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Tidally generated sea-floor lineations in Bristol Bay, Alaska, USA

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Abstract Highly reflective linear features occur in water depths of 20–30 m in northern Bristol Bay (Alaska, USA) and are, in places, over 600 m in length. Their length-to-width ratio is over 100:1. The lineations are usually characterized by large transverse ripples with wavelengths of 1–2 m. The lineations trend about N60°E, and are spaced between 20 and 350 m. Main tidal directions near the lineations are N60°E (flood) and S45°W (ebb), which are parallel to subparallel to the lineations. They suggest that the lineations may be tidally generated. The lineations may be bright sonar reflections from a winnowed lag concentrate of coarse sand.

Introduction

In 1997, approximately 188 line-km of side-scan sonar, 3.5-kHz seismic-reflection data, and 22 line-km of underwater video were collected in northern Bristol Bay, Alaska, USA (areas A and B, Fig. 1). These data were collected from the fishing trawler *F/V Golden Dawn* as part of a study of Bristol Bay biological habitats in cooperation with the National Marine Fisheries Service (NMFS, National Oceanic and Atmospheric Administration).

Sides-scan sonographs and underwater video from the Bristol Bay survey show features indicating active sediment transport on the sea floor. These features include sand wave (area A, Figs. 1 and 2) and lineations (area B, Figs. 1, 3–6). Similar sand waves and lineations have been reported from southwestern Bristol Bay near the Alaska Peninsula (Fig. 1) (Schwab and Molnia 1987).

Bristol Bay is an area that has been heavily fished during the last few decades, often with bottom-trawling gear (Forrester et al. 1983 and references therein). Such trawling invariably disturbs the seabed (and associated biota) during operations (Jones 1992), but whether such activity results in long-lasting impressions, including furrows on the sea floor is unknown (Lindebroom and de Groot 1998). Thus, lineations that are imaged on the sea floor should be documented to determine if they are naturally occurring or are anthropogenic.

Geologic setting

Bristol Bay occupies the southeastern corner of the Bering Sea shelf – a broad, flat continental shelf flanking western Alaska and the Alaska Peninsula (Fig. 1). According to Johnson (1983 and references therein), surficial sediment textural patterns suggest that Bristol Bay is a relict (Late Wisconsin) graded outwash plain that has been only slightly modified by local currents and wave action following marine transgression. The distribution of glacial deposits indicates that glaciers extended far into Bristol Bay from onshore (Coulter et al. 1965). Because no major rivers discharge into Bristol Bay, sources of present-day sediment are limited to the adjacent lowlands of mainland Alaska and the igneous terranes of the nearby Alaska Peninsula (Johnson 1983). Parts of Bristol Bay shelf are covered with sand and muddy sand that contain minor amounts of gravel (Johnson 1983). The texture of contemporary sediment varies generally from gravel and coarse sand in nearshore regions to progressively finer sediments offshore (Sharma 1974).

The few bottom and near-bottom current measurements in Bristol Bay are shown in Fig. 1 and are from Hebard (1961), who recorded near-bottom tidal-currents with velocities between 18 and 35 cm s^{-1} during a 38-h period. Kinder and Schumacher (1981) and Schumacher

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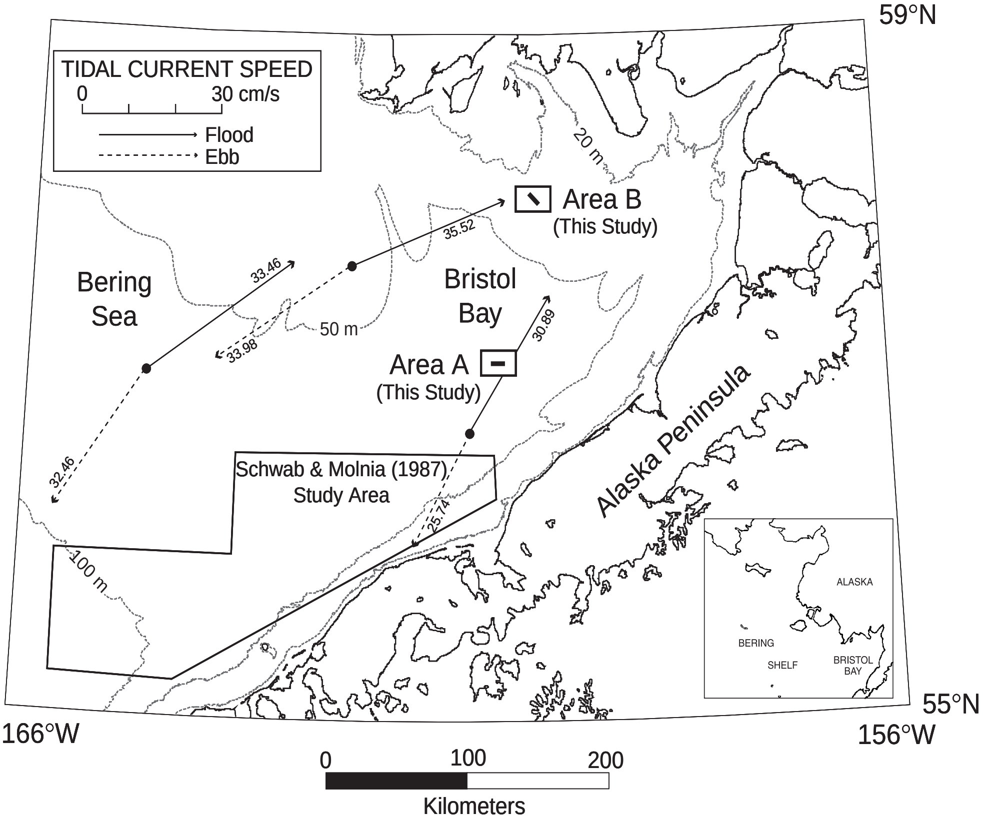

Fig. 1 Index map showing location of study areas A and B in Bristol Bay, Alaska, USA. Survey lines are within solid rectangles inside outline boxes A and B. Tidal vectors and stations are from Hebard (1961)

and Kinder (1983) report vector mean flow parallel to the 50-m isobath for the coastal region of southern Bristol Bay in water depths of 50 m or less (Fig. 1). Mean flows are generally between 1 and 6 cm s^{-1}, with the higher values during the winter. Currents are strongly tidal and can reach speeds up to 50 cm s^{-1}. The average direction of these tidal currents is NE–SW, roughly parallel to the linear bands imaged on side-scan sonographs.

Storms, often with gale-force winds, produce waves that affect the bottom in shallow water. These storms occur year-round in Bristol Bay at an average rate of 3 to 5 events per month (Overland 1981). The mean wind direction is from the southwest in the summer and from the south during the winter (Brower et al. 1977). About 3–15% of observed storm waves exceeded 3–3.5 m depending on the season, and the maximum wave height for a 1% wave, occurring every 100 years, is estimated at 23 m (Brower et al. 1977). The significant wave height estimate in Bristol Bay for a recurrence interval of 5 years is about 11 m (Quayle and Fulbright 1975). This wave activity undoubtedly affects bottom sediment distribution in shallow water.

Data acquisition

Side-scan sonar images were collected using a Klein 2000 system and a 100/500-kHz towed fish that also contained

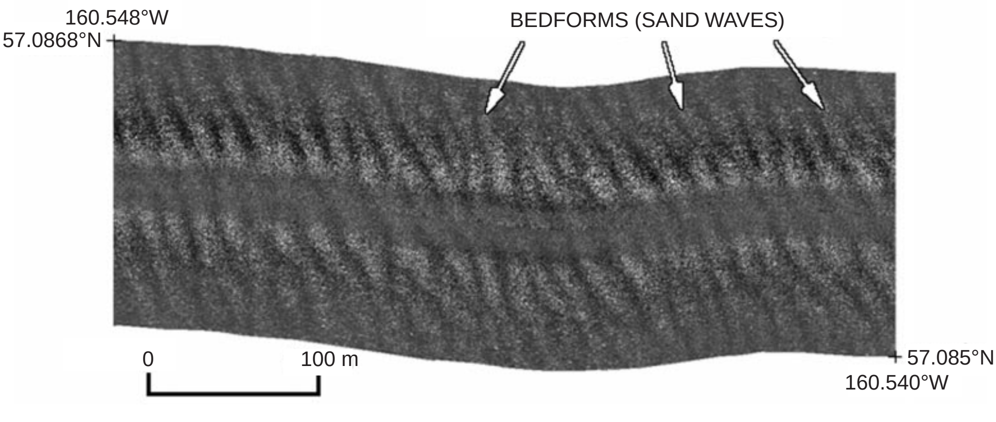

Fig. 2 Typical single side-scan profile from area A in central Bristol Bay (see Fig. 1 for location of area A). The prominent bedforms (sand waves?) have a wavelength of 15–20 m

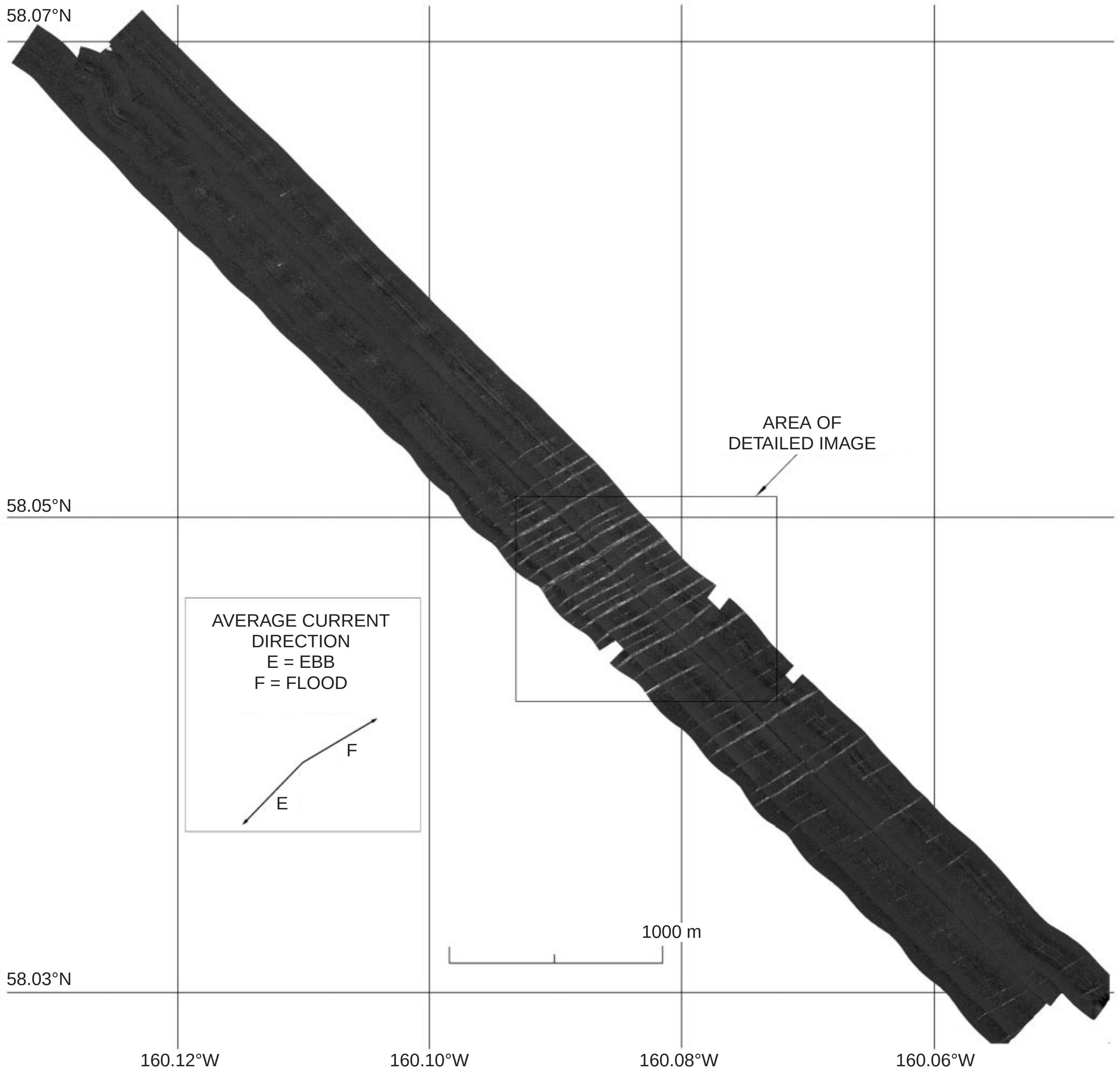

Fig. 3 Mosaic of side-scan data collected along the side-scan tracklines shown in Fig. 1 (area B). Lineations show as white lines of high return that trend NE–SW. Plots of average flood and ebb current directions are for the two northern stations in Bristol Bay (Fig. 1). The box around the center of mosaic is the detailed image area shown in Fig. 4

a 3.5-kHz profiler source. A shipboard fathometer recording system was inoperable during the survey. The side-scan data were recorded digitally at a 10-kHz sample rate over a swath width of 100 m. The 6 swaths of 100-kHz data, which comprise the mosaic shown in Fig. 3, were anamorphosed, filtered, overlaid and projected to produce a spatially correct, georeferenced image of the sea floor with pixel resolution of 20 cm.

About 8 h of bottom video data were collected along 22 km of trackline within area B (Fig. 1). Video data were collected using a Sony 8-mm Handycam mounted on a sled that was towed 1–2 m above the bay floor. Separation distances on the images were measured by two laser beams aimed at the bottom. A representative video image of a sand wave is shown in Fig. 6.

Sea floor features

Sand waves

Side-scan sonographs from Bristol Bay reveal sand waves with wavelengths between 15 and 20 m and

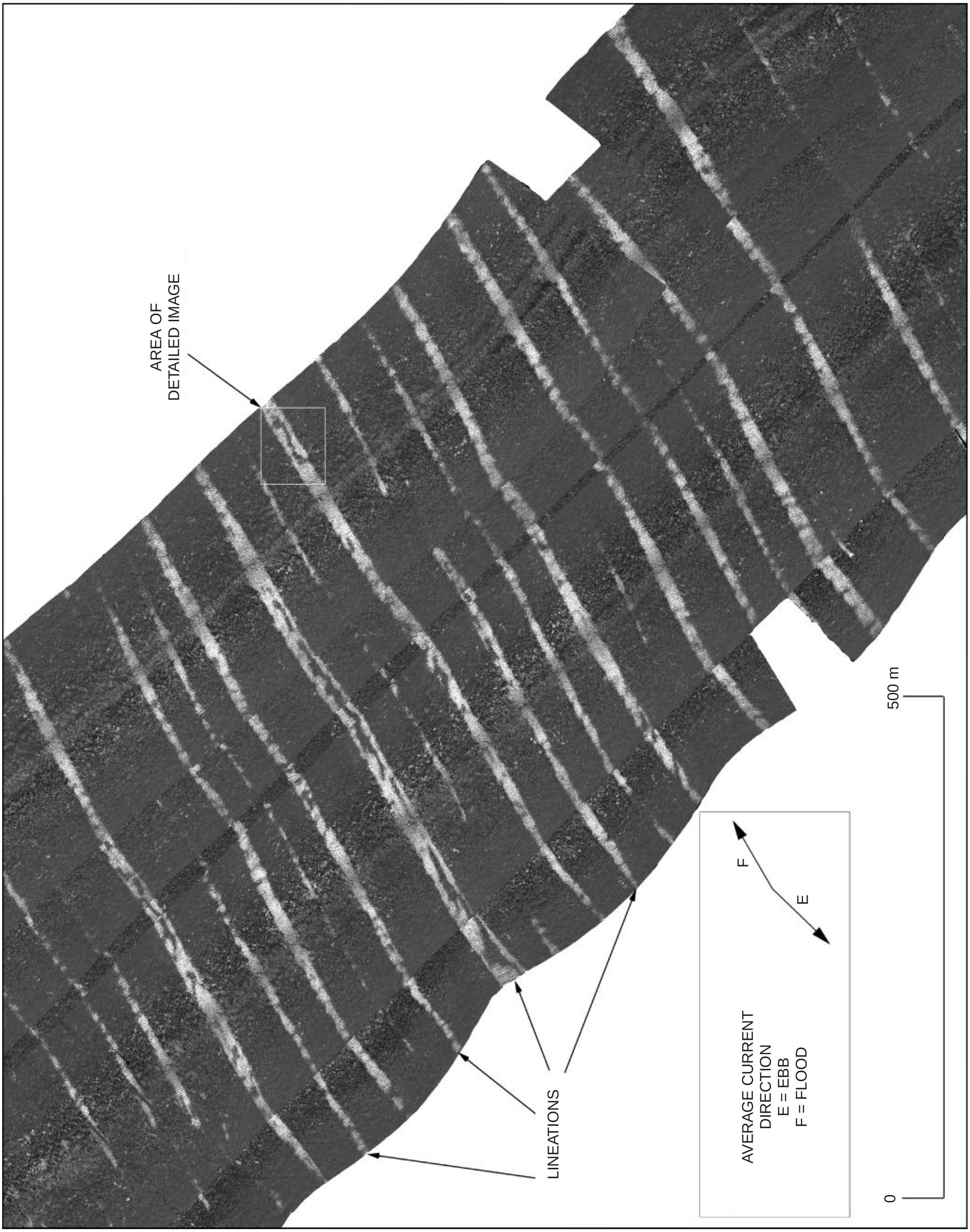
AREA OF
DETAILED IMAGE
LINEATIONS
AVERAGE CURRENT
DIRECTION
E = EBB
F = FLOOD
F
E
0
500 m

Fig. 4 Detailed image of central mosaic region; see Fig. 3 for location. Plots of average flood and ebb current directions are for the two northern stations in Bristol Bay (Fig. 1). The lineations are all parallel or subparallel to one another and have ripple features developed at right angles to the long axis of the lineations. Some lineations are characterized by dark (low return) areas within the lineation, which may be either burial or erosional features. The box in upper right of mosaic shows location of detailed image shown in Fig. 5

heights of 0.5 to 1.5 m (area A, Figs. 1, 2). These sinuous-crested, symmetrical sand waves occur at water depths of about 60 m (area A, Fig. 1) in central Bristol Bay, about 50 km north of similar features reported by Schwab and Molnia (1987). The long axis of the sand waves is oriented about NNW–SSE, which is approximately orthogonal to the local current direction (Figs. 1, 2). Sand waves are present throughout much of area A (Fig. 1).

Lineations

Sonographs also show prominent lineations characterized by ripples having wavelengths of 1–2 m (area B, Figs. 1, 3–6). The lineations occur in water depths between 20 and 30 m (bathymetric data from Robertson 1997). The lineations do not show any relief on 3.5-kHz records collected from the side-scan fish. The shipboard fathometer recording system was inoperable, so we do not know if the lineations have any small-scale relief. Similar lineations, apparently depressions located further south in Bristol Bay near the Alaska Peninsula (Fig. 1), were reported by Schwab and Molnia (1987). Many similar features, although often less linear, occur as depressions on continental shelves (Cacchione et al. 1984; Black and Healy 1988).

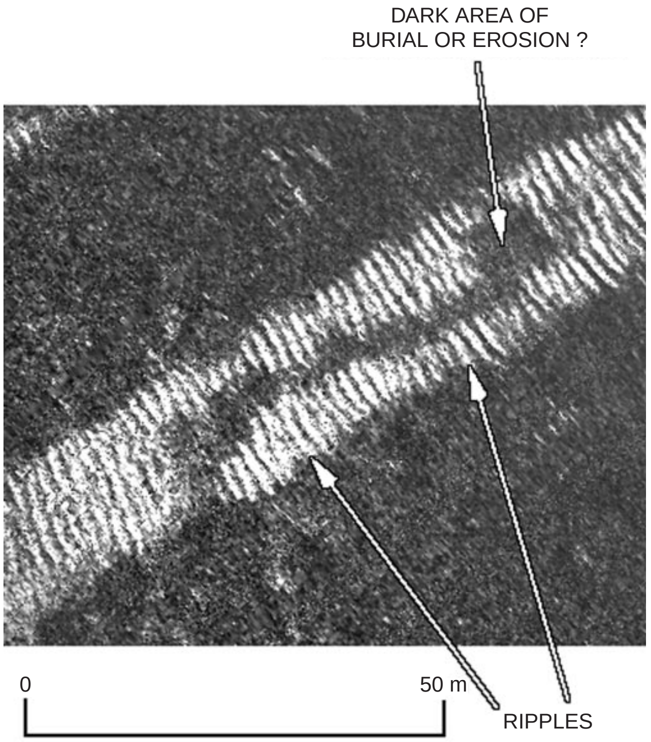

Fig. 5 Detailed side-scan image of part of a single lineation showing ripples orthogonal to the lineation direction. Dark areas within the lineation may be areas of burial deposition or erosion, causing a decrease in the return side-scan signal. The location of image is shown in Fig. 4

The lineations are most concentrated and are brightest near the center of the mosaic, where, in aggregate, they form a field (Fig. 3). To the northwest and southeast the lineations become fainter and less continuous. The spacing between lineations is also greater away from the center of the mosaic (Fig. 3), and they gradually disappear to the northwest and southeast.

Figure 4 shows an enlarged view of the area in which lineations are brightest and most continuous. The apparent slight bends in the lineations result from degraded image projection and mosaic-building between adjacent lines. On single-line displays of the sonograph records the lineations are remarkably straight over the entire record length. Some lineations are “mottled” by irregular zones of low reflectivity (dark areas in the lineations in Fig. 4). A detailed enlargement of one of these mottled areas is shown in Fig. 5. Here ripples within the lineation appear either to be buried or eroded within the dark zones of lower reflectivity.

Video tows over the lineations in area B (Fig. 1) did not reveal differences in visual bottom texture between areas with and without lineations, nor were differences evident in visual texture at the edges of lineations or within the dark, mottled zones (e.g., Fig. 5) of individual lineations. The video data, however, may not differentiate zones of sandy silt from areas of mostly silt. Most of the video data show small-scale, symmetrical ripples that are oriented roughly NW–SE, perpendicular to the lineations and parallel to the larger ripples (e.g., Fig. 5) observed within the lineations. A typical set of small-scale ripples observed in the video data is shown in Fig. 6. Note that the wavelength of the small-scale ripples in the video data is about 20 cm (Fig. 6), whereas the wavelength of the larger ripples in the sonar data is about 1–2 m (Fig. 5), which is larger than the viewing area of the video system.

Figure 7 presents a plot of the length of individual lineations in the lineation field from NW to SE. The plot shows that the relatively shorter and more discontinuous lineations occur at each end of the lineation field, especially at the southeast end (Fig. 3).

Discussion

Schwab and Molnia (1987) reported lineations similar to those imaged in this study in the southern area of Bristol Bay near the Alaska Peninsula (Fig. 1). The lineations they reported are linear depressions up to 5 m deep,

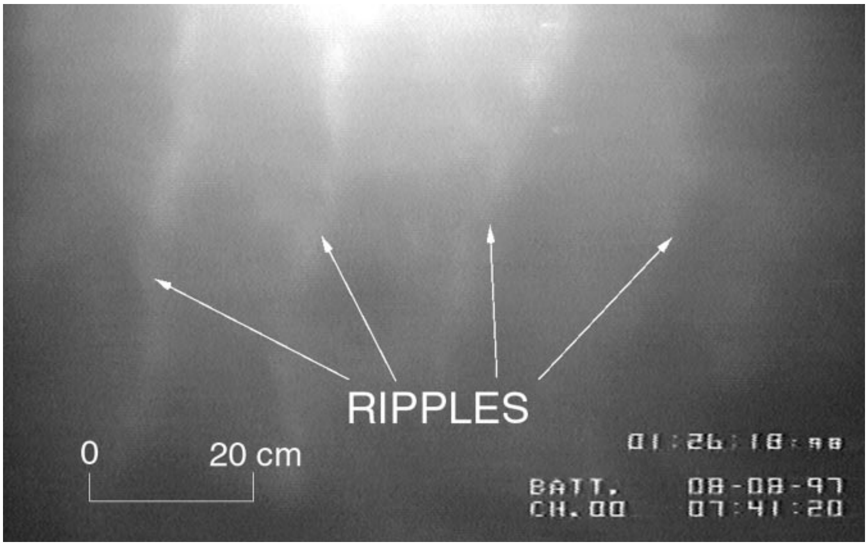

Fig. 6 Typical video still image from zone of lineation in area B (Fig. 1). The ripples or bedforms imaged have wavelengths of about 20 cm each

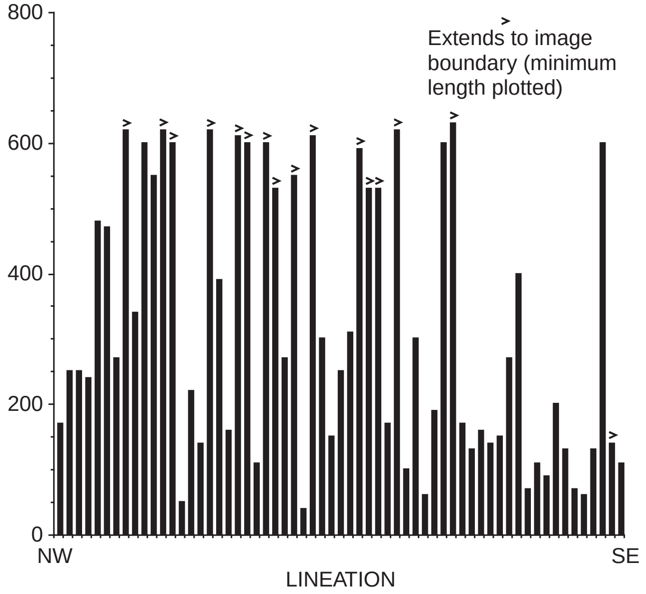

Fig. 7 Distribution plot of lineation (from northwest to southeast) versus lineation length. Sixteen of the lineations extended from one edge of the mosaic to the other edge (Fig. 3), so their minimum length is plotted with a > symbol above the bar

incised into the sandy sea floor. These depressions range from a few meters to more than 250 m wide, and, in places, are more than 800 m long. Depressions are oriented shore-normal close the Alaska Peninsula and become shore parallel in deeper water farther from shore. These linear depressions occur in groups or sets, some of which contain more than 200 distinct linear features. The orientation of depressions in deeper water is NE–SW, the same orientation as the lineations in northern Bristol Bay. The linear depressions described by Schwab and Molnia (1987) are commonly floored by large ripples having wavelengths of about 1–2 m, the same wavelength observed in this study.

Samples recovered by Schwab and Molnia (1987) consist of sandy gravel and gravelly sand in six locations within the southern Bristol Bay linear depressions. Other grab samples, collected from areas of smooth, undisturbed seabed outside the linear depressions, contain sand and muddy sand-rich sediment. Schwab and Molnia (1987) suggested that the rippled floors of these depressions may be covered with a winnowed, gravel-rich lag, a supposition supported by underwater video data collected at three locations in their study area (Fig. 1). These gravels are presumably derived locally from the nearby Alaska Peninsula. In contrast, the video data in our study were collected farther offshore (to the north) within areas of finer sediment. Sediment size differences within and adjacent to the lineations imaged in northern Bristol Bay are not apparent in our video data, but the data may not allow differentiation of sandy silt from mostly silt.

Side-scan sonar data from both north and south Bristol Bay show bright lineations with large transverse ripples. The lineations are zones of bright reflectivity, which probably result from a change in composition of the seabed. Schwab and Molnia (1987) conclude that the lineations in southern Bristol Bay may be floored by a winnowed lag of coarse material, perhaps gravel. Based on their conclusions and video data from this study, we believe that the lineations in northern Bristol Bay may be underlaid by sandy silt and surrounding areas by mostly silt. The lineations in northern Bristol Bay are apparently not depressions as are the lineations in southern Bristol Bay.

If the lineations indeed owe their “bright” sonar aspect to sea-floor relief or to selective sediment winnowing, then questions arise as to the cause of this relief or winnowing and why the lineations have such a large length-to-width ratio. One mechanism may be draping of an underlying linear structural fabric such that the sediment drape mimics this underlying fabric at the sea floor. The structural grain of bedrock and faulting exposed on land does trend southwestward into Bristol Bay (Beikman 1980), in a direction subparallel to the Bristol Bay lineations. However, preexisting bedrock fabric probably is not a cause of the lineations in Bristol Bay because most of the bay is floored by tens to hundreds of meters of sediment (Worrall 1991).

Another possibility is that the Bristol Bay lineations result from commercial fishing using bottom trawls that impact the sea floor. Side-scan sonar images from elsewhere (e.g., Stellwagen Bank offshore of the eastern United States) clearly show the effects of commercial trawling (Valentine et al. 1995). The marks left on the sea bed, however, are not linear, but rather are curved and crossing, unlike the lineations in Bristol Bay.

The lineations may result solely from wave action associated with major storms. Ripples in the lineations are well developed and are oriented principally at right angles to the lineations, indicating the involvement of strong current activity that could be storm-related. The lineations, however, are apparently not widespread in Bristol Bay, as might be expected if they resulted solely from storm activity. Bottom topography, though, might confine storm-related activity to selected areas.

Some workers ascribe the origin of rippled linear depressions to storms, but do not agree on the exact mechanism (Cacchione et al. 1984). The relatively narrow elongate lineations in south Bristol Bay, which have individual lengths approaching 1 km, suggest that a quasi-steady current is a more likely cause for those lineations (Schwab and Molnia 1987) and, by extension, for the northern lineations in this study.

Schwab and Molnia (1987) conclude that the linear depressions in south Bristol Bay are caused by strong tidal currents (Hebard 1961) that are periodically enhanced by storm wave- and wind-induced current activity. They cite the parallel NE–SW direction of both the tidal currents (Hebard 1961) and prevailing winds (Brower et al. 1977) as evidence linking the linear depressions to these agents. We concur with their interpretation, and we speculate that the NE–SW lineations in north Bristol Bay, although not depressions, are also caused by strong parallel tidal currents (see Figs. 3, 4) aided by storm wave- and wind-induced current activity.

Conclusions

Side-scan sonar records from northern Bristol Bay show brightly reflective lineations that trend northeast–southwest, parallel to the main tidal current in the bay (Figs. 1, 3, 4). Some of the 53 lineations observed are at least 600 m long and have length-to-width ratios of more than 100:1. These lineations vary in width from 2 to 27.5 m, with widths of 5, 7.5 and 10 m predominant. These lineations are usually characterized by large ripples that are roughly orthogonal to the lineation trend, suggesting that the ripples are created by quasisteady currents. The predominant orientation of the lineations is closely aligned with the main tidal direction and suggests that the lineations are natural features created by tidal currents.

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