RECENT MARINE SEDIMENTS IN SAANICH INLET, A STAGNANT MARINE BASIN[1]

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ABSTRACT

Saanich Inlet, a fjord on the eastern side of Vancouver Island, has H_2S in the bottom waters during most of the year. Recent marine sediments in the inlet include three distinctly different types. Black, fine-grained, varved clayey silts containing H_2S and large amounts of diatom frustules and carbonaceous organic materials occur in the central part of the inlet. Olive-gray silts with moderate concentrations of organic materials and reducing capacities occur on the sill at the entrance to the inlet. The nearshore sands and gravels have low organic contents and low reducing capacity. Carbonate-rich sediments occur near a limestone quarry and cement factory. A carbon–nitrogen ratio of 7 is typical of the sediments in the inlet.

Five sources of sediment can be distinguished: (1) carbonaceous and siliceous organic matter from marine organisms, principally planktonic diatoms, (2) suspended sediment in low-salinity water brought from the Fraser and Cowichan rivers, (3) material eroded from adjacent shorelines, (4) streams discharging into the inlet, and (5) the cement plant and limestone quarry at Bamberton. The varved sediments in the central basin consist of olive-gray laminae, apparently formed during the peak diatom production in spring or summer and olive-black laminae, containing larger mounts of terrigenous sediment, probably formed during the autumn and winter. Zones of nonlaminated sediment may be formed by terrigenous material or by the disruption of the laminated sediment by other physical processes. No evidence of burrowing organisms has been detected.

Four to 6 mm of wet sediment are deposited each year in the southern portion of the inlet. If this rate is typical of the basin as a whole, approximately 10^5 metric tons of sediment are deposited each year. At least 25–35% of this sediment is derived from marine organisms.

INTRODUCTION

Saanich Inlet, in southeastern Vancouver Island, British Columbia, at 48°35′ N lat and 123°30′ W long (Fig. 1), is a fjordlike marine basin (Fig. 2). Its width varies from 0.4 to 7.6 km over its 25.7-km length (Table 1). At its northern end, the inlet is connected with the Strait of Georgia through Satellite Channel. The drainage basin for the inlet is small and has no large rivers. The nearest rivers are the Cowichan River, discharging into Cowichan Bay north of Saanich Inlet (Fig. 1), and the Fraser River, discharging into the Strait of Georgia, approximately 50 km northeast of the inlet.

A sill rises to within approximately 70 m of the surface, restricting the circulation of water between the inlet and Satellite Channel. South of the sill, the bottom slopes gradually into a small depression where the maximum depth, 236 m, is located (Fig. 2). In Squally Reach and Finlayson Arm, the bottom shoals to the Goldstream River Delta. The sides of the inlet increase in steepness toward the southern end. Small, narrow gravel beaches occur at the mouths of the small creeks and along the shores of various bays.

This survey was undertaken to describe the sediments and their distribution in Saanich Inlet and to study the effects of the oceanographic conditions in the inlet on the physical and chemical properties of the sediments.

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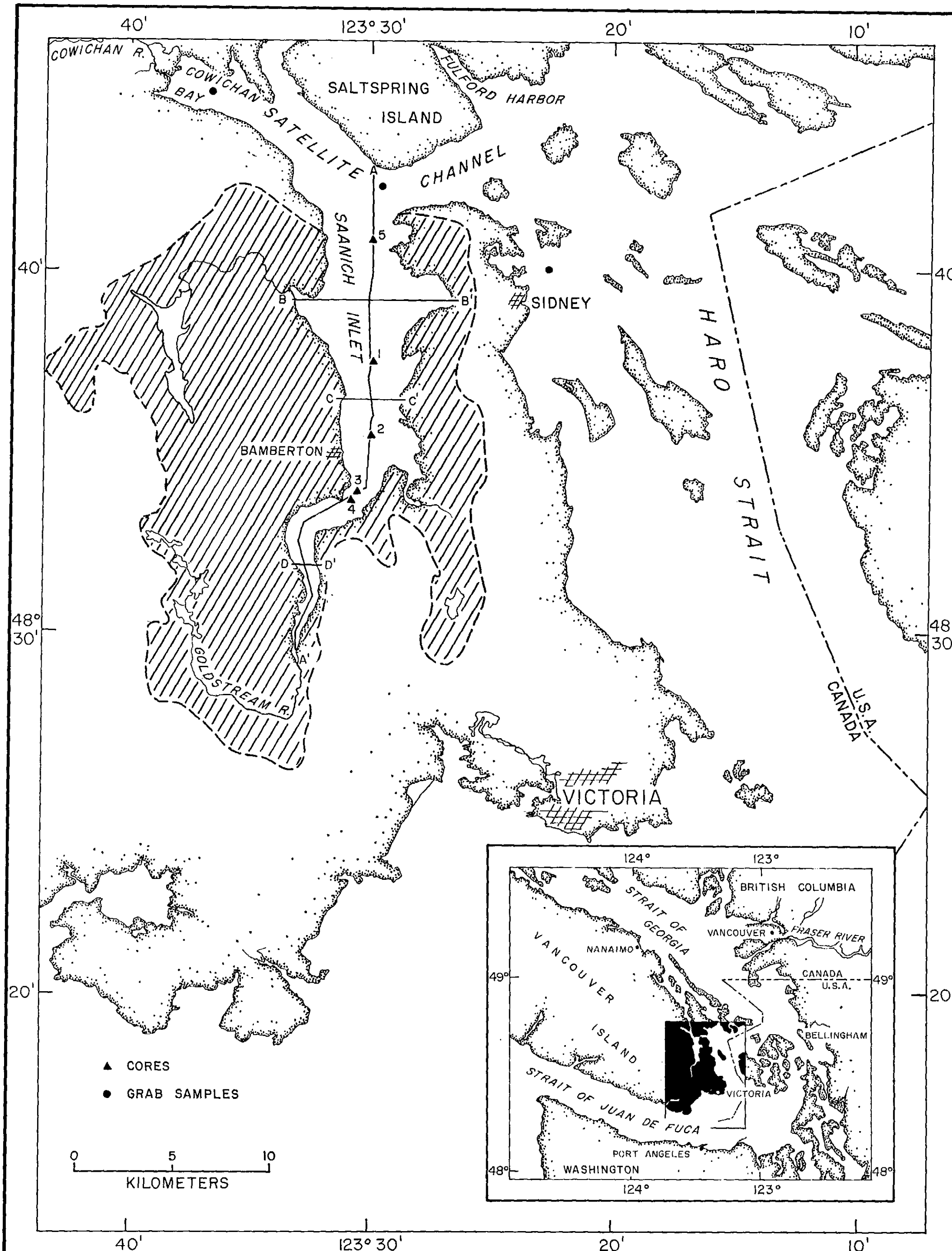

FIG. 1. Saanich Inlet and its environs, showing the location of the longitudinal and cross-sectional profiles in Fig. 2. The ruled area shows the approximate limits of the drainage basin.

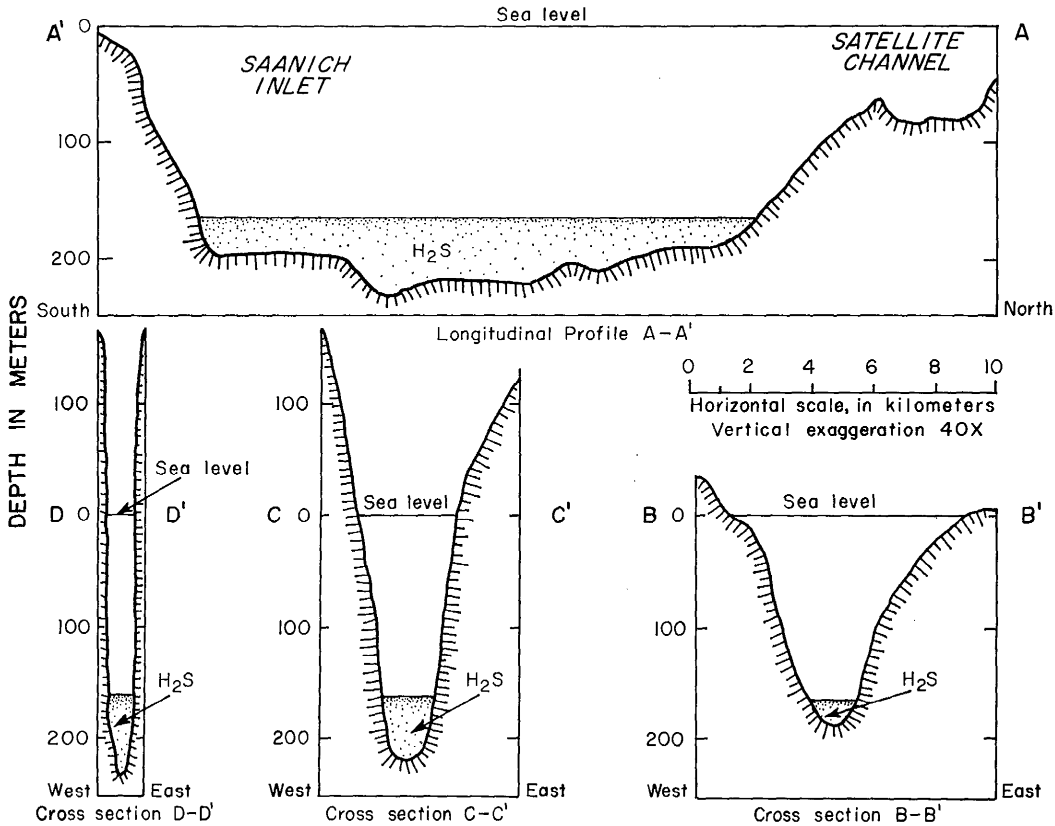

FIG. 2. Longitudinal and cross-sectional profiles of Saanich Inlet, showing the approximate limits of the hydrogen sulfide-bearing water observed in November 1961 (F. A. Richards, personal communication).

Previous reports on Saanich Inlet and its environs include little information about recent marine sediments. Clapp (1913) reported that an "odious ooze" saturated with H_2S occurred in the sediments and bottom waters. Waldichuk (1953) noted that the sediments consisted mainly of mud with sand and gravel in some near-shore areas. A preliminary report on this study (Gross et al. 1963) dealt with the varved sediment in a core from the central portion of the inlet.

TABLE 1. *Dimensions of Saanich Inlet, British Columbia*

Length	25.7 km
Average width	2.6 km
Surface area	69.8 km²
Mean depth	119 m
Maximum depth	236 m
Sill depth	70 m
Mean water volume	8.3 km³
Mean tidal range	2.44 m

The sediments in similar marine environments have been described by Strøm (1939) for certain Norwegian fjords and by Manheim (1961) for parts of the Baltic Sea.

Oceanography

The oceanographic conditions within Saanich Inlet are not well known. The earliest observations, made by Hutchinson et al. (1929), Hutchinson and Lucas (1931), and Carter (1932, 1934) are summarized and discussed by Herlinveaux (1962). There is no complete sequence of data for even one year, and the picture derived from a combination of the observations obtained over a period of years provides

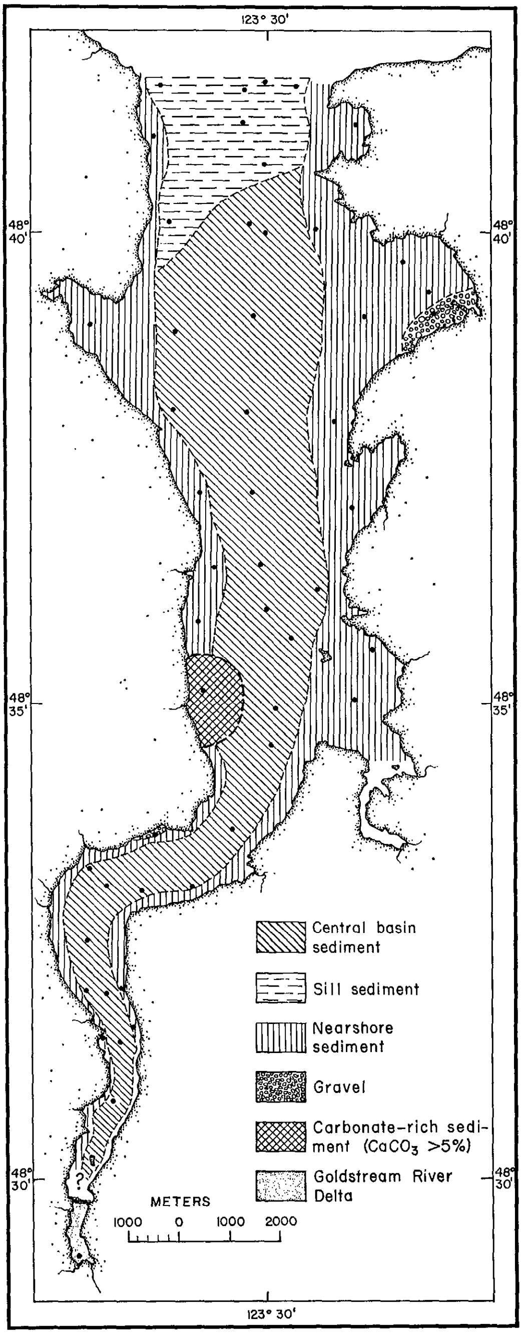

FIG. 3. Location of the surface sediment samples and distribution of the major sediment types.

only a suggestion of the processes operative in the inlet.

According to Herlinveaux (1962), H_2S occurs in the bottom water most of the year. Carter (1934) reported that the upper limit of an "oxygen deficient zone" varied from 150 m in December to 70 m in October, but he did not indicate if H_2S occurred below these depths. Hydrogen sulfide was present in water below 160 m during April and August 1961 but was not detected in November 1961, which suggests renewal of the bottom water (F. A. Richards, personal communication). Herlinveaux (1962, p. 30–31) suggested that water in Satellite Channel above the sill depth of the inlet may become dense enough to displace the bottom water in the inlet.

Pickard (1961) contrasted the circulation in Saanich Inlet with that observed in the inlets on the British Columbia mainland. He postulated that the low runoff of streams emptying into Saanich Inlet causes a weak estuarine circulation resulting in stagnation of the bottom waters. The freshwater in the inlet is derived from precipitation, local runoff, and the intrusion of low-salinity water through the mouth of the inlet (Herlinveaux 1962). The low-salinity water is apparently derived from the discharge of the Cowichan and Fraser rivers which is mixed with seawater in the Strait of Georgia (Fig. 1).

The various oceanographic studies mentioned above have included determinations of the dissolved oxygen, phosphates, nitrates, and silicates at selected depths, but no data are available as a basis for comparison of the biological activity in Saanich Inlet with that in the adjacent Strait of Georgia. Herlinveaux (1962) reported high concentrations of phytoplankton, zooplankton, and fish in the inlet.

SAMPLING AND ANALYTICAL TECHNIQUES

Sample collection

Sediment samples were collected in Saanich Inlet from the *RV Brown Bear* in April 1961, November 1962, and July 1963; from the *MV Astor* in August 1961; and from the *RV Hoh* in September 1962. Surface sediments were collected using Van Veen grab-samplers (Thamdrup 1938).

The cores were collected using a piston coring device, with the exception of core 5, which was collected using a gravity corer. Sample positions (Figs. 1 and 3) were located by resection.

Analytical techniques

As soon as a sample was brought aboard ship, the pH was measured by inserting electrodes into the wet sediment. The presence or absence of a hydrogen sulfide odor was recorded, and the color of the wet sediment was noted (National Research Council, Rock-Color Chart Committee 1951). The samples were immediately frozen to inhibit bacterial action.

Grain-size analyses were performed using a combination of sieving and sedimentation methods (Krumbein and Pettijohn 1938). The particle-size data for the sediments are expressed in terms of phi-notation ($\phi = -\log_2 \xi/\xi_0$), the diameter of the particles ξ is expressed in millimeters (McManus 1963), and ξ_0 is 1 mm. The Inman sorting coefficient (Inman 1952) was used to provide a measure of the uniformity of sorting of the sediments; the more poorly sorted the sediment, the larger its Inman sorting coefficient.

The nitrogen content was determined by standard micro-Kjeldahl techniques (Jackson 1958). The P_2O_5 concentrations were determined by digestion of a known amount of finely ground sediment in hydrogen peroxide and concentrated sulfuric acid to which ammonium molybdate and Fiske-Subbarow solutions were added. The absorbance at 700 mμ was measured with a Beckman Model DU spectrophotometer and compared to a series of standards (Barnes 1951, p. 159–161). The carbonate content was determined by reacting the sediment with excess sulfuric acid and back-titrating with sodium hydroxide (Herrin, Hicks, and Robertson 1958). The results are reported as $CaCO_3$. The water content was determined by drying the sediment at approximately 100C.

The opal content was estimated by X-ray diffraction methods (Goldberg 1958). The washed, carbonate-free sediment was heated for 4 hr at 900C to convert the opal to cristobalite, which is detected by standard X-ray diffraction techniques.

The total carbon content was determined by heating the samples in an induction furnace in an oxygen atmosphere and measuring the volume of carbon dioxide produced by decomposition of the carbonates and oxidation of the carbonaceous compounds. The organic carbon content was computed by subtracting the amount of carbonate carbon from the total carbon content.

Reducing capacity (Trask 1939, p. 432), or amount of oxidizable matter (Jackson 1958, p. 206–207), was determined by oxidizing the sediment in a known amount of boiling, concentrated sulfuric acid and potassium dichromate. The excess dichromate was titrated with ferrous ammonium sulfate. No corrections were made for the oxidation by the dichromate ion of the chlorine remaining in the washed sediment. The results are expressed as the equivalent amount of carbon that would produce the same reducing capacity.

The reproducibility of the various analytical techniques is shown below:

Analysis	Reproducibility
Reducing capacity	±0.03%
Total carbon	±0.02%
Nitrogen	±0.01%
Phosphorus	±0.05%
Calcium carbonate	±0.1%
Opal	±10% of amount reported

The mineral content of sediments from six locations in the inlet and individual laminae from core 4 were analyzed by X-ray diffraction techniques (Brown 1961). The technique proposed by Weaver (1958, p. 270–271) was used to estimate the abundance of chlorite, mica species, and montmorillonoids.

The diatoms and silicoflagellates in 22 laminae were analyzed by W. A. Dawson. About 10 cc of filtered, distilled water containing 1% formalin were added to each aliquot of approximately 4–8 cc. This was then stirred thoroughly, and one drop of the suspension was pipetted onto a new, clean microscope slide. The preparation was scanned at 400× magnification for

TABLE 2. *Particle-size statistics of the sediment types*

Sediment types	Median diameter average (Range)	Inman sorting coefficient average (Range)	Textural constituents				Sediment description*
			Clay-sized (%)	Silt-sized (%)	Sand-sized (%)	Gravel (%)	
Central basin sediment	7.4ϕ (4.97 to 9.42ϕ)	2.8 phi-units (1.08–4.86 phi-units)	43.8	44.4	11.2 (All wood chips and diatom frustules)	0.6 (All wood fragments)	Olive-black to black, very poorly sorted, clayey silt
Sill sediment	5.3ϕ (4.77 to 6.16ϕ)	2.2 phi-units (1.54–2.74 phi-units)	23.3	66.2	10.5 (Some diatom frustules)		Light olive-gray, very poorly sorted, clayey silt
Nearshore sediment	1.9ϕ (−1.38 to +3.77ϕ)	1.4 phi-units (0.50–3.07 phi-units)	2.9	7.7	79.3	10.1	Yellow-green to olive-green, poorly sorted, fine sand

* Sediment class nomenclature follows Shepard (1954).

several traverses of the slide. Frustules were identified as they were encountered on the traverse until a total of at least 200 cells and chains of the chain-forming genera (*Skeletonema* and *Melosira*) had been counted. The stirring and pipetting were repeated at least once for each aliquot without regard for the total counted; the count was continued without a break. The counter did not know the identity of a given aliquot or whether it came from a dark or a light layer.

SURFACE SEDIMENTS

Distribution of major sediment types

Three different types of sediment can be distinguished on the basis of physical, chemical, and mass properties of the sediment. The distribution of the three sediment types is shown in Fig. 3, and the textural parameters are given in Table 2.

Below a depth of 100 m, most of the inlet is covered by olive-black diatomaceous clayey silts, here referred to as the central basin sediment. These very poorly sorted sediments contain H_2S as well as an abundance of diatom frustules and some wood chips. On the sill near the entrance to the inlet, are light olive-gray silts, somewhat coarser than the central basin sediment and lacking H_2S. These clayey silts have fewer diatom frustules than the central basin sediments and no wood chips.

The coarsest sediments in the inlet occur near the shores, on narrow beaches, or in small bays or inlets. The typical nearshore sediment is yellow-green to olive-green, poorly sorted, fine sand, although in certain areas gravels are present (Fig. 3). These coarse-grained sediments have the lowest organic carbon and nitrogen contents of the sediments in the inlet.

In a general way, the location of the major sediment types and the distribution of the various parameters such as grain size or sorting are controlled by the topography of the inlet. The coarsest and best-sorted sediments occur near the shores, whereas the finest-grained and most poorly sorted sediments are found in the deep central portions of the inlet.

Diatom frustules are most abundant in the central basin sediment. The recognizable diatom frustules include *Melosira sulcata* (chains of cells), *Coscinodiscus excentricus*, *Thalassiosira decipiens*, and *Skeletonema costatum* (chains of cells), and the resting spores of several *Chaetoceros* species. Frustules in the central basin sediment are much better preserved than in the sill sediment. Recognizable frustules are rare or absent in the nearshore sands.

Chemical and physical properties

The bulk chemical properties of the major sediment types are summarized in Table 3. The distributions of the reducing capacity (Fig. 4), nitrogen content (Fig. 5), and $CaCO_3$ content (Fig. 6) all show similar patterns and a close correspondence to the sediment type. The greatest values occur in the hydrogen sulfide-bearing central basin sediments. Intermediate values occur in the sill sediments, and the lowest values occur in the nearshore sands and gravels. The only exception is the concentration of $CaCO_3$ near the limestone quarry at Bamberton on the western side of the inlet.

The central basin sediments in Squally Reach and Finlayson Arm contain more nitrogen and $CaCO_3$ and have higher reducing capacities than the central basin sediments in the main portion of the inlet. Also, the sediments in Finlayson Arm have the most constant pH values (6.8 ± 0.1).

The grain density of the sediments is greatest in the nearshore sands (2.82 g/cc) and decreases in the finer-grained sediments. In the diatomaceous clayey silts from the central basin area, the grain density is 2.40 g/cc.

Composition

The sand-sized grains, coarser than 62μ (4ϕ), consist of subangular to angular, equidimensional, dark-colored lithic fragments and grains of quartz, feldspar, muscovite, clinopyroxene, and hornblende. Montmorillonoids and chlorite were detected by X-ray diffraction. Calcite is present near the limestone quarry at Bamberton. No sulfide minerals were recognized or detected by X-ray diffraction techniques.

Lithic fragments are most abundant in the nearshore sediments, constituting up to 90% (by weight) of the total sediment, and least abundant in the central basin, where only a few fine sand-sized angular quartz and feldspar grains occur. In the sill sediments, quartz and mica grains and a few lithic fragments are present.

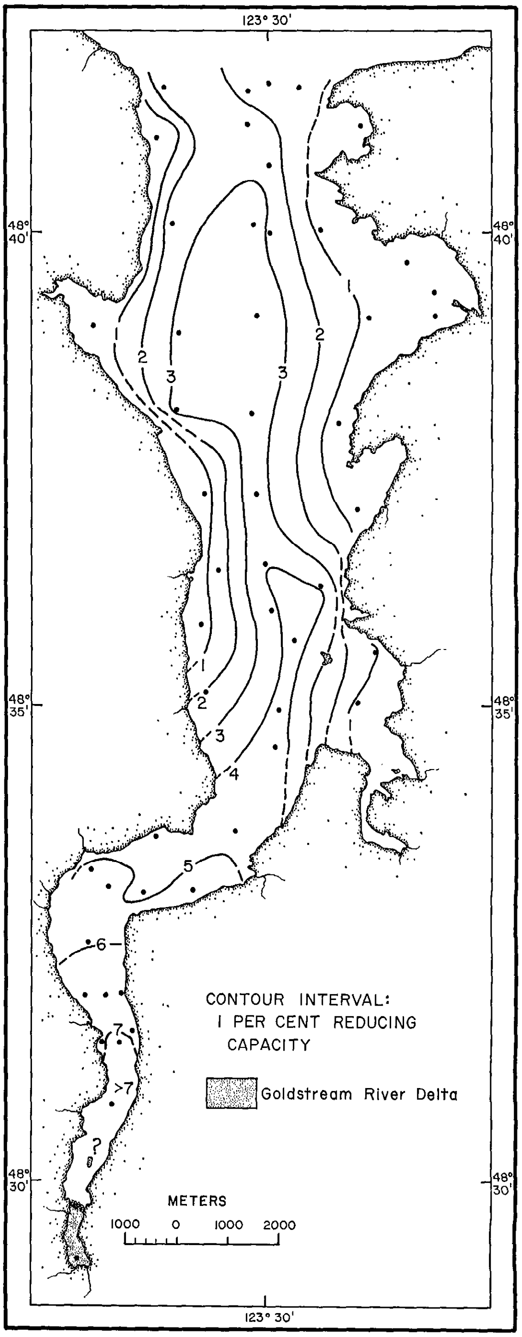

FIG. 4. Distribution of the reducing capacity, expressed as the equivalent amount of carbon that would produce the same reduction of potassium dichromate.

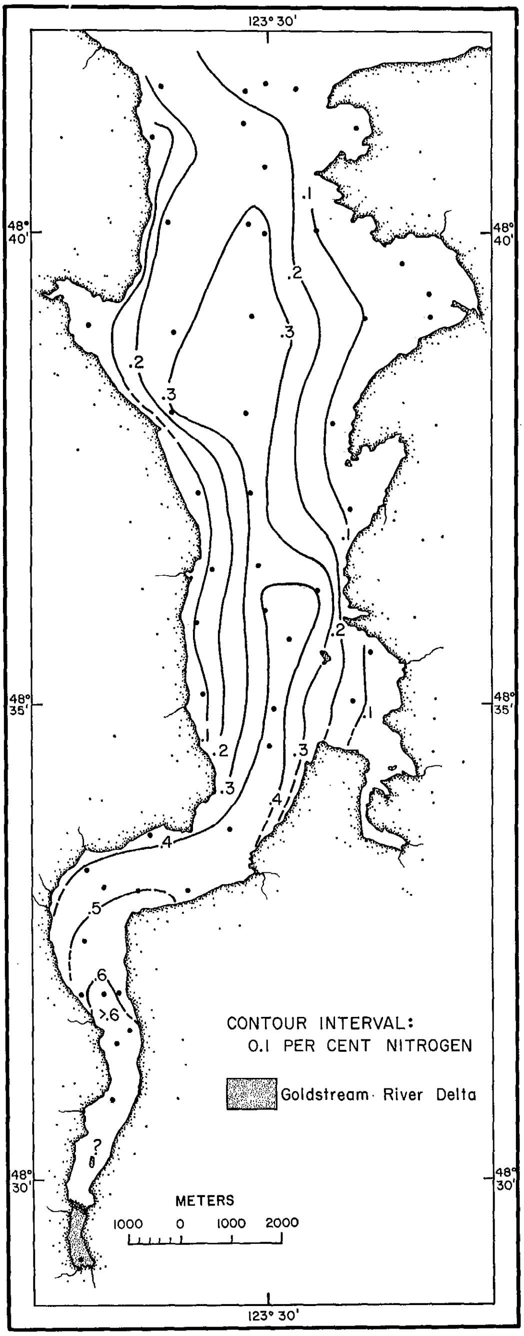

FIG. 5. Distribution of the nitrogen content of the sediments.

Wood fragments, larger than 2 mm (–1ϕ), and wood chips and diatom frustules, 0.12–0.062 mm (3–4ϕ) in diameter, make up the coarser fraction of the central basin sediment. The wood chips are uniformly distributed throughout the central portion of the area, whereas the larger wood fragments are most abundant in the southern half of the central basin and in the nearshore samples. Only plant fibers, seeds, and stems are found in the sill sediments. Diatom frustules and quartz grains, primarily between 0.25 and 0.062 mm (2 and 4ϕ) in diameter, adhere to the fibers and stems in the sediment.

SUBSURFACE SEDIMENT DISTRIBUTION

Five cores, up to 19.5 m in length, were obtained from the sill and central basin areas of the inlet (Fig. 1) in order to study the features of the sediments below the sediment–water interface. Preliminary results were reported by Gross et al. (1963).

Sill sediment

Core 5, 52 cm long, of grayish olive-green silt was recovered from the sill (Fig. 7). The sediment in the core appeared uniform, and no H_2S was detected.

Central basin sediment

Four cores from the central basin penetrated alternating olive-gray and olive-black laminae (Figs. 7 and 8). The average thickness of individual laminae was between 1 and 3 mm, although light-colored laminae up to 7 mm thick were present in core 4 (Fig. 8). Both dark and light laminae were composed of silt- and clay-sized grains containing abundant diatom frustules. After exposure to air and drying, the olive-black laminae changed to light gray.

Core 4 had several nonlaminated zones at depths below 400 cm (Fig. 8), but there were no nonlaminated zones in the shorter cores.

Mineralogy

Individual laminae were separated from core 4, and the fractions finer than 62μ were analyzed by X-ray diffraction.

Quartz and feldspar were ubiquitous in the laminae, and no consistent variations in their abundance could be demonstrated. Although there is considerable uncertainty in the estimates of the quantities of the various clay mineral species, it appears that the light-colored laminae may contain slightly more chlorite and mica species than the dark-colored laminae. Montmorillonoids appear to be slightly more abundant in the dark-colored laminae.

Chemistry of the cores

The data for the reducing capacity of the sediments and the concentration of nitrogen, $CaCO_3$, phosphorus, carbon, and opal are plotted in Figs. 7 and 8.

In general, there is no obvious chemical change with depth in the cores except for the reducing capacity that diminishes with depth in cores 3 and 5. In core 4, this decrease in reducing capacity is reflected in the absence of H_2S below 8.4 m in the core. The water content of core 4 also shows a general decrease with depth.

The chemical properties of individual light- and dark-colored laminae in cores 3 and 4 were compared. Nitrogen and opal are more abundant in the light-colored laminae, whereas the phosphorus content and reducing capacity are greater in the dark-colored laminae. Total carbon and $CaCO_3$ contents of the light- and dark-colored laminae appear to be essentially the same.

Diatoms

The diatoms recognized in samples from core 4 were marine planktonic forms,[3] and

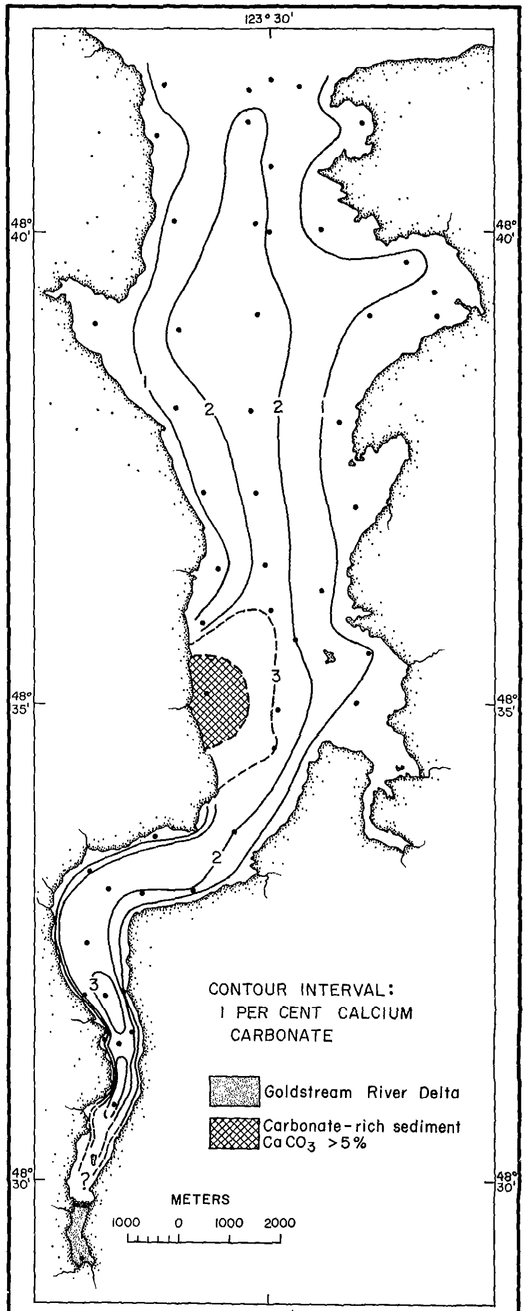

FIG. 6. Distribution of the calcium carbonate content of the sediments. Note the carbonate-rich sediment near the limestone quarry and cement factory at Bamberton, on the west side of the inlet.

[3] The following species of diatoms and silicoflagellates were identified in core 4 by W. A. Dawson. The taxonomy follows Gemeinhardt (1930) and Cupp (1943).

Diatoms:

Chaetoceros radicans (resting spore)
C. compressus " "
C. cinctus " "
C. seiracanthus " "
C. subsecundus " "
C. lorenzianus " "
C. didymus " "
C. debilis " "
Chaetoceros species "A" (paired resting spores)
Thalassiosira decipiens
Coscinodiscus excentricus

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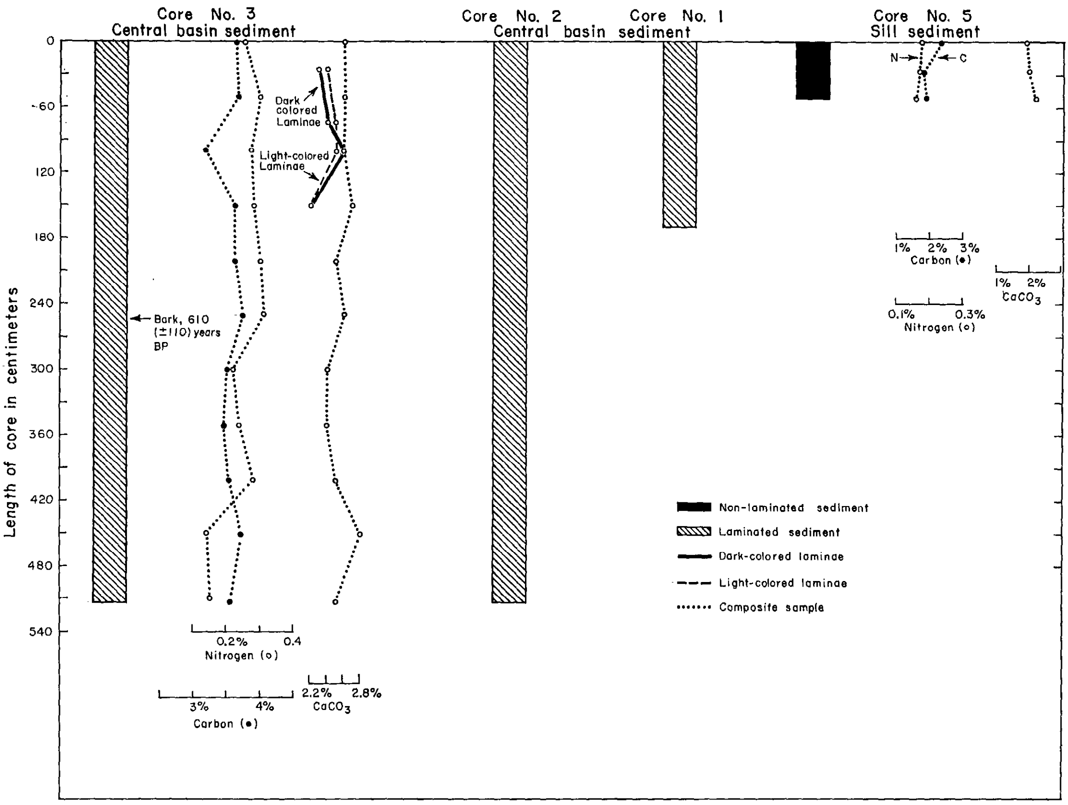

FIG. 7. Textural and chemical properties of the cores from the sill and central basin areas. Note the general lack of variation of the chemical properties with depth in these cores.

the total diatom content of individual laminae appears to be approximately equal. Fig. 9 shows the variation in abundance of the most common diatom species in the

Thalassiosira nordenskioldii
Skeletonema costatum (chains of cells)
Melosira sulcata (chains of cells)
Nitzschia-like spp.
Nitzschia sp.
Thalassiothrix longissima
Coscinodiscus granii
C. curvatulus
C. concinnus
Ditylum brightwelli (fragments)
Actinoptychus undulans
Naviculoid spp.
Cocconeis sp.
Biddulphia aurita
Grammatophora sp.
Stephanopyxis sp. (resting spore)
Rhizosolenia setigera
Silicoflagellates:
Ebria tripartita

laminae. The most obvious difference between the laminae is the greater abundance of *Skeletonema costatum* in the light-colored laminae and of *Melosira sulcata* in the dark-colored laminae. *Thalassiosira decipiens* and *Coscinodiscus excentricus* together showed no consistent variations.

A conspicuous part of the diatom assemblage consists of the resting spores of the genus *Chaetoceros*. These are more abundant in the light-colored laminae (averaging 42.5%, ranging from 8.0 to 68.9%) than in the darker-colored laminae (averaging 31.6%, ranging from 17.0 to 48.7%).

Pollen was not common, occurring in only three light- and three dark-colored laminae. Silicoflagellates were present in all the darker-colored laminae; *Distephanus speculum* made up 30.2% of the recog-

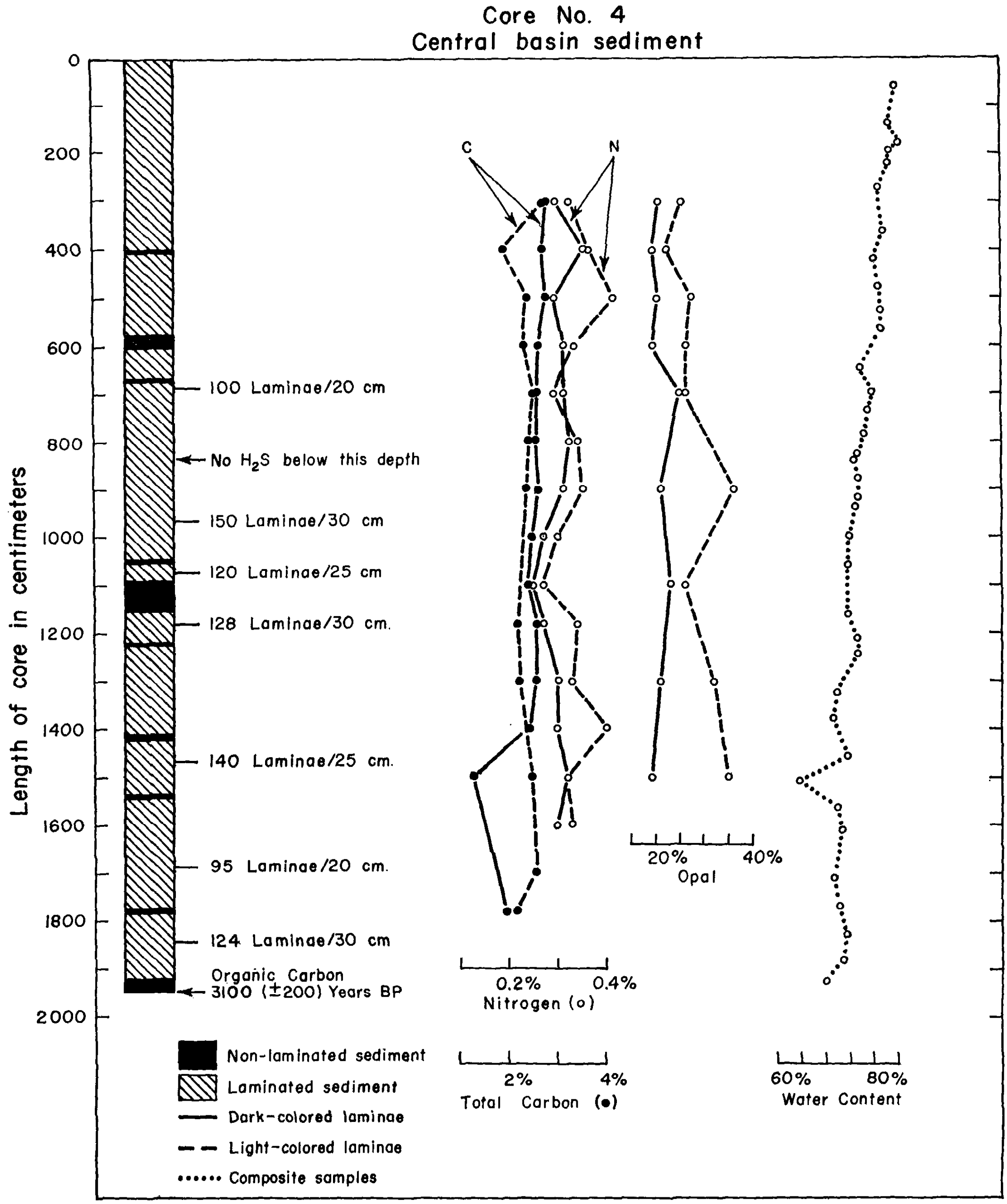

FIG. 8. Textural and chemical properties of the individual laminae in core 4 from the central basin sediment. Note the absence of hydrogen sulfide below approximately 8 m.

nizable biota in the dark lamina at 1,780 cm. Silicoflagellates occurred in all but three of the light-colored laminae and never made up more than 6.2% of the sediment.

DISCUSSION

Color of sediments

The black to olive-black color of the highly reduced sediments is probably

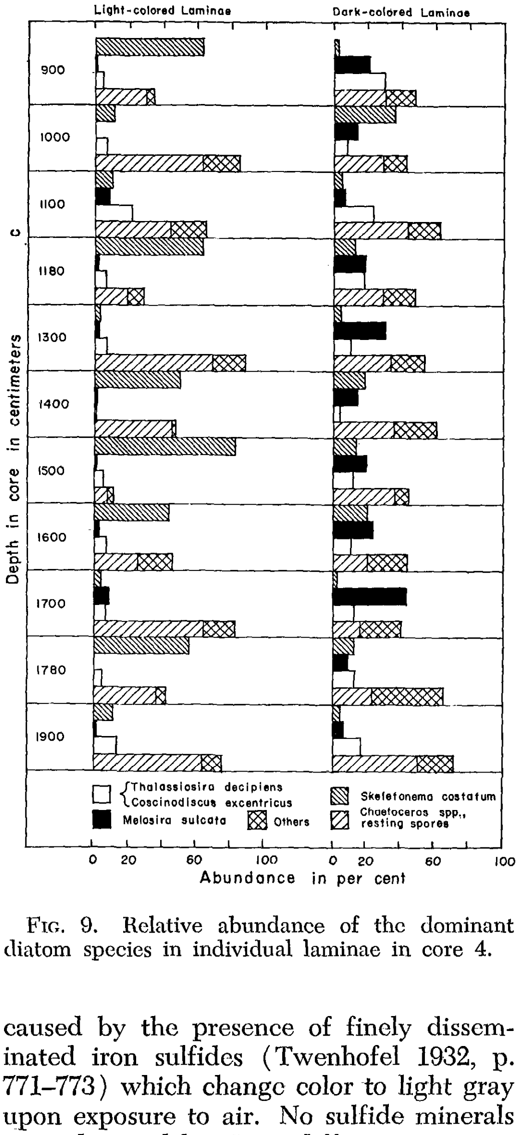

FIG. 9. Relative abundance of the dominant diatom species in individual laminae in core 4.

caused by the presence of finely disseminated iron sulfides (Twenhofel 1932, p. 771–773) which change color to light gray upon exposure to air. No sulfide minerals were detected by X-ray diffraction.

The olive-gray color of the light-colored laminae is caused by the abundance of diatom remains. Certain of the light-colored laminae have yet thinner, lighter gray bands near their base that appear to be almost entirely composed of diatom frustules and probably represent particularly large phytoplankton blooms.

Calcium carbonate content

Much of the carbonate in the sediments of Saanich Inlet is in the form of mollusk shell fragments, although a small amount may be derived from limestone outcrops in the drainage basin. The limestone quarry at Bamberton obviously supplies $CaCO_3$ to the nearby sediments (Fig. 6). The absence of significant variations in the $CaCO_3$ content with depth in the cores (Figs. 7 and 8) suggests that the influence of the quarry is not significant over most of the inlet.

Except near Bamberton, all of the sediments containing more than 2.2% $CaCO_3$ also contain H_2S, suggesting a possible relationship. The sediments in Finlayson Arm contain more $CaCO_3$ than similar sediments in the rest of the inlet; they also show the most consistent pH values (6.8 ± 0.1).

Phosphorus

The phosphorus contents of the three sediment types in Saanich Inlet are nearly identical (Table 3), showing no correlation with the concentration of carbon, nitrogen, or opal in the sediments. The concentrations observed are well within the range of phosphorus contents of modern marine sediments (Kato 1956, p. 104–105), shales (Clarke 1924, p. 552), and carbonaceous shales (Pettijohn 1957, p. 361). Strøm (1939) reported that the P_2O_5 content of the sediments from stagnant Norwegian fjords was always low, averaging 0.23% in the muds analyzed.

The coarse-grained nearshore sediments have the highest and the lowest concentrations of phosphorus (0.31% P_2O_5 in sample 12, and 0.07% P_2O_5 in samples 33 and 35). This variation is apparently related to the distribution of detrital minerals containing phosphorus.

Analyses of individual laminae from core 4 show that the P_2O_5 content of the dark-colored laminae (0.15 and 0.16%) is greater than that of the light-colored laminae (0.09 and 0.12%). This is probably caused by the abundance of opal in the light-colored laminae, which would reduce the relative abundance of phosphorus-containing detrital minerals.

TABLE 3. *Average chemical and physical properties of the sediment types*

	H_2S odor	Average pH (Range)	Average reducing capacity* (Range in %)	Average organic C content† (Range in %)	Average nitrogen content† (Range in %)	Average $CaCO_3$ content† (Range in %)	Average P_2O_5 content† (Range in %)	Average opal content† (Range in %)	Density (g/cc)
Central basin sediment	All samples	7.01 (6.62–7.60)	4.70 (2.78–7.21)	2.92 (1.63–5.26)	0.45 (0.29–0.66)	2.4 (1.1–3.8)	0.16 (0.14–0.26)	24 (17–28)	2.40
Sill sediment	None	7.13 (6.90–7.30)	2.22 (1.54–2.62)	1.41 (0.66–1.96)	0.22 (0.15–0.26)	1.6 (1.3–2.2)	0.16 (0.15–0.17)	14 (10–18)	2.67
Nearshore sediment	None	7.09 (6.74–7.35)	0.63 (0.25–1.42)	0.48 (0.19–0.89)	0.08 (0.04–0.14)	0.7 (0.1–1.8)	0.14 (0.07–0.31)	No analyses	2.82

* Expressed as the weight per cent of carbon that would produce the same reducing capacity.
† Values in weight per cent.

Reducing capacity and organic carbon content

The reducing capacity of the sediments is consistently greater than can be explained by the amount of organic carbon (Fig. 10). The discrepancy is least in the nearshore sands and gravels and greatest in the central basin sediments containing H_2S. This excess reducing capacity indicates the presence of reduced species other than carbon. In the case of the sediments with hydrogen sulfide, this is easily understood, but even the sill sediments that did not contain H_2S have some excess reducing capacity. Thus, the reducing capacity of the sediments cannot be used as a measure of the organic carbon content.

Organic carbon and nitrogen contents

The highest values of organic carbon and nitrogen occur in the fine-grained black sediment in the deep central basin of the inlet. The high organic carbon and nitrogen contents of this sediment are a result of the following factors: 1) association of organic material with fine-grained sediment (Trask 1939), 2) organic productivity in the waters of the inlet, and 3) the absence of oxygen in the bottom waters, which prevents oxidation of the organic matter or its utilization by a bottom fauna.

Relatively low organic carbon and nitrogen contents were found in the sill and nearshore sediments. These low concentrations of carbonaceous organic material indicate either little deposition of organic material in these areas or the rapid decomposition of organic matter due to oxidation and utilization by benthic organisms.

The presence of wood fragments, leaves, and stems in the central basin sediments indicates that some carbonaceous organic matter is derived from terrestrial sources.

Carbon–nitrogen ratios of the sediments

According to Wadsman (1933), the carbon–nitrogen ratio in soils is nearly constant at 10, and results from a "decomposition equilibrium" of soil organic matter. A carbon–nitrogen ratio of 8.4 in sediments from the Channel Island area, California (Trask 1931), is attributed to differences in the source of organic material. Bader (1954, 1955) explained the wide variation of carbon–nitrogen ratios in marine sediments in terms of the wide variations in the lignin content of marine sediments and the resistance of lignin to decomposition.

In Saanich Inlet, the carbon–nitrogen ratios of the surface sediments vary from 2.7 to 10.3, with an average of approximately 7 (Fig. 11). Carbon–nitrogen ratios of less than 6.5 generally occur in coarse-grained, nearshore sands that have low organic carbon and nitrogen values. Carbon–nitrogen ratios greater than 6.5 are found in the central basin sediment, asso-

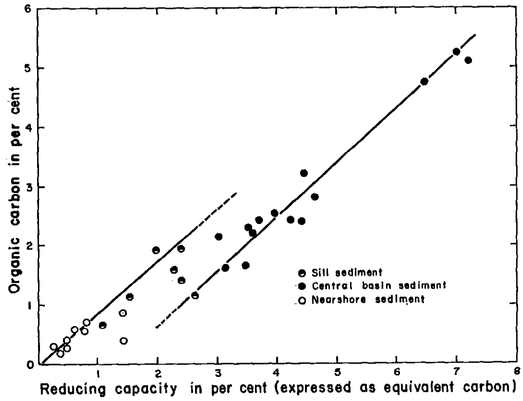

FIG. 10. Relationship between reducing capacity and organic carbon content of the sediments.

ciated with higher concentrations of organic carbon and nitrogen, the finer-grained sediment, and the wood fragments.

The data on the chemical composition of plankton (Fleming 1940) and wood (Clarke 1924), both of which may contribute carbonaceous matter to the sediment, are given below:

	Carbon (%)	Nitrogen (%)	C:N
Phytoplankton	42	7.0	6.0
Zooplankton	40	7.4	5.4
Average plankton	41	7.2	5.7
Wood	49.65	0.92	54.0

Studies of the carbonaceous material in a similar but smaller fjord showed that the presence of large amounts of terrestrial plant material can result in carbon–nitrogen ratios of up to 50 (Anderson 1962).

The close correspondence between the carbon–nitrogen ratio observed in the sediments from Saanich Inlet and those reported for marine phytoplankton and zooplankton suggests that the bulk of the carbonaceous material in these sediments is derived from plankton rather than from terrestrial plants growing on the surrounding land masses. If the carbon–nitrogen ratios observed in the sediments are caused by a simple mixing of the unaltered carbonaceous materials, terrestrial plant material must constitute less than 5% of the carbonaceous material, with the remainder being supplied by marine plankton.

When the carbon and nitrogen concentrations in the sediments are plotted against each other (Fig. 11), the regression line for the data does not pass through the origin but intersects the ordinate at a value of approximately 0.02% nitrogen. This suggests that some nitrogen recovered during the Kjeldahl digestion of the sediment is not associated with carbonaceous material but is a constituent of the detrital silicate sediment. Thus, in the coarse-grained nearshore sediments with nitrogen concentrations of 0.1% or less, a significant portion of the nitrogen may occur in the lithogenous part of the sediment and should, therefore, be excluded from any computation of the carbon–nitrogen values. The problem of fixed nitrogen in rocks has recently been discussed by Stevenson (1962).

Source of the sediment

The major source of terrigenous sediment in Saanich Inlet is apparently the low-salinity water that enters the inlet from Satellite Channel (Herlinveaux 1962). This water is formed by mixing of salt water with freshwater from the Cowichan River, which discharges into Cowichan Bay 6 km northwest of Saanich Inlet, and from the Fraser River, which discharges into the Strait of Georgia approximately 50 km northeast of Saanich Inlet. During the peak discharge of the Fraser River in May and June, "clouds" of sediment-laden water have been observed moving in the direction of Saanich Inlet, especially on an ebb tide (Tully and Dodimead 1957, p. 278–279; Waldichuk 1957, p. 363–365).

Waldichuk (1953) suggests that in the central and southern portions of the Strait of Georgia the Fraser River is the major source of sediment. Mathews and Shepard (1962) report that the Fraser River discharged 8.3×10^6 metric tons of silt and clay into the Strait of Georgia during 1950–52. Thus, the Fraser River is known to contribute large amounts of sediment to the Strait of Georgia, where the circulation pattern can transport some of it in the direction of Saanich Inlet. No data on the sediment load of the Cowichan River are available.

From these data it is concluded that sediment is supplied to the inlet by the Cowichan River, which apparently has a small amount of suspended sediment but discharges into Cowichan Bay near Saanich Inlet, and by the Fraser River, which discharges a large amount of sediment into the Strait of Georgia some distance from Saanich Inlet.

It is clear that diatoms are another major source of sediment, since opal, presumably from diatom frustules, constitutes up to 25% of the sediments. No data on the phytoplankton production in Saanich Inlet are available, although scattered observations suggest that it is large (Herlinveaux 1962).

The approximate organic content of the sediments can be estimated by multiplying the organic carbon values by 1.7 (Jackson 1958, p. 206). Thus, for the surface sediments in the southern end of Saanich Inlet, the biogenous component constitutes at least 34% of the sediment; of this, approximately 9% is carbonaceous organic material and 25% is opal derived from diatom frustules.

The coarse-grained nearshore sediments are probably derived from the erosion of the adjacent shore. These coarse sediments are not widely distributed in the inlet and apparently are not transported in any quantity into the deeper parts of the inlet, where the sand-sized grains consist entirely of diatom frustules and wood fragments. Apparently no wood fragments are deposited in the nearshore area.

Little is known about the sediments on the sill. Further work is necessary to determine whether these sediments are being deposited at present or whether they represent the reworked surface of an older depositional feature.

The central basin sediments are much finer grained than the sill and nearshore sediments and are most probably derived from sources outside the inlet. The sill at the mouth of the inlet prevents the introduction of any coarse-grained sediment

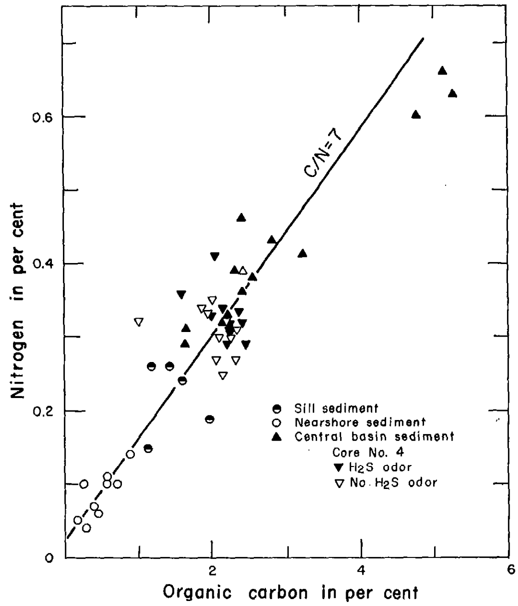

FIG. 11. Relationship between the nitrogen and organic carbon contents of the sediments.

that might enter as turbidity currents along the bottom from Satellite Channel. Consequently, the fine-grained terrigenous sediment brought into the inlet must have entered suspended in the water.

Some sediment may enter the inlet from the local streams. The largest of these, the Goldstream River, probably contributes little sediment because it goes through a series of lakes and reservoirs before flowing into the inlet. No data are available on the sediment load of the streams discharging into Saanich Inlet.

Origin of the laminated sediments

The laminated clayey silts of the central basin area are the most striking feature of the sediments in Saanich Inlet. These resemble the well-known varved deposits of glacial lakes (Twenhofel 1932). Varved marine sediments have been reported from the Gulf of California (Byrne and Emery 1960), Santa Barbara Basin (Emery 1960; Hulseman and Emery 1961), the Clyde Sea (Moore 1931), and Drams Fjord, Norway (Strøm 1939). The laminated sediments of the Black Sea are a classical example of varved sediments (Twenhofel 1932, p. 260; Caspers 1957, p. 827–830), and the Miocene Monterey formation (Bramlette 1946) is an example of marine, diatomaceous sediments in which varves may be preserved.

The regularity of the laminae (Fig. 8), the differences in the diatom species found in the light- and dark-colored laminae (Fig. 9), and the variations in opal content (Fig. 8) are consistent with our hypothesis (Gross et al. 1963) that the laminae are formed during different seasons of the year and that each pair of laminae represents one year's deposit of sediment. If the seasonal variation of the diatom species in Saanich Inlet were known, this could be used to determine when the individual laminae were formed. Lacking this information, one can only assume that the opal-rich, light-colored laminae form during the time of maximum diatom production, probably in the spring and summer.

The age of a piece of bark from a depth of 253 cm in core 3 (Fig. 7) and the age of a sample of organic carbon from sediment at 1,940 cm in core 4 (Fig. 8), estimated by dividing the depth of the sample by the average thickness of the varves in each core, were approximately 600 and 4,620 years, respectively. The carbon 14 activities indicate ages of 610 ($\pm$110) and 3,100 ($\pm$200) years BP respectively, corresponding to sedimentation rates of 4.1 and 6.3 mm of uncompacted sediment per year, respectively. The two determinations of the age of the bark in core 3 are in good agreement; the age obtained from the carbon 14 activity of the organic carbon in core 4 is significantly less than the estimated age based on the varve thickness. Both cores are from essentially the same area (Fig. 1).

No satisfactory explanation for the discrepancy in the apparent ages of the sample from core 4 can be offered. Part of the difficulty may lie in the carbon 14 method, which is known to give ages significantly younger than those obtained by other methods for samples 3,000–4,000 years old (Libby 1963). If it could be shown that only two laminae are formed each year, the varved sediments in Saanich Inlet might provide an independent means of dating samples for a study of the accuracy of carbon 14 techniques (A. W. Fairhall, personal communication).

The nonlaminated zones in core 4 are apparently the result of destruction of the laminae. Disturbance of the laminae during the extrusion of the core probably caused some of the nonlaminated zones. Others may represent the effects of penecontemporaneous disturbance of the sediments due to slumping. The thinner nonlaminated zones may form when diatom production is inhibited for some reason. No evidence of burrowing organisms has been detected in the nonlaminated zones.

Rate of sedimentation

With these data, it is possible to estimate the amount of sediment deposited each year in the central portion of Saanich Inlet. An annual accumulation of 4–6 mm of sediment, consisting of 75% water (by weight) and 25% solid material (density of 2.4 g/cc), means that 0.24–0.36 g of sediment per square centimeter are deposited each year. Assuming that the sediment is deposited uniformly over the bottom of the inlet at depths greater than 100 m, approximately, 10^5 metric tons of sediment are deposited each year in the central portion of Saanich Inlet.

Opal, carbon, calcium carbonate, nitrogen, and phosphorus derived from biological processes constitute up to 35% of the sediment. The remainder is terrigenous sediment, primarily silt- and clay-sized material, probably derived from the Cowichan and Fraser rivers.

SUMMARY AND CONCLUSIONS

1) Saanich Inlet, a small, fjordlike marine embayment on Vancouver Island, has H_2S in the bottom water during most of the year because of the restricted water circulation. The drainage area of the inlet is small, and no large streams flow into the inlet.

2) Three major sediment types may be differentiated:

a) Fine-grained, laminated, light olive-gray to olive-black clayey silt, containing H_2S, large amounts of opal, and organic materials, occur in the central part of the inlet at depths greater than 100 m.

b) Olive-gray silts, containing no H_2S, with intermediate concentrations of organic materials and opal and moderate reducing capacities, occur on the sill.

c) Fine sands and gravels with low organic contents and low reducing capacities occur near the shore and in the small bays and inlets.

3) Five sources of sediment can be distinguished:

a) Marine organisms, principally planktonic diatoms.

b) Suspended sediment in the low-salinity water derived from the Fraser and Cowichan rivers.

c) Erosion of adjacent shorelines that is probably the only source of the coarse-grained nearshore sediments.

d) The cement plant and limestone quarry at Bamberton.

e) Streams discharging directly into the inlet.

4) The organic carbon and nitrogen contents are lowest in the coarse-grained, well-sorted nearshore sediments, and highest in the fine-grained, highly reduced central basin sediment. The factors controlling the organic carbon and nitrogen content of the sediments appear to be the presence or absence of dissolved oxygen in the water, the grain size, and the rate of phytoplankton production in the overlying waters.

5) The carbonaceous and siliceous organic matter in the sediment appear to be derived from marine organisms, principally planktonic diatoms, with only small contributions from terrestrial sources. A carbon–nitrogen ratio of 7 is typical of the sediments in the inlet.

6) The light-colored laminae probably are formed during the peak phytoplankton production in the spring or summer, and dark-colored laminae probably form during the remainder of the year.

7) The nonlaminated sediment, below 4 m in core 4, may be deposited by slumping from adjacent areas, or it may simply be the result of disruption of originally laminated sediment by physical processes such as penecontemporaneous deformation. The presence of burrowing marine organisms is apparently not a factor.

8) Approximately 10^5 metric tons of sediment are deposited in the central part of the inlet each year. Marine organisms contribute 25–35% of the sediment.

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