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FIRST OBSERVATIONS OF BENTHOS AND SESTON FROM A SUBMERSIBLE IN THE LOWER ST. LAWRENCE ESTUARY

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ABSTRACT Six dives with the submersible PISCES IV have permitted a unique description of the benthic and pelagic environments of a large, deep Canadian estuary. The estuarine floor and continental slopes are divided into five depth-dependent benthic zones. In order of decreasing depth are the Bathyal Trough Zone, the Infaunal Zone, the *Ophiura* Zone, the Ice Rafting Zone and the Wave Base Zone. The zonal boundaries are based on changes in the faunal community, sediment texture, current energy, level of bioturbation and suspended particulate loading. Biological resuspension appears important in the Bathyal Trough and Infaunal Zones. Current resuspension dominates the *Ophiura* and Ice Rafting Zones with storm waves additionally reworking the Wave-Base sediments. Seston characteristics are strongly influenced by the source and dynamics of the host water mass. The Surface Layer, the entrained outflow from the St. Lawrence River, is the source of most suspended matter found beneath. Large particles, mostly organo-mineral aggregates, become even larger with depth and indicate a rapid downward transfer of suspended sediment. The upper Intermediate Layer is complicated by stratified zones of turbulence that temporarily reduce the floc size. With the absence of such fine water structure, the lower Intermediate Layer is characterized by long chains of marine "snow" joined by delicate filaments. The Bottom Layer, a zone of increased turbulence, had aggregates breaking up into a haze of fine particles.

RÉSUMÉ *Premières observations du benthos et du seston à partir d'un submersible dans l'estuaire maritime du Saint-Laurent*. Six plongées à bord du submersible *Pisces IV* ont permis de décrire les milieux benthique et pélagique de l'estuaire, large et profond, du Saint-Laurent. Le fond de l'estuaire et les talus continentaux ont été divisés, selon la profondeur, en cinq zones benthiques. Ce sont, du fond vers la surface, la zone bathyale du chenal Laurentien, la zone endobenthique, la zone à *Ophiura*, la zone de dépôts glaciels et la zone sous l'influence des vagues. Ces zones ont été déterminées à partir des variations des populations macrobenthiques, de la texture des sédiments, de l'énergie des courants, du niveau de bioturbation et de la concentration des particules en suspension. La resuspension biologique semble être importante dans les zones bathyale et endobenthique, mais la resuspension par les courants domine dans les trois autres zones. Les sédiments de la zone sous l'influence des vagues peuvent aussi être remaniés par les vagues de tempêtes. Les caractéristiques du seston sont fortement influencées par la source et la dynamique des différentes masses d'eau. Une grande partie du matériel en suspension provient de la couche superficielle, entraîné par le courant du Saint-Laurent. Les grosses particules, surtout les agrégats organo-minéraux, sont de plus en plus grosses en profondeur, ce qui suppose une descente rapide du matériel en suspension vers le fond. Dans la couche intermédiaire supérieure, des zones de turbulence stratifiées réduisent temporairement la taille des agrégats. La partie inférieure de la couche intermédiaire ne contient pas de ces stratifications fines et est plutôt caractérisée par la présence de longues chaînes de particules rattachées par un filament délicat. Dans la couche de fond, l'accroissement de la turbulence transforme les agrégats en un brouillard de fines particules.

ZUSAMMENFASSUNG *Erste Benthos und Seston Beoachtungen von einem U-Boot aus, in der unteren Skt Lorenz Strom Mündung.* Sechs Tauchmanöver mit dem U-Boot Pisces IV haben eine einzigartige Beschreibung der benthischen und pelagischen Umgebung einer grossen, tiefen, kanadischen Mündung erlaubt. Der Aestuarboden und die Kontinentalhänge sind in fünf tiefenbedingte benthische Zonen eingeteilt. Der Ordnung nach, in abnehmender Tiefe, liegen die bathyal Zone des Skt-Lorenz Kanals, die endobenthische Zone, die *Ophiura* Zone, die Eisstrandungs Zone und die Wellen-Einfluss-Zone. Die Zonengrenzen sind auf Veränderungen in der Faunenwelt, Sedimenttextur, Strömungsenergie, Niveau der Bioturbation und der Konzentration der Schwebstoffe gegründet. Biologische Resuspension ist in der bathyalen und endobentischen Zone wichtig, während die Resuspension durch die Strömung in der *Ophiura* und Eisstrandungszone überwiegt, mit zusätzlicher Bearbeitung der Wellen-Basis-Elemente durch Sturmwellen. Seston Kennzeichen sind durch die Dynamik der Gastgewässer stark beeinflusst. Ein grosser Teil der Schwebstoffe kommt aus der oberen Schicht und wird durch die Strömung des Skt Lorenz Stromes mitgeschleppt. Grosse Teile, meistens organisch-mineral Aggregate werden mit wachsender Tiefe noch grösser und zeigen ein schnelles Sinken der Schwebstoffe an. In der oberen Zwischenschicht verringern die stratifizierten Turbulen Zonen zeitweilig die Grösse der Aggregate. Der untere Teil der Zwischenschicht zeigt keine solche feinen Stratifikationen und kennzeichnet sich eher durch die Gegenwart von langen Ketten von Schwebstoffteilchen, die durch einen dünnen Faden zusammenhalten. In der Grundschicht, einer Zone mit vermehrter Turbulenz, werden die Aggregate zu einem Nebel feiner Teilchen aufgebrochen.

INTRODUCTION

The use of research submersibles by marine scientists has proved to be an 'eye-opener' to many, especially in regard to the discovery of new processes (CORLISS *et al.*, 1979; TUNNICLIFFE and SYVITSKI, 1983). Detailed submersible surveys have provided a means of: a) comparing "ground truth" with on board data (MacILVAINE and ROSS, 1979); and b) quantifying sea bottom parameters and processes such as benthos diversity and density, sedimentary structures and resuspension events (FARROW *et al.*, 1983; YORATH *et al.*, 1979). During the summer of 1981, we attempted the first reconnaissance of the lower St. Lawrence Estuary with PISCES IV, a Canadian submersible (SYVITSKI *et al.*, 1983). Our objectives were threefold: 1) to investigate the flat estuarine floors and the steep trough walls in terms of variation in the sedimentary environment and occupying macrobenthos; 2) to investigate the contributions of currents and benthos activity to bottom resuspension of sediments; and 3) to observe and describe the variability of suspended particulate matter (SPM) with depth and position in the Estuary. The immensity of the system and availability of few dives (6) made us confine our activity to the lower St. Lawrence Estuary, landward of Pointe-des-Monts (fig. 1).

PHYSICAL, OCEANOGRAPHIC AND BIOLOGICAL SETTING

The Laurentian Trough is a 300 to 500 m deep, glacially-modified channel whose seaward limit is the continental slope between Nova Scotia and Newfoundland (fig. 1). The Trough extends inland some 1200 km along the St. Lawrence Valley to just seaward of the confluence of the Saguenay Fjord, where the Estuary shoals abruptly to less than 50 m. The sedimentary history of the Trough has been described in detail by LORING and NOTA (1973). Our study area (fig. 1) is bordered by narrow platforms (shelves) that are covered with both fluvio-glacial clays of the post-glacial Goldthwait Sea (9000-12000 BP) and reworked poorly-sorted muddy sands and gravels of recent age (LORING and NOTA, 1973; SILVERBERG, 1976). The Trough slope and floor are characterized by poorly-sorted post-glacial silty clays, as much as 20 m thick, overlying remanent till deposits (LORING and NOTA, 1973).

The physical oceanography of the lower St. Lawrence Estuary has been summarized by EL-SABH (1979) with recent contributions by INGRAM (1979), KOUTITONSKY (1979) and TANG (1980). The character and distribution of suspended particulate matter has received detailed investigation (d'ANGLEJAN and SMITH, 1973; SUNDBY, 1974; KRANCK, 1979; COSSA and POULET, 1978; and CHANUT and POULET, 1982). Although the size of the system permits internal circulation, a general three-layer estuarine circulation is present. Residual transport calculations (KOUTITONSKY, 1979) suggest that the surface layer (upper 50 m) flows seaward, the intermediate layer

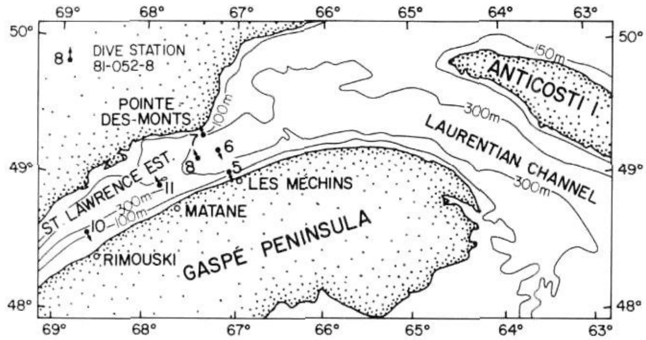


FIGURE 1. Location of submersible dives, place names and general bathymetry of the Lower St. Lawrence Estuary. The arrow indicates the direction of submersible traverse.

Carte de la région étudiée avec la localisation des plongées et la bathymétrie générale de l'estuaire maritime du Saint-Laurent. La flèche indique la direction de la plongée.

(50 to 200 m) flows upstream, and the bottom mixed layer (lower 50 m) exhibits variable flow. The surface layer contains the highest SPM levels ($\approx$ 0.5 to 2 $mg \cdot \ell^{-1}$) of which up to 75% is combustible, with a polymodal size frequency distribution. The SPM concentration and mineral matter proportion increase upstream towards the turbidity maximum located in the middle Estuary. Cold intermediate water extends below the pycnocline: water character is typical of open Atlantic water with little SPM, *i.e.* 0.05 to 0.1 $mg \cdot \ell^{-1}$ having a broad size-spectrum of fine particles mostly smaller than 10 μm. The bottom waters appear to be well mixed, with salinities of $\approx$ 34.5‰ and temperatures of $\approx$ 4°C. SPM concentrations (0.1 to 0.4 $mg \cdot \ell^{-1}$) increase towards the bottom, with occasional values greater than 1 $mg \cdot \ell^{-1}$. This material appears to contain much less organic matter (<50% by weight after ashing, wt. $\cdot vol^{-1}$ ratio > 2) and has a modal size around 8 μm. In general, the residual current velocity decreases with depth (from 50 to 5 $cm \cdot s^{-1}$). Instantaneous bottom velocities are thought to be strong enough to resuspend and transport sediment. This influences the distribution of reactive geochemical components such as Fe, Mn and other metals, especially in terms of diagenetic processes between the surficial sediment and overlying SPM (SUNDBY *et al.*, 1981; SILVERBERG *et al.*, 1982). The influx of SPM from the Saguenay Fjord combined with the Coriolis Force acting on the seaward-flowing surface circulation (COSSA and POULET, 1978) produces a marked increase in SPM concentration, and associated metals and organic components along the southern half of the Estuary.

The St. Lawrence Gulf and Estuary generally has a high plankton productivity. STEVEN (1974) concluded that the principal reason for the high productivity was the presence of a "nutrient pump" mechanism at the head of the Laurentian Channel, wherein the surface waters are continually enriched in nutrients: for details, see THERRIAULT and LACROIX (1976) and COOTE and YEATS (1979). Levels of primary production given are very high (up to 5000 mg C·m⁻²·day⁻¹) in the northwest part of the Gulf between April and October. The standing stock of zooplankton is also large (sometimes > 200 mg·m⁻³) during the second half of the summer. Other investigators put less emphasis on the nutrient pump mechanism (SINCLAIR *et al.*, 1976; GREISMAN and INGRAM, 1977) and indicate productivity values (≈ 500 mg C·m⁻²·day⁻¹) smaller by an order of magnitude (SEVIGNY *et al.*, 1979) for the Gaspé current, and even lower elsewhere.

Few studies report on the quantitative aspect of the benthic fauna of the Laurentian Channel. Molluscs are described by ROBERT (1974, 1979) and the polychaetes by MASSAD (1975) and MASSAD and BRUNEL (1979). These investigators noted a gradual impoverishment of the estuarine Trough fauna in both density and diversity with increasing distance from the head of the Channel (*e.g.* polychaetes decreased from 900 to < 300 individuals ·m⁻²). LEDOYER (1975) and BELLAN (1977, 1978) studied the benthic fauna of the Gaspé Passage (Honguedo Strait) between Anticosti Island and the Gaspé Peninsula. They defined the bathyal fauna of the St. Lawrence Trough floor as beginning at a depth of 200 m and becoming dominant below 300 m.

METHODS

Six submersible dives, each lasting two to four hours, were carried out over positions located in Figure 1. Descents and ascents were intentionally slow (0.1 to 0.2 m·s⁻¹): the submersible maintained depth when *in situ* water samples were collected by aspiration. SPM values obtained from these water samples (*i.e.* on 0.45 μm nominal pore size Nucleopore[R] filters) were used to calibrate the 660 nm Oregon Red[R] attenuance meter attached to the outside hull of the sub and used to monitor inorganic SPM concentrations (fig. 2). These data were supported by visual observations of particles greater than 60 μm, in terms of their size, shape and number: particles < 60 μm appeared as a milky haze and were registered on the attenuance meter. Water samples filtered onto Ag-filters were eventually treated in a sonic bath of Calgon[R] solution for particle disaggregation and size analyzed on a computerized TAII Coulter Counter[R] for nominal diameter. Nucleopore filters were eventually combusted in a high temperature muffle furnace for proxy calculation or organic matter concentrations.

Bottom transects were also run slowly at 0.2 to 0.3 m·s⁻¹ (≈ 0.8 to 1.1 km·hr⁻¹) while observations were voice recorded and photographed with a hand-held 35 mm camera, outside strobe and colour video system. The submersible manipulator arm was used to dig around in the bottom sediment to ascertain a measure of sediment cohesiveness and thickness of the oxidized surficial layer. For further details of PISCES IV submersible operation and capabilities, see SYVITSKI *et al.* (1983).

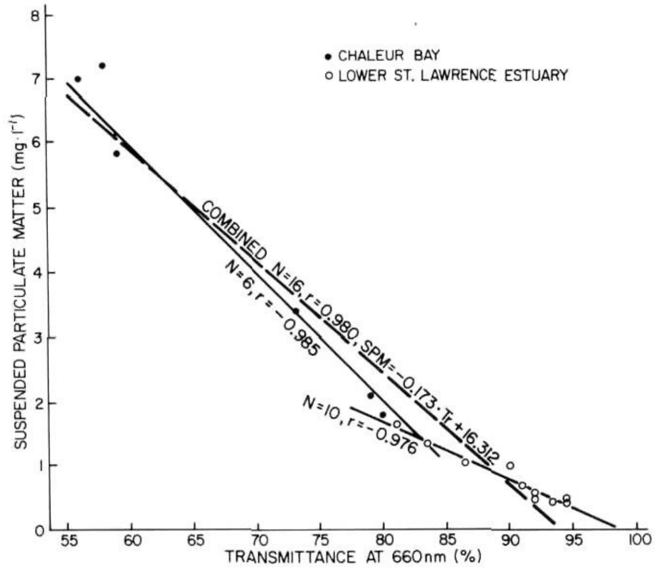


FIGURE 2. Relation between suspended particulate matter (SPM) collected *in situ* and Oregon Red transmittance data.

Relation entre les concentrations de la matière particulaire en suspension (SPM) recueillie in situ *et les données de transmittance de l'appareil Oregon Red.*

SCTD Guildline[R] profiles were run before and after each dive so that SPM observations and attenuance data could be qualified with the water structure.

BATHYAL TROUGH ZONE

Three dives, Nos. 81-052-6, 8, 11 (fig. 1), were made to the Trough floor at depths of 300 to 350 m, and another (81-052-10) included a portion of the adjoining slope off Rimouski between 230 to 250 m. The sea floor at these sites was composed of fine-grained mud, low microrelief, and dominated visually by scattered sea pens and anemones (fig. 3). Fist-sized holes, unevenly dispersed every 5 to 10 m and sometimes occupied by eel-shaped fishes, were observed on all the deep dives.

The sea pens vary in abundance between 0.5 and 4·m⁻² but changes are gradual from place to place. Pink, dark red, yellow and white coloured individuals were noticed and are tentatively identified as *Pennatula*, either *P. borealis* or *P. aculeata*, and a tall orange form as *Pavonaria finmarchica*. Anemones showed the same range of density and were variably more or less numerous than the sea pens. Several species were present (large white forms and small white and pink forms) with diameters between 5 and 20 cm. Some appeared to be attached to rare pebbles and most were poorly anchored to the substrate and were easily bowled over by the pressure wave of the PISCES advance. Unlike the sea pens, which are occasionally sampled using Van Veen grabs (OUELLET, 1982), the anemones are unknown from grab samples and have not been even tentatively identified.

Evidence of abundant infauna took the form of polychaete tubes and holes in patches of several hun-

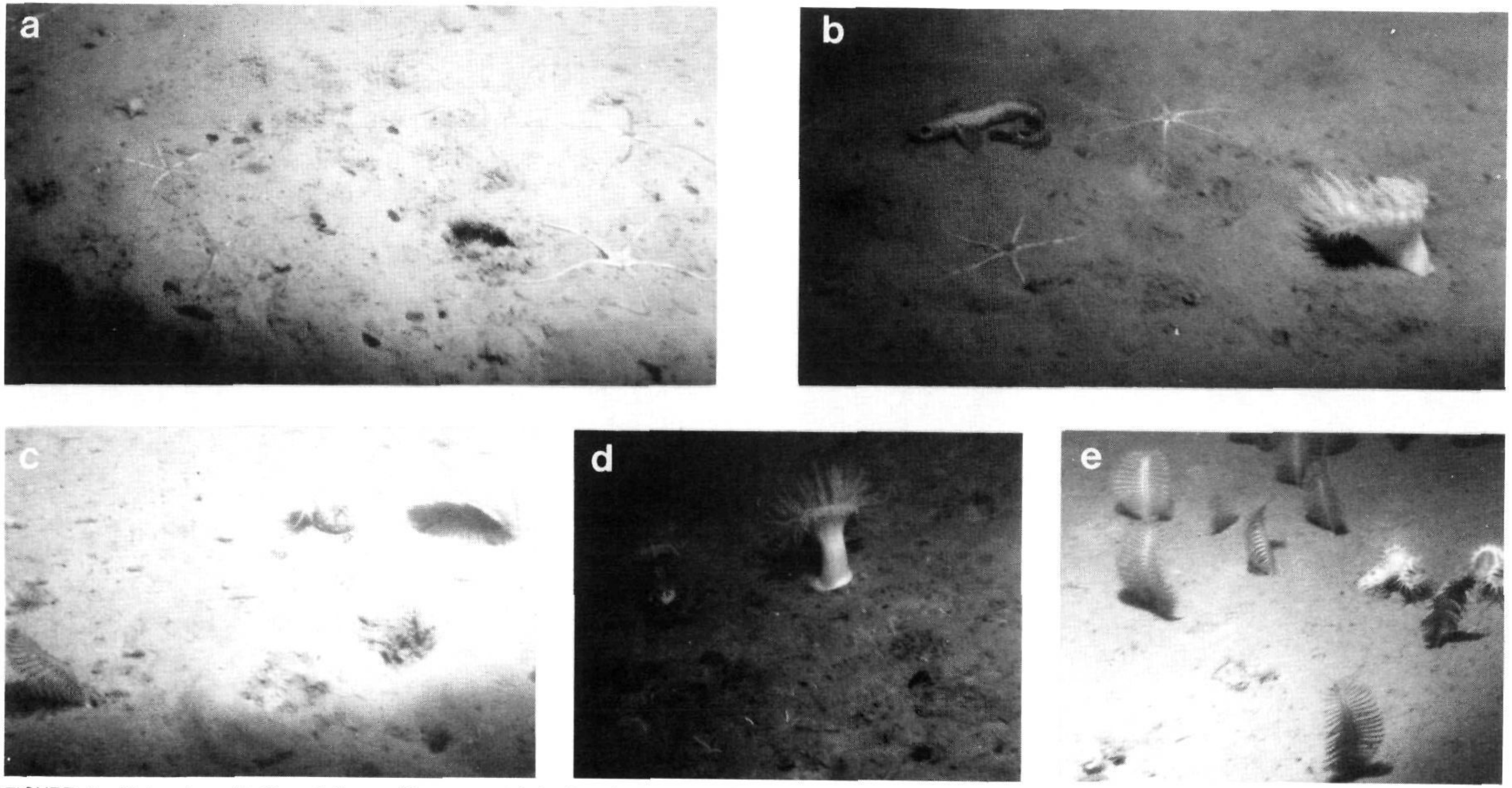


FIGURE 3. Flat and muddy Trough floor: a) bottom mottled with polychaetes and brittle stars; near circular shadows are from *Oikopleura* houses in transport (photo width scale (*pws*) ~ 1 m); b) eelpout and anemone on feces-laden sediment (*pws* ~ 1 m); c) large burrow openings surrounded by excavation rims (*pws* ~ 0.4 m); d) tiny protruding extremities of brittle star arms (*pws* ~ 0.5 m); and e) typical bottom of sea pens and anemones (*pws* ~ 0.6 m).

*Fond plat et vaseux du Chenal: a) fond tacheté avec des polychètes et des ophiures; les ombres presque circulaires sont celles des logettes d'*Oikopleura *en mouvement (la photo représente une largeur réelle* (plr) *~ 1 m); b) lycode et anémone sur fond couvert de fèces* (plr *~ 1 m); c) larges ouvertures de tunnels entourées des rejets d'excavation* (plr *~ 0,4 m); d) extrémités saillantes des bras d'ophiures* (plr *~ 0,5 m); e) fond typique de plumes de mer et d'anémones* (plr *~ 0,6 m).*

dreds per m^2, and ophiuroids partly buried and surface dwelling (fig. 3a, d). In the eastern portion of the Estuary, the brittle stars (*Amphiura* sp. recovered in a test grab sample) were mostly buried in the sediment, so that only the uplifted extremities of the arms were visible. During the more westerly dives, we observed a larger form of ophiuroid (*Ophiura* sp., 8-10 cm in diameter, having both white and black colorations). These were totally exposed at the sediment surface in concentrations up to 10 $\cdot$ m^{-2}. Also observed were patches of sabellid polychaetes (3-4 $\cdot$ m^{-2}), white sponge mounds (0.2 $\cdot$ m^{-2}) and the occasional holothurian. Among the highly mobile benthos population, we noted a large (20 cm) red coloured prawn, pandalid shrimp, and several different kinds of fish: eelpouts (*Lycodes* sp.), the Atlantic soft pout *Melanostigma atlanticum*, skates, flatfishes, and large eel-shaped fishes.

Local relief consists of gentle saucer-shaped depressions, 4 to 10 cm deep, and microrelief of $\approx$ 1 to 3 cm, most often associated with groups of polychaete tubes or shallow pits around large exposed tubes. Currents along the bottom, estimated by observing the drift of particles when PISCES was stationary, were weak to moderate (up to 12 cm $\cdot$ sec^{-1}). This was enough to maintain a steady drift of debris along the bottom and the bending of sea pens. It was not enough to cause direct resuspension of the bottom sediment, however, and no current-derived sedimentary structures were noticed. Biological resuspension was observed frequently as discrete events, such as the swirls created by suddenly moving prawns, sediment poking by fish, and ejections from worm tubes and mud volcanoes. This material often stayed in suspension long enough to disappear from view. The visibility from PISCES varied between 3 to 5 m. Sediment reworking was also noted as coils and small piles of fecal material and radiating streamers of reduced grey sediment around worm tubes, extending over the pale-brown surface of oxidized sediment. The grey sediment was also exposed in some of the fist-sized holes.

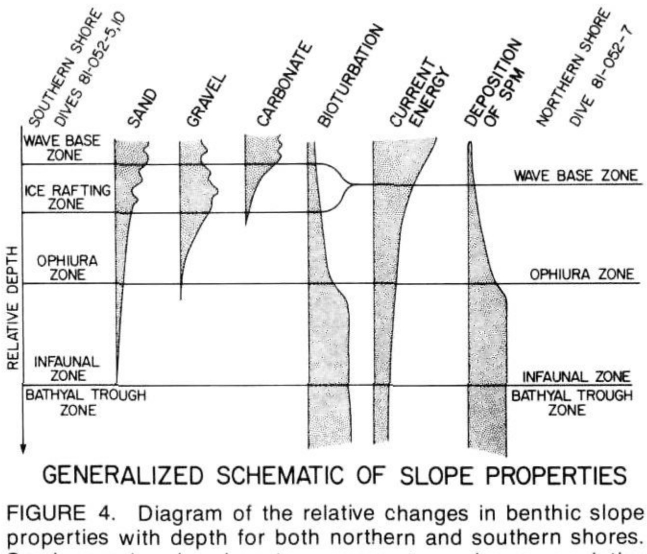
Specific tests were performed using the mechanical arm on PISCES to examine the erodibility of sea floor sediment. In one test, long grooves about 5 cm deep were cut into the surface, revealing the grey sediment less than 1 cm below the surface. This produced a cloud of very fine particles, like smoke, which persisted in the groove for several minutes after the cloud above the sediment had dispersed. The walls crumbled very slowly under their own weight, with pieces falling gently into the groove. Another test consisted of aspirating surface sediment through a tube (normally used for water sampling) fitted to the arm and positioned about 5 cm from the sediment surface. Particles were slowly sucked into the orifice from a distance of several centimeters but no large quantity of sediment was moved and no depression formed under the tube. These tests show that the sediment-water interface is quite definite in the Laurentian Trough. There is no sign of a "fluff" layer, such as the organic-rich sapropel of lake beds, and considerable energy must be expended to resuspend the surface layer. This is another indication of the importance of biological initiation of sediment redistribution.

SIDE WALL SLOPES

Three slope dives were undertaken at stations 5, 7 and 10 (fig. 1). The sand content on the sea floor, current energy and therefore horizontal flux of SPM increased with decreasing depth. In contrast, the level of bioturbation and deposition of SPM decreased up slope. We used the relative changes in these parameters, in conjunction with dominant benthos, to tentatively identify four benthic slope zones in ascending order above the Bathyal Trough Zone. They are 1) Infaunal Zone, 2) *Ophiura* Zone, 3) Ice Rafting Zone and 4) Wave Base Zone (fig. 4). The northern slope dive (7) showed a deeper lower limit to its Wave Base Zone, a shallower upper limit to its *Ophiura* Zone, and no Ice Rafting Zone. Drifting winter ice flows dominantly along the south shore (EL-SABH, 1979), and appears to explain the increase in ice rafted debris found along the southern shore.

1. *DIVE 81-052-5 (49°00'N, 67°09'W)*

The dive traversed from 140 m to 25 m on the south shore near Les Méchins. The Infaunal Zone (> 140 m to 100 m) is characterized by high bioturbation with a surface micro-relief of 4 to 8 cm in muddy sediment: mud



GENERALIZED SCHEMATIC OF SLOPE PROPERTIES

FIGURE 4. Diagram of the relative changes in benthic slope properties with depth for both northern and southern shores. Sand, gravel and carbonate component are drawn as relative percent. Level of bioturbation was deduced from type and density of proxy indicators of infauna. Current energy is given as a proxy indicator of current and shear velocity. Details on the variability in the zonal depth limits are discussed in the text.

Variations des propriétés benthiques des pentes selon la profondeur, pour la côte nord et la côte sud. Les proportions de sable, gravier et carbonate sont en pourcentage. Le degré de bioturbation a été estimé à partir du type et de la densité des indicateurs apparents d'endofaune. L'énergie du courant est donnée comme indice des vélocités du courant et du cisaillement. Les détails sur la variabilité des limites de profondeur des différentes zones apparaissent dans le texte.

volcanoes and agglutinated polychaete tubes (Sabellidae?) protruded from the sea floor to give the impression of tidal flat surface morphology (*e.g.* SWINBANKS and MURRAY, 1981). Surface faunal densities were low and included the eelpout (*Lycodes* sp.), wolf eel, crabs (*Hyas* sp.), flatfishes and pandalid shrimps (fig. 5a). One notable exception was a large fish carcass being devoured by some twenty crabs (fig. 5c).

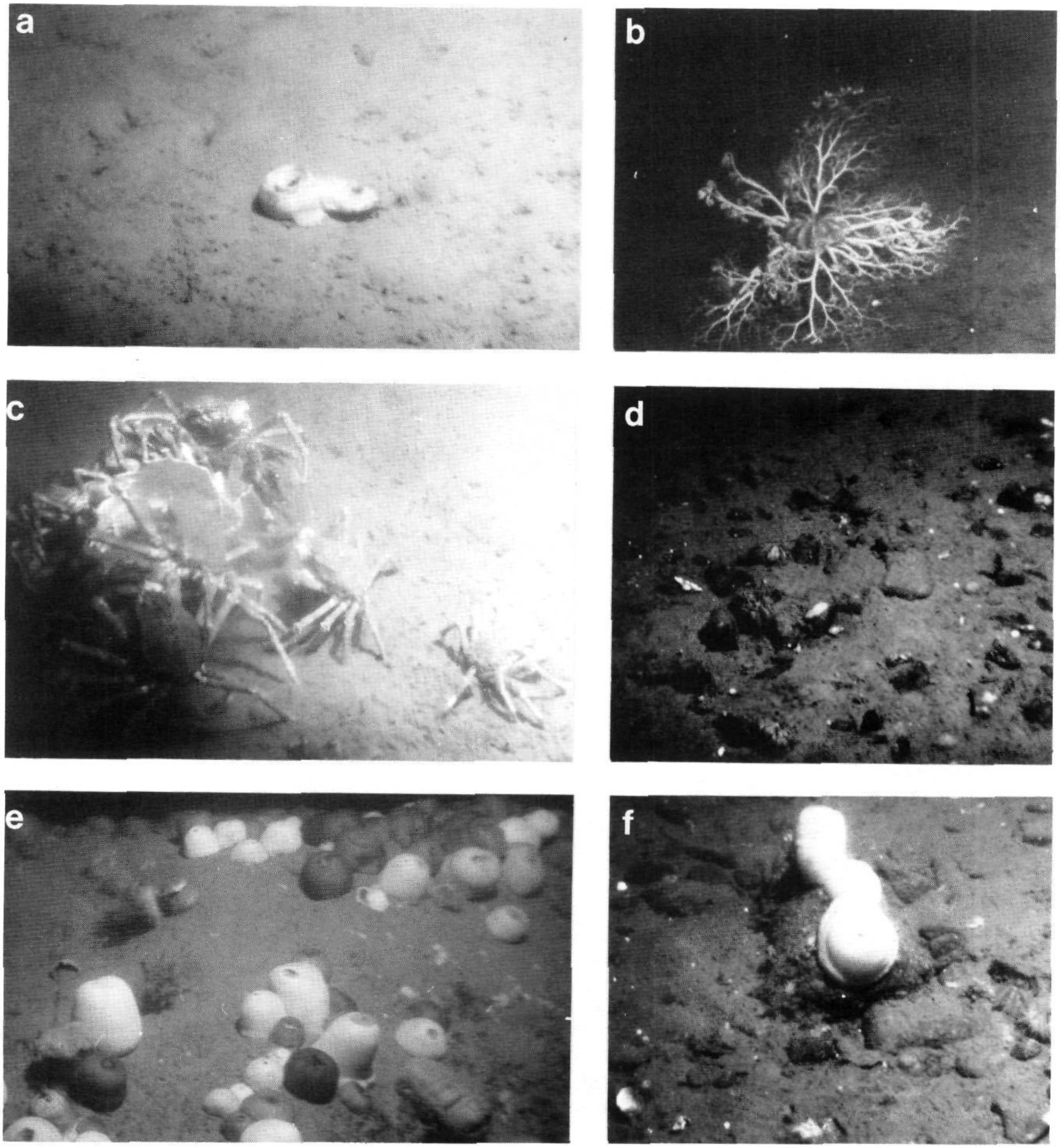


FIGURE 5. Seafloor character of southern trough-wall slope: a) *Lycodes* resting on polychaete-laden mud of the Infaunal Zone (*pws* ~ 0.6 m); b) *Gorgonocephalus* in motion over sandy sediment (*pws* ~ 0.6 m); c) large fish carcass attracting crabs (*pws* ~ 1.2 m); d) ice-rafted gravel in the process of being covered by deposition of suspended matter (*pws* ~ 0.9 m); e) and f) large boulders covered with closed anemones, urchins and holothuroid [(e) *pws* ~ 1 m and (f) *pws* ~ 0.6 m].

Caractéristiques de la pente sud du Chenal: a) Lycodes *sur vase couverte de polychètes de la zone endobenthique (*plr ~ *0,6 m); b)* Gorgonocephalus *en mouvement sur sédiment sableux (*plr ~ *0,6 m); c) crabes attirés par une grosse carcasse de poisson (*plr ~ *1,2 m); d) dépôts de glaces flottantes sur le point d'être recouverts par un matériel plus fin (plr ~ 0,9 m) e) et f) gros galets couverts d'anémones fermées, oursins et holothurie [e)* plr ~ *1 m et f)* plr ~ *0,6 m*].

The *Ophiura* Zone (100 m to 50 m) had the maximum number ($20 \cdot m^{-2}$) of brittle stars at 74 m: other benthos included crabs (*Hyas* sp.), Ascidiacea (*Boltenia ovifera*), polychaetes, and the common sea urchins (*Strongylocentrotus* sp.). The urchins became obvious at 83 m and abundant at 70 m. The zone is characterized by coarser lag-deposit sediment (sandier with shell debris and fecal matter left behind on the surface by local currents) and increasing gravel component with decreasing depth (fig. 5d). The gravel is poorly sorted with nominal diameters ranging from 3 cm to > 100 cm and was in part covered with sediment. Observed currents averaged 25 to 30 $cm \cdot s^{-1}$ downstream, yet bedload motion was not observed during the dive: evidence of stronger currents were given by: a) tops of mud volcanoes eroded away in the lower depths, and b) scour pits on the upstream side of many boulders, with deposition of a sand tail on the downstream side (fig. 6a). The dominance of the residual downstream current is indicated by the bending direction of *B. ovifera* (fig. 6b).

In the Ice Rafting Zone (50 m to 30 m) gravel dominates the sea bed surface. Although it is difficult to separate gravel exposed through erosion by currents from gravel of an ice-rafted origin, the gravel is thought to be mostly derived from ice-rafting since: 1) some large boulders are without epilithic growth and thought to be of recent origin (erosion of a meter of sediment is hard to explain in so short a time period); and 2) smaller gravel particles are occasionally found on top of larger boulders (again suggesting a recent addition). Occasional large boulders provide substrate for abundant anemones, most of which were closed (fig. 5e, f). Other epifauna included urchins, holothuroids, crabs, five-armed starfishes and sponges.

In water less than 30 m, we observed evidence for a Wave Base Zone (30 m to < 25 m) characterized by contour parallel ridges of shell and pebble lag consisting of scallop, razor and horse mussel shells, separated by silty sand intermixed with pebbles. The alternating shell layers may indicate wave erosion of successive storms. A maximum storm wavelength of 60 m may be derived if we assume that the effective depth of erosion by storm waves (given here as 30 m) is one-half the wavelength. Epifauna life is scarce and dominated by urchins and crabs.

2. DIVE 81-052-10 (49°34.2′N, 68°40′W)

This dive, off Rimouski, began at a bottom depth of 250 m. The side-wall slope environment is considered to begin landward of 235 m, the depth where *Pennatula* sp. disappeared and the angle of slope greatly increased. The Infaunal Zone (235 m to 130 m) is intensely bioturbated with the sea floor being highly pock-marked in muddy sediments: many 2 cm openings among 15 cm diameter depressions. The larger depressions, that may reach up to 70 cm (fig. 6d), give indication that their origin may not be biogenic but possibly related to the escape of methane: the walls are vertical with no excavation lip. Many of these 'pockmark' openings afford shelter for crabs and eelpouts. Polychaetes which dominate the zone have tubes protruding 5 to 15 cm into the water: densities reach 200 to $300 \cdot m^{-2}$. Polychaete fecal coils coat the sea floor. Other mobile fauna include the pandalid shrimps and sediment-burrowing eelpouts (*Lycodes* sp.). In addition, skates and crabs and one scavenger shark contributed to a significant resuspension of the sediment, resulting in a two fold increase in bottom SPM (fig. 7). Ophiuroids were present in low numbers (0.5 to $2 \cdot m^{-2}$) throughout this zone; anemones were rare.

The *Ophiura* Zone (130 m to 90 m) is characterized by an abundance of brittle stars (up to $40 \cdot m^{-2}$) over a low micro-relief (< 2 cm) sea floor. The ophiuroids were found both buried in the siltier sediment as well as on the surface. *Strongylocentrotus* also reached maximum densities (2 to $5 \cdot m^{-2}$) and were found coated with captured debris such as the sediment-laden *Oikopleura* houses that roll along the bottom in a steady flux. Polychaete tube density was highly variable (0 to $50 \cdot m^{-2}$); many had lost the agglutinated sediment, possibly due to current winnowing, leaving only a mucous coating. Anemones, though rare, were occasionally found in patches. The zone ends at about 90 m depth with black ophiuroids more abundant than the whitish ophiuroids.

In the Ice Rafting Zone (90 m to < 60 m), the matrix sediment changed from silt to sand with shell debris: the gravel component increased with decreasing depth. Basket stars (*Gorgonocephalus* sp.) are abundant throughout the zone (fig. 5b), but some are in transit. Infauna was not visually evident except for rare polychaetes. Ophiuroids were present with minor sightings of anemones, sponges and gastropods. Scour pits on the upstream side of boulders with corresponding deposit of sand on the lee, as well as eroded exposures of bedrock indicate the high current regime of the zone. The dive was aborted during a resuspension event (fig. 7) when the bottom currents averaged 100 $cm \cdot s^{-1}$ and the visibility became very poor.

3. DIVE 81-052-7 (49°19′N, 67°23′W)

This dive, off Pointe-des-Monts, was the only one along the northern slope. The depth ranged from 205 m to 25 m: the submersible experienced currents up to 150 $cm \cdot s^{-1}$. Two distinct zones were found, based on the presence or absence of ripples and *Ophiura*.

The *Ophiura* Zone (205 — 60 m) is characterized by brittle stars (maximum density at 190 m: 30 to $40 \cdot m^{-2}$), rippled sediment, or both. Grain size decreased with depth from medium sand to silty sand. The largest ripples occurred at 200 m and were linguiform megaripples (λ = 150 cm and h = 35 cm), but straight crested current ripples were more usual (λ = 20 cm, h = 8 cm) (fig. 8a). The ripple crests trended upslope and had current bearings of 90°. Heavy mineral segregation was readily evident between troughs and crests. Bedrock outcroppings

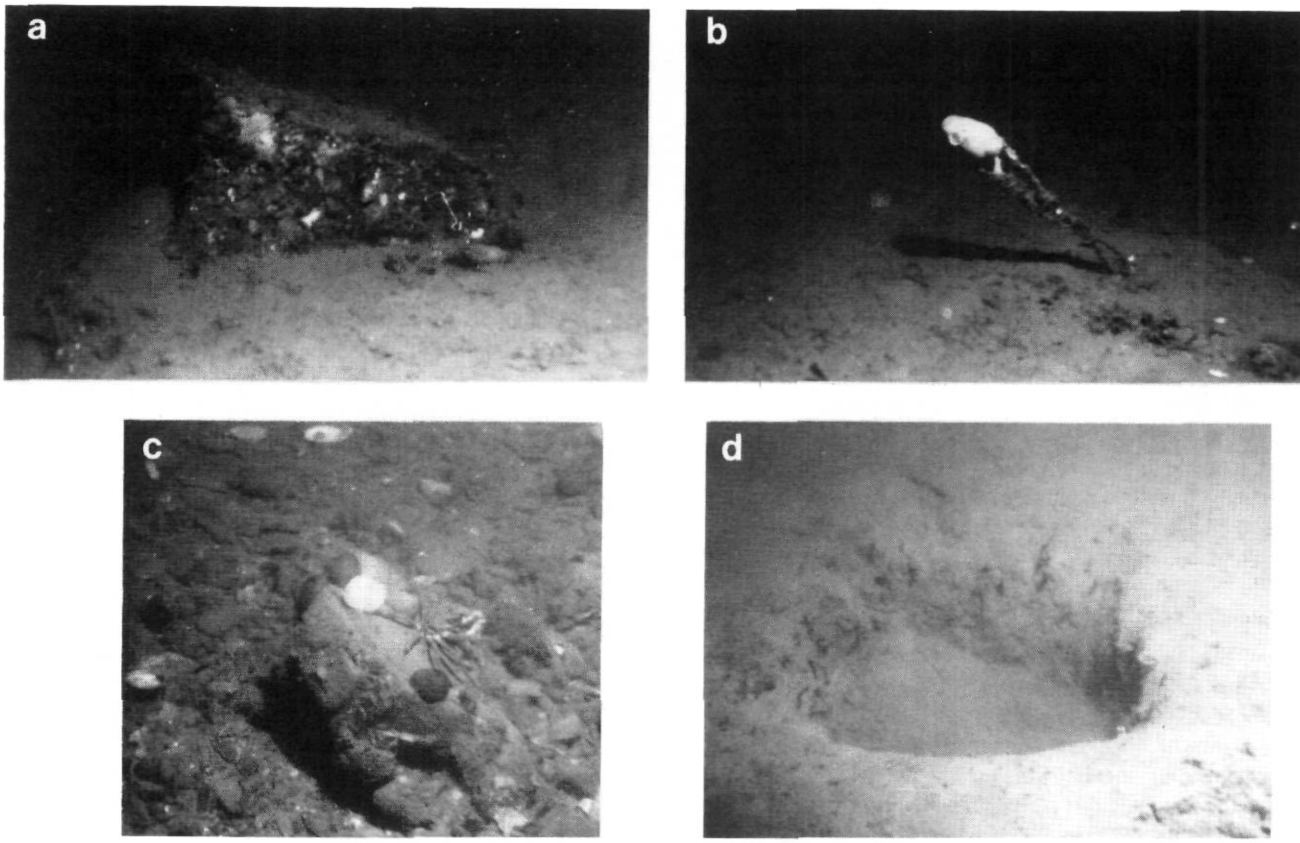
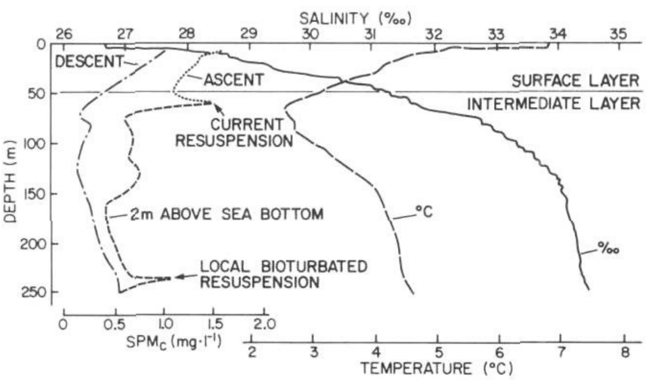


FIGURE 6. Bottom evidence of strong currents (a, b, c) or gas production (d): a) boulder with scour pit and sand shadow (*pws* ~ 1.4 m); b) the ascidian *Boltenia ovifera* bent in direction of residual current (*pws* ~ 1 m); c) gravel lag without surficial sediment covering: note shell debris (*pws* ~ 1 m); d) a large depression that may be related to sediment-generated gas (*pws* ~ 1 m).

*Quelques éléments témoignant des forts courants de fond (a, b, c) ou de la production de gaz (d): a) gros galet avec une cavité due au balayage et une ombre (dépôt) de sable (*plr *~ 1,4 m); b) ascidie* Boltenia ovifera *inclinée dans la direction du courant résiduel (*plr *~ 1 m); c) traînée de graviers sans couverture de sédiments fins: noter les débris coquilliers (*plr *~ 1 m); d) large dépression pouvant être reliée à des gaz formés dans le sédiment (*plr *~ 1 m).*



intermixed with sand patches between 180 m and 90 m. Epibenthic fauna dominated over infauna, with the sandy seafloor having low densities of ophiuroids, sand dollars, crabs, skates, and gastropods. Epilithic fauna had densities between $20 \cdot m^{-2}$ to $200 \cdot m^{-2}$, although densities were generally moderate ($50 \cdot m^{-2}$) (fig. 8c). Anemones were dominant; other epilithic forms included gastropods, holothuroids, bryozoans, serpulids, sponges, starfishes, tunicates (*Boltenia ovifera*) and urchins (*Strongylocentrotus* sp.).

The Wave Base Zone is interpreted as landward of 70 m and is characterized by an upper flat-bed current (MIDDLETON and SOUTHARD, 1978) in coarse sand. The sand was partly overlain by a broken shell lag where the carbonate content on the seafloor may reach 30%. No ripples were observed. Partly buried boulders were

FIGURE 7. Salinity, temperature and concentration of suspended particulate matter (as calculated from transmittance data; see fig. 2) for dive 81-052-10. The descent took place directly through the open water column while the ascent followed the slope of the bottom, with the attenuance meter about 2 m above the bottom. Note the peak in SPM concentrations below 200 m depth (due mostly to biological resuspension) and that near 60 m depth (due to current resuspension).

Salinités, températures et concentrations de matériel particulaire en suspension (calculées à partir des données de transmittance; voir fig. 2) pour la plongée 81-052-10. La descente a eu lieu au large tandis que la remontée a été effectuée le long de la pente du Chenal. Les mesures de transmittance ont été prises à environ 2 m au-dessus du fond. Noter les maximums de concentration du matériel particulaire en suspension (SPM) à plus de 200 m de profondeur (resuspension due aux organismes benthiques) et à environ 60 m de profondeur (resuspension due aux courants).

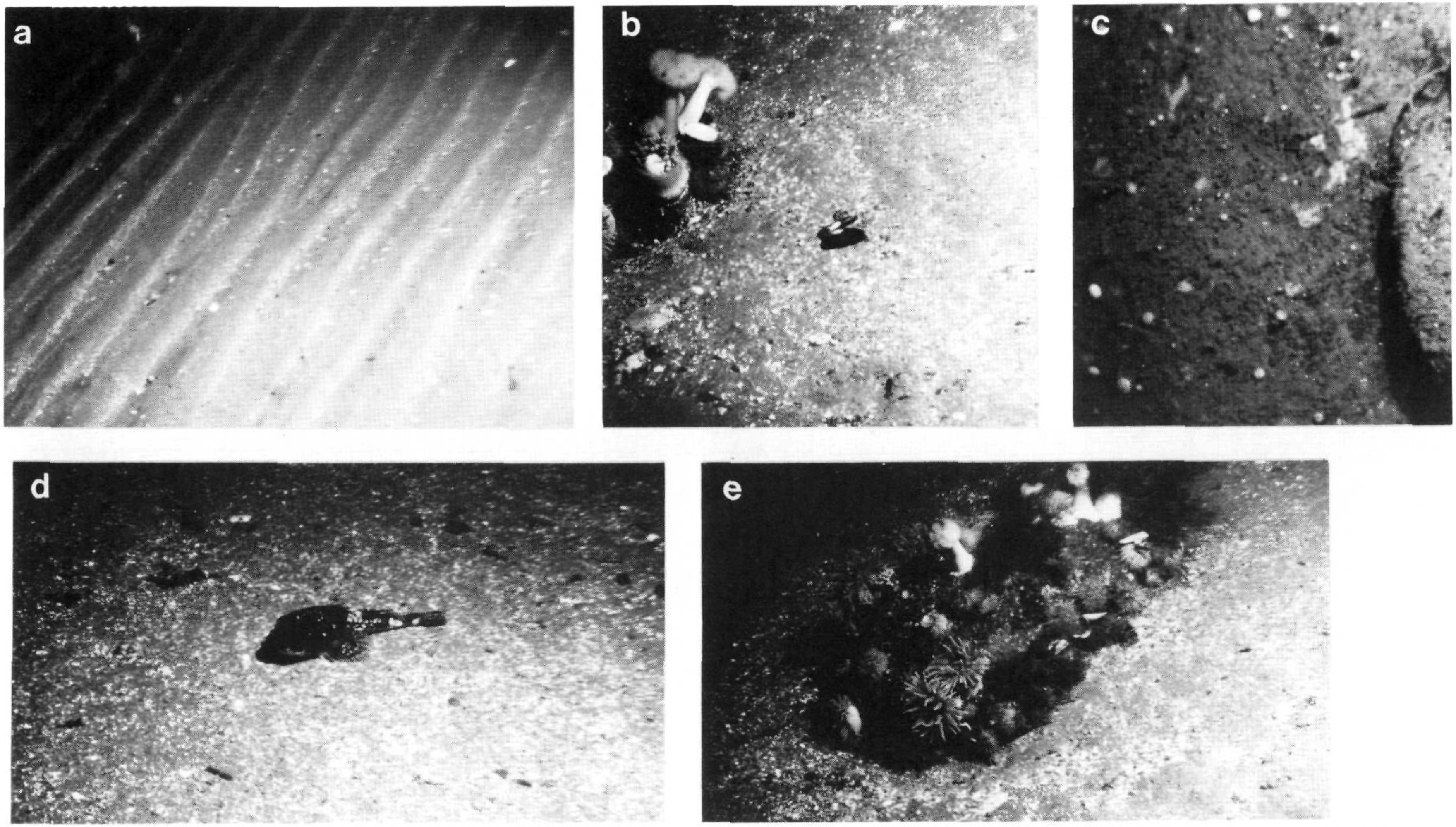


FIGURE 8. Northern trough-wall slope character: a) straight-crested current ripples, depth 200 m (*pws* ~ 1.5 m); b) and e) anemone- and urchin-covered boulders dispersed in flat beds of sandy sediment: boulder in e) is in shallower water (38 m) and is covered by algae (*pws* ~ 1.6 m); c) moderate to low density of epilithic life on cliff overhang (*pws* ~ 1.0 m); d) rare benthic life (sculpin) in sandy Wave Base Zone.

*Caractéristiques de la pente nord du Chenal: a) rides de courant à crête droite; profondeur 200 m (*plr *~ 1,5 m); b) et e) gros galets couverts d'anémones et d'oursins sur des sédiments sableux: le galet en e) est en eau moins profonde (38 m) et est couvert d'algues (*plr *~ 1,6 m); c) densités moyennes à faibles de l'épifaune sur une paroi rocheuse (*plr *~ 1,0 m); d) vie benthique peu abondante dans la zone sous l'influence des vagues (chaboisseau).*

common between 70 m and 50 m, each covered by dense colonies of anemones, urchins, and algal filaments (fig. 8b, e). Contourites of well-sorted pebbles first occurred at 40 m : pebbles were covered by encrusting red algae. The pebbles gave the appearance of a submerged beach line, although more probably indicate the depth of erosion due to storm surges. Benthic life was not abundant on the sandy seafloor, with rare sightings of *Gorgonocephalus* sp., sculpins, flatfishes and sand dollars (fig. 8d).

SESTON

The water structure and SPM distribution, at least in terms of the concentration of inorganic and organic matter, was similar to that found in previous studies: differences center on our *in situ* observation of large seston, not amenable to normal ship-board sampling. Seston observation in the upper 30 m was only partly successful due to the interference of surface light penetration. The Surface Layer (upper 50 m) had the following characteristics: a) the upper 10 m were well mixed from recent wind and wave generated turbulence, below that was the sharp halocline and thermocline (figs. 9, 10); b) surface water (1 m) was rich in copepod fecal pellets (up to $35 \cdot \ell^{-1}$) that were composed mostly of inorganic particles; c) SPM levels, 80% inorganic, increased towards the sea surface from 0.3 to 1.0 $mg \cdot \ell^{-1}$ (figs. 7, 9); and d) below the wave base but near the surface ($\approx$ 20 m) was a dense accumulation of *Oikopleura* houses (B. Hargrave, personal communication, 1981) with concentrations of 15 to $20 \cdot \ell^{-1}$ (fig. 11a) occurring within a few meters in depth. The *Oikopleura* layer is considered to be the source of globular flocs seen below in the deeper parts of the water column. The layer may also represent accumulations on a density surface in the water column. According to BARNES (1974, p. 821), the house of *Oikopleura* is continually shed and replaced every three hours.

The Intermediate Layer is of variable thickness (usually 50 m to 250 m) between the Surface and Bottom Mixed Layers. The layer contains the temperature minimum at 65 to 100 m, below which temperature and salinity increase (fig. 9). Superimposed on this is a "fine structure" characterized by step-ladder-like CTD profiles (fig. 10): steep pycnoclines, $\Delta\sigma_T = 0.18 \cdot m^{-1}$, overlying thicker mixed water layers ($\Delta\sigma_T = 0.001 \cdot m^{-1}$). These steep pycnoclines (and thermoclines) were visually marked by a zone of thermal distortion possibly due to internal shear, the origin of which is still under investigation (C. Tang, A. Hay, personal communication, 1982). Between 175 m and 250 m where the fine structure is no longer detected by CTD or visually, the pycnocline is very gradual with $\Delta\sigma_T = 0.005 \cdot m^{-1}$.

The Intermediate Layer was found to have SPM levels of 0.3 to 0.5 $mg \cdot \ell^{-1}$ of which 50% was combustible. *Oikopleura* houses (2 to 4 cm in diameter) covered by sediment reached maximum densities in the temperature minimum zone (2 to $3 \cdot \ell^{-1}$) (fig. 11b). Sediment on the globular flocs dislodged into smaller particles on contact with the extended submersible arm. The water column also contained marine snow (large organic-rich agglomerates), 0.5 to 1 cm in diameter, and evenly distributed through much of this layer. The water was clear of visible particles between the globular flocs and

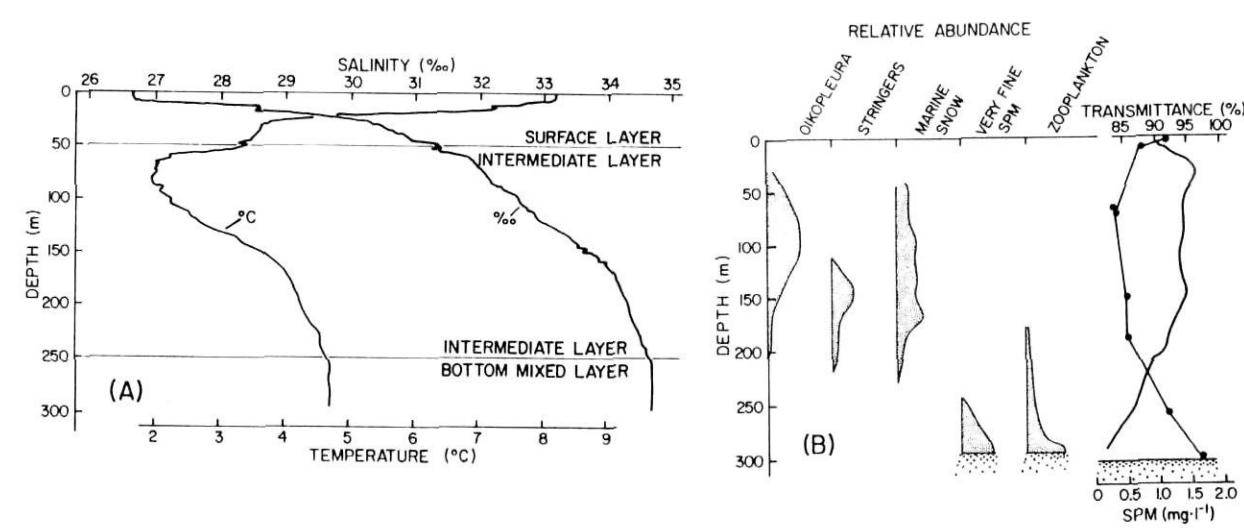


FIGURE 9. A) Typical STD profile of the lower St. Lawrence Estuary with the three water layers (see text for description). B) Summary of seston observations during dive 81-052-11. The SPM curve (dots) shows the positions of submersible-collected water samples and follows an inverse relation with the transmittance curve.

A) Profil typique de STD dans l'estuaire maritime du Saint-Laurent pour les trois couches d'eau (description dans le texte). B) Sommaire des observations du seston faites au cours de la plongée 81-052-11. La courbe des concentrations du matériel particulaire en suspension (SPM) montre les endroits (points) où les échantillons d'eau ont été recueillis avec le submersible. Cette courbe est inversement proportionnelle à la courbe de transmittance.

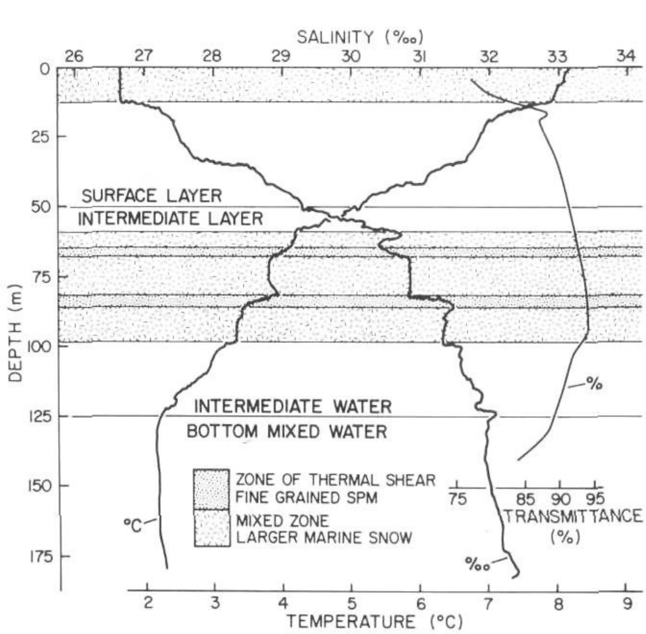


FIGURE 10. Fine structure in the Intermediate Layer. Indicated are some mixed zones with large marine snow, and thermal shear zones containing only fine-grained SPM. The attenuance meter did not record these observable changes.

Structure fine dans la couche intermédiaire. Les zones mélangées contiennent de grosses particules marines, tandis que les zones de cisaillement thermique ne renferment que du matériel fin. Ces changements visibles n'apparaissent pas sur les données de transmittance.

marine snow. The visual impression, particularly when submersible motion was slight, was that the SPM was organized in what appeared as a uniform lattice structure. Although some variation in particle concentration (layering) was visually evident, the attenuance meter noticed none (figs. 7, 10); this may be a function of the meter's short path length (30 cm). The fine structure produced noticeable change in the observed SPM, but this again was not detected by the attenuance meter (fig. 10). In the zones of steep pycnoclines (those with thermal shear), the larger particles of marine snow were reduced in size, producing an increase in fine flocculent

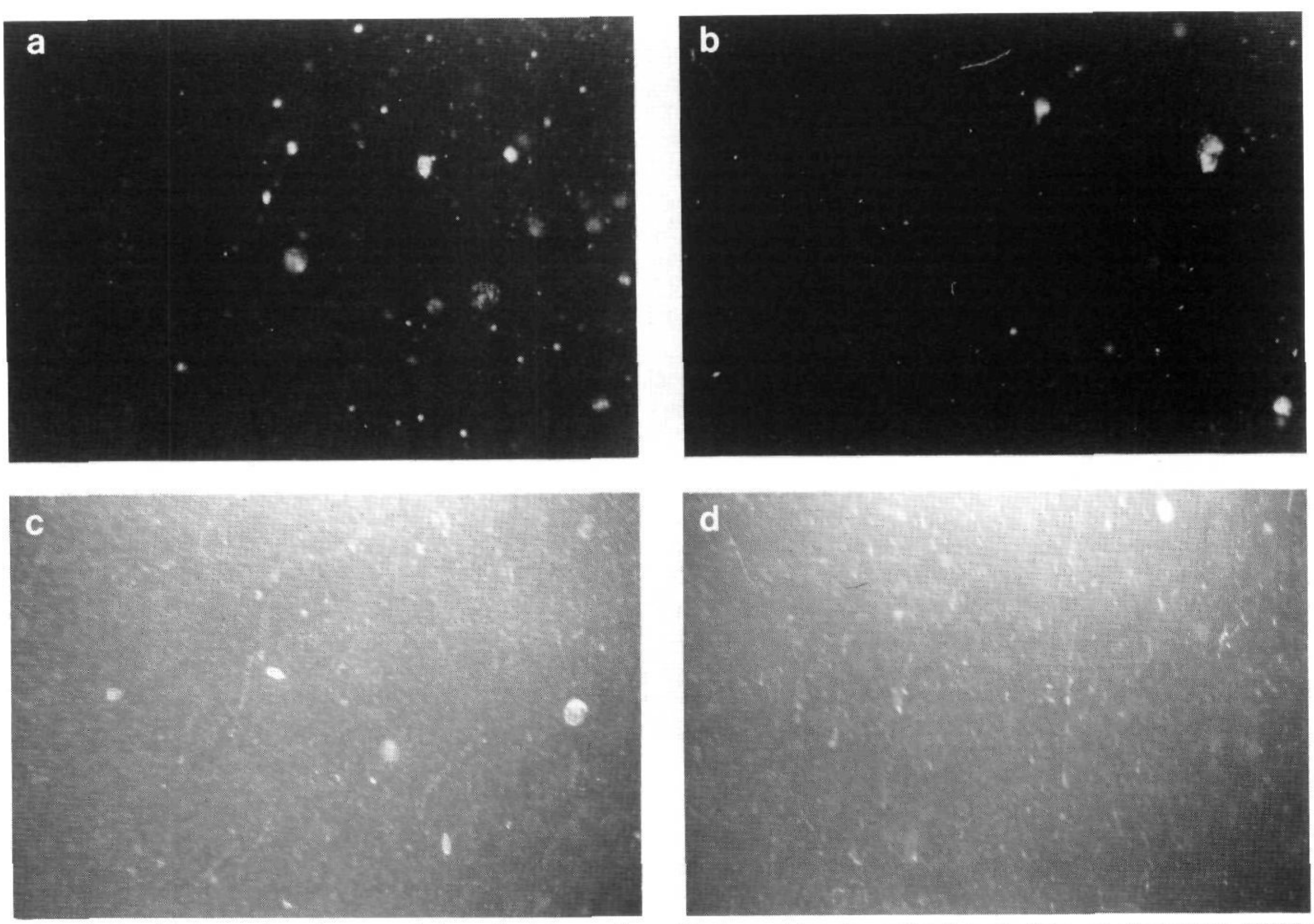


FIGURE 11. Photographs of suspended particulate matter (SPM): a) dense accumulation of *Oikopleura* houses in Surface Layer; b) decreased SPM content in Intermediate Layer temperature minimum: note smaller particles of marine snow; c) and d) were taken below the influence of fine structure and above the Bottom Mixed Layer: note the long stringers with attached particles of snow. (Photo width scale is approximately 1.7 m.)

*Photographies du matériel particulaire en suspension (SPM): a) accumulation dense de logettes d'*Oikopleura *dans la couche de surface; b) contenu plus faible de matériel particulaire en suspension dans la zone de température minimale de la couche intermédiaire: la taille des particules est plus petite; c) et d) photographies prises au-dessus de la couche de fond: remarquer les longs filaments de particules (plr ~ 1,7 m).*

material, yet retaining a constant concentration. Similarly, the *Oikopleura* houses were often cleaned of their SPM coatings in these zones.

The lower part of the Intermediate Layer, below the zone of "fine structure", contained stringers, *i.e.* long chains of marine snow joined together by an extremely delicate filament (fig. 11c, d). Some were forked on the bottom, all were vertical (weighted more on one end by higher concentrations of particles). The strings were 2 to 8 cm long and varied in abundance from scattered to dense at different sites. Extremely long stringers (1 to 3 m) made up mostly of a thick filament joining a few large clumps of particles were rare but spectacular. Observations of marine stringers was first discussed by SYVITSKI and MURRAY (1981) and FARROW *et al.* (1982). They are found throughout the deeper parts of the water column of British Columbian fjords where currents are small, turbulence negligible (SYVITSKI and MacDONALD, 1982). The filaments are thought to be composed of bacteria: when all internal and external lights were turned off, the stringers displayed bioluminescence when breaking on contact with the extended submersible arm. This was also true of sediment-covered *Oikopleura* houses that burst clean and displayed bioluminescence, again suggesting that bacterial decomposition of the house surface was underway. The stringers reached maximum abundance between 120 m and 200 m. Deeper in the water the stringer size decreased, suggesting an increase in the intensity of turbulent shearing, until they became absent in the Bottom Mixed Layer. Before complete disappearance of the stringers, there was a marked zone of poorly sorted SPM (in terms of size) above the Bottom Mixed Layer, with the number of finer particles increasing as the larger marine snow, globular flocs and stringers broke up.

The Bottom Mixed Layer with $\Delta\sigma_T \approx 0$ was 50 m thick above the sea-floor. As documented in Figure 7, the SPM concentration of near-bottom waters on the Trough walls was always higher (by at least 0.2 to 0.3 $mg \cdot \ell^{-1}$) when compared to open water values at the same depth. The Bottom Mixed Layer of the central channel was well defined from 250 m to 300 m. There the SPM concentrations reached a water column maximum and ranged from 1.0 $mg \cdot \ell^{-1}$ near the 250 m level to 1.7 $mg \cdot \ell^{-1}$ near the sea-floor. The SPM appeared very fine-grained and milky (hazy), with relatively few large grains.

Figure 9B provides a synopsis of SPM observations throughout the water column as seen during dive 81-052-11. Zooplankton abundance increases with depth below 150 m and concentrates in the Bottom Mixed Layer. With the submersible almost dead in the water, copepods appeared to be selectively feeding: they swam rapidly towards individual large suspended particles, then dashed off towards another. This stop-start motion is normal for copepods (BARNES, 1974; p. 534) but has not been associated with purposeful feeding on large particles. In the Bottom Mixed Layer, zooplankton (copepods, euphausiids, ctenophores) activity and concentration increased significantly.

Size analyses (component particles after disaggregation) of the SPM collected from the submersible reveal little difference in the mean size of particles ($\Delta\bar{x} = 2.5\ \mu m$) through the water column, regardless of differences in their concentration (fig. 12). The shape of the size frequency distribution at any given station also remains the same regardless of depth. The size frequency distribution of SPM from water collected during dive 81-052-11 had three distinct modes, while that collected during dive 81-052-8 had only one mode. The large aggregates, stringers and *Oikopleura* houses are probably responsible for the rapid transfer of particles from the surface to the deeper layers and the sea floor. Although resuspension does supply particles to the bottom waters, the constancy of the component particle size distributions does not appear to be altered.

CONCLUSIONS

The Bathyal Trough Zone has little microrelief ($\approx$ 1 to 3 cm) yet can be highly bioturbated with burrow openings and other infaunal activity. The faunal assemblage consists of scattered anemones and sea pens as well as the more mobile brittle stars, shrimps, eelpouts, skates, flatfishes and large eel-shaped fishes; polychaetes are ubiquitous and abundant. The sediment-water interface is sharp with no flocculent layer. Resuspension appears related mainly to biological activity; the bottom current ($<$15 $cm \cdot s^{-1}$) appears to maintain the material in suspension only for some time or distance.

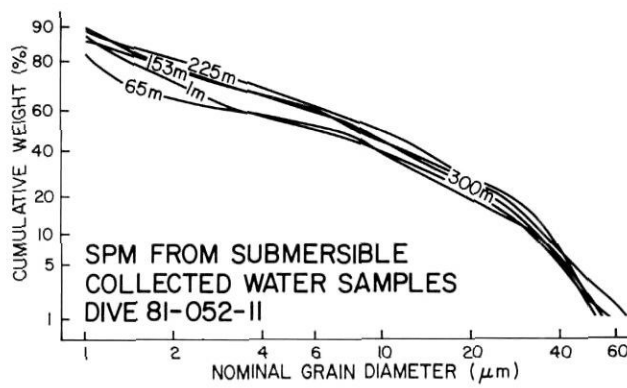


FIGURE 12. Cumulative size frequency distributions of suspended particulate matter (SPM) from samples collected at five depth levels (as given on fig. 9). The curves indicate that the disaggregated size spectrum does not change much with collection depth.
Courbes cumulatives des fréquences de taille du matériel particulaire en suspension (SPM). Les échantillons ont été recueillis à cinq niveaux de profondeur tel qu'indiqué sur la figure 9. Les courbes montrent que le spectre de la taille des particules désagrégées varie peu selon la profondeur.

Above the Bathyal Through Zone, the side wall slopes have four semi-distinct benthic zones, each with variation depending on estuarine position. The transition from Bathyal Through to Infaunal Zone has sea pens disappearing, anemones only as epilithics, crabs becoming important, micro-relief increasing (to 4-8 cm), and grain size increasing concomitant with current energy (*i.e.* effective shear velocity). Next, the *Ophiura* Zone has brittle stars and urchins reaching their maximum abundance. Current energy is high (25-30 $cm \cdot s^{-1}$) with surficial sand content increasing. Vertical flux of SPM is low (little sediment covering the spotty ice-rafted gravel), and there is good evidence of bedload transport (*i.e.* rippled sand, scoured boulders). Resuspension by currents is now much more important than biological activity.

The Ice Rafting Zone is only evident on the southern shore where ice floes are concentrated (as documented from sequential air photos). The gravel component dominates the sea bed, with coverings of anemones, urchins, holothuroids, starfishes and sponges. On the sandier and flatter sea floor areas in this zone, basket stars and crabs are dominant. A carbonate shell lag is scattered among the gravel.

The Wave Base Zone has little benthos with rare occurrences of sculpins, sand dollars and flatfishes. Flat sandy areas alternate with contourites of pebble and shell lags indicating maximum depth of erosion by waves.

Rapid sedimentation occurs between Surface Layer SPM and the underlying water and seafloor: the Surface Layer (< 50 m) is an apparent source of fecal pellets, organic matter aggregated with mineral matter, and globular flocs (see section on seston). The upper reaches (50-175 m) of the Intermediate Layer has a fine structure characterized by steep pycnoclines overlying thicker homogeneous layers. Shearing in the pycnoclinal zones apparently decreases the floc size, and produces fine-grained SPM. Globular flocs and marine snow are evenly distributed: copepods were observed hopping from aggregate to aggregate. In the lower reaches of the Intermediate Layer, stringers of sediment connected by filaments are found. These suggest less turbulent water conditions at this depth (175-250 m). The Bottom Mixed Layer is a zone of increased turbulence: floc size decreases, stringers disappear, and the water becomes hazy with fine particles.

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