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HISTORY OF FISH POPULATIONS INFERRED FROM FISH SCALES IN ANAEROBIC SEDIMENTS OFF CALIFORNIA

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INTRODUCTION

Over the years the remains of many marine organisms along with land-derived detritus, fall to the floor of the ocean. There, if conditions are favorable, the sediment accumulates and so preserves a record of biologic and oceanographic events. In most regions this natural record is destroyed or distorted by the activity of large benthic animals. The burrowing and digestive actions of benthonic animals destroy fragile organic structures, promote bacterial decay and inorganic dissolution, stir the sediment, and destroy potential layering.

There are, however, exceptional situations where benthic animals are excluded and sediments are permitted to accumulate undisturbed. The factor responsible for the exclusion of macro-benthos is a continued anaerobic condition. Dissolved oxygen is mainly consumed in the decomposition of organic matter. Thus, besides other factors, a high productivity in the overlying waters is conducive to the formation of low-oxygen bottom water. Since the highest productivity occurs in regions of upwelling relatively close to shore, it is not surprising that the highest incidence of anaerobic sedimentation also occurs in these same regions. Off the west coast of North America there are several such areas (Figure 1). These are: the Santa Barbara Basin, the Santa Monica Basin, the San Pedro Basin, California (Emery, 1960); the Saanich Inlet, British Columbia (Gucluer and Gross, 1964); the basin north of Cabo San Lazaro, Baja California (d'Anglejan, 1965); and the Gulf of California (Revelle, 1939; Calvert, 1966).

Some elevated formations that are thought to have been deposited under conditions similar to those now present in these basins, have been examined. The Monterey shales, as an example, are highly stratified. Cleavage faces along bedding planes of these shales display an abundance of marine fish remains, and particularly a dense "peppering" of scales of pelagic fish. The sediments of the Santa Barbara Basin are strongly stratified, and the following discussion will be concerned principally with these materials.

SETTING OF THE SANTA BARBARA BASIN

The Santa Barbara Basin off Santa Barbara, California, has been studied in some detail. Situated inside Point Conception and receiving surface waters from a reverse arm of the main southward flow of the California Current System, the above sill depth portions of the basin are reasonably representative of the surrounding ocean. The surface waters are near the end of the well-defined intrusion of subarctic waters into the subtropical zone. To the south mixing with the Central water is rapid and by lat. 25° N. the mixed waters turn westward into the North Equatorial Current (Reid *et al.*, 1958). The Santa Barbara Basin thus lies in a position to be sensitive to major oceanographic and biologic events emanating from both the north and the south. The basin is also adjacent to and part of important spawning, growing, and fishing areas of several major pelagic fish species.

THE MICROPALEONTOLOGIC RECORD OF THE SANTA BARBARA BASIN

The biologic record within the sediments of the Santa Barbara Basin covers a wide range of ecologically- and economically-important organisms (Soutar, in press).

The ecologically-important organisms include species of Diatomacea, Radiolaria, planktonic Foraminifera, and pelagic Mollusca. Significant records of Coccolithophoridae and Dinoflagellitae most likely also exist. Much of the informational value of these taxa lies in their reflection of oceanic productivity, water masses and other oceanographic conditions.

The economically- and ecologically-important organisms include the major pelagic fish species of the California Current System. Bones, otoliths, and the scales of many species have been observed, and the scales of the Pacific sardine (*Sardinops caerulea*) the northern anchovy (*Engraulis mordax*), and the Pacific hake (*Merluccius productus*) are regularly encountered in the sediment (Soutar, 1967).

The truly unifying aspect of anaerobic sediments results from their ability to preserve in detail compositional changes in sediment reaching the bottom. At the latitude of the Santa Barbara Basin winter rains result in runoff from land, which produces a relatively dense layer of sediment. The summer sediment, composed mainly of diatom frustules, is less dense. The alternation of layers constitutes a varve and is in general thought to be equivalent to a single year. The alternation of sediment composition is not limited to gross features. Near-surface Radiolaria, which undergo a seasonal change in species composition, apparently show this change in the winter and summer sediment layers (Casey, pers. comm.).

Previous workers had considered the time record too incomplete for detailed paleo-ecologic study

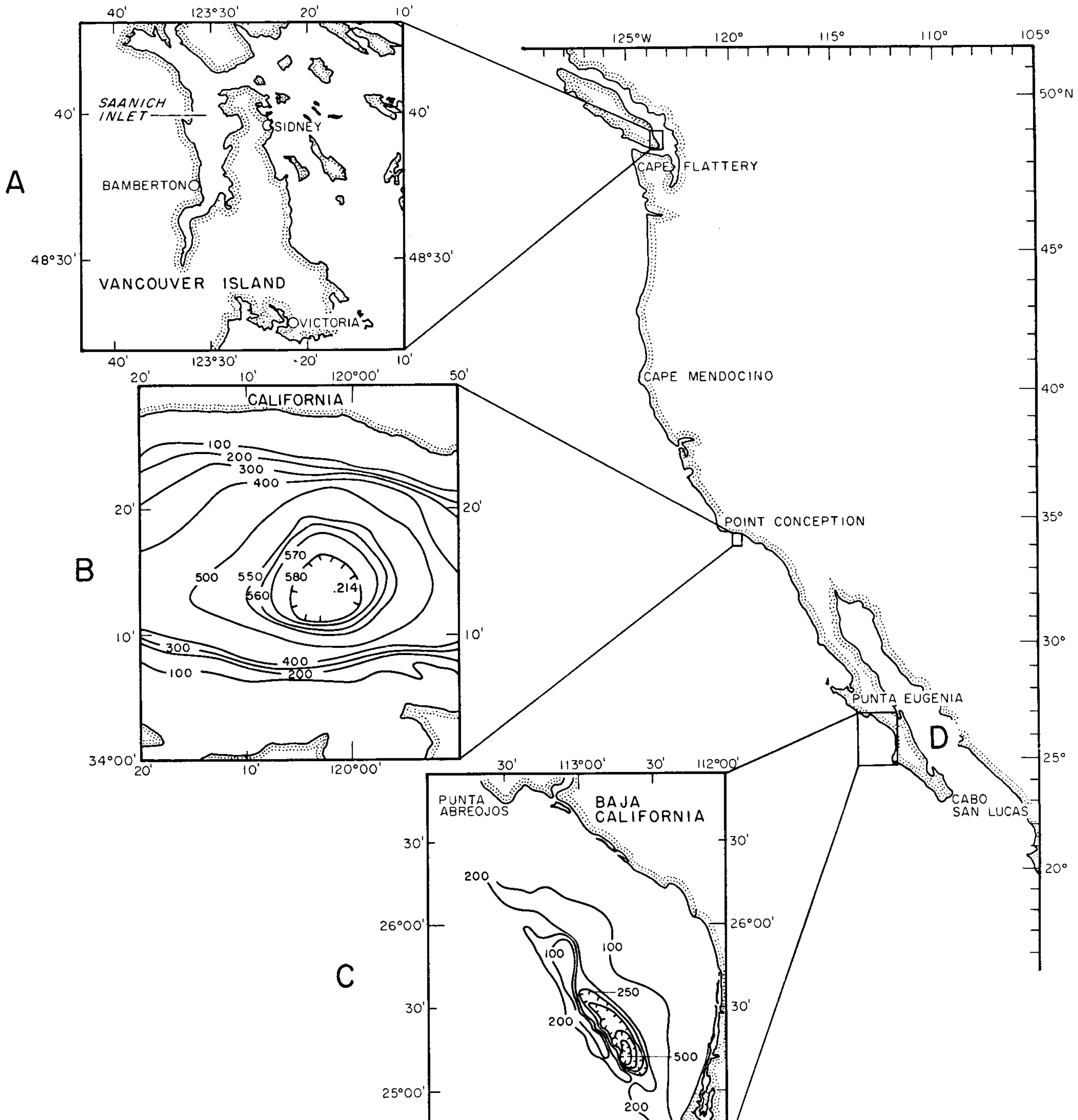

FIGURE 1. A. Saanich Inlet, British Columbia; B. Santa Barbara Basin, California. (The San Pedro and Santa Monica Basins lie just south of the Santa Barbara Basin.); C. Basin north of Cabo San Lazaro, Baja California; D. Gulf of California.

(Hulsemann and Emery, 1961). However, improved coring and observation techniques have subsequently shown quite complete sequences of varves and so revealed a remarkable time-biologic record (Soutar, in press). As an example, Figure 2 is a positive print of a radiograph of the top of core 230 from the Santa Barbara Basin. This core shows that the sediment varves extend up to the sediment-water interface.

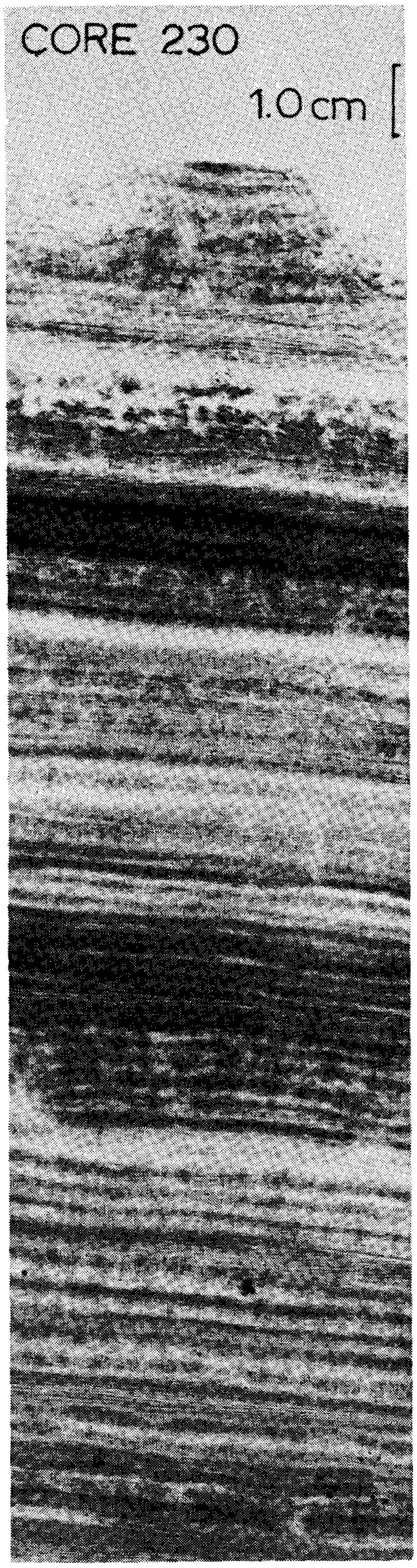

FIGURE 2. Santa Barbara Basin Core 230. Positive print of radiograph of core. Dark areas are the most dense and represent winter sedimentation. The lighter and less dense layers are mainly composed of diatoms and represent summer sedimentation. The layering extends to the water-sediment interface.

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TREATMENT OF SEDIMENT SAMPLES

Core samples are subsampled at precise centimeter by centimeter intervals. The subsamples are disaggregated and wet screened into various size fractions from 500 to 25 microns. The basic data collected from the core subsamples is the number and sizes of the various inorganic and biologic components and the number of varves. A time series for each component may be constructed from these data. The high sedimentation rates within the Santa Barbara Basin now allow the construction of series with time intervals down to 10 years, and eventually, perhaps, to even finer time increments.

SANTA BARBARA BASIN, CORE 214

The specific sediment record that will be considered is that of Santa Barbara Basin, Core 214. This core is a 2.5 m (8.20 feet), 7.6 cm (3.0 inches) diameter fixed-piston core collected from the central basin area at lat. 34° 13.6′ N., long. 120° 01.7′ W. at a depth of 585 m (1,917 feet). This core is one of a series of complementary cores designed to extract a detailed and well-defined historical record from the basin.

The time series constructions for the Pacific sardine, the northern anchovy, the Pacific hake, the northern pteropod, *Limacina helicina,* and varve counts, are presented in Figure 3. The time interval is 10 years and in this figure is given as estimates of years before the year 2000 AD and of the year AD. The time series in Figure 3 shows a number of features, which are generally and qualitatively supported by data from all cores taken in the basin.

These are:

1) The occurrences of scales of the Pacific sardine are distinctly aggregated throughout the 1,850 year record. The clumps of scales are of varying intensities, the greatest occurring about 1,000 years ago. The most recent clump associated with the past sardine fishery is relatively moderate in intensity.

2) Northern anchovy scales decrease in occurrence from about 1,600 years ago to the present, but are always abundant.

3) The occurrences of Pacific hake scales continuously dominates the numbers of scales present but appears cyclical. This cyclic tendency is especially developed in the past 1000 years.

4) The combined fish group presents a relatively even distribution through time.

These same observations can be made on a set of cores taken three miles to the east (Soutar, 1967). This parallel set of observations suggest that on the size scale or core samples information pertinent to the entire basin has been preserved.

There are two main threads of information interwoven in the time series constructions of core 214. These are: information concerning the individual series of scales from a species and information on the interrelationships between the several series. Only the individual scale series will be considered here. The northern anchovy may be taken as an example. The scale-width-frequency-distribution of the scales of

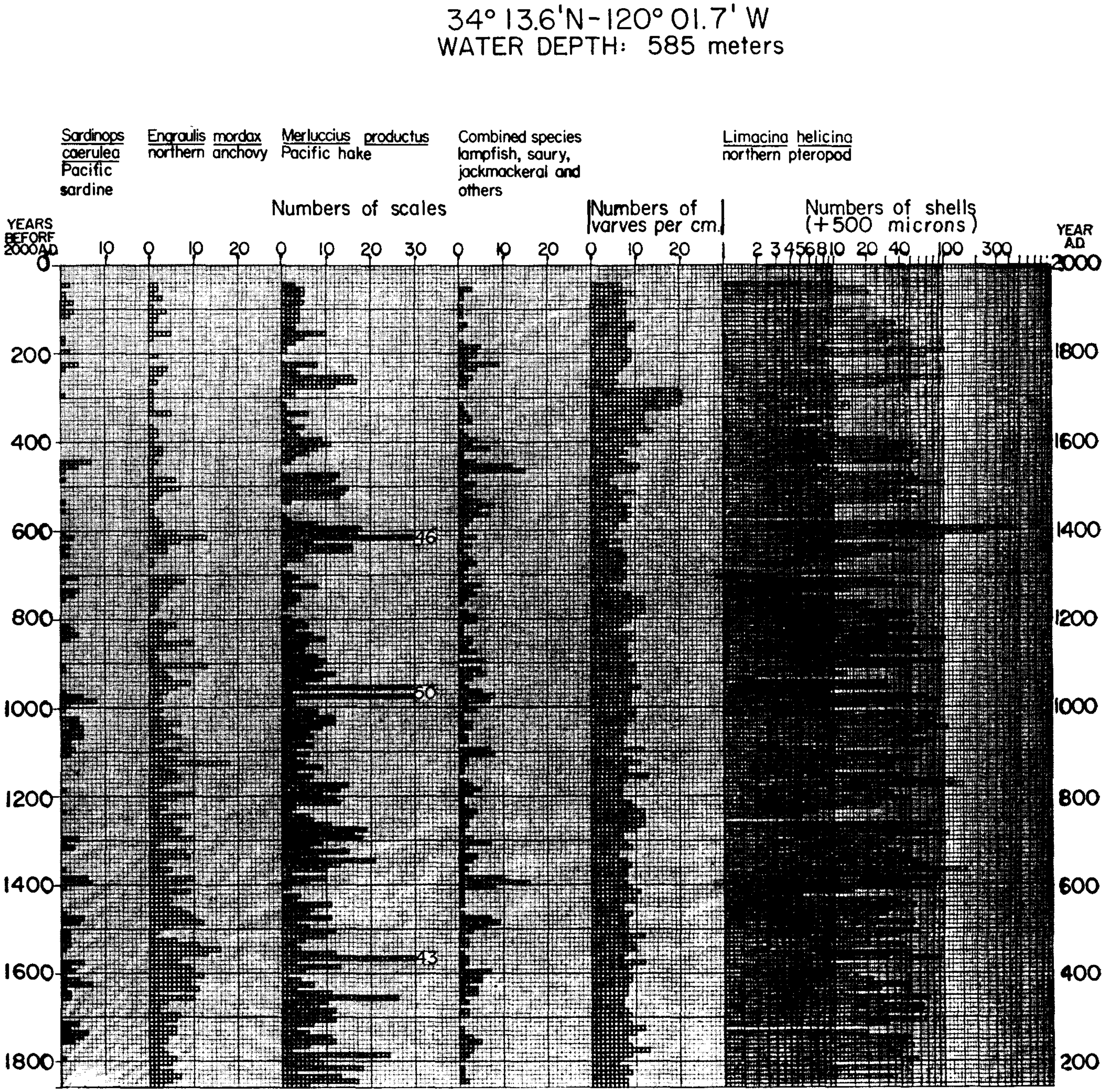

FIGURE 3. Santa Barbara Basin Core 214. Time series construction for the Pacific sardine, the northern anchovy, the Pacific hake, a combined fish species group, the northern pteropod *(Limacina helicina)*, and varve count.

this species for Santa Barbara Basin, core 214, is shown in Figure 4. The scale width may be used to estimate the length of the fish from which it originated. This transformation results in a derived length-frequency distribution (Figure 5). The peak of the distribution occurs at about 100 mm (3.94 inches), and limits the reliability of information to fish larger than 100 mm. Such a peaked distribution is characteristic of many sampling programs and the sediments appear to be no exception. For example, length-frequency distributions for fish taken from the fish surveys of the California Fish and Game Department, during 1950–1961 (Heimann, 1965–67) show a similar break at the 100 mm length. The derived length-frequency distribution can be regrouped into a derived age-frequency distribution by means of the growth curve of the northern anchovy, which relates length to age. The result of the regrouping in the case of the sediment data is given in Figure 6. The semi-log plot used in Figure 6 is a useful method of

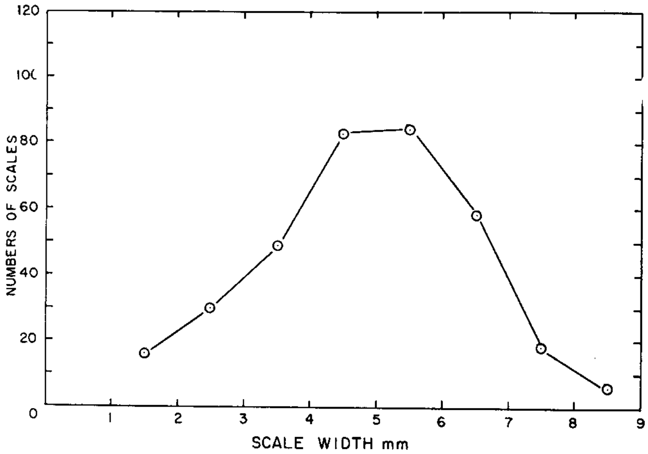

FIGURE 4. Northern anchovy, Santa Barbara Basin Core 214: scale width-frequency distribution. The scale width was chosen as it is a better preserved parameter of the scales in the sediments.

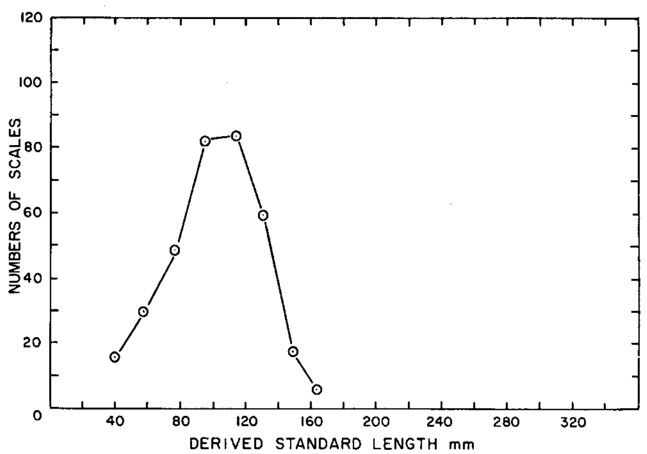

FIGURE 5. Northern anchovy, Santa Barbara Basin Core 214: derived standard length-frequency distribution.

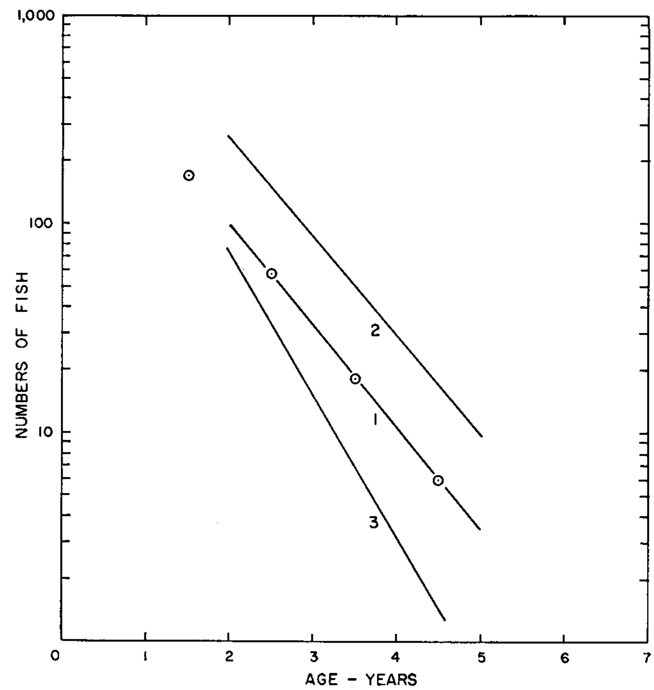

FIGURE 6. Northern anchovy, derived age-frequency distribution. 1. Derived* age-frequency distribution, Santa Barbara Basin Core 214; 2. Derived* age-frequency distribution, CalCOFI 1953–1961 data; 3. Age-frequency distribution, CalCOFI 1953–1961 data.
* Length to age transformation by growth curve.

presenting age-frequency distributions. The observed exponential decrease of fish of a single year class tends to a straight-line relation in such a plot. The slope of this line then contains a measure of survival. Furthermore, the mortality for a single year class is also an exponentially-decreasing function that has the same slope as the age-frequency distribution. This characteristic allows a direct comparison between sediment information and contemporary ecologic information. Included in Figure 6 is a summary plot of relative age-frequency taken from the 1953–1961 CalCOFI data reports. In general it can be seen that the sediment and the ecologic information agree.

The same kind of development can be made for the Pacific sardine and the Pacific hake. The agreement of the sediment and ecologic data in the case of the Pacific sardine seems quite good. The lack of ecologic information on the Pacific hake limits an assessment of the sediment information.

The minimum number of fish that sedimented scales represent may be estimated by dividing the total number of scales deposited over a given area by the number of scales per individual fish. Furthermore, the estimates of fish numbers may be limited to one year old and older fish by means of the age-frequency distribution (Figure 6).

If the estimates of minimum numbers of fish are thought of as estimates of yearly natural mortality, then an estimate of the number of living fish necessary to support the mortality may be attempted. Basically the method involves assuming that an average or steady-state population concentration and age-frequency distribution exists for a period of time. This allows a measure of an average minimum population level for that particular time period.

APPLICATION TO SANTA BARBARA, CORE 214

Minimum population levels per km^2 (0.386 sq. miles) for pelagic fish have been estimated for the area of the Santa Barbara Basin. A certain amount of subjectivity is involved in selecting time periods that will adequately portray the features of the sediment record. In the case of the Pacific sardine, the clumped distribution naturally defines periods of time. The average minimum [1] population levels for these periods are presented in Figure 7. The core record suggests that there have been 12 main occurrences of sardines over the past 1850 years. The average time between occurrences is 80 years with a range of 20 to 200 years and with a duration of occurrences of 20 to 150 years. The highest levels for the minimum population estimate are around 30,000 fish/km^2. The aver-

[1] Since all scales do not find their way to the bottom.

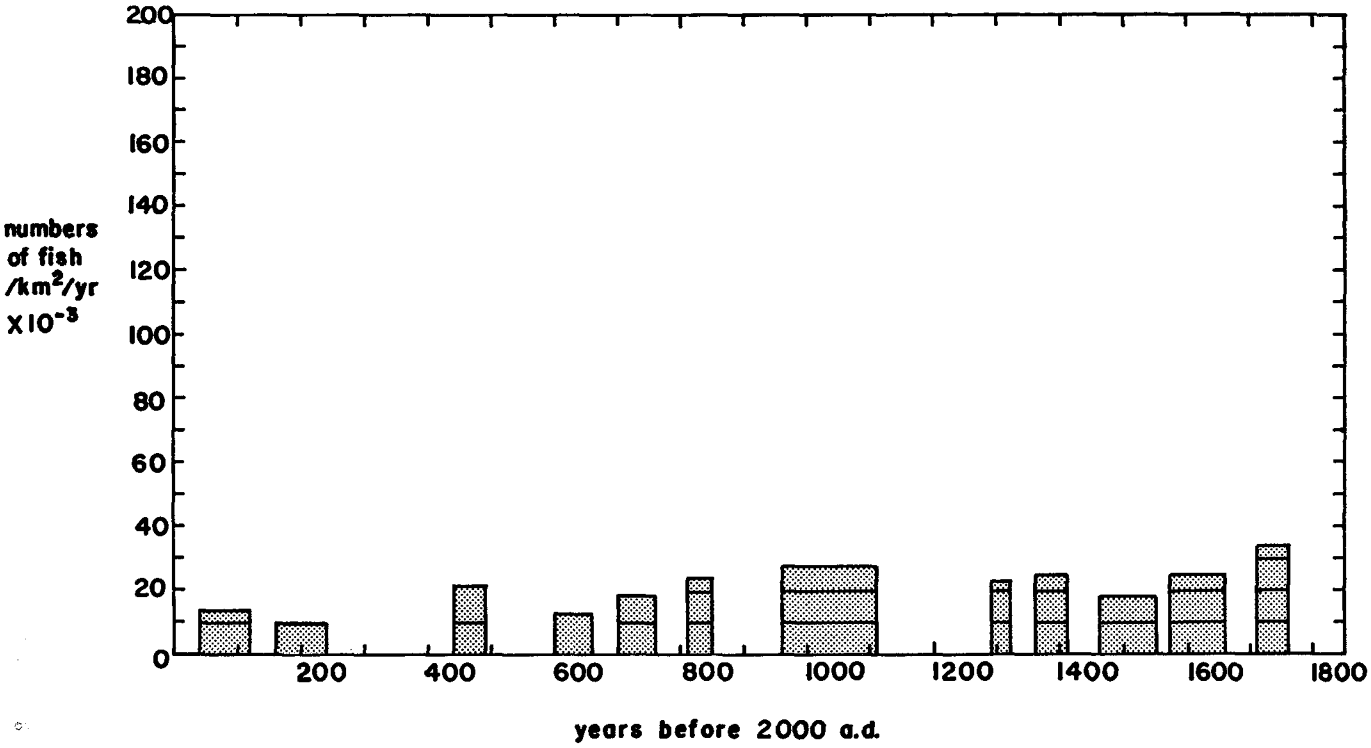

FIGURE 7. Santa Barbara Basin Core 214. Minimum population estimates for one year old and older Pacific sardine in periods of abundance. The average number of scales during each period of abundance was used to estimate the minimum population.

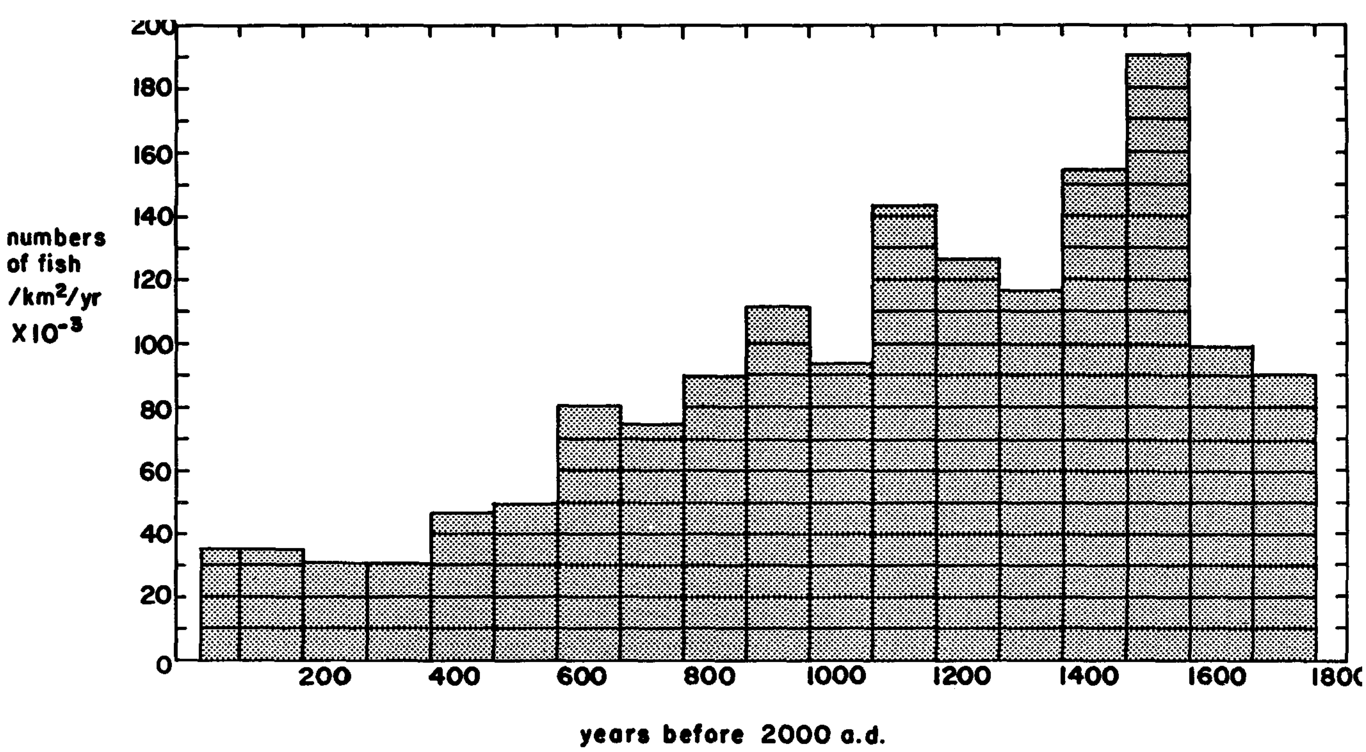

FIGURE 8. Santa Barbara Basin Core 214. Minimum population estimates of one year old and older northern anchovy for 100-year means. The mean number of scales for each century was used to derive the minimum population estimate.

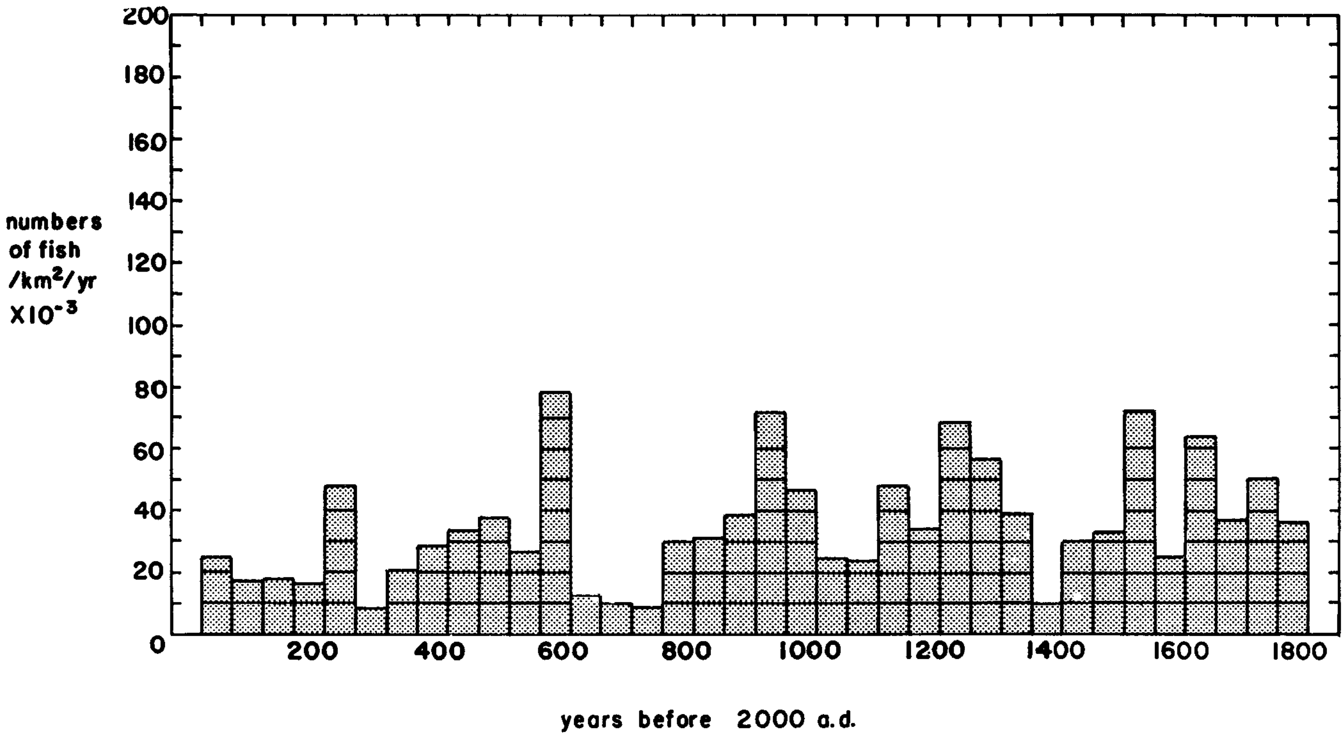

FIGURE 9. Santa Barbara Basin Core 214. Minimum population estimates of one year old and older Pacific hake for 50-year means. The mean number of scales for each 50-year period was used to derive the minimum population estimate.

age level associated with the past sardine fishery was about 15,000 fish/km^2.

The minimum population estimates based on 100-year intervals are presented for the northern anchovy in Figure 8. The average levels are considerably higher than in the case of the sardine; furthermore, there is a striking decrease from the level of about 180,000 fish/km^2 about 1,500 years ago to the recent level of around 35,000 fish/km^2.

The present estimated population of post-juvenile anchovies is 2 to 5 million tons over an area of perhaps 600,000 km^2. Hence an estimate of the present density of post-juvenile fish is 180,000 to 450.000 per km^2. Considering that only a fraction of the total scales produced reach the sediments the present day fish density is in reasonable accord with the above estimates from the sedimentary record.

In the case of the Pacific hake, 50-year intervals provide a somewhat better reflection of the distributional fluctuations shown in Figure 3. The levels, as shown in Figure 9, are intermediate between the sardine and the anchovy. The age-frequency information in the sediments for this species suggests an outward migration of fish 1 year old and older. This would conform with the observations of Best (1966) and would explain the relatively low minimum population levels of Figure 9.

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