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WORK ACCOMPLISHED

Published Papers:

G. A. Jackson, F. Azam, A. F. Carlucci, R. W. Eppley, P. M. Williams, B. Finney, C. A. Huh, L. F. Small, D. S. Gorsline, B. Hickey, R. A. Jahnke, I. R. Kaplan, M. I. Venkatesan, M. R. Landry, K. M. Wong, 1989, Elemental Cycling and Fluxes off Southern California: EOS, 70:146-155.

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Final Scientific Report:

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The Geologic Setting of Santa Monica and San Pedro Basins, California Continental Borderland

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Abstract - The California Continental Borderland's present configuration dates from about 4 to 5 X 10^6 years Before Present (B.P.) and is the most recent of several configurations of the southern California margin that have evolved after the North America Plate over-rode the East Pacific Rise about 30 X 10^6 years ago. The present morphology is a series of two to three northwest-southeast trending rows of depressions separated by banks and insular ridges. Two inner basins, Santa Monica and San Pedro, have been the site for the Department of Energy-funded California Basin Study (CaBS).

Santa Monica and San Pedro Basins contain post-Miocene sediment thicknesses of about 2.5 and 1.5 km respectively. During the Holocene (past 10,000 years) about 10-12 m have accumulated. The sediment entered the basin by one or a combination of processes including particle infall (mainly as bioaggregates) from surface waters, from nepheloid plumes (surface, mid-depths and near-bottom), from turbidity currents, mass movements, and to a very minor degree direct precipitation.

In Santa Monica Basin, during the last century, particle infall and nepheloid plume transport have been the most common processes. The former dominates in the central basin floor in water depths from 900 to 945 m, where a characteristic silt-clay with a typical mean diameter of about 0.006 mm, phi standard deviation of

Teng, 1989). This region extends 900 km northwest-southeast, with a maximum width of 250 km at about the international U.S./Mexico border (Emery, 1960; Gorsline and Teng, 1989). Two to three parallel rows of insular ridges and banks aligned northwest-southeast, separate 23 deep closed basins (Table 1). There are 15 basins in the Borderland north of the international border (Gorsline and Teng, 1989). These northern depressions and their dimensions are listed in Table 1.

The U.S. half includes a total subaqueous area of about 70 X 10^3 km^2 of which approximately 15% is basin floor (Emery, 1960; E. Trosper, unpublished data). In addition to the active sediment-receiving basins, five basins, filled in late Pliocene time, form the present Ventura, Los Angeles-San Gabriel coastal plains and are themselves sediment sources.

1.1.2. *Origins*. The Borderland is the most recent bathymetric expression of continuing major crustal plate interactions that were initiated in Oligocene time, about 30 X 10^6 years Before Present (B.P.), when the North American Plate overrode the East Pacific Mid-ocean Ridge (Atwater, 1970; Teng, 1985). As a result, large-scale lateral shearing motions were generated in the leading edge of the advancing North American Plate.

The present general expression of the Borderland dates from the end of Miocene time, about 4 to 5 X 10^6 years B.P. This morphology was initiated with rifting in what is now the Gulf of California at about 5-6 million years B.P. That rifting caused the lateral motion of blocks forming Baja California to the northwest. As that large scale shifting developed, a portion of the original continental margin south of the present Borderland drifted northwest, with rotation of secondary blocks within the larger terrane, to its present position outboard of the adjacent overlapped margin segment (Kamerling and Luyendyk, 1979; Crouch, 1979, 1981; Teng, 1985). The basement rocks of the Borderland are "granitic" and "subduction complex" types respectively in the bull's eye isopach pattern as seen in radiographs of the central basin sediments. Bottom waters generally contain above 0.2 ml/L dissolved oxygen. Bottom infauna and epifauna are sparse.

Central basin floor sediments (water depths of greater than 800 meters) of San Pedro Basin have textural characteristics similar to those of Santa Monica Basin with distal basin floor surficial sediments deposited primarily by particle infall and nepheloid flow at the present time. Mean diameters of about 0.006 mm, phi standard deviation of 2, phi skewness near 0 and kurtosis of about 2 (platykurtic). Calcium carbonate contents average 8 to 10 percent and organic carbon is about 4 percent. Contemporary sedimentation rates have been determined for only one box core, and is therefore not representative. That rate was about 25 to 29 $mg/cm^2/yr$ for a central basin floor core near the present distributary margin. Mixing is indicated by the data.

An important climatic factor is the alternation of multi-year wet and dry periods. It should be noted that the California Basin Study was done during an extended dry period of low river discharge. This undoubtedly affects the conclusions of the study related to sediment-water interactions and pollutant transport by suspended clays.

fluid operating on the individual grains in lower concentration flows (turbulent fluid flows) (Middleton and Bouma, 1973).

1.3.1: *Fine Particle Rain.* Fine particle infall (particle "rain") is probably in great part in the form of biologically-formed aggregates (bioaggregates) (Honjo and others, 1982, 1982), and some physico-chemically-formed aggregates resulting from flocculation (Reynolds, 1987b). This rain of particles is continuous but at varying rates, reflecting seasonal effects such as timing of biological blooms, rainfall and run-off, the incidence of strong storms or floods, and variations in aeolian input. Bacterial degradation of aggregates in the water column reduces fall rates of some aggregates and may reduce the aggregates to separate grains. The original infall depositional structures are typically reworked by benthic feeders and may not leave evidence of their existence except in anoxic bottom depositional sites.

1.3.2. *Nepheloid Flow.* Turbid plumes, or nepheloid flows (Ewing and Thorndike, 1965), enter the depositional system as slow, low-concentration plumes (ca. 1 to10 mg/L) that tend to move along isopycnals in the surface layer, within the deeper water column, and at or near the bottom (Eittrem and others, 1969; Drake, 1972). Oceanographic data show that these come predominantly from terrigenous sources along the sides of ocean basins, and to some extent by erosion of the seafloor by episodic strong currents, or by storm waves in shallow water (Ewing and Thorndike, 1965; Ewing and Connary, 1970; Drake, 1972; Karl, 1976).

These inputs vary in intensity seasonally with maximum input during flood seasons and in wet years in margin areas (e.g. Drake and others, 1972; Drake and Gorsline, 1973; Karl, 1976). Deep-ocean nepheloid plumes are of larger scale and subject to more complex circulation variations in the deep ocean and at the base of the continental slopes (Eittrem and others, 1969). These very low-concentration, fine particle plumes move with the ocean circulation.

These latter flows are typically fine-grained suspensions, given the generally finer grain-sizes of slope sediments. Canyon turbidity currents have access to a wider range of particle sizes and typically are sandy..

Turbidity currents are best viewed as a lower viscosity, turbulent, end-member of a sequence of processes that begin with mass slides, and, with increasing admixture of water, become debris flows, and ultimately fully turbulent flows (Nardin and others, 1979). This progression in process probably occurs to some extent whenever slope or canyon head sediment masses fail and begin to move downslope (Dott, 1963; Hampton, 1972).

1.3.4. *Mass Movement.* Submarine mass failures and resulting slides, slumps and debris flows are a geologically important process set (Almagor, 1976; Lisitzin, 1991). These processes are typical of slopes (Field and Edwards, 1980), and can deliver the largest volume of sediments as single events (up to 100's of km^3). These events, infrequent or rare on decadal or even century time scales except in very high sedimentation rate areas, are therefore also rare during the typical few year lengths of oceanographic studies. Periodicities of century length and up to thousands of years seem to be typical in the borderland (e.g. Embley, 1976; Haner and Gorsline, 1979; Thornton, 1981, 1984; Emery and Uchupi, 1984).

Figure 2 shows a high-resolution, acoustic reflection profile of a major slope slide from the San Pedro mainland slope. This slide probably occurred within the last few hundred years and may have been triggered by earthquake shocks on the Palos Verdes Fault that cuts through the San Pedro Shelf. The profile shows the slide plane, the blocky, hummocky slide and slump, and then a smooth, low-gradient apron extending basinward from the edge of the slide formed by debris flows and turbidity currents.

The largest mass failures appear to occur along passive margins, such as the U.S. Atlantic margin (Emery and Uchupi, 1984).

tectonic deformation. Outer, low-sedimentation-rate basins have more irregular floors. In those outer basins tectonic rate is equal or greater than sedimentation rate and the fine slowly accumulating sediment drape the actively changing slopes and depressions.

Santa Monica Basin has a longitudinal length in the northwest direction of 75 km and a maximum width of 38 km; San Pedro Basin is 35 km in longitudinal length along the regional trend, and has a maximum width of 30 km. The total area of San Pedro, Santa Monica Basin systems, including adjacent shelves and bank tops and the intervening Redondo Seaknoll (Figure 3) is 5470 km^2, 3860 km^2 in the Santa Monica Basin system alone. San Pedro Basin system also includes half of Lasuen Knoll at its eastern end.

In the Santa Monica Basin system, mainland shelf includes 525 km^2 (15%), insular shelves comprise 25 km^2 (1%), bank tops to the ridge-crest divide and slopes (100-700 m depth range) total 1270 km^2 (34%). The area of basin floor below 700 m depth in Santa Monica is 1930 km^2 (50%). Maximum depth is about 940 m.

In the San Pedro Basin system, mainland shelf is 300 km^2 (19%), insular shelf comprises 50 km^2 (3%), and bank tops and slopes (100-700 m depth range) total 500 km^2 (33%). Basin floor below 700 m depth in San Pedro Basin is 715 km^2 (45%). Figure 3 details the bathymetry of the two basins. Maximum basin depth in San Pedro Basin is about 910 m.

Slopes are relatively steep. Gorsline (1991) has measured the gradients normal to the slope contours of mainland and offshore slopes from bathymetric maps, and notes that the mean gradient of mainland slopes of Santa Monica/San Pedro Basins averages 16^o for a range from 8-25^o. The steepness varies as a function of the thickness of sediment mantling which tends to reduce the slope gradient. The *steepest segments* of these mainland slopes range from 15-40^o and average about 28^o. The offshore bank slopes have average gradients of about 23^o and about the same steepest

Schwalbach and Gorsline (1985) have discussed the sedimentary budgets of the Holocene Borderland basins. They note that the two major sedimentary sources are the adjacent coastal rivers and the productive upwelling sites of the northern coastal margin. Both of these sources are affected by seasonal and longer climatic cycles.

Note that the depositional data discussed in this section is based on at least century-long records and in large part on acoustic reflection data for the Holocene (last 10,000 years) (Schwalbach and Gorsline, 1985). The rates and budgets for the last two or three decades in the contemporary basins often differ from these long-period values (Huh and others, 1990; Christensen, 1991).

The contemporary rates reflect human intervention in stream drainage and discharge, and are biased by relatively short record length. They typically include only particle infall and not the larger, geologically-instantaneous, depositional events associated with turbidity currents and mass failures.

Some earlier surficial accumulation rate estimates based on Lead-210 profiles yielded higher hemipelagic rates due to use of surface bulk density values of 1.56 gm/cm^3 that are now known to be too high (Malouta and others, 1981; Christensen, 1991). Correction of these calculations using the measured bulk densities of from 1.1 to 1.2 gm/cm^3 for the surficial sediments (to 10 cm depth in core) bring these older estimates into agreement with the later work (Christensen, 1991). Average rate in the basin floor hemipelagic fine muds is 16 $mg/cm^2/yr$ for all of the studies.

2.2.1. *Fluvial Source.* River input in this region is typically concentrated in the winter months and particularly January and February. In addition, longer climatic cycles cause major floods to occur at roughly decadal to generational intervals. This is well documented by the flow of the Santa Clara River, the largest river in the region (Table 2; data from R. H. Meade, courtesy of J. Milliman).

Mexico. It is evident that those are the main terrigenous sources for Santa Monica and San Pedro Basins.

This has some interesting effects on basin morphology and depositional style. Because of the southerly direction of longshore flow and the effective trapping of much of this drift, Santa Monica Basin is characterized by the large Hueneme-Mugu Submarine Fan, the largest fan in the Borderland. Offshore surface circulation and deeper poleward slope current flow direct much suspended fine sediment to Santa Barbara Basin and it is therefore characterized by dominance of fine sediment, lack of presently active submarine fans and relatively high accumulation rates. This leads to slope instability and frequent mass failures.

2.2.2. *Biogenous Source.* The second largest source is the biological production in the surface waters of the coastal ocean. This will be documented in greater detail in other papers in this volume but suffice it to say here that the principal contributor of particulates in dry years is the biogenic source.

The three principal components are: (1) Calcium carbonate from foraminiferal tests, spines, and coccoliths on the basin floors, and shell hash on the banks and outer shelves. (2) Organic matter comes from natural and anthropogenic sources (Venkatesan and Kaplan, 1990), the latter also contributes trace metals (Chow and others, 1973; Bruland and others, 1974). (3) Biogenic silica from diatoms, sponge spicules and other lesser sources. As an order of magnitude estimate based on surficial analyses of about 2000 box cores over the Borderland area, about 15% of the total sediment is calcium carbonate, about 3-4% is organic matter (after recycling in the sediment-water interface), and 0.2-2% silica.

Schwalbach and Gorsline (1985) have estimated the net long-term mean deposition of biogenic matter in the entire Borderland to be about 2-3,000,000 tons/year (about 20% of total contribution). Figure 5 shows the content of calcium carbonate in the surface 1 to northern-source tracer, and one not typical of the weathering regime in the adjacent source areas (Fleischer, 1970).

Figure 6 (modified from Gorsline and Emery, 1959) is a schematic diagram illustrating the effect of margin topography on distribution of material from the various sources. Table 3 summarizes the sedimentary budget for the Borderland after Schwalbach and Gorsline (1985). The specific basins examined in this study are inner basins immediately adjacent to the mainland sources and in the northern portion of the Borderland within the zones of major upwelling and bioproduction.

2.3. *Significant Transport Processes for CaBS*

Within the decadal time scale of the oceanographic studies, the occurrences of the turbidity currents and mass failure process types are usually assumed to be rare except near the mouths of channels. Most of the sediments deposited on the basin floors in the past decade have been delivered by fine particle infall from the surface layer and from nepheloid plumes. However, within the top 20 cm of sediment (roughly 300 years of record), and within the depth of bioturbation, we see records of turbidity current deposition and probable distal effects of slope failures on a century scale (Thornton, 1981; Reynolds, 1987a; Huh and others, 1990; Christensen, 1991). Thus, these infrequent processes do have an indirect effect on sediment packing (fabric), texture and grading within the zone of sediment-water interactions of primary interest to the CaBS study (Reynolds, 1987b).

2.4. *Sedimentary Fill*

Figures 7 and 8, modified from Teng and Gorsline (1989), illustrate the thicknesses of the sedimentary fill in these two inner basins , and the changes in volume between early and late post-Miocene time. Figure 9 is a reproduction of an acoustic reflection turbidity currents, although at very different frequencies as noted above.

2.5.1. *Shelf Deposits.* In Santa Monica Basin, the adjacent outer and central Santa Monica Shelf is covered by relict (palimpsest) sediments and a central bedrock outcrop (Terry and others, 1956). The inner shelf is the contemporary transport path and a offshore-graded lense of sand to sandy silt occupies the inner 4-5 km of the shelf with a typical mid-lense thickness of about 8-12 m (Fischer and others, 1983).

At the western end of the shelf east of Point Dume, a lense of sediment with maximum thicknesses of 20-28 m fills the inner 4 km of the shelf surface. Another series of thick channel fills are located at the southern end of this shelf segment with thicknesses in the old channels of 20-50 m (Dahlen and others, 1991).

The Oxnard Shelf has been filled to the shelf break by Santa Clara River and Ventura River sediment discharge to maximum Holocene age thicknesses of almost 50 m. As is typical of most southern California shelves, the shelf break is a zone of non-deposition, and slope sediment drape thickens from the break to the base-of-slope (Fischer and others, 1983). The offshore bank top and the Santa Cruz-Anacapa Shelf adjacent to the basin have thin veneers of coarse relict sediments.

The adjacent mainland shelves to Santa Monica Basin contain about 2 km^3 of Holocene sediment (10,000 yrs). This compares to about 14 km^3 in the Basin for the same period. Santa Monica Shelf has a large storage capacity and will continue to receive some sands and silts over the period of present high sea level. Fine sediment and some sands will continue to pass through to the deep environments.

San Pedro Basin is bounded by the San Pedro mainland shelf which is similar to Santa Monica shelf in having only an inner shelf wedge of significant Holocene deposition and a largely relict outer the middle and upper fan facies. The large levee-distributary channel lobe is the present primary active distributary of the Hueneme-Mugu submarine fan system (Figure 11).

The basin floor includes an area of about 700 km^2, also corresponding to the area deeper than 800 m. The fan surfaces (Hueneme-Mugu Fan is the dominant one although there is also a small Dume Fan and an inactive Santa Monica Fan), comprise about 800 km^2. The fan surface is irregular and channeled and in its upper portion includes part of the lower canyon (Nardin, 1981); a large slide occupies about 120 km^2 of the large fan's central surface area.

San Pedro Basin includes submarine fan and basin plain areas and a significant area covered by a large base-of-slope slide (note above under mass failure discussion and Figure 2). Basin plain area includes about 375 km^2 of which 65 km^2 is the base-of-slope slide mass; the fan, which again includes part of the lower canyon, comprises about 160 km^2. A broad, very shallow distributary channel and associated levees extends into the basin plain in a very similar fashion to the major distributary channel and levees in Santa Monica Basin (Figure 11). The sediment mass of Holocene age on the adjacent shelves is less than 1 km^3. The basin contains about 4 km^3 of Holocene sediment which I have calculated from acoustic and core data.

2.5.4. *Distributary Lobes.* The extended, active leveed-distributary channels (distributary lobes, Figure 11) present in both basins are interesting features (Schwalbach and Gorsline, 1990). At high sea levels, only those canyons which head close to shore and intercept the longshore drifted sands and gravels remain active as conduits for sediments (Shepard and Dill, 1966). In the two basin systems, the active canyons are Hueneme, Mugu, Dume, and Redondo. All others head at the outer shelf edge, far removed from the contemporary coastal sediment supply. These inactive canyons receive only fine suspended sediments that form a draped cover periodically driven offshore by storm surges and enter the shelf sediment prism.

Silts and clays are winnowed out and move to the central shelf and beyond, in turbid plumes moving at surface, mid-water and bottom (Karl, 1976). These plumes are affected by shelf circulations and progressively deposit their loads on the outer shelves and slopes and in the canyons. Storm waves rework these fine sediments and generate bottom plumes that move fine sediments farther offshore Karl, 1976).

Fine sediments deposited on the slopes and canyon walls become unstable either due to storm wave pressures, seismic shocks, or overloading and/or undercutting. Slope sediment stability is primarily a function of slope gradient and sedimentation rate in which rate has the major effect (Field and Edwards, 1980; Field, 1987). Fast sedimentation of fine particles leads to low bulk density, high water content and low strength. In areas of very high accumulation rates as off major river deltas (Coleman, 1976; Wright, 1985; Coleman and others, 1988), sediment fails on gentle slopes (1° and less) at frequencies of a few years or less. In the Borderland, significant failure occurs at roughly century intervals and longer periodicities on low-to-moderate accumulation rate slopes (Nardin and others, 1979; Thornton, 1981).

Slope failure in canyon heads and upper canyon slopes adds fine material to slumping sands and the accompanying admixture of water produces the slurries of muds and sands that then flow as turbidity currents (Hampton, 1972). Sediments deposited from longshore drift in active canyon heads periodically slide downcanyon (Shepard and Dill, 1966), but require the admixture of mud from slope slides to develop as turbidity currents capable of transporting material out to the fans and basin floors. The conjunction of high rates of sand addition to canyon heads, and increased rates of fine deposition on canyon slopes and subsequent failure, is obviously related to times of markedly increased sediment input. In the inner accuracy of the bulk density determinations for the surficial sediments). Thus 5-10% of the total production is stored although there are some problems in the bottom sediment budgets.

In the central basin floor, the net sediment composition at any point in time and space, is a function of the varying rates of biogenous and terrigenous input. In dry years, the biogenic will dominate; in wet years the terrigenous will dominate. The mix will also vary depending on distance from each source at different basin locales.

3. BASIN FLOOR SEDIMENTOLOGY

3.1. *Sources of Samples*

The sedimentology of the surficial deposits in the two basins is based on samples collected in earlier studies supported by National Science Foundation grants (NSF samples) as well as box core samples collected during the CaBS field studies. The study has been based on more than 300 box cores collected over the entire basin system. The NSF cores, about 250 in number, were collected with a modified Reineck-NEL box Corer equipped with a camera system. The CaBS samples, nearly 60 in number, were collected using the Soutar Box Corer as well as the Reineck-NEL Corer. In both instances, 10 X10 cm square subcores were taken for sediment analysis . These subsamplers are thin-walled, square-cross-section plastic tubes about 50 cm long. Subsamples were capped and stored in a cold room (4^{o} C) prior to curation.

After samples were extruded, a vertical slab 2 cm thick was cut from one side and the remaining core was sectioned at 1 cm intervals for later analysis. Earlier cores were subsampled at a 2 cm interval. The slab was radiographed with a Hewlett-Packard x-ray unit. Subsamples, stored in ziplock plastic bags, provide material for textural, compositional and archive use. Slabs are wrapped in plastic film, and are preserved as a primary archive. After about 1 year all samples are stored dry.

water circulation gyre and is presumably the area of the low mean velocity core of that gyre (<1 cm/sec). Hence this area receives the finest suspension bottom flow.

A similar pattern exists in San Pedro with the finest surface sediments along the offshore flank of the extended distributary lobe in that basin. Note that all of these surface 2 cm sediments are particle infall deposits. If one looks at cores in the axis of the distributary channels and associated levees, turbidites dominate illustrating the frequent flow of turbidity currents through the channel and overbank.

Looking at the group characteristics of the sample set, several interesting relationships can be defined. Figure 13 shows the distribution of the four basic parameters versus depth within the Santa Monica Basin floor (depths greater than 750 m). Figure 14 shows the same parameters for the San Pedro Basin surficial sediments. It is evident that basin plain sediments (mean diameters less than 0.063 mm [4 phi]) become finer in the distal basin plain with mean diameters of 0.004-0.008 mm (7 to 8 phi) in the finest silt sizes. Variation in silt content is the principal control and is a function of distance from source. In the basin plain the active distributary channels are the immediate sources of silts via turbid flows. Note that the surface sediment characteristics described here are a composite of 2 to 3 decades of particle infall and therefore integrate individual annual variations into a longer term average condition.

3.2.3. *Standard Deviation (Sorting).* Standard deviation about the mean is not a significant factor in defining trends and is essentially the same for all basin floor sediments. This is probably the result of a relatively homogeneous silt-clay suspension load in the overlying water column.

3.2.4. *Skewness.* Skewness progressively shifts from a coarse-silt dominance to broad near-log normal textural distributions in the floor alone. It is clear that the system includes two distinct populations (also see Leroy, 1981). One is the fan-basin floor sequence, and the other is a bank-shelf sequence. In the basin floor sequence, carbonate increases away from the fan and distributaries to a roughly constant value of about 7-8% by weight (see Figure 15 showing basin floor content). This is a reflection of decreasing dilution by terrigenous sediments because of the decreasing influence of nepheloid and fine turbidity current deposition away from the distributaries. The calcium carbonate fraction enters the system by particle infall in biogenic aggregates (Reynolds, 1987b). This uniformity in bulk composition of the distal basin floor muds also supports the conclusion that central distal basin sedimentation rates are roughly constant and thus no variation in carbonate content is seen in this distal area (see Huh and others, 1990; Christensen, 1991). Central basin accumulation rates average about 1-3 $mg/cm^2/yr$ dry weight.

The highest carbonate contents are typically found on bank tops and outer shelves where shell hash makes up a large fraction of the residual and relict sediment cover.

3.3.3. *Organic Carbon.* Organic carbon content parallels the picture for carbonate...both primarily from the same pelagic source...and reaches a maximum of about 6% in the finest deepest sediments (Figure 15). The average value for central basin floor is about 4% of total sediment dry weight. As is characteristic, clay percentage and carbon percentage vary as a direct relationship. Again, as for carbonate, the trend and pattern represents decreasing dilution away from the source by nepheloid plume fine silts. Central basin accumulation rates for carbon are about 1-2 $mg/cm^2/yr$ dry weight.

3.4. *Sedimentary Structures*

Sedimentary structures in the cores are determined from radiographs of the vertical core slabs. Figure 16 shows a typical contribution of clays and silts is undoubtedly a factor and certainly produces detrital-dominated lamina (Fleischer, 1970; Kolpack, 1972; Drake and others, 1972).

Dominance of suspended load from wave-reworking of fine sediment-choked shelves after big floods may also produce a 2 to 3 year terrigenous-dominated layer suppressing the annual biogenic signal and depositing a single "varve" that actually is a multi-year event (see Drake and others, 1972).

A study by C. Christensen (1991) at USC using densitometer scanning of radiographs and quantitative comparison of "varves" with radio-isotopic dating of cores in Santa Monica and Santa Barbara Basins, shows that the "varves" in that basin are dominated by a 3 to 4 year unit that matches the El Nino signal. Other "varves" represent combined deposition events of up to more than a decade. Previous visual counting in the thicker Santa Barbara laminae shows a fair to good correlation of varves with years (ibid Soutar and Crill, 1977; Emery Hulsemann, 1962). However, it is now possible that these represent the interaction of production cyclicity, flood input and bottom water flushing.

Thin turbidites complicate all of these anoxic deposits. These typically have a conspicuously higher relative optical density as seen in radiographs (Christensen, 1991). When these are removed from the records in both Santa Barbara Basin (M. Yasuda, Scripps Institution of Oceanography, personal communication), and from the Santa Monica Basin records (Christensen, 1991), the laminae variations in thickness increasingly match the rainfall and tree ring records after smoothing these records using a three-year running average. Dry year "varves" are typically wispy and incomplete in both basins.

It is now clear that the climatic control on fine sediment deposition in these inner basins is a strong one. However, it is also

It is evident that accumulation rates on dry sediment basis have precisions that are more affected by the bulk density measurement than by the age dating error (Christensen, 1991). This has lead to some variation in the reported contemporary basin floor particle infall accumulation rates. Huh and others (1990) reports rates of about 15-20 $mg/cm^2/yr$. Using varve counts (see previous discussion of potential error) in central basin cores, I have calculated rates of 20-40 $mg/cm^2/yr$. Rates based on radiocarbon dating of longer piston cores, high resolution seismic reflection profiling and calculation of rates for Holocene time (past 10,000 yrs). These approaches yield higher rates of from 40-80 $mg/cm^2/yr$, but these include turbidites and major flood nepheloid layers not typically seen in the contemporary top few cm in box coring. The surficial few cm are dominated by laminated hemipelagic particle infall in the anoxic basin areas.

It is now well documented by Christensen's (1991) inter-laboratory comparisons that the Huh and others (1990) rates are the best estimate. His work, and that of staff of the Lawrence Livermore Laboratories (K. Wang, personal communication), have been verified by Christensen (1991) in an elegant analysis that yields general agreement for a contemporary average hemipelagic infall rate of about 16 $mg/cm^2/yr$. For the past few thousand years of piston core records, this translates into a total deposition (turbidites plus hemipelagic deposition) of 30 to 60 $mg/cm^2/yr$.

Other factors apply when looking at contemporary sedimentation accumulations. Many of the California river systems have been highly altered by construction and changes in land use. These probably have the net effect of decreasing sediment discharge to the coast. Data for the last few decades seems to support this decline (Huh and others, 1990). It is also true that major floods occur at generational intervals and in the past 50 years only one large event and a couple of minor events have been captured (1969 floods, 1978 wet year). Century-long river discharge and rainfall records show that longer term wet and dry cycles of up to decade length (sunspot cycle frequencies and longer) are present.

For the primary objectives of a contemporary ocean impact survey, we can summarize by saying that the surficial particle infall rates are probably the best to use in budget calculations. For periods of up to a couple of decades the influence of turbidites is not significant in the deep basin floor sedimentation systems.

3.6. *Non-bioturbated "Anoxic" Facies*

In the two basins, the contrast in basin floor sediment character is the presence or absence of contemporary non-bioturbated laminae preserved in the upper 0-20 cm of the basin floor sediments. Santa Monica Basin floor is now dominated by these deposits; San Pedro Basin floor sediment is bioturbated.

Examination of cores for this study reveals that the surficial basin floor sediment preserves the original primary depositional laminae. It has become evident that the thickness of the laminated sediment zone varies over the basin floor. The conclusion is that the area of near-anoxic bottom water inhibiting the entry of macro-infaunal burrowers has grown with time.

Figure 17 shows an map of the Lead-210 age of the base of the non-bioturbated sediment layer (Christensen, 1991). The original "anoxic" bottom area commenced about 350 years B.P. and was restricted to the northeastern basin floor sector. The actual *in situ* layer thickness ranges from about 20 cm in the oldest portion down to 0 at the edge of the non-bioturbated zone. In the first 50 years this zone expanded and occupied an area within the 300 year Before Present (B. P.) contour of about 120 km^2 or an expansion rate of about 2.5 km^2/yr. Over the succeeding 300 years the area has grown to about 1300 km^2 and covers the entire basin floor below about 850 m water depth.

Santa Barbara Basin's "anoxic" area. These conditions would suggest that if there is a circulation variation, it is affecting the deep basin waters south of the Northern Channel Island barrier, but not the Santa Barbara Basin whose controlling sill faces directly into the California Current System. Since the bottom water entering Santa Monica and San Pedro Basins has a much more complicated and longer pathway to follow, it may integrate longer period oceanic circulation effects. In Santa Barbara, the open access to the California Current must yield a much stronger annual signal.

San Pedro Basin is not presently anoxic and surficial sediments are bioturbated. San Pedro Basin has also been a dumping site in the past for drilling mud and cuttings, but these individual very short-term inputs do not appear to have been sufficient to significantly alter the bottom water oxygen content. In fact, such dumps would tend to bring oxygenated surface water to the bottom in the high concentration turbid dumps.

Hickey (in press) has shown that there is a strong and relatively steady slope current along the upper slope and shelf break in the northern Borderland. Suspensates from the adjoining mainland shelves are probably caught up in this flow and passes into Santa Monica Basin from these southern slope areas. Thus Santa Monica basin probably collects material from a much larger area than the immediate environs of Santa Monica Basin. Santa Monica Basin may thus serve as the sump for a much larger tributary area of the deep Borderland circulation. San Pedro Basin may, in fact, be bypassed by much of this material.

The "natural" biological production system in the area is presumably operating on a higher nutrient input than in natural conditions (pre-european entry). Thus some of the drawdown in Santa Monica Basin may not be evidenced by biological tracers, yet be strongly influenced by such factors as shifts in land use to agriculture and subsequently to urban use. An analysis of the pollen and spore content of the surficial 20 cm of basin sediments might be bottom water (oxygen < 0.1 ml/L) and nonbioturbation has expanded to cover most of the basin floor below water depths of 830 m, an area of some 1200 to 1300 km^2. The later part of this expansion coincides with the growth of the adjacent Los Angeles metropolitan area. San Pedro Basin is dysaerobic but surface sediments are bioturbated and no laminated surface layer is present.

5. The initiation of this anoxic bottom water period may reflect a warming shift in global climate following the decline of the Little Ice Age. It is suggested that the later phase (past 150-200 years) of the decline in bottom oxygen content has been amplified by changes in discharge of the natural drainages and of the rise in oxygen-demand due to increasing anthropogenic input.

Acknowledgements- The CaBS study has been supported by contracts from the Office of Ecologic Research of the Department of Energy. Much of the earlier work on borderland sediments and geologic structure has been supported by a number of grants from the Ocean Sciences Division of the National Science Foundation. This agency support is gratefully acknowledged.

Much of the background research over the past 40 years of research in the Borderland at the University of Southern California has been through student thesis and dissertation research directed by K. O. Emery, and later by the author. The contributions of all of these students and associates are gratefully acknowledged.

The final draft of the manuscript profited from the detailed reading of the early drafts by Drs. Brian Edwards, Michael Field and Laverne Kulm. Their work is appreciated and acknowledged.

large terrigenous input from coastal rivers trapped by bathymetry. Central basins receive minor suspended terrigenous load and biogenous load. Outer basins receive essentially oceanic hemipelagic particulates dominated by California Current transport.

Figure 7- Santa Monica Basin Plio-Pleistocene sediment fill based on seismic reflection profiling data courtesy of Union Oil Company of California (Teng, 1985). At typical acoustic velocity of 1800 m/sec in deeper sediments 100 msec of two-way travel time is approximately 100 m thickness for rough estimate of depth of fill.

Figure 8- San Pedro Basin Plio-Pleistocene sediment fill based on seismic reflection profiling data courtesy of Union Oil Company of California (Teng, 1985). Depth of fill can be approximated as 100 msec two-way travel time equals 100 m thickness.

Figure 9- Seismic profile of Santa Monica Basin courtesy of Union Oil Company of California. One second of two-way travel time is about 1 km thickness. The lower figure shows interpretation of acoustic reflections (after Teng, 1985).

Figure 10- Sedimentary environments based on acoustic profiling (after Nardin, 1981). The interpretation is based on the characteristics of the acoustic echos in reflection seismic sections. Compare with the side-scan data in Figure 12.

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Figure 12- Mean particle diameters (phi notation), for top 2 cm of Santa Monica Basin bottom sediments. Compare with Figure 12.

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TABLE 1: **Basin dimensions (After Emery, 1960; Doyle and Gorsline, 1977).**

BASIN	Width Km	Length Km	Depth M	Area Km^2	Deepest Sill M
Santa Barbara	27	54	615	825	468
San Miguel	10	18	1380	100	1230
Santa Cruz	36	80	1935	2225	1067
Santa Monica	36	72	925	2255	725
San Pedro	27	36	898	819	725
Patton	9	27	1300	160	
Tanner	36	108	1526	1577	1146
San Nicolas	54	90	1803	3327	1089
Santa Catalina	36	90	1335	2676	966
San Diego Trough	27	108	1350		1350
Long	14	80	1908	1036	1670
West Cortes	18	72	1768	1257	1340
East Cortes	27	63	1947	1320	1594
Velero	36	72	2530	1640	1872
San Clemente	36	108	2074	1865	1787
No Name	18	36	1885	380	1530
Outer	27	80	2050		
Animal	27	130	2020		1920
Colnett	45	140	2280		2100
Soledad	54	125	3200		2290
San Quintin	80	220	2900		2290
San Isidro	18	70	1600		
Blanca	15	25	1865		

TABLE 3: Average annual volume of terrigenous deposition X 10^6 t/yr for California Borderland (from Schwalbach and Gorsline, 1985).

BASIN	Volume ($\times 10^6$ t/yr)	Percent of Total Deposition
Santa Barbara	2.04	20
Santa Monica	1.19	12
San Pedro	0.31	3
Santa Cruz	0.37	4
Santa Catalina	0.21	2
San Nicolas	0.25	2
Tanner	0.07	0.6
Long	0.09	0.8
Velero	0.04	0.3
No Name	0.03	0.2
Cortes (West+East)	0.16	2
San Diego Trough	0.14	1
San Clemente	0.16	2
Slopes	0.65	6
Shelf	3.00	29
Southern Borderland	1.50	15
TOTAL	10.21	100

large terrigenous input from coastal rivers trapped by bathymetry. Central basins receive minor suspended terrigenous load and biogenous load. Outer basins receive essentially oceanic hemipelagic particulates dominated by California Current transport.

Figure 7- Santa Monica Basin Plio-Pleistocene sediment fill based on seismic reflection profiling data courtesy of Union Oil Company of California (Teng, 1985). At typical acoustic velocity of 1800 m/sec in deeper sediments 100 msec of two-way travel time is approximately 100 m thickness for rough estimate of depth of fill.

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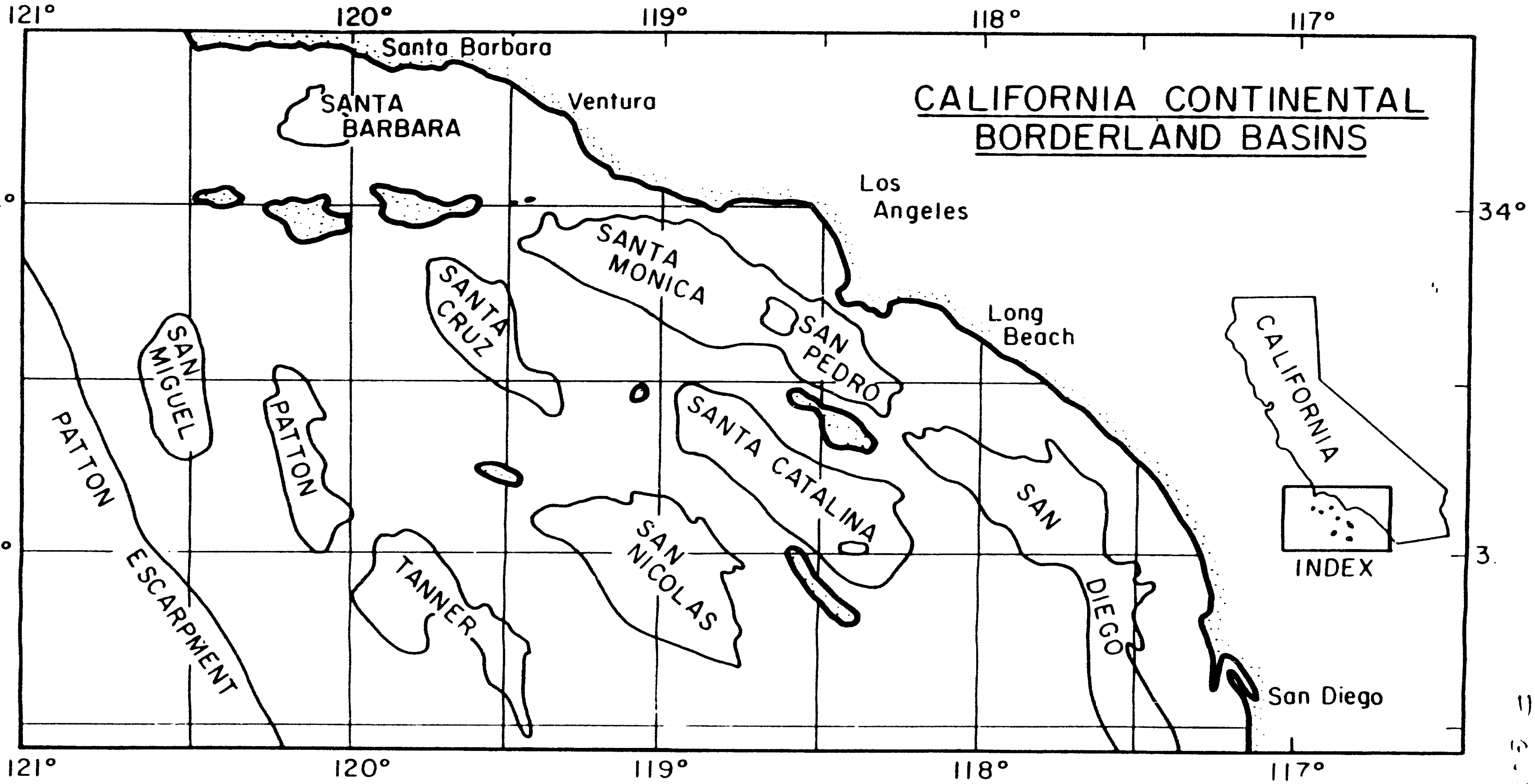
Figure 12- Mean particle diameters (phi notation), for top 2 cm of Santa Monica Basin bottom sediments. Compare with Figure 12.



CALIFORNIA CONTINENTAL
BORDERLAND BASINS
121°
120°
119°
118°
117°
34°
33°
Santa Barbara
Ventura
Los Angeles
Long Beach
San Diego
SANTA BARBARA
SANTA MONICA
SAN PEDRO
SANTA CRUZ
SANTA CATALINA
SAN NICOLAS
SAN MIGUEL
PATTON
TANNER
SAN DIEGO
PATTON ESCARPMENT
CALIFORNIA
INDEX

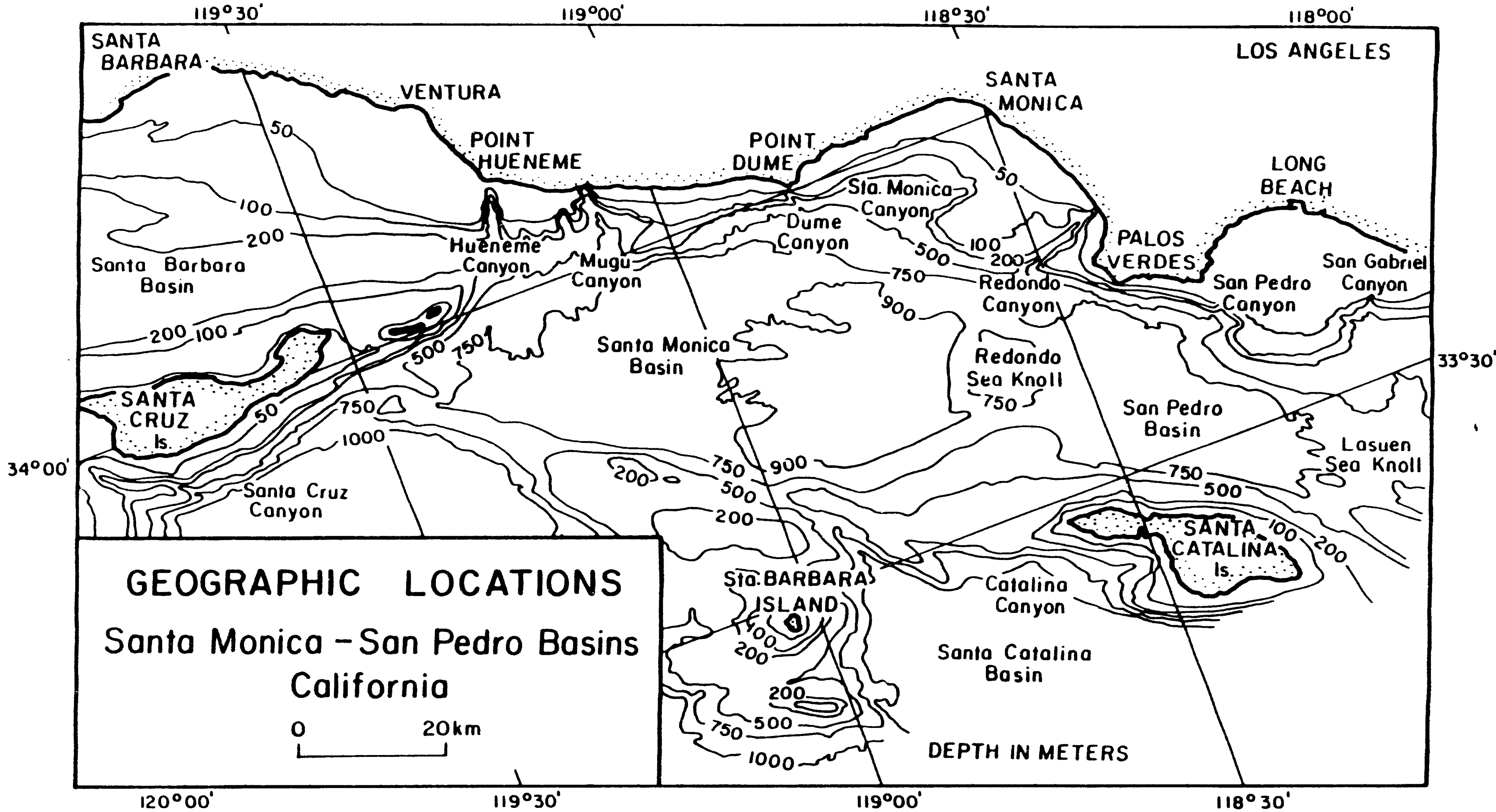

GEOGRAPHIC LOCATIONS
Santa Monica - San Pedro Basins
California
0 20km
119°30'
119°00'
118°30'
118°00'
120°00'
34°00'
33°30'
SANTA BARBARA
VENTURA
POINT HUENEME
POINT DUME
SANTA MONICA
LOS ANGELES
LONG BEACH
PALOS VERDES
Santa Barbara Basin
Hueneme Canyon
Mugu Canyon
Sta. Monica Canyon
Dume Canyon
Redondo Canyon
San Pedro Canyon
San Gabriel Canyon
Santa Monica Basin
Redondo Sea Knoll
San Pedro Basin
Lasuen Sea Knoll
SANTA CRUZ Is.
Santa Cruz Canyon
SANTA CATALINA Is.
Sta. BARBARA ISLAND
Catalina Canyon
Santa Catalina Basin
DEPTH IN METERS

Figure 3

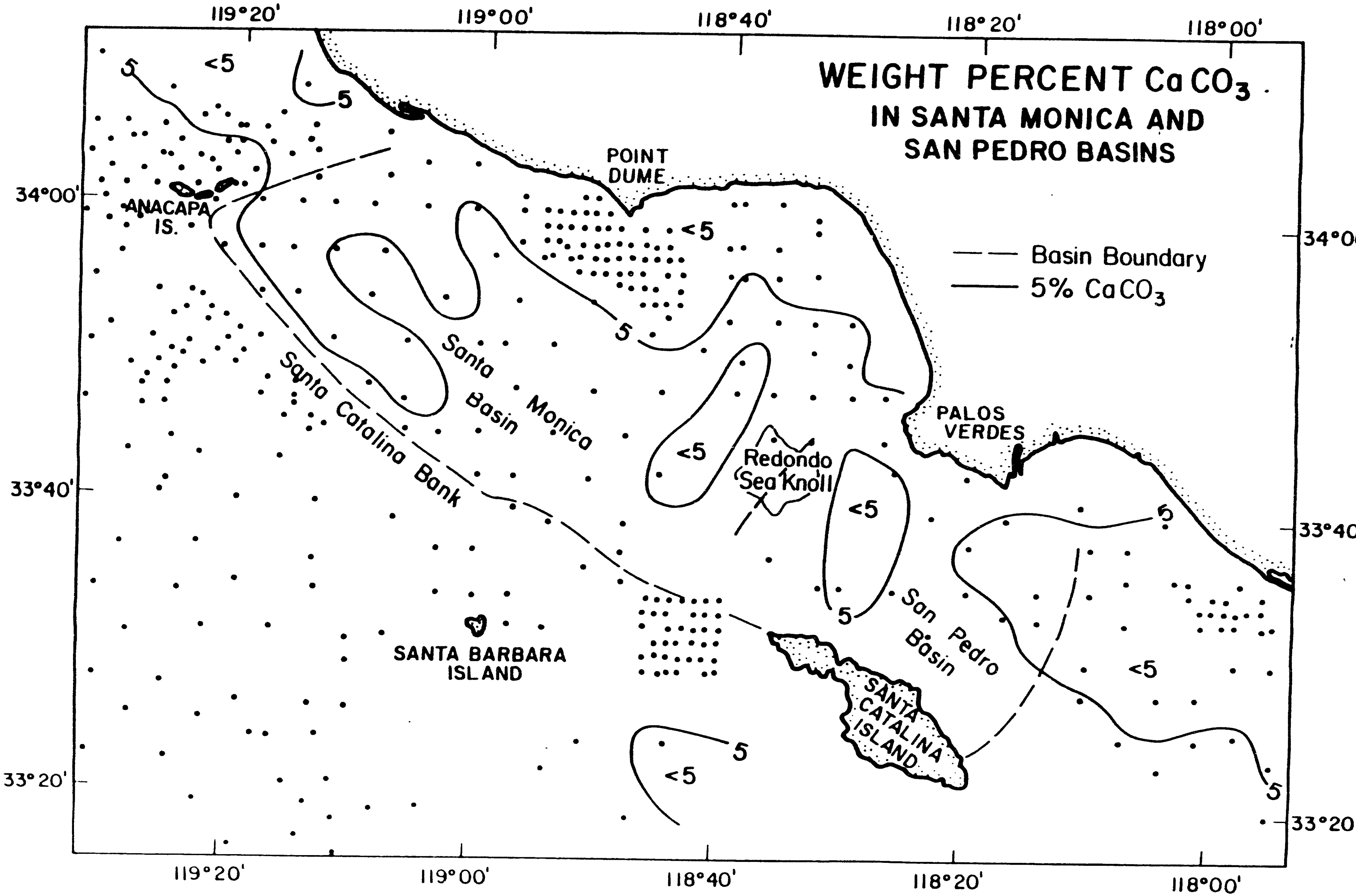
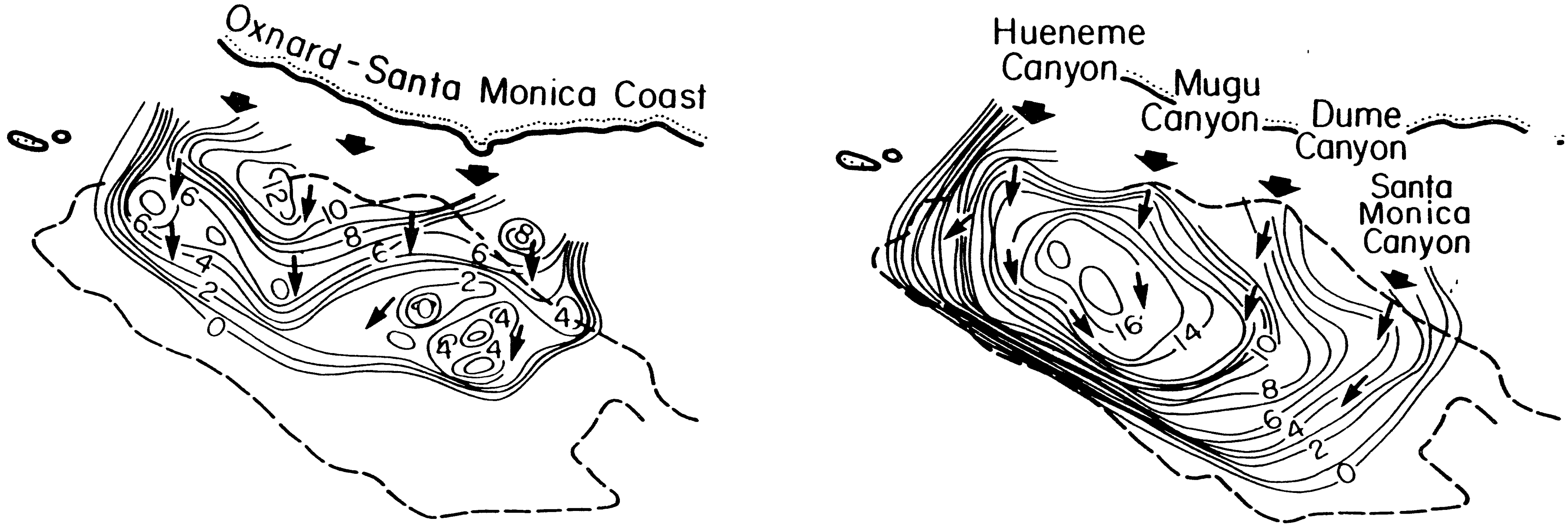

WEIGHT PERCENT $CaCO_3$
IN SANTA MONICA AND
SAN PEDRO BASINS
Basin Boundary
5% $CaCO_3$
119°20'
119°00'
118°40'
118°20'
118°00'
34°00'
33°40'
33°20'
POINT DUME
ANACAPA IS.
PALOS VERDES
Santa Monica Basin
Santa Catalina Bank
Redondo Sea Knoll
San Pedro Basin
SANTA BARBARA ISLAND
SANTA CATALINA ISLAND
<5
5

FIGURE 5

BASIN ISOPACHOUS MAPS

SANTA MONICA BASIN



P1 - Lower Pliocene

P2 - Plestocene & Upper Pliocene

BASIN OUTLINE

CONTOUR INTERVAL : 100 msec. TWO-WAY TIME

0 10 km

N

FIGURE 11

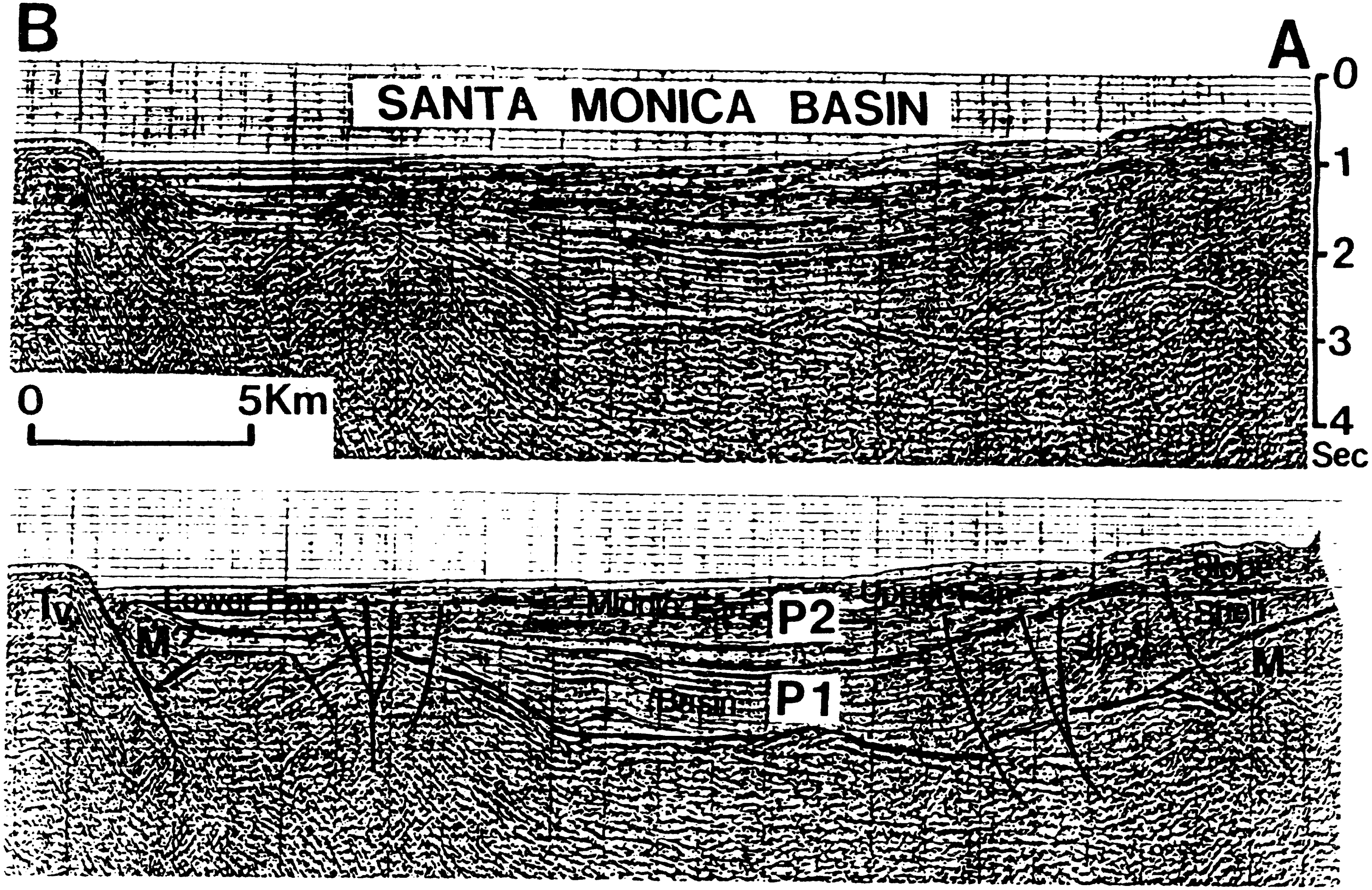
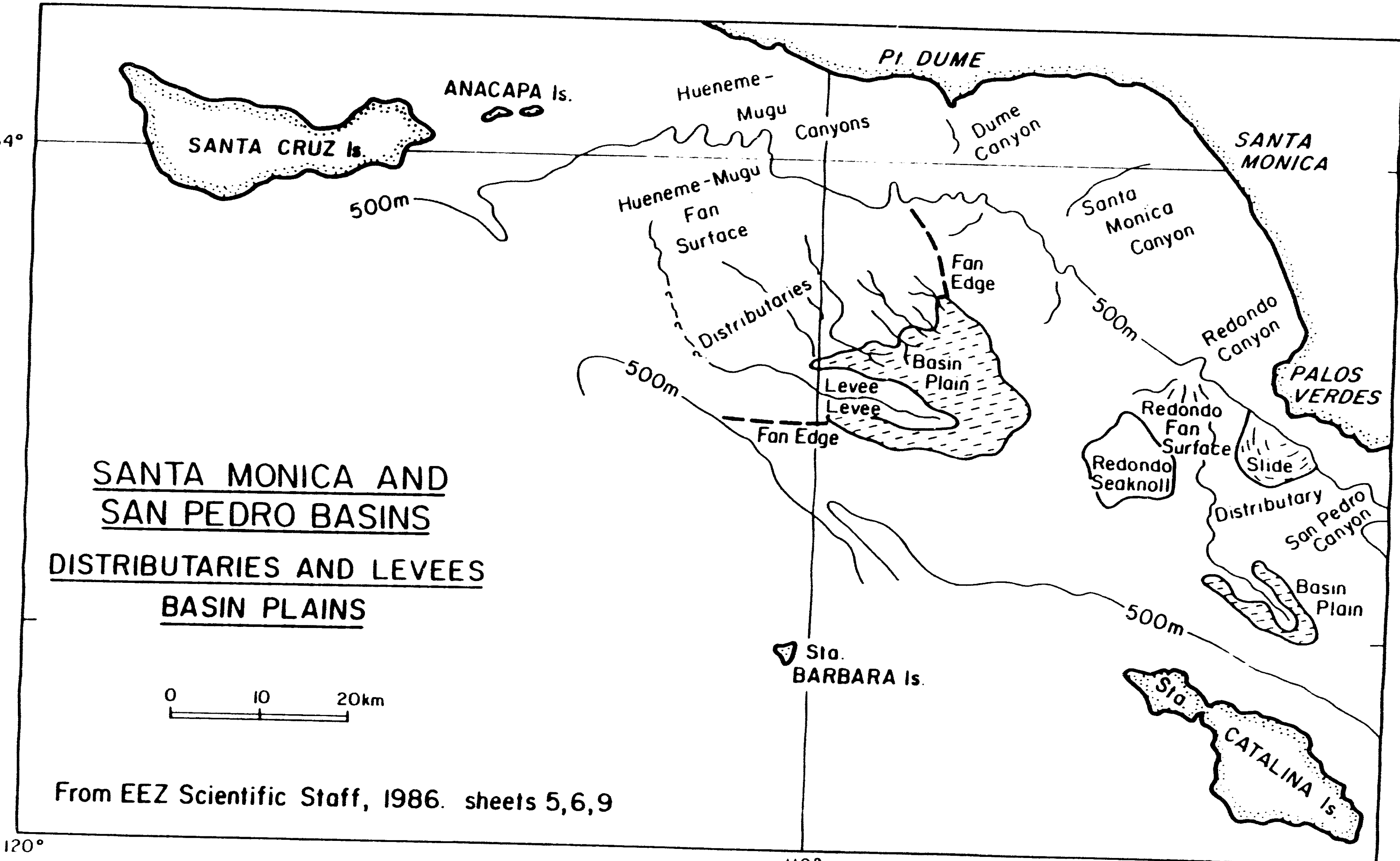

B
A
SANTA MONICA BASIN
0
1
2
3
4
Sec
0
5Km
Tv
M?
Lower Fan
Middle Fan
P2
Upper Fan
Slope
Shelf
Slope
M
Basin
P1

FIGURE 9



SANTA MONICA AND SAN PEDRO BASINS

DISTRIBUTARIES AND LEVEES

BASIN PLAINS

From EEZ Scientific Staff, 1986. sheets 5,6,9

SANTA MONICA BASIN FLOOR

0-2cm Textural Data

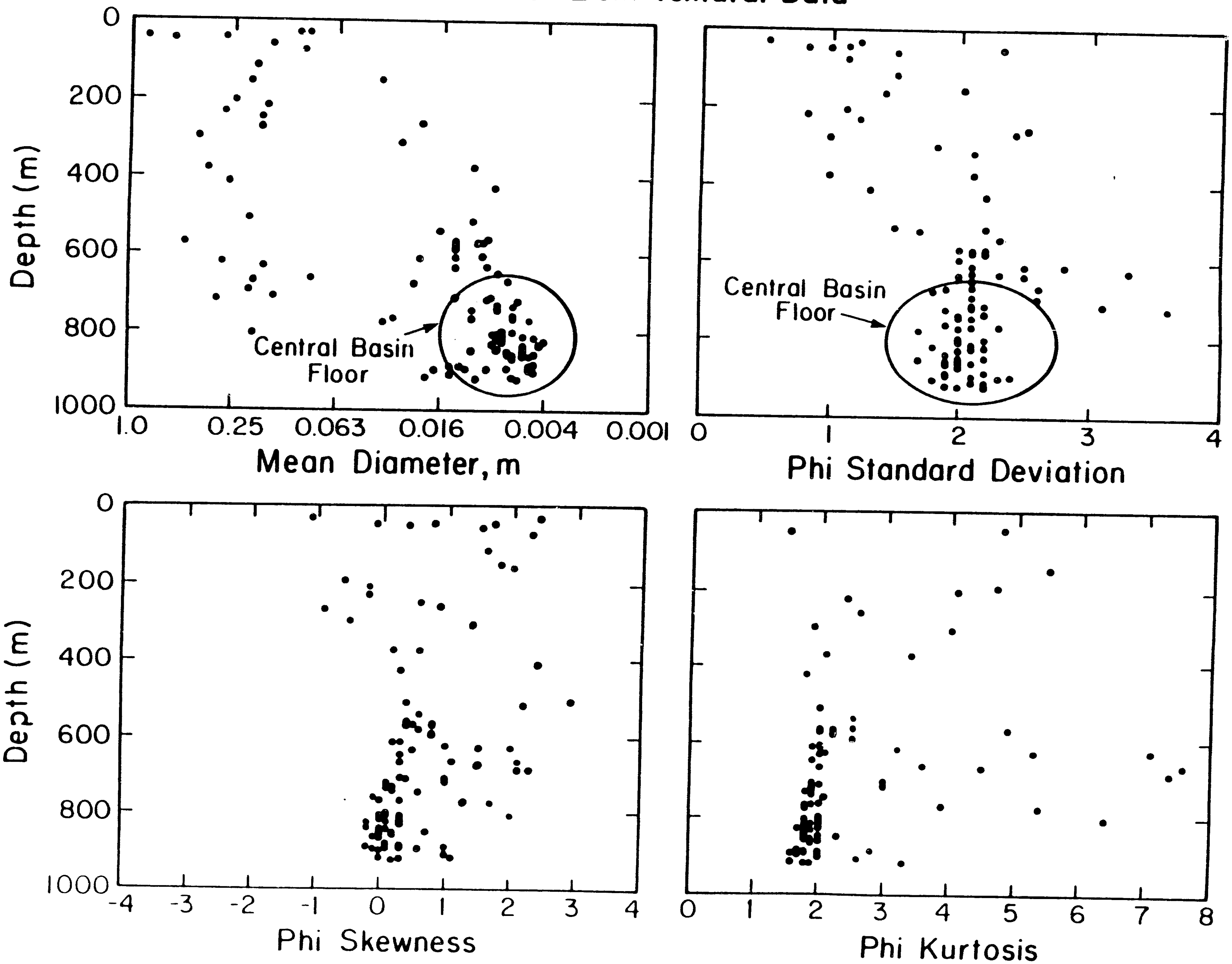
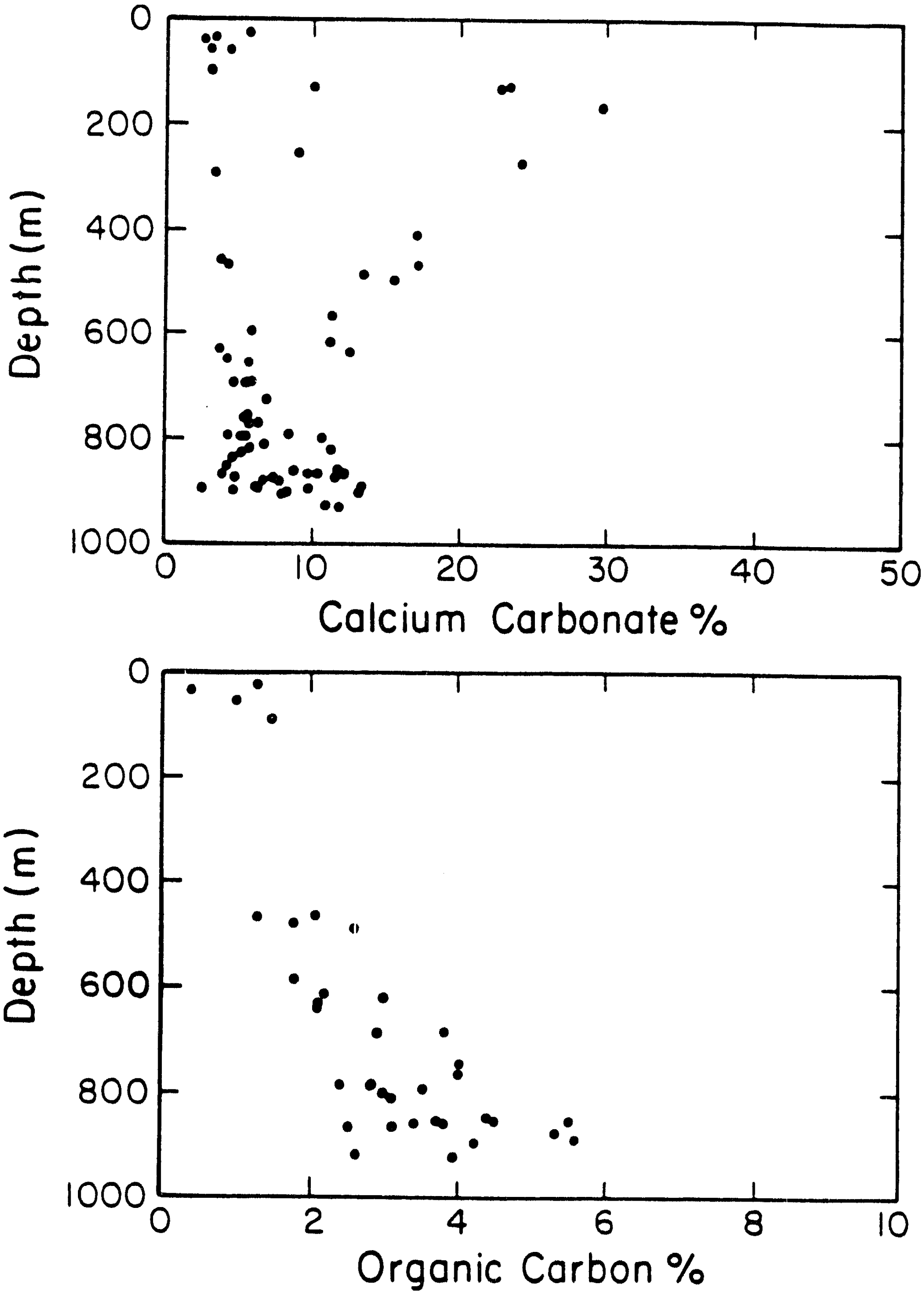


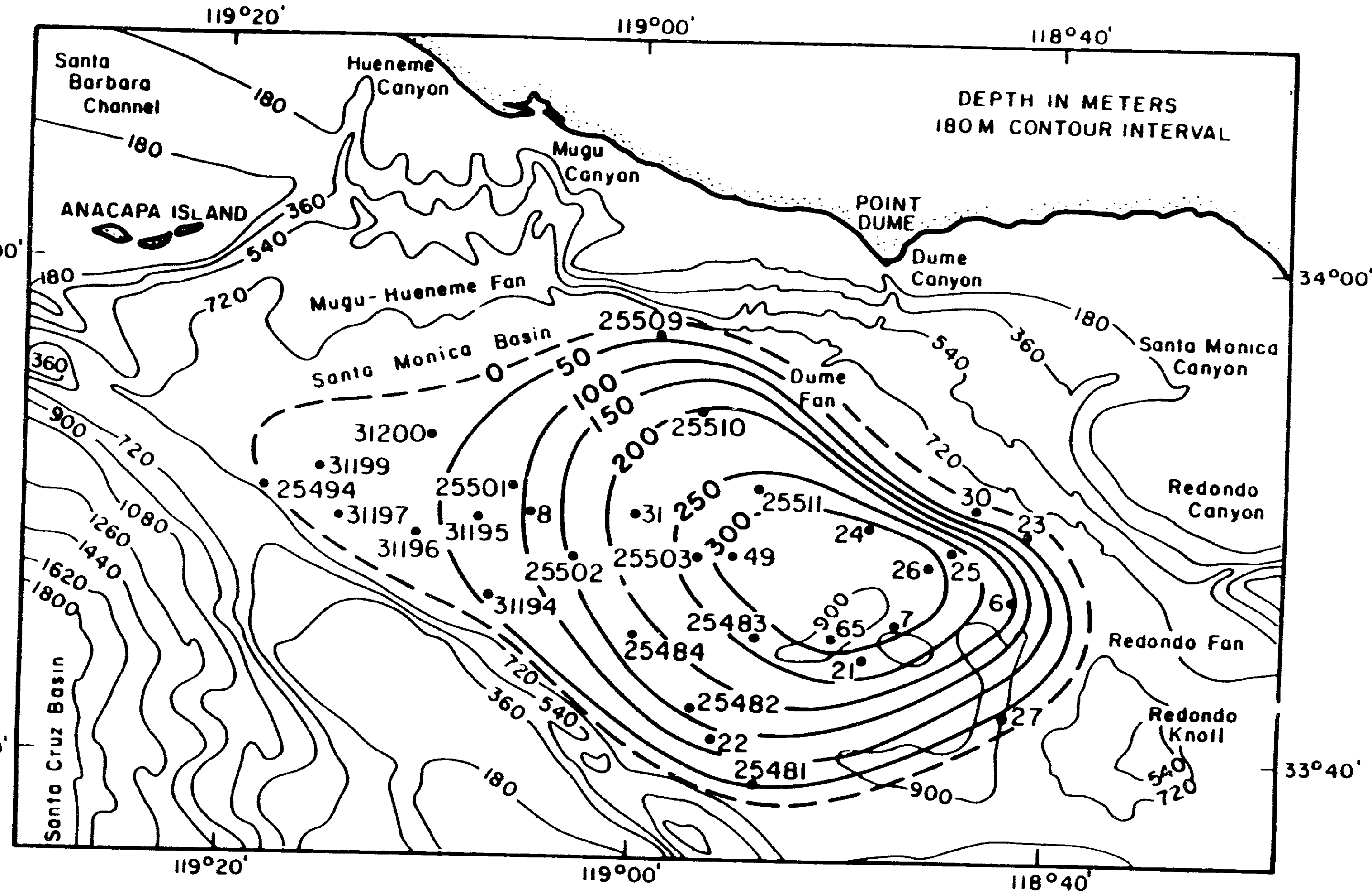
FIGURE 5

SAN PEDRO BASIN

0-2cm Carbon/Carbonate Data



SANTA MONICA BASIN
AGE OF BASE OF LAMINATED ZONE



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DATE
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2/25/94