

The Saanich Inlet Basin: A Natural Collector of Past Biological, Climatic, and Land-use Changes in Southwestern Canada Amplified by Results of ODP Leg 169S

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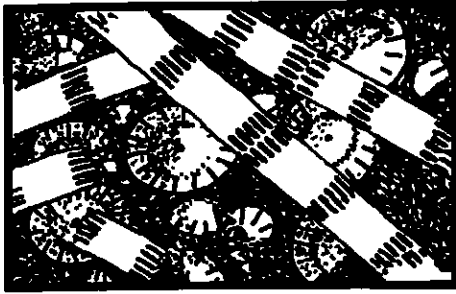
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Article abstract

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The Saanich Inlet Basin: A Natural Collector of Past Biological, Climatic, and Land-use Changes in Southwestern Canada Amplified by Results of ODP Leg 169S

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SUMMARY

Saanich Inlet sediments contain one of the best-preserved biological records in the world. Frozen 1-2 m cores representing the last ~130 years show a deforestation-related increased input of terrestrial carbon to the basin, and cyclic variations in organic carbon, diatoms, and fish remains that suggest a link to climate oscillations. Ocean Drilling Program cores from Leg 169S greatly extend the sediment record, to more than 10,000 years. Study of diatoms, carbon isotope ratios, and fish remains from these long ODP cores shows that the marine environment has been stable during the Holocene. The long ODP cores also indicate that, beginning ~10,000 years B.P., Saanich Inlet basin

rapidly assumed the broad-scale oceanographic and biologic features seen today.

RÉSUMÉ

Les sédiments de l'anse Saanich constituent l'un des registres paléontologiques le mieux préservé au monde. La colonne sédimentaire de 1 à 2 mètres d'épaisseur correspondant à 130 ans d'histoire, montre un accroissement de l'apport de carbone terrestre dans le bassin lié à une déforestation, des variations cycliques du contenu en carbone organique, des restes de diatomées et de poissons évoquant l'existence d'une corrélation avec des oscillations climatiques. Les carottes de sondage du programme de sondage des fonds marins du segment 169S permettent d'allonger le registre sédimentaire pour couvrir une histoire de 10 000 ans. L'étude des diatomées, des rapports isotopiques du carbone et des restes de poissons dans ces longues carottes du PSFM montre que l'environnement marin a été stable durant l'Holocène. Ces longs échantillons carottés montrent également qu'à partir de 10 000 ans B.P., l'anse Saanich s'est rapidement constituée selon les grandes caractéristiques océanographiques et biologiques qui la caractérisent actuellement.

INTRODUCTION

Climate change and human activities are both factors controlling the biology of coastal seas. In recent years, changes in the marine biota along the west coast of Canada have occurred, including introduction of exotic species, increased harmful algal blooms, and declining fish stocks. It is difficult to determine causes of these phenomena, especially since much of the natural variability of the coastal marine system is still unknown. Instrumental records of local sea surface conditions (*e.g.*, Freeland, 1994) extend back to the early part of the 1900s, but measurements of biological variability often encompass only recent decades, and these records are poor. Sediment records of biological variability offer a unique opportunity to extend our recent knowledge back in time.

We concentrated our efforts on anoxic sediments because organic matter is well preserved in the absence of oxygen and is not mixed by animal activities on and in near-surface sediments. Saanich Inlet, a fjord in southeastern Vancouver

Island, has abundant anoxic sediments, making it an ideal location for obtaining sediment records with high temporal resolution. However, these sediments are very difficult to sample using conventional coring techniques because near-surface sediments are not well compacted. To overcome this problem we used a freeze corer to obtain cores of about 1-2 m in length, which represent sediments produced during the past ~130 years. Fortunately, an opportunity to obtain much longer undisturbed cores in Saanich Inlet arose through the Ocean Drilling Program (ODP). Personnel of the Ocean Drilling Program used advanced hydraulic piston corers to sample up to ~100 m of Inlet sediment during ODP Leg 169S, providing a record for the period from about 400-12,000 years ago.

PRESENT DAY SAANICH INLET

The bathymetry and hydrography of Saanich Inlet (Fig. 1) produce a detailed sediment record of biological variation, climate change, and human activity. The deep (*ca.* 230 m) Inlet basin is separated from tidally well-mixed waters in the Strait of Georgia (Fig. 1) by a shallow (70 m) sill that restricts water inflow. Primary production from phytoplankton in the Inlet can be very high. The breakdown of organic matter by respiring organisms quickly depletes dissolved oxygen in the deep waters, preventing macrofauna from inhabiting the seafloor. This rare combina-

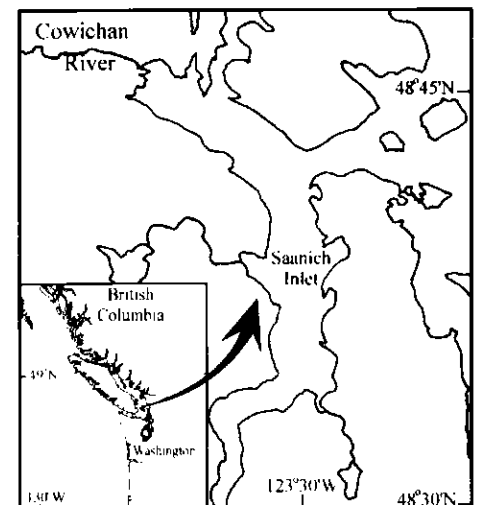


Figure 1 Map of Saanich Inlet showing its relationship to the Strait of Georgia, which separates Vancouver Island from mainland British Columbia.

tion of features results in a well-preserved sediment record in which distinct layers or varves (Fig. 2) are formed by deposits during high growth and low growth seasons (Gucluer and Gross, 1964) in a manner analogous to the formation of tree rings. Thus, the varved sediments of the Inlet have been under intense investigation for many years. The unique sediments contain an integrated record of material from the Inlet basin, the adjoining straits, and the catchment area, a record that represents changes occurring in and around southwestern Canada.

Saanich Inlet is a highly productive fjord. Annual phytoplankton production in the Inlet in recent years has been approximately 500 g C m^{-2} near the mouth, but declines toward the head of the Inlet (Timothy and Soon, 2001). Most of the primary production comes from planktonic algae (phytoplankton) and varies throughout the year. The highest production comes sometime between early March and early May when diatoms bloom in near-surface waters of the southern Strait of Georgia, including Saanich Inlet (Hobson and McQuoid, 1997). At this time, nutrients such as nitrate are ample (e.g., $20\text{--}25 \mu\text{M NO}_3^{-1}\text{-N}$) and temperature is relatively cold ($8\text{--}11^\circ\text{C}$). The main taxa present in the spring bloom are the silica-walled diatoms, *Chaetoceros*, *Skeletonema*, and *Thalassiosira* (Fig. 3) (Hobson and McQuoid, 1997). The diatom bloom in Saanich Inlet terminates after about 4 weeks because of thermal stratification in the near-surface water and depletion of inorganic nitrogen by diatom metabolism. At this time, many diatom species form resting spores that quickly sink to the seafloor to become incorporated in the bottom sediments.

After the spring diatom bloom, stratification in Saanich Inlet inhibits diffusion of nitrate ion from deeper layers into the near-surface waters, which limits phytoplankton biomasses to low levels. At this time, the taxonomic composition of the phytoplankton shifts to organisms representative of various algal groups other than diatoms (Smith and Hobson, 1994). Most of these cells have flagella, which provide cellular locomotion that helps them to remain in the stratified surface layer and increases their search area for scarce nutrients.

Outside Saanich Inlet, diatom blooms continue throughout the summer months in tidally well-mixed water, which remains cold and nutrient-rich (Hobson, 1985). These diatoms are periodically carried into Saanich Inlet by tidal currents (Hobson and McQuoid, 2001), depending on interactions between the spring-neap tidal cycle and freshwater added to the Strait of Georgia by Fraser River outflow (A. Gargett, Old Dominion University, personal communication). Thus, diatoms can be found in the Inlet at any time of the year, but generally are more numerous near the mouth than at the head of the Inlet.

Phytoplankton production is transferred through the pelagic food web. Small crustaceans like copepods and euphausiids often peak in numbers following the spring diatom bloom. These grazers, in turn, are an important food source for fish. The fish community in Saanich Inlet is dominated by herring, hake, and dogfish. Herring feed primarily on euphausiids, while dogfish prey on herring and hake. Salmon runs are also known both in Saanich Inlet and its surroundings.



Figure 2 Frozen core of Saanich Inlet sediments showing annual layers or varves. Spring and spring/summer layers are light grey in colour; fall/winter layers are dark grey in colour.

FLUX FROM SURFACE TO SEDIMENT

During the spring diatom bloom in Saanich Inlet, the silica shells of diatoms as well as diatom resting spores sink to the seafloor (Sancetta and Calvert, 1988) along with fecal pellets produced by zooplankton (crustaceans) feeding on diatoms (Sancetta, 1989). Minor fluxes of diatoms also occur at other times of the

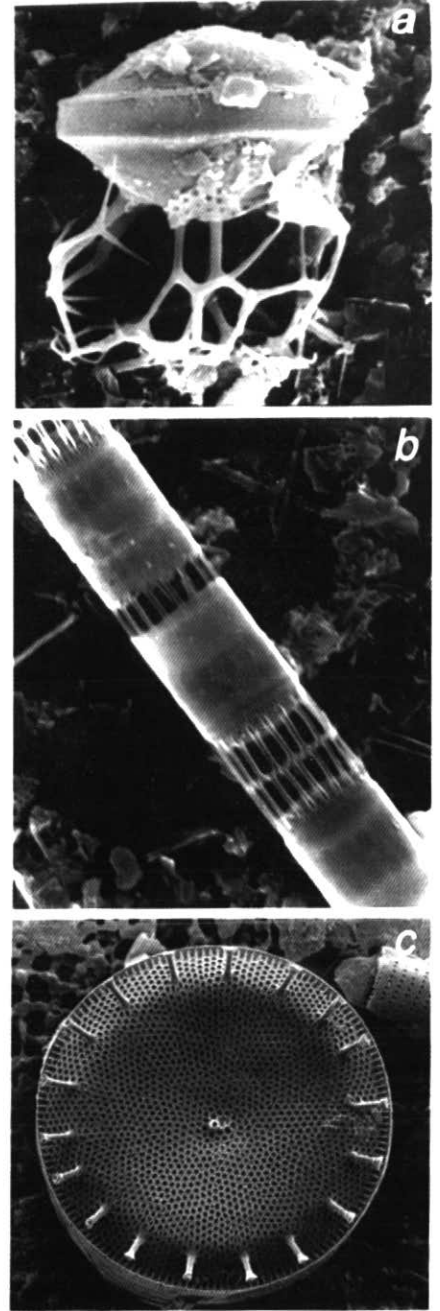


Figure 3 Scanning electron micrographs of (a) *Chaetoceros diadema* resting spore, (b) *Skeletonema costatum*, and (c) *Thalassiosira nordenskiöldii*, preserved in Saanich Inlet sediments.

year. For example, winter runoff leads to an increased input of littoral and freshwater species. During summer, tidal currents can import and deposit shells of diatoms growing outside the Inlet. Herring, hake, and dogfish, also leave their mark in the sediments as these fish all easily shed scales, teeth, and scutes (Tunnicliffe *et al.*, 2001). In contrast, salmon bones are poorly preserved and their scales are not easily shed. Thus, salmon do not leave a good signal in the sediment record.

THE RECENT SEDIMENT RECORD

Early studies of the varved sediments in Saanich Inlet found that the light-grey and dark-grey layers contain large numbers of fossil diatoms (Gucluer and Gross, 1964), reflecting differential production of these organisms in cold, nutrient-rich surface water. It was quickly realized that their presence in the sediments could be used to give historical information about the biological productivity of the water of the southern Strait of Georgia, and detailed taxonomic studies were begun (Sancetta and Calvert, 1988). Nevertheless, it was some time before recent sediments from the last 100-200 years could be dated accurately. In part, this delay was caused by the difficulty in sampling the top 20 cm of sediment that

has loose consistency and is lost using standard coring techniques. Ultimately, Crusius and Anderson (1991) developed a variant of a freezer corer to solve this type of sampling problem. The corer consisted of a rectangular aluminum tube 4.6 m in length that could be filled with a slurry of dry ice and methanol. Three sides were insulated, and the shovel-shaped tip was filled with lead weights before lowering the corer into the sediments. Once in the sediments, a layer of sediment 1-2 cm thick, 15 cm wide, and about 1 m in length would freeze to the corer in about 20 minutes. Using this new method, frozen cores were taken in the Inlet during the summer of 1993 and spring of 1994.

Cores taken with the freezer corer were usually black, with an anoxic sulphide odour when first retrieved. However, after a period of oxidation, varves are readily apparent in the cores, and X-ray analysis shows that each annual varve consists of light and dark seasonal laminae (Fig. 2) spanning the years from about 1860 to 1991. Sediment ages were determined using ^{13}C s, the quantity of which peaks in 1963-1964. Varve counting based on this temporal marker allowed us to determine the age of each annual varve. Using laminations, each year of sediment can be subdivided into

spring, spring-summer and fall-winter seasons (McQuoid and Hobson, 1997). Diatom vegetative shells and resting spores are well preserved in the layers and are representative of those found in near-surface waters (Fig. 3). Some species, which are known to bloom at specific times of the year in near-surface waters, are found in sediments produced during the corresponding seasons. For example, species of *Thalassiosira* predominate in spring sediments, *Skeletonema costatum* shells are mostly found in spring-summer sediments, and *Rhizosolenia cf. setigera* shells are abundant in the fall-winter sediments. Their sediment concentrations are similar to those from sediments of other very productive systems, such as Antarctic and Bering Sea waters. Generally, the spring and spring-summer sediments are derived from marine production and are light grey in colour, whereas the fall-winter sediment is from terrestrial sources introduced into the Inlet via runoff and is dark grey in colour (Dean *et al.*, 2001).

Investigations of interannual variations among diatom species preserved in the varved sediment were conducted by McQuoid and Hobson (1997). They discovered that *Thalassiosira* and *Chaetoceros* species were more abundant prior to the 1930s-1940s than they now are (Fig. 4). The cause of this shift to lower concentrations in more recent years is uncertain, but may be related to changes in land use. Also, a previously unknown species to the Inlet, *Rhizosolenia cf. setigera*, appeared in sediments after the early 1940s (Fig. 4) and may have been introduced to local waters by an increase in aquaculture of oysters or by discharge of ships' ballast water.

Stable carbon isotopes offer another measure of past production of organic material stored in the sediments. Measurement of the ratio of isotopically light ^{12}C to the heavier ^{13}C can help determine the relative contribution of different sources (*e.g.*, terrestrial runoff versus marine production) of organic matter deposited in the sediments (Fig. 5). Isotopic analysis of light and dark laminae for each varve confirms that light bands are primarily derived from marine production, whereas dark bands contain terrestrial, runoff material (Tunnicliffe, 2000). During the last 130 years, shifts in

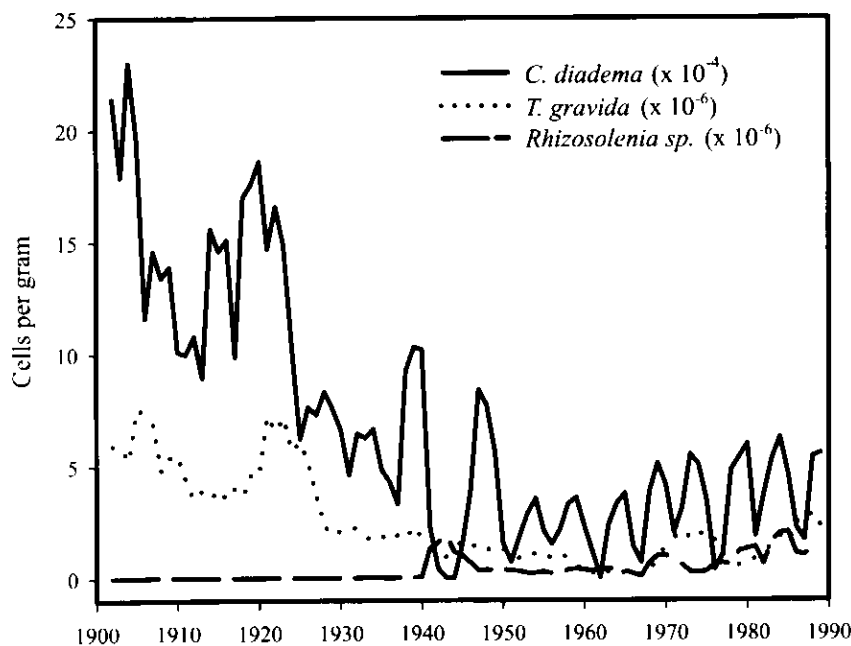


Figure 4 Variations in numbers of diatom fossils (*Chaetoceros diadema* and *Thalassiosira gravida*) in frozen cores suggest changes in production, and introduction of a new species, *Rhizosolenia cf. setigera*, years 1900-1990. Data are smoothed with a 3-point running mean.

the isotopic ratio have occurred, probably a result of land-use changes in the watershed. Logging by early settlers began in the late 1800s, and by the 1940s, many slopes around the Inlet were stripped, and three sawmills were in operation. Forest replanting in this area was not begun until the 1960s and furthermore, slopes of the Cowichan Valley were cleared in the 1930s and 1940s. Thus, increased levels of soil erosion must have begun in the late 1800s and probably contributed to the observed shift in the isotopic ratio of Inlet sediments (Tunncliffe, 2000) via transport of terrestrial sediments enriched in ^{13}C into the inlet by the Cowichan River (Fig. 1). Pollen grains collected from the sediment cores also indicate a change in the forests surrounding the Inlet. For example, numbers of alder pollen increase in the core as timber harvest progressed (Heusser, 1983). This species is an early colonizer in riparian habitats, and would have expanded in numbers as cedar and fir trees were removed.

Cycles in abundance of several biological indicators are found in the Saanich Inlet sediment record. Diatoms, such as *Skeletonema*, were much less abundant during years when warm, nutrient-poor surface waters associated with the El Niño Southern Oscillation (ENSO) phenomenon were present in local waters. This 4- to 7-year ENSO cycle is also seen in the number of herring scales found in Inlet sediments (O'Connell and Tunncliffe, 2001). The organic carbon record in Saanich Inlet sediments also shows a pattern suggesting influence from the bi-decadal climate oscillator, which has been seen to affect sea-surface temperatures and wind patterns in the Pacific (Ware, 1995). Thus, it seems that annual and longer-period variations in atmospheric pressure over the North Pacific Ocean may play important roles in rates of sedimentation of diatoms (McQuoid and Hobson, 1997), fish remains (O'Connell and Tunncliffe, 2001), and organic carbon (Tunncliffe, 2000) in the Inlet. The foregoing results suggested that longer cores could provide a fine-scale record of past environmental variations at least in the region of the northeastern Pacific Ocean. However, core retrieval from easily disturbed anoxic sediments is very difficult with standard coring techniques. Fortunately, officials of

the Ocean Drilling Program were persuaded to extend Leg 169 into Saanich Inlet (designated ODP 169S) to use their advanced hydraulic piston corers to retrieve long, undisturbed sediment cores from Inlet sediments. Thus we were able to obtain a much longer historical record of sedimentation in the Inlet than that previously available in the short, frozen cores.

THE HOLOCENE SEDIMENT RECORD FROM ODP CORES

The ODP JOIDES *Resolution* occupied two stations in Saanich Inlet during August 1996. Using an advanced hydraulic piston corer to obtain undisturbed sediments, a suite of long cores was acquired, some to ~100 m, extending from near-surface sediments (~5-10 m) into underlying glacial marine clays (Bornhold *et al.*, 1997). These cores were dated by ^{14}C analysis and therefore all dates are ^{14}C years B.P. In these long cores, varved sediments extend to 80 m below the sediment surface, indicating that anoxic conditions have existed more or less continuously in the Inlet for the past 11,000-12,000 years. Below the laminated sediments rich in organic matter, grey glacial marine clay predominates. Diatom vegetative shells and resting spores are well preserved throughout the varved sediments, but are largely absent

from the underlying marine clay. The resolution of the varves is so high that individual fecal pellets and their contained diatom remains produced by grazing animals can be recognized using appropriate electron microscope techniques (Dean *et al.*, 2001). Availability of these high-resolution ODP cores from the Inlet allowed us to use diatom fossils to infer phytoplankton production and near-surface environmental conditions in the southern Strait of Georgia during the period from ~400 to 12,000 years B.P. (McQuoid and Hobson, 2001). The sampling interval we used for diatom analysis was every 100 years in the older half of the core, and every 50 years in the younger half. Thus, the ODP cores provided us with the opportunity to extend our understanding of the history of the Saanich Inlet basin from 0 to 130 years B.P., and ~400 to 12,000 years B.P.

Diatom and Fish Remains Data

Numbers of recognizable diatom shells and resting spores increase in sediments from 12,000 to ~6,300 years B.P.; and then slowly decline to ~400 years B.P. (diatoms, Fig. 6). Superimposed on these trends are large cycles in concentrations of diatom shells and spores that occur with periodicities of ~1300 years between ~3400 and ~12000 years B.P., and ~700 years between ~400 and ~3400 years B.P.

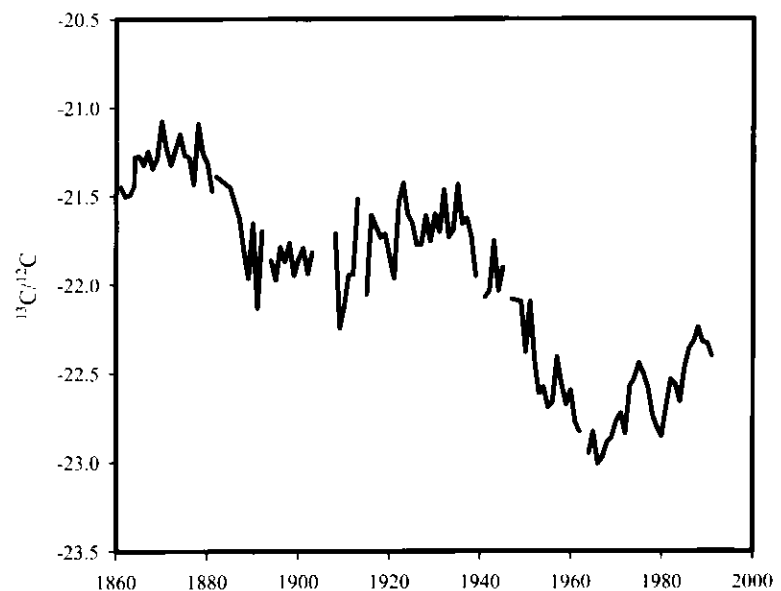


Figure 5 Annual averages of ratios of stable carbon isotopes from frozen cores indicate a decline in the $^{13}\text{C}/^{12}\text{C}$ ratio from 1860-1990s, interpreted as representing an upward increase in the amount of terrestrially-derived organic carbon in the cores.

(McQuoid and Hobson, 2001). Numbers of herring and hake remains (fish remains, Fig. 6) in the sediments reach maxima at ~9600 and ~7900 years B.P., then decline to ~4400 years B.P. before undergoing large cycles with a periodicity of ~750 years between ~1800 and ~4000 years B.P., roughly in accord with diatom results. A rapid decline in numbers then occurs to ~400 years B.P. (Tunnicliffe *et al.*, 2001). These results suggest that there are some general trends in the biological productivity of Saanich Inlet, and that the Inlet has been more productive in the past, in terms of the abundances of diatoms and fish remains.

Organic Carbon and Opal Data

Chemical measurements of production were also examined in the cores, and show a modified picture of the production history in the Inlet. Opal abundance, another measure of the quantity of diatom shells in sediments, as well as the quantity of organic carbon in the cores, show continuous increases from 12,000 years B.P. to ~400 years B.P. (McQuoid *et al.*, 2001). As noted above for the frozen cores, organic carbon in the sediments comes from both marine and terrestrial production, and therefore total organic carbon may not be a reliable indicator of purely marine production. However,

measurements of the stable carbon isotopic ratio in organic matter from the cores indicate that the percentage of organic carbon due to marine production has increased, while that from terrestrial runoff has decreased from 12,000 years B.P. to ~400 years B.P. (McQuoid *et al.*, 2001) (Fig. 6). Thus we have two data sets giving us different pictures of the history of biological productivity in Saanich Inlet. Diatoms and fish remains indicate a slow decrease in organic productivity, whereas organic carbon and opal contents suggest an increase in organic productivity.

Reconciling these Differences

These different views of the past biological productivity of Saanich Inlet, based on light microscopy of diatom and fish remains in sediments and chemical determinations of organic carbon and opal contents in sediments, likely result from trophic processes linking phytoplankton to fish production. Theoretical and observational studies in aquatic ecology suggest that the number of diatom shells and resting spores in sediments of a basin is proportional to near-surface phytoplankton production and, therefore, greater fish production. This conclusion is supported by our results, because numbers of diatom shells and fish remains are positively correlated

in the ODP cores. However, the identification of a diatom species requires visual observation of either an intact shell or large fragment. In our sediment samples many small, unidentifiable fragments were present that could not be quantified by light microscopy, whereas whole shells as well as all fragments are detected by chemical measurement of opal content. This raises an important question about the identity of environmental controls, which determine sizes of diatom fragments reaching the sea floor.

Fragment sizes of shells may be related to the abundance of crustacean grazers, such as copepods and euphausiids, because the feeding activities of these animals can break diatom shells into small pieces, some of which can be missed by light microscopic analyses of sediments. Therefore, we here suggest that when fish are abundant, they consume many crustacean herbivores, and reduction of crustacean biomasses may allow many diatom shells to escape being broken before they reach the seafloor. This suggestion leads to the prediction that numbers of diatom shells recorded in sediments using light microscopy should positively correlate to numbers of fish remains, which they do. Further, they need not correlate, which they do not, to chemical measures of biological productivity in sediments, such as either organic carbon or opal contents, and should correlate inversely with crustacean herbivore abundance. Thus, we here hypothesize that the size of a species-specific diatom shell reaching the seafloor is controlled, at least in part, by interactions between fish and herbivorous zooplankton populations. This hypothesis is currently under investigation.

Temperature and Salinity Inferences from Diatom Studies

We used the taxonomic composition of diatom fossils in the ODP sediment cores, and our knowledge of optimum conditions for their growth in near-surface layers, to infer variations in temperature and salinity of near-surface seawater of the southern Strait of Georgia over the past ~12,000 years (McQuoid and Hobson, 2001). These inferences indicate temperatures that varied between 8.5°C and 13.5°C, and salinities that varied between 28.5 parts per thousand

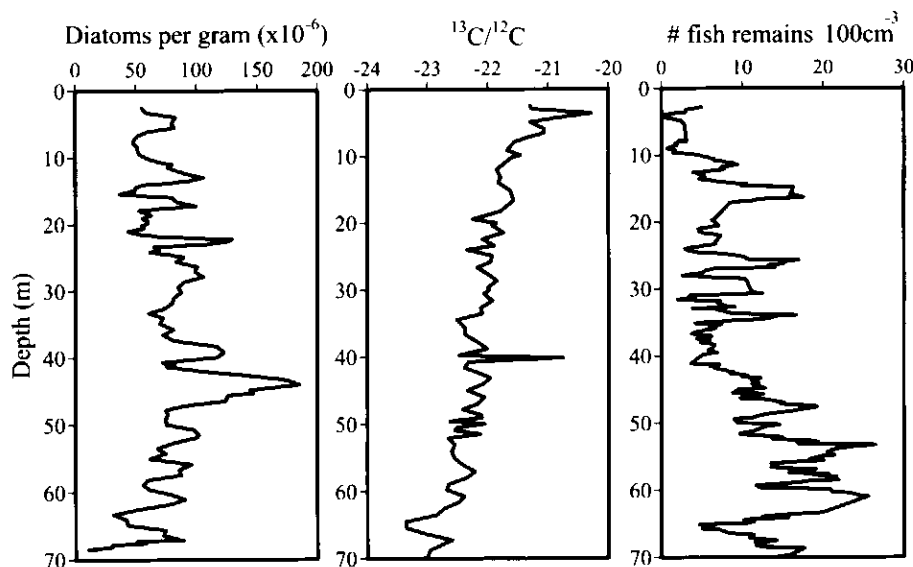


Figure 6 Variations in fossil diatoms and fish remains, and stable carbon isotopes from ODP 169S cores reflect changes in past production. Diatom data are smoothed with a 3-point running mean. Distance in metres is nonlinearly related to ^{14}C years B.P. because of sediment compaction. For example, 10 m is equivalent to 1000 yr B.P., 16 m to 1800 yr, 25 m to 3000 yr, 38 m to 4800 yr, 47 m to 6500 yr, 60 m to 9300 yr, and 70 m to 12,000 yr.

and 30.5 parts per thousand. These values are nearly identical to the seasonal variations in near-surface temperature and salinity observed in the Strait of Georgia during 1993-1994 (Hobson and McQuoid, 1997). These results suggest that the marine environment has been remarkably stable on a 100-year interval of time during the older part of the Holocene, and on a 50-year interval during the more recent part of the Holocene. The stability of the estimated values of temperature and salinity contrast to the local terrestrial climate that has undergone distinct changes from warm and dry to the present cool and wet conditions we experience in southern British Columbia (Pellatt *et al.*, 2001).

CONCLUDING REMARKS

Studies of cores from Saanich Inlet, both shallow frozen cores and deeper ODP cores from Leg 169S, reveal several interesting trends in the marine biology of the Inlet, the surrounding Strait of Georgia, and the catchment area. The detailed record of the last century reveals an increased input of terrestrial carbon to the basin owing to the deforestation of surrounding lands. Cyclical variations in carbon, diatoms, and fish remains also suggest a link to climate oscillations. The archive of ~10,000+ years obtained in the ODP cores imparts a picture of a post-glacial marine basin that rapidly assumed the oceanographic and biological features that we see today. Although this record is marked by peaks in organism abundances and by increasing primary productivity, it shows a relatively stable marine environment despite considerable terrestrial variations.

The new Integrated Ocean Drilling Program (IODP, to begin in 2003) should consider drilling other sedimented anoxic basins to provide additional long oceanographic records. Such settings include Santa Barbara Channel off southern California, Guaymas Basin in the Gulf of California, Cariaco Trench in the Caribbean Sea off Venezuela, and the Black Sea in the Ukraine.

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