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Surficial characteristics of the bay floor of South San Francisco, San Pablo, and Suisun Bays, California

by

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INTRODUCTION

San Francisco Bay is the largest estuary on the Pacific Coast of the United States. Although the hydrology and biology of the bay have been extensively studied, almost no studies have been conducted on the surficial characteristics and composition of the bay floor, and how physical processes both form and modify it into different morphologies. Rubin and McCulloch (1979) conducted such a study in central San Francisco Bay. This study was designed to study the southern and northern parts of the bay in a manner analogous to that of Rubin and McCulloch (1979). Our reconnaissance investigation characterizes the surficial morphology of the bay floor as revealed by side-scan sonar imaging and high-resolution bathymetry and deduces the general nature of sedimentation, bedload sediment transport directions, and areas of deposition versus erosion. Our results should apply to current issues involving sedimentation, dredging, pollution, and the disposal of dredge spoils in the San Francisco Bay system and the highly developed urban areas that border it.

PHYSICAL SETTING

The San Francisco Bay estuary is a large, complex system comprised of broad intertidal and subtidal flats and narrow, relatively deep tidal channels. In this report, the shallow embayments within the bay are referred to as South Bay, Central Bay, and North Bay (San Pablo and Suisun Bays) (Fig. 1). The average depth of the bay is 6 m at mean lower low water and the volume of the bay is 6.66×10^9 m^3 with a tidal prism of 1.59×10^9 m^3 (Conomos, 1979). Tides in the bay are mixed and semidiurnal in nature. The highs in each cycle are usually quite different in height as are the lows (Conomos, 1979). Ninety percent of the fresh water that enters the bay is derived from the Sacramento and San Joaquin Rivers. This combined riverine system receives runoff from 163,000 km^2 of drainage basin, which is about 40% of the land area of the State of California.

Basic flow patterns within the bay are principally tidally induced and fairly consistent throughout the year. Tides within the bay generate reversing currents that are strongest in the tidal channels and weakest over the shoal areas. Nontidal currents can be generated by winds and river flow although their velocities are typically only 10% that of tidal currents (Conomos, 1979). North and Central Bays exhibit an estuarine circulation due to the ebb dominance of surface water and the flood dominance of bottom water (Peterson, et al., 1975). This circulation system is characterized by a landward flowing density current and occurs in parts of the bay where a significant freshwater inflow is present. The South Bay, with only a small amount of freshwater inflow from local streams, has no definite estuarine circulation system. McCulloch et al. (1970), however, suggested that South Bay may have a reverse estuarine circulation system that is generated during periods of peak delta outflow. Their theory is that low salinity water moves southward from North Bay into South Bay, which displaces the more saline water of South Bay northward. Conomos (1979) further suggests that a sluggish, transient three-dimensional circulation exists in South Bay that is apparently both density- and wind-induced.

Climate over the bay is variable; near San Francisco the climate is dominated by the Pacific Ocean yielding warm winters, cool summers, and small seasonal temperature changes. In contrast, inland areas have a more continental climate with warmer summers and cooler winters. During summer, winds dominantly blow from the west or northwest while during the winter they mostly blow from the east or southeast except during storms when they blow from the south. Strong winds generate waves where fetch is sufficient and thus resuspend sediment as well as mix and oxygenate the water (Conomos, 1979). The largest waves generated by summer winds have wave periods of 2 to 3 seconds and heights of 1 m plus. Winter storms, where fetch is significant, may generate waves with 5-second periods (Conomos, 1979).

METHODS

Field work for this study was conducted using the USGS Water Resources Division Research Vessel Polaris. Side-scan-sonar profiles were collected using a Klein system operated at a frequency of either l00 kHz (South Bay) or 500 kHz (North Bay). This system is comprised of a graphic recorder and towfish that can be operated at varying frequencies and slant ranges. In general, slant ranges of l00 m (200-m swath) or 150 m (300-m swath) were used for optimum resolution of bottom features on the bay floor. Towing speed averaged 7.4 km/hour, although this varied greatly with tidal current speed and direction as well as local wind regime. No attempt was made to acquire overlapping side-scan sonar images.

The side-scan sonar has a theoretical resolution on the order of about 1 m in range scale and 10 to 20 cm in vertical scale (ripples were therefore not resolved by the sonar). The side-scan sonar emits a high frequency (100 or 500 kHz) sonic signal that insonifies the sea floor, producing a continuously recorded oblique view of it on both sides of the vessel. The intensity of the sound scattered back to the sonar varies as a function of several parameters, the most important of which are the bottom roughness (morphology, relief) and the angle of incidence. Thus, areas with distinct relief, such as areas floored by bedforms, typically produce dark patterns that are readily discernible from areas with little to no relief. The texture of the sea-floor sediment is important as it greatly influences the bottom roughness and hence the darkness/lightness of the image produced on the side-scan profile. The coarser and rougher the sea floor the darker the image produced on the graphic recorder tends to be.

An Innerspace fathometer was used to acquire high resolution bathymetry. This system operated at a frequency of 200 kHz with a hull-mounted transducer. The bathymetry was not corrected for tidal elevation. Navigation was obtained with a shipboard Raytheon precision radar. Fixes were plotted every 5 min. and correspond to the event marks on the side-scan sonar and fathometer records.

INTERPRETATIONS

Tracklines were plotted on overlays of the 1:40,000-scale National Ocean Survey bathymetric maps of San Francisco Bay (Sheets 1, 2, 3). In general, patterns on the side-scan profiles correlate well with bottom relief. In some instances, however, the correlation is not good; for example, patterns produced by the bay floor off Hunters Point in South San Francisco Bay (Fig. 2; Sheet 1). There the bay floor appears as a patchwork of alternating light and dark tonal patches, whereas the corresponding bathymetric profile shows an irregular bottom with relief up to 0.5 m but with no consistent or regular bottom morphology as seen in other areas where the side-scan record shows distinct patterns. A second exception is the occurrence of lineations in South San Francisco Bay on the side-scan record where no discernible bottom morphology occurs on the bathymetric profile (Fig. 3). Both of these cases will be discussed in subsequent sections.

Mapping the distribution of bedforms by the remote imaging of large areas of sea floor leads to a better understanding of the hydraulic regime that created these bottom features (and most likely continues to modify them) and to inferring the direction of bedload sediment transport. Both of these issues are of great importance to the present and planned usage of this estuary by the adjoining communities.

Usually, bedload sediment is transported normal to the crestline of transverse bedforms such as sand waves (Belderson, et al., 1972; Rubin and McCulloch, 1979; Knebel, 1989) and, conversely, net bedload sediment transport is parallel to the crest/trough orientation of longitudinal bedforms such as furrows and lineations (Belderson, et al., 1972; Flood, 1983). The asymmetry of transverse bedforms indicates the net direction of bedload sediment transport (these have been reported as "ebb" or "flood"). Rubin and McCulloch (1979) demonstrated that bedload transport directions inferred from sand wave orientations were generally within 15% of the directions measured by current meters of the strongest near-bottom currents in Central San Francisco Bay. We thus feel that bedload sediment transport directions inferred from bedforms yield a fairly accurate measure of tractive sediment transport in the bay. In this report the arrows depicting bedload sediment transport indicate bi-directional transport if the arrow is equidimensional about the locality indicator (Sheets 1, 2, 3) or net (dominant in one direction) if the arrow is longer in the flood or the ebb direction (Sheets 1, 2, 3).

Based on the available data, we cannot establish whether and how bedforms in the bay respond to individual tidal cycles because our profiles represent only one discrete interval of time. The direction of bedload sediment transport does not however infer that suspended sediment is transported in the same direction. As Rubin and McCulloch (1979) demonstrated, some ebb-dominated parts of Central Bay are characterized by opposite directions of tractive versus suspended sediment load.

SURFICIAL BOTTOM TYPES

Five surficial bottom types can be delineated on the floor of South and North Bay by correlating distinctive patterns on side-scan-sonar and bathymetric profiles. Our maps only show bottom features formed by natural processes even though abundant evidence of man-made features are present throughout the bay. Each surficial bottom type will be discussed in regard to its characteristics, distribution within the bay, and relevance to deposition or erosion.

FURROWS

Furrows are sedimentary bedforms that have been reported from a wide variety of environments (Flood, 1983). They occur in estuarine, shelf, and deep-sea environments in a variety of substrates. Furrows are linear depressions that are aligned parallel to the dominant current flow (Fig. 4). In cross section (Fig. 4) they appear as narrow-to-wide troughs with relatively flat-topped ridges between adjacent troughs. Generally they are fairly evenly spaced, although this may vary within a short distance. The furrows observed in San Francisco Bay exhibit "tuning-fork junctions," a feature that helps to distinguish them as sedimentary bedforms and not man-made features (Fig. 4). In San Francisco Bay, furrows were observed in two locations, in South Bay and in San Pablo Bay (Sheets 1, 2).

South Bay furrows are observed only in the main tidal channel (Sheet 1). They occur more or less continuously from about San Bruno Shoal south to about the Dumbarton Bridge, an area that varies in width from 1 to 3 km and is 30 km long. Individual furrows can be traced continuously for several kilometers before they branch (tuning-fork junctions) or become unrecognizable. Water depths in which furrows occur range from 8 to 15 m; most occur in the 10 to 15 m range in South Bay. Furrows are straight crested and do not appear to migrate or change significantly. Their height varies from about 0.5 to 1.5 m with the majority being in the 0.5 to 1.0 m range.

The 100-kHz records of South Bay reveal that many of the furrows present appear to have sand waves on their walls and/or in their troughs. Because the 100-kHz records of furrows in South Bay have less resolution than the 500-kHz records of furrows in San Pablo Bay, sand waves present in the furrow field of South Bay tend to be vague on most records. Sand waves within the furrows appear to be more common in the north end of the furrow field of South Bay.

Although the mechanism by which furrows are formed is still debatable, it seems likely that some form of secondary circulation such as helical flow cells are involved in both their formation and their maintenance (Flood, 1981, 1983). Several authors (Allen, 1982; Belderson, et al., 1972; Flood, 1981, 1983) have shown that bedload sediment transport occurs parallel to the trend of these longitudinal bedforms. Furrow orientations in the South Bay are such that bedload transport in the furrowed areas is consistently parallel to the axis of the main tidal channel and hence also parallel to dominant bathymetric trends (Sheet 1). Tuning-fork junctions, which can be an indicator of the direction of strongest flow (Flood, 1981, 1983), open in both flood and ebb directions with neither favored; thus no dominant direction could be established based on the data on hand. Measurements, where possible, made on the orientation of sand waves on furrow walls/furrow troughs support the above mentioned trends--that is, bedload sediment is transported parallel to the axis of the main channel, which runs parallel to isobaths.

Furrows are fairly consistent in spacing although variations do occur. The ratio of width to spacing ranges from 1:1 to 1:5 for South Bay furrows. Both width and spacing may vary within as short a distance as the width of the tidal channel (1 to 3 km). Furrows generally occur only in the deepest part of the tidal channel and not on the channel walls or subtidal flats.

The furrowed part of the bay floor of South Bay exhibits sand waves not only in furrow troughs but also sand waves that occur adjacent to furrows. Those that occur adjacent to the furrowed bay floor occur both as discrete fields as well as in trains. In most cases the boundary is sharp but in some areas it appears somewhat gradational. In general, the orientation of sand waves outside of furrowed areas is fairly close to that for sand waves occurring within furrow troughs (or on furrow walls). Hence measurements of bedload sediment transport directions both in and outside of furrowed areas agree quite well.

Furrows also occur in San Pablo Bay mostly on and adjacent to Pinole Shoal (Sheet 2). This is a very different environment than the South Bay where furrows occur only in the dominantly muddy main tidal channel. In San Pablo Bay, they occur mostly on a subtidal shoal that is adjacent to the sandy main tidal channel. Furrows are observed over an area approximately 1.5 km wide and 5 km long. Water depths are primarily in the 6 to 11 m range; the majority occur in 10 to 11 m. These bedforms are similar in morphology to the furrows in South Bay in most respects (Fig. 5). Their height ranges from 0.5 to 1.2 m (most are in the 0.5 to 1.0 m range); they are slightly larger in relief than their counterparts in South Bay. Spacing of San Pablo Bay furrows ranges from about 7 m to 23 m. Most of the furrows observed in San Pablo Bay have sand waves in their troughs. As stated earlier, this observation, as opposed to South Bay, may be largely a function of the higher resolution of the 500-kHz side-scan system used in North Bay versus the 100-kHz side-scan system used in South Bay. Width-to-spacing ratio for San Pablo Bay furrows ranges from 1:1 to 1:6, comparable to South Bay furrows. Measurements made on both furrows and sand waves occurring in their troughs show that bedload sediment transport is primarily in a direction along the axis of Pinole Shoal and thus parallel to isobaths.

LINEATIONS

Lineations are a distinctive pattern of bay floor recognized on a number of side-scan sonar profiles from South Bay. They also are recognized in North Bay, particularly San Pablo Bay (Sheets 1, 2). It should be pointed out that the term "lineation" as used in this report is not the same as the term "lineation" as used by Flood (1981, 1983). Our use of the term is as a morphologic descriptor for a sonographic bottom type whose origin and relationship to other known bottom types (bedforms) are not clear. Flood (1981, 1983) uses the term in a genetic sense to describe bottom features that he has documented as "miniature furrows." In South Bay, lineations are observed primarily on the subtidal flats and not in the main tidal channel. They are observed both adjacent to furrowed areas and in non-furrowed areas (Sheet 1). Water depths in which lineations occur are generally less than 10 m. The best examples occur on lines near the San Francisco Airport in water depths averaging 5.5 m on the subtidal flats adjacent to the main tidal channel (Fig. 3). The lineations are linear features with a fairly regular spacing and wavelength. Observations show that the spacing between lineations ranges from 18 to 50 m; those occurring near the San Francisco Airport range from 25 to 50 m (Fig. 6).

Although the lineations appear similar to both sand waves and furrows in different aspects, they are differentiated as a separate bottom type because of their general lack of surface expression on bathymetric profiles (Fig. 6). The resolution of the instrumentation used to acquire bathymetry in this study is on the order of 0.25 m. Hence, if these lineations have topographic relief it is most likely less than 0.25 m as the bathymetric profiles show a relatively flat and featureless bay floor in the area that corresponds to the side-scan sonar profile (Fig. 6). Another possibility is that the side-scan system is imaging mostly compositional changes in the bay floor, which may be due largely to textural changes. The darker bands on the side-scan profile (Fig. 6) could represent coarser material whereas the lighter tones could represent finer material (Belderson et al., 1972).

South Bay lineations are similar to sand waves in some respects; however, their differences are marked. In plan view they appear similar to the largest sand waves found in South Bay, near the Bay Bridge (Sheet 1). However, in general their wavelength is marginally greater than for even the largest sand waves (25 to 50 m for lineations vs. 24 m for the largest sand waves). Also, the largest sand waves clearly exhibit a height on the order of 0.75 to 1.5 m whereas these lineations show no detectable relief. Large sand waves also commonly have smaller sand waves superimposed, lineations do not appear to. Additionally, the lineations occur in shallow water (5.5 m) whereas the largest sand waves occur in deep water (about 20 m and deeper). Although the crestal trends of lineations could be comparable to smaller sand waves, their wavelength is far greater than for any of the smaller sand waves. Both features have tuning-fork junctions.

Lineations could also be compared on a gross scale to furrows although their characteristics point out their dissimilarities. In plan view, furrows are straight crested and very evenly spaced. They often have tuning-fork junctions that in a very limited areal extent may open in both flood and ebb directions. Lineations appear to be more sinuous in crestal configuration and appear to have tuning-fork junctions that open largely in one direction within the limited areal extent observed on side-scan profiles. Furrows observed in South Bay have spacings and wavelengths that are vastly different from those observed for lineations (Fig. 6). The largest wavelength of furrows observed in South Bay is 20 m and the average is closer to 9 to 12 m. Lineations show wavelengths that vary from 18 to 50 m. Furthermore, no sand waves were observed in the "troughs" of lineations (light tonal areas), whereas they are fairly common in the troughs/side walls of furrows. On side-scan sonar profiles, ten or more furrows can often be delineated per 50 m alongtrack whereas only 1 or 2 lineations are commonly present per 50 m alongtrack.

The distribution of lineations in South Bay (Sheet 1) reveals that most occur in water depths less than about 9 m and the majority occur in water depths less than 5.5 m. Moreover, most of the observed lineations occur on the subtidal flat east of the main tidal channel and east of San Bruno Shoal (Sheet 1). No lineations are recognized south of the San Mateo-Hayward Bridge. Sheet 1 also shows that a significant amount of the lineated bay floor of South Bay occurs independent of bay floor characterized by sand waves or furrows. The similarity in orientation of lineations both adjacent to other bedforms and independent of other bedforms suggests that the same physical processes that form and modify the furrows and sand waves also have a significant effect on the formation and modification of lineations--only the end product differs.

SAND WAVES

Sand waves ("subaqueous dunes" of Ashley, 1990) are observed on side-scan profiles in both South and North San Francisco Bay (Sheets 1, 2, 3). They are also common in Central San Francisco Bay (Rubin and McCulloch, 1979) and appear to be the most common sedimentary bedform in the bay. Sand waves are transverse bedforms in that tractive sediment is transported in a direction transverse to the crestal orientation of the sand wave. In plan view on side-scan profiles (Fig. 7) they appear as fairly linear features of alternating light and dark streaks. In cross section on bathymetry profiles (Fig. 7) they most often appear as a "sawtooth" pattern of alternating crests and troughs. The net direction of bedload sediment transport can be established if an asymmetry can be determined from the side-scan and/or bathymetry profile (Fig. 8). In every case where sand waves were mapped, corresponding morphologic patterns on side-scan and bathymetry profiles could be determined.

Sand waves in South Bay occur both in the main tidal channel as well as on the subtidal flats (Sheet 1). They occur in discrete linear trains, in areally continuous fields (Fig. 7), and in association with furrows where they occur on the sidewalls and in troughs (Fig. 5). In general, they are straight crested to slightly sinuous and exhibit tuning-fork junctions. Sand waves are found in water depths ranging from about 6 to 23 m. The majority appear to occur in the 7 to 10 m range. The height of these bedforms varies from the bottom limit of detection on our instruments (about 0.25 m) to 1.5 m. Most are in the 0.25 to 0.5 m range. Wavelength of sand waves varies from 3 to 24 m. Sand waves in the 0.25 to 0.5 m height range generally have wavelengths on the order of 3 to 6 m while "large" sand waves occurring near the Bay Bridge (Sheet 1) have heights from 0.75 to 1.5 m and wavelengths from 22 to 24 m. These "large" sand waves have smaller (0.25 to 0.5 m high) sand waves superimposed on them (Fig. 9). No sand waves less than about 0.75 m high were observed in water depths less than 22 m.

In South Bay, sand waves are observed in areas independent of other bedform types as well as adjacent to areas with other bedforms (Sheet 1). In several instances, discrete sand-wave fields/trains occur adjacent to furrows with sand waves. The crestal orientations of discrete sand waves outside of the furrowed areas as well as within the furrowed areas are within a few degrees such that they both yield very similar bedload sediment transport directions (essentially parallel to the dominant trend of isobaths). Thus both discrete sand waves and sand waves within furrow fields yield bedload sediment transport directions parallel to the axis of South Bay (Sheet 1). None of the "large" sand waves (0.75 to 1.5 m high) are observed adjacent to furrows.

Sand waves are also found extensively in North Bay (Sheets 2, 3). They occur in discrete trains and fields mostly in the deeper main tidal channels and adjacent to and within the furrow field on Pinole Shoal in San Pablo Bay (Sheet 2). In several locations within North Bay, an asymmetry to sand waves could be established to give a net bedload sediment transport direction.

Reconnaissance tracklines in San Pablo Bay (Sheet 2) indicate that sand waves occur largely in the sandy main tidal channel and on Pinole Shoal in the furrow field. Although tracklines on the subtidal flats of San Pablo Bay are limited in number, it appears that sand waves are not common outside of the main tidal channel except for Pinole Shoal.

In the sandy main tidal channel, sand waves occur independently as well as adjacent to lineations (Sheet 2). Water depths in which sand waves occur range from about 5.5 to over 20 m. Most observed sand waves are straight crested to slightly sinuous (Fig. 10). Heights range from 0.25 to 2 m while wavelengths range from 3 to 13 m. The majority of the sand waves observed are in the 0.5 to 1 m height and 5 m wavelength range. Tuning-fork junctions are evident with no preferred direction of opening.

Measurements of sand wave orientations show that bedload sediment is transported mainly in a direction parallel to the isobaths along the axis of San Pablo Bay (Sheet 2). A local field of sand waves in the channel off Davis Point (Sheet 2) contains asymmetric sand waves that indicate net bedload sediment transport in an ebb direction. Due to the limited nature of our survey we cannot determine whether this trend is a long or short term indicator (whether it would remain ebb-oriented over several tidal cycles). Other observations from San Pablo Bay only reveal bi-directional transport (Sheet 2).

Sand waves, where adjacent to lineations and furrows in San Pablo Bay, exhibit a crestal orientation that is roughly 60-90 degrees to the trend shown by lineations and furrows (Fig. 11). Furthermore, sand waves that occur on furrow walls and in troughs (Pinole Shoal) are oriented similarly to sand waves that occur outside of furrowed areas (Fig. 11). Sand waves occurring within furrowed areas yield roughly the same bedload sediment transport directions as the furrows themselves (Sheet 2).

Tracklines in Suisun Bay (Sheet 3) show that sand waves are the dominant bottom type and the most prevalent bedform type observed within the areas we surveyed. Suisun Bay, with the general exception of the marsh islands, is largely sandy in nature and most of the bay floor is probably covered by bedforms from ripples to sand waves of different sizes. Tracklines used in this investigation (Sheet 3) occur primarily in the main tidal channel and show that the bay floor is covered mainly by sand waves and man-made features such as anchor/trawl drag marks and probable dredging related features. Subsequent side-scan sonar tracklines (J.L. Chin, H.E. Clifton, and R.J. Anima, unpublished data, 1990) in other areas of Suisun, Grizzly, and Honker Bays show that sand waves of different sizes also predominate on the bay floor.

Sand waves occur discontinuously from the Carquinez Bridge/Semple Point to New York Point (Sheet 3). They are mainly straight crested to slightly sinuous in plan view (Fig. 12). Tuning-fork junctions are evident with no preferred direction of opening. Sand waves occur primarily in localized fields although trains are also present; they are often interrupted by what appear to be dredged areas. They occur in water depths ranging from 10 to 40 m; most occur in the 10 to 15 m range. Sand wave heights in Suisun Bay vary from the bottom limit of detection (0.25 m) to about 2.75 m. The "largest" sand waves occur off Dillon Point (Fig. 13) and are 2 to 2.75 m high, 25 to 28 m in wavelength, and occur in 40 m water depth in what appears to be a large scour pool located just off the bedrock that composes the point. Most sand waves are in the 0.5 to 1.0 m height range, with wavelengths from 3 to 9 m and occur in 12 to 20 m water depth.

Measurements of sand wave orientations within Suisun Bay suggest that bedload sediment is transported primarily along the axis of the main tidal channel, which is the deepest area of Suisun Bay (Sheet 3). Relatively deep water also exists in the channels between marsh islands. This pattern of bedload sediment transport, which is in a direction parallel to the isobaths, is consistent with results obtained in San Pablo Bay and South San Francisco Bay (Sheets 1, 2). Side-scan sonar and bathymetry profiles also reveal that sand waves near Roe Island are asymmetric and yield net bedload sediment transport in an ebb-oriented direction (Sheet 3; Fig. 14).

LIGHT AND DARK TONAL PATCHES

Side-scan sonar profiles in South Bay show a bay floor characterized by alternating light and dark tonal patterns (Fig. 15). These tonal patterns appeared only in South Bay and only east of Hunters Point and west of Bay Farm Island (Sheet 1). They consist of highly irregular dark patches with light areas between and within (Fig. 15). The dark patterns are areas of higher backscatter than the light areas, which compose most of the bay floor. Both dark and light areas vary extensively in shape from semicircular to elongate to pock-marked. The boundaries between light and dark areas tend to be very ragged or serrated. Correlation with bathymetry reveals that the bay floor is irregular and somewhat hummocky (Fig. 15). Relief of the bay floor in these areas ranges from less than 0.5 to 1.0 m; no consistent bathymetric trend is evident, as opposed to areas with bedforms where very regular and distinctive patterns occur. The light and dark patches occur in water depths of 19 to 20 m near Hunters Point and 5 to 10 m near Bay Farm Island (Sheet 1). In general, these tonal patches occur only north of the Hunters Point to Bay Farm Island area in South Bay and extend about 8 km north from their southern extent before they die out just south of the Bay Bridge.

FEATURELESS

A sonographic bottom type that occurs in much of the shallower areas of the bay floor is here termed "featureless" bottom (Sheets 1, 2, 3). The characteristics are a monotonous, low contrast appearance on side-scan profiles (low backscatter/light tones are characteristic), and an absence of any distinctive patterns that might indicate that a specific bottom morphology is present (Fig. 16). On bathymetric profiles, the bottom is flat or gently sloping with little or no relief. It is possible that unresolvable ripples, small sand waves, or other morphologic features with heights less than 0.25 m occur within this bottom type. Featureless areas occur in the shallower margins of the bay and are interspersed in the tidal channels (Sheets 1, 2, 3).

SUMMARY

The floor of South and North San Francisco Bay is characterized by five surficial bottom types based on a reconnaissance survey using side-scan sonar and a fathometer. The five bottom types are: 1) furrows, 2) lineations, 3) sand waves ("subaqueous dunes"), 4) tonal patches, 5) featureless. In almost every case, features on side-scan records can be correlated with features on corresponding bathymetric profiles. Where transverse and longitudinal bedforms were delineated, bedload sediment transport directions were inferred based on the crestal orientation of the respective feature. Furthermore, where an asymmetry of sand waves could be established a net bedload sediment transport direction was inferred.

Establishing the trend of bedload sediment transport allows us to define the nature of sedimentation. Furrowed bay floor in South Bay and San Pablo Bay (Sheets 1, 2) indicates that bedload sediment is transported parallel to the axis of each respective bay and parallel to the dominant bathymetric trend. The furrowed areas are sites of both deposition and erosion as tidal currents move bedload material that scours and maintains the troughs as well as deposits bed and suspended load material that builds up the overall furrow through time (Flood, 1981; 1983). It is not clear, based on existing data, if there is a net direction of bedload transport within the furrowed areas, but it is fairly certain that bedload material is swept along the axis of South Bay and along the length of Pinole Shoal in San Pablo Bay (Sheets 1, 2). Further evidence of bedload transport in furrowed bay floor comes from the sand waves that can be delineated on the furrow walls and in the troughs (Figs. 4, 5). Measurements on these sand waves confirm previous measurements of furrow orientations.

Bay floor characterized by sand waves (independent of furrows) occurs in all of the surveyed areas of South and North Bay and tends to show that bedload sediment, as revealed independently by furrows, is transported primarily in a direction parallel to the dominant bathymetric trend within each individual bay--that is, essentially along the axis of each bay. Most bay floor with sand waves tends to be in the tidal channel areas and not on the shallow subtidal flats that border the tidal channels. Near Carquinez Strait and in parts of Suisun Bay, asymmetric sand waves show that net bedload sediment transport, at least during the time interval in which these profiles were collected, is in an ebb-oriented direction. Since our data represents only one interval in time, we do not know whether or how these sand waves respond to tidal cycles; they may, as Rubin and McCulloch (1979) found in Central Bay, move during average daily tide cycles in response to oscillating tidal currents. Areas of bay floor characterized by sand waves represent depositional sites where sand is moved back and forth.

The results of our study agree well with previous published results regarding physical processes in the bay. Based on their study of the Central Bay floor and bedforms, Rubin and McCulloch (1979) found that tidal currents are the most important physical process molding the bay floor. Cheng and Smith (1985) state that one of the most important factors affecting circulation in the bay is the bay's bathymetry. They state that tidal current is nearly linearly proportional to the local mean water depth; hence, stronger currents are found in deeper water and weaker currents in shallow water. As tidal currents are probably the most important factor in moving bedload sediment in the main channels, one would expect, based on Cheng and Smith's (1985) observations, that bedload sediment transport directions should parallel the predominate direction of tidal currents in the bay. Our results and Rubin and

McCulloch's (1979) results show that the directions are dominantly parallel and in fairly close agreement in all parts of the bay. The geometry (shallow versus deep areas) of the bay thus has a significant effect on determining the nature of the bay floor, although grain size and sediment availability also should be important factors.

Light and dark tonal patches probably represent both deposition and erosion/reworking of the sediment. Similar patterns on side-scan sonar records are reported by Belderson et al., (1972) and Knebel (1989). No distinct morphologic pattern is evident on corresponding bathymetric profiles as only an irregular and slightly hummocky bay floor can be discerned. The tonal patterns probably represent textural changes where the dark areas have coarser-grained sand than the intervening lighter areas. It cannot be established, however, whether the light areas represent a thin fine-sand veneer that is moving over the coarser sand (dark areas) and blanketing parts of it, or whether the coarser sand (dark areas) represents a thin veneer that blankets the finer sand (light areas) and is being eroded, leaving "windows" of the underlying finer sand (light areas) exposed. Dark tonal patches have light tonal patches and man-made drag marks of light tonal contrast within their boundaries, which suggests that the coarser sand may only be a thin veneer overlying finer sand.

Areas of the bay floor characterized by featureless side-scan profiles and flat to gently sloping bathymetric profiles probably represent some combination of deposition and sediment reworking by physical and biogenic processes. The featureless pattern occurs primarily in the shallow subtidal areas that border the tidal channels and extend into the intertidal areas. Unpublished core data in addition to sediment descriptions on N.O.S. charts of the area suggest that most of these subtidal flats are muddy in nature. The dominant processes operating in these parts of the bay floor are probably resuspension and deposition of fine material and biologic reworking by infauna. Rubin and McCulloch (1979) suggest that sediment turnover on the mudflats of South Bay may be due mostly to storm resuspension rather than to biologic stirring.

Features that were not mapped due to limited areal extent or presumed anthropogenic nature include strong, reflective, bottom drag and trawl marks, pits and depressions, and large dredge patterns. The strong reflective pattern occurs only in South Bay southeast of San Bruno Shoal and north of the San Mateo-Hayward Bridge (Sheet 1). This pattern is characterized by moderate tones and pockmarked patterns on the side-scan profile and a relatively featureless bathymetric profile. We think that this pattern is probably related to an area of the bay floor where oyster and other invertebrate shell material (predominantly dead) compose the bay floor, admixed with a muddy substrate. The strong reflective pattern observed on side-scan profiles would presumably be attributable to coarse shell material that produces high backscatter. This area is also quite probably an area of erosion or nondeposition as little to no sediment covers the shelly material.

Drag and trawl marks occur in all parts of the bay and are presumed to be the result of both commercial fishing nets that are dragged across the bay floor and anchors and other devices that are dragged across the bottom by a variety of vessels. These features can be delineated from bedforms by their lack of uniformity, lack of tuning-fork junctions, and the fact that they often cross each other. They occur in tidal channels and on the shallow subtidal flats and are observed in greatest abundance near harbor entrances, anchorages, and man-made features.

Pits and depressions are observed on both side-scan profiles and bathymetry. They are most common in South Bay and in most cases appear to correlate with features on the N.O.S. charts noted as cable crossings, pipelines, or other man-made features. These features can cover several kilometers of area and may be up to 10 to 15 m in relief. The sheer walls, plan view shapes, and irregularity of these features help to delineate them as anthropogenic in origin.

A bottom type (Fig. 17) that is found only southeast of the southern end of San Bruno Shoal and west of Johnson and Hayward Landing in South Bay (Sheet 1), we attribute to dredging-related activities. The features characterizing the bottom type occur in a large depression a few meters deep and appear on side-scan profiles as a series of alternating light and dark bands between and transverse to a set of 1 to 2 m ridges that enclose each respective set of these features (Fig. 17). In bathymetric profiles they appear as an irregular bottom with very little relief (0.25 to 0.75 m) bounded by 1 to 2 m ridges and occurring within the aforementioned 2-m deep depression.

In summary, the areas of South and North Bay covered by our reconnaissance survey show a variety of both physical and anthropogenic features that can be delineated on side-scan sonar and bathymetric profiles. We have delineated and mapped five bottom types that are formed (and modified) by physical processes operating in the bay. These bottom types suggest that tidal currents are probably the most important physical process in molding the bay floor in areas covered by our survey. Furthermore, they reveal that bedload sediment is transported primarily within the relatively deep tidal channels in directions parallel to isobaths and in most cases parallel to the axis of each bay. The geometry of the bay, tidal currents, sediment availability, and the grain size of the sediment are important factors in determining the nature of the bay floor.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

1. Index map of San Francisco Bay. The bay is informally subdivided into "South, Central, and North (San Pablo and Suisun Bays) Bay."

2. Sonograph (100 kHz) (top) and corresponding bathymetric profile (bottom) of alternating light and dark tonal patches in South Bay. Location is just off Hunters Point (see Sheet 1).

3. Sonograph (100 kHz) (top) and bathymetric profile (bottom) of lineations in South Bay. Location is just southwest of Bay Farm Island (see Sheet 1).

4. Sonograph (100 kHz) (top) and bathymetric profile (bottom) of furrows in South Bay. Location is in the main tidal channel just north of the San Mateo-Hayward Bridge (see Sheet 1). Note the tuning-fork junctions (TFJ), fairly regular spacing, and uniformity of furrows. Darker lines correspond to ridges between furrows while lighter lines correspond to furrows.

5. Sonograph (500 kHz) (top) and bathymetric profile (bottom) of furrows in San Pablo Bay. Location is Pinole Shoal (see Sheet- 2). Furrows are the dark streaks that run diagonally across the page. Note that the 500-kHz sonograph clearly shows sand waves (SW) in the troughs and on the walls. Furrows, and sand waves within furrow field yield a bedload sediment transport direction (BLST) parallel to trend of furrows.

6. Sonograph (100 kHz) (top) and bathymetric profile (bottom) of lineations in South Bay. Location is near the San Francisco Airport (see Sheet 1). Note that furrows (to left) and lineations (to right) have similar orientations but markedly different spacings. Note on bathymetry profile, which covers only lineated area of top profile, that lineations appear to have no recognizable surface morphology and little (if any) relief.

7. Sonograph (100 kHz) (top) and bathymetric profile (bottom) of sand waves in South Bay. Location is the deep tidal channel between San Francisco and Oakland (see Sheet 1). Note that the "large" sand waves (LSW) have "small" sand waves (SSW) superimposed on them. Note the tuning-fork junctions (TFJ) in both large and small sand waves. Small sand waves also occur independently of large sand waves.

8. Sonograph (500 kHz) (top) and bathymetric profile (bottom) of sand waves in San Pablo Bay. Location is adjacent to Davis Point near Carquinez Strait (see Sheet 2). Note that these sand waves (SW) are asymmetric and yield an ebb-oriented bedload sediment-transport direction. Steeper sides of sand waves are to the left in the figure, which is the ebb direction for North Bay.

9. Sonograph (100 kHz) (top) and bathymetric profile (bottom) of sand waves in South Bay. Location is the deep tidal channel just south of Yerba Buena Island and the Bay Bridge (see Sheet 1). Note the "large" sand waves (LSW) with "smaller" sand waves (SSW) superimposed.

10. Sonograph (500 kHz) (top) and bathymetric profile (bottom) of sand waves in San Pablo Bay. Location is north side of main tidal channel adjacent to Mare Island (see Sheet 2).

11. Sonograph (500 kHz) (top) and bathymetric profile (bottom) of discrete sand waves adjacent to furrows that have sand waves (SW) in their troughs. Location is Pinole Shoal in San Pablo Bay (see Sheet 2). Note the similarity in orientation of sand waves that occur outside of the furrowed area with sand waves that occur in furrow field.

12. Sonograph (500 kHz) (top) and bathymetric profile (bottom) of sand waves in Suisun Bay. Location is main channel just south of Roe Island (see Sheet 3). Note that these sand waves are asymmetric with their steeper face toward the left of the figure, which yields an ebb-oriented bottom transport from right to left on the figure.

13. Sonograph (500 kHz) (top) and bathymetric profile (bottom) of "large" sand waves in Suisun Bay. Location is just off Dillon Point in the main tidal channel (see Sheet 3). Note that both the sonograph and bathymetric profile reveal that these "large" sand waves (LSW) are asymmetric with their steeper face toward the left of the figure, which yields an ebb-oriented bottom sediment transport direction (BLST). Also note that the "large" sand waves have superimposed smaller sand waves (SSW); compare this figure to figures 7 and 9 from South Bay.

14. Sonograph (500 kHz) (top) and bathymetric profile (bottom) of sand waves in Suisun Bay. Location is adjacent to Roe Island and New York Point (see Sheet 3). Sand waves are asymmetric and yield an ebb-oriented bedload sediment transport direction.

15. Sonograph (100 kHz) (top) and bathymetric profile (bottom) of light and dark tonal patterns in South Bay. Location is just northeast of Hunters Point (see Sheet 1). Note the irregularity of all features and lack of any uniform patterns or definable features. The light-toned streaks are probably man-made drag or trawl marks.

16. Sonograph (100 kHz) (top) and bathymetric profile (bottom) of featureless bay floor in South Bay. Location is just east of the San Francisco International Airport (see Sheet 1). Note the absence of any discernable acoustic patterns and the relatively flat profile of the bay floor.

17. Sonograph (100 kHz) (top) and bathymetric profile (bottom) of anomalous features on the bay floor of South Bay. Location is just north of the San Mateo-Hayward Bridge and southeast of San Bruno Shoal (see Sheet 1). Note that the alternating light and dark streaks (more or less vertical on the figure) are "enclosed" by streaks that cut diagonally across the figure. At this time, we attribute these features to man-made activities such as dredging.

SHEETS

Sheet 1. South San Francisco Bay. Scale = 1:40000.

Sheet 2. San Pablo Bay. Scale = 1:40000.

Sheet 3. Suisun Bay. Scale = 1:40000.

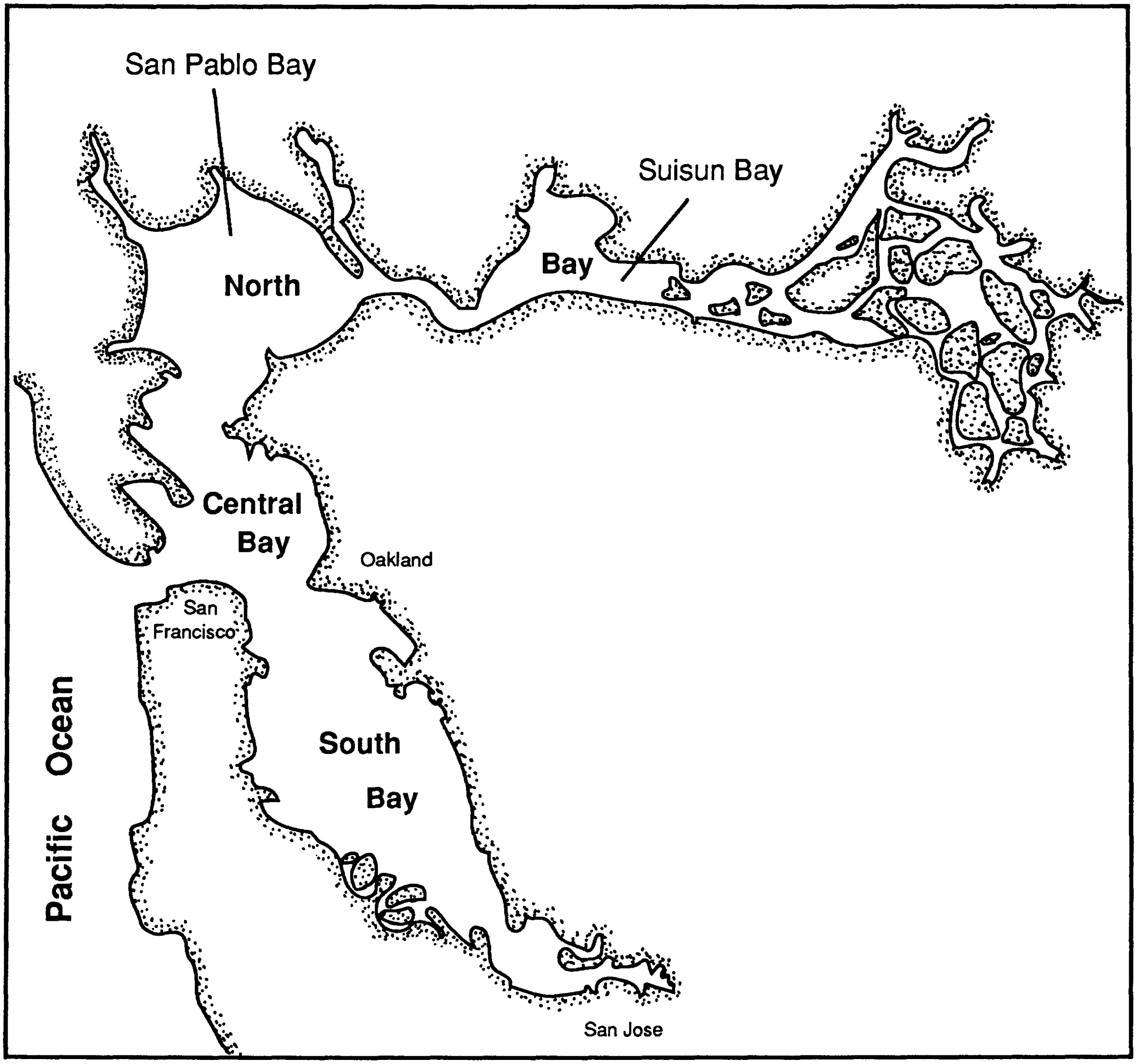

San Pablo Bay
Suisun Bay
North
Bay
Central
Bay
Oakland
San
Francisco
Pacific Ocean
South
Bay
San Jose

FIGURE 1

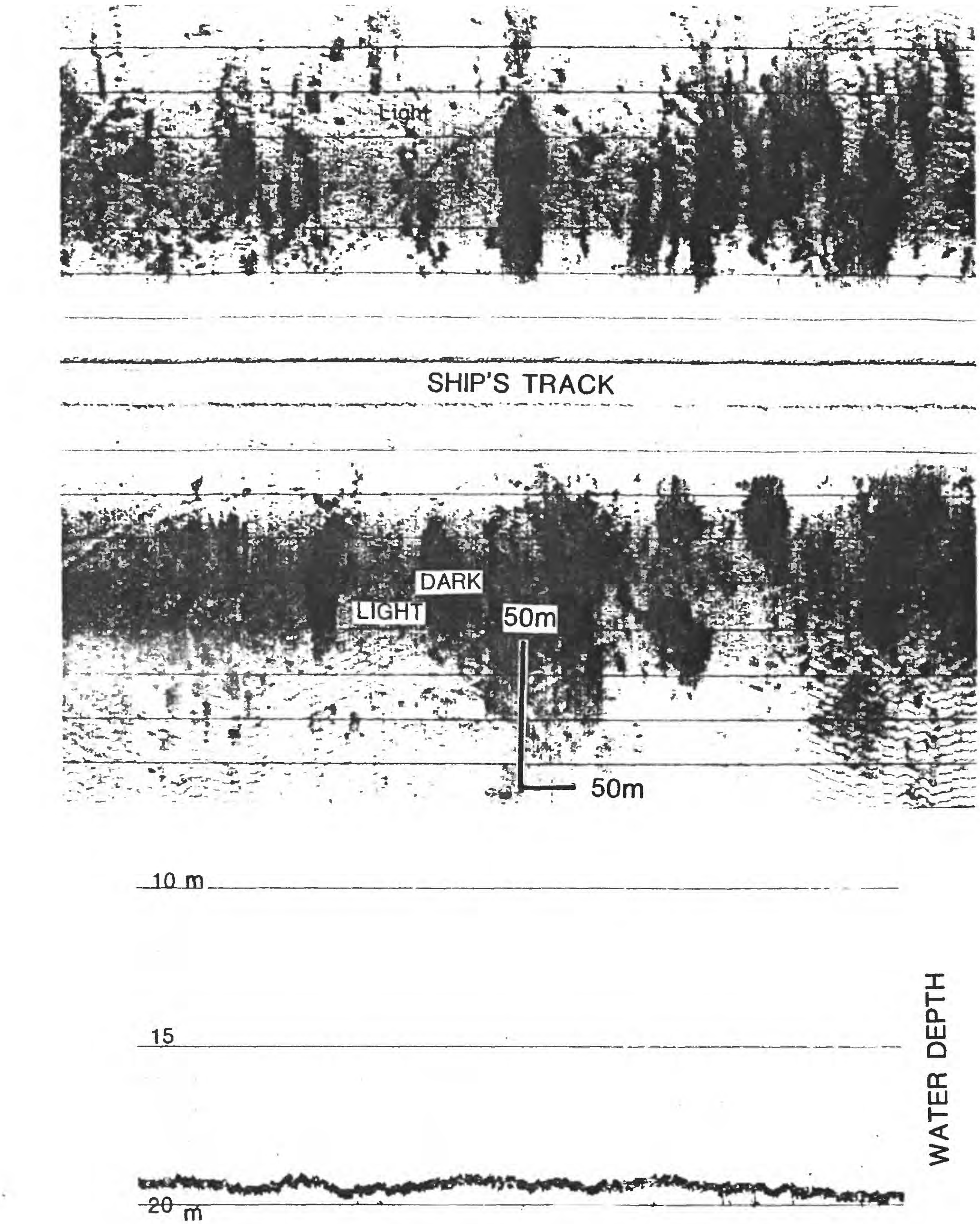
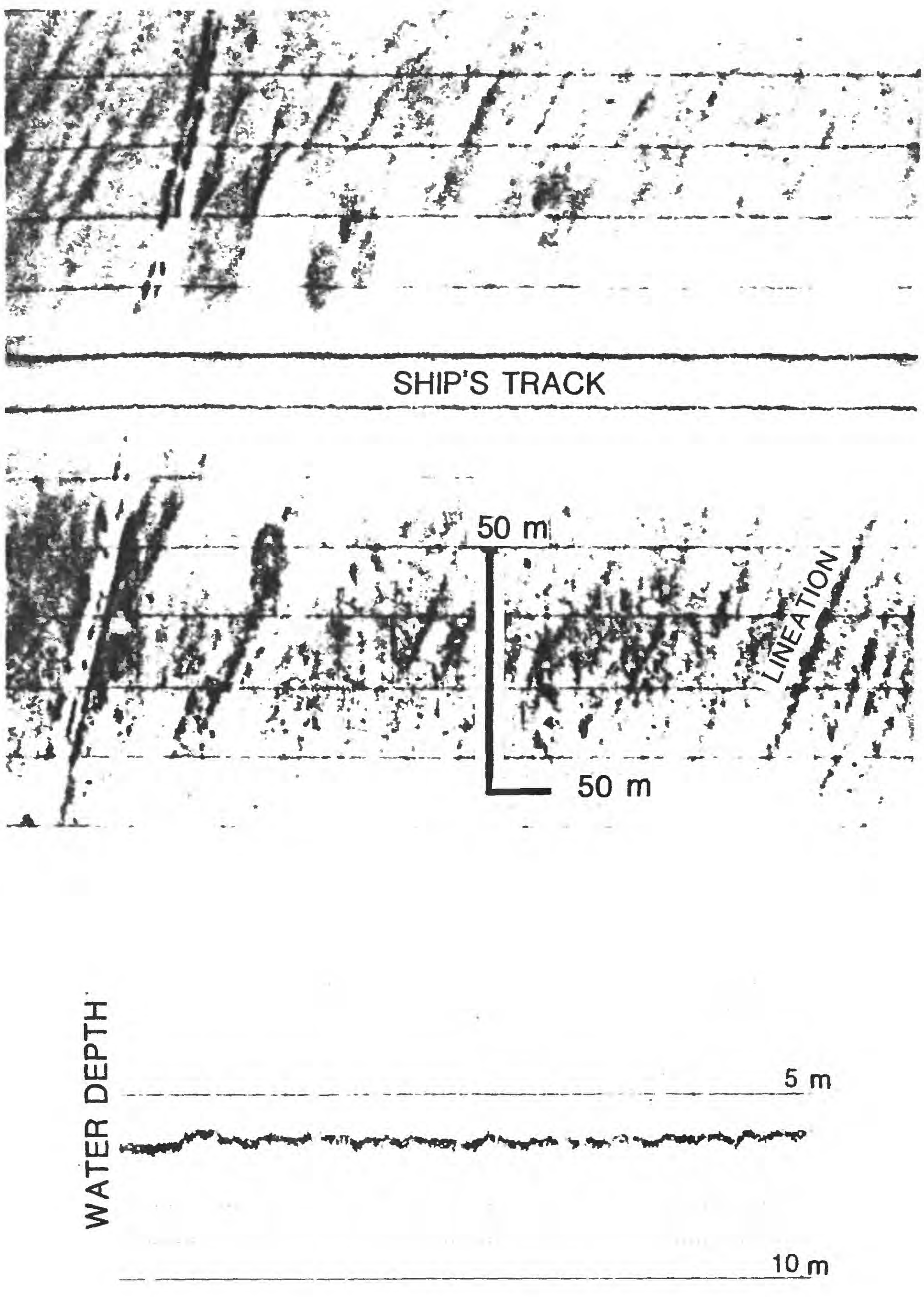


FIGURE 2



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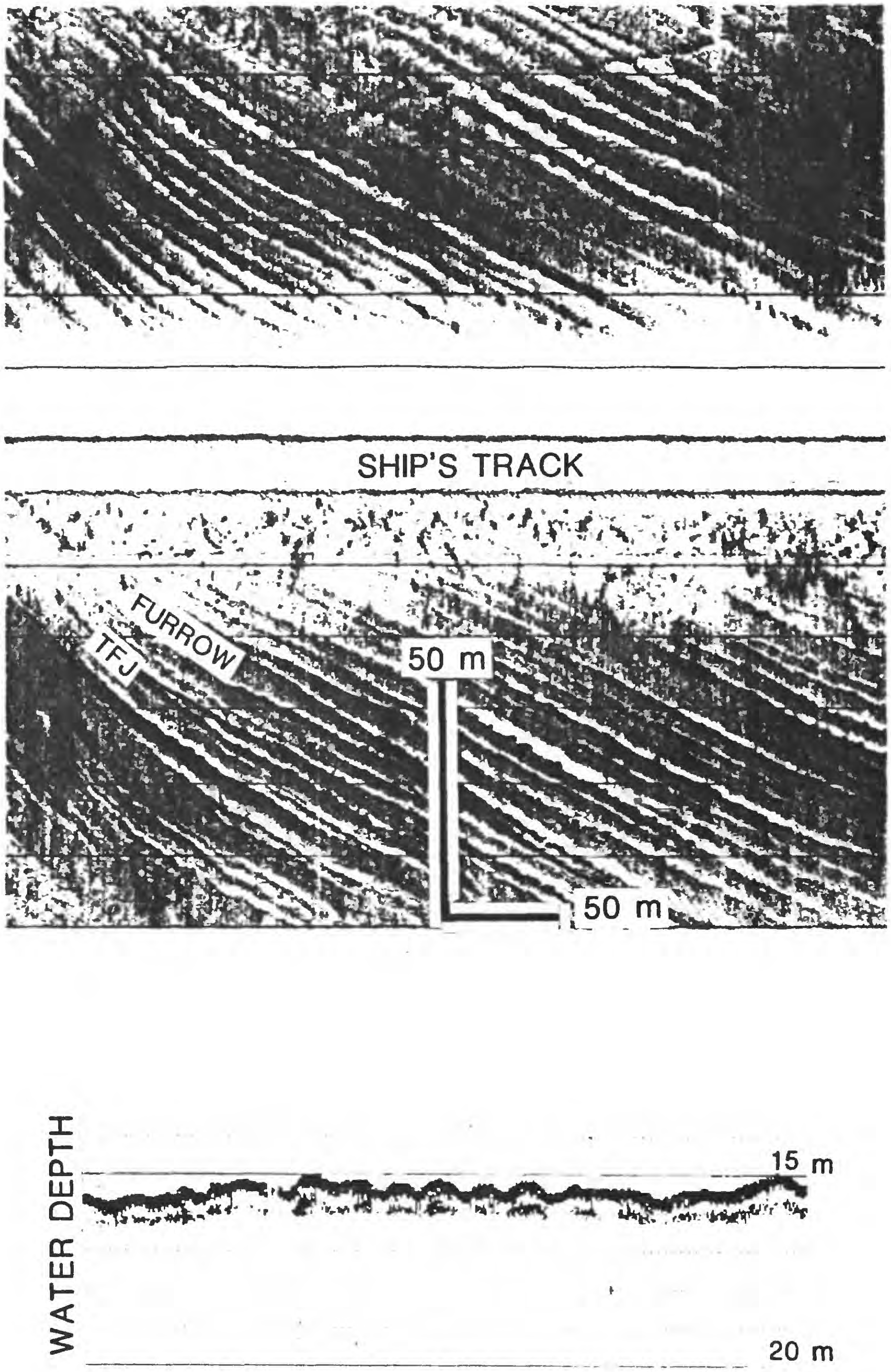


Figure 4

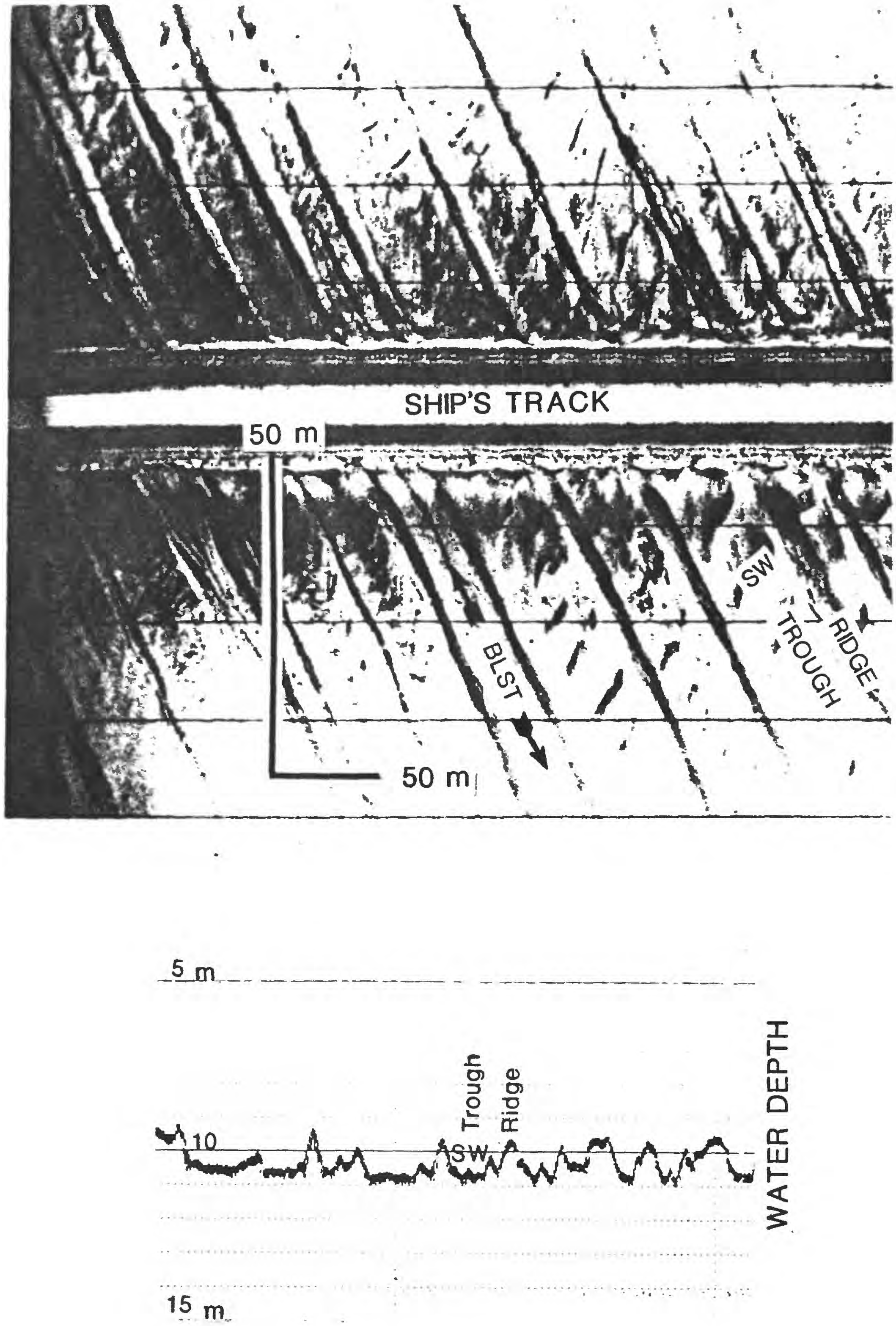

SHIP'S TRACK
50 m
50 m
BLST
SW
TROUGH
RIDGE
5 m
Trough
Ridge
10
SW
WATER DEPTH
15 m

FIGURE 5

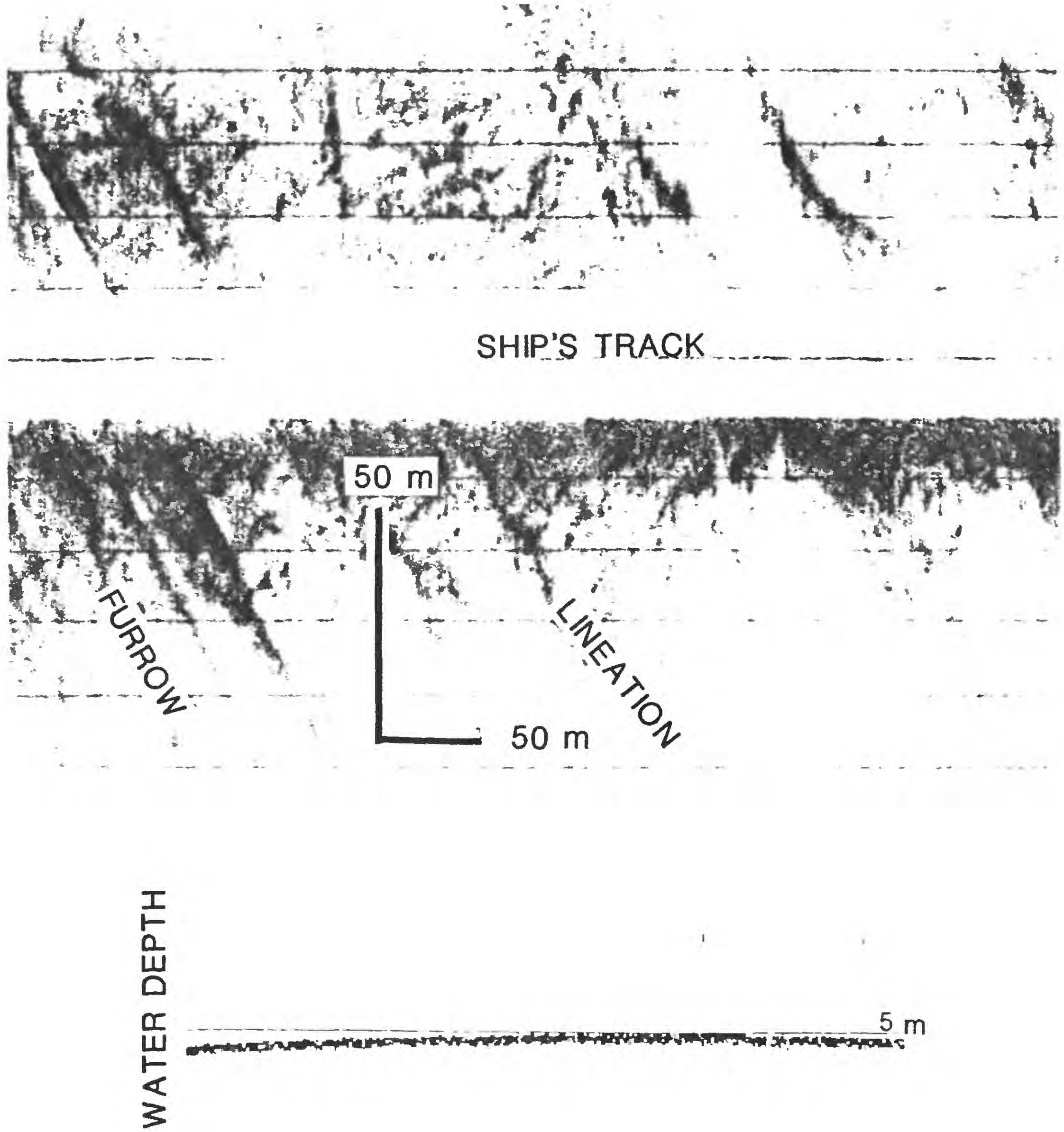


Figure 6

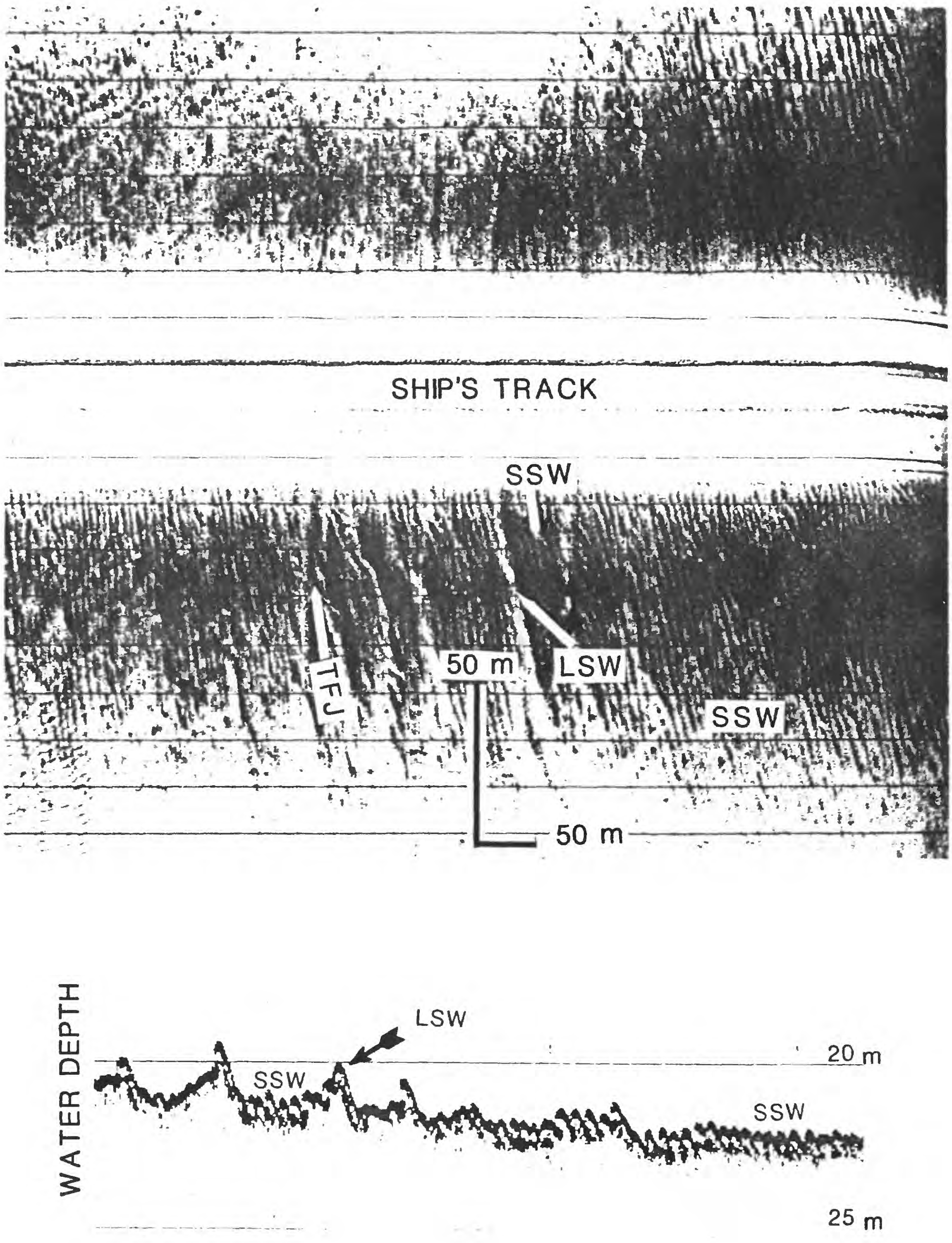

SHIP'S TRACK
SSW
TFJ
50 m
LSW
SSW
50 m
WATER DEPTH
LSW
SSW
20 m
SSW
25 m

Figure 7

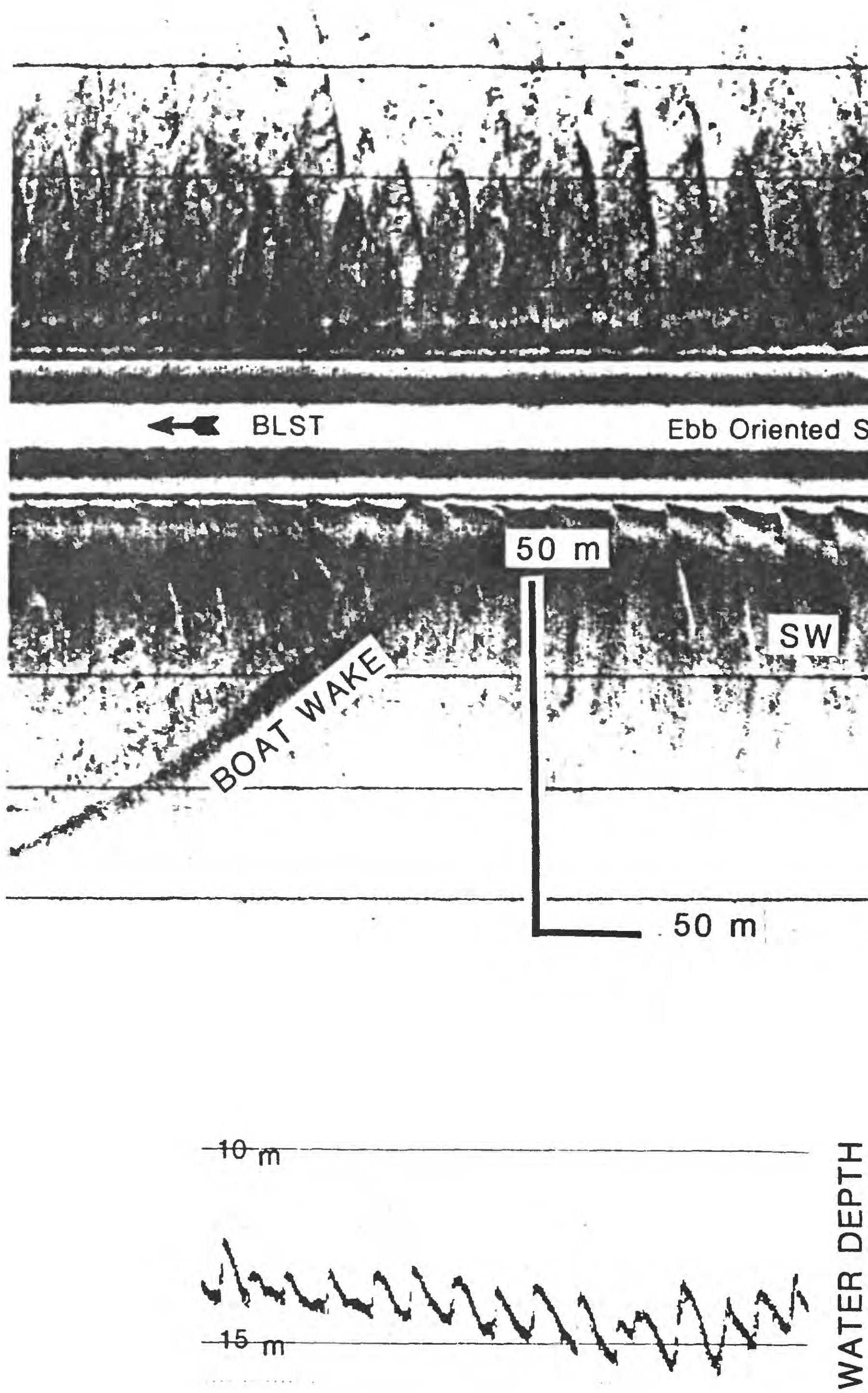


Figure 8

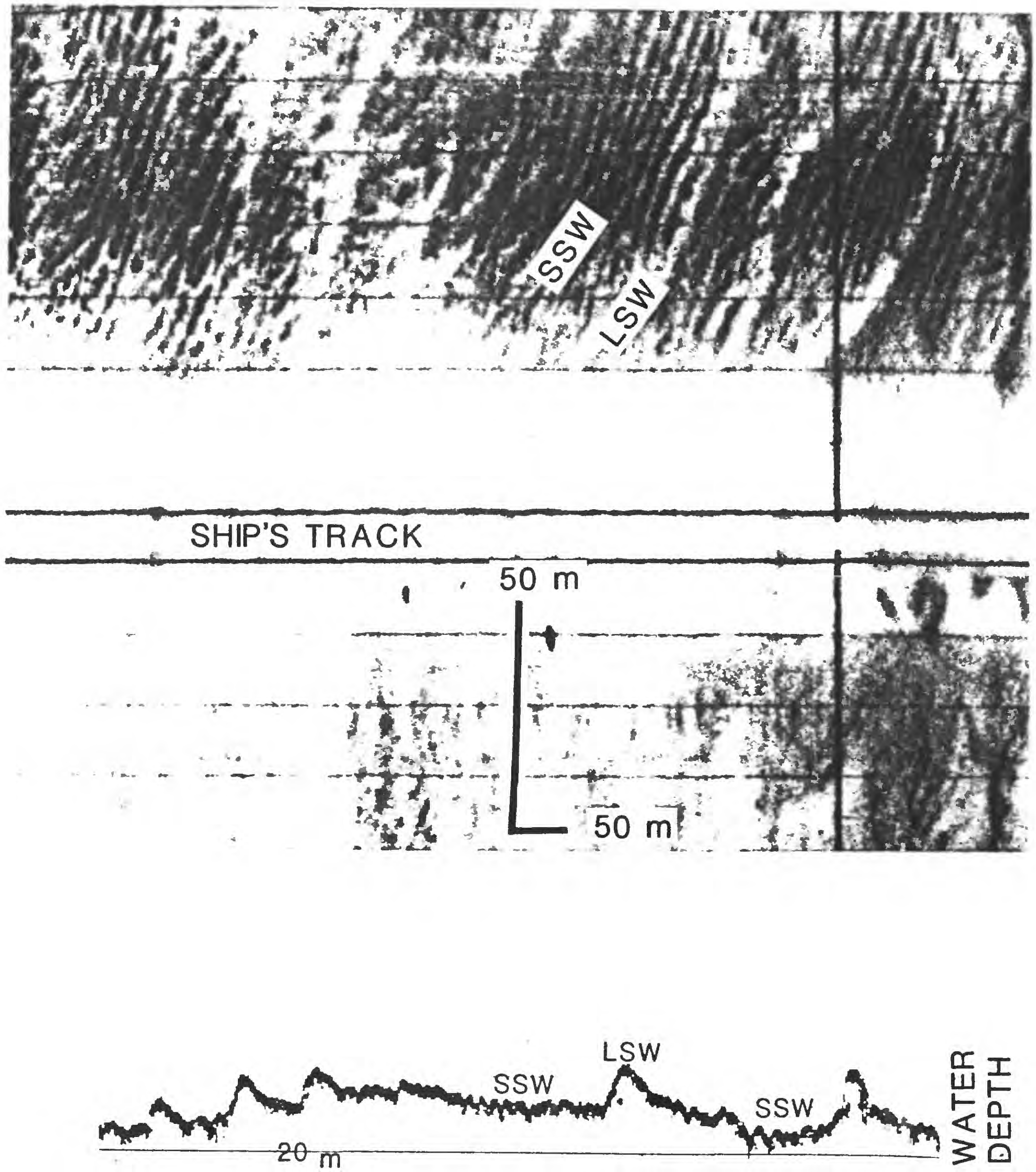
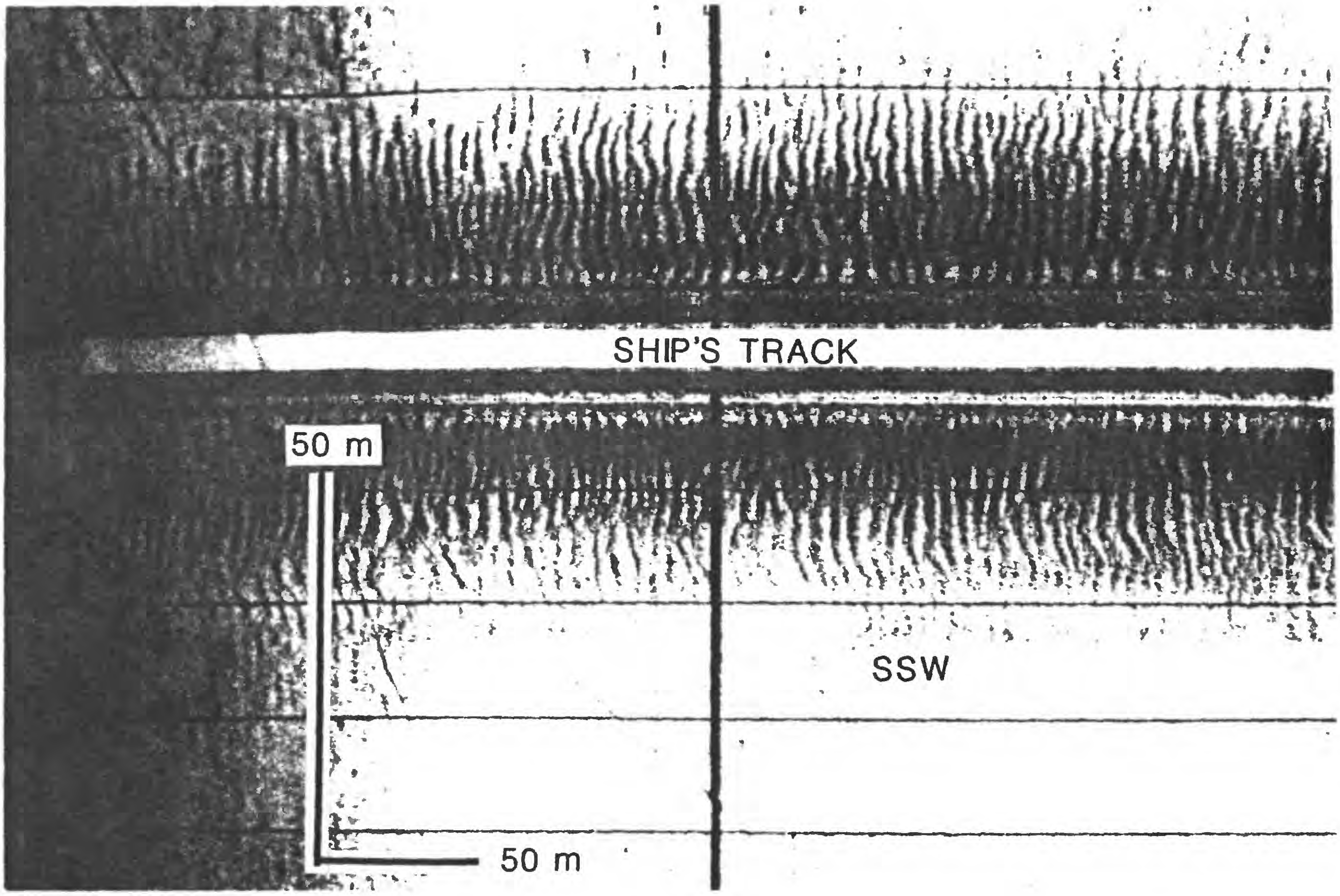


Figure 9



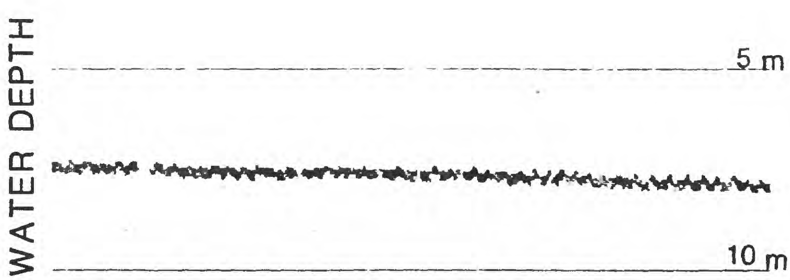


Figure 10

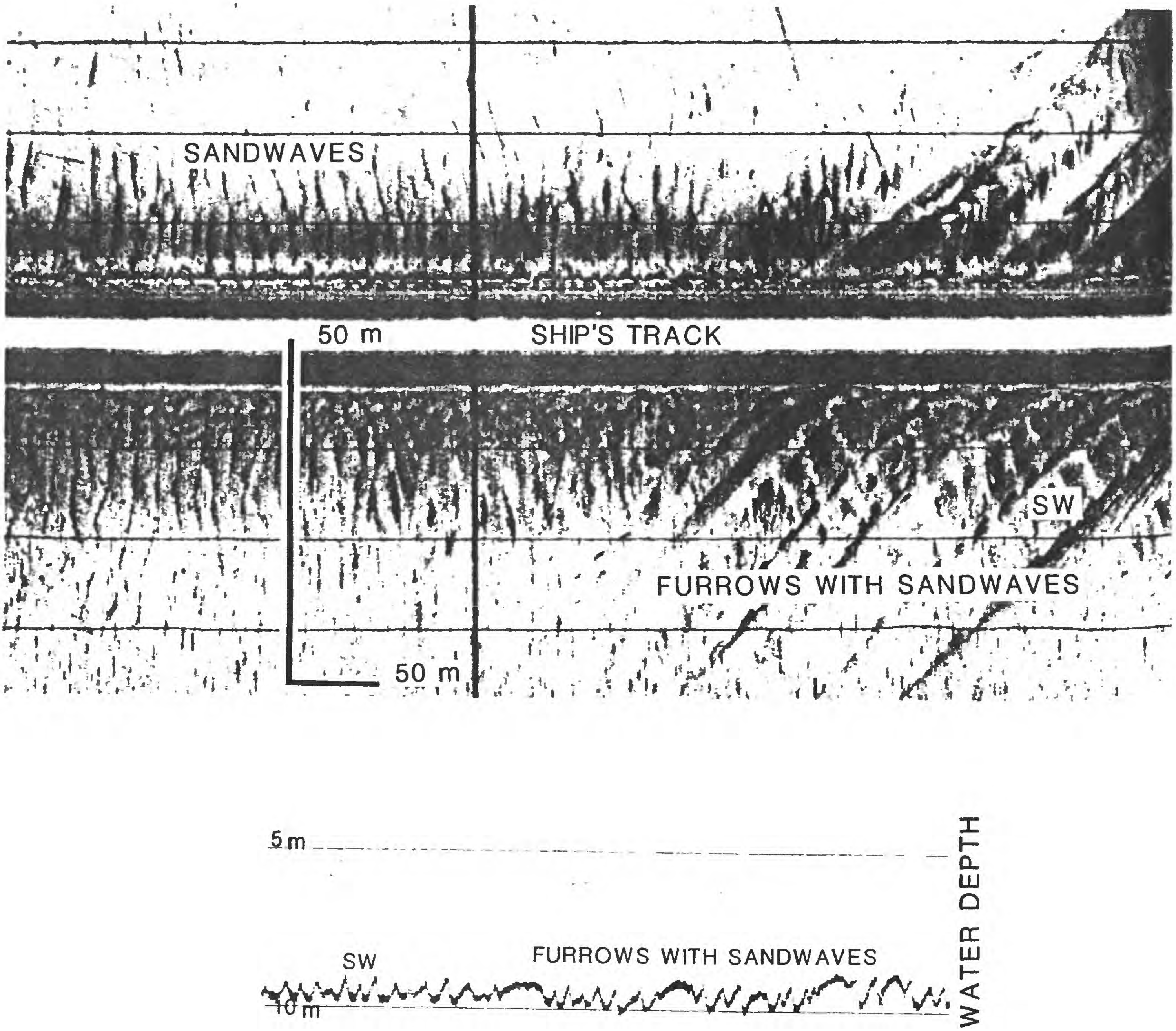

SANDWAVES
50 m
SHIP'S TRACK
SW
FURROWS WITH SANDWAVES
50 m
5 m
SW
FURROWS WITH SANDWAVES
10 m
WATER DEPTH

Figure 11

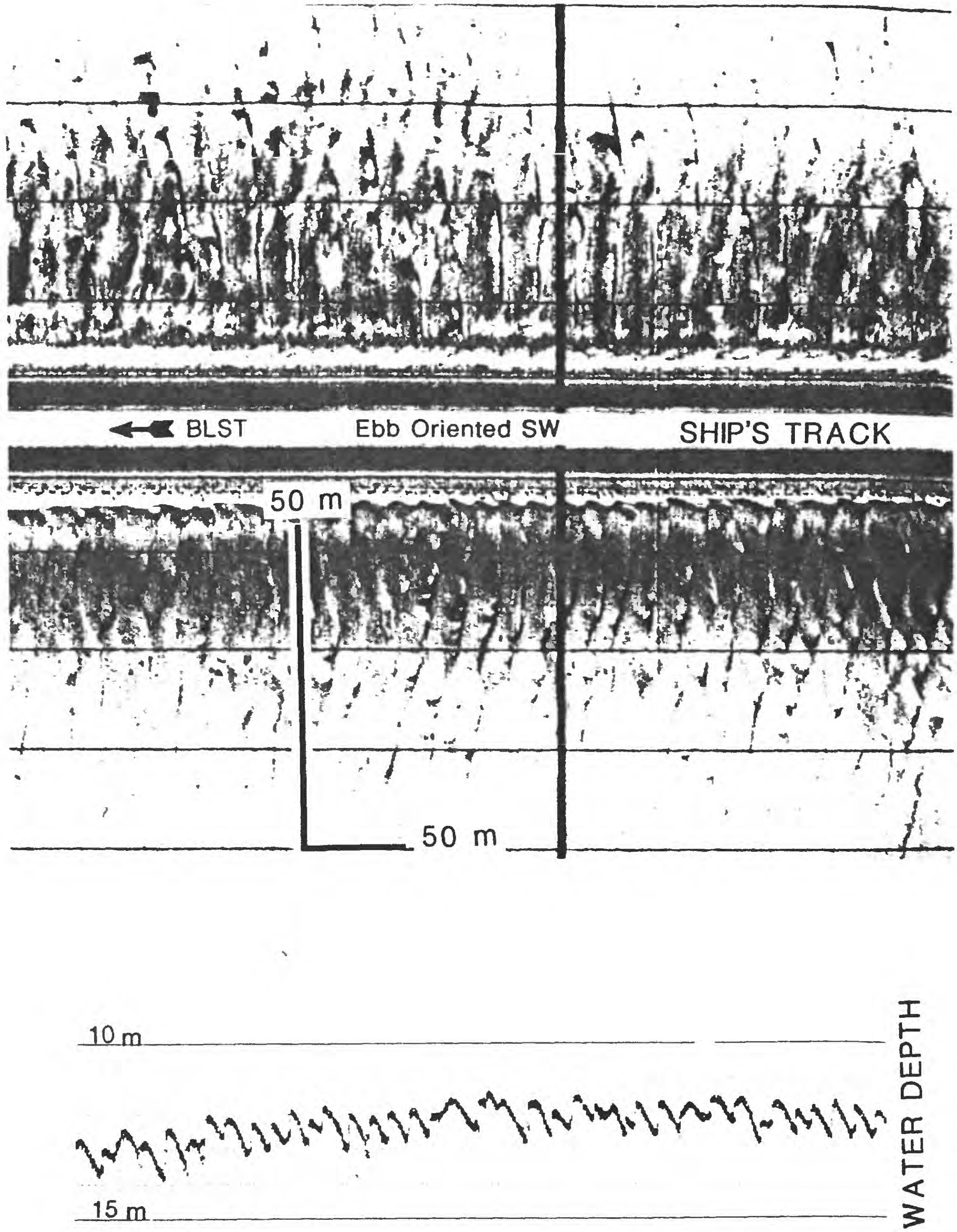
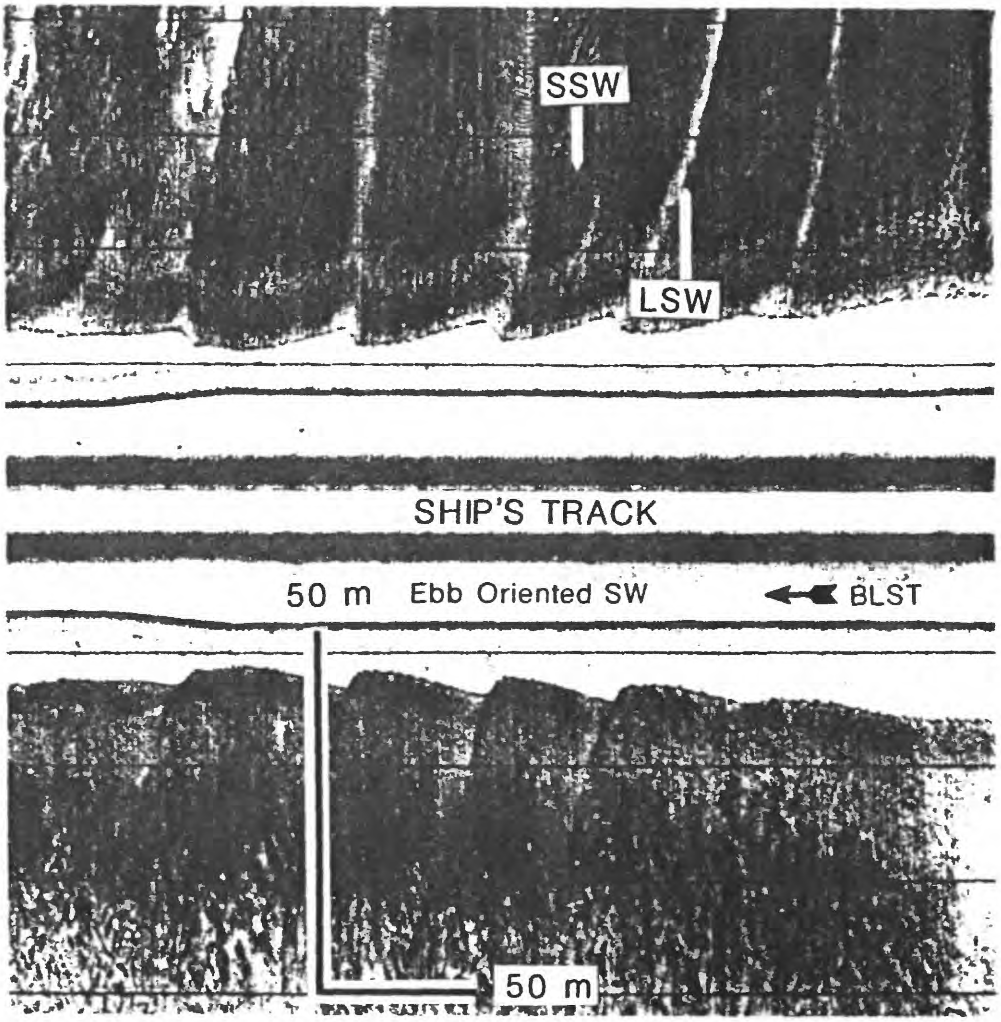


Figure 12


SSW
LSW
SHIP'S TRACK
50 m
Ebb Oriented SW
BLST
50 m

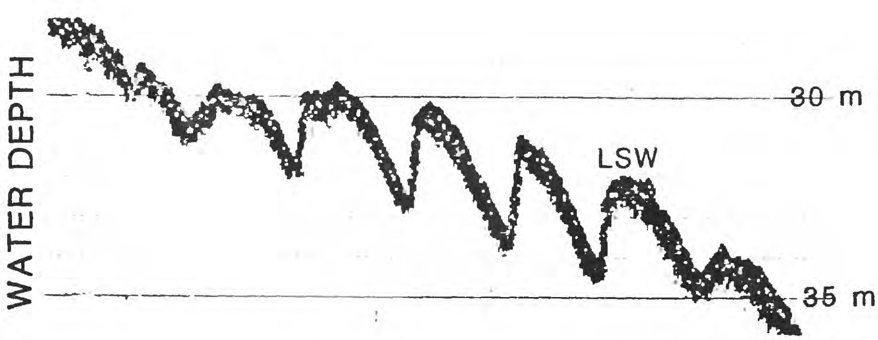
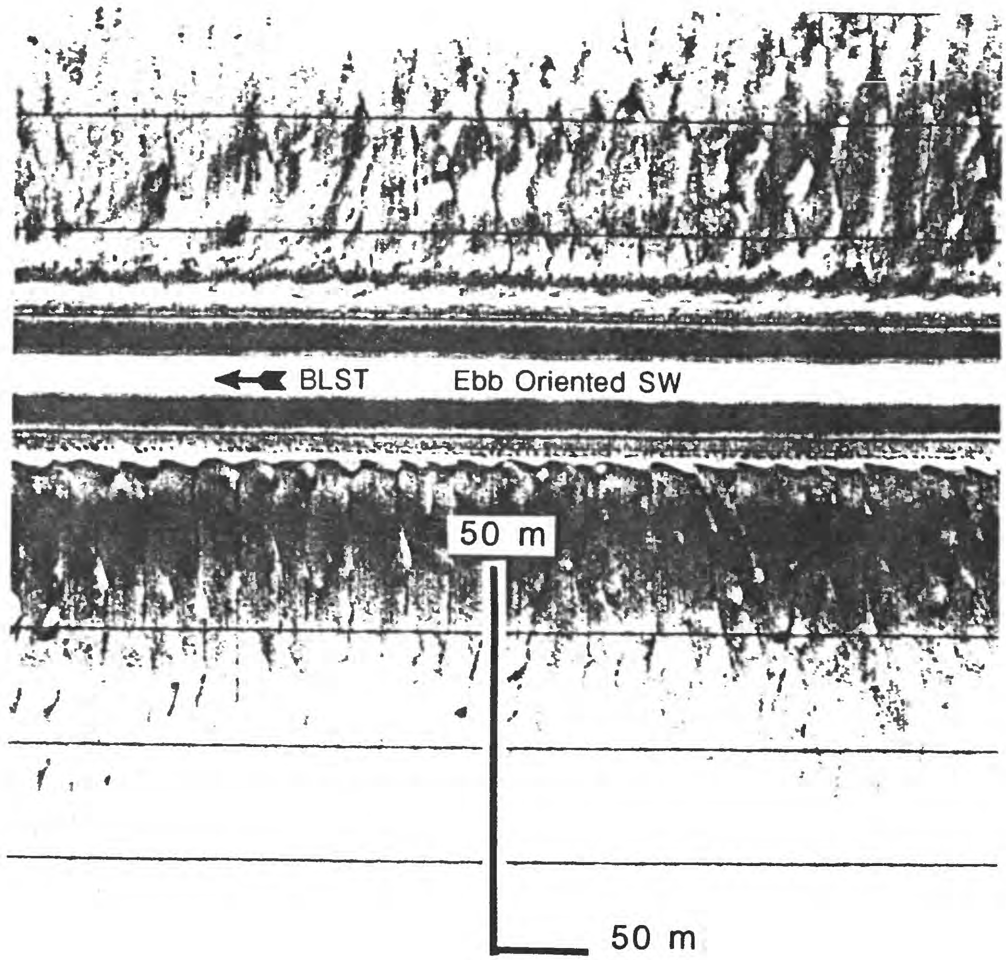

WATER DEPTH
30 m
LSW
35 m

Figure 13



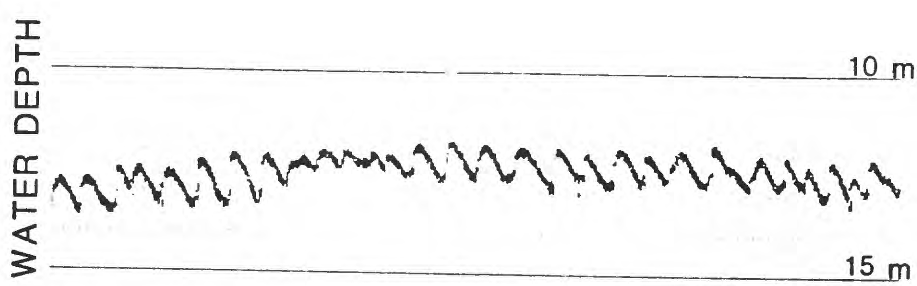


FIGURE 14

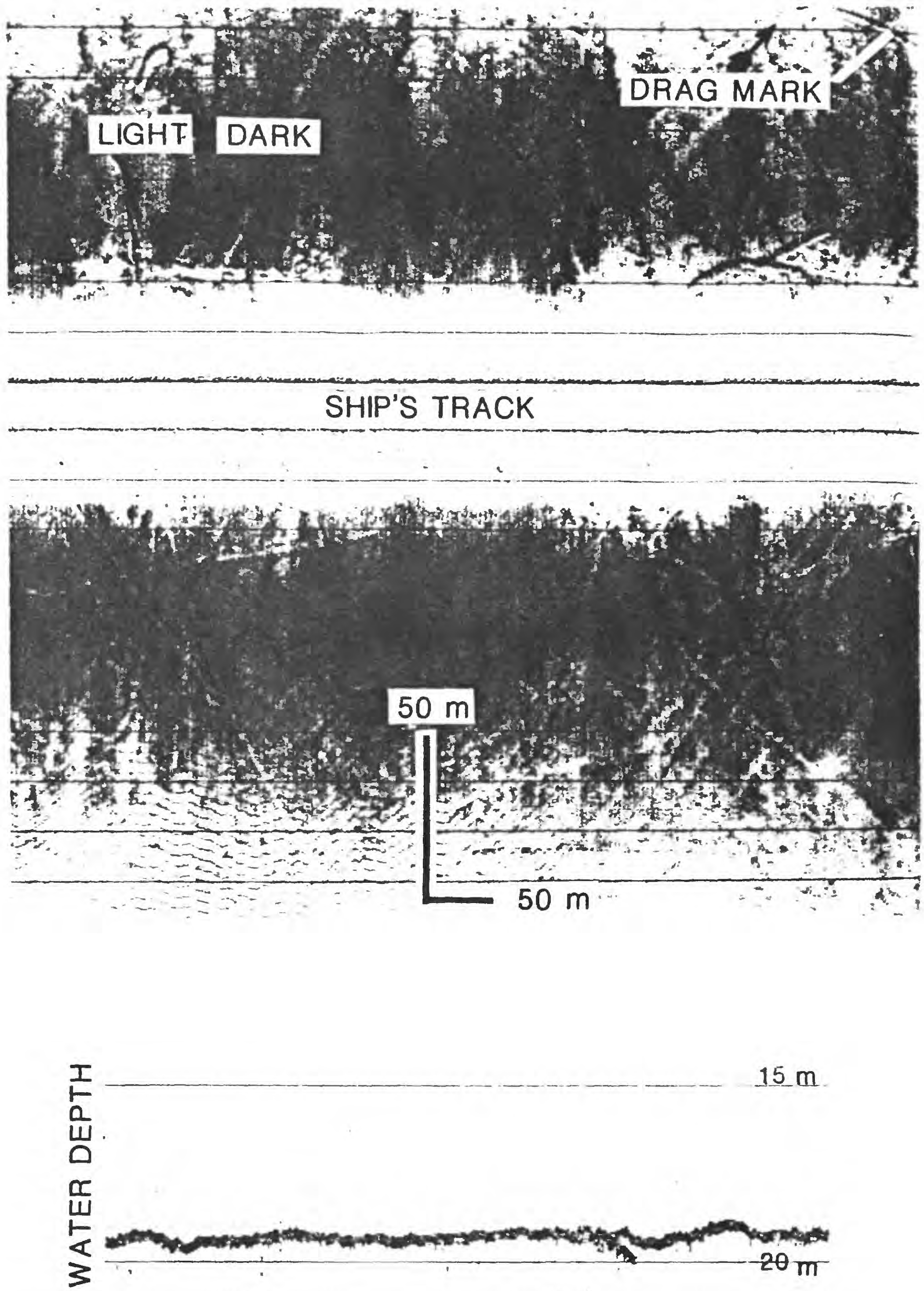
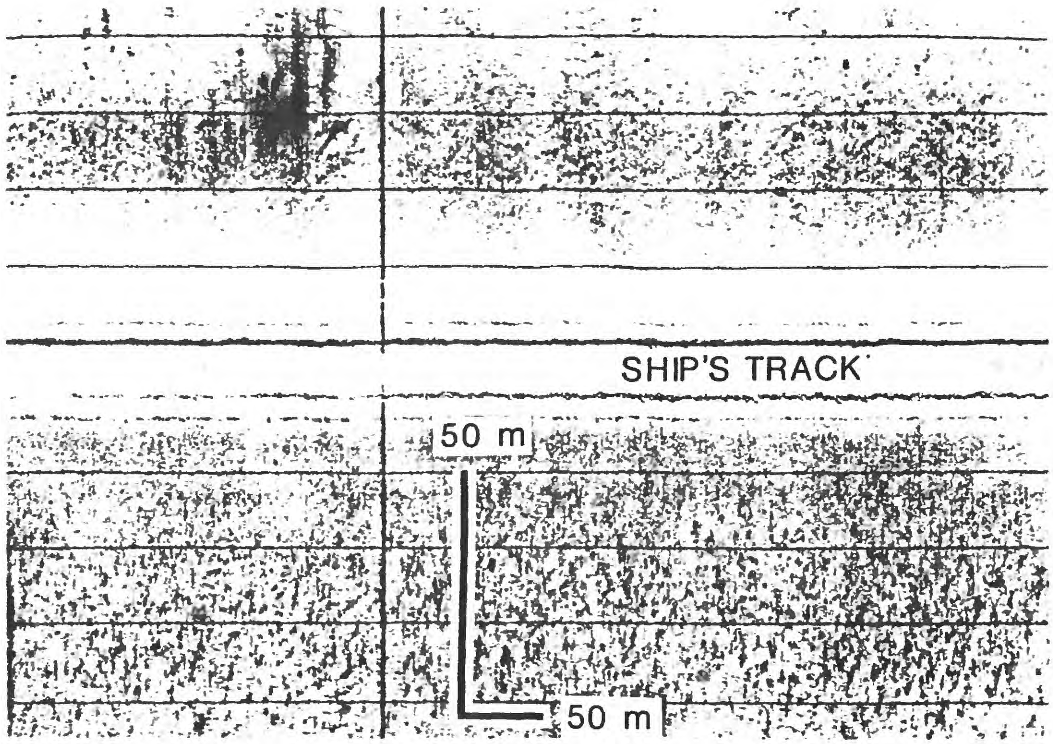


Figure 15



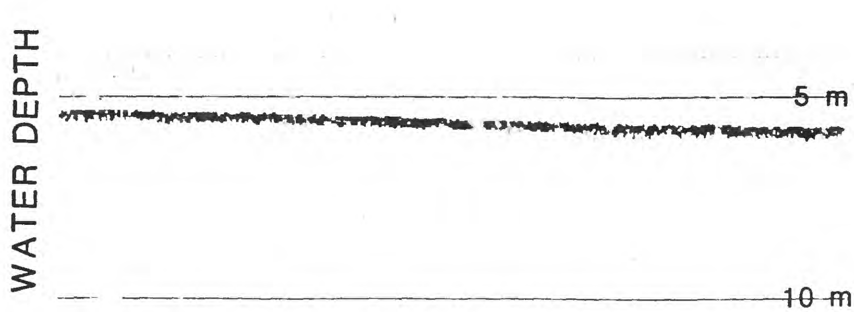


Figure 16

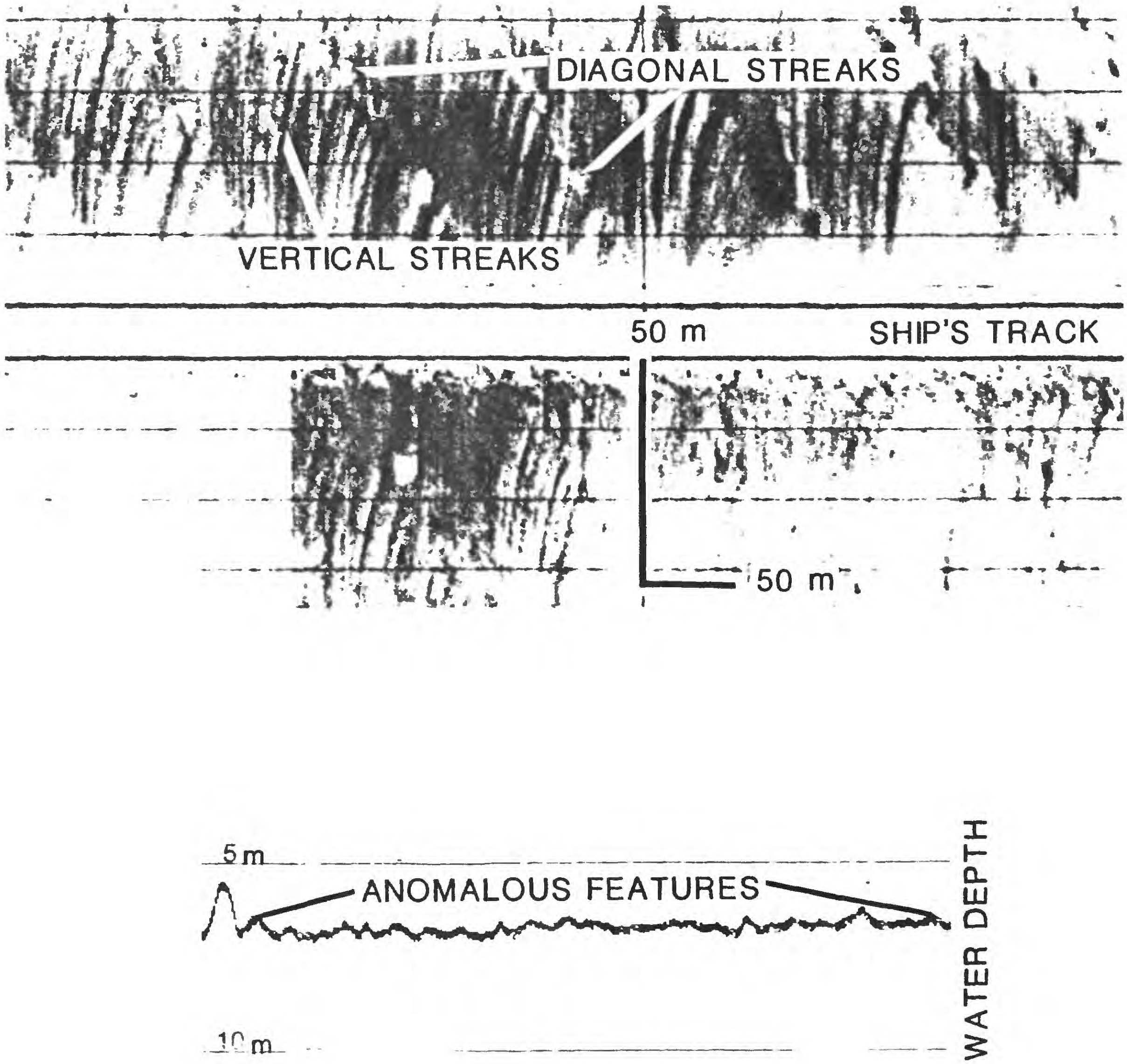

DIAGONAL STREAKS
VERTICAL STREAKS
50 m
SHIP'S TRACK
50 m
5 m
ANOMALOUS FEATURES
WATER DEPTH

Figure 17