High rates of bedload transport measured from infilling rate of large strudel-scour craters in the Beaufort Sea, Alaska

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ABSTRACT

Strudel scours are craters as much as 20 m wide and 4 m deep, that are excavated by vertical drainage flow during the yearly spring flooding of vast reaches of fast ice surrounding arctic deltas; they form at a rate of about 2.5 km^{-2} yr^{-1}. Monitoring two such craters in the Beaufort Sea, we found that in relatively unprotected sites they fill in by deposition from bedload in 2 to 3 years. Net westward sediment transport results in sand layers dipping at the angle of repose westward into the strudel-scour crater, whereas the west wall of the crater remains steep to vertical. Initially the crater traps almost all bedload: sand, pebbles, and organic detritus; as infilling progresses, the materials are increasingly winnowed, and bypassing must occur. Over a 20-m-wide sector, an exposed strudel scour trapped 360 m^3 of bedload during two seasons; this infilling represents a bedload transport rate of 9 m^3 yr^{-1} m^{-1}. This rate should be applicable to a 4.5-km-wide zone with equal exposure and similar or shallower depth. Within this zone, the transport rate is 40,500 m^3 yr^{-1}, similar to estimated longshore transport rates on local barrier beaches. On the basis of the established rate of cut and fill, all the delta-front deposits should consist of strudel-scour fill. Vibracores typically show dipping interbedded sand and lenses of organic material draped over very steep erosional contacts, and an absence of horizontal continuity of strata--criteria that should uniquely identify high-latitude deltaic deposits. Given a 2- to 3-year lifespan, most strudel scours seen in surveys must be old. The same holds true for ice gouges and other depressions not adjusted to summer waves and currents, although these features record events of only the past few years. In view of such high rates of bottom reworking of the shallow shelf, any human activities creating turbidity, such as dredging, would have little effect on the environment. However, huge amounts of transitory material trapped by long causeways planned for offshore development would result in major changes in the environment.

INTRODUCTION

The yearly spring flooding of vast expanses of fast ice on the inner shelf in the Arctic, and the commonly violent draining of these floodwaters through the ice, result in the formation of large scour craters called strudel scours. Strudel scours, and their subsequent sediment fill, are important erosional and depositional features of high-latitude deltaic environments (Reimnitz, et al., 1974); their recognition may serve as a criterion for identifying similar paleoenvironments. Industry considers strudel scours to be one of the most serious geologic hazards to pipelines on shallow-shelf areas affected by the phenomenon (L. J. Toimil, oral communication, 1981). The purpose of this report is to present data and observations on the infilling rate of two strudel scours in diverse environments of the shallow Beaufort Sea shelf near Prudhoe Bay, Alaska. Both scours are similar in size, with lips at 2.5-m water depth, but one is sheltered by a nearby barrier island, whereas the other lies on an exposed prodelta.

A comparison of the measured rapid rate of strudel-scour excavation and infilling with the generally slow rate of delta accretion in arctic regions demonstrates strudel-scour fill as an important compositional component of prodeltas. We present strong evidence that this strudel-scour fill consists of materials supplied almost entirely by bedload transport. Thus, the rate of infilling allows calculations of bedload transport rates that probably are more reliable than those obtainable by any other means known to us. Among the requirements for an efficient bedload transport sampler (Hubbell, 1964) are the following:

(1) it is very large compared to seabed relief, and therefore gives a good average,
(2) it should not alter bedload discharge by changing local flow patterns,
(3) it should collect the largest as well as the smallest bedload particles,
(4) it should give all particles an equal opportunity for entrance, regardless of size and direction of movement,
(5) sampler is stable, and
(6) sampling period is long relative to period of changing hydraulic conditions. As the strudel scours monitored meet these requirements better than most manmade devices, the bedload transport rates determined from this study should be close to actual rates of transport.

Wave and current reworking of the inner-shelf surface is restricted to the short open-water season starting in July and extending to the onset of freezeup in late September to early October. Current-meter records from November to January show maximum flow velocities decreasing from 10- to less than 2-cm s^{-1} (Matthews, 1981). On diving operations under the ice during the winter, we have observed signs of only very low current velocities. Under-ice current observations made during the time and within the area of overflow are too sketchy to indicate whether reworking of bottom sediment occurs during overflow. Currents do not increase noticeably until about mid-July, when the ice breaks up (Barnes, 1982). The rivers of northern Alaska begin carrying water to the sea by the end of May or early June, when the fast ice is 1.7 to 2 m thick and still intact. This ice is inundated by 0.5 to 1.5 m of fresh water for distances of as much as 15 km or even more from the river mouths (Reimnitz and Bruder, 1972; Reimnitz et al., 1974; Walker, 1974). Figure 1 shows a part of the Beaufort Sea shelf in the vicinity of the Prudhoe Bay oilfields at a time when those rivers with headwaters in the Brooks Range are beginning to flow, while those with drainage basins entirely within the coastal plain are still dormant.

When the coastal-plain drainage systems thaw and the flooding is at its maximum, the inundated ice areas may nearly merge, especially between the Colville and Kuparuk Rivers. Within a few days, however, most of the floodwaters drain off the ice. This draining occurs at orifices within the ice (Fig. 2) that serve as focal points for vertically oriented axial jets with vortical motion; these orifices are called strudel, after the German word for "whirlpool" (Reimnitz and Bruder, 1972). Because seawater depths in the flooded areas are generally shallower than 6 m, the vertical jet encounters the bottom and may excavate craters more than 4 m deep and 20 m across (strudel scours) below the drainage points. The formerly flooded areas of fast ice generally show only very small amounts of fine-grained surficial sediment after draining is completed (Reimnitz and Bruder, 1972). There is a

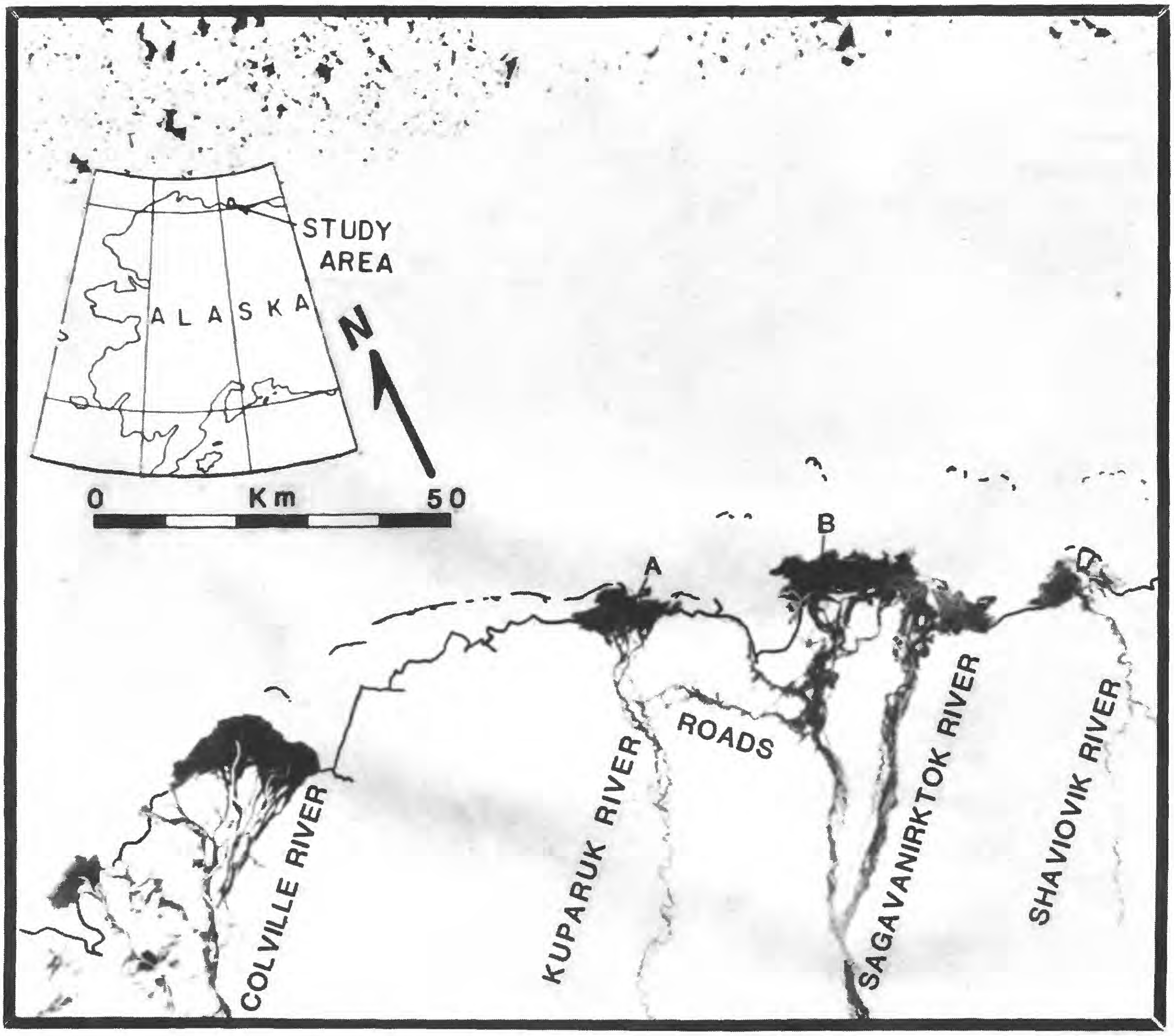

Figure 1. Landsat image of Prudhoe Bay area (between A and B) on June 6, 1976, showing larger rivers flowing out across the fast ice. In many years, flooded ice areas nearly merge in this area.

Figure 2. Overflow water from Kuparuk River draining at a strudel situated on a crack in 2-m-thick fast ice. Overflow at this point is estimated to be 1 to 1.5 m deep, and the water below the ice is 1 to 2 m deep. Distance across center of the photograph is about 15 m.

growing body of information indicating that the Sagavanirktok River contributes very little sediment at the time of river overflow.

The Holocene marine sediment in the study area are only 2 to 10 m thick (Reimnitz, et al., 1974), and delta accretion is virtually absent in the area (Reimnitz, et al., 1979). This Holocene sediment generally consists of fine muddy sand (Barnes, et al., 1980); the underlying Pleistocene sediment ranges in composition from overconsolidated silty clay (Reimnitz and Kempema, 1980) to gravel (Reimnitz et al., 1974). In most areas this older sediment lies within the range of modern strudel penetration, and deposits of relict and modern sediment are mixed by the scouring action. This mixing results in wide lateral variation and great complexity in the surficial-sediment types in the areas affected by strudel scour (Reimnitz et al., 1974; Barnes et al., 1980). High-resolution seismic records taken within the area of river overflow show an absence of coherent subbottom reflectors because of the cut-and-fill process. Vibracores taken in arctic shallow-water-delta areas contain sedimentary structures interpreted as representing strudel scour fill (Barnes, et al., 1979); as discussed below. These structures, however, are small and lack horizontal continuity, and so they are not resolvable on the seismic records. Previously, Reimnitz et al. (1974) speculated that strudel-scour relief seen near river mouths may represent several decades of strudel scour and that the scours fill in only slowly; the present studies, however, indicate otherwise.

METHODS OF STUDY

The key to the study of the infilling rate of strudel scours was precise navigation, which allowed us to revisit the same strudel scours in successive field seasons. This precision was provided by range/range navigation systems (Del Norte Trisponder and Motorola Miniranger*) aboard the 13-m research vessel <u>Karluk</u>. Side-scan sonar and a narrow beam high-resolution fathometer were used to locate and survey particular strudel scours. To determine the maximum depth of a particular crater, many crossings were made in various directions, with closely spaced buoys used as reference points. Once the deepest point of the crater was located, we let the boat drift across with the fathometer running. This technique provided detailed cross sections.

One of the two strudel scours monitored was also marked by a metal post driven by divers into the center, by a 45-kg weight placed next to the post, and by a 35-m-long steel cable stretching from this weight to a Danforth anchor well away from the rim of the crater. The cable was located in successive years and led divers back to the post. The post was notched at 10-cm intervals to provide detailed observations of sediment accretion.

RESULTS

<u>Strudel scour A</u>

One of the strudel scours monitored is located near Egg Island Channel (A, Fig. 1), a tidal channel connecting Simpson Lagoon with the open ocean.

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The bathymetric map (Fig. 3) is the result of a detailed bathymetric survey of the channel on September 3, 1978, during which we crossed the strudel scour. Figure 3 shows the position of the strudel scour, the trackline crossing it, and the fathogram recorded along this track. In this fathogram, the axis of Egg Island Channel lies at a depth of 6 m, the center of the strudel scour at 5.5 m, and the surrounding lagoon floor at 2.4 m. No attempt was made, however, to determine the maximum depth of this crater during this first year of record, although from past experience with strudel-scour surveys, a maximum depth of 1 m greater than shown on this chance crossing is likely.

Strudel scour A was resurveyed on August 24, 1980, with more than 20 trackline crossings; Figure 3 shows the deepest cross section recorded. The crater was still a symmetrical cone, but its maximum depth in 1980 was 4.4 m. Considering that 2 years earlier the strudel scour was more than 5.5, possibly 6.5, m deep, 1.5 to 2.1 m of sediment had accumulated within that period. Sediment reworking is known to occur from July through September, but may also occur during the overflow in June. Therefore the strudel scour actually trapped sediment for 8 months, at a rate of 15 to 25 cm of sediment per month.

Strudel scour B

A specific side-scan-sonar search for strudel scours on the Sagavanirktok delta on September 17, 1978, resulted in the selection of strudel scour B (Fig. 1) in an area generally 2.5 m deep. The base of the scour-crater was 3.5 m below the surrounding sea floor, and the crater was 16 to 25 m in diameter (Fig. 4). The side-scan sonar shows the surrounding sea floor marked by an irregular pattern of distinct curving to jagged reflectors, visible on the fathogram as 20- to 30-cm-high ledges (northeast side of strudel scour, Fig. 4). During dives across this terrain along the steel grappling cable, we found small scarps cut into bedded firm sandy silt, which could be broken off by hand; low terrain between these scarps was blanketed by fine sand. The upper lip of the crater itself was a 10- to 50-cm-high scarp cut into bedded sandy silt. Entering the crater from the east side and descending to the floor, we first traversed several small scarps of bedded silt, thinly draped by soft sandy sediment at the angle of repose. In the lower half of the strudel scour was muddy sand, 20 to 70 cm thick, sloping evenly toward the center at an angle of about 30°. Although visibility inside the crater was very poor, we could feel the floor as a dish-shaped depression covered mainly by coarse fibrous organic matter, including sticks and branches. Driving a 3-m-long metal fencepost with a sharpened tip to about 80 cm presented little difficulty, but afterward this fencepost could be driven no farther by pounding with a 1.8-kg mallet. We believe that this point represents the original bottom of the strudel scour and that the scour was originally 80 cm deeper than at the time of our survey. Ascending, we found the west wall to consist entirely of firm sandy silt, forming ledges 50 to 80 cm high, overhanging in places as much as 50 cm, and lacking any soft sediment cover; several ledges were rich in fibrous organic matter. Slight angularity of the firm faces of the ledges which had sharp edges, suggested erosion by undercutting and calving of firm materials. A large sample of organic material from the floor of the scour contained a few pebbles up to 5 cm in diameter, algal debris along with distinctly terrestrial organic material, and muddy sand.

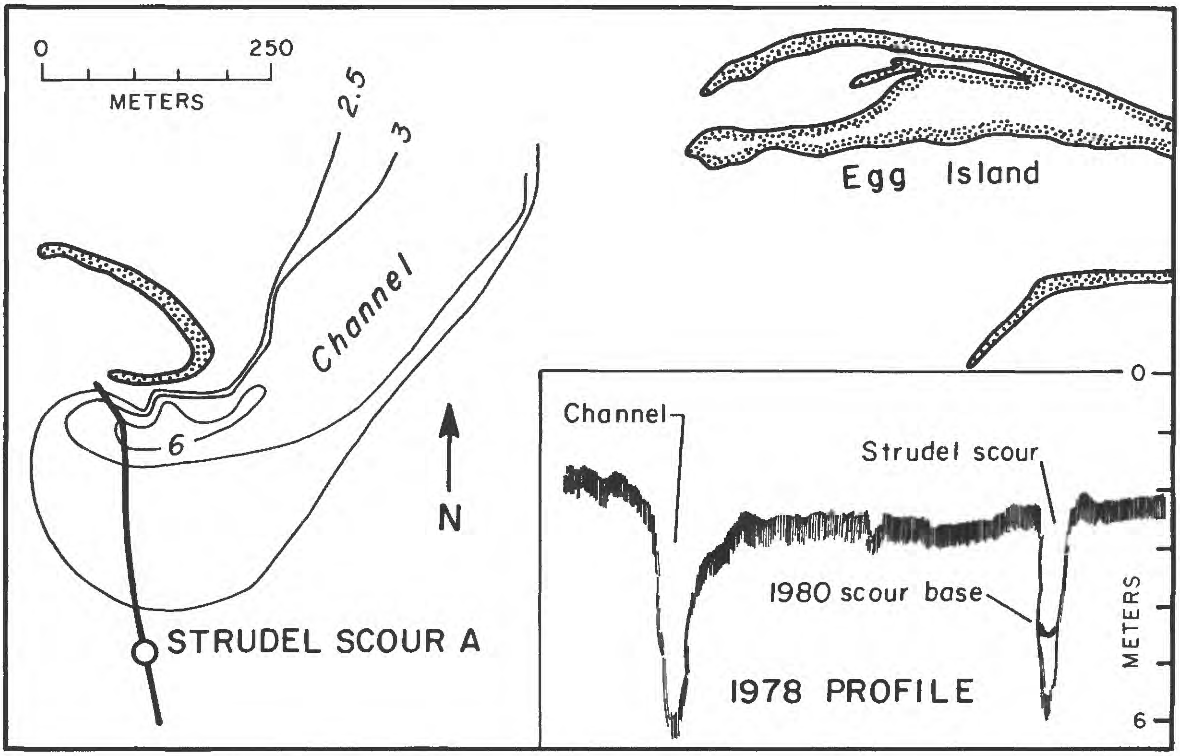

Figure 3. Site of strudel scour A adjacent to Egg Island Channel, in relatively sheltered locatity. Inset shows fathogram across tidal channel and scour in 1978, with 1980 profile superimposed. 1978 crossing of strudel scour A was by chance, and scour could have been deeper than actually measured.

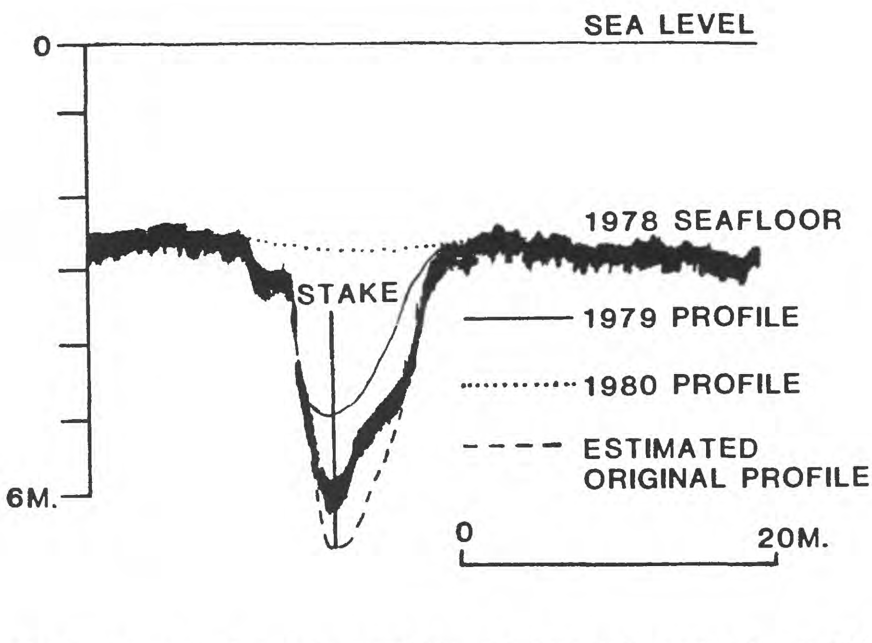

Figure 4. Fathogram of deepest profile of strudel scour B in 1978, and two successive years. Divers found vertical walls on upper 1 m of left (west) side and estimated original scour depth by driving the stake shown.

Divers revisited the strudel scour on July 26, 1979 by following the steel cable to the pole, where the cable disappeared in very soft fill. At least surficially this fill was muddy sand and again formed a dish-shaped, rather than a flat, crater floor. Measured against the fencepost, 85 cm of material had accumulated since September 19, 1978 (Fig. 3), preferentially on the east side of the scour. Assuming that this sediment must have accumulated during a 10-day period in September 1978 and a 2-month period (June-July) in 1979, the sediment accumulation rate was 35 cm mo^{-1}. Divers again descended on strudel scour B on August 22, 1980; by this time major modifications had occurred on the sea floor, and the strudel scour was nearly filled in. We followed the cable to the point where it disappeared vertically into the sediment, extending toward the former strudel-scour floor.

The surface of the strudel-scour fill was rippled fine sand. The top of the fencepost did not protrude because we had purposely kept it below the level of the surrounding terrain to avoid ice damage. Extending away from the crater, the cable was slack, draped across or around ledges of firm bedded sandy silt with angular fresh-appearing scarps as much as 50 cm high. Between ledges, the cable was deeply buried in fine muddy sand that required considerable effort to clear. Figure 5 shows a sonograph of the rough terrain adjacent to strudel scour B, as recorded on the date of the final inspection, when 2-m visibility and fresh-appearing exposures on this day allowed a closer study of the firm friable bedded sandy silt exposed in scarps. Individual bedding planes were highly contorted on a small scale and over distances of 1 to 2 m showed large-scale distortions that changed the attitude from horizontal to nearly vertical. Bedded exposures in places were rich in coarse fibrous organic material.

In the period between the 1979 and 1980 observations of strudel scour B at most 4 months of open-water and sediment-transport conditions and infilling of the strudel scour elapsed. During this period, 2.65 m of fill accumulated in the scour, at an average infilling rate of approximately 60 cm mo^{-1}.

SPACING OF STRUDEL SCOURS

Reimnitz et al. (1974) used side-scan-sonar records to map the distribution of strudel scours in coastal areas of the Beaufort Sea. Because of the difficulties in identifying with certainty all strudel scours within the seafloor areas scanned, they preferred to present only counts of strudel scours per kilometer of ship's track rather than per square kilometer of sea floor. Many additional years of shallow-water work in the same areas have convinced us that those original counts (max 25 scours km^{-1}) are much too high. Not all isolated patches of high reflectivity are strudel scours, and positive identification requires considerable fathometer-survey time. Therefore, we used the best available aerial photographs for counting the number of strudels in the ice canopy of the study area. Figure 6 shows the Sagavanirktok delta June 26, 1970, when one of us also made ground and aerial observations in the area. All the river water had drained off the ice 2 to 3 weeks earlier, and only the outer fringes of the formerly inundated ice remained intact. In counting the number of strudel, we drew large circles to mark areas with distinct apparently coherent channel patterns on the ice. S rficial drainage channels feeding a particular strudel do not seem to extend

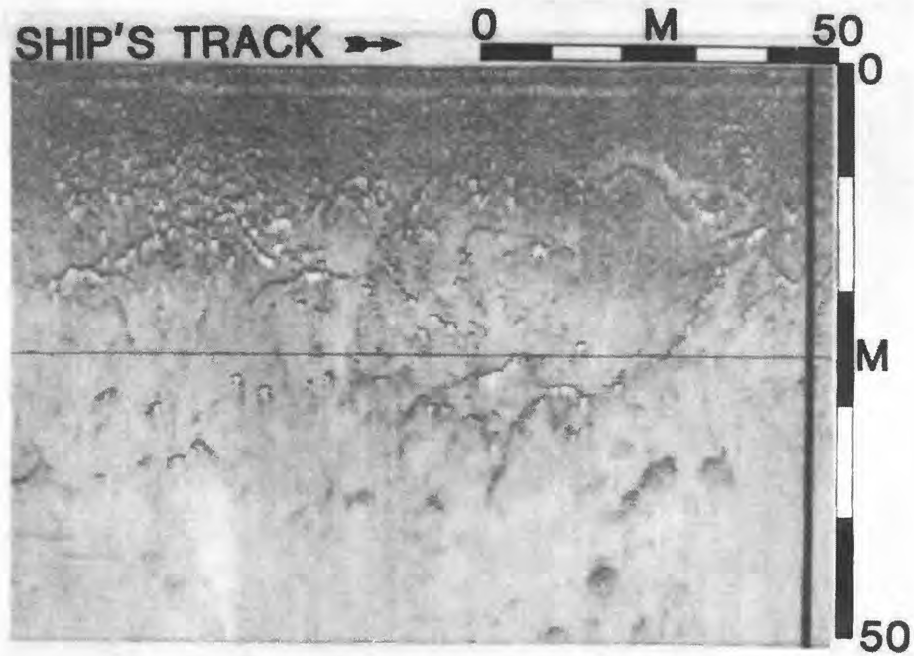

Figure 5. Sonograph of sea floor adjacent to strudel-scour B after complete infilling in 1980, showing the rough relief with fresh-appearing ledges seen by divers.

farther than about 100 m; thus, even where the exact spot of drainage through the ice cannot be detected in this photograph, a strudel lies somewhere within each circle. These circles mark major strudel, likely to result in substantial bottom excavations; in addition, however, many more minor strudels are present. In the ice areas so studied, there were an average of 2.5 major strudel per square kilometer.

DISCUSSION

The two strudel scours monitored in this study, situated in strongly contrasting environments, were quickly infilling natural sediment traps. Strudel scour A was sheltered from all sides by barrier islands or by areas shallower than 2 m. Westerly storms, resulting in high sea levels, could provide for longer fetch than the predominant northeasterly wind and, probably, for bottom reworking at the site, but such storms did not occur during the monitoring period. Thus, sediment transport in the area was associated mainly with currents flowing through the nearby tidal channel. The flow is either lagoonward or seaward, and we have measured surface current velocities unrelated to tides of about 100 cm s^{-1}. A current-meter array deployed in the axis of the tidal channel from May to November 1979 was buried by sediment to about 2 m above the original channel floor during a period of several months (Brian Matthews, oral communication, 1979). The lower accumulation rates in the strudel scour, not subject to scouring by horizontal currents, are unexplained.

Strudel scour B is exposed to a fetch of 20 km from the northeast, the dominant wind direction. Much of the area between strudel scour B and the windward barrier islands has a water depth of 6 to 7 m; furthermore, there is no flow obstacle to wind-driven currents that develop here with easterly winds (Barnes, et al., 1977). The more exposed position of this site relative to that of strudel scour A probably accounts for the more rapid infilling of strudel scour B.

A current meter moored at a depth of 5.5 m several kilometers north of strudel scour B for most of one summer recorded mainly westerly currents, averaging 15 cm s^{-1} but peaking at 53 cm s^{-1} (Barnes et al., 1977). No major storms occurred during those 52 days of recording, although peak velocities were high enough to move coarse sand easily. Also, numerous bottom drifters released in Stefansson Sound washed ashore far westward of their release points (our own unpublished data, 1979); thus, net water movement near the bottom clearly is westward. The magnitude of westward bedload transport at another site on the Sagavanirktok delta, with nearly identical setting and 2.5-m water depth, during 13-m s^{-1} easterly winds, was documented during a diving investigation in 1976 (Reimnitz and Toimil, 1977). Near-bottom currents of 25 to 50 cm s^{-1} moved fine sand, kelp, willow leaves, grassy material, and twigs in 1- to 2-m-wide current-parallel streaks. At the time of the investigation, divers observed drag marks formed by pebbles with attached kelp moving along the bottom.

These data and the following additional observations on strudel scour B suggest that its fill represents largely bedload transport: (1) the fathogram and diving observations show an asymmetric cross section, with the deepest

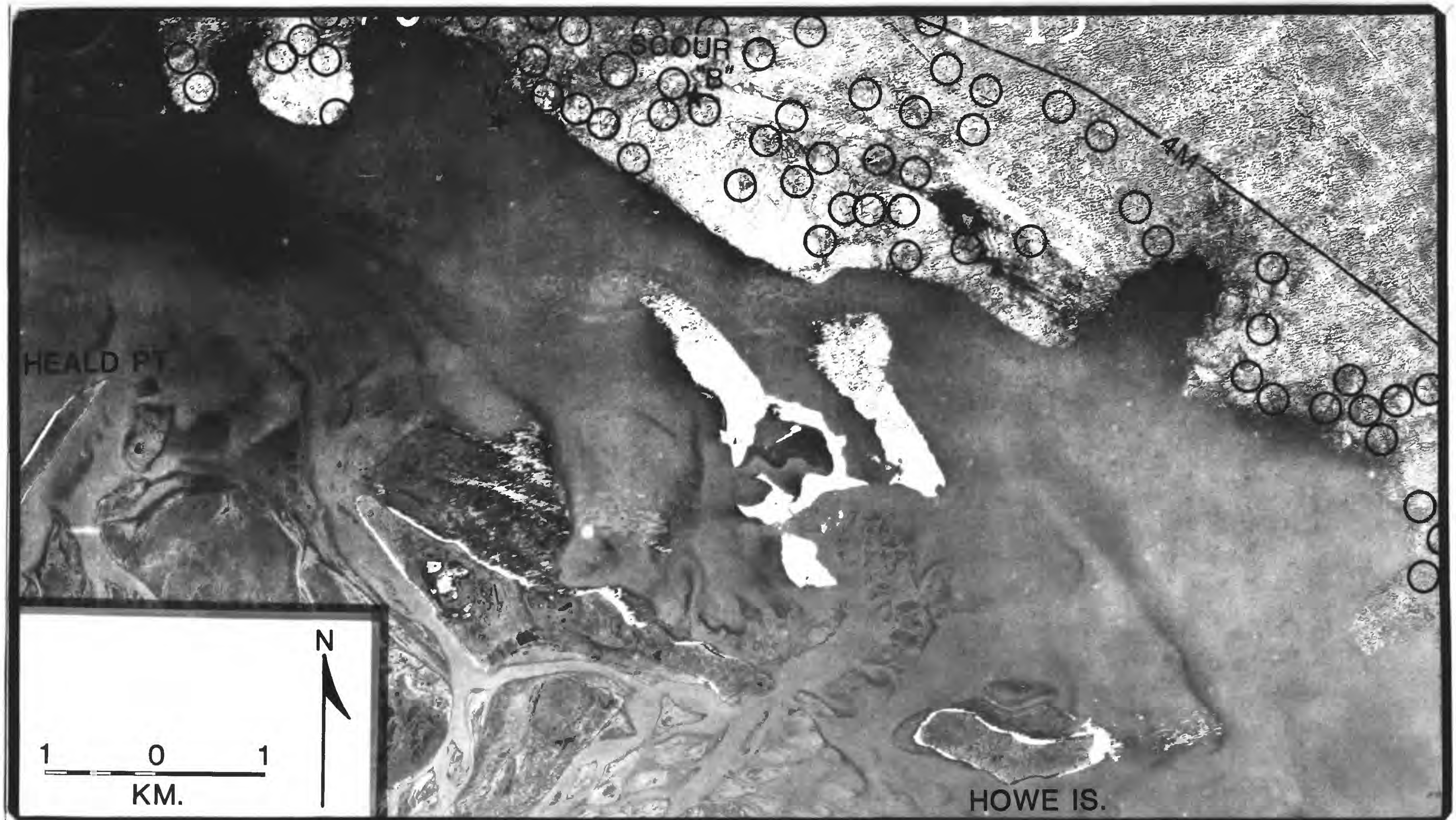

Figure 6. Orthophoto of Sagavanirktok delta showing remnants of fast ice on June 26, 1970. Drainage systems feeding former strudels are circled.

point closer to the southwest wall and foreset beds of fine sand draped at the angle of repose from the northeast lip of the crater toward the center; (2) the fill consists largely of sand-size material, coarse fibrous organic matter, and a few pebbles, whereas summer-suspended matter is largely silt and clay size (Drake, 1977); the fibrous organic matter is rarely seen on the sea surface but is abundant on the bottom, and (3) observed at two intermediate stages of infilling, the strudel scour was conical, whereas infilling from suspension load should have resulted in nearly horizontal bedding planes and a flat floor.

Another strong argument in support of our contention that the strudel-scour fill represents mainly bedload transport is provided by the data from seven suspended-sediment traps deployed nearby in 1980. These traps, which had orifices of 30.5 cm at a height of 30.5 cm above the bottom, were placed in a 2-km^2 area 4 km east of our study area, at a water depth of 3.5 m, from mid-July 1980 to about the end of the year. During these 5 to 6 months of deployment, an average of 13.5 cm of sediment accreted in the traps (Northern Technical Services, 1981). This accumulation, representing approximately one seasonal sediment-settling cycle, was an order of magnitude lower than the accretion rate in strudel scour B.

During the 1978 and 1979 diving inspections, we found coarse fibrous organic matter and a few pebbles near the bottom of the crater; higher above these organic deposits, sandy materials rested along the sides. During the final inspection dive, when infilling was complete, the surficial deposits of the strudel scour consisted of clean sand. This vertical sequence of materials probably is typical of all strudel scour fill in this area. The internal sedimentary structures of strudel-scour fill should reveal the mechanism of lateral infilling, and sediment textures should show better sorting higher up, and during the final stages of infilling.

In support of the above speculation on the nature of strudel scour fill, Figure 7 shows a 1.5-m-long vibracore collected 2,000 m southwest of strudel scour B. Barnes et al. (1979) reported that this core is typical of a series of 12 cores taken in shallow waters on four arctic river deltas. Only features relevant to strudel scouring of the seabed, and the strudel-scour infilling are mentioned here. The core shows evidence of several erosional episodes: ripup material and mudballs, a thick unit of coarse fibrous organic matter on an erosional surface, and a thick unit of steeply dipping bedded sand on an erosional surface; the core also contains several ripple-bedded sand units. The orientation of the coring device was recorded, and the beds dip westerly. This core may record several scour-and-fill events. Most important, very little sediment suggestive of settling from suspension is seen in this and the other 11 shallow-delta cores of Barnes et al. (1979); the bulk of the material probably was supplied as bedload, and deposited in scour depressions. The structures observed by divers in 30- to 50-cm-high ledges on the sea floor surrounding strudel scour B could also well fit the concept of erosion, bedload transport, and deposition, as described above.

Assuming that the fill of strudel scour B indeed represents bedload and that the crater is an efficient trap, we can use the rate of infilling to calculate the rate of bedload transport past the site. A north-south oriented cross section of the crater measured 20 m wide at the sea floor; the crater volume, calculated from the first-measured profiles and assuming a conical

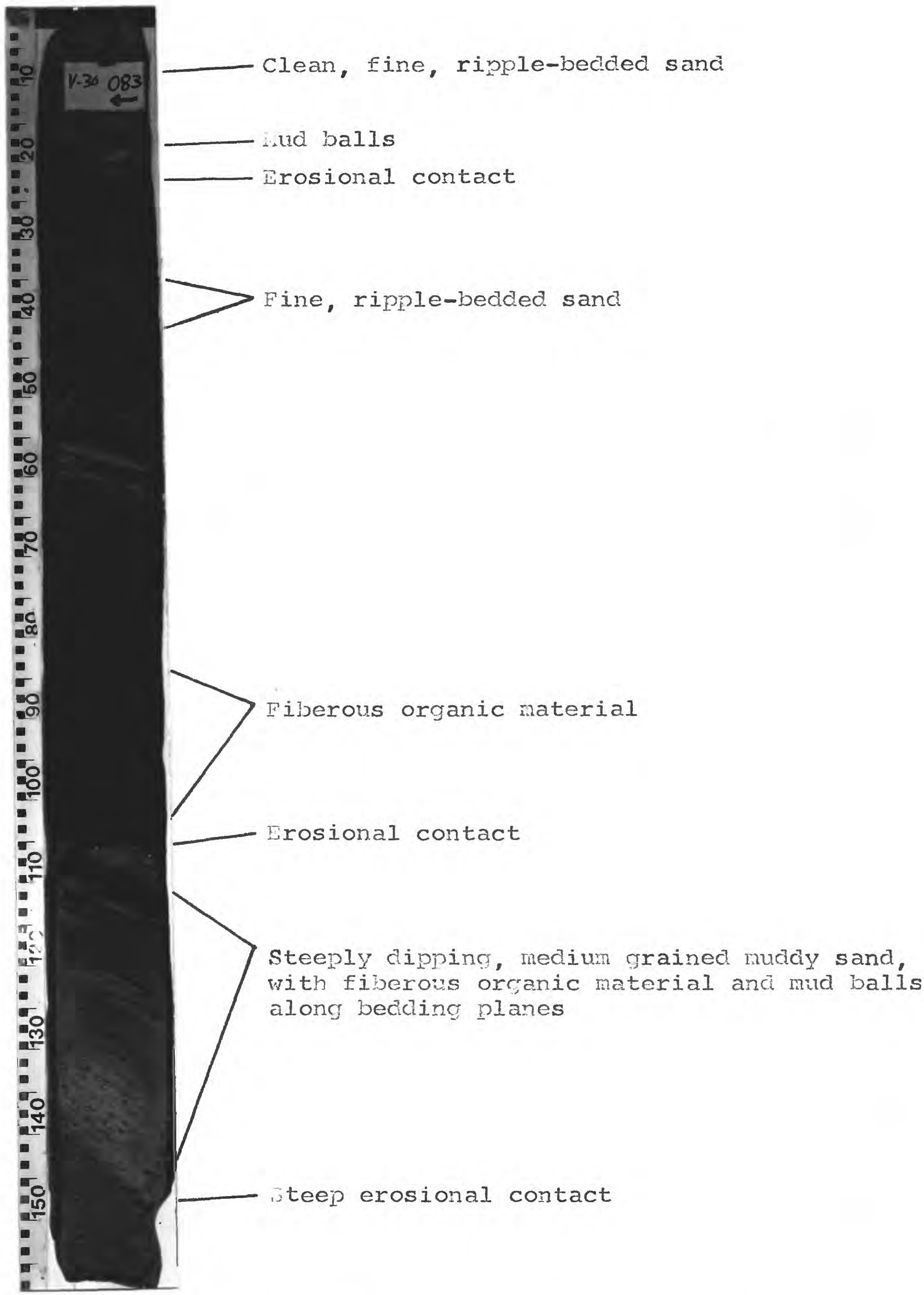

Figure 7. Resin peel of a vibracore taken 2,000 m from strudel scour B. Core records several scour-and-fill events. Core is oriented with right side to west (from Barnes et al., 1979).

shape, was 360 m^3. In reality, the original shape was probably more cylindrical than conical, judging from the nearly vertical west wall. Thus, the crater collected 180 m^3 yr^{-1} of bedload; divided by the 20-m width of the trap, the bedload transport rate past a 1-m seafloor segment is 9 m^3yr^{-1}. During the final stages of infilling, the well-sorted sands collected to form a cap for the fill, and the former crater was no longer an efficient trap for bedload. We believe that the final stages of infilling occurred during particularly windy fall days of 1979, not during the summer of 1980, when we last looked at strudel scour B. Thus, because of the decreasing efficiency and early completion, and the conical shape conservatively used in the calculations, the actual bedload transport rate certainly is higher than the calculated rate. Because weather records for the two seasons of bedload trapping show very little westerly wind influence, the calculated bedload-transport rate probably nearly equals the net westerly transport rate.

The following considerations will demonstrate the significance of the above measurements. The transport rate of 9 $m^3yr^{-1}m^{-1}$ past strudel scour B, which probably applies to a wide area, suggests very high rates of sediment movement on the shelf. The delta front, from the shore to the 3-m isobath, is a gently sloping surface, which, at right angles to westerly transport, is about 4.5 km wide. Strudel scour B lies near the outer edge of this platform, where transport rates probably are lower than at shallower depths shoreward. Applying the measured transport rate to the total width of this platform gives a value of 40,500 m^3yr^{-1} of sediment, most likely a conservative estimate. Nummedal (1979), on the basis of his own calculations and a summary of published data from the north shores of Alaska, estimates the transport rate along present barrier beaches at "a few tens of thousands of m^3yr^{-1}." This longshore-transport estimate nearly equals our measured bedload-transport rate over only a narrow segment of the shallow shelf. Resolution Island, an artificial island built several hundred yards from strudel scour B, contains 131,000 m^3 of gravel, a small volume relative to the sediment volume moved by nature. As another comparison, the base of the Holocene marine sediment in the area, or the base of the modern Sagavanirktok River delta seen in seismic reflection records, lies only 2 to 3 m below the sea floor; This depth was confirmed by drilling (Evans, et al., 1980).

The high rates of bedload transport, together with the low rates of sediment accretion, attest to the dynamics of this depositional environment. The fresh ledges observed by divers and seen on side-scan sonar, and the deep burial of our grappling cable below clean sand, are further evidence. These findings suggest that the abundant ice gouges seen in the shallow shelf areas unprotected by barrier islands from drifting ice, represent only a few years of ice activity. Barnes and Reimnitz (1979) showed that waves and currents in one relatively ice-free sea with long fetch can transform a heavily ice-gouged terrain into one of sediment waves extending out to 10-m water depths without leaving remnants of previously existing gouges. This bottom reworking probably occurred during only one or two storms.

Given such high transport rates under natural conditions, the effects of most dredging, drilling-mud discharge, and island-construction activity on the environment would seem to be insignificant. However, the contemplated construction of long causeways for offshore oil development, which probably would trap much of the sediment in transit (Barnes and Minkler, 1982), would result in drastic changes to the environment within only a few decades.

The ongoing strudel scouring and subsequent infilling of such excavations result in characteristic structures that should serve as unmistakable criteria for the recognition of ancient high-latitude deltaic deposits formed in similar environments to a water depth of at least 5 m. The following considerations reveal just how dominant the structures resulting from such cut and fill action should be. An average of 2.5 large strudel per square kilometer were mapped in the ice canopy off the Sagavanirktok River. We estimate that all these drainage systems were large enough to create a typical 15-m-diameter 3-m-deep scour depression on the sea floor below. Given these values, any square kilometer of sea floor in this area would be reworked to a subbottom depth of at least 2 m, where the craters still have vertical walls, every 2,300 years; reworking to the full 4-m depth of strudel scouring would require more time. BARNES et al. (1979) noted the typical delta sequence seen in 12 vibracores and the importance of strudel scour structures. They further noted that of three vibracores taken over a 50-m distance, each vibracore showed a typical delta sequence: bedded and crossbedded clean sand layers alternating with layers of fibrous organic matter. None of these distinct units, however, could be correlated over distances of 20 to 30 m. The vibracore taken near strudel scour B clearly indicates the futility of trying to trace individual beds even for short distances.

CONCLUSIONS

(1) Strudel scours 15 m across and 3- to 4-m deep are excavated at a rate of 2.5 $km^{-2}yr^{-1}$ and are infilled with sediment after 2 to 3 years. At this rate the entire delta front of arctic rivers should be totally reworked in several thousand years and, therefore, should consist entirely of strudel-scour deposits.

(2) Strudel scours trap materials supplied almost exclusively by bedload transport. For the first year or two, they are efficient natural traps and, therefore, should provide accurate bedload-transport rates.

(3) The calculated transport rate past one strudel scour is 9 $m^3yr^{-1}m^{-1}$. This rate, applied to a 4.5-km-wide strip of shallow water with similar conditions, gives a bedload-transport rate of 40,500 m^3yr^{-1}, comparable to estimates of longshore transport rates along local barrier beaches.

(4) This rapid infilling rate implies that the chances of seeing a strudel scour without fill and, therefore, measuring the maximum depth on any one survey is small, and further implies that all strudel scours, as well as shallow-water ice gouges, record only the most recent events.

(5) The characteristic deposits and structures: steep erosional unconformities overlain by bedded sand and coarse fibrous organic matter at the angle of repose, and the absence of horizontal continuity can be used to identify ancient deposits from similar environments.

6) In view of the very high rates of sediment transport determined for natural conditions, the sediment input from human activities, such as dredging operations, seems insignificant. However, long causeways planned for the offshore oil development would act as groins and result in large-scale shoreline modifications.

ACKNOWLEDGMENTS

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