4 Variability from scales in marine sediments and other historical records

David B. Field, Tim R. Baumgartner, Vicente Ferreira, Dimitri Gutierrez, Hector Lozano-Montes, Renato Salvatteci, and Andy Soutar

CONTENTS

Summary

Records of variability in populations of small pelagic fishes exist from a variety of historical sources that precede industrial fishing catch records. We review the historical records of artisanal fisheries, archeological remains, and fish remains from marine sediments. Fish scale deposition rates from ocean sediments offer the most quantitative records with little bias from anthropogenic factors. As quantitative estimates from fish scale deposition rates and their comparison with other records depend on chronostratigraphies, we discuss chronological development in detail, as well as the preservation and significance of fish scale flux. The different historical records indicate considerable variability in small pelagics prior to industrial fishing. However, the historical records provide little support for paradigms of ecosystem variability based on industrial catch records, such as synchronous worldwide fluctuations in abundance of small pelagic from different boundary currents or alternations of sardines and anchovies within a given boundary current. Rather, a variety of different modes of variability in small pelagics is consistent with paleoceanographic evidence for many different climate states and modes of variability.

Introduction

Some of the best evidence of long-term variability in marine populations comes from different records of pelagic fishes. There is evidence from industrial catch records of many decades in length, artisanal catch records, historical observations, archeological remains, and fossil remains in marine sediments. Small pelagics reflect many aspects of climate change on fisheries, since their recruitment and population size are sensitive to environment conditions. However, understanding variability in population size of small pelagics populations is intertwined with understanding their migrations (presumably in search of ideal environmental conditions). This chapter reviews the collective evidence for variability in small pelagic populations observed prior to industrial catch records and what these different records reveal about past variability in small pelagic fishes.

The use of fish scales as indicators of variability in pelagic fish populations began with the innovative work of Soutar (1967) and Soutar and Isaacs (1969). By sifting different layers of Santa Barbara Basin (SBB) sediments Soutar and Isaacs (1969) quantified changes in the numbers of scales of sardines and anchovies deposited to the sediments during different decades in time. Finding a large amount of natural variability in scale deposition rates (SDR) to the sediments they inferred natural fluctuations, independent of industrial fishing, in the populations of *Sardinops sagax* (Pacific sardine), *Engraulis mordax* (northern anchovy), and *Merluccius productus* (Pacific hake) off California throughout the last two millennia. Their results implied that the collapse of the California sardine fishery may have been largely due to natural variability.

Interannual ENSO variability was just becoming recognized as having an impact on ocean circulation, biogeochemistry, and ecosystems that could be discernable over meso-scale variability when fish scale deposition rates

to the Santa Barbara Basin were reported (Soutar, 1971). Nonetheless, the Holocene was generally considered a stable time period with little consideration of decadal-scale variability in marine populations. Skepticism remained over the significance of changes in the number of scales from a single core taken from a single point in the ocean. Baumgartner *et al*. (1992) showed that the results of several cores from the SBB were consistent with one another, and could be used to define multiple collapses and expansions of sardines over interdecadal timescales. The variability in small pelagics documented by Baumgartner *et al*. (1992) was persuasive in illustrating that a shift in climate and ecosystems that occurred in the mid 1970s was not unlike prior variability. While it is clear that there is some influence of the warming trend on the mid 1970s climate shift in the North Pacific (Field *et al*., 2006), it is now accepted that there is substantial variability in marine populations on decadal to millennial timescales, which we refer to here as long-term variability.

Understanding the dynamics of long-term variability requires multiple historical records of small pelagic fish populations across the habitat range (see Figs. 4.1 and 4.2). We first discuss records from historical observations and archeological remains that primarily reflect the presence of populations in coastal environments. We then focus on sedimentary sequences, as these offer continuous records of quantifiable variations in time. However, the inferred temporal variations are also highly susceptible to issues associated with chronological development and degradation of remains. Therefore, we discuss the assumptions and problems associated with developing chronostratigraphies, beginning with the biogeochemical conditions necessary for the preservation of fish scales in marine sediments. We then discuss the assumptions and significance of fish scale deposition records followed by the major lessons learned from all of the different historical records.

Historical observations

A compilation of historical records of sardine and herring fisheries off northern Europe and comparison of these records with large-scale climate change associated with the North Atlantic Oscillation (NAO) was done by Alheit and Hagen (1997). They reported on multiple records of fisheries on small pelagics from France, England, and Sweden over the last 500 years, with records of herring fishing off the Swedish coast of Bohuslän extending back nearly a thousand years.

Bohuslän herring events represent periods where mass abundances of herring were frequently available to Swedish fisherman in skerries and fjords during fall and winter. Decades of Bohuslän herring catch using beach seines were followed by decades of absence. Herring presence (absence) along the Bohuslän coastline occurred during periods of absence (presence) of spring-spawning herring off northern and northwestern Sweden. The variations in catches of different stocks of Norwegian spring-spawning herring and Bohuslän herring on different parts of the coast of Sweden appear to be related with changes in the NAO, which affected both total stock size and the migration of stocks to nearshore environments (Alheit and Hagen, 1997).

Records of coastal fishery catches in northern France and England also reflect changes in availability of different species and stocks to coastal fisheries. The English Channel is the northern biogeographic edge of sardine and southern edge of herring. There was an apparent alternation between sardine and herring fisheries around the English channel, with sardines occurring during warmer periods and herring during cooler episodes. As fishing was local with little capacity to search for fish offshore across the range of their distribution, the records reflect some combination of fish stock migrations and abundance (Alheit and Hagen, 1997). Remarkably, the periods of presence absence of different stocks in the English Channel generally coincided with the variations off the Norwegian coast, reiterating the role of large-scale climate forcing associated with the NAO (Alheit and Hagen, 1997).

Several qualitative descriptions of good and poor sardine fishing years in the Japan Sea have been kept since the sixteenth century while records from multiple areas off Japan have been documented since the eighteenth century (Hiramoto, 1991 and references therein). These records generally reflect fishing success in coastal areas by qualifying each year as "good" or "poor." The records probably reflect an increase in population size associated with an expansion of its range since sardine distribution and commercial fishing effort off Japan extend well offshore during years of an expanded population. Fishing success records indicate persistence of good periods lasting from 7–45 years and poor periods lasting from 14–35 years, which may be related to broader North Pacific climate (Yasuda *et al*., 1999).

Observations from early explorers, fur-traders, naturalists, and surveys also offer some glimpses of past population states. While such records are not consistently maintained in time, they can reflect presence/absence across biogeographic ranges. For example, the presence of sardine off Oregon, Washington, and British Columbia in the Northeast Pacific is believed to reflect population range expansion associated with warmer conditions. Historical observations of sardines in the Northeast Pacific have been reported by Field *et al*. (2001). Sardines were observed by multiple sources in the late 1700s, including by trained naturalists. However, multiple naturalists, observations, and surveys done in the late nineteenth century, including investigations of the US Fish Commission in 1880–81, failed to locate sardines in the northern California Current. Sardines were
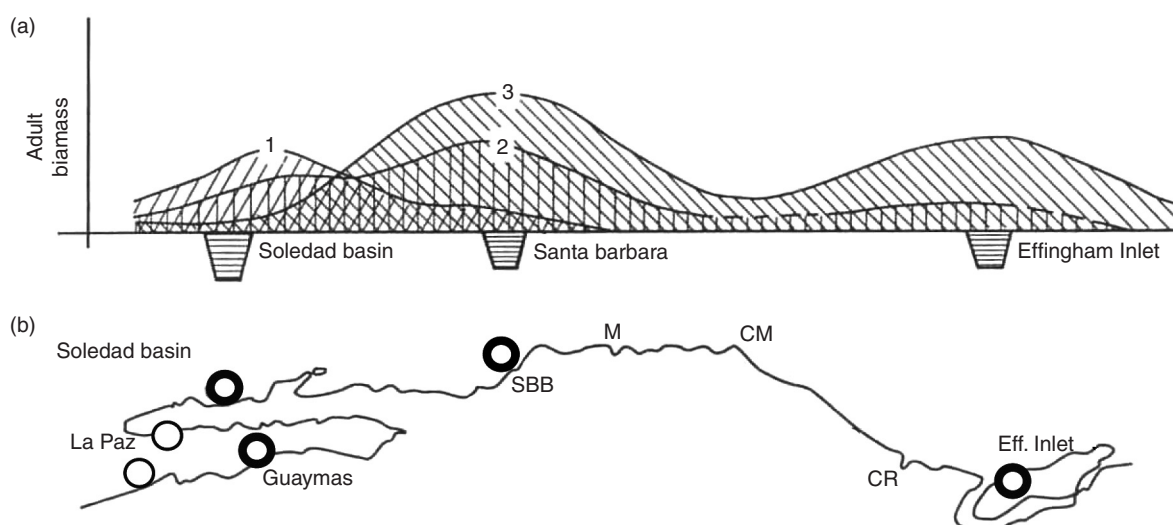
Fig. 4.1. (a) Model of how multiple sedimentary environments from the California Current region (British Columbia to the right and Baja California to the left) could reflect different scenarios for population abundance and distribution of the California sardine: (1) A diminished population contracted to Baja California and the Gulf of California; (2) a moderate population distributed throughout the coast, with highest densities off central California; and (3) an expanded population with a distribution centered off central California and the northern regions of the California Current. (b) Location of known sedimentary sites capable of resolving SDR (bold circles) and potential sites (thin circles). Monterey (M), Cape Mendocino (CM), and the Columbia River (CR) are indicated for reference.
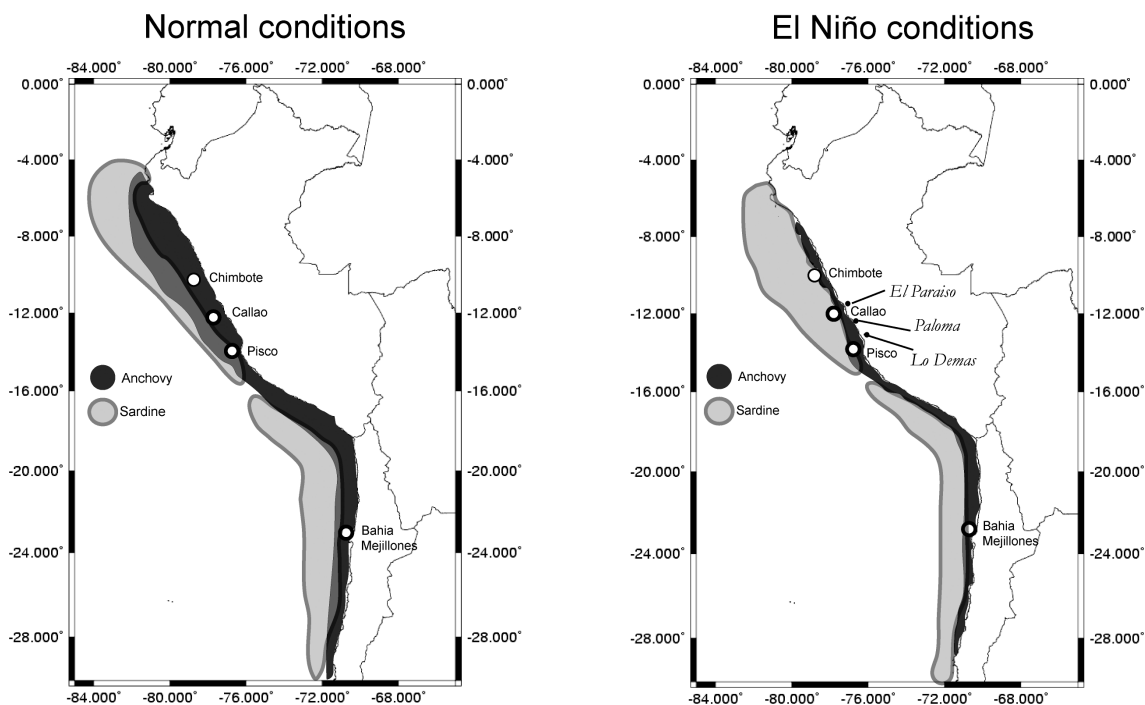

Fig. 4.2. Theoretical distribution of anchovy and sardine off Peru and northern Chile during times of population expansion of anchoveta during Normal conditions and contraction of anchoveta towards the coast and south during El Niño conditions. Sardine are found further offshore than anchoveta (Normal conditions) but move south and closer to shore during population expansions (El Niño conditions). Location of sedimentary sites (circles) where SDR records are being developed and may resolve shifts in population density and distribution. Also shown are archaeological sites where fish remains have been recovered.

reported by multiple different sources shortly thereafter, beginning in 1888 (Field *et al.*, 2001).

While historical observations of sardines by explorers and naturalists have yet to be reported in recent literature for the Humboldt Current and Benguela Current, they may exist in archives and might be compiled in the future to indicate times of a substantial sardine population size and its expansion to different parts of the coast. Off Namibia, South Africa, and Peru, records of guano harvest and seabird abundance may also be indicative of pelagic biomass (Gutierrez *et al.*, 2006; Crawford *et al.*, 2007).

Archeological records

While written historical observations are of limited in length in the Americas, fish remains in the form of bones, vertebrae, otoliths, and scales are often reported from archeological middens. These records have revealed information on the range of marine diets of Native Americans, and presumably the fishes available to them (Fitch, 1969; Rick and Erlandson, 2000; Sandweiss *et al.*, 2004), including terrestrial communities that utilized salmonids (Butler and O'Conner, 2004).

Fish remains from middens may reflect the availability of different populations in the nearshore environment where most fishing occurred prior to industrialization. Cultures of British Columbia and Alaska may have had the capacity to navigate further offshore, but probably did so to hunt whales and large fish rather than small pelagics (Crockford, 1997). Fish remains are reported as the percentages of different species, number of identified specimens (NISP), or minimum number of individuals (MIN), which represents an estimate of the minimum number of fish that could have contributed to the total remains found. Variations in fish remains occurring with depth in the middens can reflect different periods in time, including different cultural occupations of a site. Midden dating is done with radiocarbon, as well as changes in other remains that indicate well-known changes in cultural occupations.

Detailed analysis of fish remains from the Santa Barbara area (California) and Channel Islands from the early Holocene (approximately 8000–10000 years ago) have been reported by Rick and Erlanderson (2000) and Rick *et al.* (2001). The NISP and MIN of smaller-sized fish, including small pelagics, make up a noteworthy percentage of the total fish remains in excavated units when they are sieved at 1/16 or 1/8 inch mesh size, rather than ¼ inch mesh size used by many other studies (Rick and Erlandson, 2000), which suggests the use of nets during this time period (Rick *et al.*, 2001). There is evidence for varying amounts of clupeoids (sardine and herring) relative to other fish species in different strata, but neither of these studies reported the presence of anchovy remains. The absence of anchovy could be

due to climate conditions, cultural preferences, or the use of a mesh size to coarse to adequately capture otoliths and vertebrates of anchovy. However, midden samples sieved in fine size fractions from other parts of southern California revealed predominantly anchovy remains (Fitch, 1969).

It is also well known that small pelagics played an important dietary role for early Holocene cultures in the Atacama desert (Keefer *et al.*, 1998). In four different levels of middens from cultures of the mid-Holocene at the site of Paloma (Fig. 4.2; ca. 8600–5400 cal yr B.P.[1]) anchoveta remains were consistently more abundant than sardines (Reitz *et al.*, 2003). A domination of anchovy remains was also reported at El Paraíso (Fig. 4.2) from about (ca. 4200–3250 cal yr B.P.), although sardine remains were present (Quilter *et al.*, 1991).

A study of different strata of common fisherman dwellings within the remains of the Lo Demás archeological site in the Chincha Valley, Peru (Fig. 4.2) were chronologically constrained by changes in ceramics and introduction of foreign seeds (Sandweiss *et al.*, 2004). The chincha culture was conquered by the Inca in 1479, who in turn were invaded by the Spanish in 1532. Sandweiss *et al.* (2004) found a change from an anchovy dominant MNI during the Chincha period to a more equal split between sardine and anchovy MNI during the Inca period at Lo Demás. While technological advances and/or cultural preferences may affect the relative numbers of these species found in the middens, these arguably had much less effect on fisheries of small pelagics than availability of the species in the nearshore environment (Sandweiss *et al.*, 2004).

When interpreting changes in relative variations between species' remains found in archeological sites, it should be noted that class preferences, in addition to cultural advances and preferences, can affect the species composition found in archeological middens. Marcus *et al.* (1999) analyzed fish remains from different rooms of a structural complex at Cerro Azul in central Peru. The complex was occupied by the Chincha culture, which had established some specialization in fishing and agriculture prior to Incan conquest. Marcus *et al.* (1999) found that a midden from the rooms of a noble family had much higher percentages of sardine remains (as well as remains of other species that are considered quality fish species today) than did the rooms belonging to lower class families, which had much greater concentrations of anchovy and other lower quality species.

Many archeologists do not sieve excavation material at sufficiently fine meshes to capture many fish remains, but this is possible (Fitch, 1969). Thus archeological remains from many sites offer the potential to examine changes in species available in nearshore environments, particularly if independent records, such as those from sedimentary environments, suggest a change in abundances of small pelagics or climate that could be further corroborated.

Sedimentary records

Oceanographic settings for sedimentary records

The presence of pelagic fishes over a particular sedimentary environment at some point in time is, of course, a prerequisite for using fish scales to reconstruct population variability. However, records from both the fringes of historical ranges, or possible historical ranges, as well as those from the center of the population's distribution, are all important to understanding past variation in population dynamics (see Figs. 4.1 and 4.2).

The most limiting factor is finding sedimentary environments with sufficiently low oxygen and high sedimentation rates to result in a continuous, high-resolution sedimentary sequence. Disoxia helps to both preserve fish remains and eliminates the presence of benthic fauna that bioturbate sedimentary sequences. Fortuitously, low oxygen conditions that are necessary for preserving stratigraphic sequences and fossil remains often coincide with regions of high productivity, including pelagic fishes. Sufficiently low oxygen concentrations occur due to some combination of the following processes: (1) intermediate waters that are relatively old and depleted of oxygen through remineralization of organic matter during water mass passage through the ocean conveyor circulation, (2) active upwelling of nutrient rich (and oxygen deficient) water resulting in high primary productivity and increased vertical transport of organic matter to the subsurface, which further reduces local oxygen concentrations, and (3) reduced circulation due to a basin or sill, which prevents water mass renewal and results in depleted oxygen concentrations.

The type of sedimentary environment confines the degree to which taking cores across lateral distances can be done for chronostratigraphic development and to span different points of a population's range. The Santa Barbara Basin (SBB) and Soledad Basin (San Lazaro) have all three of the aforementioned characteristics (Fig. 4.1). Fjords such as Effingham Inlet or Saanich Inlet have shallow sills that result in very long residence times and hence disoxia, even though waters entering the basin are not initially as depleted in oxygen as other regions. Although oxygen levels are much higher in the western Pacific, a bay in Japan apparently has adequate productivity to result in high sedimentation rates and preservation of fish scales (Kuwae *et al.*, 2007). Margins that have large ranges of laminated sediments throughout a very depleted oxygen minimum zone include the Peru shelf, Guaymas in the Gulf of California, and the Benguela Current. In these regions, cores can be taken across large lateral distances of 10s to 100s of miles to develop chronostratigraphies and comparisons of records between cores (Fig. 4.3).

Chronostratigraphies and fish scale deposition rates (SDRs)

There are a multitude of sedimentary factors to consider in the development and interpretation of records of fish scale deposition rates (SDRs). Of these, the chronostratigraphy is of fundamental importance to calculating relative dates and sedimentation rates, which give the temporal period of any given sampling interval for estimating SDR. Other important factors are core type, sediment area and volume provided, sampling resolution, and sampling replication.

Coring and sampling techniques

Recovery of surface sediments is important for calibration and development of the chronostratigraphy and can be achieved with a multi-core or Soutar Box core. A Soutar box core provides more sediment area (20×20 cm) for quantification, rectangular slabs that facilitate X-radiography, and development of other proxy records of climate change. The recovery of deeper sedimentary histories can be done with Kasten cores and piston cores. Kasten cores provide much greater sampling area (15×15 cm) and can capture up to ~3 m of sediments. Piston cores generally provide insufficient material (~4–12 cm diameter) for reliable presence/absence estimates of many fish species or decadal-scale resolution of abundant species, but can capture much deeper sedimentary histories (Tunnicliffe *et al.*, 2001).

Fish remains can also be recovered by sieving sediments of outcropped sediments (Fitch, 1969). There are also numerous fossil imprints of scales and even whole fish throughout the Monterey formation, a Miocene analog of the SBB sedimentary environment and other uplifted sedimentary sequences. Similar sequences off Peru also contain abundant scales and other remains (DeVries, personal communication).

Chronostratigraphy

Chronological development is a critical factor for records of temporal variability. The ideal scenario is that of the SBB or Saanich inlet where counts of annual laminae or "varves" facilitates chronostratigraphy development. The uncertainty in estimating varves (and hence years and SDR) may stem from erasure of laminae, presence of seasonal laminae within an annual varve pair, or the presence of slumps that appear to be varves or bioturbated sequences. While error in absolute dates years increases downcore in all record, the confidence in the number of years in a given sampling interval remains high in varved records because they are identifiable despite changes in sedimentation rates, hiatuses, or instantaneous deposits. The error in estimating SDR and absolute dates increases in sediments that are laminated, but not varved, and increases even more in sediments that are bioturbated.
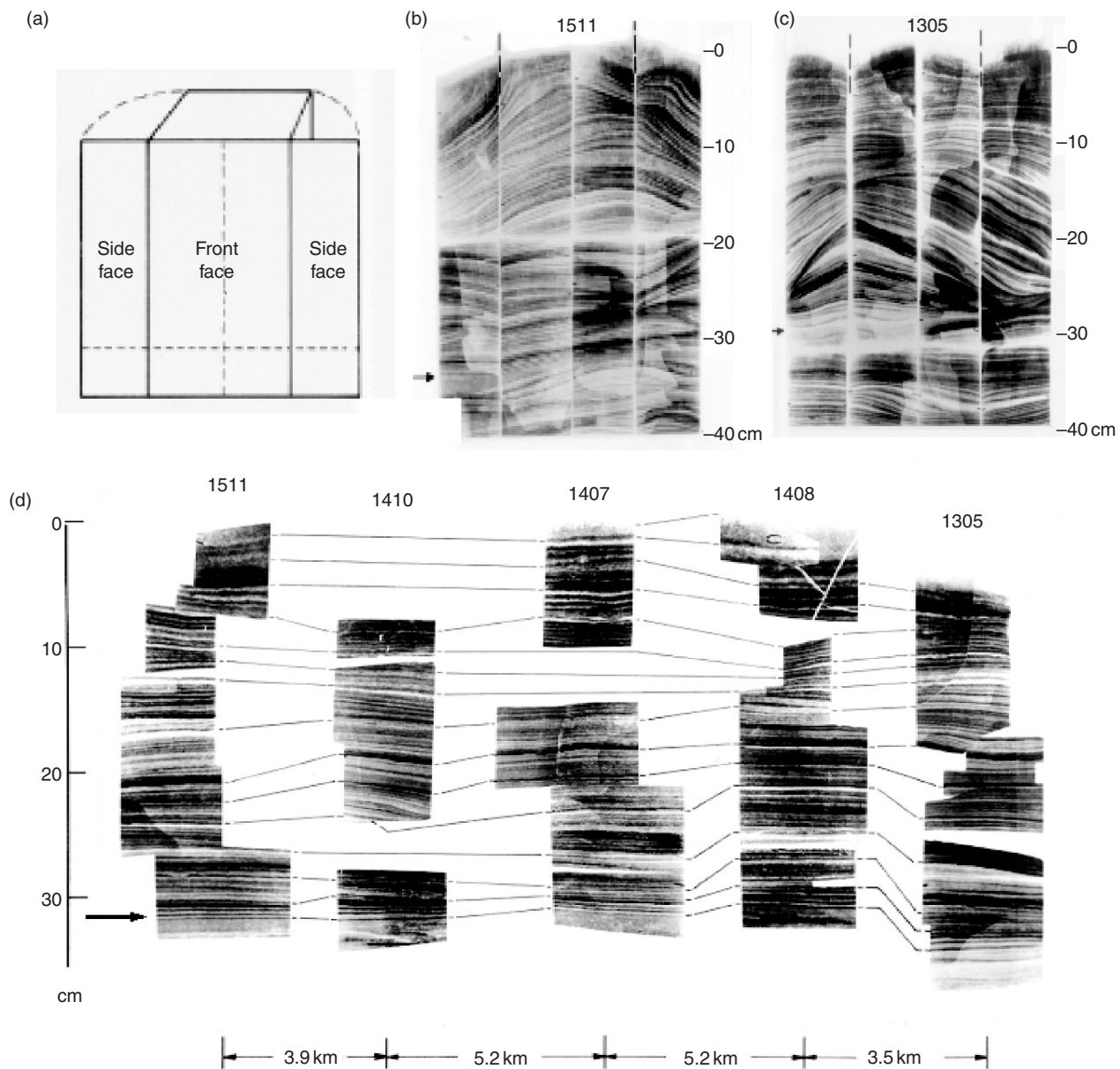
Fig. 4.3. Comparison of laminae structure both within and between cores from the Guaymas slope (Gulf of California) illustrating the horizontal variability in laminae structure that can confound chronostratigraphies. (a) Diagram of the slabs of core faces used for X-radiograph composites of the upper 40 cms of box core. (b) Radiographs of four sides of core GCBC-7807–1511. (c) Radiographs of four sides of core GCBC-7807–1511. (d) Reconstructed lamina sequences from five box cores from the Guaymas slope. Vertical continuity within each core is maximized by fitting selected sections from different regions of the cores. Correlation lines mark prominent laminae which are clearly identifiable among the five cores. Blank areas within the lamina sequences indicate discontinuities which occur across an entire core. Distances between core sites are shown at the bottom of the figure. Arrows indicate a sediment gravity flow forming the base of each reconstruction. The gravity flow is dated at ~1907 by ^{210}Pb, which is consistent with a known 7.5 seismic event in the Gulf of California in 1907 (from Baumgartner *et al.*, 1991).

Chronostratigraphies are usually most accurate in the last 100–200 years where there is good control with radioisotopes and less accumulation of errors. The half-life of ^{210}Pb is 22.3 years, meaning that it can be used to estimate sediment ages up to ~100–150 years ago. ^{241}Am in the atmosphere resulted from bomb testing in the 1950s and 1960s, and thus serves as a good tracer for these time periods. Beyond the last 100 years, ^{14}C is considered the most reliable constraint on absolute dates and sedimentation rates where varves are not present. However, ^{14}C values must be corrected for the oceanic reservoir age, which can vary as intermediate water masses change. Tephra layers (volcanic

ash) or seismicly induced slumps attributable to historically known dates may provide additional chronological constraints (e.g. Baumgartner *et al*., 1991).

Chronostratigraphic obstacles

It is well known that varve thickness, and hence sedimentation rates, vary considerably on interannual to centennial timescales due to changes in productivity and terrestrial run-off (Soutar, 1967; Soutar and Crill, 1977; Lange *et al*., 1996). Sediment winnowing and erosion by bottom currents can also occur on continental platforms. Changes in sedimentation rate are occasionally taken into consideration at coarse resolution in a core, but rarely considered at the sampling resolution. However, such changes can have major effects on estimated SDR and chronologies.

Physical disturbances, such as bioturbation and slumps, complicate the development of a chronostratigraphy in otherwise continuous sedimentary sequences. Slumps can be associated with both instantaneous deposits of sediments from upslope and/or erasures of material to the downslope. Bioturbation disturbs the continuity of a record but generally does not result in a hiatus. Physical disturbances also include variations, sometimes dramatic, on the scales of centimeters (Fig. 4.3b, 4.3c).

Multiple cores, separated by 100s to 1000s of meters, can reveal the differences in structure of physical disturbances to indicate the mechanism and significance of the disturbance. Figure 4.3d shows how cores taken from kilometers apart in the Gulf of California vary widely in their preservation of particular sedimentary sequences and laminae structure (Baumgartner *et al*., 1991). There are both discontinuities and changes in laminae structure that would otherwise be missed in a single core, or even a single slab of a particular core (Fig. 4.3). X-radiographs of Kasten cores from different locations throughout the SBB also reveal slumps of varying thickness (Fig. 4.4). The relative different thickness of each slump not only indicates that they are instantaneous deposits from upslope (rather than bioturbation events) but is also indicative of the area of greatest intensity of the slide (Fig. 4.4). Additionally, some cores from different areas of the SBB preserve particular laminae or varve sequences that are not observed in all cores.

The most well-studied sites show that there is considerable horizontal variability in laminae sequences with many slumps that are not resolvable with single cores. Consequently, records having weak chronological constraints should only be compared with other records (sediment cores, tree rings, corals, ice cores, historical data, etc.) within the limits of the chronology. Due to possible uncertainties in chronologies that increase downcore, sufficient confidence regarding decadal-scale variability is probably only resolvable up to 100–150 years ago. Beyond 200 years ago, reliable comparisons between records with independent chronologies may be efficient only on the interdecadal timescale while centennial-scale variability can probably be effective up to several thousand years ago.

Variability in scale deposition rate (SDR) between sites

Multiple cores within a region can also verify the extent to which records of SDR to one area of sediment reflect fluxes to the sediment environment within a broader region. Differences may arise from random events, sedimentary differences, and/or in association with movements of fish populations. Variability in SDR across centimeters has been quantified in different slabs of sediments from the same core (Table 4.1). The correlations are low in part because the number of scales in each slab generally ranges from 0–10 and are insufficient to result in a reliable estimate of SDR (Lozano-Montes, 1997). Estimates of sardine SDR between a Kasten core and two piston cores in the SBB show that the principal downcore signals are quite coherent and can be reproduced despite being separated by kilometers (Fig. 4.4; Table 4.1; Baumgartner *et al*., 1992). While the records in Fig. 4.3 were developed with independent chronologies, the decadal and centennial-scale patterns of SDR are clearly coherent between cores.

O'Connell and Tunnicliffe (2001) also showed clear coherence in herring SDR between cores from Saanich Inlet. On a larger scale, there is some coherence in anchovy SDR over multidecadal to centennial timescales from Peruvian sediments taken 100s of kilometers. apart (Gutierrez *et al*., 2006). Lack of coherence at decadal timescales could be from chronological differences, erosive or more oxic sedimentary environments, or from differences in local populations.

Interpreting scale deposition rates

SDRs calculated from a given sampling interval are generally representative of the actual fluxes to a sedimentary environment when sufficient areas of sediment and number of scales are examined. We here discuss the basis for interpreting SDR to the sediments. Multiple lines of evidence show that fish SDR reflect local abundances of fish, primarily from shedding of scales from live fish; the deposition of a piece of a fish from a mortality event is very rare. We discuss the population dynamics that can affect relationships between the local abundance of small pelagics and their regional variability. Finally, we review how geochemical composition of scales may contain environmental histories of fish and SDR calibrations to biomass.

Scales and scale shedding

Clupeiods and many other fish are caducous by nature (they shed their scales), which may enhance escape from predators via visual confusion by a flurry of scales. New
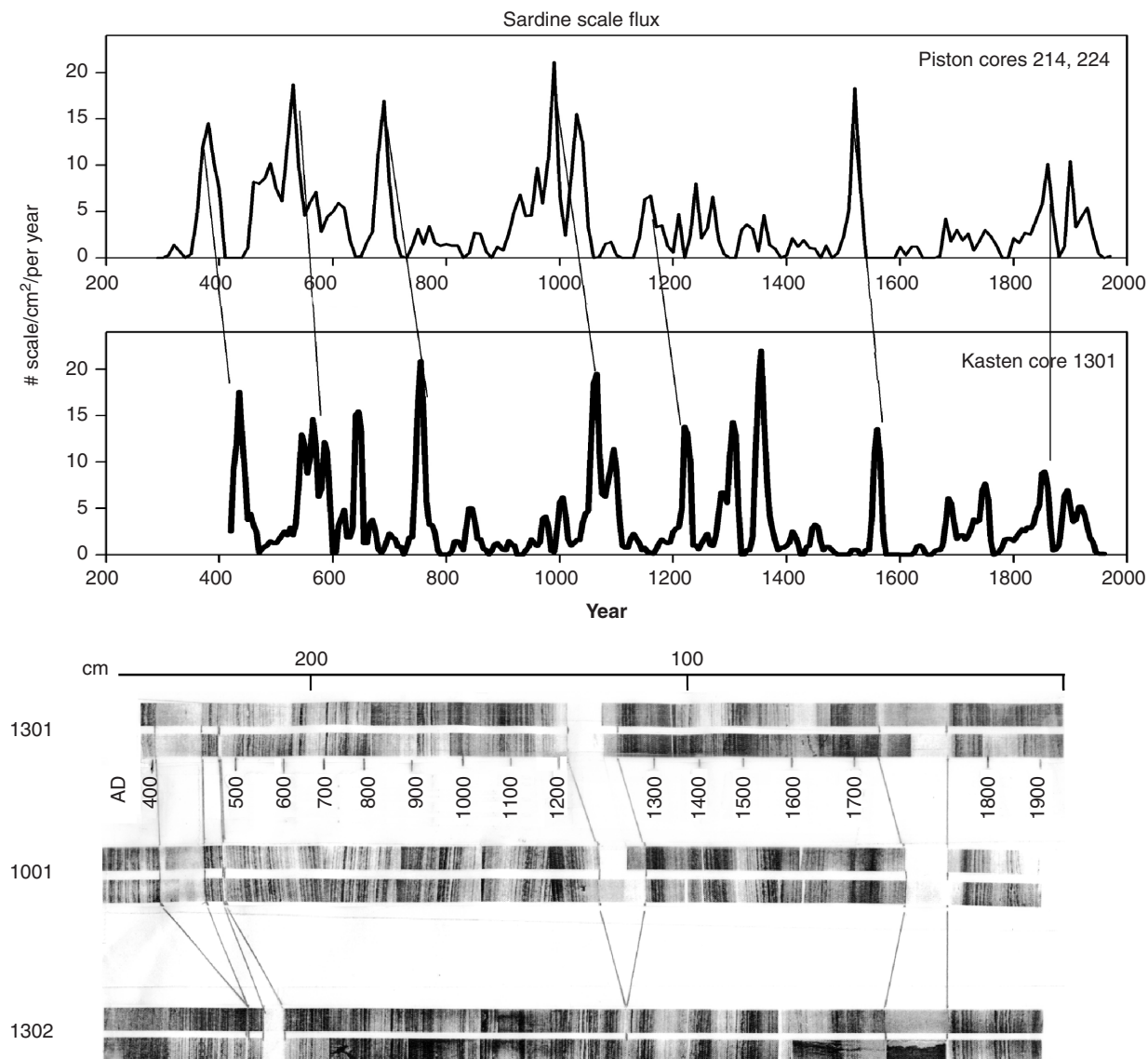
Fig. 4.4. Comparison of sardine scale deposition rates (SDRs) from the composite counts of two piston cores (from Soutar and Isaacs, 1969) with Kasten core SBKC 9110–1301. Lines indicate correlations between SDR records, each of which is dated with independent chronologies. Note the offset of nearly 50 years in the chronology from independent varve counts from two piston cores relative to three Kasten cores. X-radiographs from three Kasten cores were used to anchor the master chronology used for SBKC 9110–1301. Lines between each two sets of X-radiographs from a Kasten core show slumps of varying thickness between cores.

scales that grow where previously scales were lost (which are generally thinner and without clear circuli) are common on living fish (Shackleton, 1986). Fish scales are made of hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$ embedded within an organic matrix of fibrous protein collagen. As fish grow, scales grow laterally through deposition of both hydroxyapatite and the organic matrix. Thickening of the organic matrix continues during fish growth (with no addition of hydroxyapatite).

The types of scales found in the sediments indicate that they are primarily derived from scale shedding. Scale morphology varies over the body of clupeoids and can be characterized into five seven different categories (Fig. 4.5; Shackleton, 1986; Lozano-Montes, 1997). Typical scales ("type T" in sardines; e.g. Fig. 4.5) are found along the lateral line and make up ~35% of the total scales on a sardine. In anchovy, Typical scales have been found to make up from 42%–49% of the total number of scales and have been

Table 4.1. *Shared variability between different time series of scale deposition rates (SDRs) from Santa Barbara Basin sediments*

Time series	R value
Sardine between slabs	0.30 (0.38)
Anchovy between slabs	0.37 (0.43)
Sardine between cores	0.53
Anchovy between cores	0.54
Sardine with anchovy	0.32

Variability between slabs is the average coefficient of correlation between four different slabs of sediment from Kasten core 1301 (and 1302) after Lozano-Montes (1997). Correlations between cores come from the comparison of two piston cores with a low amount of sediment area quantified. The correlation between sardine and anchovy is the average of the two piston cores (after Baumgartner *et al.*, 1992).
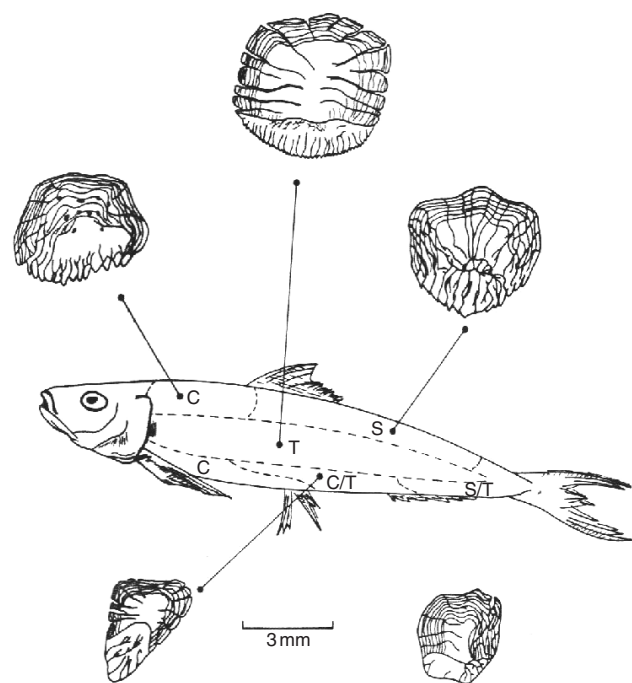

Fig. 4.5. Five representative scale morphologies and their locations on the body of a Pacific sardine (*Sardinops sagax*) using the nomenclature proposed by Shackleton (1986) for *Sardinops ocellata*. Typical scales ("type T") are those along the lateral line.

classified as "type X or Y" (Shackleton, 1988; Table 4.2). Collections of scales shed from fish in controlled aquarium environments have shown that Typical scales are highly disproportionately shed from living fish (Table 4.2). Since the majority of sardine and anchovy scales in the sedimentary records are Typical as well (Table 4.2), most of these scales originate from shedding.

Scales are shed during schooling behavior, but scale loss is much higher during pursuit, predation, and/or mortality events (Lozano-Montes, 1997; O'Connell and Tunnicliffe, 2001). A predation event would most likely result in the loss of scales during pursuit or impact. Scales do not pass through the guts of most predators, while bones, vertebrae, and otoliths have been documented to pass through the guts of some predators, but not others (DeVries and Pearcy, 1982; O'Connell and Tunnicliffe, 2001). Other scale types are as durable as Typical scales, but are not observed in as high proportions in the sediments or aquariums as observed on fish (Lozano-Montes, 1997). Thus only scale shedding, rather than mortality and consequential passage through guts, can account for the disproportionate representation of typical scales in marine sediments.

Several independent observations show that, on very rare occasions, deposition of many scales (and bones) can be instantaneous, likely derived from a part of a single fish. Observations include many hake scales and bones found in part of a core from the SBB with rapidly diminishing numbers in slabs several centimeters further away (Soutar, 1967; Field, personal observation). There is also an observation of four vertebrae lined up with each other within a piece of sediment from Peru with scales and bones lining up on either side, which is clearly the consequence of the preservation of a part of an anchovy. In contrast, one frequently encounters individual scales while cutting sediment, with no nearby scales, bones, or vertebrae associated (Ferriera, Field, and Salvateci, personal observation). Additionally, O'Connell and Tunnicliffe (2001) noted that one of four box cores analyzed had a large spike in herring scales in one sampling interval that was an order of magnitude higher than the background levels and not present in other cores.

Replicate sampling can clearly identify rare events of instantaneous deposition of many scales from a portion of a fish. After elimination of one outlier interval, O'Connell and Tunnicliffe (2001) found consistent downcore variability in SDR between four box cores spanning 130 years. Their result is consistent with the signal to noise ratios found between different slabs of the same core (Table 4.1) and different cores from the SBB (Baumgartner *et al.*, 1992; Table 4.1; Fig. 4.4). The coherent signals across horizontal sampling intervals indicate that SDR stem primarily from a rain of scales from shedding and predation that varies with fish density.

Scale degradation

The oceans are undersaturated in apatite, which could result in dissolution of scales and bones (Suess, 1981). Bacterially mediated degradation may be common within the organic matrix of the scale in oxygenated environments. In scales from laminated sediments, there is a loss of organic matter in the fossil scales relative to scales from living fish (Table 4.3).

Table 4.2. *Percent of "Typical" scales (those derived from the lateral line characterized by having a symmetric form) found on living fish (see Fig. 4.5), shed during aquarium experiments, and found in ocean sediments.*

Source of scales	Shackleton (sardine)	Lozano (sardine)	Shackleton (anchovy)	Lozano (anchovy)	Salvatteci (anchovy)
Living fish	34%	36%	47%	49%	42%
Aquarium	65%	85%	na	na	55%
Sediments	67%	66%	na	na	85%

Typical scales from sardine are 'type T' (Fig. 4.5) while those from anchovy are 'type X and Y' (after Shackleton, 1986). Observations from Shackleton (1986) are for pilchard (*Sardinops ocellata*) and anchovy (*Engraulis japonicus*) off Namibia, Lozano-Montes (1997) examined California sardine (*Sardinops caeruls sagax*) and northern anchovy (*Engraulis mordax*) from the California Current, and R. Salvatteci (unpublished data) examined Peruvian anchoveta (*Engraulis ringens*) from the Humboldt Current (following Shackleton, 1986).

Table 4.3. *Percent of total scale weight that is composed of nitrogen (N) and carbon (C) and their standard deviations for living California sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*) as well as fossil scales from these same species and Peruvian anchoveta (*Engraulis ringens*).*

Source of scales	% N	Stdev	% C	Stdev	N
Living Northern anchovy	14.2	0.32	46.8	1.17	38
Living Pacific sardine	13.8	0.37	47.7	1.13	41
Fossil sardine scales (La Paz)	3.9	0.17	12.5	0.35	2
Fossil anchovy scales (La Paz)	3.0	0.17	11.2	0.10	2
Fossil anchoveta scales (Peru)	3.6	0.76	12.9	2.28	36

Each measurement is done on 4–15 scales (D. Field, unpublished data).

Scales from the Peruvian margin have been observed to have fissures forming throughout the scale (Fig. 4.6a, 4.6c with 4.6b and 4.6d). Scales with large quantities of fissures become brittle and more likely to break during handling (D. Field and R. Salvatteci, unpublished data). Some scales vary in color (D. Field and R. Salvatteci, unpublished data; Patterson *et al.* 2004). O'Connell and Tunnicliffe (2001) found that sections of piston cores sampled 19 months after initial sampling had vertebrae, but no scales, indicating post-coring degradation of scales. Furthermore, initial sampling showed a large decrease in the ratio of scales to vertebrae downcore, suggesting degradation of scales prior to coring (O'Connell and Tunnicliffe, 2001). There is a greatly diminished number of scales from the slope of the SBB (Soutar, 1971), but no observation of degradation of scales or development of fissures from the deepest part of the Santa Barbara Basin, despite the fact that many cores have been quantified years after coring (D. Field, unpublished data). In fact, there is a trend towards greater scale abundances in the SBB further back in time (Baumgartner *et al.*, 1992). While degradation is not currently understood, it undoubtedly varies with sedimentary chemistry and could bias SDR estimates through time.
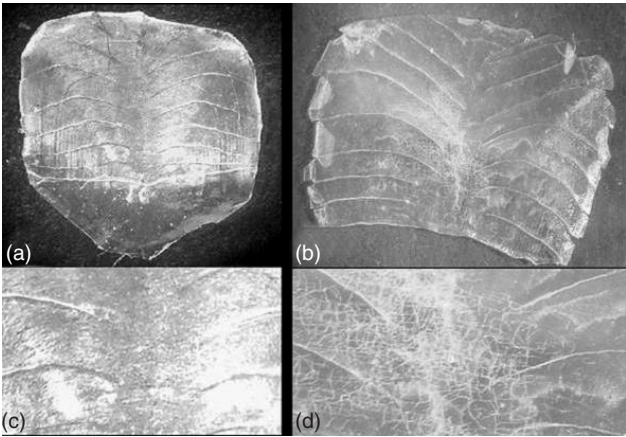

Fig. 4.6. Photos of typical sardine scales ('type T') from (a) living sardine (*Sardinops sagax sagax)* and (b) fossil sardine from sediments off Peru. (c), (d) Close-up of the foci of each scale. (d) Note the formation of fissures, that are neither the circuli around the scale or radii extending to the focus, in the center of the fossil scale from the Peruvian shelf.

One way to address the degree to which degradation may be affecting downcore records is by examining the ratio of scales to otoliths, vertebrae, and/or bones. Otoliths are aragonite and quite rare, while bones and vertebrae are generally present and composed of hydroxyapatite, but with lower surface area to volume ratios and less organic matter than scales. Scales can be identified to species more accurately. Otoliths often have dissolution affecting key characteristics, and bones and spines are not usually distinguishable among species. Devries (1979) documented that oxygenated areas of the Peruvian shelf have considerably lower scale to vertebrae ratios as well as lower total concentrations of both scales and vertebrae. Although changes in scale to bone ratios could also be derived from changes in community assemblage towards species with much different SDRs.

Another method for assessing degradation is by noting the different stages of development of fissures on scales (Fig. 4.6). Other paleo proxies of oxygen concentration, such as Mo concentrations, can also be useful in assessing the potential degree of degradation affecting scale abundances in the sediments.

SDR and regional variations in fish abundance

SDR to a sedimentary environment should vary directly with the integrated fish abundance (as schools move across the area in time). But how well do local fish abundances over a given area reflect fish abundance over a broad region of a boundary current? Pelagic fish populations generally expand both their habitat range and regional densities during population expansions (MacCall, 2008). Figure 4.1 shows three different scenarios for the relative abundance and distribution of sardines in the California Current System, and how the population state could be reflected in SDR records from different anoxic areas. For example, an expanded population distributed in the northern range of the California Current would be captured by SDR to Effingham Inlet and SBB (Fig. 4.1a, ex. 3), while a contracted and southern population would be limited to sites around Baja California (Fig. 4.1a, ex. 1).

While migrations of sardine adult biomass could complicate SDR to the SBB as an indicator of total biomass, sardine SDR in this region probably reflects recent recruits, rather than adult biomass (Baumgartner *et al.*, 1992). Figure 4.7 shows very clear differences in sardine scale widths in the SBB as compared with scale widths from Effingham Inlet. Although different scale types vary in width from one another (e.g. Fig. 4.5), there are strong correlation between scale width and fish length within each scale type (Lozano-Montes, 1997). Scale widths from the SBB, which are primarily "'type T," indicate that the record is composed primarily of 0–2-year-old fish (Fig. 4.7; Lozano-Montes, 1997). Thus the SDR to SBB sediments
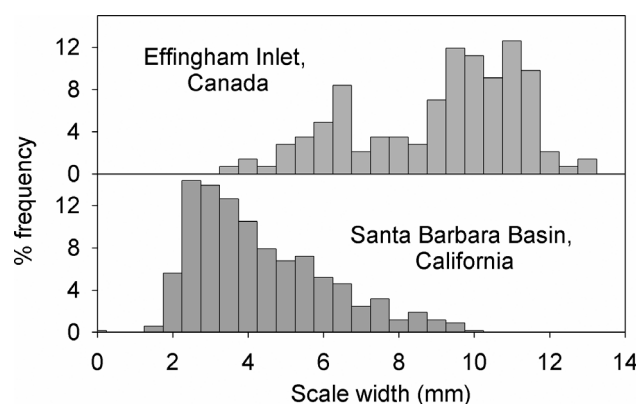

Fig. 4.7. Histogram of sardine scale widths from the Santa Barbara Basin (SBB) and Effingham Inlet, British Columbia.

can be considered an integrated estimate of sardine recruitment over multi-annual timescales. In contrast, scales from Effingham Inlet are from much older fish (Fig. 4.7), suggesting that presence of sardines in the northern region occurs when an expanded population of sardines has reached sufficient age to migrate and persist to its northern range (e.g. Fig. 4.1a, ex. 3).

Anchovy in the California Current (and other regions) tend to be found in the more coastal upwelling regions, are generally less migratory (this volume, Chapter 3 and 12), and local densities may more closely reflect regional biomass. Soutar and Isaacs (1969) found that anchovy scale widths in the SBB generally correspond to 1–3-year-old fish, which is the age distribution of the population in that region.

Off Peru, it is well known that anchovy modify their spatial distribution both alongshore and cross-shore on seasonal and interannual timescales. There are tendencies towards more northern and offshore distributions during winter months of greater upwelling. In contrast, anchovy are found closer to the coast, further south, and deeper during summer and El Niño events when cool, productive waters are limited to the coastal upwelling regions (Fig. 4.2). The existence of laminated sedimentary records off Chimbote, Callao, Pisco, and Bahia Mejillones (a coastal bay off northern Chile) provides a means to examine spatial variability in small pelagic populations along different latitudinal (and cross-shore) environments of the coast (Fig. 4.2).

Scale geochemistry

Additional information on environmental conditions and/or population movements may be inferred from both the hydroxyapatite and organic matrix components of fish scales. There is generally sufficient organic matter within a fossilized scale to measure the $\delta^{15}N$ and $\delta^{13}C$ of the organic matter within the scale (Struck *et al.* 2004). Fish scale $\delta^{15}N$

and δ¹³C values are influenced by trophic level and nutrient input into the base of the food web. Thus variations in δ¹⁵N and δ¹³C may reflect changes in trophic level, eutrophication, or productivity within their environment (Wainright *et al.*, 1993; Gerdeaux and Perga, 2006).

Alternatively, fish may incorporate an isotopic signature (δ¹⁵N of scales or δ¹⁸O of otoliths) of their region of recent growth and be traceable to their origin upon migration to another region. For example, sardines from Bahia Magdalena have a δ¹⁵N signature of several per mil higher than other regions of the California Current, likely due to the different nutrient recycling. Hence δ¹⁵N could be a useful indicator of sardine stocks that migrate in and out of Magdalena Bay (Field and Vetter, 2005). Trace elements in scales and otoliths also offer potential to resolve life histories of individuals with respect to environmental conditions, particularly within different rivers and bays, but the trace elements are not always stable in fish scales (Wells *et al.*, 2003).

Calibrations to biomass variability

Scale shedding rates (and thus SDRs) vary with species and require independent calibrations with each species and ocean region (Shackleton, 1987; Baumgartner *et al.*, 1992; Lozano-Montes, 1997). Calibrations of sardine SDR to estimated biomass have been done for averaged five-year intervals from the SBB up to 1969 (Soutar and Isaacs, 1974; Baumgartner *et al.*, 1992). This coarse calibration indicates that, at a population size of approximately 400 000 (200 000) tons of sardines (anchovies) off California, zero scale counts become common and the calibration loses definition. Recent sampling of several box cores in two-year intervals shows the increase in northern anchovy during the 1960s and 1970s and the presence of sardines scales again in the SBB since the early 1990s. While more material is needed for an accurate high-resolution comparison, a reliable calibration is difficult due to number of scales counted per limited temporal interval. Yet the calibration is useful in indicating that past times of high SDR were likely associated with very high sardine recruitment off central California relative to the early twentieth century (Baumgartner *et al.*, 1992).

Variations in combined SDR of Peruvian anchoveta from cores taken at Callao and Pisco reflect nearly 50% of the variance in catch records during the developed fishery, indicating that SDR is fairly consistent with catch records (Salvatteci *et al.*, 2006). Both SDR and catch records can be considered biased. SDR is sometimes based on a small area of sediment and/or low number of scales and fish can migrate to other regions. Changes in sedimentation rates and sampling interval may also affect calibrations. Fish catch records and biomass estimates are affected by sampling effort as well.

O'Connell and Tunnicliffe (2001) reported the most rigorous examination of SDR to date by examining herring

SDR from five box cores taken in the Saanich Inlet. Visual comparison of the combined record from these cores shows that it reflects the principal variations in estimated herring biomass of the area.

Significance of the historical records

The historical records of SDRs reveal many aspects of long-term variability. Many ideas of interdecadal-scale ecosystem change in the North Pacific relate to inferred changes between basin-wide, bimodal states or "regime shifts" associated with the Pacific Decadal Oscillation (PDO) over 50–60-year timescales. Some of these ecosystem paradigms, are that expansions and contractions of the Aleutian Low on 50–60 year timescales, as reflected by the PDO, result in out-of-phase alternations in abundance of sardines and anchovies (Lluch-Belda *et al.*, 1992; Chavez *et al.*, 2003), out-of-phase fluctuation in salmon between the California Current and the Gulf of Alaska (Mantua *et al.*, 1997), and in-phase fluctuations between populations of small pelagics in different boundary currents of the Pacific and South Atlantic (Kawasaki, 1991; Lluch-Belda *et al.*, 1992). There are many indications that both the modes and timescales of ocean variability and the response of pelagic fish populations far exceed the range of variations observed in the twentieth century.

Presence/absence

The presence or absence of scales (or other remains) can be an important indicator of variability when sufficient sediment is quantified. Anchovies appeared in the Gulf of California sardine fishery for the first time in the late 1980s, raising speculations that anchovy were occupying an ecological niche recently opened from the fishing of sardines (Holmgren-Urba and Baumgartner, 1993). However, the presence of anchovy scales in Guaymas sediments decades and centuries prior reiterated the importance of natural variability not just in the California Current System, but in the surrounding seas as well (Holmgren-Urba and Baumgartner, 1993; Fig. 4.8).

The occurrence of many species in Saanich Inlet by about 6000 years ago indicates that colonization of the fjord region since deglaciation was complete by this time, if not earlier (Tunnicliffe *et al.*, 2001). The presence of bluefin tuna remains in British Columbia middens suggests that bluefin tuna, generally found further south and offshore, have reached those latitudes in the past (Crockford, 1997).

Remains of many species of small pelagics in the California Current today have been found in Native American middens from the Holocene and in outcropped Pleistocene deposits around southern California spanning both glacial and interglacial periods (Fitch, 1969). Noteworthy observations by Fitch (1969) are that otoliths of
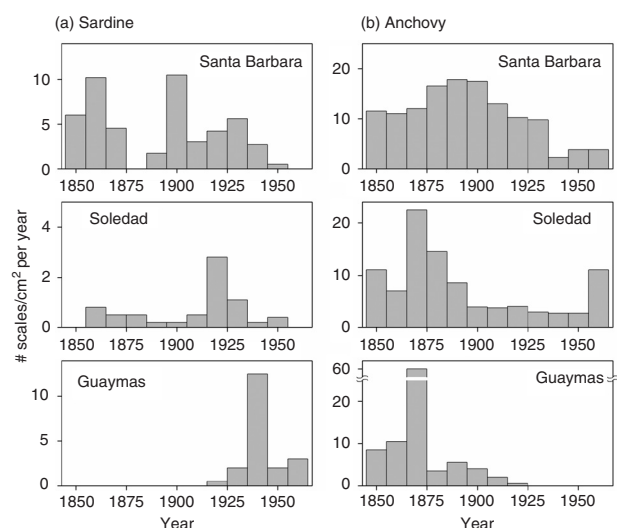
Fig. 4.8. SDRs for (a) Pacific sardine and (b) Northern anchovy from central California (Santa Barbara Basin), Baja California (Soledad), and the Gulf of California (Guaymas slope). Locations shown in Fig. 4.1 (from Holmgren and Baumgartner, 1993).

northern anchovy were found continuously throughout the last 12 million years, including during different glacial and interglacial periods as well as warmer Pliocene periods. In contrast, herring remains were only found during cool glacial periods. Neither sardines nor Pacific Mackerel otoliths were found in glacial sediments and sardine otoliths were not found from Pliocene sediments, despite the fact that the Pliocene was a relatively warm period. Absence of sardine may reflect its shallow evolutionary history in the California Current (see MacCall, this volume, Chapter 12).

Relationships between sites and records

The case of sardine in the California Current offers the potential to compare different historical records. Changes in the distribution of sardines have been documented by Holmgren-Urba and Baumgartner (1993). Variations in sardine SDRs in cores from the SBB, Soledad Basin, and Guaymas shelf shown in Fig. 4.8 show how sardines from the central California Current contracted to a reduced population with a more southern distribution during the collapse of the California fishery, as proposed in Fig. 4.1.

Following the model of population expansions and contractions in Fig. 4.1, high abundances of sardines off central California would correspond with an expansion of sardine populations into the northeast Pacific. However, Holmgren-Urba (2001) reported the presence of sardine scales in Effingham Inlet, British Columbia to be out of phase with sardine scale deposition in the Santa Barbara Basin. Yet chronological uncertainties associated with a homogenous layer question this result and reiterate the

importance of accurate chronostratigraphies. Considering the homogenous section as a slump rather than bioturbated event would result in simultaneous sardine scale deposition in Effingham Inlet and the SBB (T. Baumgartner, unpublished data).

Chronologies from historical observations and annually laminated sediments are more reliable. Figure 4.9a compares fish scale abundance in the SBB with historical observations in the Pacific northwest. The increase in scale fluxes to the SBB around 1885 corresponds with observations of sardine presence in the Pacific northwest in 1888. Although surveys in the Pacific northwest did not detect sardines in the early 1880s when scale flux to the SBB was low, there were no positive observations in the mid-nineteenth century either, when scale flux indicates high sardine abundances off Central California (Fig. 4.9). While observational data may not be exhaustive, the combination of historical records do not support the hypothesis that all sardine population expansions are similar.

The combination of historical records of artisanal sardine catch off Japan and sardine scale deposition records in the SBB do not support the hypothesis of simultaneous basin-scale variations in small pelagics. The basin-scale hypothesis asserts that sardine and anchovy populations in different regions of the Pacific (and South Atlantic) vary coherently. While sardines were apparently abundant in the California Current from 1890 through the early twentieth century, this was a period of poor catch throughout different regions of Japan (Fig. 4.9, Hiramoto, 1991). The other most conspicuous period of poor catch of sardine throughout Japan began around 1730 and lasted until around 1775, which corresponds with a large peak in sardine scale deposition in the SBB (Fig. 4.9). Furthermore, good fishing years occurred throughout Japan from 1690–1725 and again from 1790–1830, but these two periods are characterized by moderate, not high sardine scale fluxes to the Santa Barbara Basin (Fig. 4.9). Although these observations do not capture the whole distributional ranges of sardine populations, the compilation of historical records of sardine do not support the basin-scale hypothesis of coherent variations in sardine population abundance.

Schwartzlose *et al*. (1999) reported a general correspondence between anchovy and sardine SDR in the Santa Barbara Basin and Bohuslän herring events off Sweden for several centuries, but their proposed relationship is not present throughout the record. An analysis of instrumental records indicates that the atmospheric circulation in the N. Pacific and N. Atlantic has varied both in phase and out of phase during the twentieth century (Schwing *et al*., 2003). Just as large-scale coherency between regions observed in the twentieth century may have been weaker in the past, there may be relationships between oceanic regions in the past that were not predominant in the twentieth century.
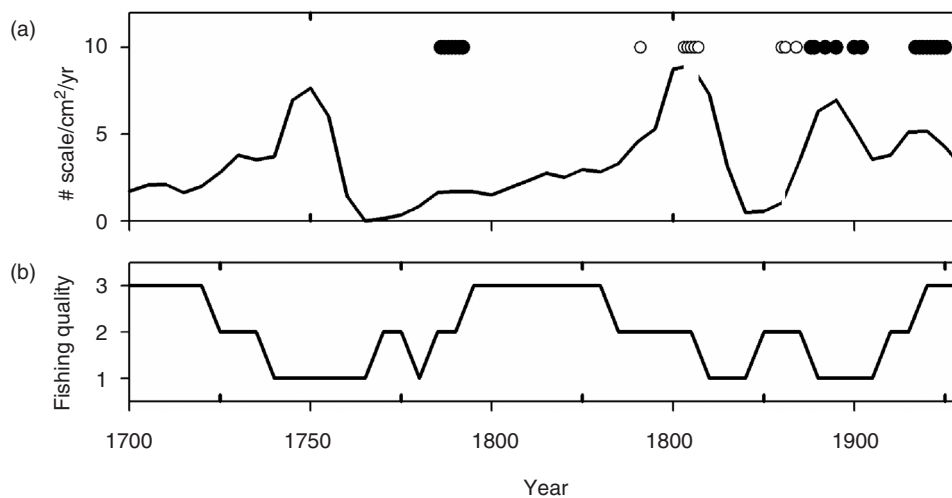
Fig. 4.9. Comparison of different historical records of sardine abundance in (a) the California Current and (b) off Japan. (a) Fish scale deposition rate of sardines in the Santa Barbara Basin (central California) are shown as a 3-term smoothing of 5-year sampling intervals. Closed (open) symbols are historical observations of sardine presence (absence) in the northern California Current region, around Puget Sound and British Columbia (from Field *et al*., 2001). (b) Quality of sardine fishing around Japan (after Hiramoto, 1991) corresponding to good sardine fishing in all areas (3), a mix between good and poor fishing in different regions (2), and poor fishing throughout Japanese waters (1).

However, there was no reported relationship of Bohuslän herring events with sardine SDR in the SBB, which may be a better indicator of the PDO. Their observation reiterates the importance of chronological uncertainties when comparing records, both with respect to finding relationships or absence of relationships, since even the annually laminated SBB sediments have considerable dating uncertainty beyond several centuries.

Off Peru, cores from several sites that have been examined to date and lie within the population range of anchovies shown in Fig. 4.2 (Pisco and Callao, Peru) indicate diminished abundance of anchovy scales prior to ~1820 (Gutierrez *et al*., 2006). Part of this diminished abundance may be due to scale degradation. This period of diminished anchovy scale deposition was characterized by a reduction of scales of all species, rather than an increase in scale deposition rates of sardine (which are more resistant to degradation). However, a relatively greater increase in sardine remains has been reported from Peruvian middens during the time period coinciding with the decrease in total scales (Sandweiss *et al*., 2004). While sediment chronologies this far back in time are associated with considerable uncertainties, the increase in sardine remains in middens might reflect a shift of the sardine population towards the nearshore rather than an increase in total biomass.

Relationships between species
The records of SDR from the SBB are the most high-resolution, continuous, and reliable records to date. Scale deposition records of sardine and anchovy show a weak positive relationship with each other throughout the SBB record (Fig. 4.10; Table 4.1; Baumgartner *et al*., 1992) rather than a negative relationship, which characterizes the twentieth century (Chavez *et al*., 2003). Although there are some periods of abundance of one species or another, the sediment records do not support the idea of negative fluctuations in population recruitment and abundances of these species as a predominant mode of variability in prior centuries. There are many periods when both species have relatively high or low SDR. However, Lasker and MacCall (1983) found that anchovy scale widths, and thus lengths, were smaller when sardine SDR were moderately high, suggesting some reduction in anchovy growth during periods of high sardine recruitment and abundance.

Scale deposition rates of pilchards and anchovy off Namibia show no clear relationship with one another (Shackleton, 1987). In two different cores examined at 4-year sampling intervals, periods of both high or low scale flux of pilchards occur during periods of high and low flux of anchovy scales (Shackleton, 1987).

Holmgren-Urba (2001) found no consistent relationships between SDR of different species in recent sediments from Effingham Inlet, although one period dominated by anchovy SDR has fewer remains of other species. There is no clear relationship between herring and anchovy SDR to Effingham Inlet on longer timescales, they have weak positive covariability during the past five thousand years (Patterson *et al*., 2004). Patterson *et al*. (2004) proposed that herring and anchovy varied out of phase within the
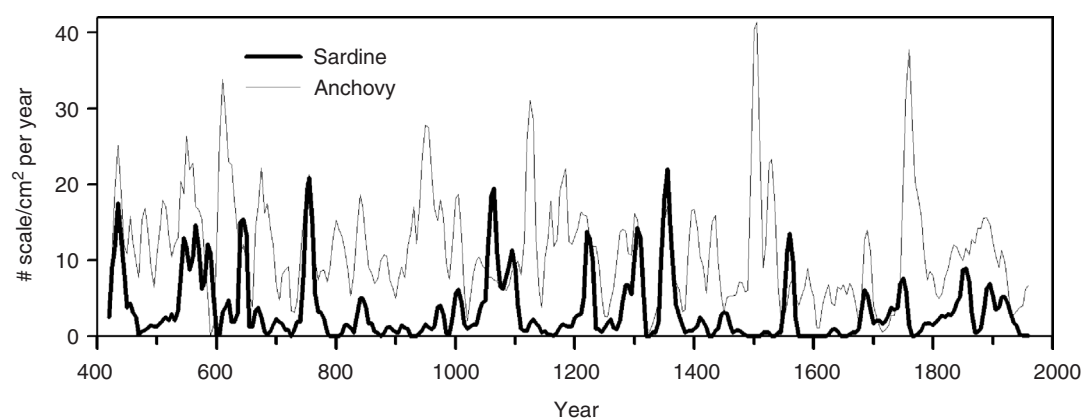
Fig. 4.10. Sardine and anchovy scale deposition rates in the Santa Barbara Basin from Kasten core SBKC 9110–1301. Lines are three-term smoothing of continuous 5-year sampling intervals (updated from Baumgartner *et al*., 1992). The positive relationship between SDR of each species is very weak, but significant (r^2=0.03, P<0.005).

centennial-scale time domain, although their chronology was only constrained by three ^{14}C dates and homogenous layers were not defined as bioturbations or slumps.

While there appears to be a positive relationship between anchovy and hake SDR in sediments off Peru on decadal to millennial timescales, there is no clear relationship between sardine SDR with either of these species (DeVries and Pearcy, 1982; Salvatteci *et al*., 2006).

Only the records from historical fisheries in the N. Atlantic show clear alternations of species prior to the twentieth century (Alheit and Hagen, 1997). The alternations between species in the N. Atlantic are probably due primarily to changes in biogeographic distributions.

The lack of clear relationships between SDR of different species of small pelagics in cores from different oceanic regions indicates that abundances of each species are determined by different combinations of environmental changes that could include circulation, productivity, and the abundances of top-down predators, which affect mortality and recruitment. The majority of the evidence points to climatically driven changes modifying recruitment, with interactions between species playing a less significant role.

Timescales of variability

Inferred changes in fish populations varies across a large range of timescales. While the average period of "good" or "poor" sardine fishing off Japan is around 20–30 years and coincides with the timescale of variability observed in the twentieth century, Yasuda *et al*. (1999) noted that a given time period of "good" or "poor" fishing could last from 7–45 years and 14–35 years respectively. Baumgartner *et al*. (1992) emphasized that sardine SDR could be characterized by multiple periods of recoveries and collapses that last from 20–30 years in duration (Fig. 4.10). However, periods of sustained sardine SDR persisted for nearly a century

in different parts of the record, indicating nearly continuous sardine recruitment off central California beyond the multidecadal timescale (Fig. 4.10). After removing the low frequency variability, there are peaks in spectral power of both anchovy and sardine SDR from 50–70 years, consistent with observations from the twentieth century (Baumgartner, 1992). While this is an important characterization of the variability, these time series have not been shown to have a preferred periodicity that differs statistically from the null hypothesis of an oceanic red-noise spectrum, which results from the oceanic integration of atmospheric white noise (Pierce, 2001).

Off Namibia there are large variations in the composition of scales from pilchard, anchovy, hake, and mackerel on both decadal and millennial timescales (Shackleton, 1987; Baumgartner *et al*., 2004). Although records from the last three thousand years are not currently continuous, the differences in species composition between different centennial-scale portions of the core examined may be associated with large variations in the alkenone unsaturation index, a coccolithopohorid-based proxy of near-surface temperatures (Baumgartner *et al*., 2004). Taken together, the records are suggestive of large centennial to millennial-scale variations that exceed the magnitude of fluctuations observed in the twentieth century.

The strongest downcore signal from records of anchovy SDR off Peru show a centennial-scale period of low abundance that is associated with changes in numerous other proxies of ocean variability (Gutierrez *et al*., 2006). The only time period in which sardine SDR was higher than that of anchovy off Peru was in the early Holocene, a time period when varied insolation resulted in a different hemispheric heat balance (DeVries and Pearcy, 1982).

Tunnicliffe *et al*. (2001) documented large millennial-scale variability in total fish remains that varies with

diatom abundances in Saanich Inlet. The mid-Holocene, a relatively warm period in much of the northern hemisphere, was characterized by much higher remains of both total fish and diatom abundances while the recent 1000 years was one of the periods of lowest inferred productivity. Patterson *et al*. (2004) also noted considerable variability on millennial timescales that may be related to solar forcing.

Thus the combined evidence of several different studies from different sites is consistent with red-noise spectra of variability in fish populations, whereby there is increasing variability at longer timescales. While there may be preferred timescales of variability (e.g. periodicities) within a red-noise spectrum, no study with a reliable chronology has shown interdecadal variability that differs from the null hypothesis of a red-noise spectrum (Pierce, 2001). The historical records of abundance do not show interdecadal oscillations of sufficient strength for predicting future changes. Furthermore, modelling studies that have shown that oceanic red-noise is a more dominant source of variability than periodic variations that may arise from gyre-scale circulation (Yeh and Kirtman, 2006).

Implications for ocean variability

The historical records clearly suggest many different patterns of ocean and ecosystem variability that have not been observed in the twentieth century. The relationship between SDR of sardines and anchovies in the California Current with proxy records of salmon abundance in the Gulf of Alaska is opposite the relationship observed in the twentieth century (Finney *et al*., 2002). The paleo records are consistent with the speculations of Isaacs (1976) that "there are probably a great number of possible regimes; multifarious regimes involving biology or climate, or oceanography, or migrations, temperature, or weather, or combinations of these."

In the Santa Barbara Basin, no clear relationship has been observed between sardine or anchovy SDR and other proxy records of ocean variability prior to the twentieth century (D. Field and T. Baumgartner, unpublished data). While this does not mean a relationship doesn't exist, it does imply that it may not be sufficiently strong to be clearly observed between different types of paleo records. In contrast, sediment records from Peru do show consistent relationships between anchovy scale deposition, organic carbon flux, and other proxy records of productivity and oxygen, suggesting a stronger coupling between primary productivity and anchovy production in this system (Gutierrez *et al*., 2006).

Paleoecological patterns that are considerably more complex than the twentieth century are consistent with other studies of past climate changes in the Pacific. The relationships between coral records and tree rings indicate that the tropical forcing of the eastern Pacific and the associated Pacific Decadal Oscillation (PDO) pattern of variability

has varied in strength during prior centuries (Gedalof *et al*., 2002; D'Arrigo *et al*., 2005). Changes in the predominant position (rather than just the strength) of the atmospheric highs and lows are likely sources of variability in the North Pacific that do not necessarily resemble the PDO (La Marche, 1974; Bond *et al*., 2003). Teleconnections between different regions, solar forcing and volcanic activity are generally considered to be important drivers of the atmosphere (Crowley, 2000). Moreover, the global warming trend has a notable effect on long-term ecosystem records from the California Current (Field *et al*., 2006) and may dominate future changes. Climate and ecosystem variability may shift from familiar modes of variability to an entirely different climate regime.

Box 4.1. What if paradigms of small pelagic population variability were based on nineteenth-century observations?

Are paradigms of decadal-scale changes in pelagic ecosystems too strongly linked with the changes observed in the twentieth century? It is well known that each El Niño event evolves differently and is associated with different regional climate and ecosystem responses. Our understanding of the effects of El Niño on climate and ecosystems would be greatly skewed if it came from only two El Niño events. Thus it should come as no surprise that historical records indicate a wide range of long-term climate and ecosystem variations relative to twentieth century observations. Moreover, the twentieth-century observations have been affected by increasing anthropogenic alterations of ecosystems, biogeochemical cycles, and climate.

The twentieth century fluctuations in fish catch have been characterized as oscillating variations between sardines and anchovies in different upwelling environments with approximately 50–60-year periodicity (Kawasaki, 1991; Lluch-Belda *et al*., 1992; Mantua *et al*., 1997; Chavez *et al*., 2003). These paradigms are based on observations that are, at most, a few decades longer than the inferred periodicity and patterns. Would our scientific perspectives on long-term ocean and ecosystem variability be much different if they were formed from observations in the nineteenth century?

If we take the implications of some of the historical records at face value, then we can imagine the following scenarios for N. Pacific variability during the nineteenth century. Historical records of fishing off Japan and sardine scale deposition off California are suggestive of a negative relationship between sardine abundance off Japan and California (Fig. 4.9), rather than a

positive relationship as seen in the twentieth century. It is not clear that all sardine population expansions off central California were associated with sardine presence off British Columbia (Fig. 4.9). In addition, scale fluxes from Santa Barbara Basin sediments indicate that both anchovy and sardines were abundant off southern California throughout much of the nineteenth century, rather than having alternated in abundance (Fig. 4.10). While it is debatable whether historical records are sufficient to reject hypothesized paradigms, they do not support them as dominant modes of variability. The different historical records suggest that the ecosystem paradigms of the twentieth century are only a small part of the range of ecosystem response to climate change and intrinsic variability. Likewise, studies of tree rings and coral records indicate that PDO type variability was not a dominant form of variability during the nineteenth century (Gedalof *et al*., 2002; D'Arrigo *et al*., 2005).

Does the paradigm of 50–60-year fluctuations, based on twentieth century observations, offer much hope of long-term predictions? Some tree ring evidence suggest that variability on 8–16-year timescales was more dominant than variability in 50–70-year timescales in the nineteenth century and beyond (Biondi *et al*., 2001), while other evidence supports a continuous 50–70-year periodicity (Minobe *et al*., 1997). Persistent sardine scale deposition to the SBB has persisted for periods of 70–100 years in the past (Fig. 4.10). With the strong La Niña of 1999, some were expecting a persistence of negative PDO conditions for several decades. Looking back, there were three negative years followed by four positive years – hardly a persistent negative PDO phase. Finally, the advent of anthropogenic global change will likely result in little practicality of using past periodicities for predicting future changes.

Undoubtedly, the twenty-first century ecosystem and climate changes will be dramatically different from those of the twentieth century and will result in paradigm shifts. Useful paradigms of ecosystem variability will be those that are consistent with past variations, can be successfully modelled, and are strongly linked with well-founded mechanisms of change, rather than with broad correlations. Like fossils in ocean sediments, paradigms of climate and ecosystem regimes based on just twentieth-century observations and unfounded correlations will be buried in the archives as we continue into the twenty-first century.

What could be learned in the future?

There remain many issues concerning variability in small pelagics that can be answered with fish scales. Most hypotheses concerning decadal-scale variability in small pelagics are based on observations in the twentieth century that span 1–2 fluctuations. The apparent synchronization of fluctuations in abundance of small pelagics, both within and among boundary currents, has called considerable attention, yet effectively only two decadal-scale fluctuations have been documented. To date, the historical evidence shows little support for this hypothesis. However, cores from additional regions with very good dating may be enable testing global synchrony of pelagic fish stocks as well as the different scenarios shown in Fig. 4.1 within a boundary current. In particular, sufficient chronological controls to test the hypothesis might be obtained over the last 150–200 years.

Perhaps one of the most insightful lessons for the future of small pelagics will be learned from different periods of longer-term climate forcing, such as the mid-Holocene maximum or different periods of insolation. Having a time period far different from the recent Holocene, as well as a relatively warm time period with many differences in global circulation, may be instructive to mechanisms of change. The future of ocean climate and marine populations will undoubtedly differ from this more recent time period of the Holocene and even from the last 2000 years. Although preservation issues may be prevalent at some sites, there are many clues to be found deeper in the sedimentary records indicating the response of small pelagics to variable climatic conditions not seen in recent centuries or millennia.

NOTE

1 Before Present.

REFERENCES

Alheit, J. and Hagen, E. (1997). Long-term climate forcing of European herring and sardine populations. *Fish. Oceanogr.* **6**: 130–9.

Baumgartner, T. R., Ferreira-Bartrina, V., Cowen, J., and Soutar, A. (1991). Reconstruction of a 20th century varve chronology from the central Gulf of California. In *The Gulf and Peninsular Province of the Californias*, Dauphin, J. R. and Simoneit, B. R. T., eds. pp. 603–616.

Baumgartner, T. R., Soutar, A., and Ferreira-Bartrina, V. (1992). Reconstruction of the history of Pacific sardine and northern anchovy populations over the last two millennia from sediments of the Santa Barbara Basin, California. *CalCOFI Rep.* **33**: 24–40.

Baumgartner, T. R., Struck, U., and Alheit, J. (2004). GLOBEC investigation of interdecadal to multi-centennial variability in marine fish populations. *PAGES News* **12** (1): 19–21.

Biondi, F., Gershunov, A., and Cayan, D. R. (2001). Winter PDO reconstructed from Southern California tree-ring records. *J. Climate* **14**: 5–10.

Bond, N. A., Overland, J. E., Spillane, M., and Stabeno, P. (2003). Recent shifts in the state of the North Pacific. *Geophys. Res. Lett.* **30** (2183): doi:10.1029/2003GL018597.

Butler, V. L. and O'Conner, J. E. (2004). 9000 years of salmon fishing on the Columbia River, North America. *Quat. Res.* **62**: 1–8.

Chavez F. P., Ryan, J., Lluch-Cota, S. E., and Niquen, M. (2003). From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science* **299**: 217–221.

Crawford, R. J. M., Dundee, B. L., Dyer, B. M., Klages, N. T., Meÿer, M. A., and Upfold, L. (2007). Trends in numbers of Cape gannets (Morus capensis), 1956/57–2005/06, with a consideration of the influence of food and other factors. *ICES J. Mar. Sci.* **64**: 169–177.

Crockford, S. J. (1997). Archaeological evidence of large northern bluefin tuna, Thunnus thynnus, in coastal waters of British Columbia and northern Washington. *Fish. Bull.* **95**: 11–24.

Crowley, T. J. (2000). Causes of climate change over the past 1000 years. *Science* **289**: 270–276.

D'Arrigo, R., Wilson, R., Deser, C. *et al.* (2005). Tropical-North Pacific climate linkages over the past four centuries. *J. Climate* **18** (24) : 5253–5265.

DeVries, T. J. (1979). Nekton remains, diatoms, and Holocene upwelling off Peru. MS thesis, Oregon State University, Corvallis, Oregon. 85 pp.

DeVries, T. J. and Pearcy, W. G. (1982). Fish debris in sediments of the upwelling zone off central Peru: a late Quaternary record. *Deep-Sea Res.* **28**: 87–109.

Field, D. B. and Vetter, R. (2005). Can carbon and nitrogen isotopes be used to infer trophic level and movement in Pacific sardine?, In *Trinational Sardine Forum*, November 14–15, Ensenada, Mexico.

Field, D. B., Baumgartner, T. R., Charles, C., Ferriera-Bartrina, V., and Ohman, M. D. (2006). Planktonic foraminifera of the California Current reflect twentieth century warming, *Science* **311**: 63–66.

Field, J. C., Francis, R. C., and Strom, A. (2001). Toward a fisheries ecosystem plan for the Northern California Current. *CalCOFI Rep.*, **42**, 74–87.

Finney, B. P., Gregory-Eaves, I., Douglas, M. S. V., and Smol, J. P. (2002). Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years. *Nature* **416**: 729–733.

Fitch, J. E. (1969). Fossil records of certain schooling fishes of the California Current System. *CalCOFI Rep.* **13**: 71–80.

Gedalof, Z., Mantua, N. J., and Peterson, D. L. (2002). A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral. *Geophys. Res. Lett.* **29**: 54–57.

Gerdeaux, D. and Perga, M. E. (2006). Changes in whitefish scales d13C during eutrophication and reoligotrophication of subalpine lakes. *Limnol. Oceanogr.* **51**: 772–780.

Gutiérrez, D., Field, D., Salvatteci, R. *et al.* (2006). Decadal to centennial variability of the Peruvian upwelling ecosystem during the last centuries as inferred from fish scale deposition rates of anchovy and other marine sediment records. In *International Conference on the Humboldt Current System, November 2006.*

Hiramoto, K. (1991). The sardine fishery and ecology in the Joban and Boso waters of central Japan. In *Long-Term Variability of Pelagic Fish Populations and their Environment*, Kawasaki, T., Tanaka, S., Toba Y., and Taniguchi, A., eds., Oxford, UK: Pergamon Press, , pp. 117–128.

Holmgren-Urba, D. and T. R. Baumgartner. (1993). A 250-year history of pelagic fish abundance from anaerobic sediments of the central Gulf of California. *CalCOFI Rep.* **34**: 60–68.

Holmgren-Urba, D. (2001). Decadal-centennial variability in marine ecosystems of the northeast Pacific Ocean: the use of fish scale deposition in sediments, Ph.D. Dissertation, University of Washington.

Isaacs, J. D. (1976). Fishery science: Fact, fiction, and dogma. *CalCOFI Rep.* **18**: 34–43.

Kawasaki, T. (1991). Long term variability in the pelagic fish populations. In *Long-Term Variability of Pelagic Fish Populations and their Environment*, Kawasaki, T., Tanaka, S., Toba Y., and Taniguchi, A., eds. Oxford, UK: Pergamon Press, pp. 47–60.

Keefer, D. K., deFrance, S., Moseley, M., Richardson, J., Satterlee, D., and Day-Lewis, A. (1998). Early maritime economy and El Niño Events at Quebrada Tacahuay, Peru. *Science* **281**: 1833–1835.

Kuwae, M., Okuda, N., Miyasaka, H., Omori, K., Takeoka, H., and Sugimoto, T. (2007). Decadal- to centennial-scale variability of sedimentary biogeochemical parameters in Kagoshima Bay, Japan, associated with climate and water-shed changes. *Estuar. Coast. Shelf Sci.* **73**: 279–289.

LaMarche, V. C. (1974). Paleoclimatic inferences from long tree-ring records. *Science*, **183**, 1043–1048.

Lange, C. B., Schimmelmann, A., Yasuda, M. and Berger, W. H. (1996). Marine varves off southern California, *Scripps Inst. Oceanogr. Ref. Ser.* **96**: 122.

Lasker, R. and MacCall, A. D. (1983). New ideas on the fluctuations of the clupeoid stocks off California. *In C.N.C./SCOR Proceedings of the Joint Oceanographic Assembly 1982 – General Symposia, Ottawa, Canada*, pp. 110–120.

Lluch-Belda D., Schwartzlose, R. A., Serra, R., *et al.* (1992). Sardine and anchovy regime fluctuations of abundance in four regions of the world oceans: a workshop report. *Fish. Oceanogr.* **1**: 339–347.

Lozano-Montes, H. 1997. Reconstruction of marine fish populations using fossil fish scales deposited in Santa Barbara Basin (USA). Master of Science thesis. Centro de Investigación Científica y de Educación Superior de Ensenada, Mexico. 97 pp.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., and Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteorolog. Soc.* **78**: 1069–79.

Marcus, J., Sommer, J. D., and Glew, C. P. (1999). Fish and mammals in the economy of an ancient Peruvian kingdom. *Proc. Natl. Acad. Sci.* **96**: 6564–6570.

Minobe, S. (1997). A 50–70 year climatic oscillation over the North Pacific and North America. *Geophys. Res. Lett.* **24**: 683–686.

O'Connell, J. M. and Tunnicliffe, V. (2001). The use of sedimentary fish remains for interpretation of long-term fish population fluctuations. *Mar. Geol.* **174**: 177–195.

Patterson, R. T., Prokoph, A., Wright, C., Chang, A. S., Thomson, R. E., and Ware, D. M. (2004). Holocene solar variability and pelagic fish productivity in the NE Pacific. *Palaeontol. Electron.* **7**: 17 pp.

Pierce D. W. (2001). Distinguishing coupled ocean-atmosphere interactions from background noise in the North Pacific. *Progress in Oceanography*, **49**, 331–352.

Quilter, J., Ojeda, E. B., Pearsall, D. M., Sandweiss, D. H., Jones, J. G., and Wing, E. S. (1991). Subsistence economy of El Paraíso, an early Peruvian site. *Science*, **251**, 277–283.

Reitz, E. J. (2003). Resource use through time at Paloma, Peru. *Bull. Florida Mus. Nat. Hist.* **44**: 65–80.

Rick, T. C. and Erlandson, J. M. (2000). Early Holocene fishing strategies on the California coast: Evidence from CA-SBA-2057. *J. Archaeolog. Sci.* **27**: 621–33, doi:10.1006/jasc.1999.0493.

Rick, T. C., Erlandson, J. M., and Vellanoweth, R. L. (2001). Paleocoastal marine fishing on the Pacific coast of the Americas: Perspectives from Daisy Cave, California. *Am. Antiquity* **66**: 595–613, doi:10.2307/2694175.

Salvatteci, R., Gutierrez, D., Field, D. *et al.* (2006). Fluxes of scales and other fish remains en marine sediments in front of Callao, Perú en the last 550 years. *XIII Congress of Geology, Society of Geologists of Peru, Lima, Perú.*

Sandweiss, D. H., Maasch, K. A., Chai, F., Andrus, C. F. T., and Reitz, E. J. (2004). Geoarchaeological evidence for multidecadal natural climatic variability and ancient Peruvian fisheries. *Quat. Res.* **61**: 330–334.

Schwartzlose, R. A., Alheit, J., Bakun, A., *et al.* (1999). Worldwide large-scale fluctuations of sardine and anchovy populations. *S. Afr. J. Mar. Sci.* **21**: 289–347.

Schwing, F. B., Jiang, J., and Mendelssohn, R. (2003). Coherency of multi-scale abrupt changes between the NAO, NPI, and PDO. *Geophys. Res. Lett.* **30** (1406): doi:10.1029/2002GLO16535.

Shackleton, L. Y. (1986). An assessment of the reliability of fossil pilchard and anchovy scales as fish population indicators off Namibia, M.Sc. thesis, Univ. of Cape Town, South Africa, pp. 141.

Shackleton, L. Y. (1987). A comparative study of fossil fish scale from three upwelling regions. *S. Afr. J. Mar. Sci.* **5**: 79–84.

Shackleton, L. Y. (1988). Scale shedding: an important factor in fossil fish studies. *J. Cons. Int. Explor. Mer.* **44**: 259–263.

Soutar, A. (1967). The accumulation of fish debris in certain California coastal sediments. *CalCOFI Rep.* **11**: 136–139.

Soutar, A. (1971). Micropalaeontology of anaerobic sediment and the California Current, In *The Micropalaeontology of the Oceans*, Funnel, B. M. and Riedel, W. R., eds. Cambridge, UK: Cambridge Univ. Press, pp. 223–230.

Soutar, A. and Crill, p. A. (1977). Sedimentation and climatic patterns in the Santa BarbaraBasin during the 19th and 20th centuries. *Geol. Soc. Am. Bull.* **88**: 1161–1172.

Soutar, A. and Isaacs, J. D. (1969). History of fish populations inferred from fish scales in anaerobic sediments off California. *CalCOFI Rep.* **13**: 63–70.

Soutar, A. and Isaacs, J. D. (1974). Abundance of pelagic fish during the 19th and 20th centuries as recorded in anaerobic sediment of the Californias. *Fish. Bull.* **72**: 257–273.

Struck, U., Heyn, T., Altenbach, A., Alheit, J., and Emeis, K. C. (2004). Distribution and nitrogen isotope ratios of fish scales in surface sediments from the upwelling area off Namibia. *Zitteliana* **A44**: 125–132.

Suess, E. (1981). Phosphate regeneration from sediments of the Peru continental margin by dissolution of fish debris. *Geochim. et. Cosmochim. Acta* **45**: 577–588.

Tunicliffe, V., O'Connell, J. M., and McQuoid, M. R. A. (2001). Holocene record of marine fish remains from the Northeastern Pacific. *Mar. Geol.* **174**: 197–210.

Wainright, S. C., Fogarty, M. J., Greenfield, R. C., and Fry, B. (1993). Long-term changes in the Georges Bank food web: trends in stable isotope composition of fish scales. *Mar. Biol.* **115**: 481–493.

Wells, B. K., Thorrold, S. R., and Jones, C. M. (2003). Stability of elemental signatures in the scales of spawning weakfish (Cynoscion regalis). *Can. J. Fish. Aquat. Sci.* **60**: 3619.

Yasuda, I., Sugisaki, H., Watanabe, Y., and Minobe, S.-S. (1999). Inter-decadal variations in Japanese sardine and Ocean/Climate. *Fish. Oceanogr.* **8**: 18–24.

Yeh S.-W. and Kirtman B. P., (2006). Origin of decadal El Niño–Southern Oscillation-like variability in a coupled general circulation model, *J. Geophys. Res.* **111**: C01009, doi:10.1029/2005JC002985.