each electrode reduced reverberation and allowed stratigraphic resolution of about 1 m.

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FAULT PATTERN

The subbottom survey of the bay and bight revealed many faults. In fact, so many faults exist that we found it difficult to correlate the smaller ones from track to track, despite an average profile spacing of about 500 m in the bay and 1 km in the bight. The most conspicuous faults revealed by the survey are plotted in figure 1, and selected profiles are reproduced in figure 2.

In the bight, most faults extend up to the sea floor, a truncated surface generally overlain by virtually no Holocene deposits (fig. 2, profile *C–C′*). Most of the faults, which trend slightly east of north (fig. 1), show displacement downward to the east toward the San Diego structural basin, which is centered offshore near the city of Imperial Beach. Within San Diego Bay, the fault pattern includes several conspicuous northwest-trending fault strands. At some crossings of these strands as well as at some faults in the bight, the deformation bears features suggestive of strike-slip displacement, such as minor fault-bounded anticlines, chevron-shaped dilational synclines, and other complex folds that are not in harmony with dip-slip drag.

Faults such as La Nacion fault to the east of San Diego Bay (Artim and Pinckney, 1973), while possessing similar trends, have a mirror-image sense of displacement, downfaulted toward the bay and the San Diego structural basin (fig. 3). The regional array of faults in the San Diego area suggests that the pattern of the Rose Canyon fault zone broadens and becomes en echelon at the San Diego basin. The downfaulting toward San Diego Bay from both sides is clearly related to the origin of the bay and of the structural basin. We believe that the basin is an area of tension at a junction between right-stepping strands of the right-lateral fault zone.

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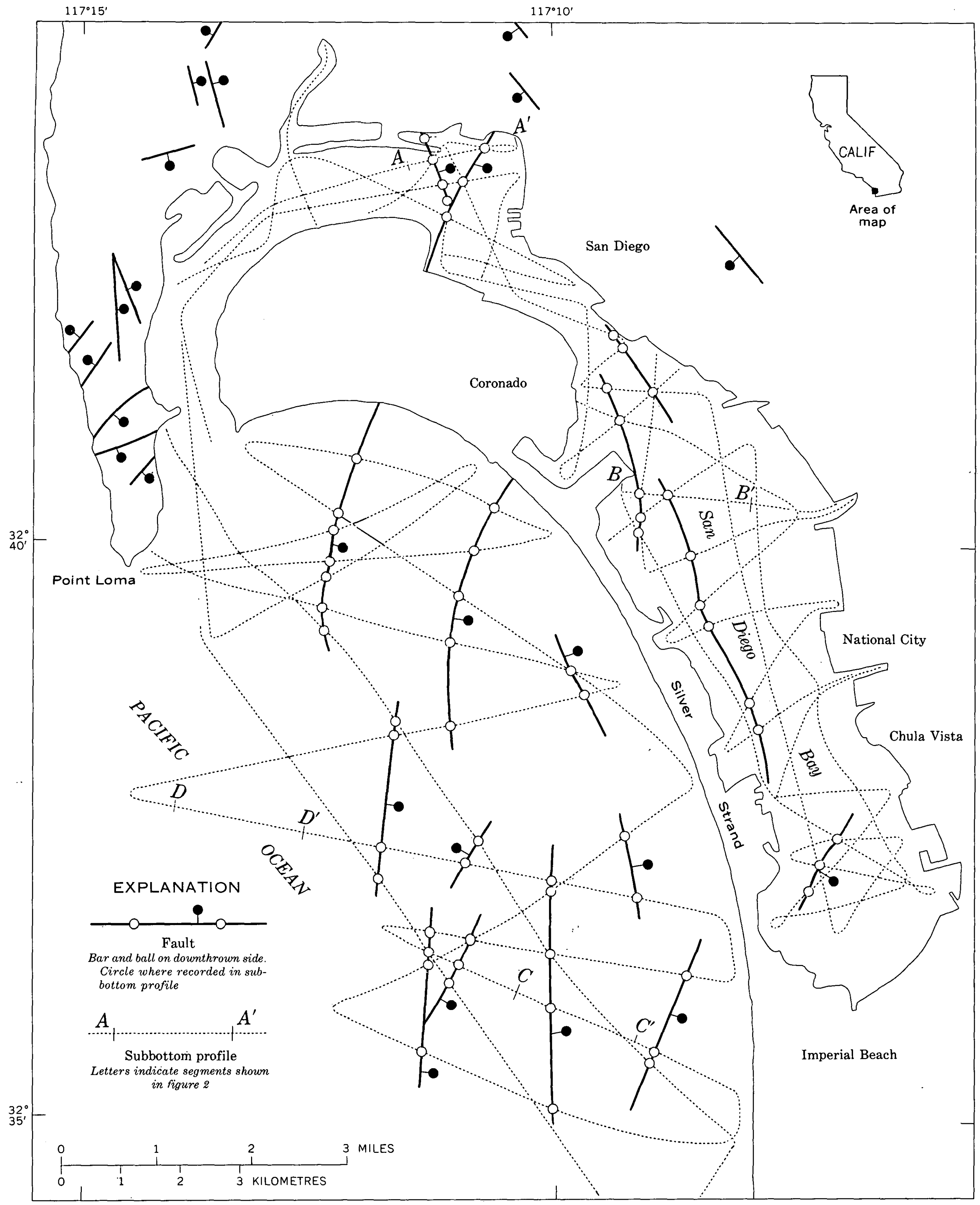

FIGURE 1.—Location of conspicuous faults on floor of San Diego Bay and adjacent areas.

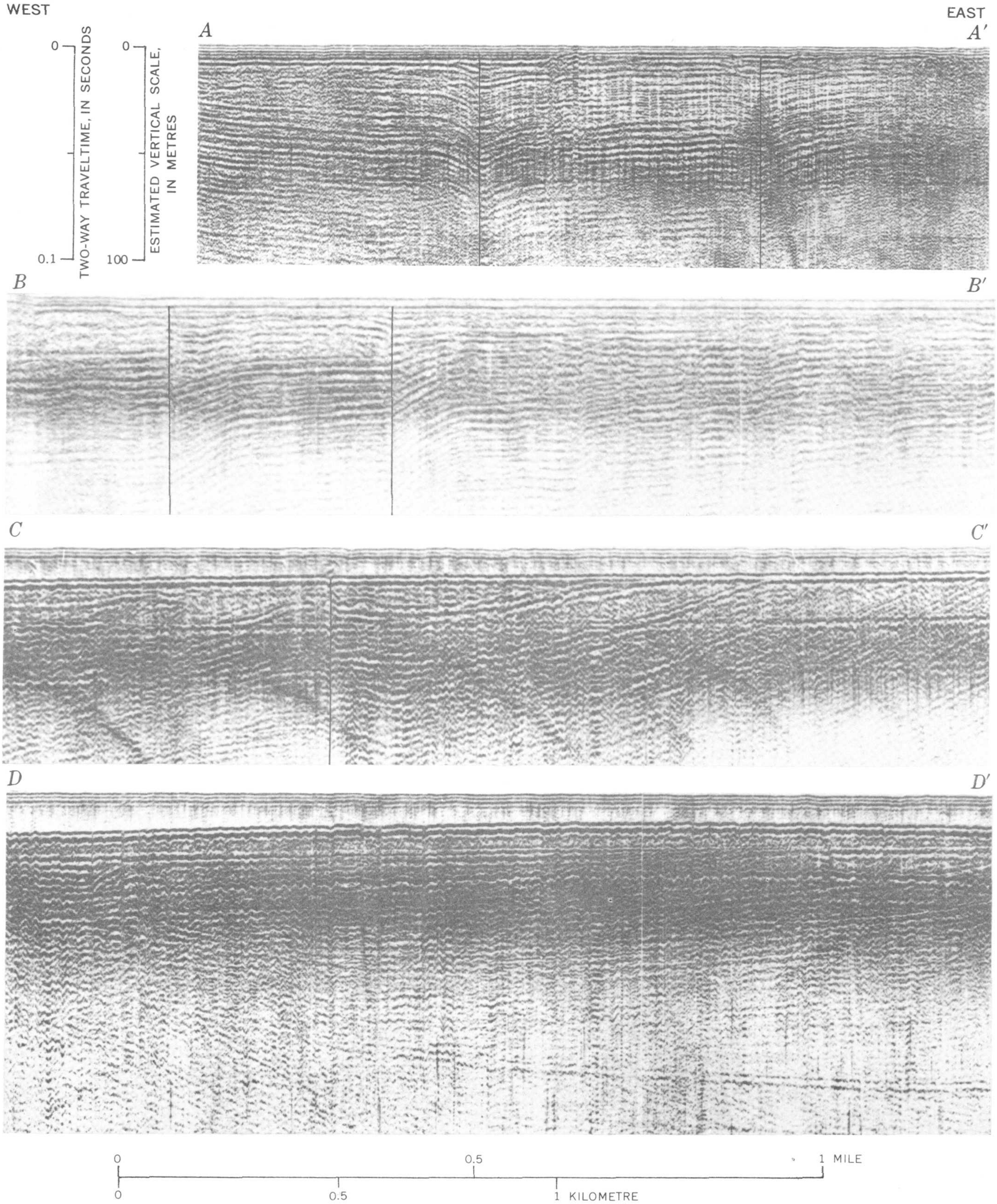

FIGURE 2.—Selected acoustic-reflection profiles of the floor of San Diego Bay and adjacent areas on which the larger faults have been inked. The horizontal scale is approximate owing to minor changes in vessel speed along the tracks. See figure 1 for locations.

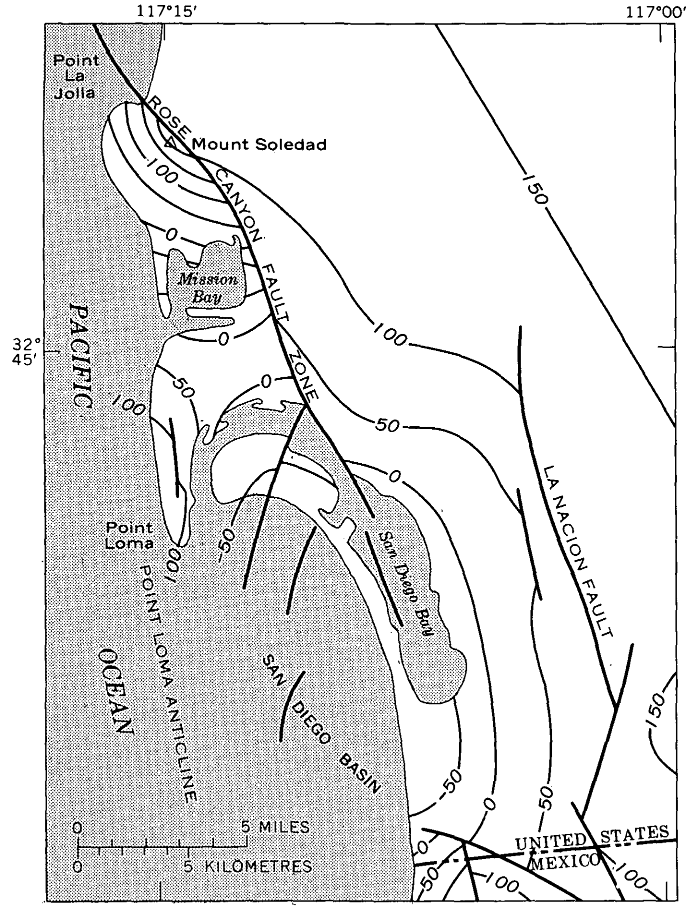

FIGURE 3.—Structure contours drawn on a wave-cut surface of early Pleistocene age at the base of the Lindavista Formation, showing offset and folding associated with major faults of the Rose Canyon fault zone, indicated by heavy lines. Contour interval, 50 m. Datum is mean sea level.

AGE OF FAULTED STRATA

The San Diego basin contains a thick section of Pliocene and Pleistocene deposits. The axis of downwarping in the basin has migrated toward the west with time, and the Pliocene San Diego Formation now crops out in a crescentic belt on the east side of the basin beyond about 4 km east of San Diego Bay. Thick Pleistocene deposits occur farther seaward. A sample considered probably Pleistocene on the basis of contained species of pine and sunflower pollen and the absence of palynomorphs indicative of a Pliocene age occurs at a depth of 36 m at the bottom of a boring at lat 32°37.6′ N., long 117°06.3′ W., on the bay shoreline at Chula Vista (Jane Gray, written commun., 1968). At San Diego–Coronado Bridge Borehole No. 8, approximately in the middle of the bridge, *Turritella gonostoma*, a fossil gastropod known only from the Pleistocene in southern California, occurs at a depth of 47 m (W. J. Zinsmeister, written commun., 1974). The Pleistocene is reported to be 91 m thick in an exploratory oil well near Imperial Beach (Hertlein and Grant, 1944, p. 59).

Two Pleistocene formations occur in the San Diego basin, the Bay Point Formation of late Pleistocene age and the Lindavista Formation of early Pleistocene age. The Bay Point Formation, inferred to have been deposited approximately 100,000 yr ago during Sangamon time when sea level was about 8 m higher than it is now, occurs as shelly sand in thin discontinuous patches as on the flanks of Point Loma, on the landward shore of San Diego Bay, near the coast at the international border, and at the city of Coronado (Stephens, 1929). The deposit at Coronado is believed to be a former barrier beach adjusted to the higher stand of sea level and hence alined about 1 km landward from the axis of the present Silver Strand barrier beach. To the south of Coronado the Sangamon barrier beach is submerged in the center of the sinking basin, and on land near the axis of the actively rising Point Loma anticline the Bay Point Formation is abnormally high at about 15 m.

The Lindavista Formation occurs as a terrace deposit a few metres thick at an average altitude of about 125 m over much of San Diego; locally it contains molluscan fossils (Kennedy, 1973). The formation is faulted and gently folded, slopes downward in the San Diego basin, and passes below sea level about 1 km east of the bay (fig. 3). Strata of the Lindavista Formation constitute the main part of the record in the acoustic-reflection profiles of this study. Offshore, near the east flank of the Point Loma anticline, where the Lindavista Formation lies with angular discordance on older rocks, the formation reaches a thickness of about 120 m (fig. 2, profile *D–D′*).

All the faults mapped in this study are believed to offset the Lindavista Formation, and the faulting is therefore younger than early Pleistocene. This is in harmony with the known relation on land where the Rose Canyon, La Nacion, and other faults also offset the Lindavista Formation (Moore, 1972; Artim and Pinckney, 1973).

Within San Diego Bay, vertical offsets of the order of 10 m occur at a subbottom depth of about 30 m in strata believed to belong to the Lindavista Formation (fig. 2, profile *B–B′*). Small offsets also occur in deposits of uncertain age at shallower depth. A possible Holocene age for faulting is suggested by a profile at the edge of the pre-1853 delta of the San Diego River that shows offsets of 1–2 m within 10 m of the bay floor (fig. 2, profile *A–A′*).

In the San Diego Bight, where the Lindavista Formation was truncated during the Holocene transgression (approximately 10,000 yr ago), most movement on the faults there took place before the truncation. On some faults, however, steps 1–2 m high occur at the sea floor (fig. 2, profile C–C'). Although differential erosion along the wave-cut platform cannot be entirely discounted, this evidence suggests that Holocene movement has taken place. Definite evidence, at least for post-Sangamon movement on this family of faults, comes from the land on nearby Point Loma where Kern (1973) reports that the fault nearest the point (fig. 1) offsets the Bay Point Formation a total of 12 m. Also, to the north at Point La Jolla, the Bay Point Formation has been uplifted about 30 m adjacent to the Rose Canyon fault zone (Peterson, 1970).

RATE OF DEFORMATION AND EARTHQUAKES

Previous investigations of the Rose Canyon fault zone onshore and this offshore survey indicate a systematic relation between the maximum dip-slip offset along individual faults and the age of the displaced beds. Vertical offset is 30–130 m for the Lindavista Formation (approximately 1,000,000 yr), 12–30 m for the Bay Point Formation (100,000 yr), and probably 1–2 m for the Holocene platform (10,000 yr).

Strike-slip displacement also can be measured along the fault zone. The north edge of the San Diego basin has been offset 6 km right laterally, as marked by the Eocene-Pliocene unconformity at Mission Bay (Kennedy and Moore, 1971, fig. 1). The 200-m depth contour has been offset about 4 km right laterally where the fault zone passes out to sea near Point La Jolla. We believe that the larger part of the displacement on the fault zone is strike-slip, and that the generally more easily observed vertical displacement is an effect of it.

Near the shoreline, wave erosion that preceded deposition of the Lindavista Formation has removed topographic evidence of displacement older than approximately 1,000,000 yr. At Mount Soledad, the Lindavista Formation and underlying rocks have been uplifted 130 m adjacent to the Rose Canyon fault zone as a result of compression caused by strike-slip movement at an S-shaped bend in the fault zone (Moore, 1972). The coast on opposite sides of the fault zone where it passes out to sea near Point La Jolla has rocks of similar resistance to erosion and a similar structural elevation of the Lindavista Formation. The southwest coast has been moved seaward right laterally about 1 km to form the point. Hence, in the Mount Soledad–Point La Jolla area, where the maximum vertical uplift is 130 m, the vertical displacement is about 13 percent of the horizontal. To the south at Mission Bay, a presumably similar horizontal slip, but along an oppositely curved length of the fault zone, is associated with a contrasting downward displacement of the Lindavista Formation to a position below sea level (Peterson, 1970).

The Quaternary deformation along the Rose Canyon fault zone attests to the tectonic importance of the zone. Although no major earthquakes have occurred near San Diego in historic time, several earthquakes of about magnitude (M) 3.5 have been recorded around San Diego Bay during the past 41 yr of systematic earthquake data collection (fig. 4). Eleven took place near the Rose Canyon fault zone within the city of San Diego. As the magnitude of an earthquake is known to bear a systematic relation to slip along a fault (Bonilla and Buchanan, 1970), and as our field studies have revealed no fault creep in San Diego, the magnitude-slip relation can be used to evaluate whether these recorded earthquakes are sufficiently frequent to account for the observed Quaternary deformation.

Bonilla and Buchanan (1970) have shown that individual earthquakes of M 3.5 are associated with an offset of about 8 mm and a fault rupture length of 1 km. The 1-km offset of the coast at Point La Jolla that has occurred in the approximately 1 million years since the Lindavista Formation was laid down indicates an average horizontal slip there of 1 m/1,000 yr or 1 mm/yr.

If this long-term rate of offset were related only to earthquakes of M 3.5, such as the eleven that occurred in San Diego during the past 41 yr, then an average of 2.5 earthquakes associated with surface offset would be expected on each 1-km segment of the fault zone during the 41-yr period of record. The actual number is less than that by more than an order of magnitude, as an average of 0.2 earthquakes per kilometer occurred near the 50-km length of the fault zone in San Diego, and some segments more than 10 km long had none. Furthermore, not all the faulting associated with earthquakes of M 3.5 would be likely to cut the surface, as that would require nonseismic creep below about 1 km, a depth equal to their length of rupture (Brune, 1968). Assuming that the seismicity extends to a depth of at least 15 km, as is the case elsewhere in California, nearly 1,000 earthquakes of M 3.5 would have been expected in San Diego during the past 41 yr. The great inadequacy of the 11 earthquakes that did occur to account for the indicated long-term rate of slip suggests that strain for a larger earthquake may be accumulating.

The Rose Canyon fault zone is believed to be tectonically related to the Newport-Inglewood fault zone of the Los Angeles area. Both lie in similar structural

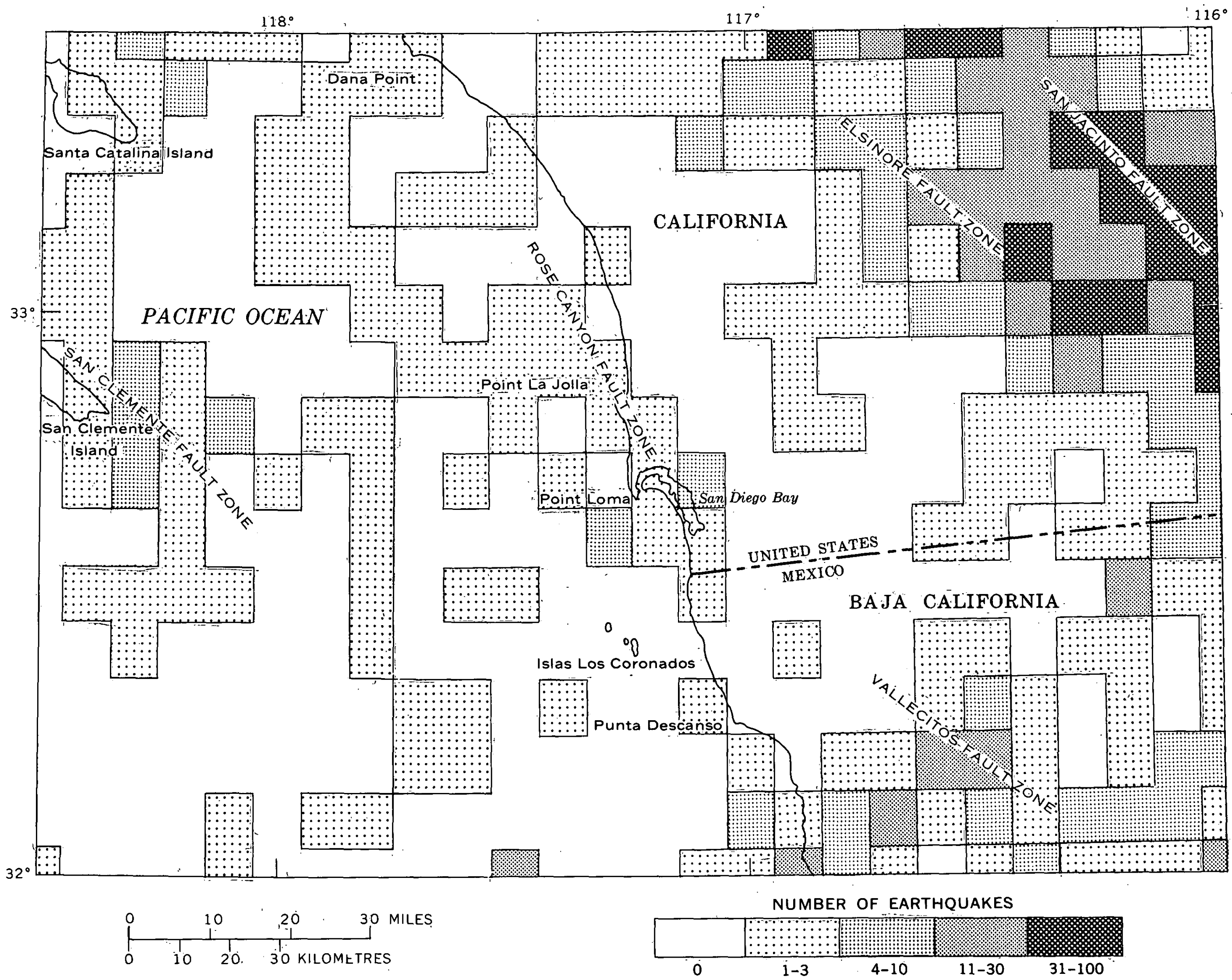

FIGURE 4.—Frequency of earthquakes of magnitude 3 and greater in each square one-tenth of a degree of latitude and longitude near San Diego Bay, 1932–72. Data from Hileman, Allen, and Nordquist (1973).

positions on the west side of the batholithic Santa Ana block (Morton and Gray, 1971), a nearly earthquake-free block that is bounded on the east by the Elsinore fault zone and that extends from the Los Angeles basin to the San Miguel fault zone in Baja California. Earthquakes of approximately M 6.5 were recorded at Long Beach, Calif., in 1933, and at San Miguel, Baja California, in 1956. If these can be inferred to be the principal earthquakes that occur along the west side of the Santa Ana block, then their expected frequency can be calculated along fault-zone segments where the rate of slip has been estimated.

Earthquakes of M 6.5 are associated with a surface rupture approximately 25 km long and have an offset of about 0.6 m (Bonilla and Buchanan, 1970). On the basis of the estimated slip rate of 1 m/1,000 yr at Point La Jolla, (both this rate and the inferred magnitude are subject to uncertainties), such an event could occur there once every 600 yr. Within the city of San Diego, which lies along about 50 km of the fault zone, (or two M 6.5 rupture lengths), an earthquake of approximately magnitude 6.5 would be expected every 300 yr on the average.

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