ABUNDANCE OF PELAGIC FISH DURING THE 19TH AND 20TH CENTURIES AS RECORDED IN ANAEROBIC SEDIMENT OFF THE CALIFORNIAS

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ABSTRACT

Anaerobic sediment preserves a chronographic record of the bioclimatological conditions in coastal seas. Of the myriad elements within this record, the accumulation of pelagic-fish debris is of particular interest. The deposition of scales of the Pacific sardine, the northern anchovy, the Pacific hake, the Pacific saury, and the Pacific mackerel in the sediment of the Santa Barbara Basin, Alta California, and the Soledad Basin, Baja California, is generally in accord with available population estimates. The relation between scale deposition and population, when applied to the sedimentary record over the past 150 yr, suggests that major pelagic-fish productivity between 1925 and 1970 was substantially below pre-1925 levels.

Man in his search for an environmental perspective has unearthed a number of natural chronographic records. These include the well-known growth rings of trees (Fritts, 1972), the deposition of annual strata in the snowfields of Greenland and Antarctica (Murozumi et al., 1969), the incremental growth of coral and stromatolites (Knutson et al., 1972; Panella et al., 1968), and the formation of annual layers in certain lacustrine and marine sediments (Seibold, 1958).

Perhaps no richer records exist than those finely laminated deposits encountered beneath the sea in regions of anaerobic sedimentation. A web of circumstance involving productivity and topography serves to produce and protect such records, but no factor can be more important than the exclusion of burrowing animals from the sediment by a persistently low dissolved oxygen concentration in the bottom water. Here such diverse and informative fragments of the air-sea-land system as the tests of the microplankton, skeletal and integument debris from the nekton, air- and river-borne detritus, natural radioisotopes, and more recently, anthropogenic products fall in sequential association to a common resting place. Undisturbed, these threads of information accumulate to form a remarkable sedimentary chronicle combining the rhythmic pulse of the seasons with the vagaries, trends, and inconsistencies of ocean life, chemistry, and currents.

Of the myriad elements within the anaerobic sediment record, the temporal framework and the distribution of pelagic fish scales at depth in the sediment in the Santa Barbara Basin, Alta California (Figure 1a), and in the Soledad Basin, Baja California (Figure 1b), compose a particularly relevant set—relevant not only in relation to the continuing importance of pelagic fish as a resource off the Californias, but also as a potential indicator of long-term productivity and change. Such knowledge of ocean conditions within the broader context of the North Pacific gyre and the Northern Hemisphere climate can aid man in his search for a rational interaction with his environment, guide him toward a wise stewardship of marine resources, and aid him in discriminating between those changes that he produces by his interventions and those that are a part of the natural order.

Time in the laminated sediment of the Santa Barbara Basin can be estimated through the serial assignment of the year of deposition to each laminae pair (Figure 2a). It was suggested that the regular alternation of sediment density is a direct response to the monsoonal climate affecting southern California (Emery, 1960). Confirmation of this and the laminae pair sequence as a yearly depositional record has come through the correlation of regional rainfall and sediment-laminae patterns.[2] As indicated (Figure 3), the essentially random pattern of southern California seasonal

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[2]Soutar, A., J. D. Isaacs, P. A. Crill. Recent paleoclimatology and paleoecology of the Santa Barbara Basin. Unpubl. manuscr.

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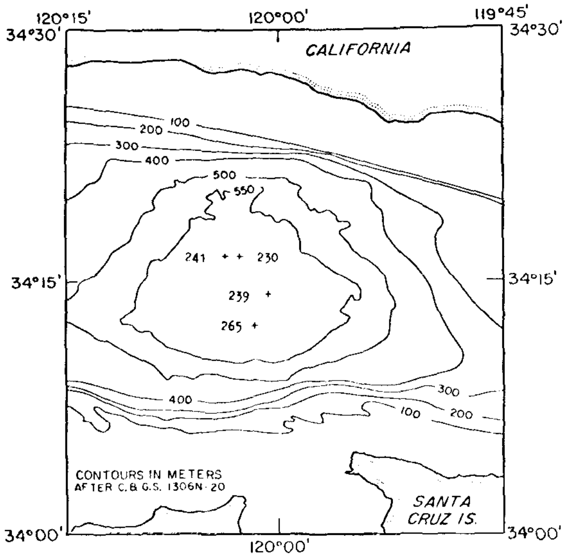


FIGURE 1a.—Santa Barbara Basin, California. The basin lies under the Santa Barbara Channel and reaches a maximum depth of 589 m (Hülsemann and Emery, 1961). Pertinent box-core locations (230,241,239, and 265) are shown.

rainfall can be simply transformed into a clear reflection of the serial pattern of varve thickness. This transformation corresponds to factors such as upstream aggradation (Schumm, 1969) which could cause a considerable delay in basin sedimentation.

Further development of the anaerobic-sediment chronology has been possible through the close agreement of Pb-210 and Th-228/Th-232 radiometric ages and the varve-sequence year (Koide et al., 1972, 1973; Krishnaswami, 1973) (see Figure 4a, b). These relatively short-term radiochronologic tools can be used to considerable advantage in the Soledad Basin sediment. Though this basin is morphologically and oceanographically similar to the Santa Barbara Basin in that there is virtually no dissolved oxygen in the bottom water, the absence of consistent seasonal rainfall inhibits the formation of distinct sequential varves (Figure 2b). Nevertheless, a reasonable time framework can be estimated for the near-surface sediment of the Soledad Basin from the measurement of Pb-210 and the Th-228/Th-232 ratio at depth (Koide et al., 1973) (see Figure 4c, d).

The distribution of pelagic fish-scale debris can be determined within the time-sediment framework. Specifically, large (20 × 20 cm) cores were frozen, then cut into longitudinal sections measuring 5 × 15 × ~40 cm. X-radiograph representations were obtained for each of the sections, and by means of recognizable stratigraphic patterns 5-yr block templates were drawn. In the case of the Santa Barbara Basin sediment, specific laminae can be identified within cores and between cores as to the year of deposition; therefore, precise templates can be constructed. This is particularly so for the time period 1860-1970 in which the laminae are well defined. The period from some time before 1810 to 1860 is partly obscured by bioperturbation apparently supported by a marginal increase in bottom-water dissolved oxygen. Only general sedimentation rates are available for the Soledad Basin sediment; therefore linear estimates of the 5-yr blocks were made for the core slab from which the radiometric ages were obtained. These estimates were carried out to the 90-yr limit of the Pb-210 method and were transferred by available stratigraphic markers to the other core sections. Furthermore, these linear estimates were continued to the bottom of the core, an additional 80 estimated years. It should be noted that the Th-228/Th-232 method permits age estimates in the uppermost sediment of the Soledad Basin that are comparable in accuracy to those in the Santa Barbara Basin. The templates

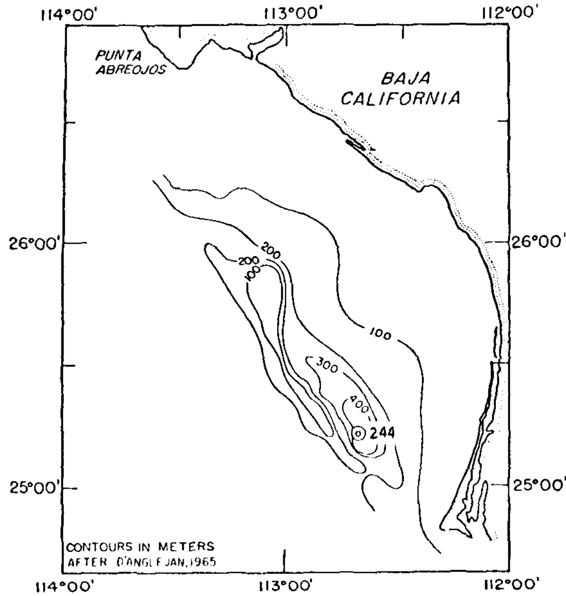


FIGURE 1b.—Soledad Basin, Baja California. This basin lies in a trough trending northwest from Cabo San Lazaro. The maximum depth is nearly 520 m and it occurs in the vicinity of core 244.

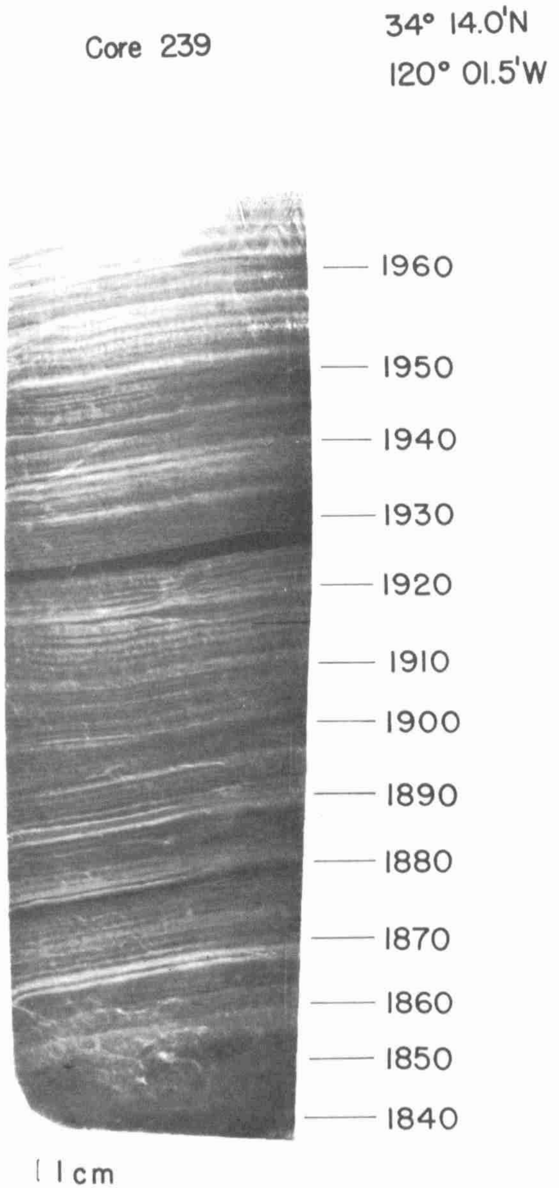


FIGURE 2a.—Radiograph of core 239, Santa Barbara Basin. The radiograph was obtained from a frozen core slab approximately 2 cm thick. The darker laminae are the more dense (negative print of radiograph transparency). Each pair of laminae are considered to be a single year with the denser sediment representing detritus brought in by winter rains (Soutar et al, in prep.).

so constructed were fitted to the frozen core sections by means of morphologic and stratigraphic markers, and the sections were split into the 5-yr blocks. These sediment blocks were subsequently treated with a buffered dilute H_2O_2 solution and gently washed on a 500μ screen. The retained coarse fraction was transferred to vials and stored wet with ethanol as a preservative. Identification and enumeration of the material was carried out at low magnification.

The presence of fish scales in contemporary laminated sediment should not be unexpected, particularly to those acquainted with the stratified diatomite of the Monterey Formation cropping out along the Coastal Range of California (David, 1943). In some instances whole or partial skeletons of fish are present in these deposits.

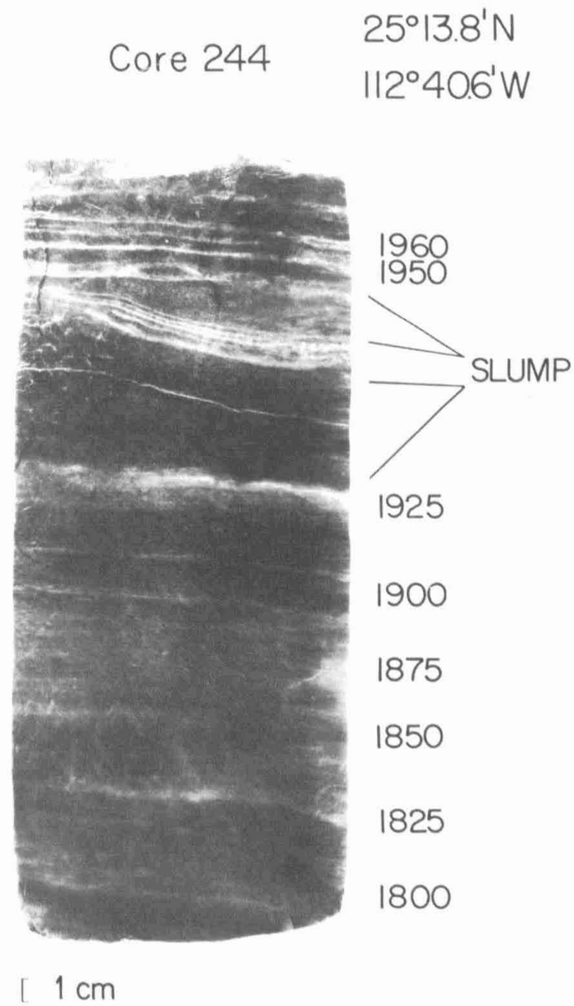
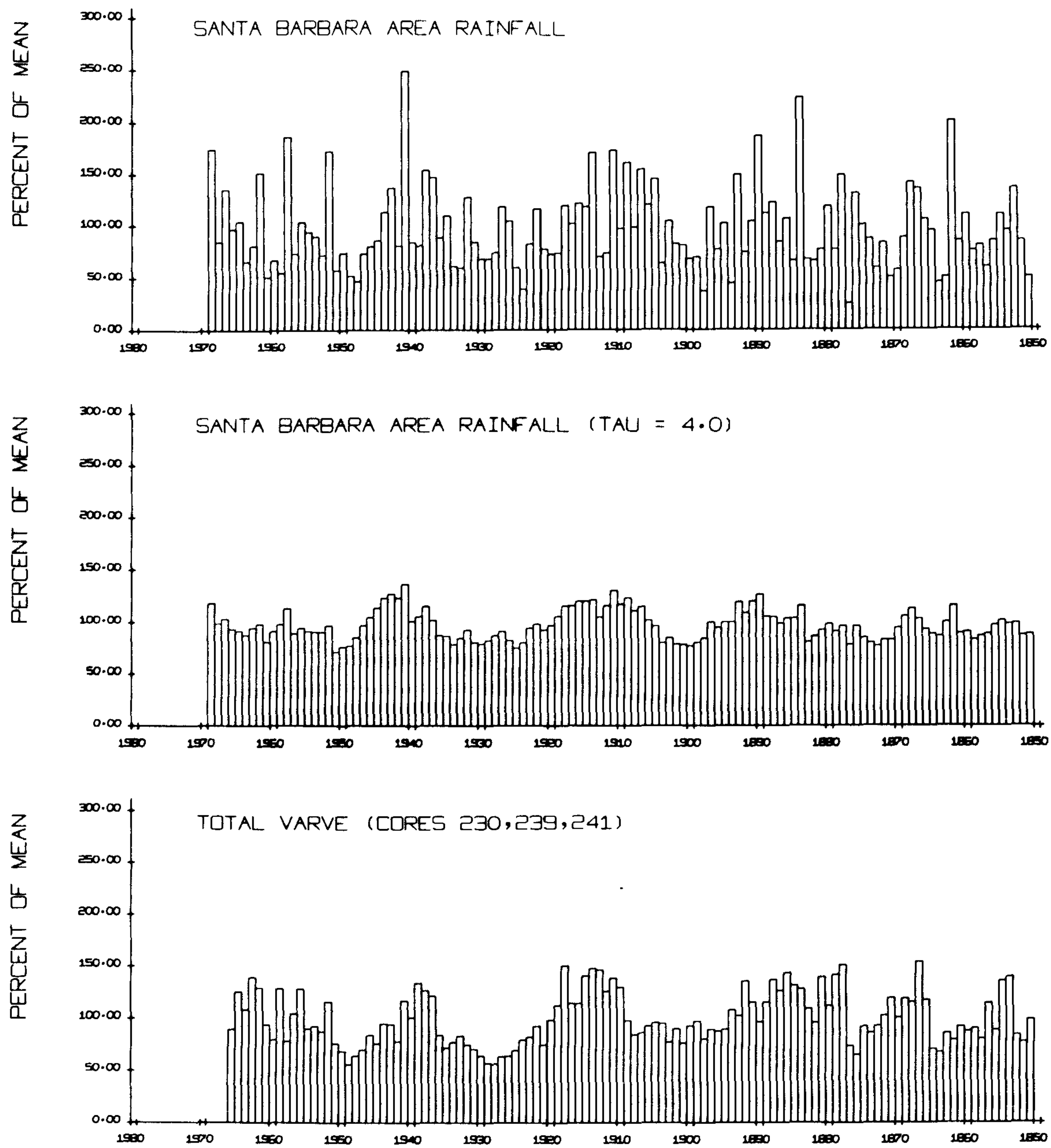


FIGURE 2b.—Radiography of core 244, Soledad Basin. Although laminae are present there are no consistent patterns that would suggest varves. There is, however, enough information to physically correlate between slabs and to identify irregular sedimentation events.



Such are likely victims of mass mortality resulting from an invasion of hydrogen sulfide water or red water situations which, while reported in Walvis Bay, South Africa (Brongersma-Sanders, 1957), do not seem characteristic of the present coastal waters off the Californias. On the other hand, the occurrence of separate scales is likely the incidental result of serious if not fatal trophic interactions. Previous investigation has indicated that, with few exceptions, fish scales are deposited in Santa Barbara Basin as individual events (Soutar, 1967).

Interstitial-water measurements (Sholkovitz, 1973) indicate an increase of dissolved phosphate within the anaerobic sediment from 20 μmoles $PO_4^{\equiv}$ near the surface to levels in excess of 100

FIGURE 3.—Comparison of Santa Barbara regional rainfall, smoothed Santa Barbara regional rainfall, and total varve thickness. Spearman rank-correlation coefficient between Santa Barbara regional rainfall and total varve thickness is 0.26 ($P = 0.02$, $n = 99$). The highly variable pattern of seasonal rainfall is smoothed by the filter:

$$Y_t = \sum_{i=1}^{t} \frac{R_i}{\tau} \left(1 - \frac{1}{\tau}\right)^{t-i}$$

where Y_t = smoothed seasonal rainfall at year t; R_t = actual seasonal rainfall at year t; and τ = a time constant (years). Thus Y_t is the sum of $\frac{1}{\tau}$ of year t rainfall and exponentially decreasing portions of previous year's rainfall. The function tends to dampen rapid oscillations and lag slower oscillations at a slightly lower amplitude. The value of τ is derived by multiple regression analysis. Varve thickness at year t is the dependent variable and rainfall at year t, year t-1, year t-2, etc. are the independent variables. τ is found by fitting a log linear line to the regression coefficients. The Spearman rank-correlation coefficient between the filtered rainfall and the total varve thickness is 0.50 ($n = 99$). Due to the autocorrelation induced by the filter, no probability is assigned. Mean Santa Barbara regional rainfall is 42.2 cm, and mean varve thickness is 1.74 mm (at 60% water by weight).

μmoles at depth. Since the composition of fish scales is essentially an intermixture of microcrystalline apatite and a collagen-ichthylepidin matrix (Wallin, 1957), a potential for the degradation of the scale record is present. However, ichthylepidin, an albuminoid approaching keratin in composition, is unlikely to be degraded in an anaerobic environment (Kaplan and Rittenberg, 1963). Thus the organic matrix may contribute significantly toward the preservation of scales. The distinctly higher frequencies of scales at core depths in excess of 2 m further suggest a nondegraded record (Soutar and Isaacs, 1969).

The record of scale deposition in the Santa Barbara Basin (16 subcore-sample mean, 1810-1970) and the Soledad Basin (4 subcore-sample mean, 1780-1970) is in part presented (Figure 5a, b) and statistically summarized (Table 1) for: *Sardinops caerulea* (Pacific sardine), *Engraulis mordax* (northern anchovy), *Merluccius productus* (Pacific hake), *Colalabis saira* (Pacific saury), and *Scomber japonicus* (Pacific mackerel).

Of particular interest are those portions of the scale record covering the past few decades for which population estimates exist. Considerable attention has been directed towards the elucidation of the historical population levels of the Pacific sardine. Estimates of the population (fish 2 yr and older) derived from the solution of a fishery catch equation extend from 1930 up to 1959 (Murphy, 1966). These biomass estimates presented in single- and 5-yr averages (Figure 6) document the historical decline of the fishery and the population. Comparison of the 5-yr averages of the biomass and the scale-deposition rate in the Santa Barbara Basin sediment indicates a parallel but offset decline. The derived age frequency of the sedimented scales (Table 2) indicates that most (92%) of the contributing fish were less than 2 yr old, suggesting a relatively fast response on the part of the sediment to particular year-class sizes. Comparison of the 5-yr averages of the year-class size (numbers of 2-yr-old fish entering the fishery) and the scale-deposition rate indicates a direct proportional relationship (Figure 7 and Table 3).

Population estimates for the central, southern, and total populations of the northern anchovy for the years 1951 to 1966 have been made (Smith, 1972). The estimates of the total spawning population presented in single- and 5-yr averages, and the 5-yr averages for the subpopulations, record the recent ascendancy of the anchovy. Comparison is made of these population estimates with the northern anchovy scale-deposition rate in the Santa Barbara and Soledad Basin sediments (Figure 8 and Table 4). In the three 5-yr intervals having sufficient information, the scale deposition is proportional to the spawning biomass. The direct relation to spawning biomass may be associated with the relatively rapid mat-

Table 1.—Statistical summary of scale deposition (numbers/10^3cm^2/yr) for Santa Barbara Basin sediment, 1810-1970, and Soledad Basin sediment, 1780-1970.[1]

Sediment	Mean	Median	Variance	Maximum	Minimum
Santa Barbara Basin (N=32)					
Pacfic sardine	3.6	2.8	13.6	15.2	0
Northern anchovy	10.0	9.8	27.8	19.4	2.0
Pacific hake	24.8	21.8	310.1	73.0	5.5
Pacific saury	0.8	0.3	3.2	8.4	0
Pacific mackerel	0.3	0.2	0.2	1.9	0
Other	8.5	8.1	24.3	17.8	0
Total	48.1	44.7	532.6	108.1	21.0
Soledad Basin (N=38)					
Pacific sardine	0.4	0.2	0.4	3.0	0
Northern anchovy	9.2	7.5	43.5	26.4	0.6
Pacific hake	6.1	6.1	8.3	12.0	1.3
Pacific saury	0.3	0	0.8	3.9	0
Pacific mackerel	0.3	0	0.3	1.6	0
Other	2.9	2.2	4.0	6.8	0
Total	19.2	17.9	52.4	39.0	5.6

[1]In the case of the Santa Barbara sediment, the statistics are drawn from a 16 subcore set representing a combined area of 980 cm^2. The statistics for the Soledad Basin are drawn from a 4 subcore set having a combined area of 260 cm^2.

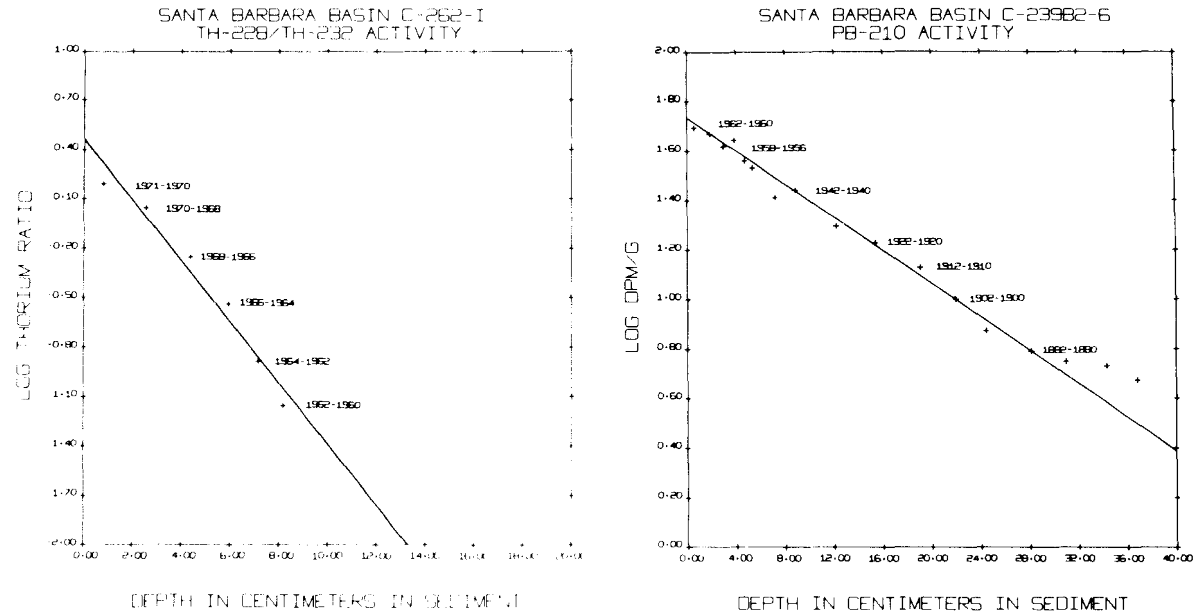


FIGURE 4a,b.—Santa Barbara Basin Th-228/Th-232 activity and Pb-210 activity at sediment depth. An excess of both the thorium isotopic ratio Th-228/Th-232 and the lead isotope Pb-210 are present in coastal surface sediments (Koide et al, 1972, 1973). In the case of Pb-210 (22.3 yr half life), the varve age estimate and the radiometric age estimate may be directly compared. The thorium ratio on the other hand cannot be directly estimated as function of time but may be calibrated against the accepted varve age.

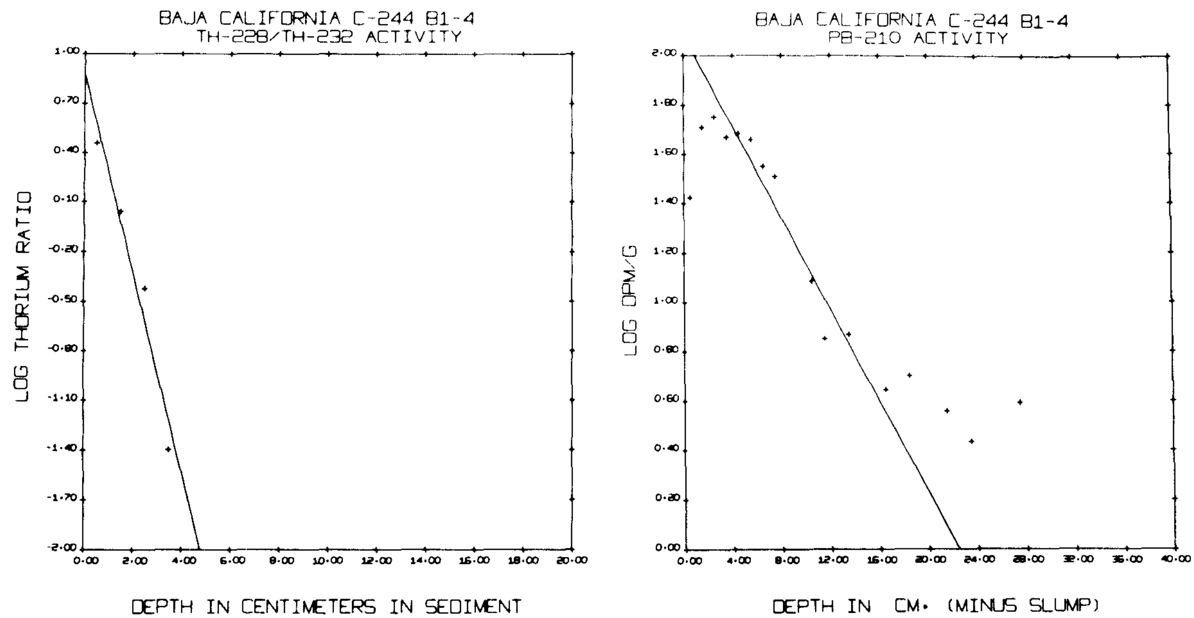


FIGURE 4c,d.—Soledad Basin Th-228/Th-232 activity and Pb-210 activity at sediment depth. The information gained from the study of these radiometric tools in the Santa Barbara sediment may be applied to the anaerobic sediment of the Soledad Basin. Here, despite the absence of consistent laminae, the radiometric ages provide the basis for a time framework. It should be noted that the scatter of Pb-210 points at the lower end (circa 1880) signals the merging with the supported background activity (U-238 series).

Table 2.—Derived-age[1] frequency of Pacific sardine, northern anchovy, and Pacific hake scales in sediment of the Santa Barbara and Soledad Basins.

Sediment	Age in years 0	1	2	3	4	5	6+
Santa Barbara Basin							
Pacific sardine	163	46	9	8	7	2	7
Northern Anchovy	62	110	78	48	18	1	9
Pacific hake	685	592	15	3	0	1	0
Soledad Basin							
Pacific sardine	13	1	1	0	0	0	0
Northern anchovy	139	16	12	36	(older than 3 yr)		
Pacific hake	208	22	1	1	0	1	0

[1]The derived age is an estimate of age based on the measurement of scale width. The scale width is a more reliable feature of sedimented scales than is the scale length as, for example, in the case of the sardine the exposed "wing" of the scale is often separated. The scale width is converted to an estimate of standard length and the estimate of standard length is converted to an age estimate by the growth curve.

uration of the northern anchovy. Considering that 50% of the anchovy mature in 2 to 3 yr (Clark and Phillips, 1952), then the derived-age frequency of the anchovy scales (Table 2) suggests that for Santa Barbara 35% and for Soledad 24% of the contributing anchovy are mature.

No direct population estimates are available for the Pacific hake; however, larval abundances thought to be proportional to the adult biomass have been provided.[3] In view of the estimate that 54% or more of the scale information in the sediment is derived from hake less than one year old, a proportional relationship between larval abundance and scale deposition might be anticipated. However, this comparison for the inshore region of southern California and southern Baja California from 1950 to 1965 indicates a non-systematic relationship (Table 5). One explanation of the inconsistency may be that between 1950 and 1965 the inshore larval populations were generally low and had no strong trend. It should also be noted that the inshore and total abundances are in themselves not entirely consistent, and, in fact, the total larval abundances tend toward an inverse relationship with the scale-deposition rate.

Information on the spawning population of the Pacific saury for the period 1950 to 1966 has been reported (Smith et al., 1970). Comparison of the spawning biomass and the scale-deposition rate (Table 6) indicates a sparse but sensible relation.

Egg abundances and catch information for the Pacific mackerel which could reflect the population are available, but the extremely low rate of scale deposition for this species limits an evaluation (Table 7).

The generally consistent relationships between the available estimates of pelagic fish populations and scale deposition provide an entree into the past. Such relationships are perhaps not unreasonable considering the strategic location of the basins adjacent to major spawning grounds. The short time over which population estimates and scale-deposition rates may be compared in the case of the anchovy, hake, saury, and mackerel is presently a limitation; nevertheless, relative measures of high and low spawning biomass may be made from the sedimentary information. The record for the Pacific sardine, however, should be amenable to direct interpretation in terms of year-class size and projected biomass, with the exception perhaps of those times when scale deposition far exceeds our experience.

Consideration of the scale record (Figure 5) as a population record affords a fascinating look into the flow of ocean life at the higher trophic level. The historical decline of the sardine, seen in perspective, appears as a subdued finale to a movement that had begun in 1890, thirty years before the inception of the fishery, and this movement in turn belongs to a theme extending into the millennia (Soutar and Isaacs, 1969). Levels of year-class success in excess of 10^{10} fish occurring in the late 1930's, which are historically considered impressive, appear in broader context to be at most moderate. Even higher levels of success suggested by the sedimentary record between 1855 and 1865 afforded insufficient reserve against a precipitous and natural decline. Nor can the virtual absence of the sardine from the waters off Alta California be

Table 3.—Comparison of Pacific sardine population (Murphy, 1966) and scale–deposition rate in the Santa Barbara Basin sediment.[1]

Year interval	2 yr and older annual biomass (10^6 metric tons)	2 yr old year annual class in year spawned (10^9)	Scale-deposition rate (no./10^3cm^2/yr)
1959-55	0.25	1.7	0
1954-50	0.63	2.1	0
1949-45	0.64	3.3	0.4
1944-40	1.84	3.5	0.5
1939-35	1.71	9.1	3.1
1934-30	[2]3.52	6.8	2.0

[1]The Spearman rank-correlation coefficient between the 2-yr and older biomass and the scale-deposition rate is 0.81, n = 6; and for the 2-yr-old year class and the scale-deposition rate is 0.99, n = 6. While these are highly suggestive of a significant relationship, no probabilities are assigned due to inherent autocorrelation in these series.
[2]Incomplete data.

[3]Smith, P.E. CalCOFI—the first twenty-five years. Unpubl. manuscr.

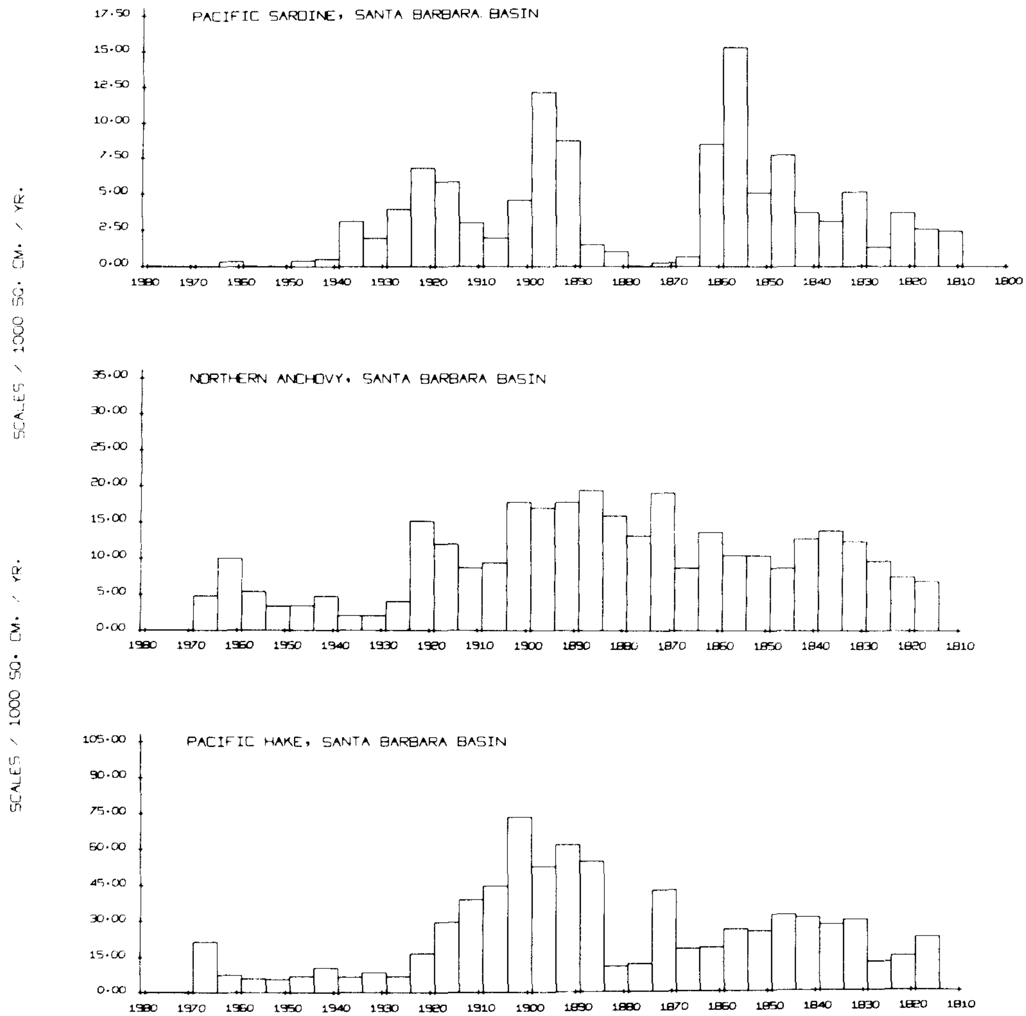


FIGURE 5a.—Histogram plot of the scale-deposition rate of the Pacific sardine, the northern anchovy, and the Pacific hake in sediment of Santa Barbara Basin, 1810 to 1969.

considered an unnatural circumstance. The levels of year-class success between 1865 and 1880 were likely as low as those estimated after 1940. It may be argued that in the previous period the sardine had moved offshore or migrated southward, thereby causing a decline in scale deposition. However, abandonment by a substantial population of a major spawning ground would seem problematic, and in regard to a southern immigration it can be said that during the apparent year-class failures from 1865 to 1880 no substantial sardine population occupied the southern waters near the Soledad Basin, Baja California. Indeed, the only time the sardine appears even moderately influential in these waters is the period 1920 to 1935, coincidental with the development of the fishery to the north. While the evidence from previous decades makes it impossible to accuse the sardine of avoidance, the coincidence may nevertheless underline the naturally intermittent occurrences of abundant sardine populations in California waters.

As in the case of the sardine, one's view of the distribution of the anchovy through time is colored by perspective. The sediments in both the Santa Barbara and Soledad Basins have responded to the recent increase in the anchovy population. This response appears as part of a

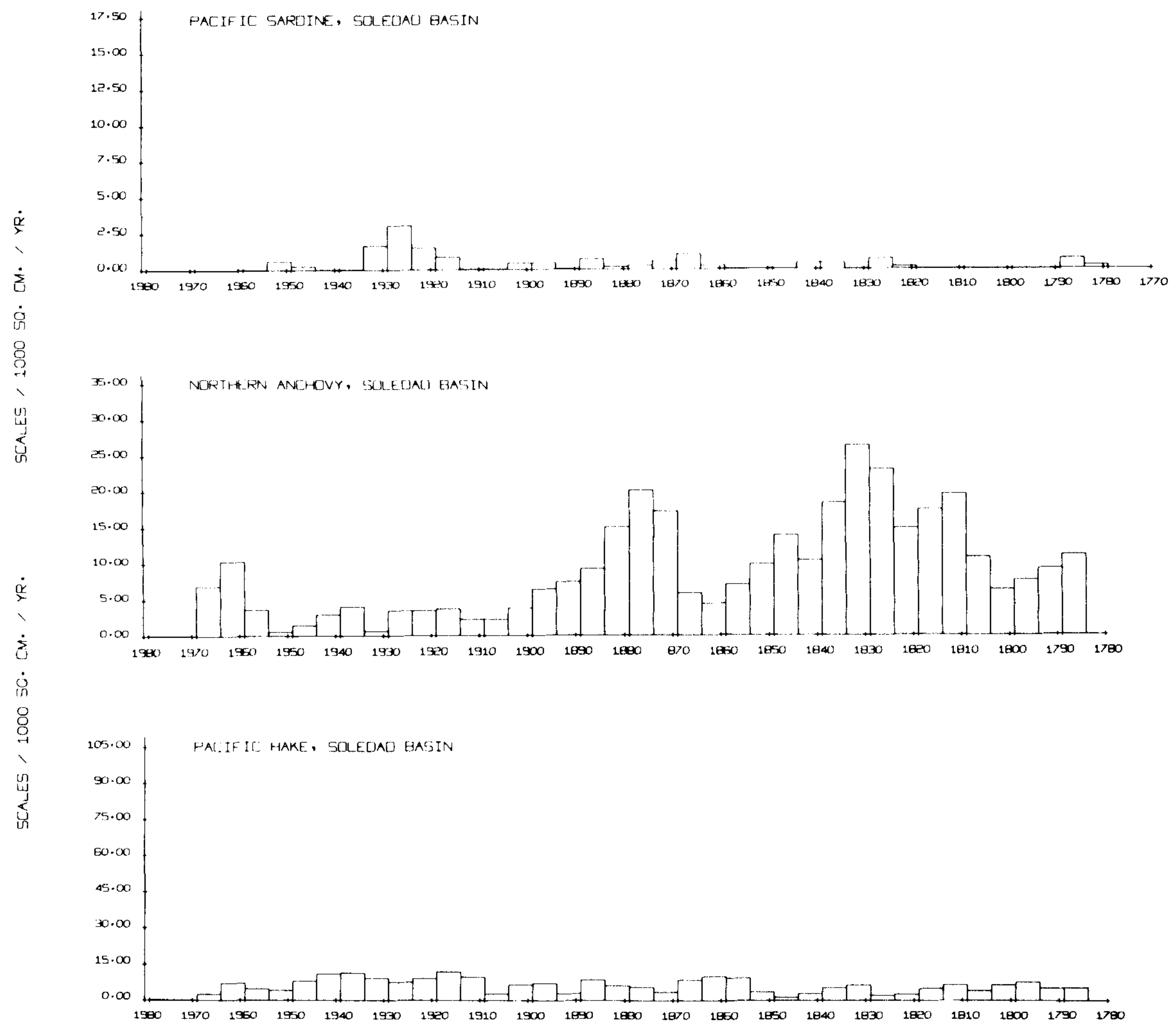


FIGURE 5b.—Histogram plot of the scale deposition rate of the Pacific sardine, the northern anchovy, and the Pacific hake in sediment of the Soledad Basin from about 1780 to 1969.

significant pattern of similarity in scale deposition (Table 8). The recorded increase in the anchovy population, while substantially above recent historical levels, when compared to the inferred population reached in most of the 19th and the early part of the 20th centuries, appears moderate. Furthermore, in contrast to the sardine, the population of the anchovy has been of comparable density in the waters of the Californias over the past two centuries. This then supports contemporary observations that the northern anchovy is regionally adapted and is capable of successful population responses covering at least the southern half of the California Current.

The inferred distribution of the Pacific hake, although made tenuous by the lack of clearly supportive population information, is, in the case of Santa Barbara Basin, strongly suggestive of the anchovy with an indication of a recent increase from low levels between 1920 and 1965 and with substantially higher levels before 1920 (Table 8, Figure 5). The inferred hake population in the water near Soledad Basin corresponds with the levels inferred for Santa Barbara back to the 1930's and in this regard is consistent with recent observations of essentially equal larval abundance in both areas. However, levels of inferred population before 1930 at Santa Barbara are considerably above those of Soledad, the latter showing a consistent level over the past 200 years.

TABLE 4.–Comparison of the northern anchovy population (Smith, 1972) and the scale–deposition rate in the Santa Barbara and Soledad Basin sediment.[1]

Year interval	Central subpopulation 5-yr average spawning biomass (10^6 metric tons)	Southern subpopulation 5-yr average spawning biomass (10^6 metric tons)	Total population 5-yr average spawning biomass (10^6 metric tons)	Scale-deposition rate, Santa Barbara Basin no./10^3cm^2/yr	Scale-deposition rate, Soledad Basin no./10^3cm^2/yr
1969-1965	[2]4.70	[2]0.92	[2]5.02	4.9	[2]7.0
1964-1960	2.95	1.18	4.29	10.0	10.3
1959-1955	1.34	0.37	1.85	5.4	3.6
1954-1950	0.54	0.47	1.04	3.3	0.6
1949-1945	—	—	—	3.4	1.5
1944-1940	—	—	[2]2.37	4.7	3.0

[1]As defined (Vrooman and Smith, 1971) the central subpopulation area includes southern Alta California inshore, offshore, and seaward and Baja California inshore, offshore, and seaward. The southern subpopulation area includes southern Baja California inshore, offshore, and seaward. Inshore includes 0–80 miles; offshore includes 80–160 miles; and seaward includes 160–280 miles.
[2]Incomplete data.

TABLE 5.—Comparison of Pacific hake larval abundance (Ahlstrom, 1969; Smith, in prep.) and scale–deposition rate in Santa Barbara and Soledad Basin sediment.

Year interval	California coastal inshore area (5-yr average)	Southern Baja coastal inshore area (5-yr average)	Total (inshore and offshore) (5-yr average)	Scale-deposition rate Soledad Basin no./10^3cm^2/yr	Scale-deposition rate Santa Barbara Basin no./10^3cm^2/yr
1969-1965	[1]3,500	[1]880	[1]10,360	[1]21.3	[1]2.5
1964-1960	480	590	3,810	7.3	6.9
1959-1955	600	420	11,850	5.8	4.6
1954-1950	540	880	12,660	5.5	4.0

[1]Incomplete data.

Consideration of the relationships of the three major species provides further insight into the distribution of pelagic fish through time. Most if not all investigators have found the hypothesis that the Pacific sardine and the northern anchovy are direct competitors unavoidable. This hypothesis is not supported by the less-than-significant positive correlation between the scale deposition of the two species in the Santa Barbara sediment (Table 8). However, fluctuations in relative abundance of even closely competitive species in the marine environment may follow quite different rules than mere abundance or autecologic correlation. The abundance of species may be directly related to advantageous conditions. However, whenever an advantageous or disadvantageous series of years is of critical duration (determined by specific differences in life history) the abundances may be inversely related. In this context the apparent decline and subsequent recovery of the sardine population between 1865 and 1890 from levels which appear substantially above historical experience, in the presence of what also appears to be substantial anchovy populations, may not be entirely enigmatic.

The associations of the anchovy, hake, and sardine in the Santa Barbara sediment (Table 8) is further suggestive of periods favorable or unfavorable to these three species. This is in contrast to the Soledad sediment from which it may be inferred the anchovy alone is able to maintain high population levels. Some idea of the total pelagic-fish productivity off the Californias may be gained by combining the inferred populations of the anchovy, hake, and sardine into a total spawning biomass estimate (Figure 9). This biomass estimate suggests that the central California and presumably the northern Baja California regions can become a dominant center of pelagic fish productivity. Even though significant densities of northern anchovy have been present in the water above Soledad Basin, available information (Table 4) suggests these represent a relatively smaller southern subpopulation. The

Table 6.—Comparison of the Pacific saury population (Smith et al., 1970) and the scale–deposition rate in the Santa Barbara and Soledad Basin sediments.

Year interval	Total population spawning biomass CalCOFI area (10^6 metric tons)	Total scale-deposition rate, Santa Barbara Basin no./10^3 cm^2/yr	Total scale-deposition rate, Soledad Basin no./10^3 cm^2/yr
1969-1965	[1]0.21	[1]1.1	[1]0.0
1964-1960	0.12	0.3	0.0
1959-1955	0.18	1.1	0.0
1954-1950	0.23	2.2	0.6

[1]Incomplete data.

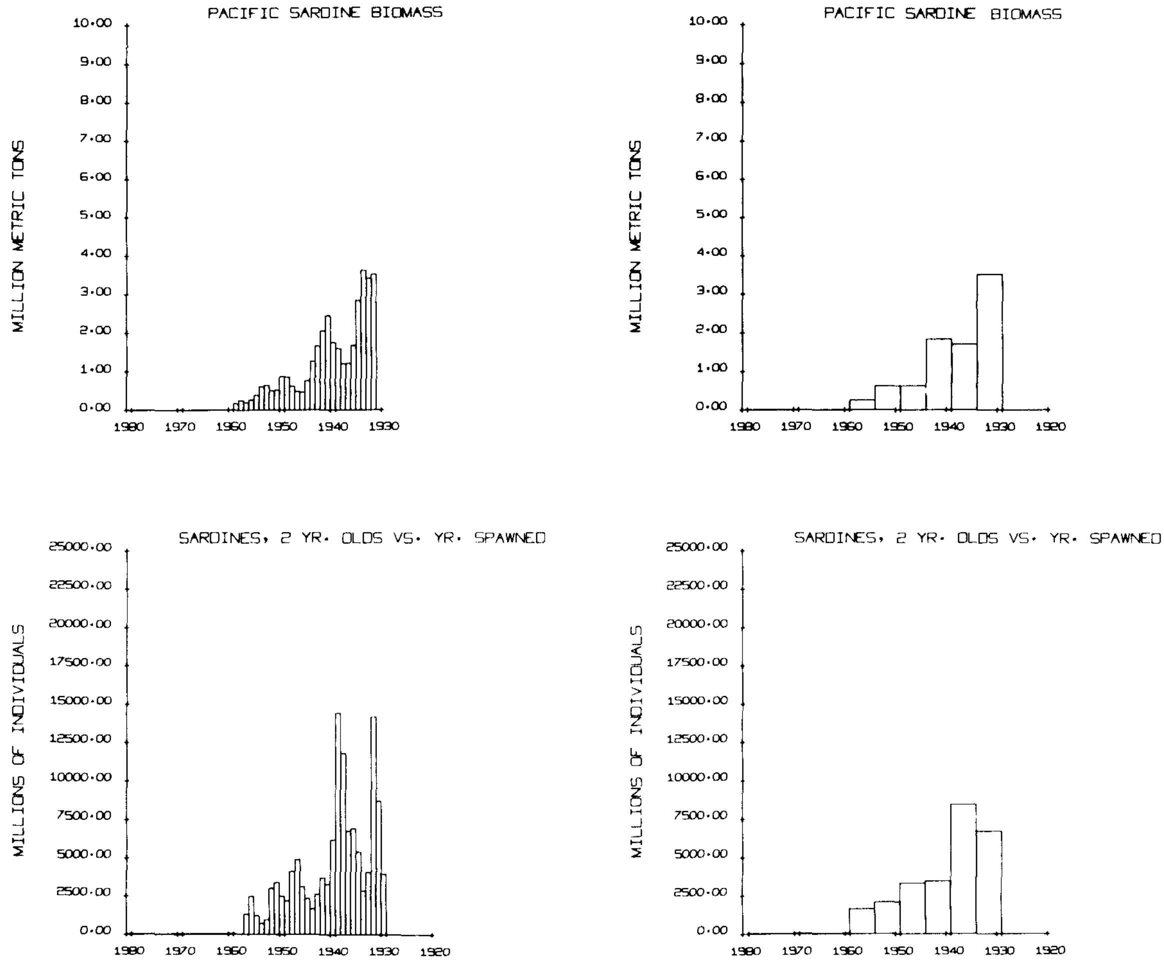


FIGURE 6.—Yearly estimates of Pacific sardine biomass 2-yr and older and year class size at 2 yr old (after Murphy, 1966). The yearly population estimates (left) are grouped into 5-yr block averages (right) that correspond to the sampling intervals in the sediment.

TABLE 7.—Comparison of Pacific mackerel larval abundance (Ahlstrom, 1969; Smith, in prep.), fishery landings (Fitch, 1952),[1] and scale-deposition rate in Santa Barbara and Soledad Basin sediment.

Year interval	Southern California coastal inshore area (5-yr average)	Southern Baja coastal inshore area (5-yr average)	Total (inshore and offshore) (5-yr average)	Southern California landings (5-yr average) (metric tons)	Scale-deposition rate, Santa Barbara Basin no./10³cm²/yr	Scale-deposition rate, Soledad Basin no./10³cm²/yr
1969-1965	[2]	[2]	[2]	1,660	[2]0	[2]0
1964-1960	560	21,000	38,600	17,830	0	0
1959-1955	1,260	3,060	16,100	18,390	0.2	0
1954-1950	650	10,100	19,000	10,780	0.2	0.8
1949-1945	—	—	—	21,660	0.6	0
1944-1940	—	—	—	35,020	0.4	1.6
1939-1935	—	—	—	45,430	0.2	1.6
1934-1930	—	—	—	—	1.6	0.8

[1]Also subsequent Cal. Dept. Fish and Game landing statistics.
[2]Incomplete data.

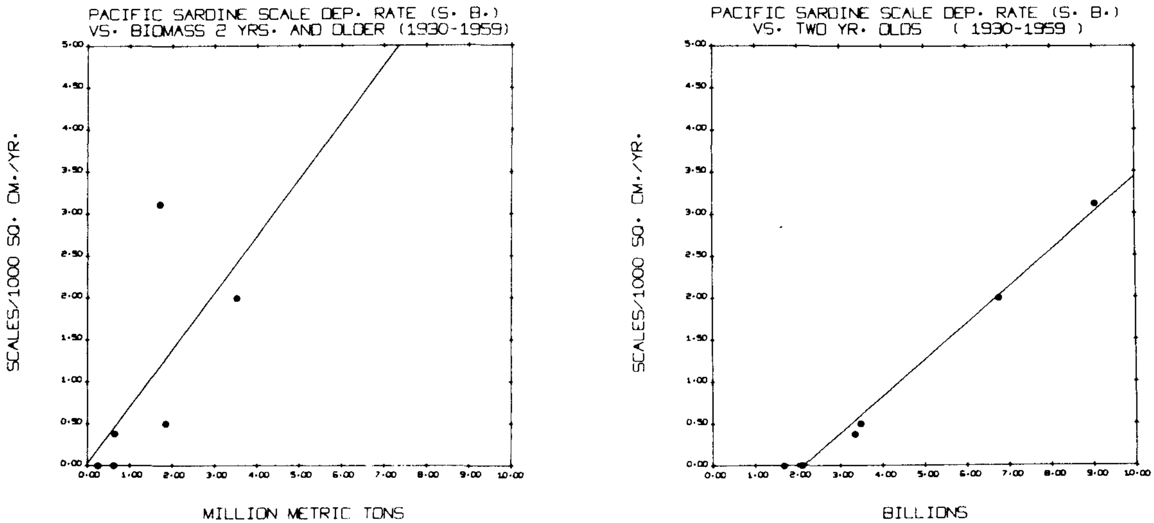


FIGURE 7a,b.—Scatterplot of the 5-yr averages of the Pacific sardine biomass (after Murphy, 1966) and the scale-deposition rate in Santa Barbara sediment, 1930 to 1959. The plot of biomass versus scale deposition though indicating a significant relationship (Spearman rank-correlation coefficient is 0.81, $n = 6$) shows considerable scatter. If, on the other hand, the year-class size at 2 yr of age is plotted against the scale-deposition rate in the year spawned, the scatter is markedly reduced and a highly significant relationship emerges (Spearman rank-correlation coefficient is 0.99, $n = 6$). The reduction in scatter can be explained through the observation that most of the scales encountered in the sediment were derived from younger fish.

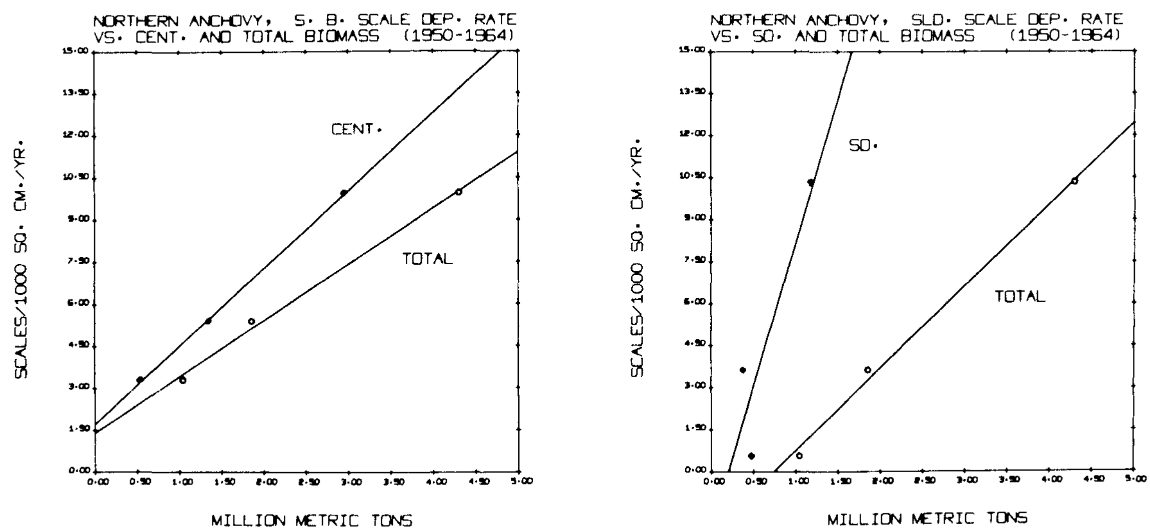


FIGURE 7c,d.—Scatterplot of the 5-yr averages of the northern anchovy spawning population estimates (after Smith, 1972) and the scale-deposition rates in Santa Barbara and Soledad Basin sediment, 1950 to 1965. The scale-deposition rates in both the basins vary directly with increasing population estimates of the northern anchovy. The relatively steep slope of the southern subpopulation (S) relative to the central subpopulation (CNT) reflects the smaller southern population.

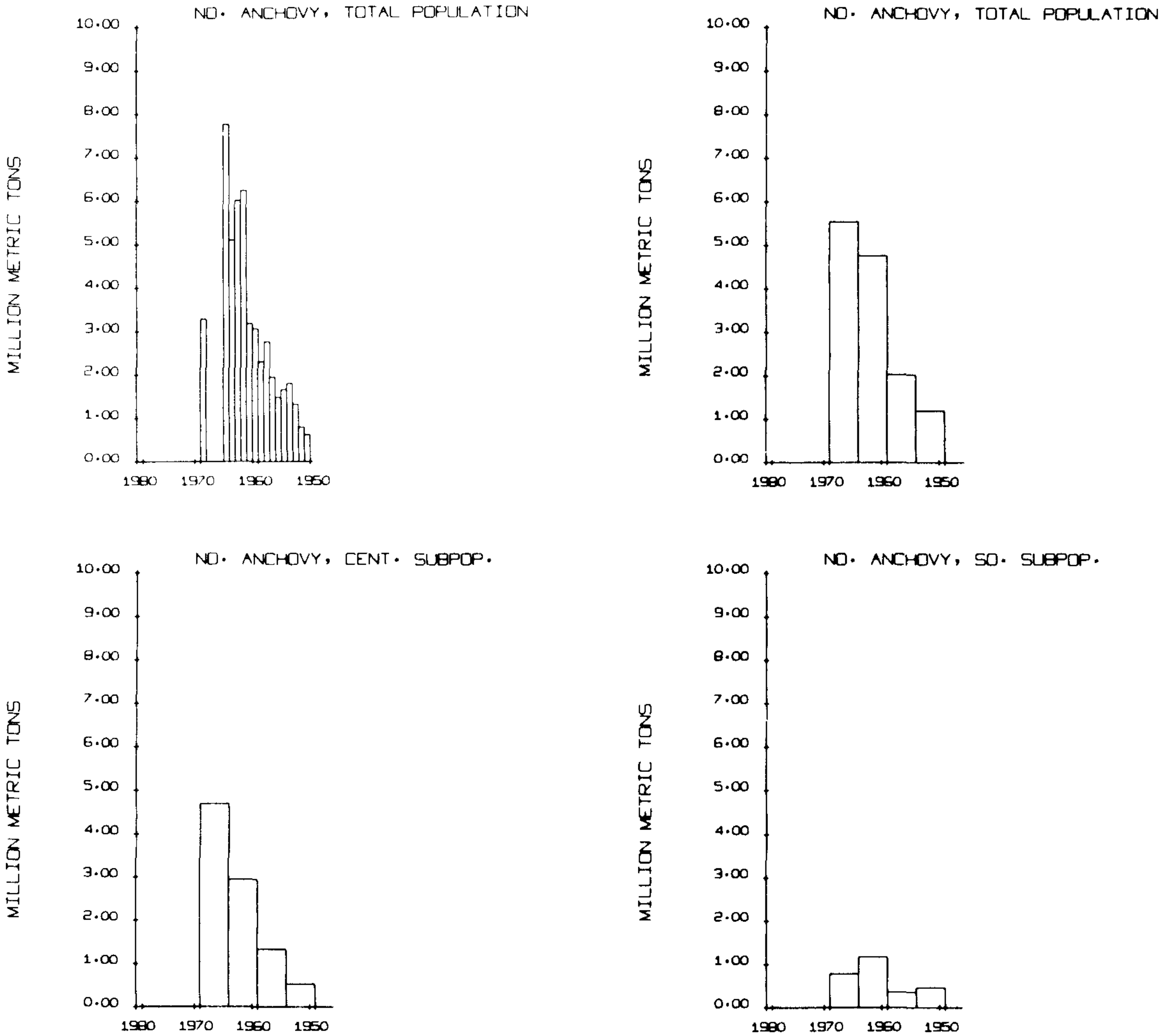


FIGURE 8.—Yearly estimates of the northern anchovy biomass (after Smith, 1972). The yearly total population estimates (upper left) are grouped into 5-yr block averages (upper right). Also given are the central and southern subpopulation 5-yr block averages (lower).

Table 8.—Rank-correlation coefficients[1] between the scale occurrences of the Pacific sardine, the northern anchovy, and the Pacific hake in sediment of Santa Barbara and Soledad Basins (n = 32).

	Pacific sardine		Northern anchovy		Pacific hake	
	Santa Barbara	Soledad	Santa Barbara	Soledad	Santa Barbara	Soledad
Pacific sardine						
Santa Barbara		−0.02	0.34	0.05	0.49	0.19
Soledad			0.20	−0.19	−0.09	0.20
Northern anchovy						
Santa Barbara				0.37	0.65	−0.08
Soledad					0.26	−0.46
Pacific hake						
Santa Barbara						0.17
Soledad						

[1]While the correlation coefficients above 0.35 appear significant, nevertheless due to autocorrelation inherent in these time series the probabilities associated with these coefficients are likely to be greater than if the series were internally independent.

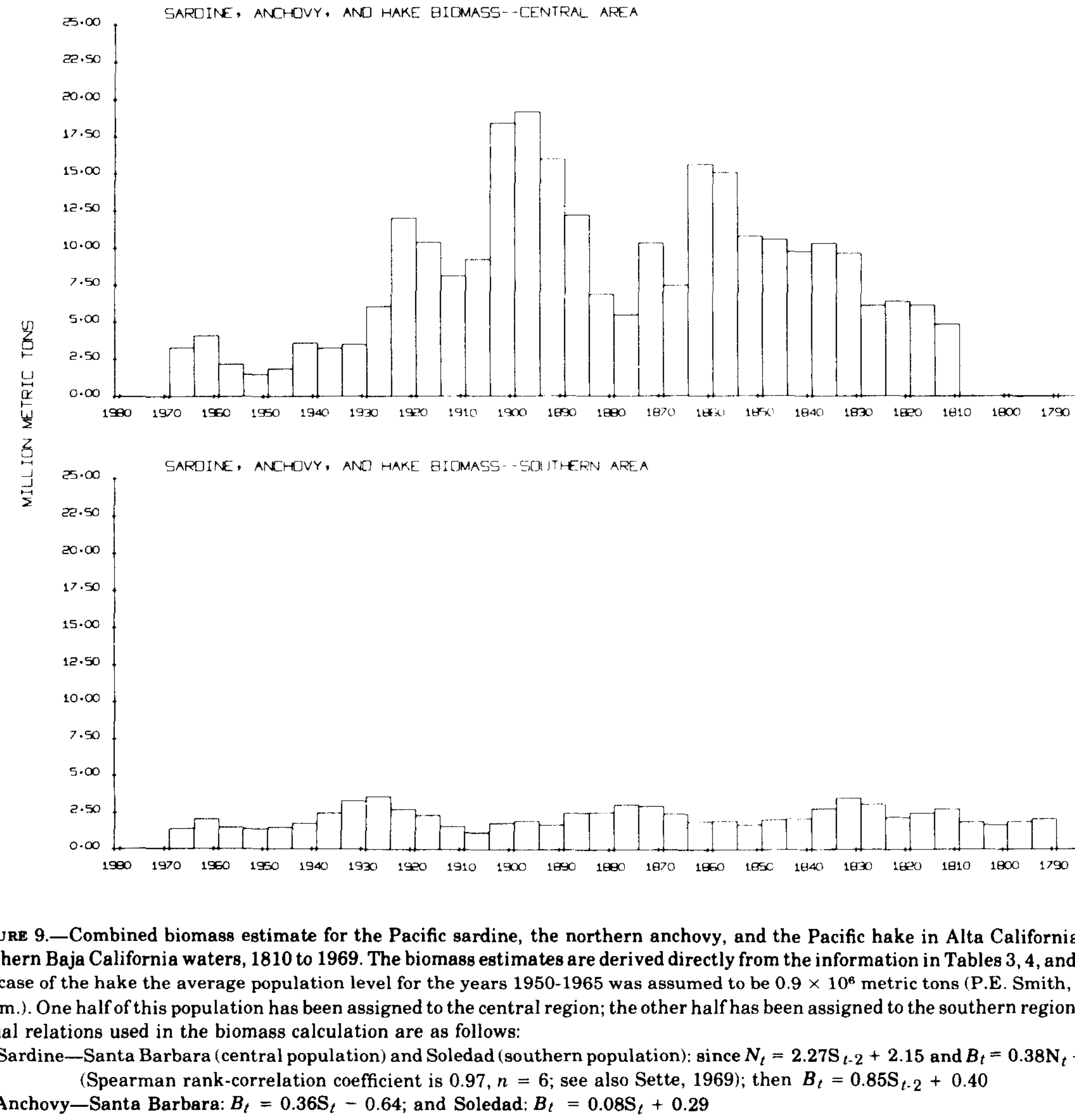


FIGURE 9.—Combined biomass estimate for the Pacific sardine, the northern anchovy, and the Pacific hake in Alta California and southern Baja California waters, 1810 to 1969. The biomass estimates are derived directly from the information in Tables 3, 4, and 5. In the case of the hake the average population level for the years 1950-1965 was assumed to be 0.9×10^6 metric tons (P.E. Smith, pers. comm.). One half of this population has been assigned to the central region; the other half has been assigned to the southern region. The actual relations used in the biomass calculation are as follows:

Sardine—Santa Barbara (central population) and Soledad (southern population): since $N_t = 2.27S_{t-2} + 2.15$ and $B_t = 0.38N_t - 0.40$ (Spearman rank-correlation coefficient is 0.97, $n = 6$; see also Sette, 1969); then $B_t = 0.85S_{t-2} + 0.40$

Anchovy—Santa Barbara: $B_t = 0.36S_t - 0.64$; and Soledad: $B_t = 0.08S_t + 0.29$

Hake—Santa Barbara and Soledad: $B_t = 0.08S_t$

where N is number of 2-yr olds, B is annual spawning biomass, S is scale deposition rate, and subscript t refers to year. The mean spawning biomass estimates for the sardine, anchovy, and hake are 3.5, 3.0, and 2.0 million tons for the central population and 0.7, 1.0, and 0.5 for the southern area.

importance of the central region would also likely extend to the north through the seasonal migration of these fish.

The projected mean biomass level for the three main species off California over the past 30 years is roughly 2 million metric tons and over the past 150 yr is 8 million metric tons. Thus the recent rise of the anchovy population may simply be a return to reasonably productive conditions. It is ironic that most of man's experience in the waters off the Californias appears to be associated with low pelagic-fish productivity. Conceding a significant effect of the fishery on the Pacific sardine does not mitigate the synchronous low population levels of the anchovy and the hake. As a matter of perspective, it should be emphasized that most of the understanding regarding the California Current system and pelagic fish, particularly that from

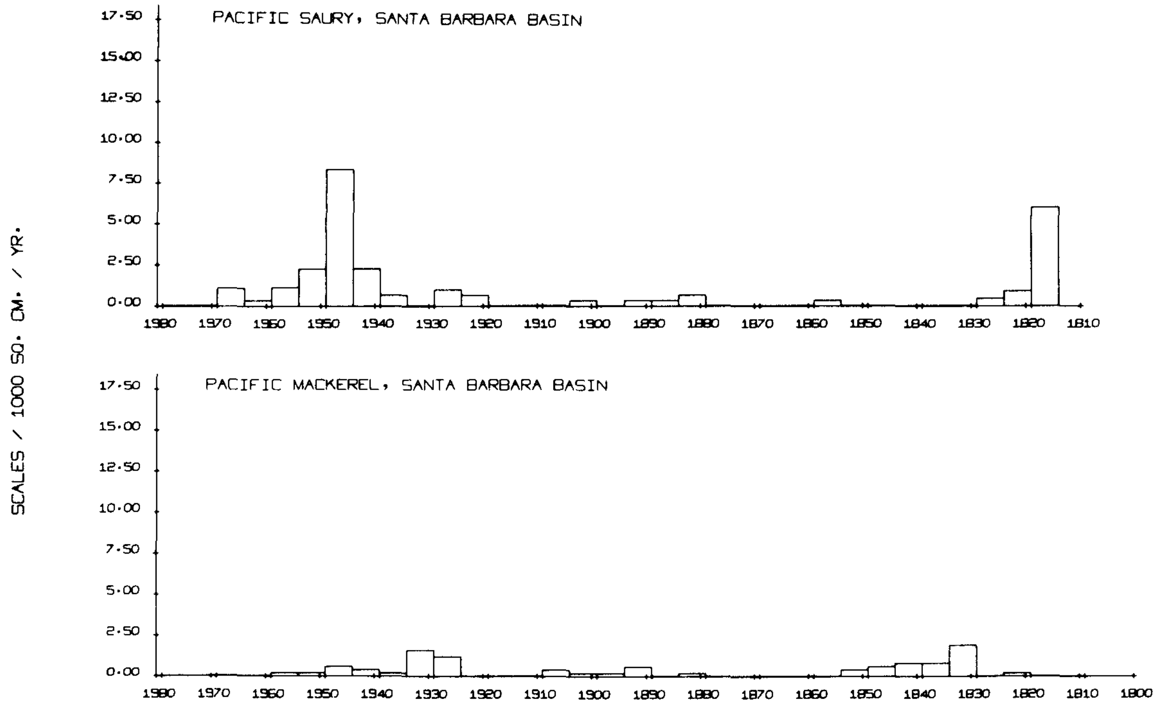


FIGURE 10a,b.—Histogram plot of the scale-deposition rate of Pacific saury and Pacific mackerel in sediment of the Santa Barbara Basin, 1810 to 1969.

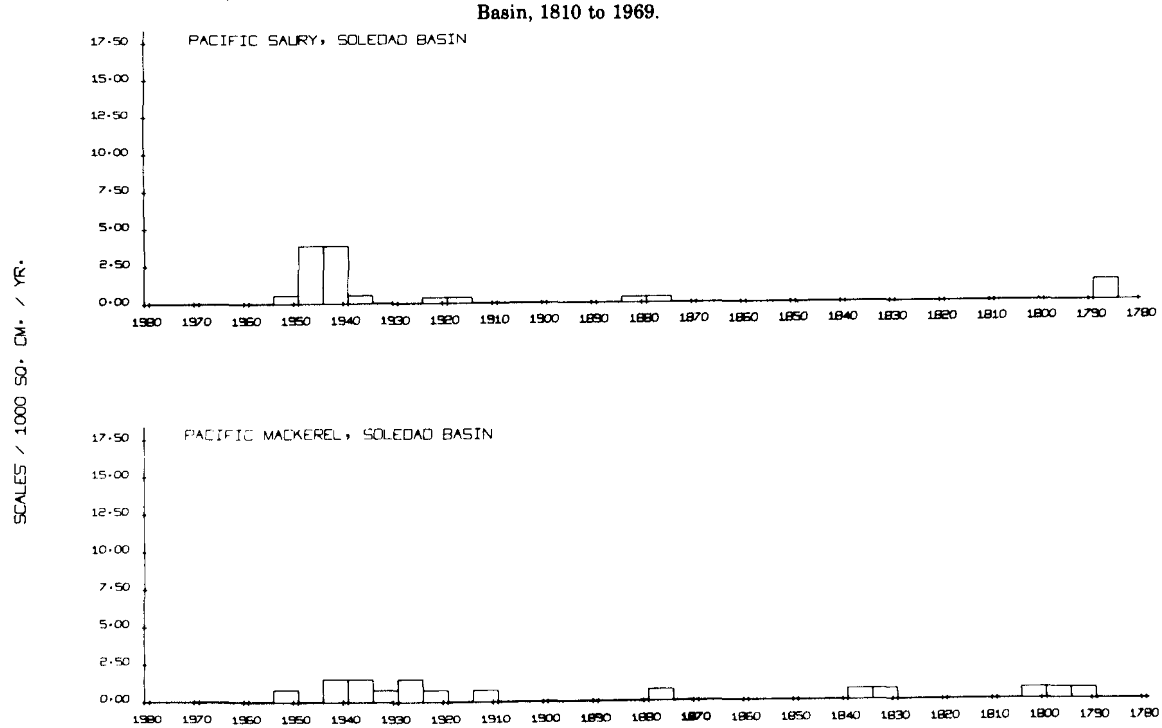


FIGURE 10c,d.—Histogram plot of the scale-deposition rate of Pacific saury and Pacific mackerel in sediment of the Soledad Basin from about 1780 to 1969.

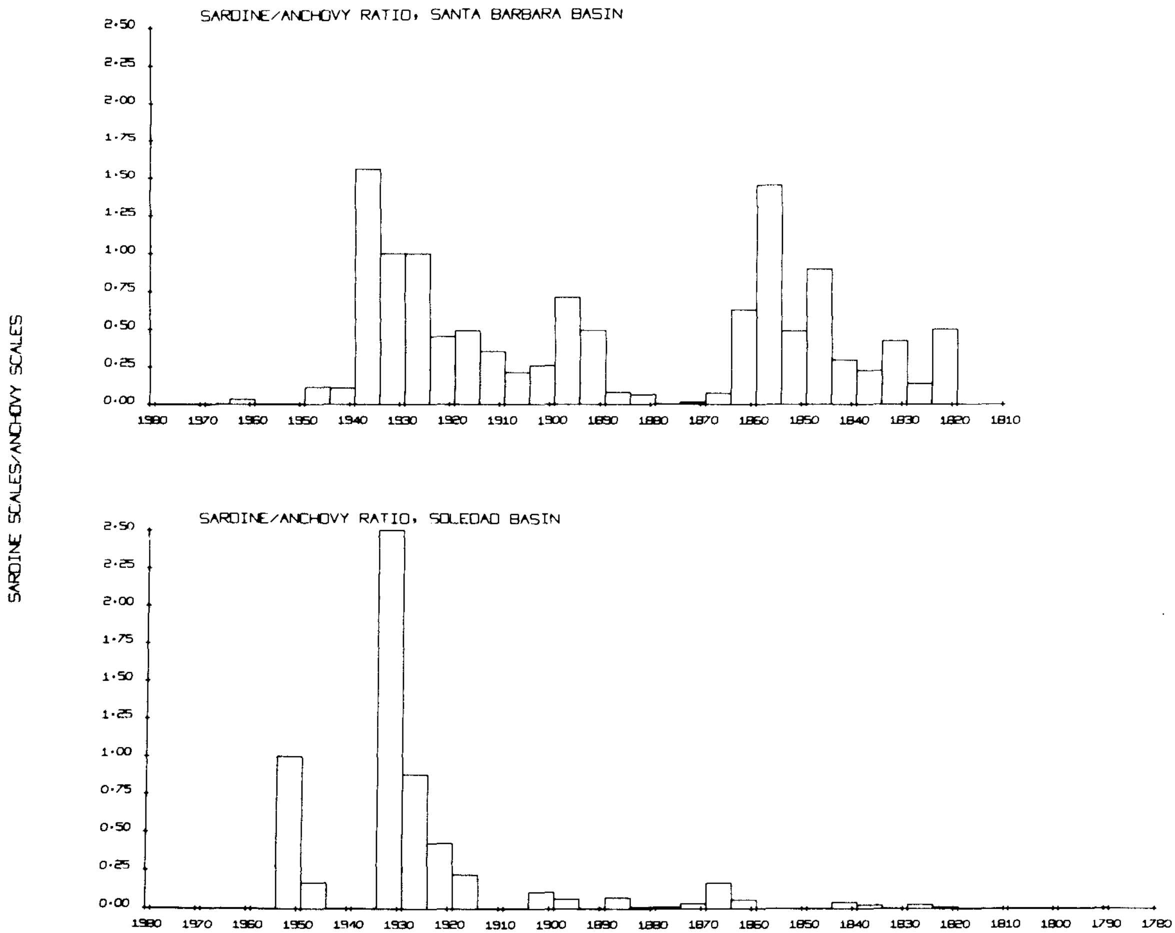


FIGURE 11.—The ratio of Pacific sardine scales to northern anchovy scales in the sediments of the Santa Barbara and Soledad Basins.

intensive efforts over the past 20 yr, has been gleaned from unproductive times, and there is yet limited appreciation of the capacity of the system. In regard to this point, a level of 15 million metric tons is suggested for the 1890's.

The scale records of two other pelagic fish serve to underscore the preceding observations. The record of the Pacific saury (Figure 10a, c) indicates an intrusion by this fish during the 1940's into the coastal waters. It would appear the saury found these waters attractive in the anomalous paucity of the more regular inhabitants. Although the information in the case of the Pacific mackerel is meager, the scale record (Figure 10b, d) resembles that of the saury in that the higher scale occurrences are near the ends of the record.

The records preserved in the sediments display a panorama of pelagic-fish abundance in the California Current over the past 150 yr. Interpretations of these records in the limited light of present knowledge point in both disturbing and exciting directions: disturbing, in revealing the magnitude and duration of the effort needed to encompass such a system; exciting, in the temporal glimmer of its flow and potential. The character of pelagic-fish abundance in California Current waters is perhaps best summarized in graphic form (Figure 11). The records of the two critical species, the Pacific sardine and the northern anchovy, when treated as a simple ratio exhibit a marked cyclical distribution (Santa Barbara) and a unique-event distribution (Soledad). The basic factors which gave rise to these distributions are most likely interspecific and autecologic. The former is susceptible to scrutiny through the analysis of the projected fish populations through time. The latter is no less susceptible, for the sediments contain a rich record of fossil microplankton which promises to further define oceanic conditions off the Californias in relation to pelagic-fish productivity.

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