Interplay of Physical and Biological Sedimentary Structures of the Bering Epicontinental Shelf

by

Hans Nelson
U.S. Geological Survey
Menlo Park, California 94025

Robert W. Rowland
U.S. Geological Survey
Reston, Virginia 22092

Sam W. Stoker
University of Alaska
Fairbanks, Alaska

Bradley R. Larsen
U.S. Geological Survey
Menlo Park, California 9405

ABSTRACT

Distinctive Holocene tran.sgressive sand and post-transgressive mud with ndant physical and biological structures occur on the shallow (<60 m, shelf he northern Bering Sea. Thin gravel lag layers, formal during the Holcene eline transgression, veneer exposed glacial moraines. Epifauna dominate e relict gravel areas and cause little disruption of physical structures. relict submerged beach ridges contain faint rippling that probably is caused odern current reworking. Well-sorted medium sand on exposed shoal crests is rked by the sand dollar and tellinid clan communities. Buried thin layers of sgressive beach sand and gravel retain rare original medium-scale cross-nation and flat lamination that have been intensively bioturbated. A thin r of an offshore fine-grained sand facies that was deposited by the Holocene sgression remains unburied by modern mud in central Chirikov Basin. Primarily use of ampeliscid amphipod bioturbation, this facies has no physical ctures.

Post-transgressive silty mud from the Yukon River blankets the shallow m) areas of Norton Sound. In places the silty mud cent.ins thin beds of ls and pebbles, and thin sand interbeds and lenses that exhibit ripples and l-scale flat and cross-lamination. These coarse-grained interbeds are inter-ed to be storm layers formed by modern storm waves and storm surge currents. ical sedimentary structures are well preserved only near the delta fringe; e? the frequency of physical reworking is highest, the potential for ervation by a high rate of deposition is greatest, and the inhibition of urbation by low salinity is most severe.. At greater ances from shore, infaunal deposit-feeding bivalves, polychaete worms, and l amphipods cause progressively greater disruption of bedforms in prodelta Almost all modern physical structures have been destroyed at water depths :er than 25 m. As a result the following sequence of storm deposits is acteristic of profiles extending away from the delta: thick (>5 cm) storm layers, thin storm sand layers, isolated and bioturbated sand lenses, faint urbated shell and pebble beds.

INTRODUCTION

Purpose

The northern Bering Sea region from St. Lawrence Island to Bering Strait 1) has continually strong bottom currents, an extremely rich benthic fauna, wide variety of sediment substrates. These factors, coupled with shallow ontinental shelf depths that are affected by wave and tidal current activity, ce a wide variety of physical and biological sedimentary structures. Our se is to map the distribution of these structures and to correlate the dis- tion patterns with the controlling physical and biological factors. Such ses provide a model of factors controlling development of physical and bio- al structures on continental shelves in general and assist in specific eenvironmental reconstruction of ancient epicontinental shelf deposits.

Oceanographic Setting

Three water masses have been defined on the northern Bering shelf: Alaskan tal Water, Bering Shelf Water, and Anadyr Water (Fig. 2, Coachman et al.,). Alaskan Coastal Water, generated primarily from the Yukon and Kuskokwim rs and other runoff (Fig. 2; Saur et al., 1954), has pronounced seasonal nity changes. This is particularly true in southern Norton Sound, where t changes in discharge from the Yukon River occur from summer to winter. re June, salinities are close to 30 0/00 throughout southern Norton Sound. ng the summer and early fall salinities below 20 0/00 are common (Fig. 2; man et al., 1941; Sharma et al., 1974).

Typically, current speeds in the offshore part (>30 km from shore) of the kan Coastal Water are 10 cm/s near the bottom and 20 cm/s near the surface, currents trend northward except for the counterclockwise gyre into Norton d (Fig. 3). Nearshore surface and bottom water travels generally northward llel to the Alaskan coast at typical speeds of 30-40 cm/s (Coachman and gard, 1966; Fleming and Heggarty, 1966; Husby, 1969; 1971; McManus and Smyth, 70; Coachman et al., 1976).

The maximum current speeds are found where the Alaskan coast protrudes stward and constricts water flow. At the smallest constriction, Bering Strait, ttom speeds reach 180 cm/s in water depths of 55 m (Fleming and Heggarty, 1966; g.). Currents in the other two water masses are generally slower, reaching a kimum of 50 cm/s in eastern Anadyr Strait and minimums of 5-15 cm/s in central trikov Basin (Fleming and Heggarty, 1966; Husby, 1971; McManus and ners, 1977).

Changes in atmospheric pressure and wind velocity during storms can cause current speed to fluctuate by as much as 100 percent over periods of a day or e (Coachman and Tripp, 1970) and can produce storm surges causing sea level up of 4 m along the southern coast of Seward Peninsula (Fathauer, 1975).

Calculations based on linear wave theory suggest that the waves hindcasted normal wind conditions can affect the bottom to water depths of 20 m (McManus al., 1977). Wave reworking of bottom sediments may extend considerably deeper ing intense storms. For example, the storm of November, 1974 generated waves m high and may have produced water motion capable of affecting the bottom at ths exceeding any found in the northern Bering Sea (A. Sallenger, oral nun., 1977).

Geologic Setting

The entire northern Bering Sea floor is less than 60 m deep and generally :, but. it has distinctive topographic features in several locations (Fig. 1; :ins et al., 1976). The eastern margins of both Bering and Anadyr Straits ex-.t relatively steep scarps. Southeast of Bering Strait and in central Shpan-; Strait, a series of linear ridges and depressions are found. Large linear ls also occur off the northwestern and northeastern flanks of St. Lawrence nd. The shallowest area in northern Bering Sea is off the modern Yukon sub-a in southern Norton Sound.

The northern Bering epicontinental shelf is a mosaic of modern and relict ace sediments. The relict sediments formed in shallow water, at the strand, n subaerial environments at times when sea level was lower than at present ;. 4}. During these times continental glaciers pushed debris toward the center hirikov Basin, and valley glaciers deposited sediment several kilometers nd the present shoreline of Seward Peninsula (Nelson and Hopkins, 1972). eline regressions and transgressions, most recently during the rise of sea l since 18,000 BP, reworked the glacial moraines, leaving a lag gravel on the floor north and west of St. Lawrence Island and along the southern side of rd Peninsula. Transgression of the shoreline across the Bering shelf blan- d the remainder of the Chirikov Basin with a relatively coarse-grained basal r ranging from medium-grained sand to gravel with an overlying thin layer of -sand. Except in central Chirikov Basin, the transgressive deposits are only w tens of centimeters thick and overlie Pleistocene glacial debris, alluvium, freshwater mud and peat dated at 10,500 BP or older (Nelson and Hopkins, 2; Nelson and Creager, 1977).

Holocene sandy silt, mainly originating from the Yukon River (called Yukon hereafter in the paper), has been deposited in Norton Sound. This sediment ns deposits tens of centimeters thick in parts of central Norton Sound and de- its several meters thick off the present subdelta and around the margins of ton Sound (Nelson and Creager, 1977). Currents apparently have inhibited de- ition of Holocene Yukon sand and silt over the older relict transgressive sand gravel found in Chirikov Basin (McManus et al., 1974).

Biological Setting

The continental shelf of the northern Bering Sea is an area of rich macro- thic standing stock (Neyman, 1961, Filatova and Barsanova, 1964; Kuznetzov, 4; Rowland, 1972; Stoker, 1973), though it has a relatively low diversity in ms of major species (Stoker, 1973). While major faunal communities are as yet

letely defined, affinities of species for sediment types have been defined
elled forms (Rowland, 1973) and work is in progress to delineate overall
ation patterns (Stoker, unpub.). The primary benthic ecosystem is based
on a detrital food web (Kuznetzov, 1964), though other feeding types exist
s the sessile seston feeders of the Bering Strait.

A major problem in describing either trophic structure or distribution of
ring Sea benthos is the extreme patchiness of the populations (Stoker,
The reasons for such patchiness are incompletely understood but result
combination of variable habitats and biological interactions (Stoker,
and unpub.).

The major forms in the benthic macrofauna are bivalve mollusks, ophiuroid
hinoid echinoderms, ampeliscid amphipods, and polychaete worms; other
such as tunicates, holothurians, sipunculids, and gastropod, may be
y dominant (Neyman, 1961, Rowland, 1973; Stoker, 1973 and unpub.). Infer-
on the bioturbating capabilities and substrate preference of some taxa can
wn from general accounts of functional morphology (Stanley, 1970), distri-
al studies in other areas (Ockelmann, 1958) and recent Alaskan studies
1).

Methods of Study

ne hundred twenty box cores were obtained from the northern Bering Sea
at water depths greater than 10 m (Fig. 5). The cores were sectioned to
labs, photographed, and x-rayed; the texture, stratigraphy, and structures
hen described (Fig. 5). Identification of fauna was based primarily on
ens from the greater-than-2-mm sediment fraction of 25 kg Van Veen grab
s (Nelson and Hopkins, 1972; Rowland, 1973; Stoker, 1973). Photos of live
observed in box cores at the time of collection also were available. These
ere compiled to estimate distribution and abundance of types of structures
nthic fauna from the region.

PHYSICAL SEDIMENTARY STRUCTURES

External Form

ebble Lag Layers consist predominantly of clasts from 4 to 64 mm in diameter 6A and B) with little matrix, although large boulders have been reported by s in lag areas off Nome (G. E. Greene, oral commun. , 1967). Generally, th e lags occur at the sediment-water interface in layers 5 to 15 cm thick 6A)* However, a well-sorted "pea gravel" interpreted to be on an ancient strandline at -30 m in Anadyr Strait is more than 32 cm thick (Fig. 5B). surficial pebble lags generally overlie glacial till but locally cover b outcrops in topographically elevated regions (Nelson and Hopkins, 1972) 1, 4, 5, 7).

Shell Lag Layers in the subsurface, several centimeters thick, and composed ely of shell debris, were encountered in transgressive sands at several ons off north-central St. Lawrence Island (Fig. 6). They also were found l-sorted, medium-grained sands on shoal crests of Shpanberg Strait and east Bering Strait (Fig. 6D). Clam shells predominate in layers off St. ce Island, while sand dollar fragments make up layers of the shoal crests. region southeast of Bering Strait, basal coarse-grained, pebbly sands com- have a high content of shell fragments, but not enough to be classed as layers.

Lag Layers of Mixed Pebbles and Shells are widespread in the upper sub- e, particularly in the mud of the shallow northern and eastern parts of Sound (Figs. 5, 6G). However, a few such layers occur in subsurface basal sand and gravel at water depths of 40 m or greater in the strait areas 4, 5, 6H, and 7). In both cases, shell and pebble concentrations range istinct layers a few centimeters thick, composed entirely of pebbles and (Fig. 6C), to diffuse zones 5-10 cm thick containing a matrix of sand and Fig. 6H).

Solitary Rafted Pebbles are ubiquitous in all water depths, bathymetric ttings, and sediment types (Figs. 4, 7). They are most common in sediment sur-ınding gravel deposits (Fig. 4), although solitary cobbles up to 20 cm in dia-ter were encountered in Yukon mud far from gravel sources (Fig. 6J).

Storm Sand Layers are most common in silty muds of the shallow parts of ıthern Norton Sound (Figs. 4, 5, 6E, F, G), but a few thin (<1 cm) coarse- and lium-grained sand storm layers are found in fine sand on deeper scarps (>40 m) ıtheast of Bering Strait (Figs. 4, 5, 61, and 7). The sand layers in Norton ›ically are 1-2 cm thick except close to shore where they are thicker igs. 6E-G). In the shallowest sampling sites near the main distributaries of present Yukon subdelta, surface sand layers from 4 to 12 cm thick have been ected in areas where mud was sampled in previous years.

In addition to the changes in distribution areally at the surface, the ındance of sand layers varies with depth in the subsurface. For example, off ıart Island approximately 20 sand layers occur in the uppermost 12 cm of the e, and none are found in the 12 cm of the core beneath (Fig. 6F). In a long 32 cm) core of Yukon sediment from southeastern Norton Sound, four sand layers e found from 0 to 15 cm, two from 15 to 60 cm, and two from 60 to 132 cm.

Internal Structures

Flat Lamination is the most common and widely distributed internal structure all sediment types, water depths, and topographic settings (Figs. 5, 7). It observed most often in sand layers of Norton Sound, where the lamination is ut 1 mm thick and is defined by minor variations in grain size (Fig. 6F and Lamination is least common in gravels, where layers are about 1 cm thick .g. 6B). The best examples of flat lamination are found in pre-Holocene depo-s of limnetic mud (Fig. 8A). Although the whiteness of some laminae suggests canic ash or diatom varves, no glass shards or microfossils were found under microscope.

Cross Lamination like flat lamination, is widely distributed and is best loped in the sand layers of Norton Sound. Characteristically the sets of s-laminae are of small scale and are inclined at low angles (Figs. 4, 6F and Crossbedding in gravel is rare, but when observed is larger in scale and er in dip angle than finer-grained sediment (Figs. 6B and 8A).

Ripples are very common at the tops of sand layers of Norton Sound and in at the margin of Chirikov Basin (Figs. 5 and 7). The ripples are generally metric and small scale (6-8 cm wavelength, 5-1.5 cm wave height) and are rpreted to be current ripples and combined flow ripples commonly found in or silt (Harms and others, 1975) Figs. 6F and G). Where sand layers are c, ripple forms appear to be nearly continuous (Figs. 6F and G), unless bio-ated, in which case the ripples are disrupted, producing sand lenses , 6E).

Miscellaneous Structures

Natural load and slump structures are observed in laminated Pleistocene lake sits in a large depression off St. Lawrence Island (Fig. 8F). Other load- features are present near the tops of some box cores, but they are suspected e coring artifacts (Fig. 6F). Extremely disturbed sediment in a box core the shallow area near the Yukon subdelta is the only apparent example of ctures related to ice gouging (Fig. 8E). A paradox is that new studies show gouging to be ubiquitous at depths less than 20 m over the northern Bering Floor (Thor et al., 1978), but it rarely produces noticeable effects in box s (Fig. 9). Large-scale bedforms such as sand waves have a wide distribution e topography and bathymetry constrict bottom currents (Figs. 1, 3and 9) dan, 1962; Grim and McManus, 1970). Characterization of these large bedforms ice gouge effects must await detailed investigation with sidescan sonar.

BIOTURBATION

General

Once the primary physical structures associated with erosion and deposition 'e developed, secondary processes such as slumping, loading, and bioturbation ;in. In this generally flat epicontinental shelf region, biogenic structures ıally predominate over other secondary structures in the upper 30 cm of the liment.

The size of the area and the patchiness of the benthos (Stoker, 1973) make impossible to map benthic faunal distribution in detail or to correlate all ›es of structures with the organisms. Where single or very limited types of ›turbation characterize certain broad areas of sea floor, complete biologic ıctures can be traced to specific species. In other areas some species, for ample, sand dollars are restricted to certain habitats (Table 1, Figs. 6I, 8C, 9 1 IO) and can be documented to disturb shallow sands (Fig. 13A), but no disnct structures can be identified. Commonly only parts of burrows are observed box cores, and the burrow may not be assignable to a single species (Figs. 13 d 14); this is particularly true for the numerous species of burrowing clams. rtunately, distribution for each major group of bioturbating organisms (surce, shallow, intermediate, and deep) can be outlined by analysis of screened gafauna from grab samples (Rowland, 1973; Stoker, 1973) (Figs. 10, 11).

Surface Disturbers

Several species of small organisms disturb the sediment surface over large eas of the Bering Sea floor (Fig. 10, 12). Brittle stars are one of the domint organisms in eastern Bering Sea (Neyman, 1961), but they are most common in ddy areas closer to land and least common in central Chirikov Basin (in Fig. 10 te the absence of brittle stars at the predominant sandy 30-40 m depth of offore Chirikov Basin). Distinctive surface tracks of brittle stars can be entified on the top surface of box cores, but burrows (Hertweck, 1972) are not ident even where massive populations cover the bottom (Fig. 12).

The carnivorous gastropods occasionally leave surface trails also but may :row to shallow depths after prey; they are widespread, being rare only in the illow region around the Yukon subdelta (see Tachyrhynchus Fig. 10). Crabs and urchins typically are found on gravel substrates and both may excavate slight ressions, however, they are fewer in number than the other surface disturbers g. 10). Crabs are common also in sandy areas except for central Chirikov in.

In response to the benthic food resources, large populations of walrus, rded seal, and gray whale inhabit the northern Bering Sea on at least a sonal basis and are likely to be responsible for considerable reworking of the 11ow sediments over much of the northern Bering shelf. Gray whales are known disturb bottom sediment to a depth of several centimeters to feed mainly on hipods (Tomilin, 1957). The distribution of the large amphipod populations g.11) and the pathways of whale migration (Nasu, 1974) suggest that gray les may cause surface disturbance of the Chirikov Basin area. Walrus and rded seals also may disturb the sediment surface as they feed upon large bi- ves and other infauna (Fay and Stoker, unpub. data).

Shallow Burrowers

The most widespread shallow burrowers (0-5 cm depth) are small, bright- ored amphipods possibly of the genus Protonedeia, Melita, or Hippomedon g. 11). These taxa are most abundant off southeastern St. Lawrence Island and the western and northern areas of Norton Sound, where they inhabit patches of on-derived sediment. One or more of these species probably is the builder of haped burrows about 5 mm in diameter (Fig. 11C, and D). Completely preserved rows are distinctive, but fragments are not separable from burrows made by ychaete worms such as Nephthys (Fig. 13D). In general, we believe most incom- te burrows were constructed by the more abundant amphipods (Figs. 10 and 11).

Several species of shallow burrowing gastropod (Table. 1) with no posily identified burrowing structures are present throughout northern Bering Sea pt off the Yukon delta (Figs. 10 and 13). Tubes of the polychaete Pec- ria also are widespread (Fig. 10) (Stoker, 1973), and these organisms are n to develop shallow burrows (Hertweck, 1972), but no identification can be in Bering Sea sediment . Numerous bivalves, such as Yoldia, Macoma, Nucu- , Tellina, and Nucula (Rowland, 1973; Stoker, 1973) are undoubtedly responsi- for widespread shallow disturbance (Figs. 20 and 1A), but they also have pro- d no distinctive burrows.

Intermediate Burrowers

Intense bioturbation from the sediment surface to 10 cm depth can be defined entral Chirikov Basin and southwest and southeast of St. Lawrence Island. In e areas, abundant populations of large tube-building ampeliscid amphipods in fine-grained sand (Figs. 20, 22B, 14A and B; Table 1). In most other s, except central and southern Norton Sound, l-mm-diameter burrows of small chaete worms are common to abundant. These structures are particularly com- in the silty mud on the northern and eastern margins of Norton Sound s. 11, 6G, 14C and D). Bivalves such as Serripes and Clinodardium are par- larly abundant throughout northern Bering sea region, however, the preponder- of amphipod aburrowing in Chirikov Basin and polychaete burrowing in Norton d appears to obliterate most other physical and biological structures at rmediate depths.

Deep Burrowers

Bivalves such as Mya and Spisula are the most common deep burrowing (0 to cm depth) organisms. Their widespread distribution suggests that many deep ows are caused by pelecypod bioturbation (Figs. 20, 11 and 15; Table 1). rarely (Fig. 8A) is it possible to correlate the burrow type with clam spe- , since normally only portions of the burrows are evident.

Several species of polychaete worms, holothurians, and sipunculids also ow deeply into the sediments. Though deep-burrowing worm species occur roughout the area, they are most common in silty and very fine-grained sand in eper water (Figs. 10, 11 and 15A and B).

DISCUSSION

Factors Controlling Distribution of Physical Sedimentary Structures

lict Structures in Relict Sediments

The physical sedimentary structures of northern Bering Sea are either relict om Quarternary conditions or developed by modern wave and bottom currents. In aces, the Holocene shoreline transgression reworked Pleistocene moraines and drock outcrops exposed on the sea floor. The fine-grained debris was winnowed t leaving behind surface lag gravel deposits (Fig. 6A) (Nelson and okins, 1972). These deposits remain on the surface of current-winnowed topo- aph ic elevations where deposition of Holocene muds has bee prevented. In the stern parts of Anadyr and Bering Straits as well as along nearshore south- stern Seward Peninsula and St. Lawrence Island, the mineralogy and large grain e of gravel lags plus old radiocarbon dates (15-40,000 BP; Nelson, unpub. ta) of underlying sediment both indicate deposition" under older, high-energy nditions not present today (Nelson and Hopkins, 1972; McManus and others, 74). The coarser grain size and different mineralogy of the Chirikov Basin nd blanket compared to the silty-sized sediment of the main modern Yukon sedi- nt source suggest that Chirikov Basin sand also is relict.

Relict physical structures in relict sediments are best preserved in the surface sediment of strait areas with the deepest water, where present-day 'e effects are minimal, coarse gravel armors the bottom surface, and strong rents prevent burial by modern deposits. Here box cores have penetrated into er transgressive sediments, and even into Pleistocene freshwater deposits with ict lamination (Fig. 8D). Coarse-grained relict sediment overlying Pleisto- e tills contains flat lamination and associated high-angle, medium-scale cross ding that evidently originated during the Holocene shoreline transgression gs. 6B, A, 4, 7). Subsurface shell and pebble horizons in such relict sedis are now in sufficiently deep water and buried deeply enough to ensure iso- on from modern day storm wave and bottom current effects. These structures rently formed as storm lags during lower sea level stands (Figs. 6C, 611).

rn Structures in Relict Sediments

The relict fine-grained sand of central Chirikov Basin is interpreted to been deposited as a nearshore belt of sand that migrated along with the cene shoreline as it transgressed across the epicontinental shelf. The mo- Yukon silt- has not prograded over the transgressive sand, and it has, there- , been exposed to intense bioturbation for thousands of years. Additionally, Chirikov Basin sand has been covered by 35-55 m of water since the sea hed its present level several thousand years ago, and the development of ical sedimentary structures by waves thus has been limited. Bottom currents his central area generally are sluggish (Fig. 3; McManus et al., 1977) and in places probably are insufficient to develop structures. Even though waves ottom currents occasionally possess sufficient energy to create structures in noncohesive sediment, the binding effect of the dense network of ampeliscid ipod tubes should inhibit formation of such structures (Fig. 14B; ds, 1970). Consequently, the sand is completely devoid of sedimentary struc- s" except on a few shoal crests where the sediments are reworked by strong om currents (Figs. 61, 8C).

Recent evidence from sidescan sonar, underwater television, and vibracores fies physical formation of sedimentary structures in certain shoal areas of :t sediment in Chirikov Basin. In the shallower upper parts of sand ridges sand waves (Figs. 1, 4 and 9), the surface and near-surface coarse sand and 1. storm lags (Fig. 6D) along with faint ripple structures (Figs. 61 and 8CK) ar to be near-surface modifications of relict sand by modern storm waves and om currents. On underwater television, storm waves have been observed to ow shell pavement and to superimpose small-scale oscillation ripples over the er sand--wave structures (Figs. 9A and B). Sidescan sonar records show large-

: asymmetric sand waves covering' ridge tops and trending northward in phase the present strong northward bottom currents in northeastern Chirikov Basin 3) (Fig. 9C, Nelson et al., 1977; Nelson, 1977); a thousand-year-old radio- ›n date (Teledyne Isotopes I-9773) on wood from 30 cm depth in a sand wave l documents that modification of sediments by sand wave formation has taken : recently during the present stand of high sea level.

Either wave or current effects could be responsible for individual faint le structures observed in specific box cores from sand ridges. However, the ıance and type of asymmetric sand wave and ripple fields in all sidescan re- s and bottom photographs from the region indicate that the majority of mo- ripple structures in Chirikov Basin must derive from bottom current activity , 9).

rn Structures in Modern Sediments

Numerous radiocarbon dates substantiate that the blanket of mud with inter- ed sand in Norton Sound has a Holocene origin and contains contemporary sedi- ary structures (Nelson et al., 1975; Nelson and Creager, 1977). Development preservation of these physical structures varies widely both spatially and tigraphically over the contemporary surface in Norton Sound. Historical ge from complete bioturbation to complete preservation of physical structures in the past several thousand years can be demonstrated in several locations so 6F, G). In those locations closest to the Yukon delta, such dramatic ration in preservation of physical structures may be attributable to salinity circulation changes caused by a shift in location of a major Yukon distribu- (Fig. 6F; Nelson and Creager, 1977).

The storm sand layers that are interbedded with mud surrounding the Yukon a contain the best developed physical sedimentary structures because of se- 1 interacting factors. The prodelta area is subject to the most intense and uent wave reworking of any northern Bering Sea area owing to its extreme .lowness. In addition, the Norton Sound shape acts to focus storm surge set-

of water level (Fathauer, 1975) and this in turn results in development of 'ong bottom currents as storm-surge water runoff moves northward from the re-
n (Fleming and Heggarty, 1965 ; Nelson and Creager, 1977). Such "runoff" cur-
its may be the final mechanism to rework and form physical structures in sand 'ers of the prodelta area.

Formation of the thickest sand layers and their rapid burial due to the ;h sedimentation rates in the prodelta area both inhibit bioturbation and iance preservation of the physical structures. Even more important, the low linity and more extensive ice formation in the prodelta area (Figs. 2 and 11) ›ear to restrict faunal populations and consequent bioturbation of the physical :uctures. The complete bioturbation of physical structures at similar water ›ths but normal salinity on the northern side of Norton Sound appears to ıfirm this hypothesis.

Much of the cross-lamination and lenticularity in modern sand layers of rton Sound appears to result from rippling by unidirectional bottom currents. ɜ ripples are usually asymmetric, and the ripple form, where it can be observed box cores, bottom photographs, underwater TV, and sidescan sonar, is sinuous ɨ irregular, not straight-crested like oscillation ripples (Nelson, 1977), igs. 8 and 9). Furthermore, the basal surfaces on sand layers are regular, the ternal structure conforms to ripple form, and bundlewise buildup or offshoots ssing from adjoining troughs and crests are absent. Each of these points ggest formation primarily by unidirectional bottom currents (Reineck and Singh, 73).

Waves still are important in forming bottom structures, and formation of :illation ripples over asymmetric ripples and sand waves has been observed in irikov Basin at water depths similar to those of Norton Sound (Nelson et al., 77) (Fig. 9). Hindcasting of wave data indicates that wave reworking can fect most of the Norton Sound sea floor (McManus et al., 1977). however, in e >10 m water depths with very fine sand that this study covers, Clifton's

6) conceptual model predicts that wave-related currents should not produce metric rippling. Apparently, the dominant storm effect on sand layers is rking by bottom currents, which are intensified by storm-induced sea level ges (Fathauer, 1975). Later modification by less intense wave effects may e some oscillation ripples to be superimposed over the dominant irectional features, but in general they appear to be subordinate.

Eastward and northward from the present delta, storm' sand layers become r and fewer, and only 'diffuse storm layers rich in shells and pebbles are rved. Near the delta, where biota appear to be restricted and no rocky lands are present, few shells or pebbles are encountered in storm layers. increasing distance from the delta into higher salinity water, more and more ls are. encountered and bioturbation increases. In addition, the intensity of n-wave reworking decreases and sand layers become thinner, while headlands the coast awav from the delta provide a pebble source. Figs. 6E-G; 6I; 13B-emplify such a proximal (delta) to distal (central Norton Sound) or shallow eep sequence of storm layers. The change from sand layers to coarse lags of les and shells offshore also suggests that processes change from dominantly sport and deposition of sand sheets to mainly erosion of mud leaving pebble shell lags offshore.

The Yukon muds of Norton Sound, both massive and those interbedded with i sand layers, remain nearly devoid of physical structures, except for ional laminations (Fig. 13B,E). Because the mud deposition represents slow, nual deposition under non-storm conditions, bioturbation apparently can t always keep pace with formation of physical structures, and thus physical tures are not generally preserved in muds.

nt-Day Pebble Rafting and Ice Gougin

Isolated pebbles are widespread in sediment of the Bering Sea region and may been transported by several processes. Pebbles are most common in areas unding seafloor gravel(Fig. 4). This distribution pattern may result from grounding in gravel areas. The ice may pluck pebbles from the gravel source drop them nearby after the iceberg works free rind begins melting. Other hanisms such as transport of walrus gastroliths (stomach "stones) (S.W. Stoker F.H. Fay unpub. data) and sea grass rafting (Stoker, 1973) may also carry lated pebbles offshore.

Recent studies indicate that gouging into the sea floor by icebergs occurs rywhere at depths shallower than 20 m (Thor et al., 1977) (Fig. 9), except in ait areas, where ice jams may cause gouging at much greater water depths (G. om, oral commun, 1970). The gouging is most intense (reaching depths of up to in the sediment) in the prodelta area surrounding the modern Yukon subdelta; s is the same region where physical sedimentary structures are best preserved 3.5). The question remains, why does this intense gouging have such little ect on physical structures? Perhaps sediment rates are rapid enough near the ern subdelta to keep ahead of the rate of ice gouging.

Factors Controlling Bioturbation

logical Factors

A few ubiquitous species show little environmental control and account for a ificant amount of the bioturbation anywhere in the northern Bering Sea area. nples of these species have been described in the previous bioturbation :ion such as the ophiuroid and gastropod (Tachyrhynchus erosus) surface turbers, the clams (i.e. Yoldia myalis) and small amphipod shallow burrowers, clams (i.e. Serripes groenlandicas) and small polychaete (thread worm) ermediate burrowers and the clams (i.e. Mya truncata) and large polychaete e. Ampharete) deep burrowers (Table 1, Figs. 10,11, and 12).

Except for the cosmopolitan species just mentioned, distribution of most :ies is controlled by environmental factors such as hydrographic conditions, hologic setting, and substrate type. Consequently, bioturbation of most :ies has definite patterns of areal distribution (Figs. 10 and 11). All :ies appear to be restricted by the seasonally low saliity off the modern

.on subdelta (Figs. "2, 5 and 11; Lisitsyn, 1966). Regions of strong currents
| resulting coarse. -grained sediment support epifaunal communities such as the pension-feeder assemblages found in straits, or the sand dollar (Echinavachnus ma) and bivalve community (Tellina lutes alternidentata, Spisula polynyma) ind in sandy areas on crests of shoals (Fig. 10).

Because of the small depth range (0 - 50 m) on northern Bering shelf, water th has little direct influence on' abundance or type of bioturbating organisms. tead, benthic communities typically show pronounced association with strate. For example, the large ampeliscid amphipods are the dominant ,anisms disturbing the transgressive fine-grained sand in Chirikov Basin .gs. 10 and 11; Table 2). They are not evident in Yukon silt of Norton Sound, re the smaller amphipods, brittle stars, and deposit-feeding worms and clams : predominant (Figs. 10 and 11, Table 1, Rowland, 1972, 1973). Gravel lags are itats for an abundant epifauna of rocky substrate type consisting of 'ozoans, barnacles and brachiopods. However, the thickness and coarseness of : lag layers and the sessile living habits of fauna on them seem to prevent ;nificant bioturbation. Many other substrate associations of bioturbating ;anisms, particularly bivalves, have been outlined in other Bering Sea studies ble 1; Rowland, 1972, 1973; Stoker, 1973 and unpub.).

:erplay of Biological and Physical Factors

Intensity of bioturbation is controlled by rates of several processes such the frequency of formation of physical structures, rate of reworking by ;anisms, and sedimentation rate (Fig. 16). Changes in these rates through geo- ;ic time cause variations in the intensity of bioturbation at a site. The fol- ring physical factors cause a relative increase in the rate of formation of 'sical sedimentary structures and decrease in intensity of biogenic reworking: illow water with intense wave reworking, swift bottom currents, rapid rates of)osition, and low-salinity water. "These physical variables plus other environ- ital characteristics like those mentioned in the previous section control spes dispersal and cause patchiness of faunal distribution. As a result, the e of biogenic reworking varies from one location to the next and with time at iven location.

In the shallow prodelta region off the Yukon River subdelta, bioturbation ically does not keep pace with the formation and rapid burial of physical uctures (Fig. 5). An area just east of the prodelta near Stuart Island also ws no bioturbation in deposits of the last 5,000 years (Figs. 5 and 6J; Nelson Creager, 1977). This is true even though the area has low sedimentation es and is at a greater water depth, where the formation of wave-formed struc- es is expected to be slower. The well-developed physical structures probably ult from the shoreline constriction of coastal currents. The extremely good servation of physical structures here and in the prodelta area may result both m continued formation by bottom currents or waves and from the inhibition of genie activity by the great seasonal changes in salinity. Complete bioturba- n of sediment older than 5,000 years near Stuart Island strongly suggests that on delta distributaries shifted into the region after 5,000 BP (Nelson and ager, 1977) and that salinity is the predominant factor controlling bioturba- n in this area.

Another stratigraphic sequence for the last 2,000 years in eastern Norton nd (Figs. 5 and 6G) shows complete bioturbation in the lower third of the iment, nearly complete preservation in the middle, and complete bioturbation the upper third. Either faunal populations diminished during the time of osition of the middle sequence, or frequent storms prevented bioturbation from ping pace with deposition.

GEOLOGIC SIGNIFICANCE

Geologic Effects of Bioturbation

In addition to disturbing physical structures and creating trace fossils, turbation may severely disrupt fossil assemblages and organic debris used in ing deposits. The disruption is especially severe in regions of thin transessive sequences such as the epicontinental shelf of the northern Bering Sea. several cores (Figs. 8A snd 8D), present-day burrows extend at least 30 cm to Pleistocene freshwater deposits that are tens of thousands of years old. As result, in part because of this upward mixing of older materials, radiocarbon tes of 1,740 to 5,085 BP are found for bulk organic carbon in the top 1 - 2 cm modern surface sediment on the northern Bering shelf (Teledyne Isotopes 8134, 8135, 8226, Fig. 6F). Downward homogenization of Holocene sediment by oturbation helps to explain radiocarbon dates of only a few thousand years for der buried transgressive deposits (Figs. 61, 8D; Teledyne Isotopes I-7482, 33).

Radiocarbon dates on calcium carbonate of shells again suggest significant ologic mixing of modern shells downward into buried transgressive gravel and ad (Fig.-6B, C, H, and I). Dates on fossil, surface-dwelling mollusk species e just several hundred years old, even though only those shells buried in older liment far below their normal living habitat were dated (M. Rubin, USGS Radio-rgon Lab. W-2462, 2464, 2466, 2467, 2681-2685). In Chirikov basin, where the ansgressive sequences are thin and dates on shells do not appear t-o be reli-le, mixed modern and transgressive foraminiferal assemblages are found roughout the entire transgressive sequences (Figs. 8A and 8D) (R. EchoIs, itten commun., 1974). Only where sedimentation rates are high, producing oid, deep burial such as near the modern Yukon subdelta, do radiocarbon dates shells and organic carbon agree with stratigraphy (M. Rubin, USGS, Radiocarbon , W-26180; Teledyne Isotopes 1-7316', 8134), and can unmixed transgressive quences of microfossils be detected.

Rhoads (1973) points out another aspect of bioturbation that may have par-cular geologic significance for the northeastern part of the Bering shelf. The edominance of deposit feeders can reduce the bulk density of fine-grained sedi-nt and greatly enhance the potential for erosion. The dominance of deposit eders in Norton Sound (Figs. 10 and 11; Rowland, 1972) may be a contributing actor to the resuspension of considerable fine-g rained sediment there. The esuspension of sediment by storm waves and its removal by storm-generated and ontinuous currents may have displaced about half of the Holocene sediment of ukon source from Norton Sound to the Chukchi Sea (Nelson and Creager, 1977).

Comparison of Bering Shelf and Similar Sedimentary Environments

rodelta and Inner Shelf Facies

Prodelta mud facies develop in the shallow regions surrounding the Yukon iver mouth where the low-salinity river plume is the dominant water mass (Figs. and 5). The proximal deposits are characterized by thin mud interbedded with hick storm sand layers that contain well-developed sedimentary structures esulting from waves and currents generated by storm surge (Table 2, C_1). ffshore from the most proximal prodelta facies, layers become thinner, more ighly rippled, well structured with cross lamination, and increasingly bioturated. The most distal prodelta deposits are dominated by bigly bioturbated muds ith sand lenses containing bioturbated remnants of physical structures. Further eaward, shell and pebble-rich storm lag layers occur (see Figs. 6E, 6F, 6G, 13B nd 14C for a specific sequence; Figs. 5 and 16 show general. patterns of distriution). Bioturbation in the muddier facies is dominated by tube-building detrius feeders and burrowing deposit feeders (Table 1, G-c; Fig. 10 and 11; Table 2, C_1).

The physical and biological structures in similar ancient stratigraphic seuences reflect this same proximal to distal energy gradation. For example roximal to distal sequences of physical structures and storm sand layers like iose in Norton Sound are described for Jurassic deposits by Anderton (1976). In ie Upper Cretaceus Blackhawk formation in Utah, a regressive sequence begins ith completely bioturbated offshore muds (Howard, 1972). Sand beds appear upection and thicken upward with increasingly well-preserved physical structures, idicating greater wave energy. The faunas also change up-section from deposit to ispension feeders as the depositional environments shallowed.

Variations in wave climate and topographic setting can greatly extend or .uce proximal-to-distal offshore gradation of physical structures generated by 'es. For example, in "the Gulf of Gaeta In the low-energy wave climate of the iterranean, well-developed physical structures are limited to less than 6 m of :er depth (Reineck and Singh, 1973) below which bioturbation predominates. In higher energy environments of the northern Bering Sea and off Southern .ifornia, well-preserved recent physical structures exist to 15-20 m water th (Figs. 5 and 7) (Karl, 1975). In the very high energy environment off gon, well-preserved physical structures occur in sediments in over 50 m of er (Kulm and others, 1975). Well-preserved physical structures also may exist malously far offshore on topographic elevations.

Sediment type and rate of influx also may influence the maximum offshore :ent and water depth at which physical structures are preserved. In muddy as, such as near deltas, fine-grained sand layers and their structures are dily identifiable in modern or ancient sequences (Fig. 6E-G) Moore and Scru-, 1957; Masters, 1967; Howard, 1972). Commonly, in the most distal locations deposition, isolated pods or lenses of rippled and laminated sediment are the t recognizable vestige of a storm sand layer (Figs. 6J and 13B) (Reineck, '0; Winston and Anderson, 1970). Such thin sand lenses are usually destroyed bioturbation closer to shore or at shallower depths than are similar storm lag ers composed of shell and pebble lags (Figs. 5 and 7). For example, faint ll and pebble horizons of coarse-grained storm lags are identifiable to water ths of 30 m in modern sediments of Norton Sound even after very extensive bio-bation; the last vestiges of fine-grained sand layers occur in 25 m of water .g. 7)* In most delta areas, the formation of such shell and pebble layers is ibited by the paucity of rocky headland pebble sources and by the influx of e-grained sediment and low salinity water, which appears to discourage large alve mollusk populations, the source of most shell material.

The distribution pattern of the prodelta facies may be controlled as much water circulation and freshwater plume dispersal as by the shallow, nearshore :ation and shape of the prodelta topography (Figs. 2, 3 and 5). This is :ause variations in salinity and oxygen and nutrient content of sea water can fluence benthic productivity and thus affect formation and preservation of ysical structures. The best preservation of physical structures coincides with e location of the low-salinity plumes (Figs. 3 and 5; Nelson et al., 1975) sur- unding the Mississippi and Yukon deltas; a progressive reduction in bioturba- on also has been correlated with with decreasing salinity up estuaries {Winston d Anderson, 1970; Moore and Scruton, 1957). The importance of salinity com- red to other factors, like rapid sedimentation, is suggested by thin (12 cm) te Holocene sequences that have remained unbioturbated for at least 5,000 years E the Yukon (Fig. 6F).

In some geographic settings physical structures may be preserved in un- oected epicontinental shelf areas where the benthic fauna is depauperate :ause of low oxygen content in bottom water (Seibold et al., 1971). Excellent eservation of physical structures found in the Mesaverde Formation of north- stern Colorado (Masters, 1967) suggests that these ancient deposits similar to ose off the Yukon were formed under shallow, low-salinity water near a delta, where environmental factors inhibited bioturbation.

ansgressive and Current-Winnowed Facies

The transgressive fine-grained sands in northern Bering Sea are charac- rized by a homogeneous texture, the general absence of physical structures, and tense bioturbation by tube-building detritus feeders (Table $2B_1$). This sedi- nt facies may typify thin transgressive sands on epicontinental shelves with wave energy, but where burial by offshore mud is prevented by strong bottom rents or isolation from sediment sources. In contrast, in areas where there a very high energy wave regime, such as presently off Oregon, some physical uctures are found in the offshore" relict transgressive sand facies (Kulm and ers, 1'375).

The basal transgressive gravel and pebbly coarse to medium-grained sand of ering shelf in many places overlie Pleistocene moraines either as surface t deposits or as subsurface strata beneath transgressive fine sand. These e-grained transgressive sediments take several forms that may be dis- .ishable in the stratigraphic record. The deposits with rounded pebbles, -worn and thick-shelled mollusks, and medium-scale cress and flat lamination r to be typical sediments associated with shoreline stillstands (Table 2, A_2; .on et al., 1971; Reineck and Singh, 1973). The angular pebble lags that op over glacial till and bedrock apparently form during very rapid shoreline gressions. Criteria for such deposits are angular gravels, little or no fine- ıed matrix, and the remains of a rocky intertidal fauna (Table 2, A_1). Sessile ıic 'fauna consists largely of epifaunal forms (Craig and Jones, 1966). As a .t, the thin pebble lags show little disruption from bioturbating organisms ıay remain well preserved in the stratigraphic record For example, thin, tureless, transgressive sands overlying well-preserved glacial deposits have noted in the Paleozoic transgressive sequence of the Algerian Sahara region et al., 1971).

The well-sorted current-winnowed medium sand on the shoal crests of the ıern Bering shelf is another sediment facies that may be recognizable in :nt shelf deposits (Table 2). Remnants of ripples and flat lamination are ın; shell lag horizons and clay stringers, possibly representing major fluc- .ons in currents, are locally present. An important key to such deposits in :nt sequences would be dominance of sand dollars and filter feeding bivalves .milar ancient organisms (Table B_2).

: Model

The physical and biological structures observed on the Bering shelf agree other similar studies; these data permit conceptualization of a model of tyshelf sedimentary "structures and factors controlling their distribution on n shelf with elastic deposition dominated by muds and no organic reefs 16). The inshore margin of the model presented here phases into the well-d shoreline sequences of physical structures caused by breaking waves that een depicted in the conceptual models outlined by Clifton et al. (1971). del presented here does not consider the series of large-scale bedforms by extremely strong bottom currents in constricted bathymetric regions igh tidal or dynamic current flux. Such sequences have been described by son et al. (1971) in the English Channel shelf and appear to be present in ring Strait area (Figs. 1, 4, and 16).

In the model we present, physical sedimentary structures caused by waves lominate the open shelf sediment just offshore from beach-related features. st developed physical sedimentary structures caused by strong bottom cur- associated with periodic tides (Mofjeld, 1976), storm tides and shoreline ictions of dynamic currents will generally occur just offshore from the elated structures. Seaward from strong wave- and tide-formed sedimentary ures, there occurs a spatial series of physical structures resulting from ; wave and bottom-current processes associated with storms. This complete ice of storm sand to pebble- and shell-rich layers has been well documented ton Sound (Fig. 16).

As physical energy from waves and currents diminishes offshore, the fre- of physical sedimentary structures lessens and the physical structures are bated and replaced by trace fossils to a progressively greater degree. The ice of biological structures indirectly follows gradients of wave and cur- energy because these gradients regulate substrate types, which are the main l on biological assemblages (Craig and Jones, 1966 Rowland, 1973; Stoker,

Typically, suspension-feeding organisms will be more prominent nearshore irse-grained substrates associated with high physical energy. In this onment, filtering apparatus is less likely to be clogged by fine-Erained

is (Rhoads and Young, 1970), and the circulation of suspended debris is vi-
ɹε. Suspension-feeding organisms will tend to disturb sediment less because only need to anchor onto or into the bottom surface and do not need to bur- through the sediment to acquire food. In contrast, discrete burrows and com- e bioturbation characterize offshore muds (Howard and Frey, 1973) because sit feeders and detritus feeders require the higher content of organic de- found "in fine-grained sediments of lower energy settings.

The conceptual model (Fig. 16) portrays an open graded shelf that gradually ges in depth, wave energy, sediment character, and current energy offshore. ence from the northern Bering epicontinental shelf and elsewhere indicates many variables, including topographic setting, hydrographic characteristics, ogic productivity, and type and location of sediment sources can modify this lized sequence. Several examples have already been cited to show that varia- of wave climate can greatly extend or reduce offshore extent of physical tures generated by waves.

Topographic projections outward from the adjacent shorelines such as deltas ward from the surrounding sea floor, such as offshore sand ridges (Nelson others, 1975) are important variables controlling the development of current- ed physical structures. Where water circulation is constricted and strength- by major shoreline projections as in the Bering Strait or English Channel lerson et al., 1970), bedforms and internal physical structures will be well oped no matter what the water depth or distance from shore. Offshore areas , a-floor topographic relief such as sand ridges that constrict and focus bot- currents arc also sites of well-developed physical structures without regard eir distance from shore (Fig. 6L).

Variation in the amount and type of sediment is another influence on tile opment and preservation of physical structures. Where rates of deposition igh and interbedded muds are common, as off the Yukon and Mississippi deltas e and Scruton, 1957), preservation of physical structures is enhanced and tend to unusually great depths or distances from shore considering the energy setting. The final shell and pebble remnants of an offshore storm layer xtend far offshore beyond the distance usually expected because of unusual es of pebbles and mechanisms like ice or organic rafting to disperse them the shelf.

All the factors of increased wave energy, current velocity and deposition s, in addition to decreased benthic productivity will extend areas dominated hysical sedimentary structures farther seaward than bioturbation would other- allow (Fig. 16). These variations in basic physical, chemical, and biologi- factors are predictable at least partially and must be considered when sedi- ary structures are utilized for paleoenvironmental reconstructions.

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ıLE 1 - LIST OF MOST COMMON BIOTURBATING ORGANISMS, AND, WHERE KNOWN, THEIR SUBSTRATE ASSOCIATIONS AND TYPE OF SEDIMENT DISTURBANCE IS GIVEN. WITHIN EACH GROUPTHE SPECIES ARE LISTED IN ORDER OF ABUDANCE AND WHERE KNOWN, THE PERCENT OF OCCURRENCE AT SAMPLING STATIONS IS GIVEN IN PARENTHESES IN FRONT OF THE SPECIES.

Organism	Substrate and Distribution	Living Habits	Data Source
Brachyuran crabs Choanoecetes opilio Choanoecetes bairdi Hyas coarctatus Telmessus cheiragonus	 Ubiquitous do do	Create shallow surface depressions Same as above	Stoker, unp Fig. 10
Anamuran crabs Pagarus Paralithodes Crangonid shrimp Crangon	 biquitous easonal and uncertain biquitous		
Ophiuroid echinoderms Ophiura sarsi Ophiura maculata Stegaphiura nodosa Gorgonecephalus caryi	uddy silt, nearshore! ilty sand	Create extensive surface tracks	Fig. 12; Neyrnen, 196 Fig. 10 Stoker. unp
Echioid echinoderms (6%)Strongylocentrotus drobachiensis	Gravel and pebble lags	Create shallow surface depressions	Fig. 10
Gastropod mollusks	Ubiquitous, most ommon nearshore	Surface trails and shallow burrows when preying	Fig. 10
(19%)Tachyrhynchus erosus			
(15%)Natica	Iniquitous	Predatory, drilling bivalves	Rowland, 19
(9%)Neptunea	do	Scavenger creating trails plus shallow burrows	Schafer, 19
(7%)Polinices	do	Predatory, drilling bivalves	
(2%)Buccinum		Scavenger	
Bivalve mollusks (36%)Yoldia myalis	lost common in muddy ;ediment, but widespread in all environments.	Deposit feeders?	Fig. 10, 11 Rowland, 19 Stanley, 19

Organism	Substrate and Distribution	Living Habits	Data Source
(16 %) Yoldia hyporborea or amygralea	Mud or muddy sand	Deposit feeder?	Figs. 11,14 Stanley, 1970 Rowland, 1973
(15%) Nucula tenuis	do "	do	Figs. 11, Stanley, 1970 Rowland, 1973
Nuculana radiata	do "	do	
Clinocardium ciliatum	Sandy silt substrates	Suspension feeders	Petrov, 1966
Tellina alternidentata	Current-winnowed clean sand		Figs. 13, 14
Amphipoda			
(27%) Protomedeia sp.	Mud and? fine sand	"Detritus feeders, one or more of these species create U-shaped and vertical burrows with widened circular area	
Melita sp.	do		
Hippomedon sp.	do		
Haploops laevis	do		
Pontoporeia femorata	do		
Polychaeta			
(8%) Nepthys	Ubiquitous	Errant polychaete	Fig. 13
Haploscoloplos elongata		Burrows parallel to bottom surface	Fig, 10
Sternaspis scutata			
Pectinaria hyporborea	Fine, silty sand nearshore		
Brada sp.			
Echinoidea			
(11%) Echinarachnius parma	Sorted-medium sand on shoals	Shallow horizontal burrows	Fig. 10 Lisitsyn, 19(

Organism	Substrate and distribution	Living Habits	Data Source
Bivalve mollusks			
(58%) Serripcs groenlandicus	Ubiquitous	Filter feeder	Fig. 10
(45%) Macoma calcarea	Ubiquitous, sandy silt and sand	Detritus and filter feeder	Coan 1971
Venericardia crebricostala	Sandy silt	do	
Liocyma fluctusa	Sand and sandy silt	do	
Echiroidea			
Echiurus echiurus	Fine to coarse sand	Deposit feeder	
Amphipods			
(28%) Ampelisca sp.	Silty sand	Detritus feeder that builds narrow, V-shaped, mucus-lined tube	Figs. 11, 14
Byblis gaimardi			
Polychaeta	Ubiquitous		
Myriochele herri	Fine sand		Figs. 10, 11
Onuphis sp.			
Spiophanes borbyx			
Holothuroidea			
(1%) Cucumaria calcigifera		Detritus feeder	Fig. 10
Tunicata			
(3%) Polonia corrugata	Sand to gravel	Filter feeder	Fig. 10
Bivalve mollusks			
(28%) Mya truncata	Ubiquitous, hard sand or mud	do	Figs. 10, 11 Quayle, 1970
(1%) Mya priapus		do	
(7%) Spisula polynyus alaskana	Sand	Deep burrowers and filter feeders	Chamberlain an Stearns, 1963

Organism	Substrate and Distribution	Living Habits	Data Source
(1%)Sipunculida Golfingia margaritaceum			
Polychaeta		All deposit fee	
(9%)Lumbrinereis	Ubiquitous	Errant Polychae	Fig. 10
(4%)Amphareta		Tube building	Fig. 10
Maldane sarsi Praxill.ells practermissa Axiothella catenate	Mud and silt	do	

TABLE 2-CHARACTERISTIC PHYSICAL AND BIOLOGICAL STRUCTURES OF NORTHERN BERING SEA SEDIMENT FACIES

	Sediment Facies	Physical Setting	Physical Structures	Biological Structures	Characteristic Biologic Community	Sedimentary Environment	Figures
C_2	Yukon Silt Prodelta	Best developed <15 m water depth Low salinity water	Abundant to common-sand lags, sand lenses, small-scale flat and cross lamination, asymetric ripples Rare-ice push features	Rare - 1 mm worm burrows, U-shaped amphipods, deep worm and clam burrows, brittle star tracks	Mainly infauna abundant deposit and common detritus feeders	Suspension deposition with common sediment input and reworking by low-energy traction currents from storm waves and associated bottom currents. Bioturbation, restricted low salinity.	6 E-G 8B, 8E 12A
C_1	Yukon silt offshore	<30 m and normal salinity water	Common to abundant sand lenses Rare to common shell and pebble lays with internal structures	Common to abundant 1-mm worm burrows, U-shaped amphipod tubes, deep worm and clam burrows, brittle star tracks	Same as prodelta	Like prodelta, but storm reworking less and bio-turbation not inhibited.	6J, 12B 13B and C 13E 14 C and 12 15F and G
'2	Sorted medium sand	Shoal crests and other current-reworked areas	Common - faint ripples Rare - coarse sand and shell lags (sometimes of sand-dollar fragments) clay stringers, flat lamination	Abundant bivalve and sand dollar reworking - Rare to common 1 and 5 mm worm burrows	Mainly infauna, abundant suspension feeders especially sand dollars, tellinid clams, rare to common detritus and deposit feeders	Relict transgressive sand reworked by strong bottom currents	6I, 8C 13A and D
'1	Chirikov fine sand	Open shaft areas without Holocene hard cover	Absent, except rare storm storm shell and pebble lags	Rare-surface disturbance and deep burrows Common-small amphipods and 1-mm worm burrows - Common to abundant lg. amphipod burrows.	Mainly infauna with abundant detritus and common deposit feeders.	Relict transgressive sand deposited near-shore by wave suspension and traction processes, now below wave base.	6C and D 6H 14A and a 15A and D 15E
'2	Gravelly medium sands to gravel	Overlie bedrock outcrops or glacial till	Rare-medium-scale, cross-lamination and flat lamination; pebbles well rounded, gravels sorted	Predominant bi.valve bioturbation with occasional worm and amphipod burrows	Mainly infauna with abundant suspension feeders and rare detritus and deposit feeders	*Relict* shoreline sedi-sediment winnowed lag (Swift and others, 1971), now preserved by burial or strong bottom currents	6B 8A 1 SC
A	**Coarse** pebble **lags**	Overlie bedrock outcrops or glacial till	Internal structures absent, but gravel lag layer is a distinct structure which overlies glacial till. **Angular** to rounded gravel without matrix	Bioturbation structures not evident, barnacle and bryozoan encrustations, brachipods present	Mainly epifauna anemones, bryazoas, sea urchins, barnacles, crabs, brachipods	Same as A, except not buried and usually present on scarps or elevated topography	6A

FIGURE CAPTIONS

1 -Setting, physiography, and location of large-scale bed forms presently known in northern Bering Sea. Bathymetry modified from Hopkins et al. (1976). Large-scale bedforms from Jordan, 1962; Grim and McManus, 1970; L. Toimil, 1975, oral commun., and Nelson, unpublished data.

2 -Water masses in northern Bering Sea (modified from Coachman et al., 1976). The Alaskan Coastal water (14 - 31.5 0/00, . 8°C) occupies the eastern portion of the study area, the Bering Shelf Water (sometimes called Modified Shelf Water) (31.5-33 0/00, 0-4°C) covers the central area, and the Anadyr Water (33 0/00, 1-3°C) occurs in the western portion of the study area. Data on seasonal salinity changes from Goodman, et al., (1942), G.D. Sharma (1975, written commun.) and Nelson et al., (1975). Data on shorefast ice margin from Thor et al., (1977).

3 -Offshore water circulation (from Goodman et al., 1942), and maximum bottom current velocities from available measurements in northern Bering Sea (from Fleming and Heggarty, 1966; Husby, 1971; McManus and Smyth, 1970; Nelson and Hopkins, 1972).

4 -Surface sediment distribution in northern Bering Sea (modified from Nelson and Hopkins, 1972; Knebel and Creager, 1973; McManus et al., 1974, 1977).

5 -Box core locations and descriptions of physical sedimentary structures observed in the upper 40 cm of sediment in northern Bering Sea. Structures in relict transgressive deposits and figure numbers of text photos are keyed to location.

6 -Lag and storm layers in northern Bering Sea sediments: locations of box core photos shown in Fig. 5. Individual centimeter scale is shown in lower right corner of each photograph or radiograph.

6A -Transgressive lag gravel over glacial till shown in box core slab face. Note Hemithyris psittacea (brachiopod) and bryozoan skeletons on surface. 41 m water depth.

6B -Epoxy cast of box core containing thick; well-sorted transgressive lag gravel from -30 m shoreline stillstand (Nelson and Hopkins, 1972). Note faint cross-bedding in center of cast, 30 m water depth.

6C -Box core slab face exhibiting shell lag at base of transgressive fine-grained sand. The shell layer was composed of equal amounts of Hyatella arctica and Macoma calcarea and probably formed as a storm lag during lower sea level. The layer was found in an isolated small basin at 43 m water depth.

6D -Bioturbated coarse sand and shell layer composed entirely of Echinarachnius parma (sand dollars) in current-winnowed fine sand over a shoal crest, 35 m water depth.

6E -Box core slah face showing thick light-colored storm sand layers in Yukon silt 30 km from the modern Yukon subdelta. Note that the thick upper sand most recently formed is not bioturbated, whereas only cross-laminated sand lenses remain in the lower bioturbated bed. 11 m water depth.

6F -Radiograph of well-defined thin storm sand layers in late Holocene Yukon silt 75 km offshore from the present subdelta. Thoroughly bioturbated older Yukon silt underlies well-structured beds in younger Yukon silt (after Nelson and Creager, 1977). Note rippled and wavy bedded sand beds (light-colored) with small-scale cross and flat lamination. 16 m water depth.

6G -Radiograph showing shell and pebble lags in the upper and lower parts of the core and numerous thin sand layers in between. Both probably developed by storm reworking of Yukon silt located 110 km from the present Yukon subdelta. Note that upper shell lag is only slightly disrupted, whereas basal layers are highly bioturbated. "The middle unbioturbated section has sand beds (light-colored) that exhibit discontinuous parallel bedding in the upper two layers and nonparallel and lenticular bedding in the lower three layers. Wood at the core base had an age of 2,120 years BP (Teledyne Isotopes sample No. 1-7320). Note the 1-mm-diameter burrows in the upper part of the core that probably are caused by polychaete worms (see Howard, 1969, Figs. 8, 13 and Hertweck, 1972, Figs. 3, 5). 14 m water depth.

6H -Radiograph showing bioturbated shell and pebble lag layers (lower half of core) in transgressive coarse to medium sand. Lag apparently developed during the Holocene transgression. Overlying fine-grained transgressive sand in the upper half of the core is highly bioturbated by amphipods and clams. 47 m water depth.

61 -Box core slab face of medium-grained sand from a shoal crest containing coarse sand lag layers and clay laminae probably formed by current reworking. 31 rewater depth.

6J -Yukon silt containing a large rafted pebble. Note thin sand Lenses near the surface. 18 rewater depth.

7 Frequency of various physical sedimentary structures in different depth, substrate, and topographic settings.

8 -Internal physical sedimentary structures.

8A -Radiograph showing the following sequence: transgressive fine-grained sand overlying transgressive pebbly medium-graincd sand with flat lamination and medium-scale cross-lamination, which overlies pre-transgressive limnetic clays with freshwater ostracodes (P. Valintin, written commun., 1971). Note deep burrowing probably by _Mya_ sp., after marine transgression (see Fig. 29 of _Mya arenaria_ burrows shown in Reineck, 1970). 36 m water depth.

8B -Plan section of a ripple set impression at a parting surface near the bottom of a box core, together with an epoxy slab cross section (adjacent upper right) snowing the same dark-colored lower sand layer and another surface sand layer. Note that apparent ripple crests (dotted line) are irregular and asymmetric with tongue-like projections (c f. with Harms et al. ,1975, Fig. 3-7 and Reineck and Singh, 1973, Fig. 30). Ripple index (length/height) is 5-8 basal and 10-12 for surface sand layers. 12 m water depth.

8C -Radiograph of remnant asymmetric ripples that have been altered by bioturbation of medium-grained shoal crest sand. 21.9 m water depth.

8D -Core slab face showing loading, slump or ice-disrupted structures (near the core bottom) in laminated late Pleistocene mud deposited before the Holocene transgression. Mud contains freshwater ostracodes (see reference for 8a). These have an age of 14,920 BP (Teledyne Isotopes No. 1-7318) based on organic carbon from a whole sediment sample. 51 m water depth.

8E -Radiograph showing highly contorted sand lags possibly caused by ice push or scour of the sea floor. Note shallow u-shaped burrows caused by small amphipods and large, deep burrow (on the right) probably made by a clam. 12 m water depth.

9 -Monographs and underwater TV and camera photographs of sea-floor surface features.

9A -Sand dollar pavement covering current-winnowed shoal crest at 36 m.

9B -Oscillation ripples on sand ridge crest at 9 m during severe storm.

9C -Asymmetric ripples on similar shoal crest, as 9B, with strong unidirectional currents during non-storm conditions in 17 m water depth.

9D -Sonograph showing large-scale sand waves over crests of sand ridges at 30 m water depth.

9E -Sonograph showing intense ice scour that covers most of sea floor in 10-20 m of water (14 m water depth). There is no side-scan data in less than 10 m of water.

10 -Frequency of various surface,. shallow (0-5 cm), intermediate (0-10 cm) and deep (0->10 cm) bioturbating species versus water depth, substrate, and topographic setting.

11 -Distribution of the most common shallow (0- 5 cm) (A), intermediate (0-10 cm)(B) and deep (0->10 cm) (C) biological structures that could be identified. Note that small amphipod tubes in A, ampeliscid tubes in B, and unidentified deep burrows in C are present everywhere in at least rare quantities.

12 -Surface-disturbing organisms. and sea-floor traces in northern Bering Sea. Fig. 12A-Photo of box core surface showing surface trails of brittle star *Ophiura sarsi* on Yukon silt. 14 m water depth.

12B-*Serripes groenlandicus* that has severly disturbed the box core surface of Yukon silt. 18 m water depth.

13 -Shallow burrowing (0-5 cm) organisms and their structures in Northern Bering Sea.

13A-*Ampharete* sp. burrows shown in radiograph of core 207. Sediment, type is clayey silt. 42 m water depth.

13B-Field photograph of Ampharete sp. tubes and worms from box core 207 surface just after collection.

13C-Photograph of box core vertical and horizontal surface showing cemented tubes and subsurface mucus-lined burrows of sabellid-terribellid worms that occur in large numbers within muddy gravels. Note also the live shallow burrowing Yoldia sp. in the upper center of photograph. 27 m water depth.

13D-Photograph of box core vertical slab face showing burrow of tunicate Pelonia corrugata in fine-grained transgressive sand. Note characteristic corrugations of burrow. 44 m water 'depth.

13E-Field box core photograph showing Holothurian Cucumaria calcigera burrowing vertically downward through very fine sand. 3"7 m water depth.

13F-Photo of box core vertical slab surface showing burrowing of polychaete worm (probably Lumbrinereis) in fine-grained sand. 19.6 m water depth.

13G-Box core photo of horizontal burrow of Macoma brota from specimen living at the time of core collection. Sediment is Yukon silt and burrow is at a depth of 7 cm from the sediment water interface. 19 m water depth.

14 -Intermediate burrowing (0-10 cm) organisms and their structures.

14A-Radiograph of large amphipod (Ampelisca macrocephala) tube structures occurring in great abundance in fine transgressive sand of central Chirikov Basin. Box core 237 from 27 m water depth.

14B-Field photograph of surface of box core 237 taken immediately after collection. Silt-like, mucus-lined burrows shown are typical of large amphipod species Ampelisca macrocephala.

15 -Deep burrowing structures and organisms.

15A-Sand dollar (Echinarachnius parma) burrowing in medium sands of a shoal crest; photo of box core surface was taken in the field immediately after collection; it shows organisms in living position. 31 m water depth.

15B-Radiograph of box core 103 from Yukon mud showing numerous u-shaped and straight 5-mm burrows assumed to result from burrowing of small amphipod species (see 11C). Note that nearly all storm sand layers structures are destroyed in the upper core but some sand lamination and rippling remain in the lower core. 19 m water depth.

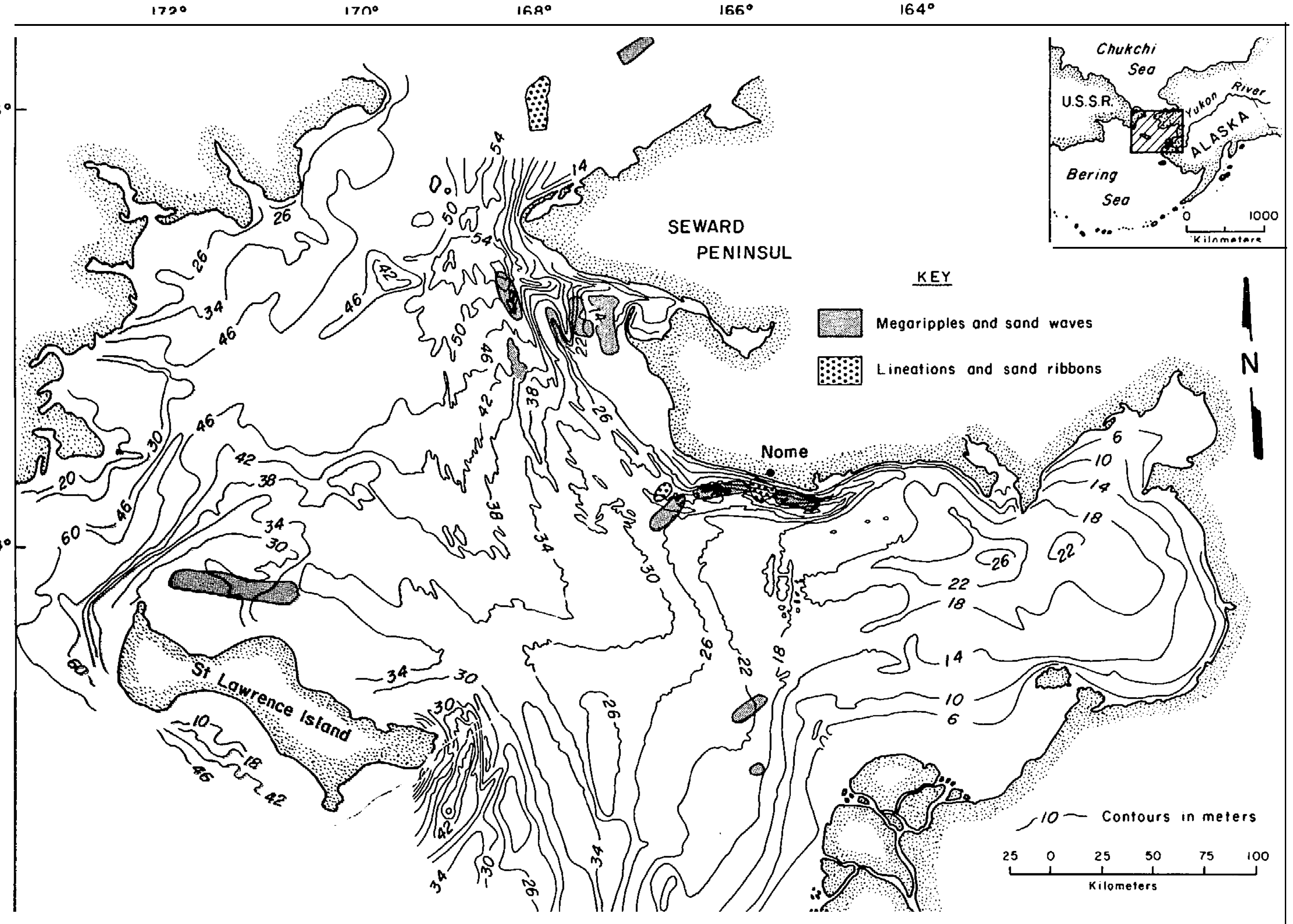
15C-Field photograph of surface of box core 103 taken immediately after collection; surface holes of small amphipods are apparent and appear to be responsible for u-shaped burrows observed in 11B.

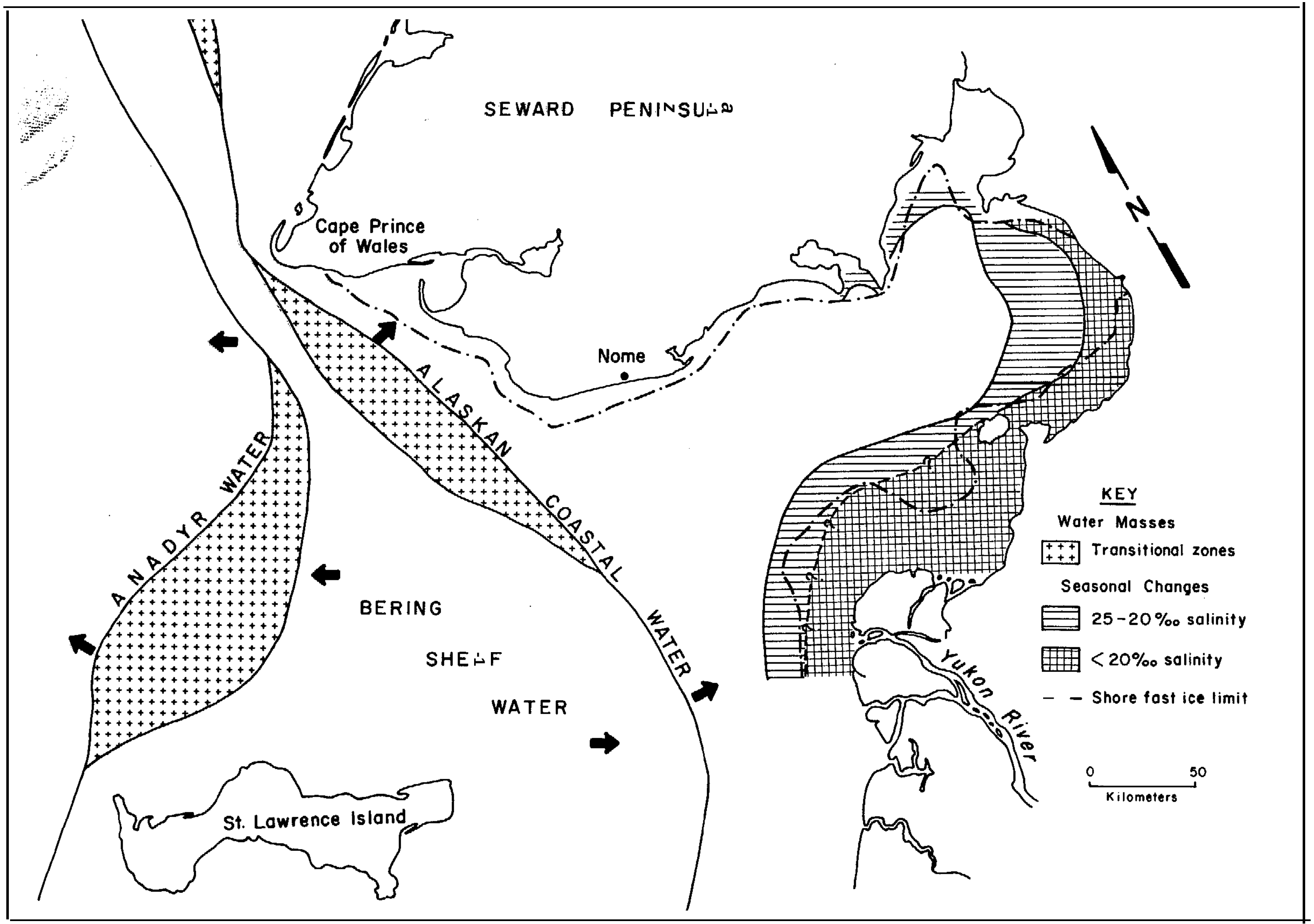
15D-Core photograph showing horizontal shallow burrowing pattern of polychaete Nepthys in Yukon silt. (T. Roonan, oral commun., 1976). 20 m water depth.

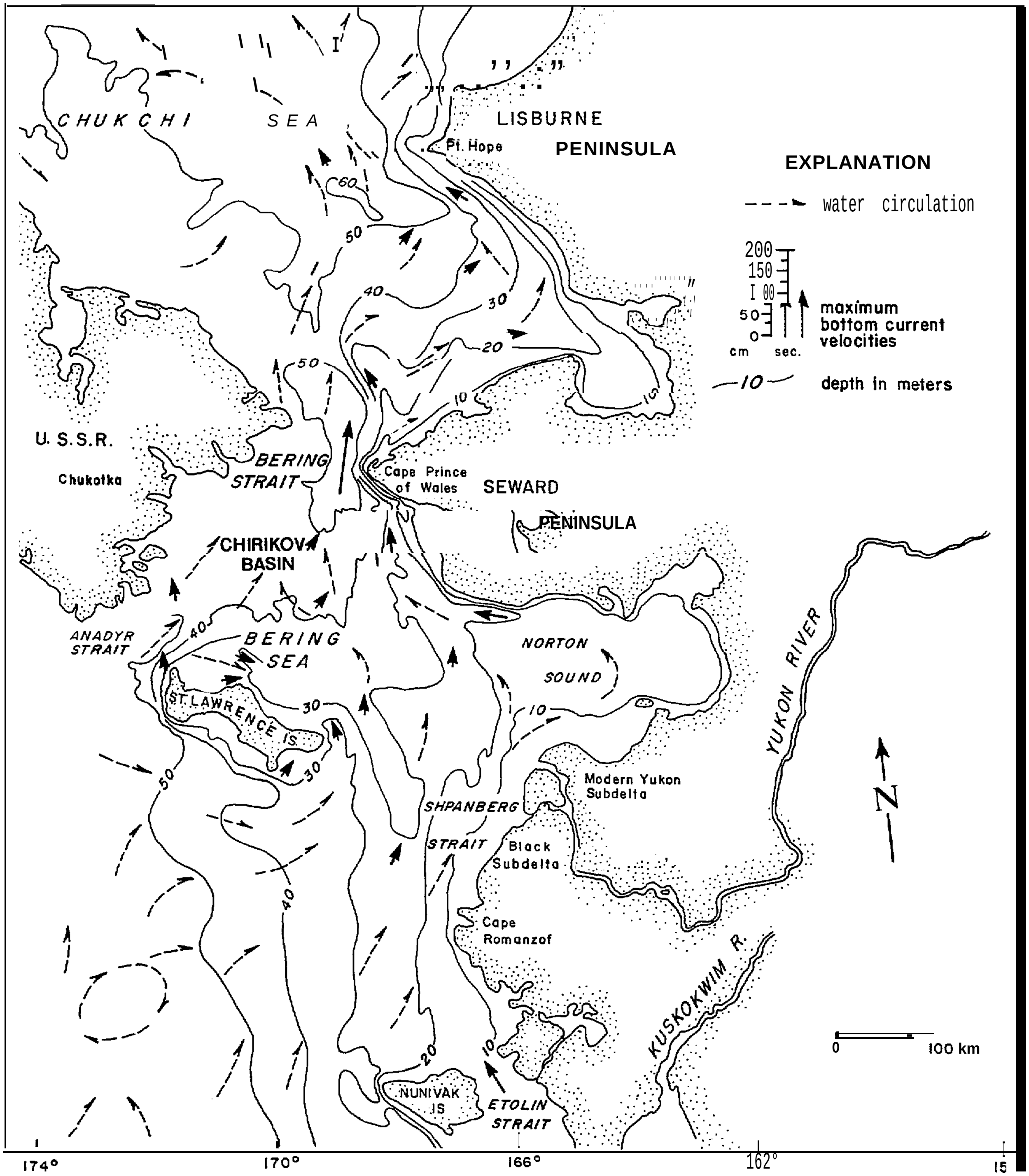
15E-Field photograph of living Yoldia sp. on surface and intermediate burrowing Serripes groenlandicus within fine-grained sand. 20 m water depth.

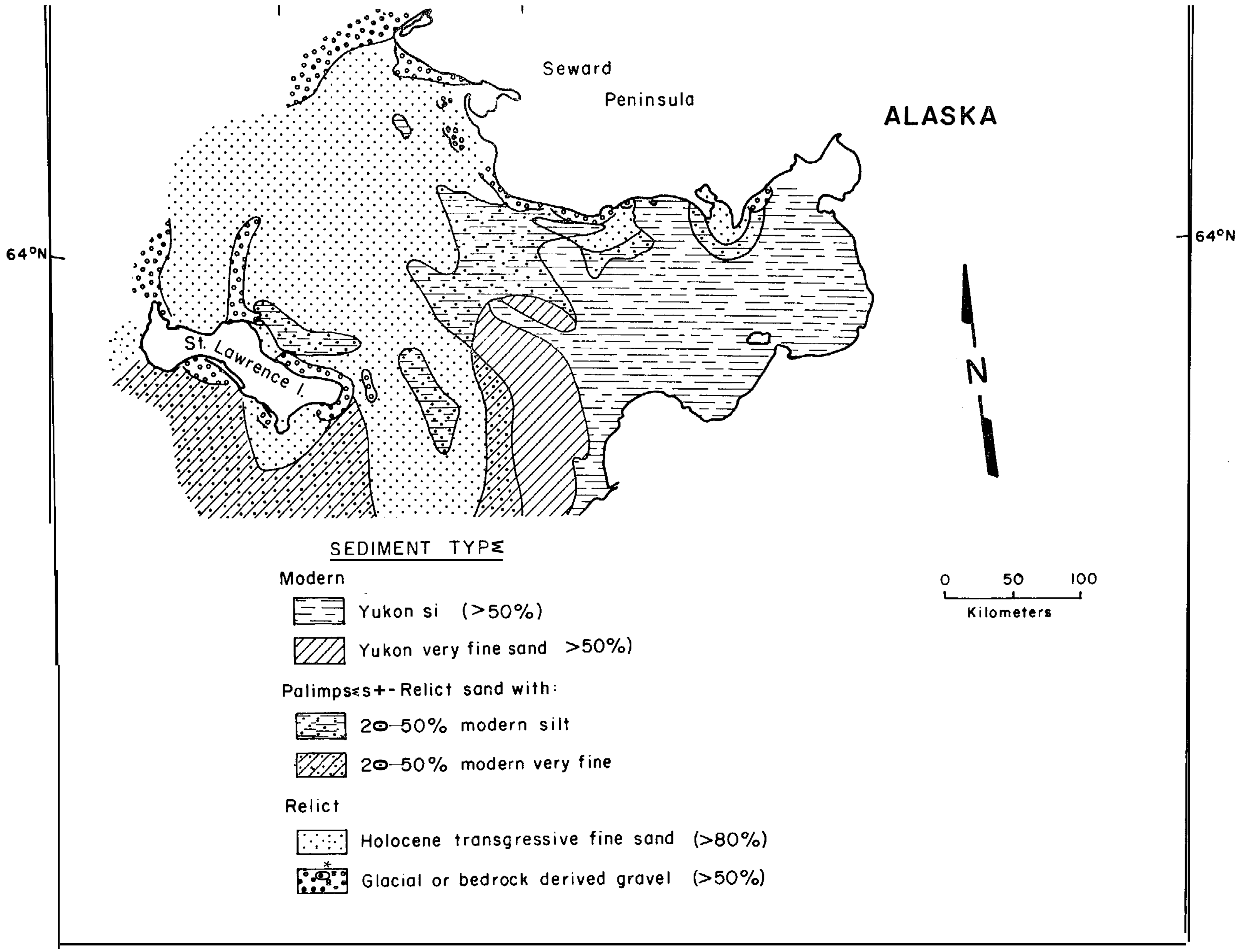
;. 151'-Radlograph showing shallow burrowing tachyrhynchus erosusin Yukon silt. 14 m water depth.

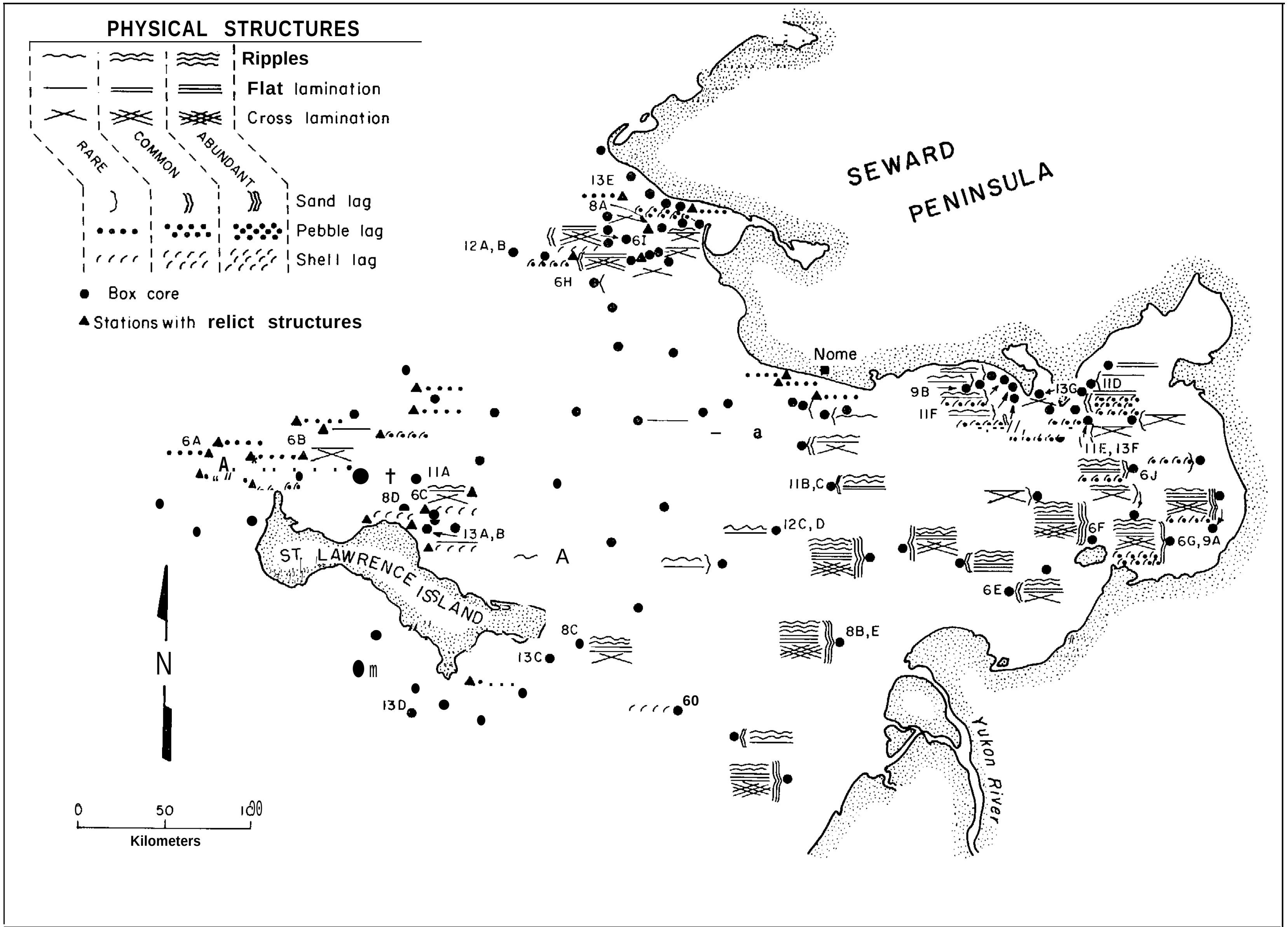
;. 16 -Conceptual model showing importance of physical structures versus biological structures in shelf sediments. Thickness of wedge depicts relative intensity of process from high energy to low energy shelf environments. Current and wave fields could be various sizes depending on current or wave domination of a particular shelf. All areas of physical structures would shift seaward with higher energy (see arr or toward shore with lower energy. Unidirectional current features on shelves will be more common seaward of nearshore wave structures but the frequency of structures will relate to current intensity rather. than distance seaward (for example, see Fig. 7)


172°
170°
168°
166°
164°
66°
64°
SEWARD PENINSUL
Nome
St Lawrence Island
KEY
Megaripples and sand waves
Lineations and sand ribbons
N
Chukchi Sea
U.S.S.R.
Yukon River
ALASKA
Bering Sea
0 1000
Kilometers
10 — Contours in meters
25 0 25 50 75 100
Kilometers


SEWARD PENINSULA
Cape Prince of Wales
Nome
ALASKAN COASTAL WATER
ANADYR WATER
BERING SHELF WATER
St. Lawrence Island
Yukon River
N
KEY
Water Masses
Transitional zones
Seasonal Changes
25-20‰ salinity
< 20‰ salinity
Shore fast ice limit
0 50
Kilometers


CHUKCHI SEA
LISBURNE
PENINSULA
Pt. Hope
EXPLANATION
water circulation
200
150
100
50
0
cm sec.
maximum bottom current velocities
10
depth in meters
68°
66″
64°
62″
60°
U. S. S. R.
Chukotka
BERING STRAIT
Cape Prince of Wales
SEWARD PENINSULA
CHIRIKOV BASIN
ANADYR STRAIT
BERING SEA
NORTON SOUND
ST. LAWRENCE IS.
YUKON RIVER
Modern Yukon Subdelta
SHPANBERG STRAIT
Black Subdelta
Cape Romanzof
KUSKOKWIM R.
N
0
100 km
NUNIVAK IS
ETOLIN STRAIT
174°
170°
166°
162°


Seward
Peninsula
ALASKA
64°N
64°N
St. Lawrence I.
N
0 50 100
Kilometers
SEDIMENT TYPE
Modern
Yukon si (>50%)
Yukon very fine sand >50%)
Palimpsest-Relict sand with:
20–50% modern silt
20–50% modern very fine
Relict
Holocene transgressive fine sand (>80%)
Glacial or bedrock derived gravel (>50%)



PHYSICAL STRUCTURES
Ripples
Flat lamination
Cross lamination
RARE
COMMON
ABUNDANT
Sand lag
Pebble lag
Shell lag
Box core
Stations with relict structures
SEWARD PENINSULA
Nome
ST. LAWRENCE ISLAND
Yukon River
N
0
50
100
Kilometers
13E
8A
6I
12A, B
6H
9B
11F
13G
11D
11E, 13F
6J
6A
6B
11A
8D
6C
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12C, D
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6E
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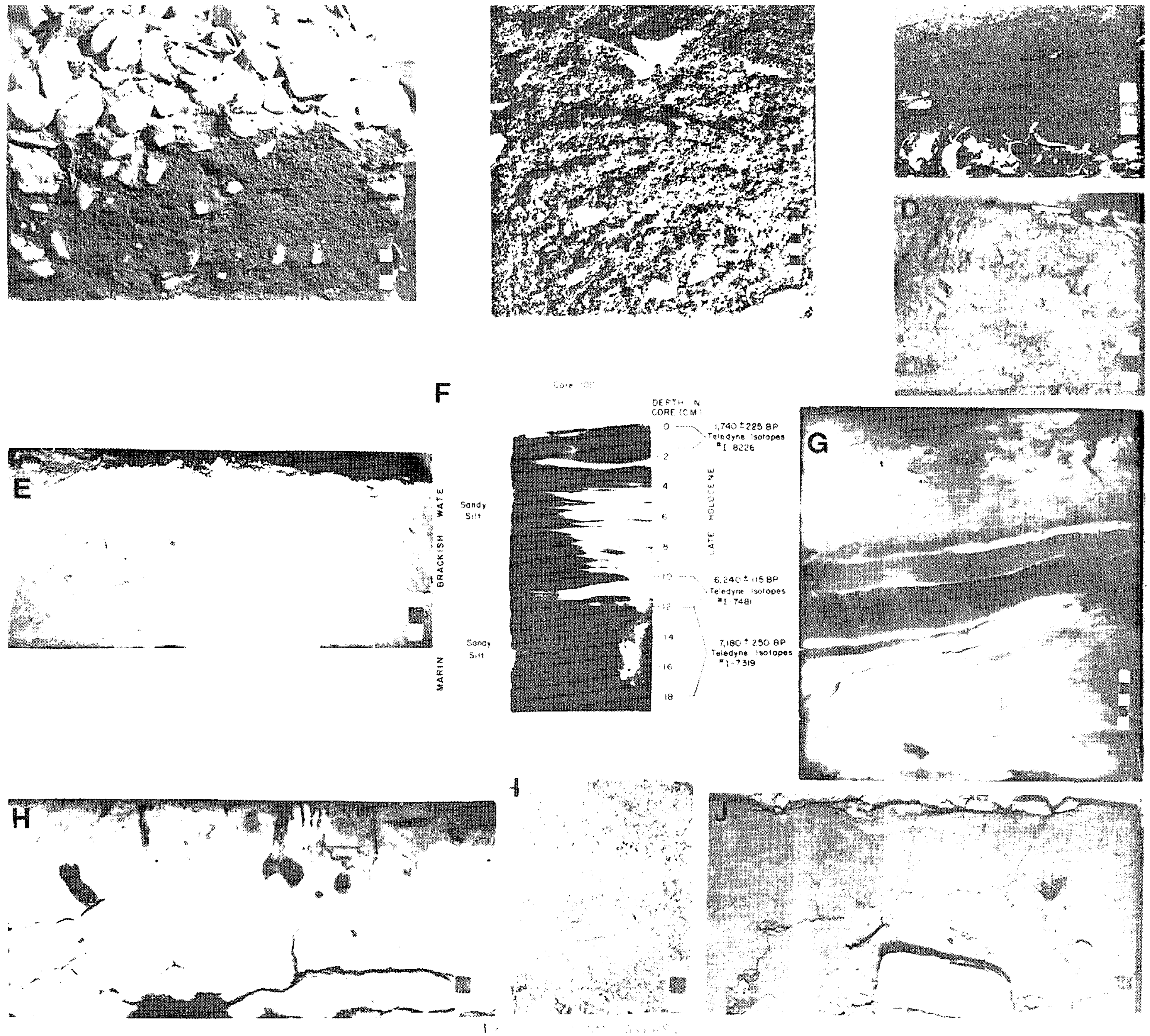
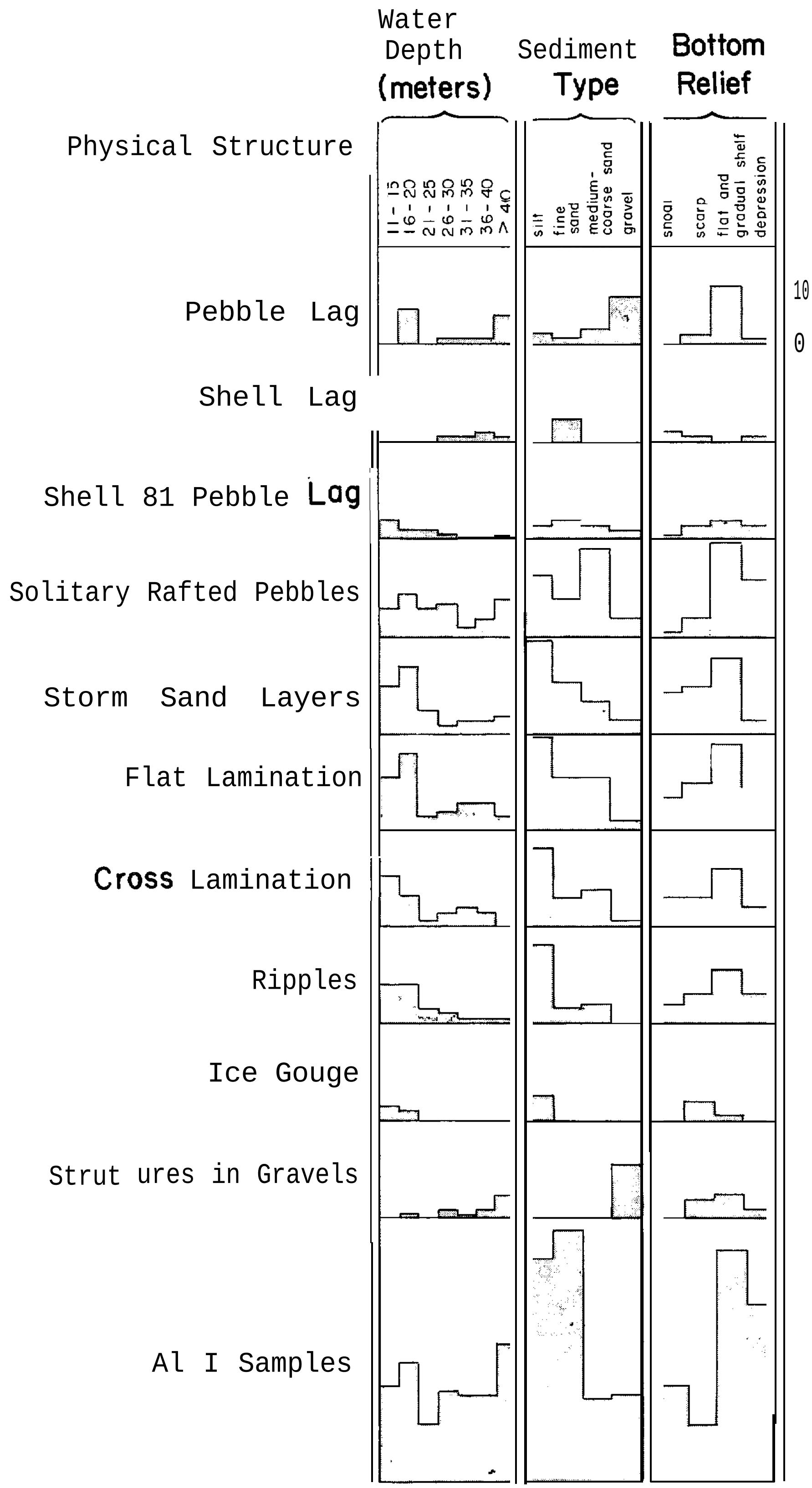
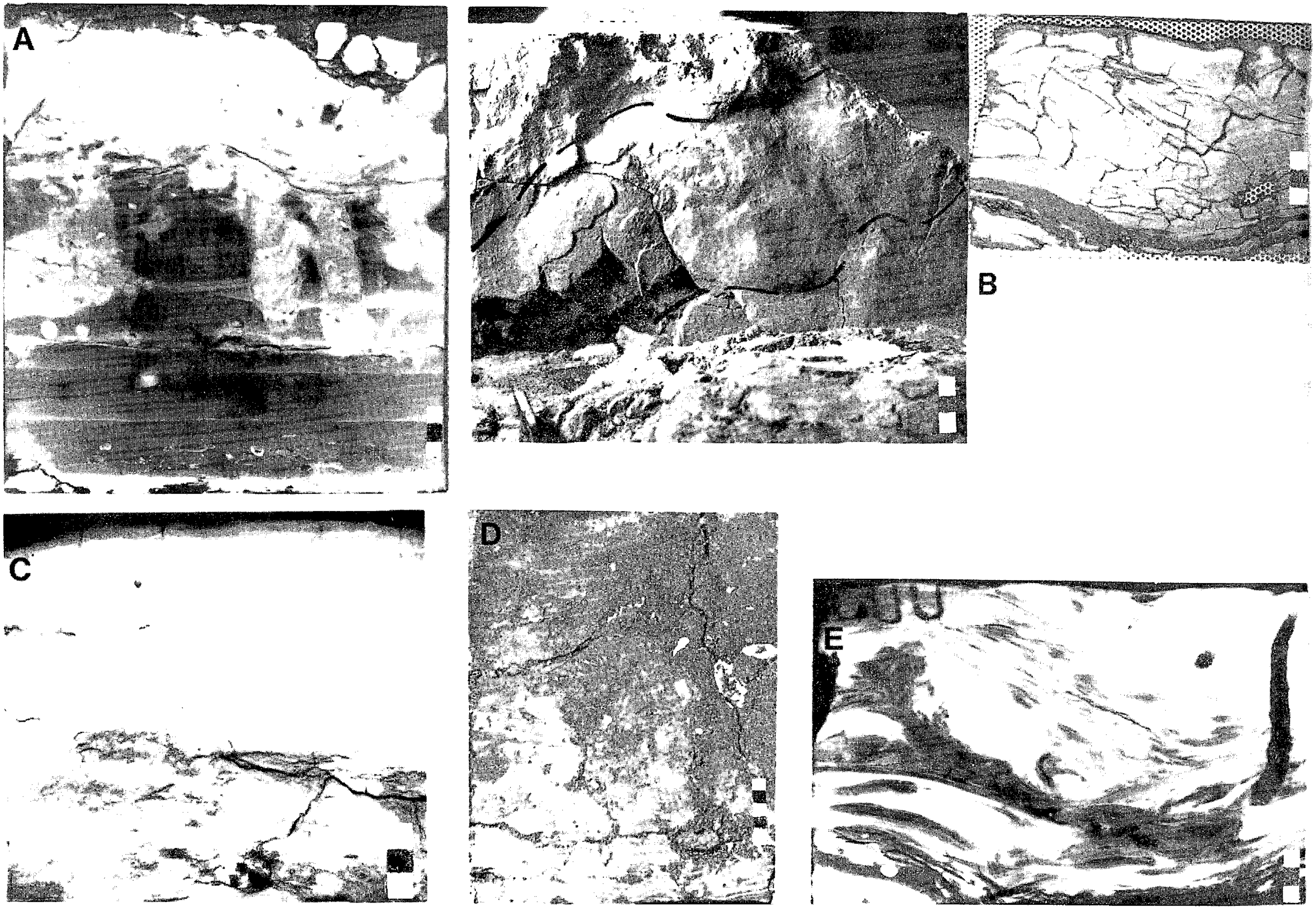
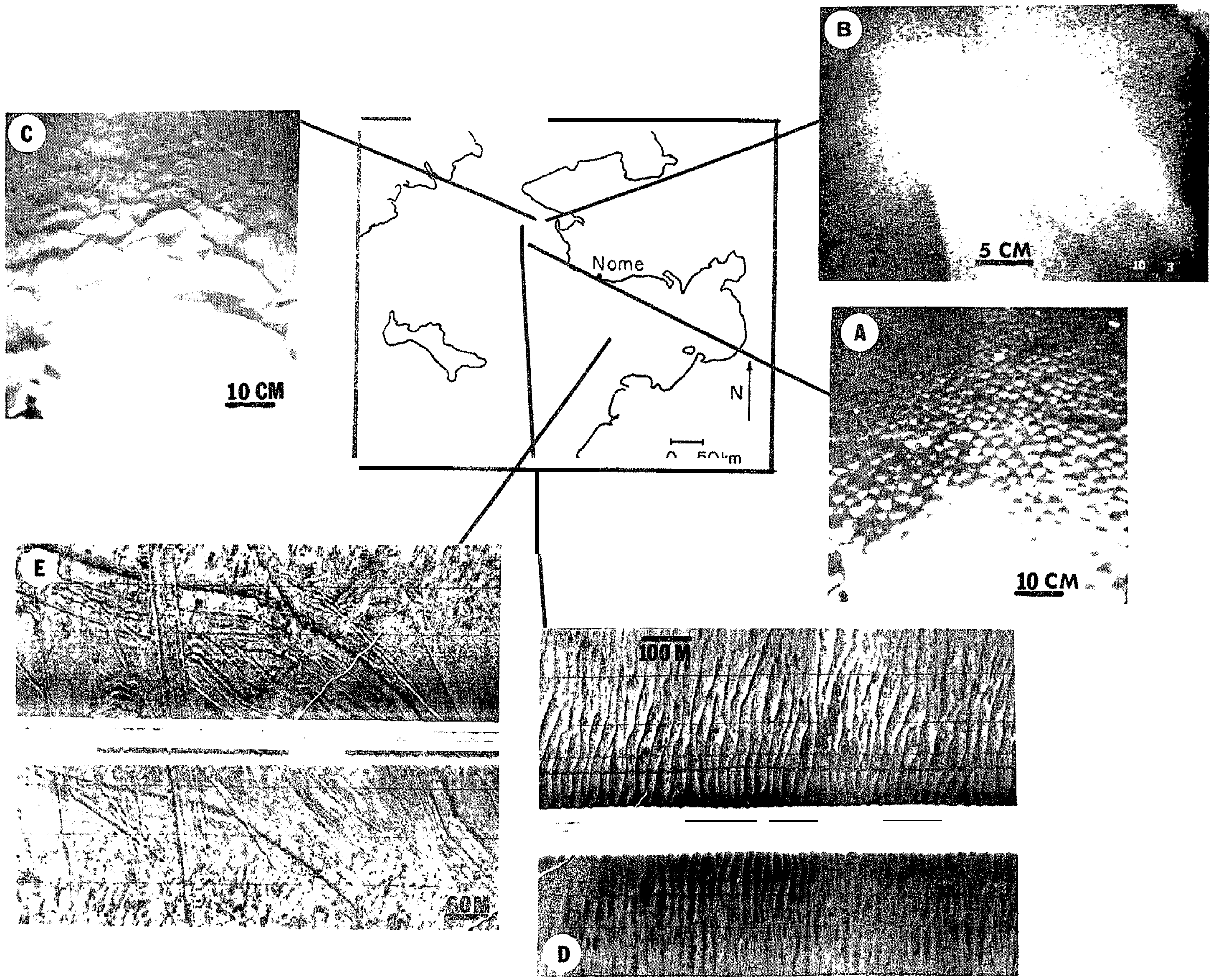
8B, E
13C
13D
60
A

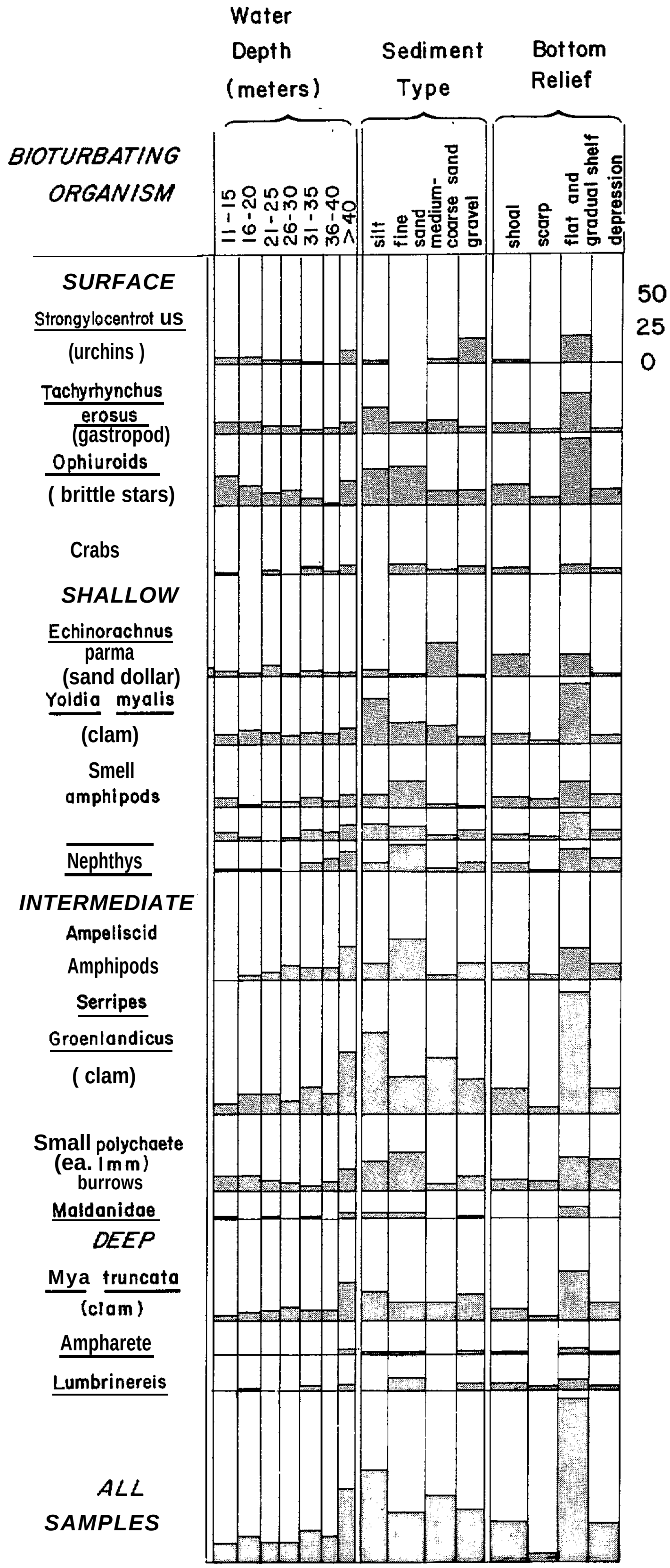

D
E
BRACKISH WATE
MARIN
Sandy Silt
Sandy Silt
F
DEPTH IN CORE (CM)
0
2
4
6
8
10
12
14
16
18
LATE HOLOCENE
1,740 ± 225 BP Teledyne Isotopes #I 8226
6,240 ± 115 BP Teledyne Isotopes #I-7481
7,180 ± 250 BP Teledyne Isotopes #I-7319
G
H
I
J

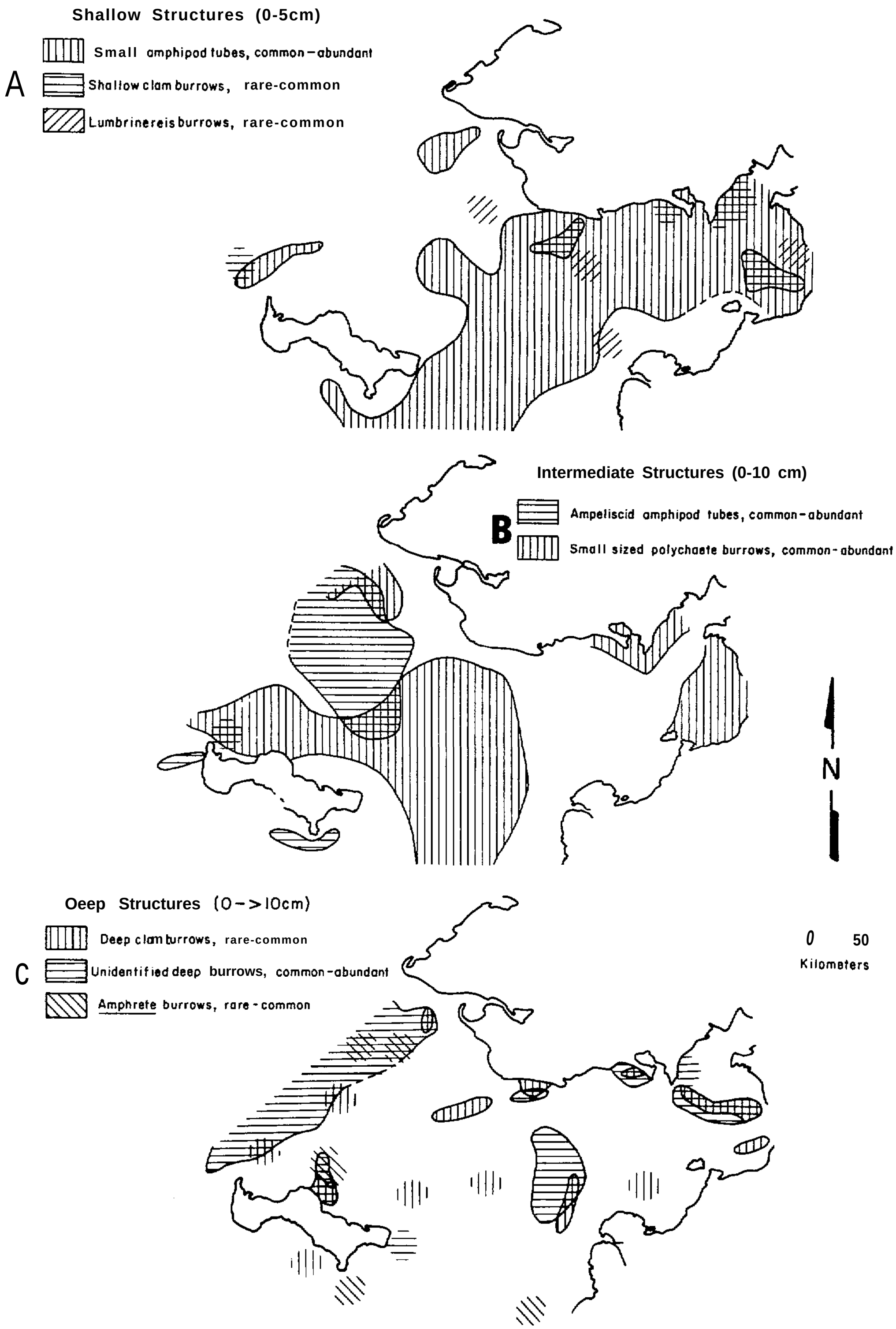


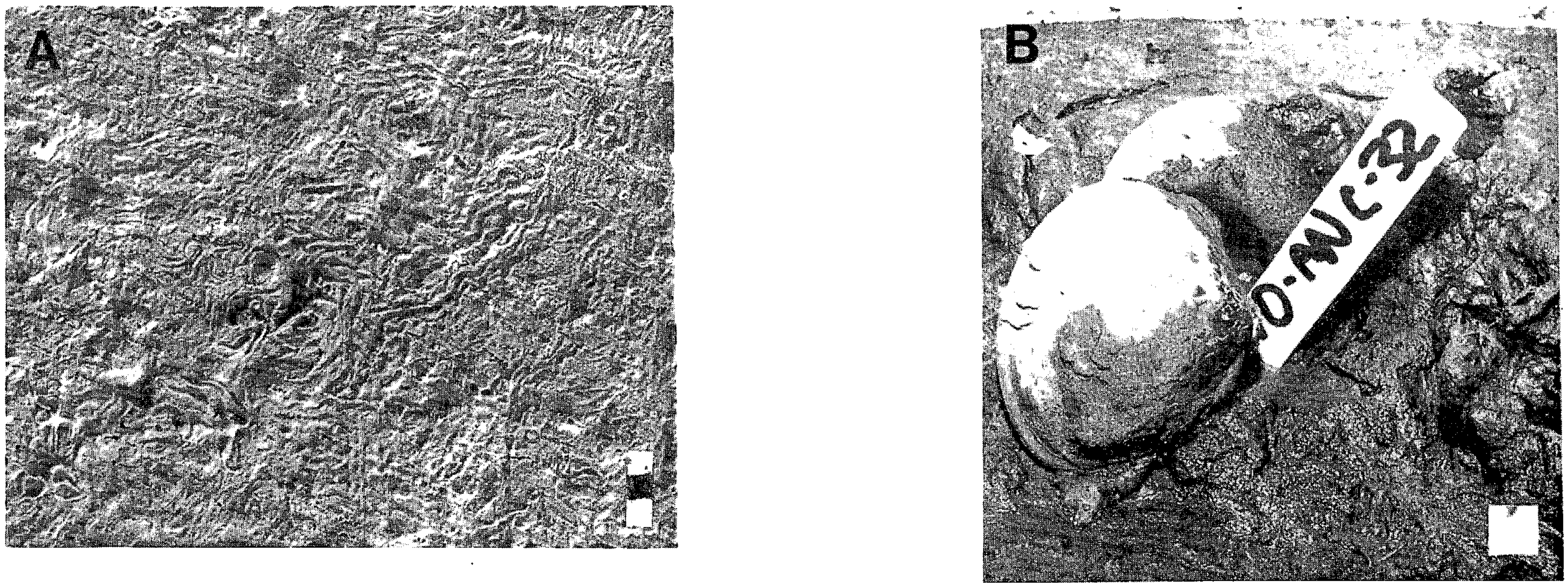
Water Depth (meters)
Sediment Type
Bottom Relief
Physical Structure
11 - 15
16 - 20
21 - 25
26 - 30
31 - 35
36 - 40
> 40
silt
fine sand
medium-coarse sand
gravel
shoal
scarp
flat and gradual shelf
depression
10
0
Pebble Lag
Shell Lag
Shell 81 Pebble Lag
Solitary Rafted Pebbles
Storm Sand Layers
Flat Lamination
Cross Lamination
Ripples
Ice Gouge
Strut ures in Gravels
Al I Samples


A
B
C
D
E

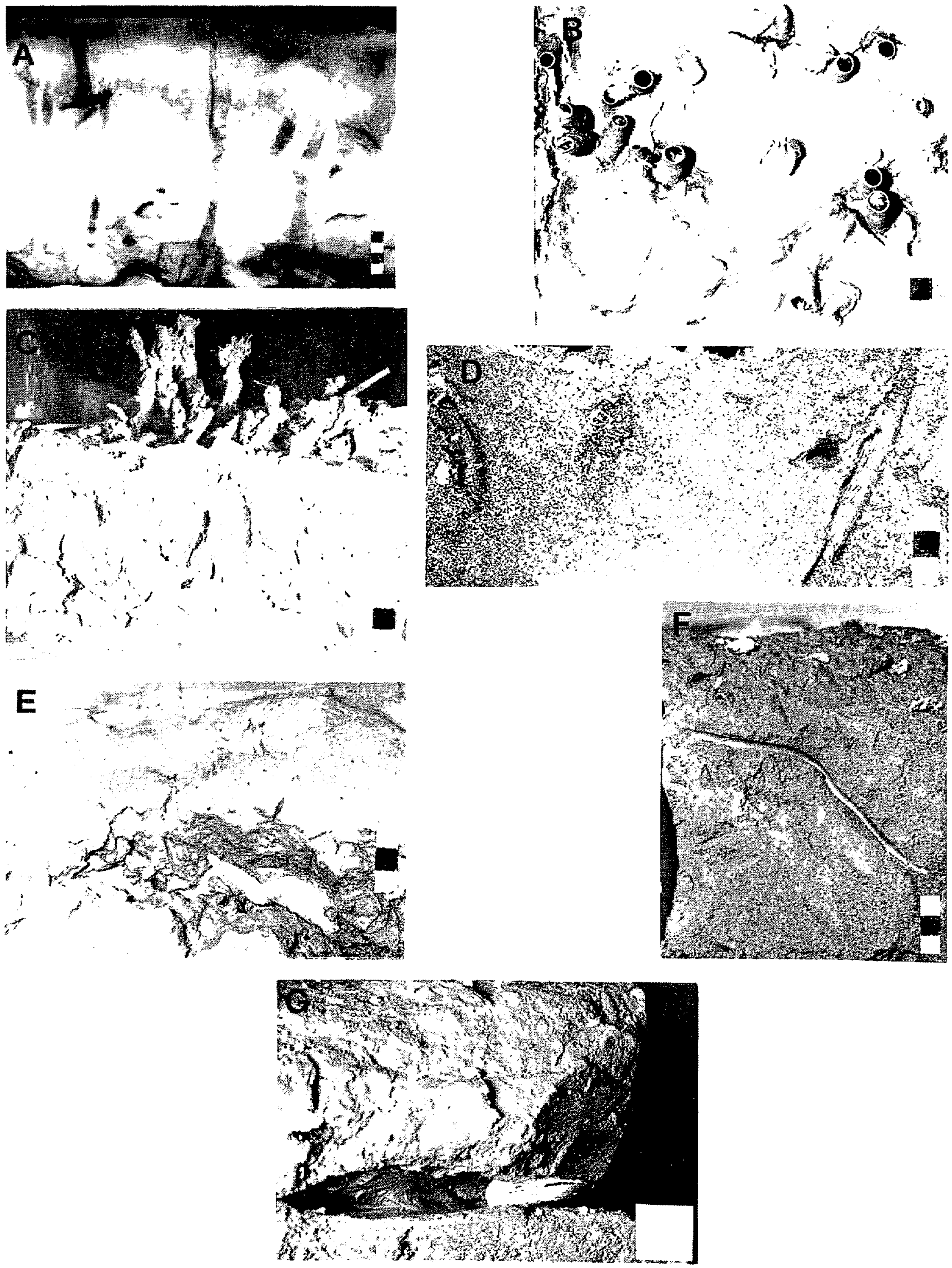

B
5 CM
C
10 CM
A
10 CM
Nome
N
E
60M
100 M
D


Water Depth (meters)
Sediment Type
Bottom Relief
BIOTURBATING ORGANISM
11-15
16-20
21-25
26-30
31-35
36-40
>40
silt
fine sand
medium-coarse sand
gravel
shoal
scarp
flat and gradual shelf
depression
50
25
0
SURFACE
Strongylocentrotus
(urchins)
Tachyrhynchus erosus
(gastropod)
Ophiuroids
(brittle stars)
Crabs
SHALLOW
Echinorachnus parma
(sand dollar)
Yoldia myalis
(clam)
Small amphipods
Nephthys
INTERMEDIATE
Ampeliscid Amphipods
Serripes Groenlandicus
(clam)
Small polychaete (ea. 1mm) burrows
Maldanidae
DEEP
Mya truncata
(clam)
Ampharete
Lumbrinereis
ALL SAMPLES

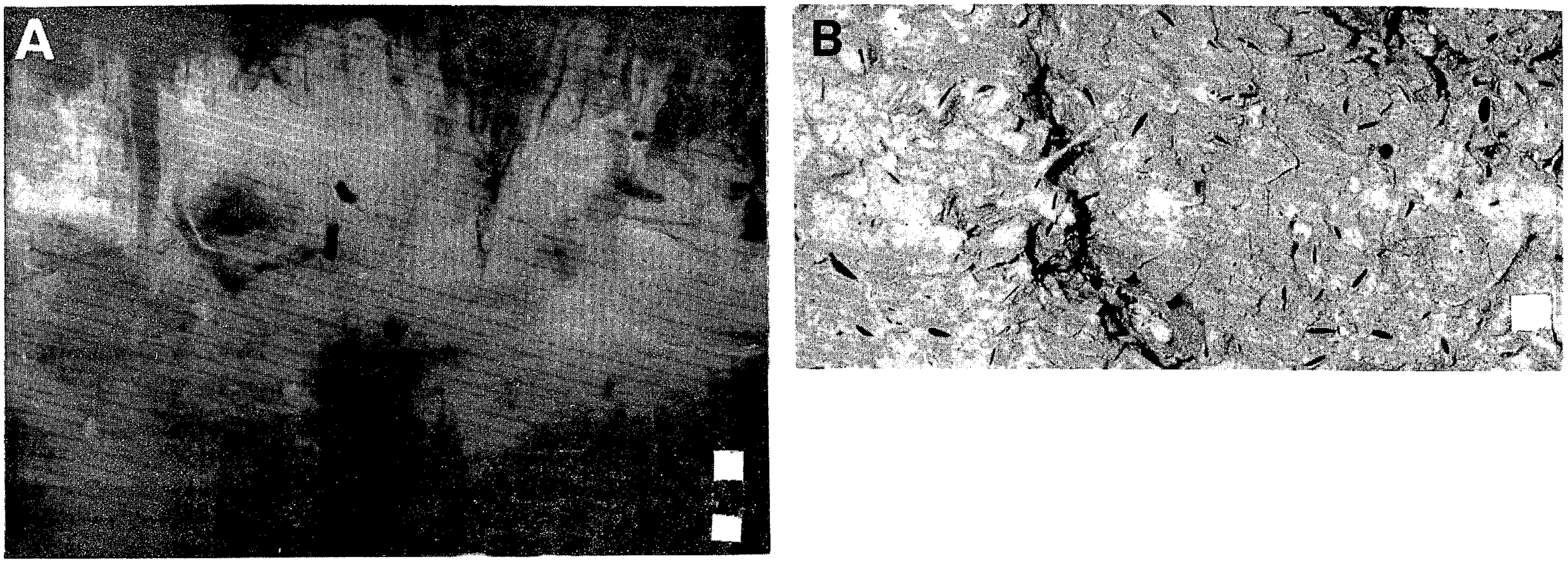

Shallow Structures (0-5cm)
A
Small amphipod tubes, common–abundant
Shallow clam burrows, rare-common
Lumbrinereis burrows, rare-common
Intermediate Structures (0-10 cm)
B
Ampeliscid amphipod tubes, common–abundant
Small sized polychaete burrows, common-abundant
N
Oeep Structures (0->10cm)
C
Deep clam burrows, rare-common
Unidentified deep burrows, common-abundant
Amphrete burrows, rare-common
0 50
Kilometers



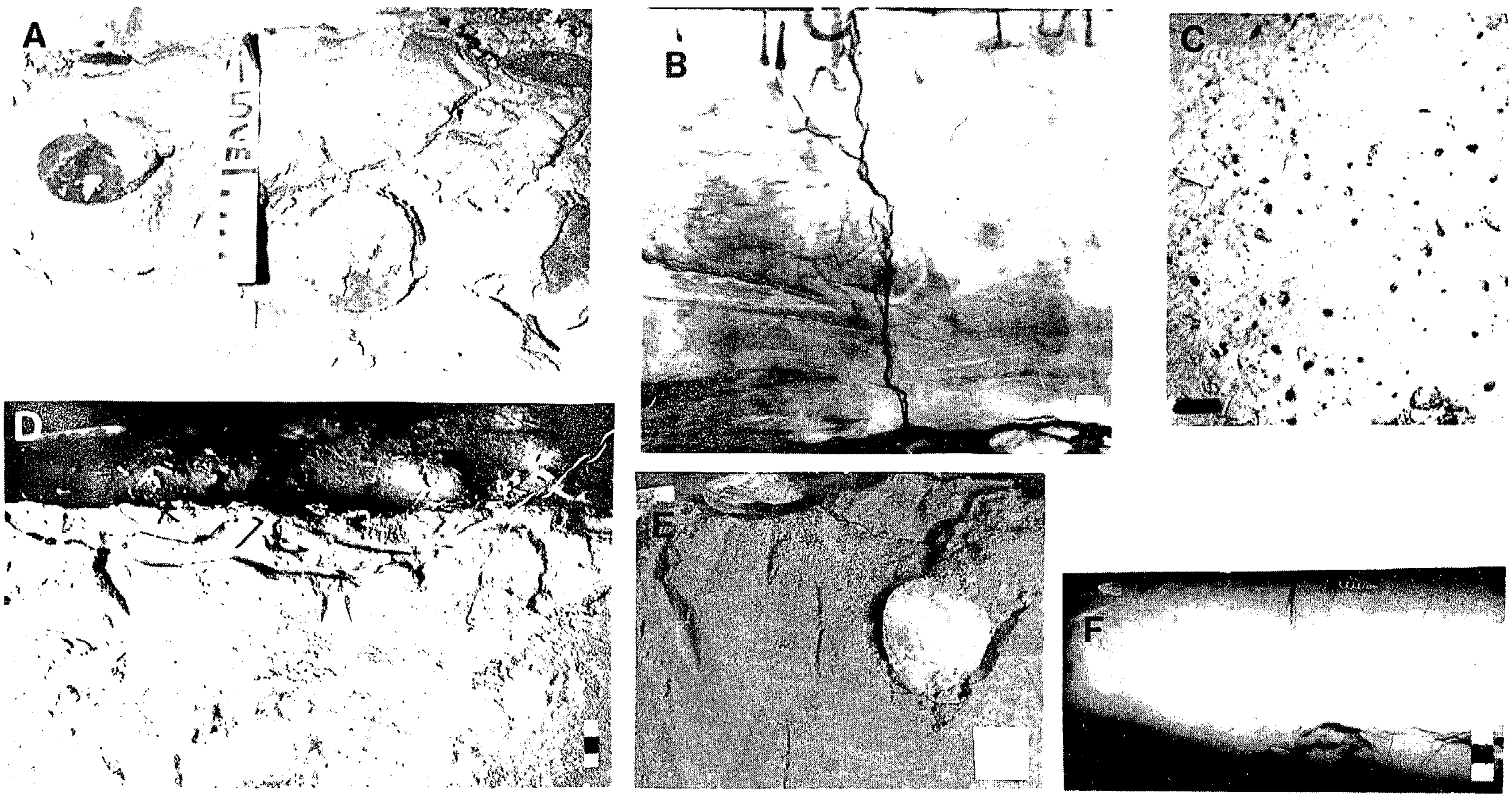
SURFACE DISTURBERS.



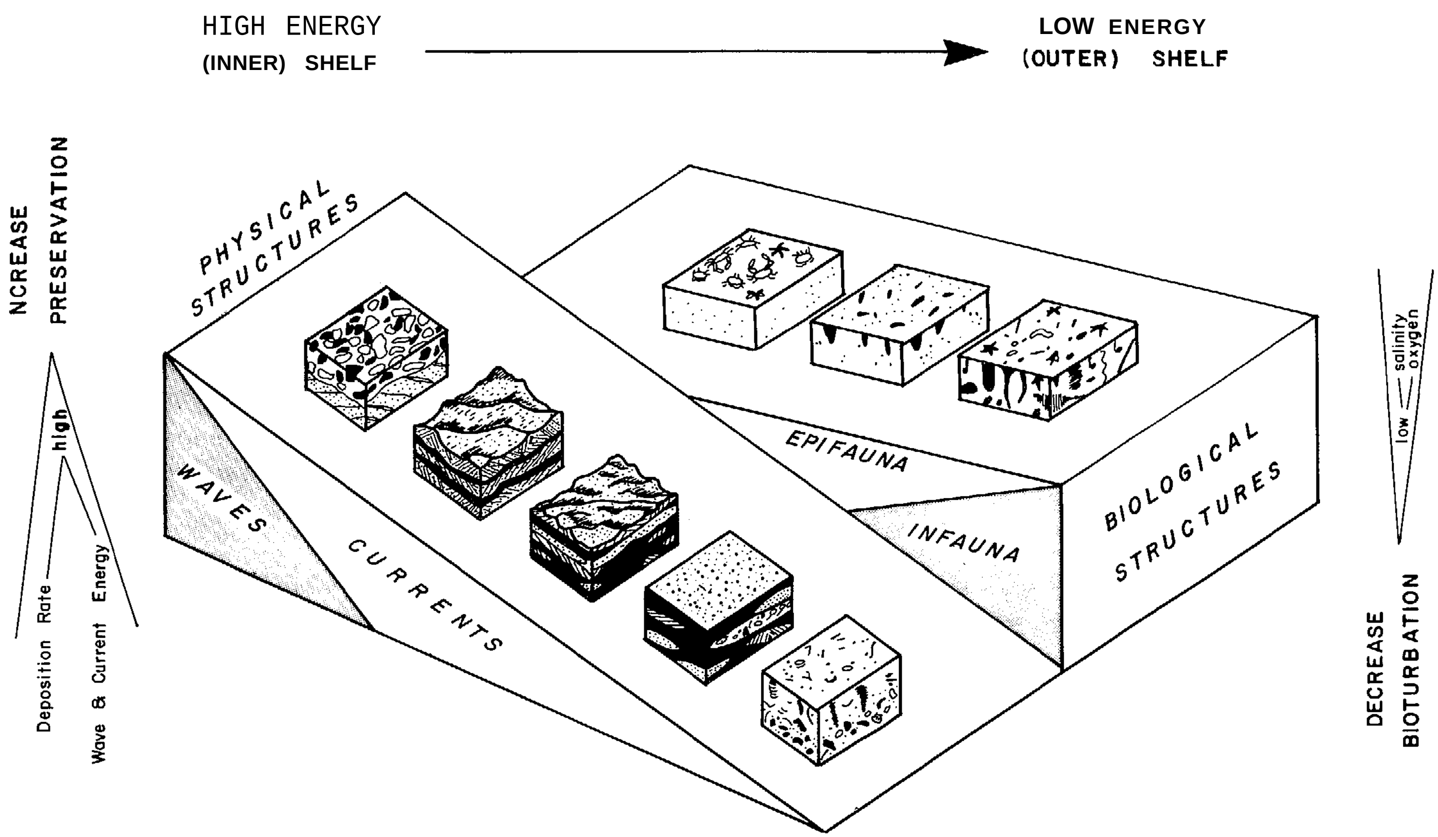
SHALLOW BURROWERS (0-5 CM DEPTH).



INTERMEDIATE BURROWERS (0–10 CM DEPTH)



DEEP BURROWERS (0->10 CM DEPTH).


HIGH ENERGY
(INNER) SHELF
LOW ENERGY
(OUTER) SHELF
NCREASE
PRESERVATION
high
Deposition Rate
Wave & Current Energy
PHYSICAL
STRUCTURES
WAVES
CURRENTS
EPIFAUNA
INFAUNA
BIOLOGICAL
STRUCTURES
low
salinity
oxygen
DECREASE
BIOTURBATION