The Status of Oyster Reefs in Galveston Bay, Texas

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INTRODUCTION

Oyster reefs make up one of the primary geological features of Galveston Bay. They affect current flow and salinity and provide a primary substrate for a wide variety of hard-bottom invertebrates and fish. The commercial oyster fishery in Galveston Bay is one of the more important ones in the U.S. and the private (or noncommercial) harvest of shellfish ranks Texas third in the country (Hofstetter, 1990; NOAA 1991a,b). Accordingly, the oyster reefs play a pivotal geological, ecological and commercial role in Galveston Bay.

Concern about the health of the oyster fishery and the oyster reefs is one of long-standing (TGFOC, 1929; Eckhardt, 1969; Benefield, 1976). However, prior to the late 1960s, few quantitative data were available for Galveston Bay despite the earlier surveys in many of the central Texas bays (Moore, 1907; Moore and Danglade, 1915) and elsewhere in the Gulf of Mexico (e.g. DeAlteris, 1988). In the late 1960s, the Texas Parks and Wildlife Department began mapping the oyster reefs of Galveston Bay, primarily in response to concerns about the extent of shell dredging activities (Benefield and Hofstetter, 1976). This survey was completed in the early 1970s. Since then, little additional information has been collected.

The purpose of this study was to survey the oyster reefs of Galveston Bay and compare them to the earlier surveys. Of particular importance were concerns about the perceived loss of reef area and the lowering of relief on the remaining reefs. Accordingly the primary objectives of this study were to resurvey the areal extent and relief of the principle reefs in Galveston Bay.

METHODS

To accurately map an area as extensive as an entire bay system at moderate cost requires a method (1) that can be used from a small research vessel, (2) that requires only a modestly-sized crew, (3) that can be used in unfavorable weather conditions, (4) which can rapidly discriminate bottom type while underway so that the mapping plan can be continuously updated as new reefs are encountered, (5) that accurately and clearly distinguishes bottom types so that little ground-truthing is required, hence maintaining the boat continuously underway, (6) that permits a relatively fast running speed, (7) that is capable of use in shallow (< 1 m) as well as deeper (> 10 m) depths, and (8) that permits precise, rapid determinations of position on a scale significantly smaller than the average-sized reef (often < 20 m in shortest dimension). Methods used previously did not meet these requirements so an improved technique was developed based on precise electronic navigation and an acoustic profiler to differentiate bottom type while continuously underway.

Technique description

Capabilities for discrimination of bottom type.

We chose a dual frequency acoustic setup consisting of a Datasonics Dual Frequency Transceiver (Model DFT-210), a Datasonics towed fish with dual transducers (22 and 300 kHz) and an EPC Multichannel Chart Recorder (Model 4800). Primary identification of oyster reefs relied on the record from the 300 kHz channel. On the chart paper, an oyster reef appears as a dark, dense series of spikes projecting well above the background signature from a mud or sand bottom (Figure 1). DeAlteris (1988) noticed a similar signature with a 200 kHz transducer, however the reliability of the signature was not satisfactory. He relied on a second echo from the hard bottom. The 300 kHz signature is unambiguous. Although we have not investigated the acoustic phenomena involved, we surmise that the oyster reef signature results from more sound energy bouncing back to the transducer. In the case of a muddy bottom, more of the sound energy is absorbed, thus the signature is reduced. Sand and shell hash give an intermediate, fuzzy signature, still readily distinguishable from reef or other oyster bottom.

In practice, we encountered only two bottom types that required occasional ground-truthing to verify their non-oyster nature: clam beds and coarse shell hash usually associated with points, nearshore sediments and dredge spoil. With experience, coarse shell hash could be discriminated with relative ease and required little ground-truthing. As examples, Figures 2 and 3 show typical returns from a spoil bank adjacent to the Houston Ship Channel with and without an associated reef, respectively. The faint second multiple seen clearly in Figure 3 and just showing through the reef signal in a few spots on Figure 2 is characteristic of dredge spoil, at least in Galveston Bay. With experience, most clam beds could also be distinguished, however dense clam beds required ground-truthing. Figure 4 shows a _Rangia cuneata_ bed near Houston Point in Galveston Bay. This technique, then, could be used to identify concentrations of most large epifaunal or semi-epifaunal shellfish, not just oysters.

We used the 22 kHz record to discriminate reefs from oysters on muddy bottom or spoil. In Galveston Bay, oysters occur on true reefs, with a hard basement, on spoil banks next to dredged channels and scattered about on muddy bottom. The latter condition is frequently found (1) on oyster leases used for depurating oysters taken from closed waters for later recapture and sale, (2) on the shore side of alongshore reefs probably as old beach lines, and (3) in extensive areas of West Bay, of unknown origin. The 22 kHz record was not always unambiguous, but usually added important information on bottom type. Small reefs and towheads frequently were too small to generate a reef-like subsurface signal although clearly reefal in nature and the substrate under points (e.g. Red Bluff or Dollar Point in Galveston Bay) frequently yielded a strong reef-like return presumably due to the relatively hard basement material forming the point and the meager amount of sediment accumulated upon it. In most cases, however, the three types of oyster bottom could be distinguished accurately using the 22 kHz signal.

Configuration of acoustic system.

In the field, the acoustic system provided reliable data even under unfavorable weather conditions. Signal quality did not deteriorate in 1-m seas, during thunderstorms, or in areas heavily trafficked by boats. Signal quality was satisfactory in depths as shallow as 0.55 m (our minimum running depth) and as deep as 12.5 m (our deepest depths) and at speeds higher than precise navigation would allow (> 5.5 knots).

During data collection, the towed fish was lowered from a boom held perpendicular to the boat, well in front of the stern to eliminate the effects of "prop-wash". As many running depths were shallow, we positioned the fish < 0.1 m below the water surface to prevent the towed fish from hanging up on underwater obstructions. Signal quality was not affected. To keep the fish from hitting the boat's side during turns and to maintain a proper orientation while underway, the boom was extended 1 m from the boat's rail and a tow rope was run from the fish to the bow to maintain forward aspect during turns and to maintain a vertical downward-facing position for the transducers while underway. The setup is shown in Figure 5.

The settings for the acoustic system will probably need to be adjusted for local conditions to optimize signal quality. As a guide, the transceiver settings we used were:

	300 kHz	22 kHz
Pulse Length	1.0 msec	0.1 msec
Output Attenuation	-10 dB	-3 dB
Band Width	10 kHz	5 kHz
Gain	Left: 0 Right: 3	Left: 0 Right: 13

The chart recorder was set to scan 100 msec with a chart speed of 150 lines in^{-1} and was programmed to key out only once every 5 sweeps of the stylus. The highest sweep rate was used because operating depths were 0.5 to 3 m. Each channel was set as follows: Time varying gain (TVG), none; Threshold, negative stop; Gain, 1.6.

Determination of position and relief.

Position was determined while underway using a Magellan Global Positioning System (GPS). Loran C proved to be too inaccurate for precise mapping. We emphasize the necessity of using a GPS system for accurate determinations of position. Many reefs were less than 20 m across in shortest dimension and larger reefs had significant variations in relief of a similar scale. In practice, the precision of our GPS unit was within 0.01 min latitude and longitude on all days. The NOAA-27 datum was used to conform to previous charts of the area.

The frequency at which positions were updated by the GPS unit limited maximum running speed to 5 knots. At speeds greater than 5 knots, the positions of reef details and boundaries could not be accurately recorded. In practice, we used a 4-to-5 knot window for running speed that proved adequate for all applications.

Relief was recorded while underway using an Apelco fathometer. Pictures of the fathometer screen were taken with a 35 mm camera (film speed ≥ 1000 ASA) to record relief of all reefal area because relief changed too quickly to be recorded manually while underway. A chart recorder attached to the fathometer would have been an adequate alternative. Fathometer accuracy declined at depths < 0.8 m. We found that a substantial change in running speed affected the depth reading so that maintaining a constant running speed was required throughout a line.

Procedure for data collection.

Use of an autopilot permitted the pilot to record fathometer data (by taking pictures of the fathometer screen) and positions as well as tend to navigational duties. A second person ran the acoustic profiler. The chart recorder was continually monitored and annotated with position and depth information at least once every minute. When reefs or rapid changes in bathymetry were encountered, positions and depths were recorded at more frequent intervals. Further details of reef relief and position were taken from the pictures of the fathometer screen and calibrated with the chart recorder knowing the speed of the chart paper and the fathometer screen. With a little practice, the entire operation could be easily performed by two people.

For data collection, N-S and E-W lines were run on a 0.125 min grid in areas with reef. An 0.25 min grid was used to map uncharted areas. Subsections having reefal components were then mapped using the 0.125 min grid. The grid choice was a compromise between (1) the detail required to adequately assess reef coverage and the accuracy of positions permitted by the GPS unit and (2) the time required to run the lines. Smaller or larger grids might be used in other applications.

Survey limitations.

The mapping survey was designed to cover the portions of the bay known or suspected to have substantial oyster reefs. The survey began in East Bay, then covered the eastern portion of Galveston Bay south of Smith Point and Trinity Bay. The survey then moved to Morgan Point and turned south covering the western half of Galveston Bay. West Bay was surveyed last.

As the survey continued, we recognized that substantial reef was present in areas not surveyed by TPWD (Benefield and Hofstetter, 1976). As such, the original plan of covering just those portions of the bay having known reef with an 0.125 min grid was modified during the project. We began to cover large areas of the bay, regardless of whether they contained known reef or not, with an 0.25 min grid and then concentrated our efforts using an 0.125 min grid in areas where reef was actually observed. For this reason, the bulk of central Galveston Bay and West Bay were mapped at least with an 0.25 min grid and a substantially larger area was mapped with an 0.125 min grid than originally deemed necessary from the circa-1970 survey of Benefield and Hofstetter (1976). For this reason, portions of Trinity, East and southeastern Galveston Bay remain uncharted. This part of the Galveston Bay system was surveyed prior to the modification of the surveying program and funds did not permit surveying them with an 0.25 min grid subsequently. The reader is cautioned to distinguish the absence of reef in unsurveyed areas from that of surveyed areas. The former is possibly an artifact of the incompleteness of the survey: the latter is a true absence of reef.

Laboratory Analysis.

Depths were obtained from field measurements and from pictures of the fathometer when depth changes occurred too rapidly to record them in the field. The speed of the fathometer trace was calibrated with the chart recorder recording the acoustic data so that depth changes obtained from the pictorial record of the fathometer screen could be correlated with changes in substrate type obtained from the acoustic data. Because depth changed during the day and from day to day with the tides and wind setup, the bathymetric data were standardized to a constant datum. To do so, we extended the 0.125 min grid used in data collection beyond the reef boundaries out over areas of relatively-deep, flat muddy bottom so that each line and the intersection of several N-S and E-W lines occurred in areas where the depth record was most accurate and where depth changes were minimal. This permitted an internal standardization of depth between lines run at different times, all of which could then be corrected to mean sea level by one standard correction. The internal standardization involved identifying all line crossings in which depth records fell within 0.06 min of each other over non-reefal bottom and in areas where depth changed by less than 0.15 m in 0.125 min. The median depth difference for all such cases for any one line was used to determine the correction for that line to the internally-standardized depth. In practice, about 90% of the lines could be corrected automatically by computer using this approach. A few lines, which perforce by their location extended nearly exclusively over reef or over areas of substantial depth change, were corrected to the internally-standardized depth by hand.

Army Corps of Engineers tide staffs were used to calibrate the bathymetry to mean sea level. Line 906 was the datum line which began at the Eagle Point tide gauge. As this line fell in the center of the surveyed area, excepting West Bay and the eastern portion of East bay, little or no cumulative error was recorded in utilizing this single line for the bathymetry calibration.

Reef designations were taken from the 300 and 22 kHz acoustic array. We distinguished three bottom types; sandy or muddy bottom, oyster reef, and unconsolidated shelly sediment (designated "shell on mud" on the accompanying maps). The distinction between reef and unconsolidated shelly sediment was somewhat arbitrary as was the distinction between the latter and sandy or muddy (non-shelly) bottom. In general, oyster reef contained a hard substrate in the immediate subsurface. Unconsolidated shelly sediment did not. Occasional ground-truthing confirmed the general accuracy of this distinction, however every individual case was not verified. Consequently the reader is cautioned to utilize the general distribution of these bottom types as the more accurate datum versus any individual location.

In many areas nearshore and in extensive areas in West Bay, the quantity of shell on the sediment surface gradually declined rather than stopping abruptly. In these areas, it was necessary to arbitrarily define the boundary between unconsolidated shelly sediment and sand or mud. In general, we took the boundary as a shell content half the average regional high, so that sediments designated as unconsolidated shelly sediment contained substantial shell and areas designated non-shelly contained distinctly less shell. However, an oyster dredge would undoubtedly recover shell in many of these latter areas.

With a few exceptions, the grid was sufficiently fine to define the extent and shape of the reefs. Exceptions were the fields of towheads frequently encountered in oil fields and occasionally elsewhere in the bay. Undoubtedly, many small towheads were missed by the survey, however areas where towheads were common are readily seen on the accompanying maps. Similarly, many small reefs along channels and associated with leases may have been missed. However, the locations where these types of reefs are common is readily observed. Accordingly, the estimated areas are probably minimums for these locations in the bay.

We made no effort to survey the fringing reefs that outline many areas of the bay. Typically a line of oysters a meters or so wide borders many of the bay shorelines in depths of 0.5 m or less. In no case were these fringing oyster populations surveyed. The acoustic apparatus was used throughout with two exceptions. First, certain shallow central reefs were too shallow to be mapped. In these cases, we ran lines up to these reefs on both sides and estimated the depth in-between. Estimations of areal extent was not compromised by this method, however depths shallower than 0.5 m are estimates only. Secondly, in the Deer Islands area of West Bay, the poling method was used because the extensive shallow water areas prohibited the use of the acoustic array. We ran calibration lines using both methods. In practice, reef (hard substrate) was equivalently identified by both techniques. Unconsolidated shelly sediment, however, was occasionally not equivalently distinguished from sand and mud using the regional high as the criterion for determining the boundary between the two sediment types. However, the calibration lines allowed us to correct for this bias. Accordingly, accuracy was not affected by the use of the poling method in the Deer Islands area.

Although *Rangia* beds were surveyed near Morgan Point, near Cedar Bayou and in middle Trinity Bay, we did not include *Rangia* beds in the survey results. The acoustic array could be used to survey these beds, however.

Data processing.

Once the depth corrections were completed, the data were processed for use by a Geographic Information System (GIS) to produce the maps which accompany this report. We used Arc/Info software. Three types of maps were created for each bay area. The bathymetry and transect line map shows the locations where the bathymetric data were obtained and the locations of interpolation or extrapolation by the Contour subroutine (TINS). Similarly, the reef and transect line map shows the location where substrate was determined and the locations of interpolation and extrapolation by the Thiessien subroutine (TINS). This map also shows the polygon structure obtained from the Dissolve subroutine (Overlay) and the numbers of the polygons used to estimate the area of each reef. The bathymetry and reef map relates the bathymetry to the reefs for estimation of relief and areal extent.

Thirteen sets of maps were generated. Each map covered 6 min in latitude and 6 or 9 min in longitude. In each case, a border of 0.01 degree was included. Consequently, adjacent maps overlapped by 0.02 degrees. The purpose of this border was to remove boundary effects that were present in the bathymetry contours. The reefs, themselves, generally had few significant boundary effects. However, the bathymetry near the boundary was normally inaccurate. Accordingly, only those data that fall within the central 6 x 6 or 6 x 9 min grid should be used. In a few cases, overlap exceeded 0.01 degree to maintain clarity of presentation. These more extensive areas of overlap were for aesthetic purposes only and do not indicate a graver problem with boundary effects.

The 0.125 min grid was too small to adequately define most channels. Only the Houston Ship Channel was large enough to be adequately defined. No effort was made to intensify the grid around other channels to better define the bathymetry. Accordingly, the bathymetric detail of most channels should not be considered accurate.

TINS was used to estimate reef area and bathymetric detail from the data. The subroutine used to estimate reef area included the formation of Thiessien polygons from the spatial array of latitudes and longitudes and substrate designations. The Contour subroutine was used to generate the bathymetry. On occasion, errors in the running of lines in the field or navigational constraints due to safety or depth failed to provide sufficient data to adequately determine reef extent. In these cases "g" lines were added to the data set during data analysis to constrain reef shape to the standard 0.125 min grid. The location of these added data are shown on the transect line maps accompanying this report. As a result, on the average, "g" lines show areas where reef area is poorly estimated. Some lines were run just to tie in the bathymetry. We recorded no substrate data from these "y" lines, but the depths were field observations. Similarly, "s" lines were added to constrain bathymetry, but these depths were added during data analysis using charts or estimates from adjacent lines. Once again, no substrate data were collected on these lines.

The precision of substrate identification in the field has been previously described. Bathymetric precision is hard to establish. In practice, in the field, depth changes of 0.09 m were significant on any one line (measurements were made in feet). However, experience in the depth standardization procedure suggests that the precision of the bathymetry probably is no better than 0.15 m. Accordingly, we used, as the smallest bathymetric contour, 0.25 m . This is at or near the limits of precision. Depth changes exceeding 0.25 m are significant in every case.

Bay boundaries were included for ease of interpretation. We did not survey the 0.0 m contour. This contour was obtained by digitization from charts and should not be considered to be as accurate as the bathymetry and reef data associated with the transect lines. In addition, in most cases, the bay shoaled by about 0.5 m between the end of the transect lines and the 0.0 m contour. Again, this extrapolation of bay bathymetry is an approximation only. The bathymetry is only accurate within the 0.125 min grid (or 0.25 min grid) as shown by the transect line maps.

In determining the area of reefs, we summed the areas of individual polygons as recorded on the reef/transect line map. In some cases, the resulting area was equivalent to that generally associated with a known reef. San Leon Reef is an example. In other cases, towheads or small reefs, which generated small "satellite polygons", were included with the primary reef. Old Yellow Reef was an example. In these latter cases, comparison to previous area measurements was difficult to impossible. We chose to lump these small reefs under previous names rather than erect a large number of new names for minor reefs. In a few cases, reef accretion has resulted in the loss of the discreteness of a previously named reef. In some cases, we attempted to estimate the reef area (e.g. Archie's reef). In other cases, we simply dropped the name from the maps (e.g. Shuttle Reefs). In every case, interested readers can determine exactly which polygons were utilized for each reef by referring to the reef/transect line map.

RESULTS

Reef Description

Overview and Perspective.

Reef and unconsolidated shelly sediments comprised a total of 36.8 square miles (9539.8 hectares) of the surveyed bay area. The surveyed area included the majority of West Bay, East Bay, Trinity Bay, and Galveston Bay. Of this, about 60.3% (5754 hectares) were in Galveston, East and Trinity Bays (Table 1). The remaining 39.7% was in West Bay and the Pelican Island Embayment. [We use the term embayment to refer to sectors of Galveston Bay proper separated by significant points, islands, or man-made dikes and channels. For example, the Clear Lake embayment is that portion of the bay between Eagle Point and Red Bluff out to the Houston Ship Channel. The Dickinson Embayment is that portion between the Texas City Dike and Eagle Point out to the Houston Ship Channel.]

Limited time and resources prevented a full survey northwest of Smith Point and southwest of Bull Hill, as well as between the barrier reef tracts of East Bay. Although large expanses of reef are unlikely to be present in these areas, the absence of reef as shown by the survey is due to the area's omission from the survey rather than any failure of the survey to identify reef in these areas. The authors believe that the first two locations are areas of potential reef accretion in the future and should be considered in any future surveys.

The Galveston Bay system was subdivided into 10 sectors (Table 2). The majority of the reef and unconsolidated shelly sediments of the bay was located in East Bay, on and north of Redfish Bar in central Galveston Bay, in the Dickinson Embayment, and along the Houston Ship Channel. Thirteen individual charts depicting the distribution of reefs and unconsolidated shelly sediments plus an overview map can be found in the associated map folio. Trinity Bay, the Red Bluff/Morgan Point Embayment and the Clear Lake Embayment contributed only 7.8% of the bay-system total and only 12.8% excluding West Bay and the Pelican Island Embayment. West Bay contributed 30.9% of the total, the majority of which was present as large expanses of unconsolidated shelly mud with little or no relief.

Natural Reef.

The reefs of the Galveston Bay system were divided into those primarily of natural origin and those primarily of anthropogenic origin. Natural reef was of five distinctive types.

(1) Barrier reefs extended significant distances across the bay. Typically, these reef tracts ran perpendicular to the prevailing shoreline. Examples include Carancahua Reef and the Confederate/North and South Deer Island Reef complex in West Bay, the Drum Village/Gale's/Middle Reef complex in East Bay, the Hanna Reef complex in East and Galveston Bays, and the Todds Dump/Redfish Bar complex in Galveston Bay.

(2) Smaller reefs extended perpendicular from shore throughout the Galveston Bay system. Examples include Dow and Big Beezley Reefs in Trinity Bay, Stephenson and Moody Reefs in East Bay, and Dollar and Red Bluff Reefs in

Galveston Bay. Most of these reefs were detached from the shoreline. The only exceptions were a few reefs in East Bay such as Richard's Reef. Many, but not all, of these reefs were associated with points suggesting an underlying geological control. Most oyster reefs begin on local topographic highs, whether natural or man-made.

(3) Alongshore reefs, like Levee Reef in Galveston Bay and Elliotts Reef in Trinity Bay, probably follow drowned beach lines. These reefs, typically, are also detached from the present shoreline. April Fools Reef is the significant exception. Most of these reefs also contain significant fractions of unconsolidated shelly mud and sand as well as consolidated reef.

(4) Patch reefs and towheads [Hill and Masch (1969) define a towhead as a reef of 10 acres or less] were small to medium-size reefs roughly circular or irregularly-elliptical in outline. This reef type was most common as it formed a discontinuous line across the mouth of Trinity Bay, along the northern and southern shorelines of East Bay, and within the major oil fields and leased areas of the bay (Anonymous, 1988; Hofstetter, 1990).

(5) Expanses of low-relief unconsolidated shelly mud were surveyed in West Bay and the Pelican Island Embayment. This bottom type was not observed elsewhere in the Galveston Bay system.

Anthropogenic reef.

We attempted to estimate the amount of reef purposefully created by man or originating as a result of man's activities in the bay. Overall, anthropogenic reef, as a rough approximation, contributed about 20% to the reef in the Galveston Bay system. Anthropogenic reef was of four types.

(1) Most oyster leases contained reef. Some leases were clearly located on preexisting natural reef. Elsewhere, whether lease-associated reef originated naturally or from shell planting could not easily be discerned.

(2) Besides lease-associated reefs, a number of other reefs originated as deliberate shell plantings. Most of these reefs, termed artificial reefs (Benefield and Hofstetter, 1976; Diener, 1975; Hill and Masch, 1969), originated as mitigation projects for shell dredging or were designed to enhance the oyster fishery (Benefield and Hofstetter, 1976). Only a rough estimate of the acreage of this reef type could be made as a full list of artificial reef sites was unavailable and many know sites occurred in areas occupied by natural reef so that the area estimated may not have been entirely of artificial origin. We estimate that leases and artificial reefs contributed about 1.6% of the total reef, 8.0% of the anthropogenic reef, or 151 hectares of the Galveston Bay reef system (Table 3).

(3) Oil field operations, through the emplacement of shell pads and pipe lines, accounted for significant reef development. Most oil fields contained a few to many patch reefs. In some cases, such as north of Redfish Bar, these patch reefs have coalesced to form extensive areas of shelly bottom mostly of low relief. Linearly-trending sequences of patch reefs probably follow pipe line routes. Once again, naturally-occurring reef probably exists in many of these areas, but could not be differentiated from anthropogenic reef, so that an estimate of reef area originating from oil field development can only be an approximation. We tentatively attribute about 375 hectares, 3.9% of the reef in the Galveston Bay system, or 19.9% of the anthropogenic reef to this mode of origin.

(4) All significant channels were lined by spoil banks that served as sites for reef development. [One of the primary requirements of reef initiation would seem to be a small (even a foot or less) elevation above the surrounding bay bottom.] These channels include the Cedar Bayou Channel, the Intracoastal Waterway, the Dickinson Bay Channel, and the Bayport Channel. In

all likelihood, little of this reef is natural, so that this fraction of anthropogenic reef is estimated more accurately than the former three. About 271 hectares, 14.3% of the anthropogenic reef, or 2.8% of the reef in the Galveston Bay system is of this origin.

(5) Besides the smaller channels, the spoil banks lining the Houston Ship Channel contributed significant reef to the bay system. Our estimates do not include that portion of South Redfish Reef (the bay's largest reef) lining the ship channel and so are certainly an underestimate, probably by several hundred hectares. We estimate a minimum of 1092 hectares associated with this channel, over half of all anthropogenic reef (57.8%), and 11.4% of the entire reef area in the Galveston Bay system. Significantly, the reef along the Houston Ship Channel contributes a minimum of 19% of the reef in the Galveston Bay system exclusive of West Bay and the Pelican Island Embayment and ranked as the third most significant single contributor to the bay's oyster shell coverage behind Redfish Bar and the expanses of low-relief unconsolidated shelly mud in West Bay.

Circa-1970/1991 Comparison

Background.

Although a few long-term trends can be assessed using pre-1970s navigational charts, the only quantitative comparison that can be made to the present survey is that with the circa-1970 survey performed by Hofstetter and Benefield at the Texas Parks and Wildlife Department (TPWD) (Benefield and Hofstetter, 1976; TPWD, 1976). Comparison of this survey with the circa-1970 survey rests on the assumption that methodology and survey coverage were similar enough to yield similar results. To this end, Benefield and Hofstetter were interviewed to obtain firsthand information about the TPWD survey to permit a more accurate 20-yr comparison.

Besides differences accruing from the true reef accretion or loss over this period, a number of discrepancies between the two surveys originate in the limitations in technology in the circa-1970 period and in differences in the areas surveyed. The circa-1970 survey was conducted using poling to determine substrate type and sightings for position (Benefield and Hofstetter, 1976). It is a credit to this survey team that many of the reefs, when compared to our survey, show only 10% to 20% differences in areal extent between the two techniques, despite the limitations in technology and navigation that faced them. Accordingly, the two methods, which certainly define the edges of the reefs somewhat differently, yield qualitatively and nearly quantitatively the same results. True reef accretion or loss might, therefore, be identified with certainty.

The limitations of the poling method limited the circa-1970 survey in several ways. First, small patch reefs were not surveyed. Surveys of areas of the bay, like Trinity Bay and the sector north of Redfish Bar, that are dominated by patch reefs, were limited because the running of long lines in search of small reefs by poling was not practical. (2) Reefs in deep water (> 3.3 m) were generally not surveyed. Poling in deep water was not practical and wave and current action made pole emplacement for sighting difficult. The majority of the Houston Ship Channel reefs which exist in 3 to 7 m of water were not surveyed for this reason. (3) Many of the leased areas were not surveyed. The circa-1970 survey concentrated on the known major reefs in the bay because of concerns at that time about shell dredging activities. (4) Upper East Bay and West Bay were not included in the survey. For West Bay, the existence of extensive areas of unconsolidated shelly mud was known to the survey team, but its areal extent made survey impractical with the standard poling method.

Two additional problems relate to the method used to define reef area. Our survey often identified small satellite patch reefs which were combined with the larger "parent" reef in our estimates of reef area. Many such satellite reefs were not surveyed in the circa-1970 survey. Accordingly, best comparisons were made between reefs where most or all of the reef area was represented solely by the larger reefs surveyed in both instances. Second, some discrete reefs surveyed in circa-1970 were no longer easily discernible today because clusters of reefs had coalesced to form larger bodies. Under these conditions, only an approximate comparison could be made. In certain cases, Shuttle Reefs and Ernest Reef north of Redfish Bar for example, the reef itself could no longer be identified even approximately and the name was deleted from the survey maps. Such instances are not the result of reef loss, but of reef accretion and the improved precision of our method for surveying fields of patch reefs.

Bearing these differences in mind, one can proceed to compare the results of the present survey with the circa-1970 survey of Benefield and Hofstetter (1976).

East Bay.

East Bay yielded 19 reefs which could be compared (Table 4), nearly all of the reef in this part of the Galveston Bay system. Of the reefs that could be compared, the circa-1970 survey recorded 1111.047 hectares. Our survey recorded 1214.951 hectares, an 8% increase in 20 yr. The uppermost reefs in the bay, Frenchy's Reef and Bob's Knob, lost a small amount of area; the remaining reefs were slightly larger. Overall, few reefs varied substantially in size.

The two barrier reef tracts in East Bay, Middle/Gale's/Drum Village and Bull Hill/Hanna Reef gained slightly. The large gain recorded for Pepper

Grove Reefs was due to patch reefs that were not surveyed in the circa-1970 survey; accordingly the apparent increase could not be unqualifiedly considered as accretion over the last 20 yr. Most of the small perpendicular reefs along the north shore were slightly larger in 1991. As both surveys were intensive in this area, this difference can be accounted for either by reef accretion or a slight variation in the definition of reef boundary between the two methods.

The East Bay area contained two uncharted reefal areas, a relatively large extension of Hanna Reef to the southeast towards Sievers Cove, probably not charted in the circa-1970 survey, and the upper bay patch reefs which were not surveyed at that time. Lynn's Lump and Sand Reef could not be relocated in our survey and several satellite reefs in the Gale's Reef/Middle Reef section could no longer be distinguished as separate entities. Referral to charts and local accounts suggests that the patch reefs of upper East Bay, Tong Reefs for instance, have lost some acreage over the years as have Frenchy's Reef and Bob's Knob; however no quantitative data are available.

Few data are available for comparison of relief. Reference was made to old charts where possible (USCGS, 1855, 1907, 1921, 1924, 1957; NOAA, 1990). In general, the Hanna Reef tract has gradually deepened since 1850 with the majority of the decline since the 1920s. The loss of shell banks, islands and shell bars is not unusual over this time frame (Marshall, 1954) and may be explained, in this case, by regional subsidence (Gabrysch, 1984; Jorgensen, 1975; Ratzlaff, 1982). The detachment of most reefs from the shoreline, a relatively unusual feature typical of most Galveston Bay reefs, can be explained by shoreline retreat that has accompanied subsidence in the area (Paine and Morton, 1986; Morton et al., 1987).

However, depth and relief should not be confused. Perusal of old charts reveals that the relief of the Hanna Reef tract in the East Bay sector has varied relatively little since 1850; certainly not enough to unequivocally conclude that a significant reduction has occurred. Like most barrier reefs, the upestuary side contains lower relief than the downestuary side, as the barrier reef has acted as a sediment dam. Old charts compare well with current observations that relief rarely exceeded 0.3 m on the upestuary side and was about 1.5 to 1.75 m on the downestuary side. As this reef is one of the more heavily fished areas of the bay, no evidence exists to support concerns that shell removal by the fishery is an important process in reducing relief or areal extent of oyster reefs in East Bay (Quast et al., 1988; Marshall, 1954). Certainly, Marshall's (1954) estimate from Virginia of a relief reduction of 0.17 m yr^{-1} due to the fishery would have been readily observed had it been the rate sustained by the reefs in East Bay.

Benefield and Hofstetter (1976) and Benefield (1976) reported that parts of the Middle/Gale's/Drum Village barrier reef tract and its extension Pepper Grove Reefs, were heavily silted after shell dredging just prior to the circa-1970 survey, which might explain the previously unsurveyed reef in the Pepper Grove area. Shell dredging removed a considerable fraction of the total reefal coverage in this area during the 1950s and 1960s (Rehkemper, 1969; Quast et al., 1988). Although much of this area continues to have very low relief and dredge hauls often contain muddy shell indicative of continued silting in the area, our slightly larger areal estimates indicate that the reef tract has remained viable. The slightly larger areas for this barrier reef may accrue from the removal of silt since the circa-1970 survey or real accretion. In addition, one cannot exclude the possible value of the many leases in the area in maintaining the viability of this reef tract. However, examination of old charts reveals that only low relief reefs existed in this area throughout recorded time, so that the present low relief has been a persistent feature of this area regardless of the activities of man.

Trinity Bay.

Overall, Trinity Bay contained about 290 hectares more reef than surveyed in the circa-1970 survey (Table 5). As this area was replete with patch reefs and smaller satellite reefs near the larger reefs, most of which were not surveyed previously, only a few reefs offered direct comparisons. These fell into three categories: (1) some reefs changed little in areal extent, like Big Beezley Reef, Clamshell Reef and Dow Reef; (2) some had lost area, like Trinity Reef and Little Bird Reef, however the total area lost was small; (3) some had gained considerably, like Tidewater Reef, Outer Beezley Reef and Vingt-et-un Reef which about doubled in size and Lost Reef which was half again as large as in circa-1970.

Trinity Bay contains a number of artificial reefs most originating as mitigation for shell dredging activities (Benefield and Hofstetter, 1976; Benefield, 1976). Of these, all but Trinity Reef had gained some area over the last 20 yr. None had gained substantial area. All big gainers were natural reefs.

Several significant discrepancies existed between the 1991 and circa-1970 areal estimates. A large alongshore reef, referred to as Fisher and Elliotts Reefs in the accompanying map folio, was probably incompletely surveyed in the circa-1970 survey. Our areal estimate is considerably larger. The large field of small patch reefs associated with the oil field around Old Yellow Reef was combined with this reef in our areal estimates, thus substantially increasing its estimated area compared to the circa-1970 survey. These patch reefs were not surveyed in the circa-1970 survey. A number of other patch reefs, including Ray's Reef, Little Beezley Reef, and Upper Beezley Reefs were also unsurveyed in circa-1970. In total a discontinuous line of patch reefs covers much of the upper half of the mouth of Trinity Bay, an area greater than 20 square miles and too large to be surveyed by the poling method used by Benefield and Hofstetter (1976). Finally, numerous small reefs reported, but not surveyed, in circa-1970, along the south Trinity shoreline were not found by our survey. In all likelihood, these reefs have disappeared over the last 20 yr.

The only relief comparison afforded by the old navigational charts is Fisher Shoals, the relief of which is approximately the same as observed in 1855 (USCGS, 1855). Evidence of subsidence comes from the shoreline detachment of most of the reefs and the likely origin of portions of Fisher and Elliotts Reef as former beach lines.

Red Bluff/Morgan Point Embayment.

Very few reefs in this area could be used for comparison between the two surveys. Of those that could be used, all showed slight to moderate growth in size over ~20 yr (Table 6). Larger discrepancies include the following. (1) Bayside Reef could not be relocated. (2) In all likelihood, reefs in the Cedar Bayou area were not adequately surveyed in the circa-1970 period as they exist as a discontinuous field of patch reefs at the mouth of the bayou and small reefs on the Cedar Bayou Channel spoil banks. In addition, some may be the result of dredging activities since the circa-1970 survey. (3) No surveys were conducted in the East Red Bluff and Bayport Channel areas in circa-1970. Our survey found a significant number of patch reefs and reefs on spoil banks in this area.

Clear Lake Embayment.

The total reef in this area has remained approximately constant since the circa-1970 survey; however individual reefs changed dramatically in size (Table 7). Most reefs deep in the embayment lost significant reef area, including Bayview Reef, Courthouse Reef and Humble Reef. Some, such as Courthouse Reef, were noted to be silting up in 1970 (Benefield and Hofstetter, 1976) so that subsidence and siltation are probably chiefly responsible for the lost reefal area. The Clear Lake Embayment has subsided more than most of the remaining parts of Galveston Bay (Jones and Larson, 1975; Gabrysch, 1984). Reefs farther out, like San Leon Reef, Halfway Reef and Smith Reef, gained area.

Both artificial and natural reefs gained acreage and both artificial and natural reefs lost acreage; hence location rather than mode of origin was important. Most of the additional reefs included in the 1991 survey that were unsurveyed in circa-1970 were small patch reefs associated with oil field development and pipeline emplacement in the central part of the embayment. Once again, shoreline separation and the presence of alongshore reefs probably originated from regional subsidence and shoreline retreat.

Dickinson Embayment.

The amount of reef present in the Dickinson Embayment was significantly greater in our survey than in the circa-1970 survey for four reasons (Table 8). (1) Significant reef accretion occurred on a few reefs. (2) Several reefs, like Dollar Reef and April Fools Reef, were not completely surveyed in circa-1970. Additionally, both include substantial areas of semi-consolidated shelly sediment which may not have been included in the earlier assessment. (3) The circa-1970 survey did not attempt to cover the central portion of the embayment and thus did not record reef associated with leases or the spoil banks along the Dickinson Channel. (4) Finally, three major reefs, Pelican Reef, Desperation Reef (termed Parallel Reef by Masch and Espey, 1967) and Resignation Reef, were not surveyed in circa-1970. Early navigational charts show some relief in these areas suggesting the presence of reef prior to the circa-1970 survey and Masch and Espey (1967) record some reef in this area, however, as significant reef accretion occurred along the Houston Ship Channel nearby, the origin or significant enlargement of these reefs through growth since the circa-1970 survey cannot be ruled out.

With the exception of April Fools Reef, all nearshore reefs were detached from the shoreline as observed elsewhere in the bay, probably due to shoreline retreat. Rehkemper (1969) shows extensive reef south of Todds Dump. No reef was recorded in this area by Benefield and Hofstetter (1976). We were unable to identify reef in this region either.

Dollar Reef occurs on all old navigational charts. Relief on Dollar Reef, about 1.7 m, has remained more or less constant since 1855 (USCGS, 1855, 1907, 1921, 1924, 1957; NOAA 1990). Although Halfmoon Reef does not appear on the original 1855 navigational chart, it does so on all subsequent ones and relief has remained approximately the same as observed during our survey throughout that period of time.

West Bay/Pelican Island Embayment.

These two sectors were not surveyed in the circa-1970 survey. The area contains two barrier reefs, Confederate/North and South Deer Island Reefs and Carancahua Reef, and several thousand hectares of shelly mud. This latter area supported an important fishery in 1983-1984 and leases were located in both the Shell Island Reef and Deer Island Shell areas as well as on Carancahua Reef in and before the early 1960s. With the exception of North and South Deer Island Reefs and Confederate Reef, the reefs and shelly mud in

West Bay and the Pelican Island Embayment are unproductive today. Accordingly, these large expanses of shelly mud were present prior to the circa-1970 survey, as were the two barrier reefs Carancahua Reef and Confederate/North and South Deer Island. Carancahua Reef appears on the earliest bathymetric survey of the area.

Paine and Morton (1976) discuss the potential impact of the Texas City Dike in reducing circulation to West Bay, particularly restricting flow from Galveston Bay produced by northerly and easterly winds. In all likelihood, this reduced flow has reduced oyster production in West Bay. Flow is an important requirement for oyster populations (Keck, 1973; Grizzle, 1990; Powell et al., 1987). Burr (1929-30) also noted only limited production in the area in the 1920s. This too was after construction of the dike.

North Redfish Bar.

Extensive coverage of patch reefs and consolidated patch reefs exist north of Redfish Bar (Table 9). This area was not extensively surveyed in the circa-1970 survey so that the apparently large increase in reefal area cannot unequivocally be considered true reef accretion during that time. Rehkemper (1969) noted some reef in this area in his mid-1950s survey. However, some reefs present in the circa-1970 survey, including Shuttle Reefs and Ernest Reef, could not be distinguished today within an extensive area of coalesced patch reefs, suggesting local consolidation of patch reefs has occurred since circa-1970. Moreover, certain large natural reefs, Sheldon Reef and Possum Pass Reef, have also increased considerably in size. Some of this increase, however, originates in less consolidated shelly sediments which may not have been included in the circa-1970 survey. No clear evidence of reef loss since circa-1970 exists in the area.

Of particular note is the relatively limited amount of reef along the Chambers County line, once the location of the original barrier reef in the bay, originally called Redfish Bar (USCGS 1855, 1907; Eckhardt, 1969). Charts through 1927 show a barrier reef, Redfish Bar, extending from Eagle Point (Edwards Point on the old charts) to Smith Point. Three passes permitted water flow through this barrier reef complex, West Pass, Middle Pass, and Opossum Pass. Only West Pass, which still exists behind Redfish Island, was deeper than ~1.7 m. Stories of cattle drives across Redfish Bar can certainly be substantiated by the bathymetry of the time. That this barrier reef acted as a significant impediment to water flow and salt transport is substantiated by Burr's (1929-30) description of the steep salinity gradients across the bar.

The only present-day remnant of this original barrier reef is Todds Dump running from Eagle Point to Redfish Island. East of the Houston Ship Channel, the present-day equivalent, still called Redfish Bar, is centered between one and two miles south of where this original bar was located and the Chambers County line where the original bar was located is noteworthy for having only a few scattered patch reefs along its extent from Redfish Island to Smith Point.

The original Redfish Bar is no longer present on the 1957 navigational chart (USCGS, 1957 - partially based on a circa-1940 bathymetric survey), but is still present on the 1927 chart (based on late 1800s and 1920s bathymetric surveys), so that the bulk of the original barrier reef probably disappeared in the first half of this century. Records of shell dredging are insufficient to determine whether shell dredging was responsible, but it is curious that the western most portion, Todds Dump, and the other large Galveston Bay barrier reef tract, the Hanna Reef tract, have remained in approximately the same location and, with few exceptional spots, of about the same areal extent and relief as can be estimated from the original 1850s survey. As significant natural changes in reefs can occur over half-century time scales (Marshall, 1954), one cannot conclude that the progradation of Redfish Bar south by one to two miles was solely caused by the removal of shell by shell dredging.

Redfish Bar.

Significant areas of accretion and loss were observed along the present-day Redfish Bar and the northerly extension of the Hanna Reef tract (Table 10). Both the natural and man-made reefs in the area offered examples of accretion and loss, once again demonstrating that location, not mode of origin, is of greatest importance in determining the change in acreage since circa-1970.

The principle area losing acreage since circa-1970 was the Mattie B. and Tom Tom Reef portion of the Hanna Reef tract. Old charts suggest that this area has been losing acreage continuously since early in the century. At one time, only two natural passes existed through the Hanna Reef tract, Ladies Pass and Moodys Pass (USCGS, 1907). It is likely that a new natural pass has gradually been formed in the Mattie B./Tom Tom Reef area by the outflow of the Trinity River, as discussed later.

Reef accretion and patch reef coalescence has occurred throughout the remainder of the Redfish Bar area and the northern extent of the Hanna Reef tract, particularly concentrated along the southern margin. The circa-1970 survey was particularly intensive in the Redfish Bar area. As most of the accretion is enlargement rather than the finding of new reefs, it is likely that the bulk of the ~500 hectares of new reef observed has accreted in the last 20 yr.

Incipient reef accretion on the southern edge of Bull Hill was noted as a shelly crust over mud and shelly mud. Most of the satellite reefs around

South Redfish Reef, like Triangle Reef, Missing Reef, "C" Reef, and Archie's Reef, can no longer be easily distinguished from South Redfish Reef. Smaller reefs like Slim Jim Reef and Pasadena Reef have increased dramatically in size. South Redfish Reef has nearly doubled in size with most accretion occurring along the southern margin. New reef, the Lost Beezley Reef area, has accreted south of the primary barrier bar in a line with Pasadena Reef, continuing a near-century-long southerly progradation of Redfish Bar. Rehkemper (1969) recorded no significant shell deposits between Pasadena Reef and Redfish Bar. Neither did Benefield and Hofstetter (1976). These low relief reefs north and east of Pasadena Reef indicate the beginnings of a major new reef complex in that area.

The rate of reef accretion is likely dependent on the subsurface geology in the area, some portions of which include > 10 m of soft mud (BUG, 1992). The higher rate of reef accretion on the southwestern section of Redfish Bar, as compared to the opposite, Hanna Reef tract, side of the new pass forming near Mattie B./Tom Tom Reef, is probably due to the lower stability of the soft bottom south of the Bull Hill area.

Long-term changes in relief are more evident in the Redfish Bar sector than elsewhere. North of the present-day Redfish Bar, along the Chambers County line, considerable loss of relief has occurred, on the order of 1 to 2 m depending on location and bathymetric survey. On the present Redfish Bar, relief has increased, although exact quantification is difficult. Pasadena Reef has existed since at least 1855 (USCGS, 1855), at that time called Hannah Island. Hannah Island disappeared prior to 1921 (USCGS, 1907, 1921) by which time up to 1 m of relief had been lost in the area. It seems unlikely that regional subsidence was responsible for this change since the bulk of the Redfish Bar and Hanna Reef tract shell islands were still present at that time. No further changes in relief on Pasadena Reef can be clearly differentiated since that time, however. Significant reef accretion on the northeastern side of Pasadena Reef and the formation of Lost Beezley Reef has not yet resulted in a significant increase of relief in this area. Fathometer traces, in fact, demonstrate a flat bottom over most of this area despite its oyster substrate.

Houston Ship Channel.

Well over 1000 hectares of reef was identified along the Houston Ship Channel (Table 11). From about buoy 63 to Morgan Point, the majority of this reef exists between the channel edge and the crest of the spoil banks paralleling each side, in the 2-3 m to 5-7 m depth range. Little reef coverage exists on the outer slope of the spoil banks in this reach. We made no effort to survey above Morgan Point; reef certainly exists in this area (e.g. site GBSC in Wilson et al., 1992). From buoy 63 to approximately buoy 47, reef extends out from the ship channel edge across the parallel-trending spoil banks and grades into the Redfish Bar reef tract and the reef in the Dickinson Embayment. This process is a gradual one. From buoy 63 south the reef gradually begins to extend farther and farther down the far or bay side of the spoil bank from its crest to the surrounding natural bottom, finally moving out onto the natural bottom as it grades into the Redfish Bar reef tract and the reefs north of Redfish Bar. Establishing boundaries for computing reef acreage in these areas proved difficult, so estimates of along-channel reef must be considered conservative in this reach.

Comparison to the circa-1970 survey shows a substantial increase in reef coverage along the entire channel from buoy 47 to Morgan Point. Difficulties in surveying by pole limited the circa-1970 survey and this limitation may account for a considerable portion of the inequity. However, substantial accretion near the crests of the spoil banks from buoy 63 to about buoy 47 certainly would have been observed circa-1970 so that the evidence suggests dramatic reef growth over the last 20 yr along the ship channel.

The Houston Ship Channel has been enlarged many times since its creation around the turn of the century (USCGS 1907, 1921, 1924, 1957; NOAA, 1990). The last significant enlargement occurred in the early 1960s. Although one cannot be sure of the effects of that enlargement on the entire spoil bank system, a reasonable conclusion is that the majority of the > 1000 hectares of reef along the Houston Ship Channel has accreted over the last ~30 yr.

DISCUSSION

Circa-1970/1991 survey comparison.

Comparison of the present 1991 survey with the circa-1970 survey of Benefield and Hofstetter (1976) revealed several important trends.

(1) Significantly more reef and unconsolidated shell exists in the Galveston Bay system then was heretofore appreciated. Our survey approximately doubles the known area of reef and unconsolidated shelly substrate in the bay system. A substantial fraction of this newly surveyed reef and unconsolidated shelly sediment was present but not surveyed in circa-1970. However, among those reefs where a precise comparison was possible between the 1991 and circa-1970 surveys, reef accretion rather than reef loss was the general rule. Reef accretion was most noticeable in 3 areas: along the Houston Ship Channel, at the southern edge of Redfish Bar and the Bull Hill extension of the Hanna Reef tract, and in the Dickinson Embayment.

(2) Reef loss, although minor overall, was concentrated in three areas; along the southern shore of Trinity Bay, in the Mattie B./Tom Tom Reef area at the northern end of the Hanna Reef tract, and in the inner portion of the Clear Lake Embayment.

(3) Reefs originating through man's activities, whether associated with spoil banks of channels, oil field development, or purposefully created (=artificial reefs), did not vary any differently than natural reefs. Rates of accretion and loss were location specific rather than dependent on the mode of origin of the reef. Clearly, artificial reefs can be markedly successful, if sited correctly to enhance reef growth.

(4) The data available to assess changes in relief are very poor. Nevertheless, the comparisons that can be made show substantial changes in relief in only one area, Redfish Bar, which has, for all intents, prograded south since the turn of the century. Relief on the remaining barrier reefs has not changed perceptibly. Depth, of course, has, but depth changes are mostly related to regional subsidence. The single possible exception is in the vicinity of Mattie B. Reef. Saying this does not necessarily discount the overall impact of shell dredging prior to circa-1970; however most of that effort was not concentrated on the barrier reefs (Benefield, 1970; Masch and Espey, 1967) which were usually the only reefs indicated on navigational charts. The causative reason for the disappearance of the original Redfish Bar cannot be precisely identified nor are data sufficient to identify the possible recovery of the many smaller reefs in East Bay and Trinity Bay that were impacted by shell dredging prior to 1970.

(5) The oyster fishery might impact relief and areal extent; relief because shell is removed, areal extent because shell might be redistributed off reef onto leases or the sides of fished reefs. Once again, appropriate data for comparison are meager. No shell budget is available for any reef [shell budgets are reviewed in Powell et al. (1989) and Cummins et al. (1986)] so that the fraction of shell produced that is removed by the fishery, the fraction destroyed naturally by taphonomic processes, which is likely to be

substantial, and the fraction preserved and thus available as cultch in subsequent years is unknown. However, effects as large as Marshall's (1954) estimates of potential impact would have been observed in a comparison of our 1991 survey to Benefield and Hofstetter's (1976) survey of circa-1970.

No evidence exists for a substantial impact of the fishery on relief. Supporting evidence from the 1991 survey includes the following. (a) Some of the most heavily fished reefs have clearly not varied much in relief since the original 1850s survey (USCGS, 1855). (b) Relief of open and closed reefs (TDH, 1992) does not vary uniformly. Some of each have relatively high relief (1-1.5 m) and low relief (< 0.5 m). Relief is primarily controlled by local conditions and individual reef history. (c) On the average, heavily fished reefs have accreted more area in the past 20 yr than reefs not fished. (d) The most significant areas of reef loss are in closed areas of the bay (TDH, 1992).

The data do demonstrate several likely impacts on reef area by the fishery. Most leases today contain reef or semi-consolidated shelly areas. At least some of this material originates from shell transplanting by the fishery. As these areas have accreted or lost as much as natural reef, their survival is, once again, dependent on siting, not mode of origin. Movement of shell off reef edges, if anything, has aided in reef growth. Many reefs are accreting area at their margins. Some unknown portion of this accretion may be due to shell movement by the fishery. We see no evidence of reef loss by this mechanism.

Accordingly, over all, areal extent of reefs has probably been increased by fishing activities. The evidence suggests that judicious siting of new leases and requirements for private shell planting on leases could substantially increase the acreage of reef in the Galveston Bay system.

(6) Relief varies considerably between the two sides of most reefs so that reference must be made to the area of the surrounding bay used to define relief. We have routinely used the surrounding bay bottom on the downestuary side. The upestuary side typically has lower or no relief. The downestuary side frequently, but not always, has substantial relief. The reason for the difference is probably the damming of sediments behind these reefs on the upestuary side. Although this mechanism certainly should result in the loss of reef, many reefs which have had little or no relief on the upestuary side for many years varied little in areal extent between 1991 and circa-1970 or even grew slightly, the Drum Village/Gale's/Middle Reef barrier reef tract being a prime example. The positive role of leases in maintaining reefs above the surrounding bay bottom in these areas should also be considered.

Persistence, malleability and modifying agents

Certain components of the Galveston Bay reef system have persisted throughout recorded time; others have exhibited substantial malleability, changing position and shape over time spans of a half century or so in response to natural and man-made changes in the bay system. Besides the difficulty of assessing changes produced by shell dredging and the likely local impacts of shell transfer to leases and artificial reefs, two regional impacts seem preeminent.

(1) Regional subsidence has resulted in the increase in depth and areal extent of the Galveston Bay system. The results of regional subsidence are threefold. (a) Most reefs are detached from the shoreline, a likely result of subsidence and shoreline retreat. (b) Regional subsidence has increased the depth over the reefs thus (i) reducing the acreage intertidally and subaerially exposed particularly on the barrier reef tracts and (ii) drowning alongshore beach deposits that have later developed into alongshore reefs.

Arguably increased depth has increased bay productivity by increasing subtidal acreage and increasing water velocity over the majority of the barrier reefs. A comparison of productivity between Galveston Bay reefs and those typical of the lower bays, many of which are currently intertidal (Copeland and Hoese, 1966) would be instructive. (c) Areas of high subsidence, such as the Clear Lake Embayment, have suffered reef attrition due to siltation. However, of necessity, this area must also no longer be adequate to support reef growth; otherwise reef growth should have kept up with siltation. What besides subsidence has reduced the area's viability is unclear.

(2) Channalization, dike construction, and loss of the original Redfish Bar have substantially changed bay circulation pattern. The Texas City dike has probably reduced circulation in West Bay. The pre-1900 circulation pattern in Galveston and Trinity Bays is unknown. Certainly today's circulation must differ substantially from that time if for no other reason that the original barrier reef dam, Redfish Bar, no longer exists and the Houston Ship Channel has been added. Redfish Bar, as it existed pre-1900, had three primary channels, only one of which, West Pass, was probably deep enough to permit substantial water flow upestuary and downestuary. A significant salinity gradient existed over this bar. In addition, the Houston Ship Channel has modified the flow structure and isohalines in the bay which now run more or less parallel to the ship channel rather than across bay as they likely originally did over much of the bay's extent.

As a consequence, today, the bulk of the Trinity River flow exits Trinity Bay along the southern shore, wraps immediately around Smith Point, and flows downestuary across Mattie B. Reef and Tom Tom Reef, reaching nearly to Bolivar Peninsula before becoming entrained in the outward flowing water at Bolivar Roads. This circulation pattern has likely existed for many decades

(Reid, 1955; Diener, 1975) although its intensity must have increased as the Houston Ship Channel became deeper and the Redfish Bar dam disappeared. The result of this changing flow pattern has been to destroy the equilibrium that once existed between the reefs and the bay circulation resulting in (a) loss of a number of small reefs along the southern shore of Trinity Bay, (b) the demise of the Hanna Reef tract in the vicinity of Mattie B. Reef and Tom Tom Reef, the present outlet for much of the Trinity River flow and (c) the accretion of reef along the southern edge of South Redfish Reef, the western and northern trend of Pasadena Reef and the southern edge of Bull Hill and associated reefs. These latter three areas adjoin the present route of outflow of the Trinity River as it crosses the present barrier reef complex in the bay.

Each of these changes is a response to changing water flow and salinity that has shifted the bay's geology (the reefs) out of equilibrium with the bay's flow structure. Some reefs are no longer optimally located for continued high productivity; many areas of low reef coverage would now support productive reef if substrate became available. One can expect a continued response to the changed flow and salinity regime in these areas in decades to come as the bay continues to develop a new equilibrium condition. However, our observations suggest that reef builds only slowly out onto muddy bottom. The rates of taphonomic processes can be expected to be high in these areas (Powell et al., 1989) so that the natural process of reef accretion may be slow. Moreover, these outgrowing margins, especially south of South Redfish Reef, may not withstand significant dredging by the fishery depending upon the extent of substrate consolidation, which is not currently known. Careful management of these areas would be prudent.

The Houston Ship Channel has extended the isohalines upestuary to the great benefit of oyster populations and the oyster fishery. In effect, the Houston Ship Channel has extended the area of oyster productivity much beyond that which would have existed prior to channelization. Like the removal of the pre-1900 Redfish Bar, which probably restricted the areal extent of the key 15°/.. isohaline (USACE, 1987), the Houston Ship Channel has expanded and modified the isohaline structure and increased water velocity, both conducive to oyster growth. Over 1000 hectares of reef have developed along this channel, a substantial fraction of which extends between the channel edge and the crest of the parallel-trending spoil banks. In the reach from buoy 63 to Morgan Point, all reef development is in this small zone.

The data show the overriding importance of the coincidence of two bathymetric features for development of reef along channels. A channel is, of course, required. However, a spoil bank is also required. Observation of channels in which the spoil banks were placed on only one side, always show that reef development is predominately or exclusively on that side.

It should be noted that the expected increase in predation and disease with increased salinity (Ray, 1987) is not necessarily an overriding influence on reef survival. A healthy oyster population with adequate food and adequate water flow can outgrow predators and diseases. High salinity reefs like Confederate Reef, in fact, offer readily observable proof of this trend. Food supply is an overriding influence on reef productivity (Powell et al., submitted).

Finally, the Houston Ship Channel has created a barrier separating the Trinity River-affected eastern part of Galveston Bay from the western part of Galveston Bay. This "dam", if you will, affects the distribution of food, turbidity and current flow. In particular, on the average, the western part of the bay is less turbid and the differential is significant in that it is in the range of values that substantially affect filtration rate in oyster populations (our unpubl. data). The substantial accretion of reef in the Dickinson Embayment is almost certainly a result of the last remnant of the original Redfish Bar (Todds Dump) and the Houston Ship Channel isolating this area from the generally higher turbidity elsewhere in the bay. These factors are important because the bay, today, is near the balance point for food supply (taking turbidity into account). A 15% reduction in food supply from current levels could result in a substantial contraction or loss of the market-size oyster population and the oyster fishery in Galveston Bay (Powell et al., submitted).

CONCLUSIONS

Overall, Galveston Bay has accreted substantial reef in the last 20 yr. The location and mechanisms of reef accretion suggest that natural responses to changes in circulation and salinity by the oyster populations are primarily responsible rather than the direct production of new reef by man. These responses have been primarily induced, however, by both natural and man-made events. These include the construction of the Houston Ship Channel and the Texas City Dike, the removal, by mechanisms not well documented, of the original Redfish Bar, and regional subsidence which has deepened the bay and facilitated shoreline retreat. Local affects like leases, artificial reefs, and, in many areas, shell dredging have had less impact.

Whether bay productivity has increased commensurate with the increased acreage cannot be assessed without recourse to a population dynamics model. As some reef has formed in present-day optimal locations, other reef, still extant, finds itself in areas of reduced quality. With the exception of the Clear Lake Embayment, the Mattie B./Tom Tom Reef area of the Hanna Reef tract and upper East Bay, conditions are not so poor as to result in loss of acreage. However it is not at all clear how much productivity is required to balance the natural and anthropogenically-mediated taphonomic processes that continually destroy shell carbonate. Accordingly, the significant reef accretion documented by this survey should not be construed as clear evidence for increased productivity in Galveston Bay as a whole. Although certainly productivity has dramatically increased in certain areas of the bay, productivity may have decreased commensurately in other areas of the bay. A bay-scale population dynamics model coupled with direct measurements of productivity in selected locations would be needed to estimate the change in productivity caused by the relatively rapid changes in reef distribution as it responds to a changed environment.

The geological stability of reefs in a bay like Galveston Bay is a misinterpretation brought about by the observation of large masses of apparently stable carbonate formed by oysters in the bay. In reality, over decades to half-century time scales, oysters are capable of substantially realigning oyster reef tracts in response to a changing environment. Under these conditions, which exist in Galveston Bay today, the presence of oyster reefs should not be equated with productivity or with optimal living conditions for oysters. Such an equation is only defensible when the geological distribution of reefs is in equilibrium with the bay's hydrodynamics, which is certainly not the case today in Galveston Bay.

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TABLE LEGENDS

Table 1. The total amount of reef and unconsolidated shelly sediments in the Galveston Bay system.

Table 2. The area of surveyed reef and unconsolidated shelly sediment in each of 10 sectors in the Galveston Bay system.

Table 3. Estimated fraction of the total reef and unconsolidated shelly sediment in the Galveston Bay system contributed by anthropogenic activities.

Table 4. Comparison of the 1991 and circa-1970 survey of East Bay. Comparisons computed as 1991 area/circa-1970 area.

Table 5. Comparison of the 1991 and circa-1970 survey of Trinity Bay. Comparisons computed as 1991 area/circa-1970 area.

Table 6. Comparison of the 1991 and circa-1970 survey of the Red Bluff/Morgan Point Embayment. Comparisons computed as 1991 area/circa-1970 area.

Table 7. Comparison of the 1991 and circa-1970 survey of the Clear Lake Embayment. Comparisons computed as 1991 area/circa-1970 area.

Table 8. Comparison of the 1991 and circa-1970 survey of the Dickinson Embayment. Comparisons computed as 1991 area/circa-1970 area.

Table 9. Comparison of the 1991 and circa-1970 survey of the North Redfish Bar sector. Comparisons computed as 1991 area/circa-1970 area.

Table 10. Comparison of the 1991 and circa-1970 survey of Redfish Bar. Comparisons computed as 1991 area/circa-1970 area.

Table 11. Comparison of the 1991 and circa-1970 survey of the Houston Ship Channel sector. Comparisons computed as 1991 area/circa-1970 area.

Table 1

TOTAL REEF AREA

Galveston Bay System	Galveston Bay excluding West Bay and Pelican Island Embayment
9539.771 hectares	5754.479 hectares
36.8 square miles	22.2 square miles
about 9.2% of bay area	60.3% of total reef

Table 2

TOTAL REEF AREA

	Area (in hectares)	Area (in sq. miles)	Percent of Total Reef	Percent of Total Reef exclusive of West Bay
East Bay[3]	1157.360	4.5	12.1%	20.1%
Trinity Bay[3]	506.146	2.0	5.3%	8.8%
Redfish Bar[2,4]	1336.049	5.2	14.0%	23.2%
North Redfish Bar[2,4]	578.038	2.2	6.1%	10.1%
Red Bluff/Morgan Point Embayment[2,5]	123.347	0.5	1.3%	2.1%
Clear Lake Embayment[2]	111.285	0.4	1.2%	1.9%
Dickinson Embayment[2]	850.024	3.3	8.9%	14.8%
Pelican Island Embayment	835.697	3.2	8.8%	
West Bay	2947.433	11.4	30.9%	
Houston Ship Channel[1]	1092.230*	4.2*	11.4%*	19.0%*

[1]Does not include extensive acreage adjacent to the channel forming part of South Redfish Reef.

[2]Exclusive of the reef associated with the Houston Ship Channel except for that associated with South Redfish Reef where a delineation between channel and non-channel reef could not be made.

[3]Exact value depends upon the boundary defined between East Bay or Trinity Bay and Galveston Bay

[4]Exact value depends upon the boundary defined between Redfish Bar and the reef system north of Redfish Bar.

[5]Includes the Cedar Bayou branch of Galveston Bay.

Table 3

TOTAL MAN-MADE REEF

	Area (in hectares)	Area (in sq. miles)	Percent of Total Reef	Percent of Total Man-made Reef
Total Man-made	1889.617	7.3	19.8%	
Houston Ship Channel[1]	1092.230	4.2	11.4%	57.8%
Other Dredged Channels	271.520	1.0	2.8%	14.3%
Oil Fields and Pipe Lines[2]	375.563	1.5	3.9%	19.9%
Artificial Reefs[3]	151.304	0.6	1.6%	8.0%

[1]Does not include extensive acreage adjacent to the channel forming part of South Redfish Reef.

[2]Rough estimate only. Little information exists to differentiate natural reef from reef originating from oil field development in these areas.

[3]Includes leases, reefs made for mitigation of shell dredging, reefs made to enhance the oyster fishery, etc. Rough estimate only; not all artificial reefs could be discretely identified, particularly in the Redfish Bar area, and little information exists to differentiate natural reef from man-made reef on leases.

Table 4

COMPARISON OF 1970 AND 1991

Reef	circa 1970 Area (from Benefield and Hofstetter (1976)	1991 Area	Fractional Change
East Bay			
Bob's Knob	3.359	2.030	0.60
Bull Hill[2]	76.568	114.052	
Buckshot Reefs[1]	4.614	8.852	1.92
Catfish Reef[1]	7.042	9.935	1.41
Cowshed Reef[1]	12.991	14.758	1.14
Drum Village Reef	47.916	37.508	
Frenchy's Reef[1]	83.246	74.879	0.90
Gale's Reef	63.901	95.578	
Hanna Reef[1]	526.103	475.067	
Lone Tree Reef[1]	7.446	8.288	1.11
Middle Reef	102.104	110.280	
Moody Reef[1]	13.760	15.900	1.16
North Bull Hill Reef[2]	20.801	59.160	
Pepper Grove Reefs	49.777	70.355	1.41
Richard's Reef[1]	12.262	17.833	1.45
Stephenson Reef[1]	12.262	10.545	0.86
Terry's Ridge[1]	13.395	17.268	1.29
Whitehead Reef[1]	18.575	32.399	1.74
Combined reefs[3]			
Drum Village/Gale's/Middle Reef[1]	213.921	243.366	1.14
Bull Hill/Hanna Reef[1, 2]	623.472	648.279	1.04
Total[4]	1076.122	1174.687	1.09

[1]Best comparison; other comparisons of limited usefulness because reef portions included in estimate might be different or because entire area included in 1991 estimate was not mapped by Benefield and Hofstetter (1976).

[2]Parts of Bull Hill and North Bull Hill Reef included here were not included in estimate for East Bay in Table 2.

[3]Comparison of circa-1970 and 1991 boundaries uncertain for individual reef estimates. The combined estimate is more likely to be accurate.

[4]Does not include reefs unsurveyed in circa-1970. See Table 2 for full area estimates.

Table 5

COMPARISON OF 1970 AND 1991

Reef	circa 1970 Area (from Benefield and Hofstetter (1976)	1991 Area	Fractional Change
Trinity Bay			
Big Beezley Reef[1]	30.109	30.927	1.03
Clamshell Reef[1,2]	4.087	4.330	1.06
Dow Reef[1]	32.335	40.830	1.26
Dryhole Reef[1,2]	6.313	5.746	0.91
Fisher Reef	69.122	123.757	1.79
Little Bird Reef	1.619	0.349	0.22
Lonesome Reef[1,2]	7.204	8.222	1.14
Lost Reef[1]	6.677	10.831	1.62
Middle Beezley Reef[1]	9.672	12.075	1.25
Old Yellow Reefs[2]	2.590	19.976	7.71
Outer Beezley Reef[1]	9.308	20.674	2.22
Spoonbill Reef[2]	1.214	6.958	5.73
Tern Reef[1,2]	13.841	14.906	1.08
Tidewater Reef[1]	2.590	7.230	2.79
Trinity Reef[1,2]	7.446	6.072	0.82
Vingt-et-un Reef[1]	13.780	28.961	2.10
Total[3]	217.907	341.844	1.57

[1]Best comparison; other comparisons of limited usefulness because reef portions included in estimate might be different or because entire area included in 1991 estimate was not mapped by Benefield and Hofstetter (1976).

[2]Partially or fully originating from man's activities.

[3]Does not include reefs unsurveyed in circa-1970. See Table 2 for full area estimates.

Table 6

COMPARISON OF 1970 AND 1991

Reef	circa 1970 Area (from Benefield and Hofstetter (1976)	1991 Area	Fractional Change
Red Bluff/Morgan Point Embayment			
Bayside Reef	0.405	0.000	0.0
Bent Pipe Reef	7.811	12.859	1.65
Crow's Nest Reef	0.809	1.840	2.27
Red Bluff Reef[1]	28.248	29.979	1.06
Tin Can Reefs	5.221	10.095	1.93
West Red Bluff Reef[1]	4.087	5.859	1.43
Yacht Club Reef[1]	13.395	19.057	1.42
Total[2]	59.976	79.689	1.33

[1]Best comparison; other comparisons of limited usefulness because reef portions included in estimate might be different or because entire area included in 1991 estimate was not mapped by Benefield and Hofstetter (1976).

[2]Does not include reefs unsurveyed in circa-1970. See Table 2 for full area estimates.

Table 7

COMPARISON OF 1970 AND 1991

Reef	circa 1970 Area (from Benefield and Hofstetter (1976)	1991 Area	Fractional Change
Clear Lake Embayment			
Bayview Reef[1, 2]	12.626	6.302	0.50
Clear Lake Channel Reefs[2]	4.209	8.237	1.96
Courthouse Reef[2]	3.359	1.953	0.58
Eagle Point Reef[1]	17.078	14.725	0.86
Halfway Reef[2]	2.954	10.778	3.65
Humble Reef[1]	2.590	0.606	0.23
Little Scott Reef[1]	2.954	3.130	1.06
Pine Gully Reef	1.497	0.000	0.00
San Leon Reef[1]	24.889	34.385	1.38
Scott Reef[1]	14.488	13.478	0.93
Smith Reef[1]	3.723	9.732	2.61
Total[3]	90.367	103.326	1.14

[1]Best comparison; other comparisons of limited usefulness because reef portions included in estimate might be different or because entire area included in 1991 estimate was not mapped by Benefield and Hofstetter (1976).

[2]Partially or fully originating from man's activities.

[3]Does not include reefs unsurveyed in circa-1970. See Table 2 for full area estimates.

Table 8

COMPARISON OF 1970 AND 1991

Reef	circa 1970 Area (from Benefield and Hofstetter (1976)	1991 Area	Fractional Change
Dickinson Embayment			
April Fools Reef	26.750	43.214	1.62
Crescent Reef[2]	8.175	3.621	0.44
Dickinson Channel Reefs[2]	2.550	40.330	15.82
Dickinson Reef[1]	78.026	64.028	0.82
Dollar Reef[1]	107.285	215.848	2.01
Experimental Reef[2]	2.954	2.344	0.79
Half Moon Reef[1]	14.852	16.717	1.13
Island Reef[2]	7.042	3.689	0.52
Levee Reef[1]	80.534	81.109	1.01
Little Half Moon Reef[1]	0.486	1.348	2.77
Marsh Reef	4.452	10.158	2.28
Moses Gate Reef[2]	1.052	6.262	5.95
Shoal Reef[2]	1.133	1.974	1.74
Todds Dump and Redfish Island[1,4]	218.130	283.722	1.30
Total[3]	553.421	774.364	1.40

[1]Best comparison; other comparisons of limited usefulness because reef portions included in estimate might be different or because entire area included in 1991 estimate was not mapped by Benefield and Hofstetter (1976).

[2]Partially or fully originating from man's activities.

[3]Does not include reefs unsurveyed in circa-1970. See Table 2 for full area estimates.

[4]Redfish Island included in the estimate of reef along the Houston Ship Channel in Table 2 rather than in the Dickinson Embayment. Redfish Island included here for comparison to estimates of Benefield and Hofstetter (1976).

Table 9

COMPARISON OF 1970 AND 1991

Reef	circa 1970 Area (from Benefield and Hofstetter (1976)	1991 Area	Fractional Change
North Redfish Bar			
Bar 24 Reefs	1.902	2.226	1.17
Bart's Pass[1]	95.508	68.956	
Bart's Pass West[2]	7.811	81.325	
Possum Pass[1]	33.428	72.181	2.13
Roberts Reef	3.318	10.884	3.28
Sheldon Reef[1]	20.801	46.164	2.22
Combined reefs[4]			
Bart's Pass/Bart's Pass West[1]	103.319	150.281	1.45
Total[3]	162.768	281.736	1.73

[1]Best comparison; other comparisons of limited usefulness because reef portions included in estimate might be different or because entire area included in 1991 estimate was not mapped by Benefield and Hofstetter (1976).

[2]Partially or fully originating from man's activities.

[3]Does not include reefs unsurveyed in circa-1970. See Table 2 for full area estimates.

[4]Comparison of circa-1970 and 1991 boundaries uncertain for individual reef estimates. The combined estimate is more likely to be accurate.

Table 10

COMPARISON OF 1970 AND 1991

Reef	circa 1970 Area (from Benefield and Hofstetter (1976)	1991 Area	Fractional Change
Redfish Bar			
Archie's Reef	3.723	3.426	0.92
Bull Shoals[1]	34.925	40.264	1.15
"C" Reef	3.723	5.432	1.46
Dee's Reef	2.954	8.174	2.77
East Redfish Reef[1]	31.607	82.014	2.59
Four Bit Reef[1,2]	9.672	9.206	0.95
Gaspipe Reef[1,2]	14.124	20.687	1.46
Mary's Reef	8.174	18.414	2.25
Mattie B. Reef[1]	20.801	14.938	0.72
Missing Reef	9.308	9.175	0.99
North Redfish Reef[1]	202.914	237.984	1.17
Pasadena Reef[1]	12.950	49.853	3.85
Santa Reefs	3.359	7.112	2.12
Slim Jim Reef[1]	8.903	31.236	3.51
South Redfish Reef[1,4]	371.874	702.109	1.89
Tom Tom Reef[1]	5.585	3.573	0.64
Triangle Reef[2]	3.723	7.796	2.09
Total[3]	748.319	1251.393	1.67

[1]Best comparison; other comparisons of limited usefulness because reef portions included in estimate might be different or because entire area included in 1991 estimate was not mapped by Benefield and Hofstetter (1976).

[2]Partially or fully originating from man's activities.

[3]Does not include reefs unsurveyed in circa-1970. See Table 2 for full area estimates.

[4]Portion of South Redfish Reef located on the Houston Ship Channel spoil banks included in this estimate, rather than in Table 11.

Table 11

COMPARISON OF 1970 AND 1991

Reef	circa 1970 Area (from Benefield and Hofstetter (1976)	1991 Area	Fractional Change
Houston Ship Channel[3]			
Morgan Point Reefs[2]	0.405	14.122	34.869
"53" Reefs[2]	15.945	177.977	11.16
"59" Reefs[2]	56.495	192.746	3.41
"63" Reefs[2]	26.022	146.898	5.65
Total[1]	98.867	531.743	5.38

[2]Partially or fully originating from man's activities.

[1]Does not include reefs unsurveyed in circa-1970. See Table 2 for full area estimates.

[3]Reef adjacent to Redfish Island and that portion of South Redfish reef on the spoil bank not included in these estimates. See Table 2 for full area estimates.

FIGURE LEGENDS

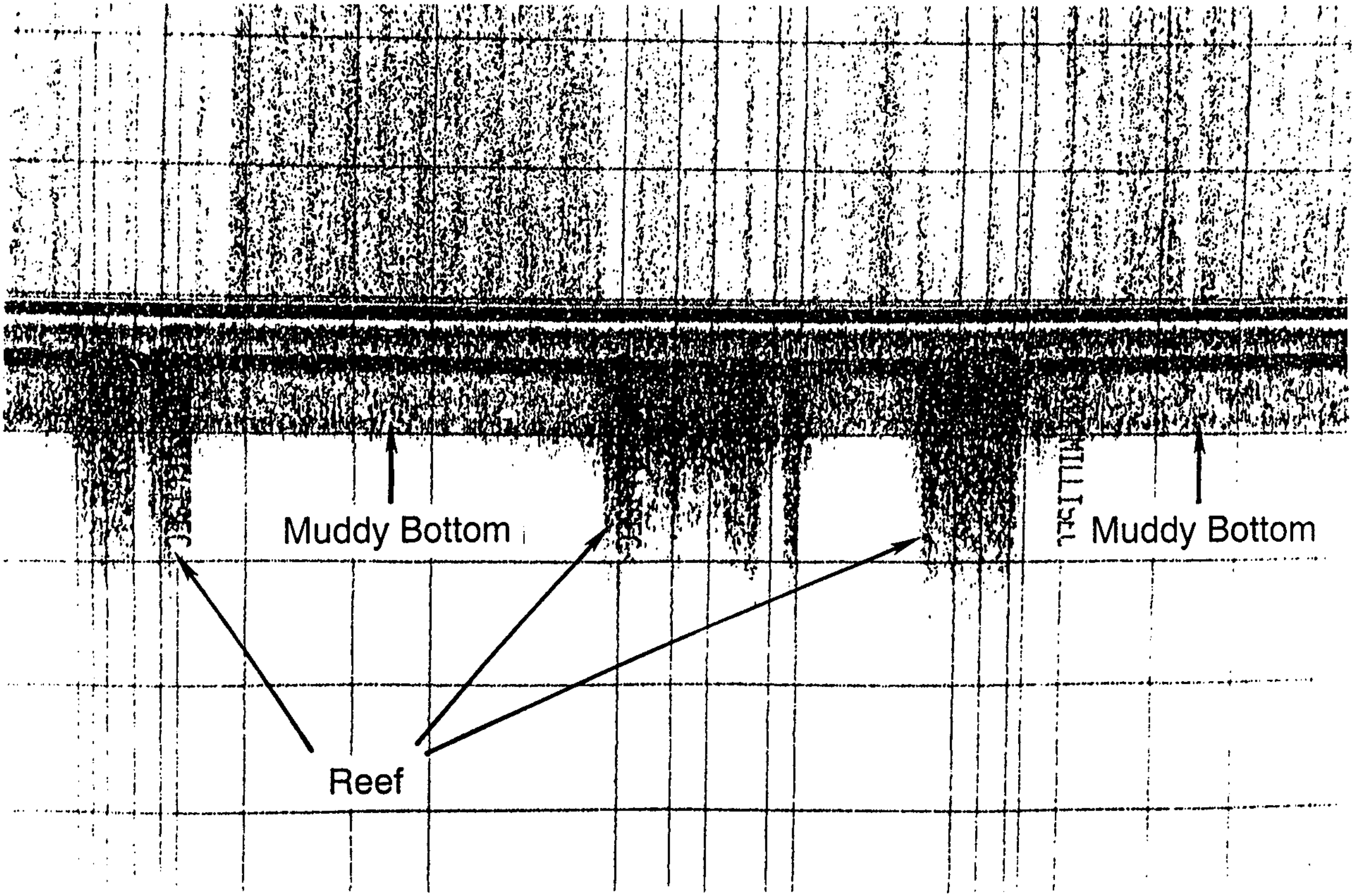
Figure 1 A typical chart record from the 300 kHz channel showing a reef within an area of muddy bottom. The reef is distinguished by a larger return extending well below the more compressed return typical of a muddy bottom.

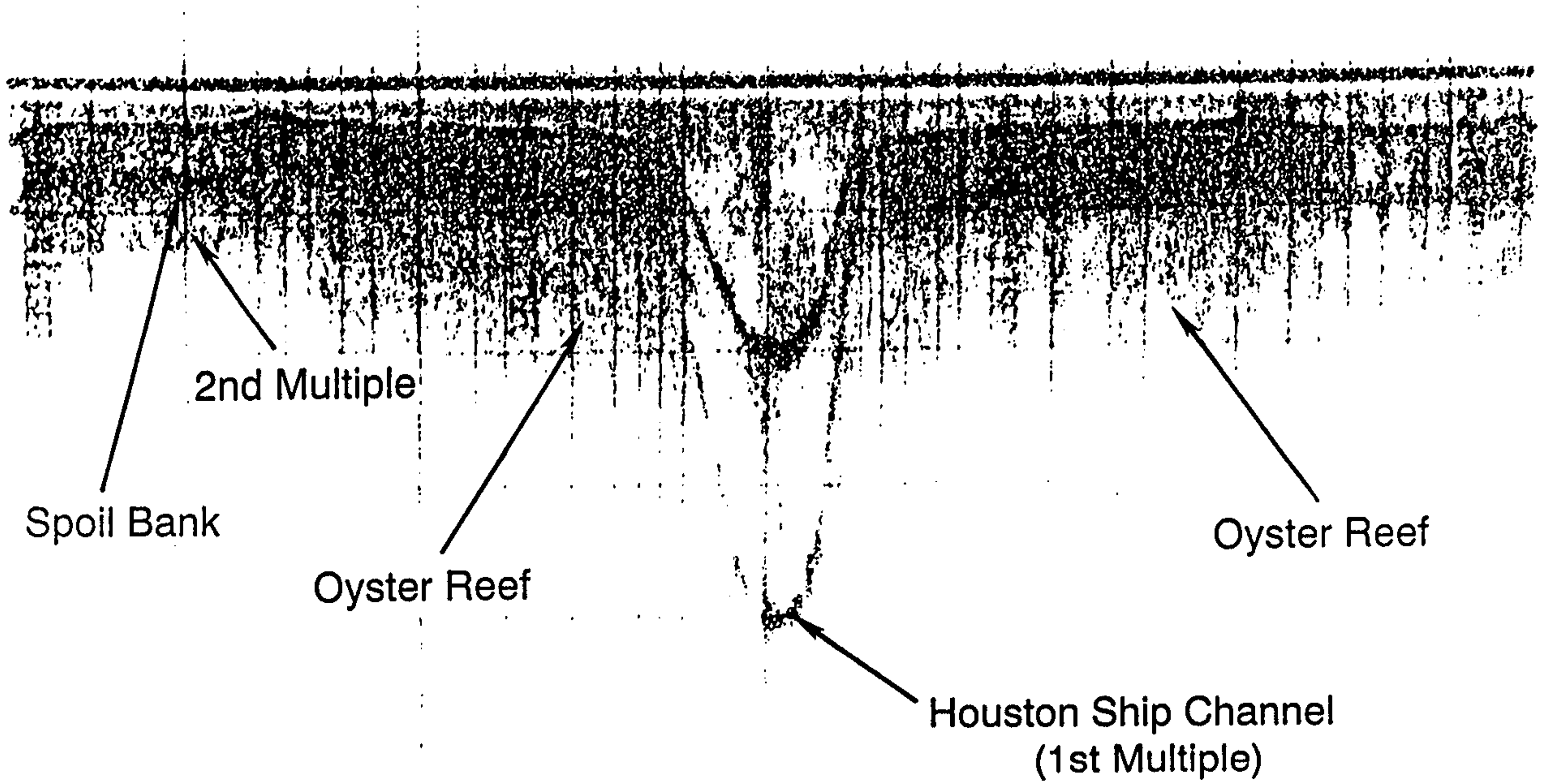
Figure 2 An example of an oyster reef on a spoil bank adjacent to the Houston Ship Channel. The record is from the 300 kHz channel. Reef is identified by the larger denser return extending below the more compressed return. The channel is the deeper V-shaped groove. Note that oyster bottom extends down the channel walls nearly to the bottom, a condition typical of many areas in Galveston Bay.

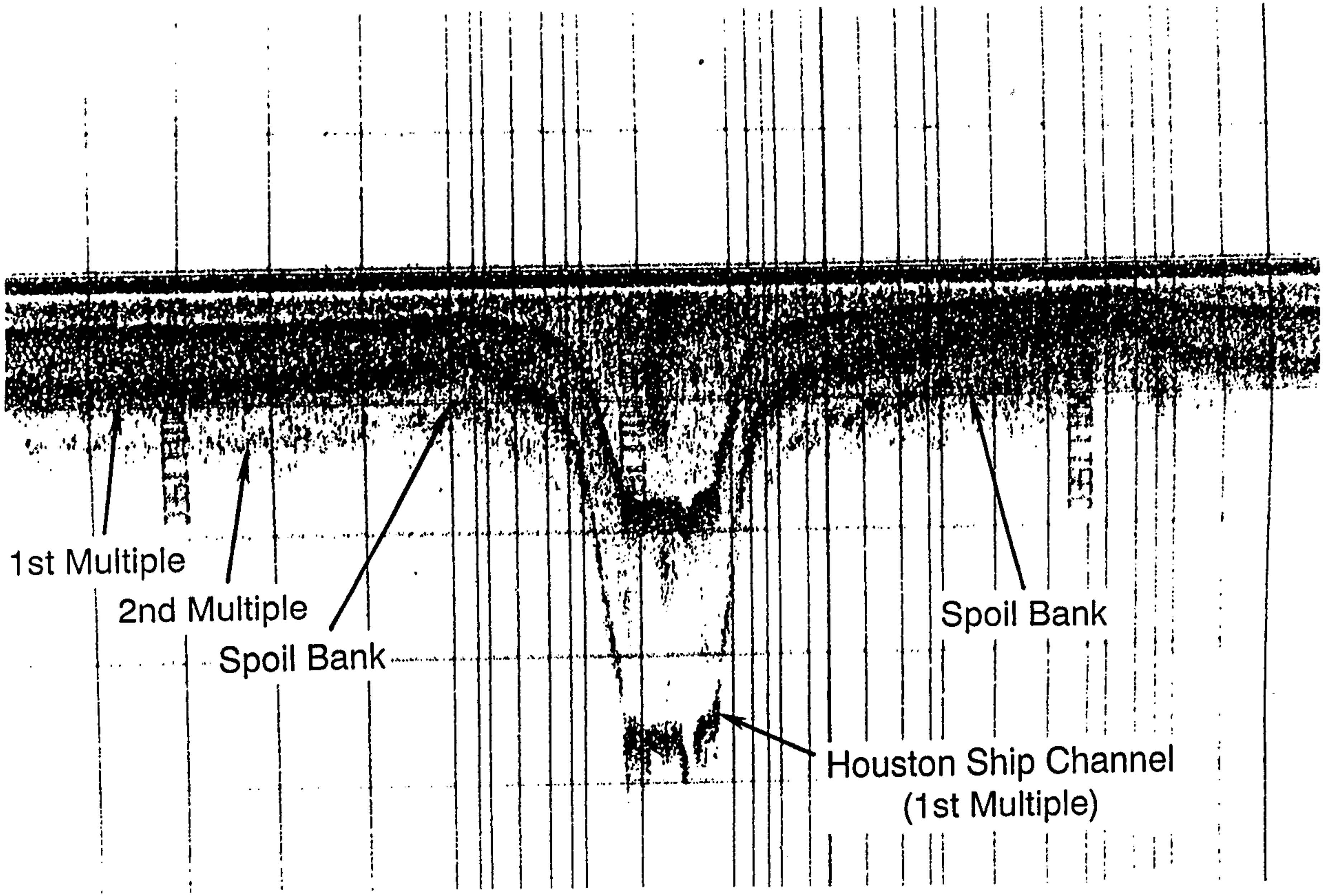
Figure 3. An example of a spoil bank adjacent to the Houston Ship Channel. The record is from the 300 kHz channel. Spoil is identified by the shorter return overlain by a faint halo probably produced by the third echo. The channel is the deeper V-shaped groove.

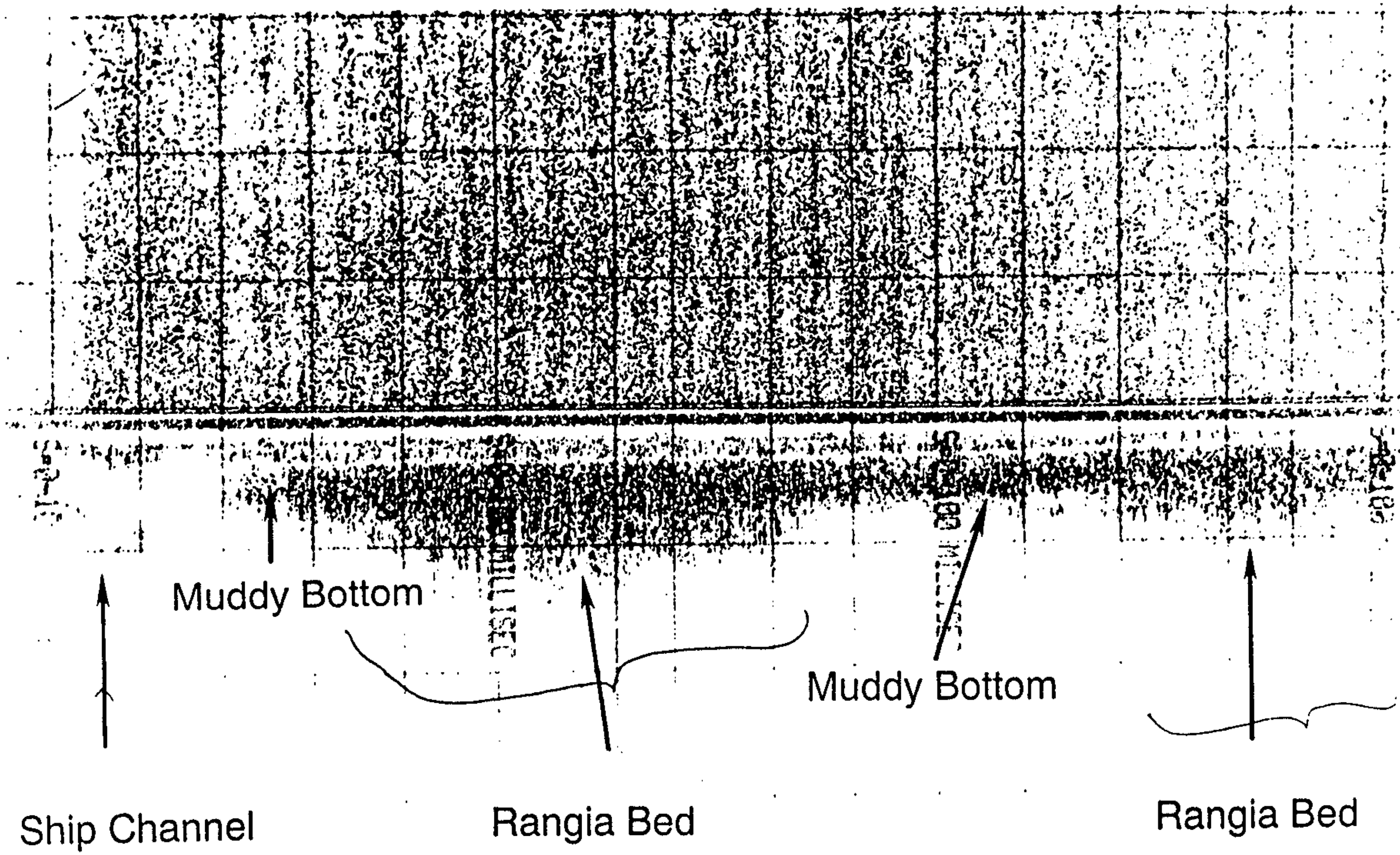
Figure 4 A *Rangia* bed off Houston Point, Galveston Bay, as recorded by the 300 kHz channel. Clams are identified by the larger denser return below the return typical of muddy bottom. Note how the clam bed fades out at the edges, a condition rarely encountered on reefs. In this case, the 22 kHz channel recorded no distinctive subsurface signal, a characteristic typical of muddy bottom.

Figure 5 The setup on the boat as it would appear underway. The towed fish extends from a boom to the side of the vessel well forward of the stern. A tow cable to the bow maintains the orientation of the fish while underway.


Muddy Bottom
Muddy Bottom
Reef


2nd Multiple
Spoil Bank
Oyster Reef
Oyster Reef
Houston Ship Channel
(1st Multiple)


1st Multiple
2nd Multiple
Spoil Bank
Spoil Bank
Houston Ship Channel
(1st Multiple)



Muddy Bottom
Muddy Bottom
Ship Channel
Rangia Bed
Rangia Bed