ACOUSTIC CHARACTERISTICS OF BAY BOTTOM SEDIMENTS IN LAVACA BAY, TX

A Thesis

by

MARY CATHERINE PATCH

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2005

Major Subject: Oceanography

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ABSTRACT

Acoustic Characteristics of Bay Bottom Sediments in Lavaca Bay, TX. (May 2005)

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The purpose of this study is to examine the sediment stratigraphy and oyster reefs of Lavaca Bay. There has been little previous research on the bay's stratigraphy, and information from this study is important for industry and resources management. The Lavaca Bay estuary is a drowned river valley containing a history of estuary development in the late Pleistocene and Holocene. We used a chirp sonar to gather acoustic reflection profiles, which were classified to categorize and trace reflectors. The data were plotted to make maps of the distribution of various reflection types and contour maps of reflector surfaces. The maps were compared with previous studies of Lavaca Bay and Galveston Bay to aid interpretation. The vertical sediment stratigraphy showed two main reflector packages. The upper package, bay bottom to ~25 m depth, is mostly acoustically transparent with a few, semi-continuous, prominent reflectors in the upper 5-10 m. The lower package ranges from 15-40 m depth with several strong reflectors sometimes underlain by unconformities. To classify reflector characteristics, the upper package was divided into two categories, each with 4 sub-categories: 1) surface reflectors—weak, medium, strong, and ringing, which describe the general acoustic return of the bay bottom, and 2) strong, shallow reflectors—surface strong, mounds, buried strong, and buried multiples, which describe strong acoustic returns in the upper 5 m of stratigraphy. Within the lower package, four categories were recognized: 1) subbottom reflectors/horizons, occurring ~20-40 m depth, 2) deep wipeout (incoherent/wipeout zone), ~10-30 m depth, 3) clinoforms, ~5-30 m depth, and 4) terraces, ~10-30 m depth. The data interpretation agrees with previous studies suggesting Lavaca Bay filled beginning with coarse sediment and grading to finer sediment. In addition, the surface type reflectors are indicative of bottom type, the strong, shallow reflectors are largely indicative of oyster reef/shell, and the subbottom reflectors are related to the Pleistocene and bay fill. The location/extent of oyster reefs in the bay does not agree well with previous studies, suggesting either oysters do not grow over older ones or differences between the chirp sonar response and other methods significantly differentiate the interpretation of their locations/extents.

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INTRODUCTION

The study of bay stratigraphy gives us insight into the history and evolution of a bay and its surrounding environment. Lavaca Bay was chosen for study, as a collaborative effort of Texas A&M (College Station and Galveston branches), Texas Parks and Wildlife, and the Texas General Land Office, because there has been relatively little research on the bay's stratigraphy and economically important oyster reefs. With a record of sedimentary layering, we can better understand the time frame in which Texas bays have filled (Bouma 1976, Sager et al. 2004, Shepard 1953, Smyth and Anderson 1988, Byrne 1975, Wilkinson and Byrne 1977) and oyster colonies have expanded, dwindled, and shifted locations (Byrne 1975, Wilkinson and Byrne 1977, Norris 1953, Powell et al. 1995, Sager et al. 2004, U.S. Bureau of Fisheries 1912). By looking at the acoustic properties of the bay, we can gain a better understanding of the stratigraphic characteristics and structure of the bay, bay history, as well as past and present oyster reef locations and extent. The information produced in this study is useful for fisheries, refineries, and other industries in the area by showing the extent of natural resources and their changes over time (Scott 1968).

Background

The current Texas coast formed by erosion and sedimentation processes associated with the rise and fall of sea level. The main coastal valleys were carved out by rivers during the glacial lowstand around 20,000 years ago (Anderson and Rodriguez 2000). Subsequently, as glaciers began to melt and sea level began to rise, barriers

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formed, the valleys flooded and gradually filled with sediment. This is the process by which Lavaca, as well as the other major Texas bays and estuaries, were formed.

Lavaca Bay is located in the central Texas coast, between Galveston and Corpus Christi, at 28°37'N, 96°35'W. It is approximately 5 km wide and 20 km long (Wilkinson and Byrne 1977), with an average depth of 1.5 meters (NOAA 1988). Three main freshwater inputs feed into the head of the bay: Garcitas Creek to the northwest and a convergence of the Lavaca and Navidad Rivers in the northeast (Wilkinson and Byrne 1977). Surface salinity ranges from approximately 8 ppt at the bay head to about 16 ppt at the bay mouth where it connects with Matagorda Bay (Wilkinson and Byrne 1977). The estuary has a tidal range of approximately 0.3 m (Pentcheff 2004).

Lavaca Bay is a wave-dominated estuary, as described by Dalrymple et al. (1992). Estuaries of this nature typically have a sand body at the mouth as a result of marine processes, a depositional, low energy central area, and a bay head delta (consisting of sand/gravel) as a result of fluvial processes (Nichols et al. 1991, Dalrymple et al. 1992). The stratigraphy typically consists of a base unconformity carved by rivers during a lowstand, filled with sand and gravel, then overlain by mud and silt (Dalrymple et al. 1992). These facies record an environmental shift from a fluvial environment, to fluvial-estuarine, to estuarine (Nichols et al. 1991).

Previous Studies

This study is part of a larger study of Lavaca Bay involving Texas A&M University (College Station and Galveston branches), Texas Parks and Wildlife, and the Texas General Land Office. The investigation consists of three major components, side-scan sonar, grab samples and cores, and chirp sonar to examine oyster reef extent/locations and bay stratigraphy. The side-scan sonar portion of the project by Bronikowski (2004) focused on distribution of sedimentary facies, recent sedimentation and sedimentation rates, hurricane effects, oyster reef extent and locations. The grab sample and core data are being used primarily to create sediment and oyster maps of the area and as comparison to the side-scan and chirp sonar data. The chirp sonar data (discussed in this paper) was used to look at the bay oyster reef extent/locations and bay stratigraphy.

There has been only one previous large scale study of Lavaca Bay sediments. This study by Byrne (1975) created a time frame of sediment facies and their depositional environments, determined sediment sources and mineralogy as well as the trace element distribution. According to Byrne (1975), Pleistocene sedimentation consisted mostly of interdeltaic mud. As the valley where Lavaca Bay now stands began to fill in the Holocene, fluvial sand and gravel were deposited in a narrow thalweg along the valley axis. As sedimentation continued, the fluvial environment changed to a deltaic environment and mud/sand mixtures were the dominant sediment type. With bay inundation, the area of deposition was widened. As the Holocene progressed, the bay changed from deltaic to estuarine and continued to fill the bay with muddy sediments, as it still is today.

Since Lavaca Bay is characteristically similar to many other upper estuaries along the Texas coast, it is relevant to use well-studied Galveston Bay as a template for Lavaca Bay bottom characteristics. The sedimentary layering of Galveston Bay has been the subject of several acoustic studies (Powell et al. 1995, Smyth and Anderson 1998, Sager et al. 2004). Powell et al. (1995) used a dual frequency echo sounder operating at 27 and 300 kHz. The 300 kHz frequency returns were used to determine the character, extent, and accretion rates of oyster reefs in the bay. Smyth and Anderson (1988) used a mini-sparker, uniboom lines, and sediment cores to examine bay stratigraphy. They determined depths of major horizons, such as the Pleistocene. Sager et al. (2004) used a side-scan sonar and chirp sonar data to determine the extent and location of oyster reefs and stratigraphy of sections of Galveston Bay. These studies are useful for gaining a general idea of horizon depth, sediment types and layering, and trends in surface sediment and reef distribution.

METHODS

An Edgetech X-Star chirp sonar was used to gather subbottom acoustic profile data from Lavaca Bay. The sonar fish was towed on a short line next to the side of the boat, about 0.5 m below the water surface. The data were recorded onto 4 mm tapes with an onboard Edgetech X-Star computer system and Edgetech Midas software. A side-scan sonar towed 17.4 m behind the boat and an echosounder attached to the boat (on the opposite side of the subbottom profiler) recorded bathymetric data simultaneously. Survey lines were run with 250 m spacing, except in Keller Bay, where lines were spaced at 500 m due to time constraints. The total survey consists of 170 lines, ranging 150 to 1800 m in length, running northwest to southeast, except western middle Lavaca Bay (just above Chocolate Bay) and Keller bay, which have lines running southwest to northeast (Fig. 1).

The subbottom data were plotted and examined on a computer using S*onarWeb*, a seismic processing program from Chesapeake Technologies, Inc. The data were used to examine the seismic stratigraphy of the bay. Common features were recognized by general acoustic stratigraphy principles, stronger versus weaker returns, wipeout, clinoforms, etc., (Mitchum et al. 1977) and similarities to profiles from other studies in areas such as Cheasapeake Bay (Powell et al. 1995, Smith and Bruce et al. 2001, Smith and Greenhawk et al. 2001, Smith et al. 2002) and Galveston Bay (Sager et al. 2004). Tracing reflectors and other acoustic signatures on the profiles, a table of 3-dimensional (x,y,z format) data were produced for plotting and mapping layers and characteristics.

The positions were loaded into the Geographic Information Systems (GIS) software package, ArcGIS to create maps, which were overlaid onto a Texas General Land Office background shoreline map of the bay. Three of the maps were depth contoured, using an inverse distance weighted function.

Chirp sonar profiles were divided into classes, based on bottom type, underlying structures, and other acoustic characteristics. These categories were used to make distribution and/or reflector contour maps of the bay. The maps were compared with grab sample data, side-scan sonar data, and Byrne's (1975) interpretation of Lavaca Bay stratigraphy. In order to compare the grab sample/core data, a map was made of the sample locations and descriptions and overlaid onto a map of the subbottom reflector types. The side-scan sonar mosaic was used to make an overlay comparison with the chirp sonar bay bottom reflection character map. This was done to correlate the side-scan sonar return strength with bay bottom reflection characteristics. A comparison of Byrne's cross sections was made by digitizing and georeferencing maps of the cross section endpoints, and scaling those cross sections to the profiles constructed from the subbottom reflector depth contours in the same locations.

RESULTS

Bathymetry

The bathymetry shows increasing depths from an average depth of 2.5 m in the northwest to 3.5 m in the southeast (Fig. 2). The edges of the bay are typically 0.5-1 m shallower than central parts of the bay. The largest gradient occurs in the channel, and the central parts of the bay are typically flat expanses with little depth change. Keller Bay appears to be an exception as it is flatter and less bowl-shaped than the rest of the sub-bays. Dredged channels (Fig. 2) run along the bay axis in the middle and southern sections of the bay, with an average depth of 19 m.

Near Surface Reflectors (Table 1)

The bay bottom is divided into four categories based on the strength of seismic reflections: weak, medium, strong, and ringing (Fig. 3). The weak surface reflector is low in amplitude and difficult to pick out from background noise. Medium return shows a stronger bottom reflection and is more easily discerned from background noise. The strong bottom reflector is a sharp, high-amplitude, short-wavelength reflector at the bay bottom interface and stands out clearly from background noise. Ringing is a signature with a strong reflector at the bay floor, with several multiples below it. It usually changes (horizontally) abruptly into the normal medium reflection character (top of Fig. 4).

The northern part of the bay bottom consists of weak and medium surface reflectors that gradually become stronger towards the south (Fig. 5). The northern third of the bay (north of the Highway 35 bridge—see Fig. 1 for locations) contains mostly medium bottom return, with weaker reflectors around the edges. There are some areas of strong reflectors in the north, near the Lavaca-Navidad River input, and just north of the Highway 35 bridge. The middle section of the bay, from the Highway 35 bridge to Rhodes and Gallinipper Points, is predominantly medium return, but has spots of weak reflectors around Point Comfort and northwestern Cox Bay. The north part of Cox Bay and its western edge contain ringing reflectors. The southwestern part of the bay shows predominately strong reflectors and Keller Bay, predominately medium reflectors. The southeastern corner of Keller Bay has a small section of weak reflectors. The area near Rhodes Point consists mostly of ringing reflectors; the middle of the area has spots of ringing reflectors as well.

Generally, the surface reflector characteristics are consistent over large areas, suggesting reflector types show regional characteristics of the bay floor and bottom types. Weak and medium returns dominate in northern and middle Lavaca Bay, changing to dominant strong/ringing in southern Lavaca Bay. Keller Bay is the exception with mostly medium reflection.

Strong, Shallow Reflectors (Table 1)

Fig. 6 shows that strong reflectors occur not only at the surface, but also within the upper sediment column. Near surface reflection characteristics were divided into four classifications of strong, shallow reflectors. The surface strong (SS) reflectors are the same as the bay bottom strong reflectors. The mounds are seen as positive bathymetric features at the bay bottom, usually about 1 m high; they usually show surface strong reflectors although they are occasionally medium or weak. The mounds range from about 10-30 m in length. The buried strong (BS) reflectors are high-amplitude, short-wavelength reflectors found below the sediment surface but within 10 m of the bay bottom. The appearance of these reflectors can vary from flat and horizontal to irregular and jagged. Buried multiples (BM) are strong near surface reflectors with a series of multiples beneath; this character is very distinct and shows an abrupt change and definition from surrounding stratigraphy (Fig. 4). It is important to note that more than one characteristic can be noted in a given location because they occur at different depths (Fig. 4).

Mounds occur in two major clusters in the bay (Fig. 7). One is a cluster around the Highway 35 bridge area, and the other is a linear chain trending northwest to southeast in the western middle portion of the bay, along the ship channel. There are also smaller clusters. A few mounds are scattered through north and middle Lavaca Bay and a line of mounds extends from Cox Bay (just above Rhodes Point) to an area slightly south of Gallinipper Point. There are a few mounds scattered through south Lavaca Bay, mostly on the western side. There is only one small cluster of mounds at the mouth of Keller Bay.

BM signatures are concentrated in the northern and middle parts of the bay (Fig. 8). There is a large cluster just north of the Highway 35 bridge and in the western middle section of the bay. This subbottom reflection type forms lineations (northeast to southwest) in three different areas of the bay: 1) in the central part of north Lavaca Bay, 2) just south of the Highway 35 bridge, and 3) from the middle of Cox Bay to just south of Gallinipper Point. There are few occurrences of BM signatures in south Lavaca Bay or Keller Bay.

SS reflectors occur mostly in middle and south Lavaca Bay (Fig. 7). North Lavaca Bay has only a few (approximately 5 % coverage) SS reflectors scattered throughout. The reflectors of this type in middle Lavaca Bay are widespread, covering about 10 % of the bay bottom. There is a concentration (approximately 90 % coverage) of this reflector type in northeast Cox Bay and all over south Lavaca Bay. Keller Bay has about 20 % coverage, with a large cluster in the north and around the edges of the bay.

BS reflector signatures occur throughout the bay, with the largest area (approximately 90 % coverage) in middle Lavaca Bay (Fig. 8). North Lavaca Bay has a few (approximately 15 % coverage) BS occurrences in the central part of the area. BS reflectors cover about 90 % of middle Lavaca Bay, and the northwest and southeast parts of Cox Bay. South Lavaca Bay and Keller Bay have buried strong reflectors scattered throughout, covering about 85 % of the area.

Subbottom Reflectors/Horizons (Table 1)

There are three categories of subbottom reflectors/horizons (Fig. 9). Reflector A is a strong, flat-lying, continuous, single reflector that occurs between 20-30 m depth. Horizon B is an unconformity package, either with shingles or sometimes underlain by a strong, continuous reflector. Horizon C is a diffuse reflector related to horizon B by lateral continuity. Horizon C consists of additional traced areas where there is not necessarily an unconformity package or reflector to indicate the presence of the horizon in the records, but indirect evidence, such as faint reflectors, depth, or a continuation of an adjacent reflector, suggests the horizon is there. Reflector A can occur simultaneously with horizon B or C because it usually appears about 5 to 10 m above horizon B and/or C (Figs. 10, 11).

Reflector A is widespread, occurring throughout the middle of the bay. It becomes deeper from northwest to southeast (Figs. 12a, b). Depths range from ~9 m to 37 m. In the northern part of the bay, the center is the deepest area, while in the south, the edges are deepest. Keller Bay shows the deepest occurrences of the reflector, at ~37 m.

Horizon B appears only along the bay axes (Figs. 13a, b). Generally, it is shallower in north Lavaca Bay and becomes deeper towards the south. Cox Bay is the shallowest section, with depths around 15 m. Keller Bay, the deepest area, shows similar depths to those in south Lavaca Bay, about 35-40 m.

Depth contours of horizon C (Figs. 14a, 13b) show an overall trend of increasing depth from ~28 m in the north to ~37 m in the south of the bay. The center of the bay contains the deepest occurrence of horizon C, which becomes shallower (to 20 m) towards the edges. Horizons B and C also show a north-south trending channel about 35 m deep extending from Cox Bay into the main channel. Keller Bay shows the horizon at a maximum of 39 m depth, becoming shallower (~30 m) toward the freshwater input to the north.

Deep Wipeout (Table 1)

Deep Wipeouts are areas of acoustic wipeout at 10-30 m depth. They appear as a blank zone with incoherent returns (Fig. 15), implying gas or acoustic turbidity occurs in these areas. While a 10-30 m depth reflector package is typical, in many places it is either weak or non-existent. The weak and non-existent areas are the ones marked as

Deep Wipeout. It is also common to see a gradation between these two end members, where a few reflectors peek through but are faint. Where most reflectors were hidden, even if some weak traces remained, this case was categorized as Deep Wipeout.

Deep Wipeout areas occur around the edges of north and middle Lavaca (Fig. 16). The subbottom type covers large portions (approximately 90 %) of south Lavaca and Keller Bay. Cox Bay is mostly covered (approximately 95 %), with the exception of the easternmost part of the bay.

Clinoforms (Table 1)

Clinoform reflectors, consisting of shingled reflectors, were traced above an unconformity (Fig. 17). Most of these occurred between 5-30 m depth although a few were found below 30 m.

Figure 18 shows a cluster of clinoforms in the northwestern part of the bay, below the mouth of Garcitas Creek. There are 6 patches in the middle of the bay, following the bay axis and stream channels. There is one cluster at the mouth of Lavaca Bay, between Indian Point and Sand Point. The clinoforms imply that deltas occurred in these locations.

Terraces

The terraces are strong subbottom returns that appear in a step-like form from 10-30 m depth (Fig. 19), implying an episodic sea level rise. The reflectors are mostly continuous, high to medium amplitude, and vary in sharpness. Onlap occurs throughout the steps, and the area below the terraces is usually amorphous and lacking stratigraphy. There are 3-4 steps in the terraces that appear in Lavaca Bay. Terraces appear in the seismic record in only one area of the bay, north of Indian Point near the bay mouth (Fig. 18).

DISCUSSION

Overview

The chirp sonar data agree with previous studies of Lavaca Bay sedimentation (Byrne 1975, Wilkinson and Byrne 1977, Bronikowski 2004), in that the chirp data are consistent with the explanation that the transition from a fluvial valley to an estuary began as the bay filled with coarse sediment and changed to finer sediment as sea level rose. This stratigraphic sequence is consistent with predictions based on the Dalyrmple et al. (1992) model of a wave-dominated estuary, and is similar to sequences described by Nichols et al. (1991) in the James River Estuary, Virginia. The records indicate that normal bay layering consists of two major sedimentary packages, with the interface changing from ~11 m depth in the north to ~17 m depth in the south. The upper package, from the bay bottom to ~25 m depth, is mostly acoustically transparent, with horizontal reflectors sometimes occurring in the upper 5-10 m of the profile. The lower package, ranging from 15-40 m depth, depending on its location, is made up of strong, horizontal reflectors sometimes underlain by unconformities. However, in most places, the normal layering is modified by acoustic anomalies. These anomalies consist of strong, shallow reflectors with a high reflection coefficient, which prevent sound from penetrating to deeper horizons, and acoustic wipeout and turbidity around 10-30 m depth, probably as a result of sound scattering from gas or masking from impenetrable layers above.

Overall, based on previous studies, bottom (Powell et al. 1995, Sager et al. 2004) and subbottom (Sager et al. 2004) structure of Lavaca Bay is similar to Galveston Bay. Both bays show similar fill patterns—a thalweg and valley filled by thin horizontal horizons (Sager et al. 2004; Byrne 1975; Wilkinson and Byrne 1977). The shallow bay bottom reflectors interpreted as oyster mounds and buried reefs in Lavaca Bay have a similar character to those deemed oyster reefs in Galveston Bay (Sager et al. 2004). In addition, the distribution of the reefs is patchy in both bays (Sager et al. 2004, Powell et al. 1995), usually occurring in patches ranging from ~10 m to hundreds of meters long (Sager et al. 2004).

Individual Reflectors and Horizons

There are several specific problems associated with each of the traced reflectors/ bottom types (Table 2). As a result, the mapped reflector distributions and areas could contain errors. One potential problem with the data interpretation is that the reflector classifications are somewhat arbitrary. The distinctions between different types are often a matter of judgment where the characteristics grade from one to another. Surface reflectors can be problematic due to reflectors appearing stronger or weaker due to gain settings. Problems with the strong, shallow reflectors include determining whether a feature is a mound (if there is a bathymetric change or not) and foreign objects, such as pipelines, giving similar acoustic signature to natural objects (oysters, shell hash, etc.). The subbottom reflector anomaly of acoustic turbidity/wipeout due to gas or overlying strong reflectors can mask reflectors. In addition, inconsistent/incoherent reflectors can make it difficult to follow a horizon.

Upper Package

The most recent sedimentation of Lavaca Bay consists of typical estuarine mud—finer grained sands and mud, with patches of oyster reef and shell hash. The reef and shell hash often create the strong, shallow reflector anomalies seen in the upper layering package, based on similar studies in Galveston Bay (Sager et al. 2004) and because a hard (rigid) substrate (such as shells/shell hash) is typically necessary for a strong return. The other typical sediments involved in the recent sedimentation of the bay, mud and sand, are not likely to produce such a strong return because the sound is dissipated/absorbed in the sediment. Weak reflectors are indicative of softer bottoms, which consist of sediment that is predominantly mud. The medium reflectors suggest some harder sediments are present, such as shell and/or sand. Strong reflectors are indicative of harder bottoms, mostly oysters and/or shells. Ringing represents very hard bottoms, probably consisting of oyster reef/shell hash, as evidenced by the strength of the returns and supported by Bronikowski's (2004) side-scan sonar interpretation. Strongly reflective features in the side-scan sonar images usually correlate well with the chirp subbottom surface reflector types (Fig. 20). The weaker returns in the chirp sonar data coincide with the weak returns (dark areas) in the side-scan sonar mosaic. Likewise, the chirp profiles of strong and ringing reflectors correlate well with strong returns in the side-scan sonar data. In addition, the weak returns seem to correlate with areas below river or stream outputs. It is expected that the chirp sonar and side-scan sonar respond to the same sediment types since they have similar responses to reflection strength and backscatter strength. In contrast, the surface type interpretations do not correlate well with the grab sample and core descriptions. This is probably due to vague descriptions (such as sand, sandy mud, mud and shell hash, etc.), omission of shell content in sand/silt/clay percentages, and the high variability in the character of the bay bottom sediments. The surface reflectors do not show any sand bodies at the bay head or bay mouth, as predicted by Nichols et al. (1991), Dalrymple et al. (1992), and Bronikowski (2004). Most likely, this is because either the sand does not have a signature in the chirp sonar records that is distinct enough to distinguish it from surrounding mud, silt, and/or shell hash, or the sand occurs in depths too shallow to survey with the side-scan sonar and chirp sonar.

The mounds are interpreted either as dredge spoils or oyster reefs, which often grow on dredge spoils (Powell et al. 1995). Bronikowski's (2004) analysis of side-scan sonar data in Lavaca Bay outlines possible oyster reefs that coincide with the majority of the mounds (Fig. 21). The navigational map of Lavaca Bay outlines the major dredge spoils in the area (Fig. 22). A comparison of the dredge spoil outlines, surface strong reflectors, and mounds reveals that most of the mounds that do not have strong returns coincide with dredge spoil areas. This is reasonable in that the dredge spoil sediments probably consist of soft sediments in many areas. The mounds with strong returns in the dredge spoil areas are probably oyster shell hash or reef growing on the stiff muds of the spoils (Scott 1968). In addition, the mounds do not correlate well with Byrne's (1975) mapping of live oyster reefs (Fig. 23). This suggests that either the reefs do not typically grow on older reefs, or that the data collection techniques and definitions of reef cause a major discrepancy between Byrne's data and the data from this study.

Buried strong reflectors are interpreted as a hard horizon, such buried shell hash, and/or oyster reef. Powell et al. (1995) states that irregular, jagged near surface reflectors can be indicative of oyster reefs. The buried multiples signature is interpreted as buried oyster reef/shell hash. This is based on the fact that the sound must be hitting a very hard (i.e., high reflection coefficient) surface in order to produce multiples.

A 1912 U.S. Bureau of Fisheries oyster bottom survey and Byrne's (1975) study mapped major reefs in Lavaca Bay. The buried multiples do not correlate well with the 1912 (Fig. 24) or 1975 (Fig. 25) oyster outlines in the bay. Although some reports suggest that present oyster reef growth/locations are related and connected to older, buried reefs (e.g., Bouma 1976), others suggest there is no relation (e.g., Norris 1953). The differences between the 1912, 1975, and current oyster extents/locations from this study better support the latter theory or suggest that the buried multiples are not necessarily oyster beds (Figs. 24, 25, 26). For instance, the linear features in north and middle Lavaca Bay and the one extending from Cox Bay to Gallinipper point can be attributed to power line poles and buried pipelines.

Lower Package

The lower package of reflectors in Lavaca Bay has three major constituents—reflector A and horizons B and C (Figs. 9,10). Subbottom Reflector A (Fig. 12a) is construed as a consistent layer approximately 5-10 m above the Pleistocene surface. The layer often mimics major topographic features, such as channels, beneath it. Its strength, nearly constant height above horizon C, and imitation of underlying surfaces point toward the conclusion that reflector A is a consistent layer at a particular height above the Pleistocene surface. Reflector A's place in the lower reflector package changes from north to south. In north Lavaca Bay, reflector A occurs ~5 m below the top of the package and grades to ~9-10 m below the top of the package in the southern part of the bay. In addition, the upper package extends to ~11m depth in the northern part of the bay, and deepens to ~17 m depth in the southern part of the bay. Increasing layer thickness in both the lower reflector package and the upper package suggests that the bay does not currently fill as it did under fluvial and fluvial-estuarine conditions. One of the problems with reflector A is that it is difficult to determine whether the strong reflector is actually the same reflector from line to line. This is a result of the 250 m distance between lines, reflectors fading in and out, and topographic changes that make it difficult to correlate layers. In addition, sometimes there is more than one closely spaced, strong reflector that could be reflector A. While the reflector may not be exactly the same one from line to line, its place within the reflector package means that the shift would occur within a range of about 5 m (vertically).

Horizon B (Fig. 13a) is interpreted as the surface of the Pleistocene exposure surface. During the last lowstand, channels and surfaces were eroded to their lowest levels, and subsequently, the channels filled in and deltas formed as sea level began to rise. Therefore, the channels and clinoforms seen at 30-40 m depth should be just above the Pleistocene surface. Studies of similar bays in the area, such as Galveston Bay, have determined the Pleistocene surface to be around at 30-40 m depth as well (Smyth and Anderson 1988, Sager et al. 2004). In addition, Byrne's (1975) maps of Lavaca Bay show that the general shape and location of the axis of the Pleistocene surface is similar, though the thalweg depths do not agree well (Fig. 27). This difference may be due to the collection methods used. Byrne (1975) used approximately 60 cores to determine the depth throughout the bay. Because these cores were georeferenced before the advent of GIS technology, there is inherent location error, and also a limited number of data points from which to base contours.

Horizon C (Fig. 14) is also thought to represent the Pleistocene exposure surface. When examining the data, there were areas that might or might not have been part of horizon B or areas where the horizon is amorphous or unrecognizable though continuous with horizon B. These questionable areas were put into their own category, horizon C, instead of combining them with the signature consistently seen in horizon B. Areas beneath channel fill and other easily defined features suggest the Pleistocene surface is just beneath those unconformities. However, there are many holes in the data and faint reflectors, which are most likely a continuation of horizon B; these are the areas labeled as horizon C. Byrne's (1975) Pleistocene map supports this interpretation in that the general shape of the depth contours is the same. However, the depths toward the edges are different, Byrne's (1975) being much shallower than the depths determined in this study. This difference could result from his maps being based mostly on core data which provided a limited number of depth locations and subsequently a more general interpretation and/or because my profiles show wipeout around the edges of the bay, making it difficult to interpret the subsurface structure.

Deep Wipeout areas are anomalies that are either gassy sediments or a zone with incoherent returns. This interpretation is based on general acoustic properties, which dictate the presence of gas in sediments will scatter sound or that the sediment stratigraphy is amorphous. The stratigraphy of Lavaca Bay laid out by Byrne (1975) shows Pleistocene muds as shallow as 0-10 m around the edges of the bay. This could mean the bay edges are amorphous because they consist of Pleistocene mud instead of Holocene fill (typically containing strong reflectors).

Most of the clinoforms found in Lavaca Bay appear to be either prograding clinoforms or channel fill, according to the definitions of Mitchum et al. (1977). In most cases, the seismic records are not clear enough to determine the type of clinoforms. The location of the clinoforms in the northwestern part of the bay, just below Garcitas Creek, indicates the features are probably part of a delta formed as a result of the creek input (Fig. 28). The clinoforms in middle and south Lavaca Bay are along the bay axis and probably formed as water filled the bay during the Holocene sea level rise. Some of the clinoforms found in Lavaca Bay show evidence of a delta lobe. There is one profile (Fig. 29) that shows clinoforms tilted in opposing directions at the same depth within a horizontal distance of 545 m. This structure is indicative of a cross section of a tidal delta lobe.

The terraces appear to be a basin edge (Fig. 28). These would have formed when sea level was stable and the bay edge could be eroded.

CONCLUSION

The chirp sonar data collected in this study show Lavaca Bay as a fluvial valley that started to fill with coarse-grained sediments, and moved into more homogeneous, fine-grained sediments typical of an estuary (Nichols et al. 1991, Dalrymple et al. 1992). The stratigraphy consists of an upper, transparent reflector package with strong reflector anomalies in the top 5 m and a lower reflector package of stronger, horizontal reflectors sometimes underlain by unconformities with scattered areas of acoustic turbidity/wipeout anomaly around 10-30 m depth.

The strength of the surface reflector return appears indicative of the bay bottom type, based on similar work by Sager et al. (2004) and because different substrates either absorb sound making weak returns or reflect more sound making strong returns. Weaker returns are interpreted as soft bottom, probably mud, and stronger returns likely indicate the presence of harder sediments, such as shells or shell hash. The ringing signature suggests a very hard surface, mostly likely a high concentration of shell or a hard ground on the bay bottom. This is supported by the strength of the returns in Bronikowski's (2004) interpretation of side-scan sonar images. Bottom types do not correlate well with grab sample and core data descriptions, which is partly due to imprecise sediment descriptions and highly variable sediments and conditions.

In the strong, shallow reflector category, mounds are interpreted either as dredge spoils or oyster reefs, based on reef outlines from Bronikowski's (2004) side-scan sonar interpretation and dredge spoil outlines from a NOAA navigation map. The mounds do not correlate well with Byrne's (1975) live reef map, suggesting either the oysters are not growing on older reefs or different data collection methods and definitions of "reef" create a discrepancy between Byrne's and present data. The buried strong (BS) reflectors are a hard horizon, probably shell or reef. Buried multiples (BM) are probably buried oyster reef or shell hash because the sound waves must be hitting a hard substrate to create strong returns, and shell is the only material in recent sedimentation that would create such strong reflectors. BM also do not correlate well with 1912 (U.S. Bureau of Fisheries) or 1975 (Byrne) maps of oyster reef locations and extents, signifying the oysters are not growing on older reefs or that data collection methods, poor georeferencing in prior studies, and definitions of "reef" are producing the differences in the location and extent of the reefs.

The subbottom reflector category, reflector A is interpreted as a consistent layer approximately 5-10 m above the Pleistocene surface due to its strength, consistent height above horizons B and C, and mimicking of underlying topography. Horizon B is interpreted as the Pleistocene exposure surface, based on the similar shape of the Pleistocene surface found by Byrne (1975) and depths found in Galveston Bay (Sager et al. 2004). Horizon C is also the Pleistocene exposure surface, but with a different acoustic signature. The contour shape of the exposure surface is similar to exposure surface determined by Byrne (1975), but there is a discrepancy between the depth of the edges of the bay which is probably because Byrne's interpretation was based on cores whereas the chirp data has acoustic wipeout/turbidity around the edges. The deep wipeout may be a result of either gas, because it scatters sound, and/or incoherent returns, because the stratigraphy in that area is mud and amorphous. The clinoforms (where distinguishable) are mostly prograding clinoforms or channel fill, based on the definitions of Mitchum et al. (1977). The terraces are a basin edge formed by episodic sea level rise, based on their structure.

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APPENDIX A

Table 1. Summary of reflector categories, names, and definitions.

	Reflector Name	*Definition*
Surface Reflectors	Weak	Weak surface reflector; considers gain and whether surface reflector has been washed out by a stronger reflector/gas beneath it
	Medium	Moderate strength surface reflectors or small scale alternations between weak and strong reflections (on the order of 1 m horizontal spacing); considers gain and whether surface reflector has been washed out by a stronger reflector/gas beneath it
	Strong	Strong surface reflectors; considers gain and whether it has been washed out by strong reflectors/gas beneath it
	Ringing	A particular, distinct signature that shows only the surface reflector with multiples beneath—it has usually wiped out any other underlying reflectors that might otherwise be visible
Strong, Shallow Reflectors	Surface Strong (SS)	High amplitude, short wavelength reflector at bay floor
	Mounds	Elevated areas, usually ~1 m height at the bay floor surface
	Buried Strong (BS)	High amplitude, short wavelength reflectors within 10 m of the bay floor
	Buried Multiples (BM)	Strong, distinct reflector within 5 m of bay floor with multiples that wipe out underlying reflectors at least 15 m below it
Subbottom Reflectors	A	Strong, relatively flat-lying, continuous, single reflector that occurs between 20-30 m depth
	B	Horizon traced below an unconformity, usually below 25 m depth
	C	Broad, amorphous horizon traced below an unconformity, usually as an extension of horizon B
	Deep Wipeout	Amorphous or incoherent reflectors between 10-30 m depth; reflectors may still appear below 30 m
	Clinoforms	Horizon traced at top of tilted beds/reflectors

Table 2. Table of reflector names, potential problems, and interpretations.

	Reflector Name	*Potential Problems*	*Interpretation*
Surface Reflectors	Weak	Reflectors can falsely appear weak if a strong reflector causes chirp sonar to reduce the gain settings and/or if there is a heavy sediment load in the water column	Soft bottom
	Medium	Reflectors can falsely appear weaker or stronger if strong reflectors cause chirp to reduce the gain settings	Medium bottom
	Strong	Reflectors can falsely appear stronger than they are if a strong reflector causes chirp to reduce the gain settings	Hard bottom
	Ringing	None	Very hard bottom
Strong, shallow reflectors	Surface Strong	Some reflectors may appear stronger or weaker if strong reflectors cause chirp to change the gain settings	Hard surface resulting from hard sediments, oyster reefs, or oyster hash
	Mounds	Can be difficult to distinguish between a distinct mound and a general change in bathymetry; it is a matter of interpretation of slope change	Oyster reefs and/or dredge spoils
	Buried Strong	Some reflectors may appear stronger or weaker if strong reflectors cause chirp to reduce the gain settings	Mostly buried oyster reefs, but can also include hard sediment layers such as sand
	Buried Multiples (BM)	It is possible for pipelines or other hard objects to display this signature as well	Buried reefs
Subbottom Reflectors	A	Layer likely to show up as strong reflector from gas trapped within and signature could easily jump from layer to layer; difficult to tell from one line to the next if it is actually same layer	Consistent layer approximately 5-10 m above top of Pleistocene
	B	Scant evidence of unconformity	Pleistocene surface
	C	No hard evidence to know if horizon is traced below an unconformity; record is spotty and incomplete due to obstruction from gas or other reflectors	Pleistocene surface
	Deep Wipeout	Areas in the “Deep Wipeout” category sometimes show stratigraphy, but is not distinct enough to be considered “clear”	Areas without mid-depth stratigraphic package, gas, acoustic turbidity
	Clinoforms	Traced area may not be full extent of tilted beds/reflectors	Cross-bedding likely associated with deltas or channel fill

APPENDIX B

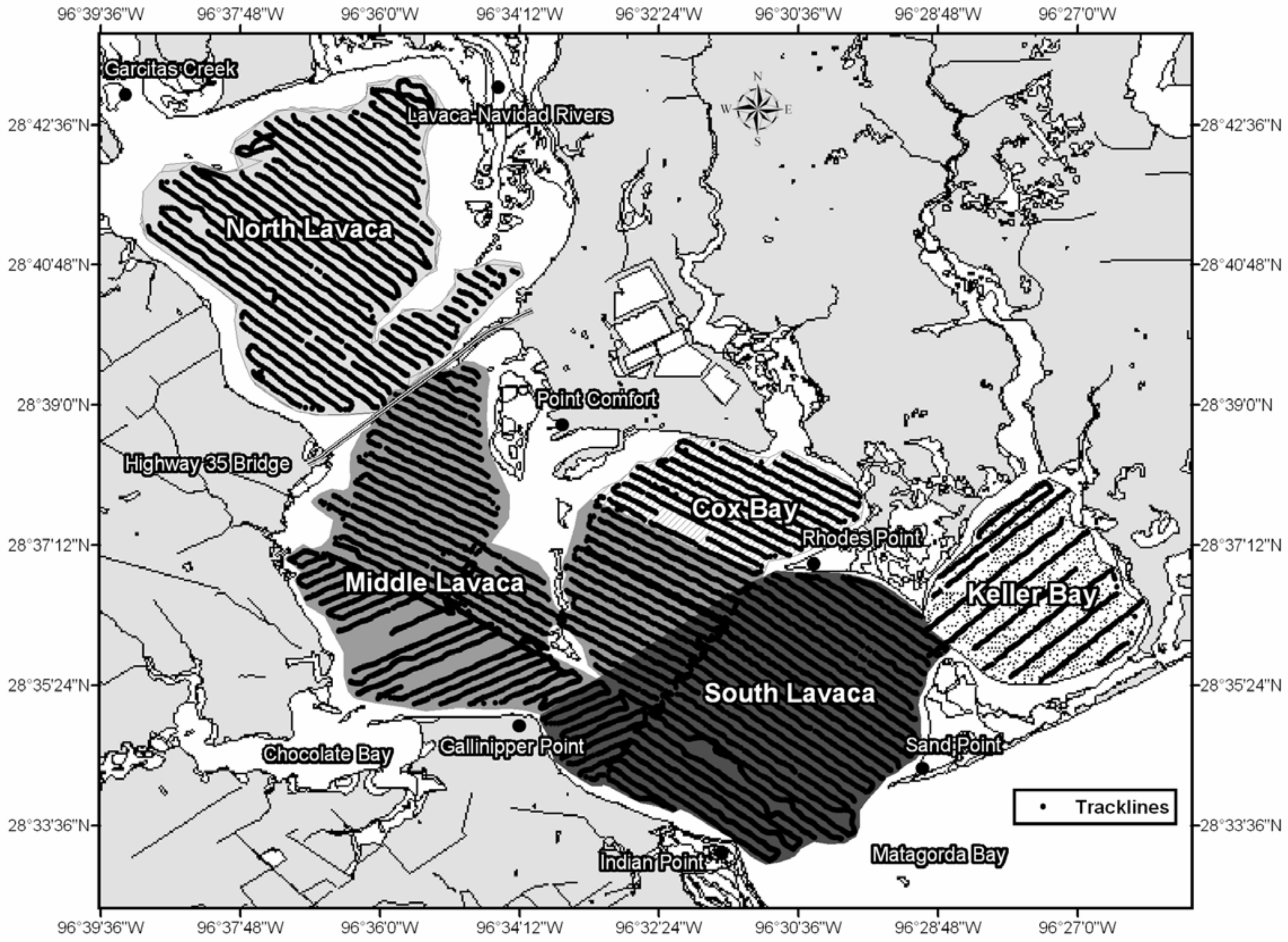

Figure 1. Lavaca Bay survey lines and bay names. Map shows divisions and landmarks of Lavaca Bay. Black lines indicate chirp sonar tracklines.

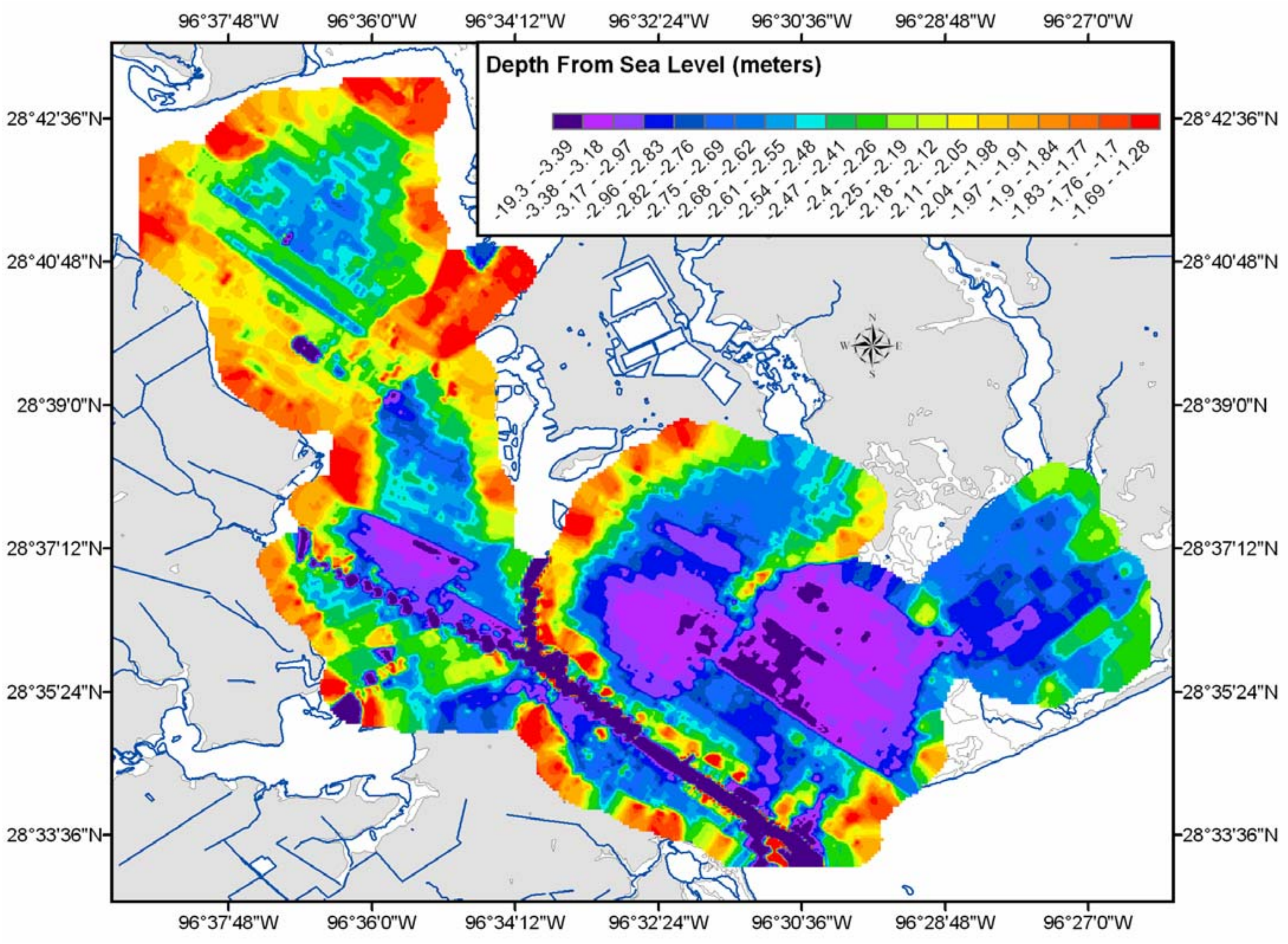

Figure 2. Lavaca Bay bathymetry (from chirp sonar data). Linear feature trending northwest to southeast in middle and southern bay is a dredged ship channel.

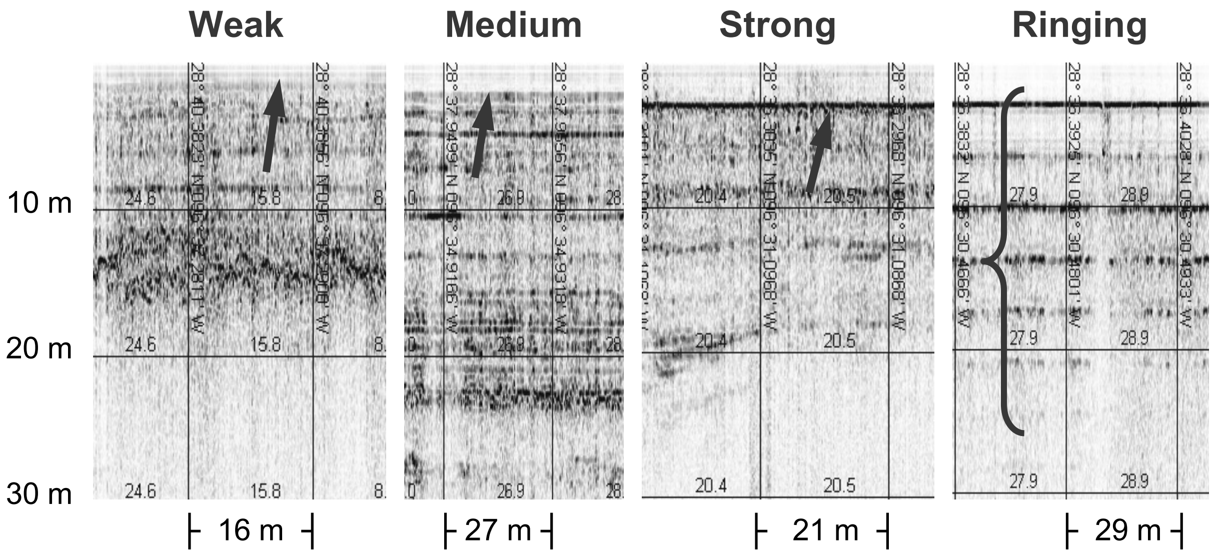

Figure 3. Chirp sonar profiles of near surface sediments showing four grades of bay bottom acoustic return. Arrows point to surface reflector; bracket shows ringing signature.

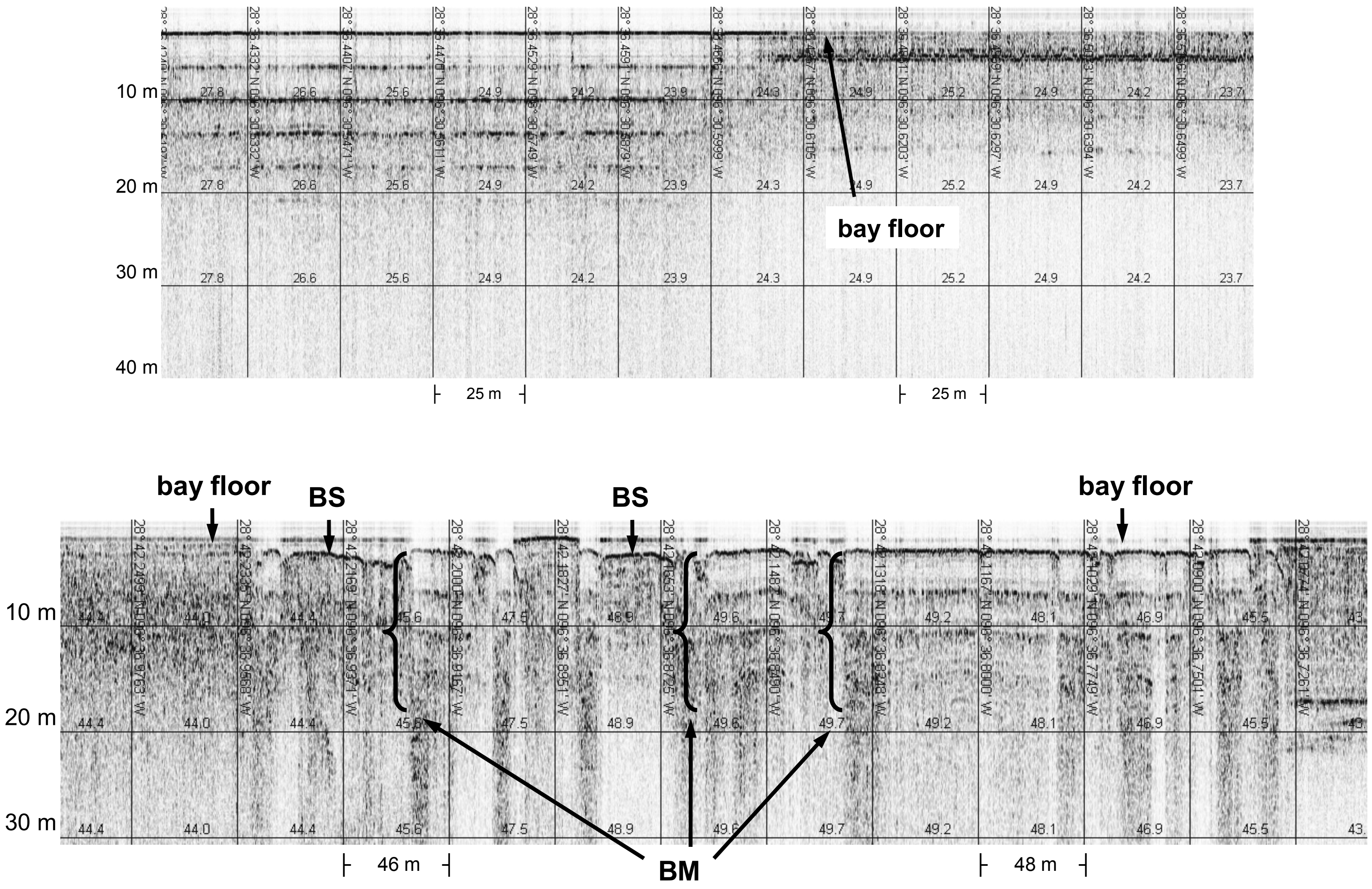

Figure 4. Example of chirp sonar profiles showing typical reflector characteristics in Lavaca Bay. Top: Profile example showing change of character from ringing surface reflector (left side of profile) to normal medium reflection character. Note the abrupt end of the ringing. Bottom: Profile showing relationship and character of buried strong (BS) reflectors and buried multiples (BM).

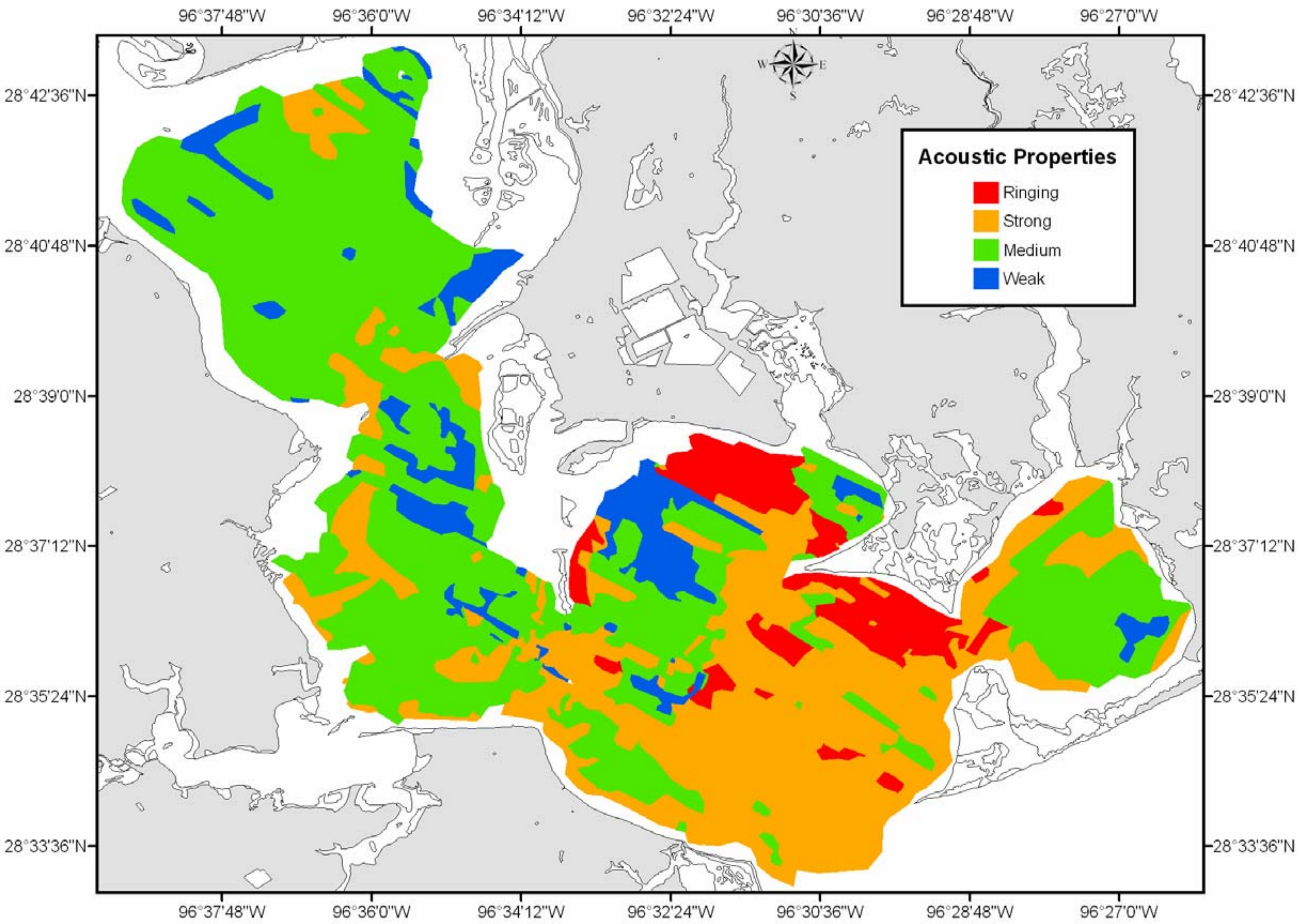

Figure 5. Distribution of bay bottom reflection character types.

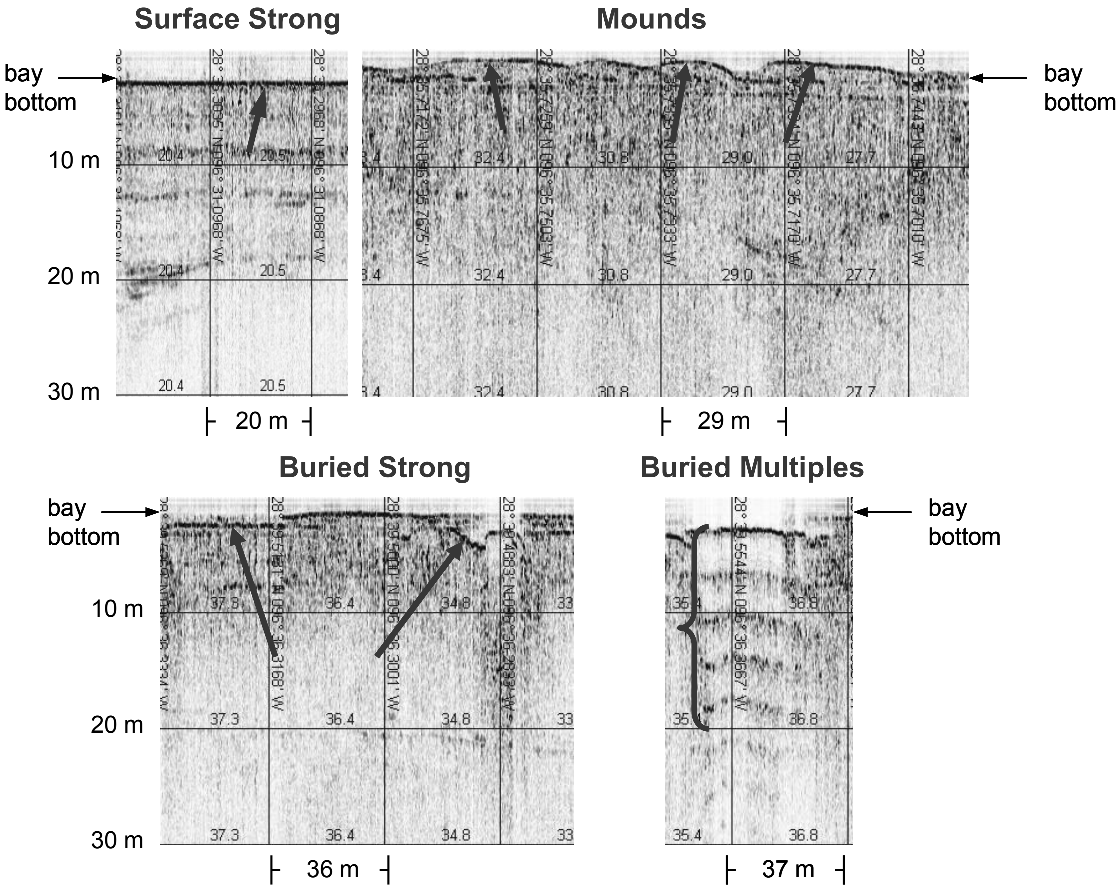

Figure 6. Chirp sonar profiles of near surface sediments showing four different classes of strong, shallow reflectors. Arrows point out example reflector of each category. Brackets in Buried Multiples signature profile denote multiples characteristic of the category.

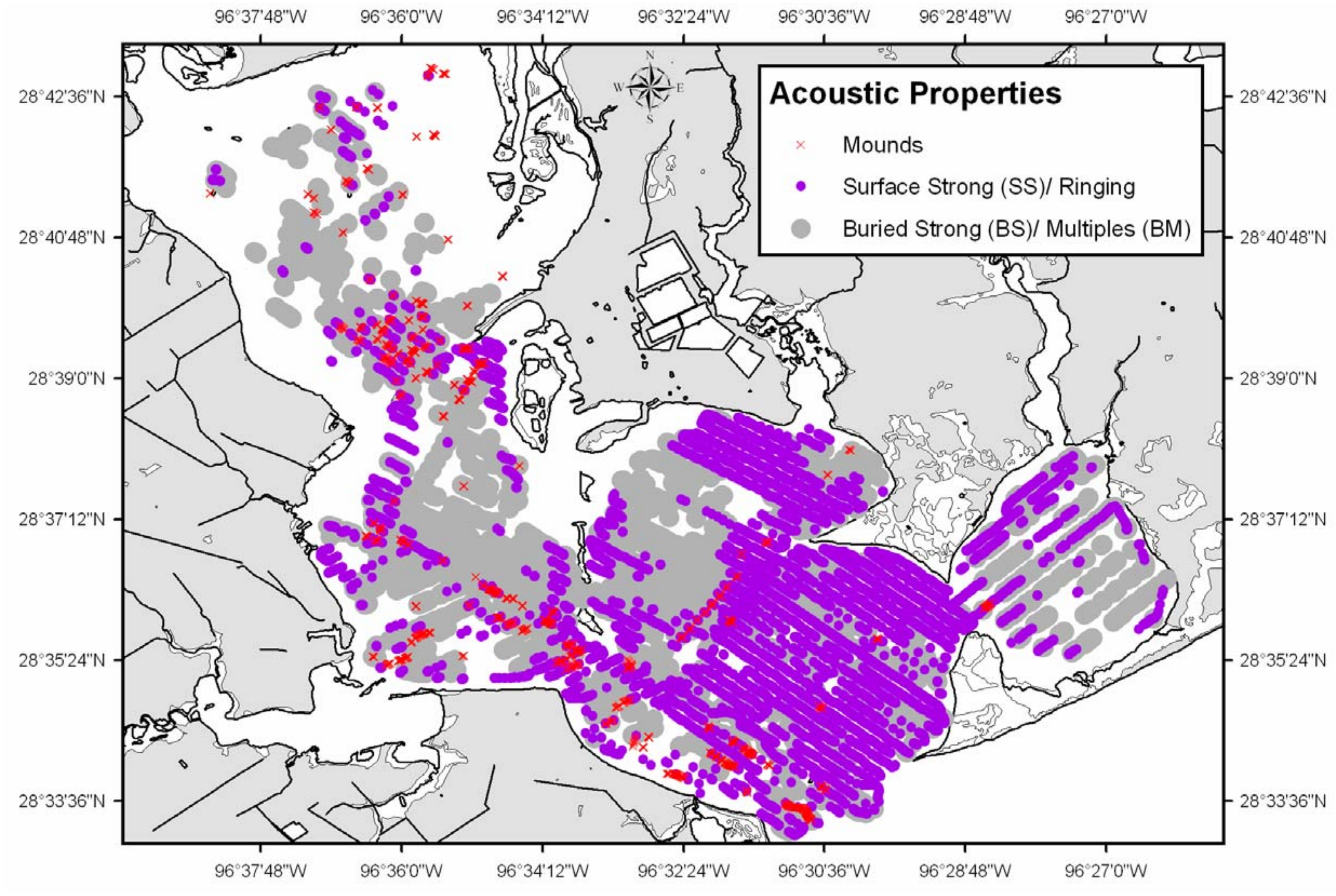

Figure 7. Map showing distribution of mounds, strong surface, and subbottom reflectors in Lavaca Bay. Note: More than one characteristic can occur at the same location at different depths; map displays reflectors shallowest (on top) to deepest (underneath).

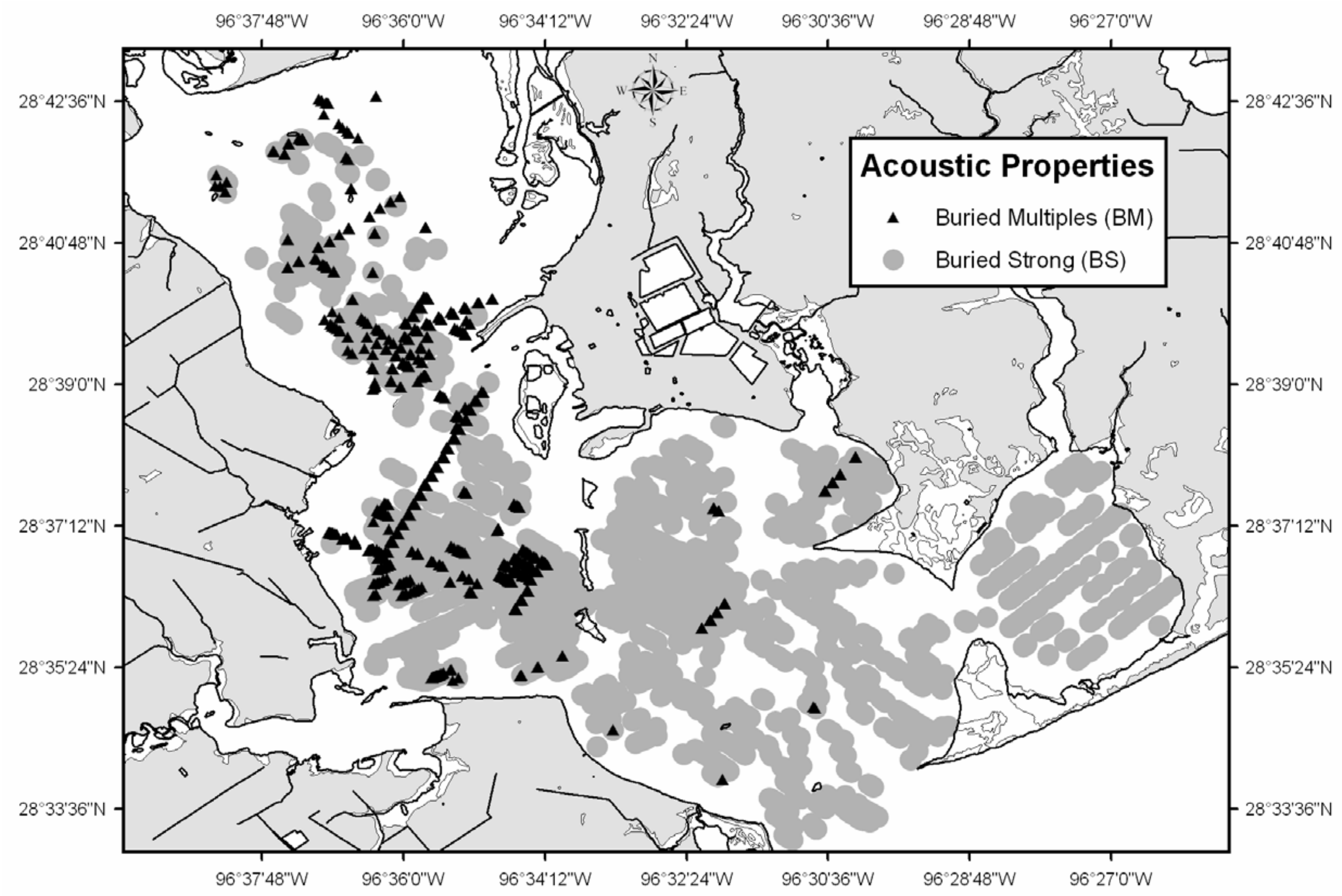

Figure 8. Map showing distribution of buried multiples (BM) and buried strong (BS) reflectors in Lavaca Bay.

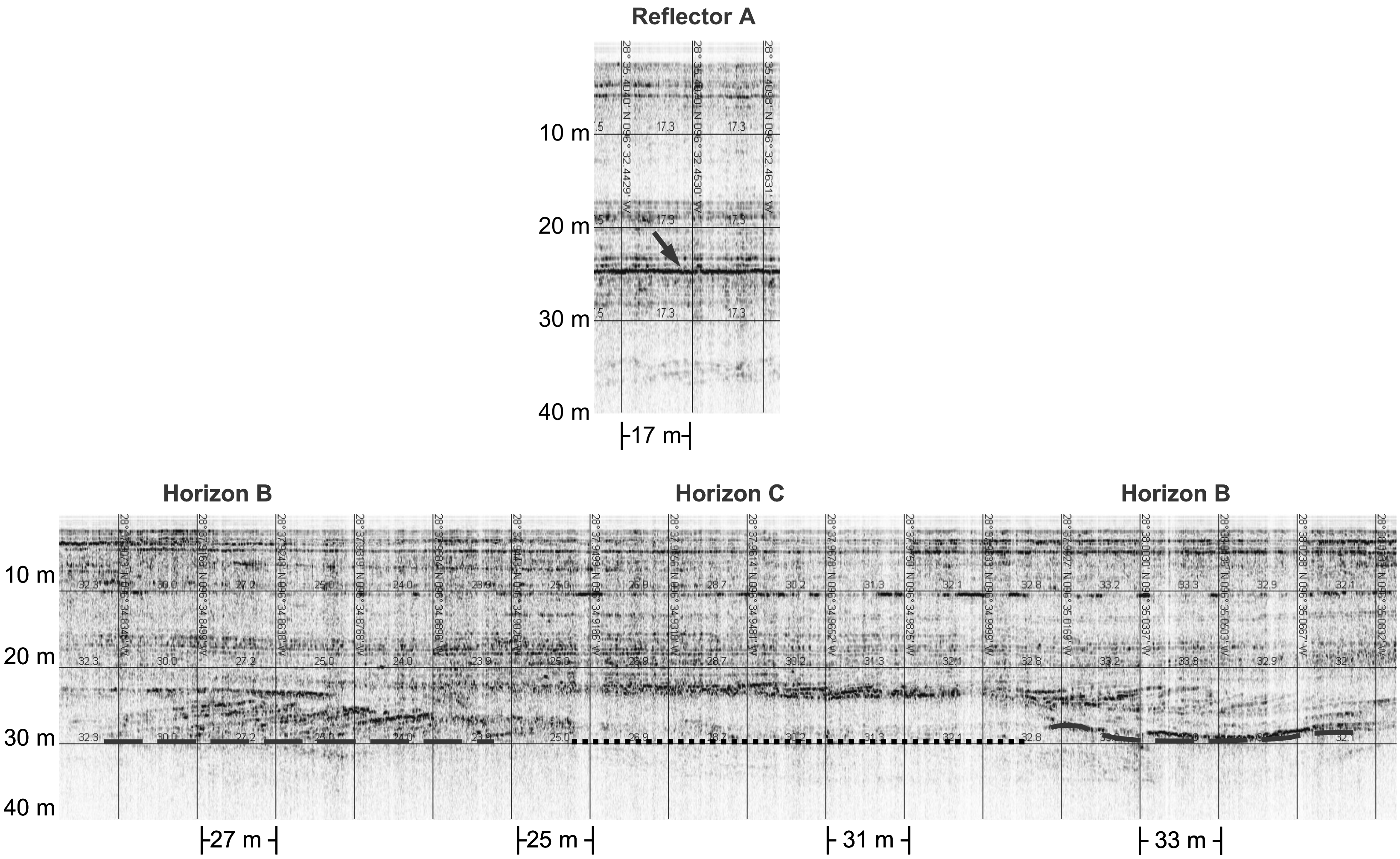

Figure 9. Chirp sonar profiles showing three different types of deep subbottom reflectors. Arrow in top profile denotes the single, discrete, strong reflector dubbed reflector A. Horizon B (dashed line) is traced beneath the package of shingled reflectors with an unconformity at the top, and Horizon C (dotted line) is a diffuse weak reflector, often continuous with horizon B.

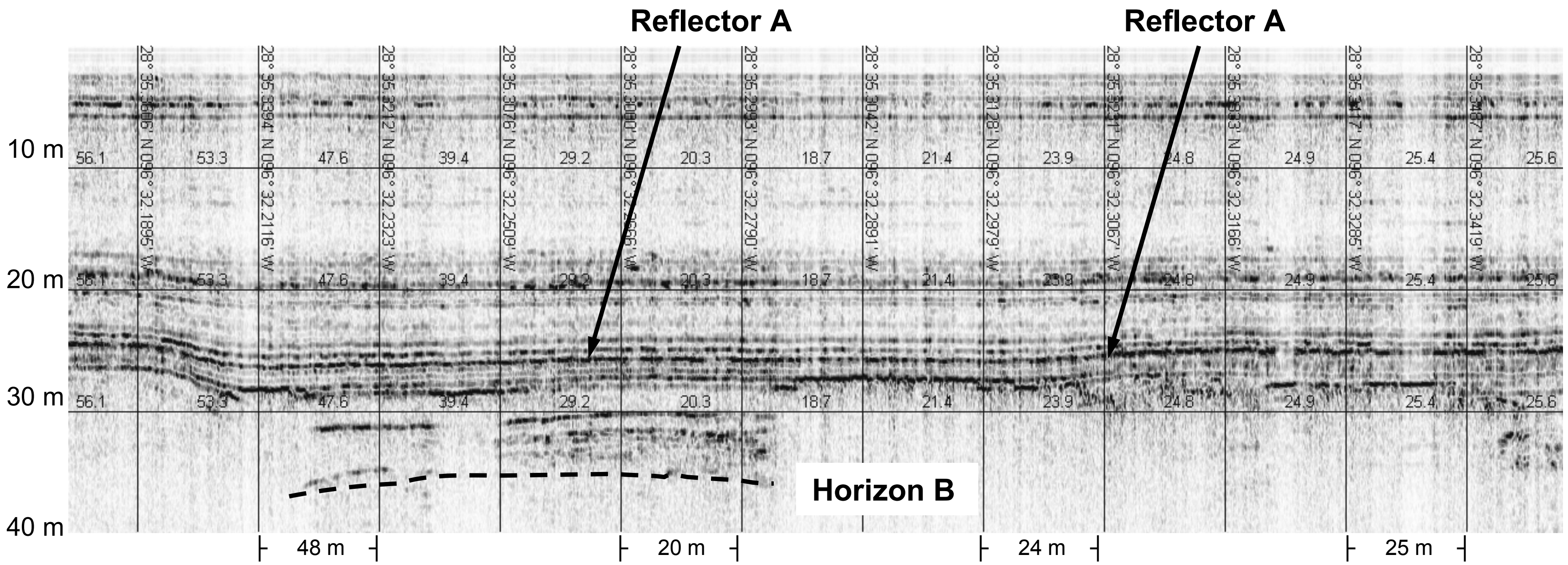

Figure 10. Chirp sonar profile showing character of reflector A and its relationship to horizon B.

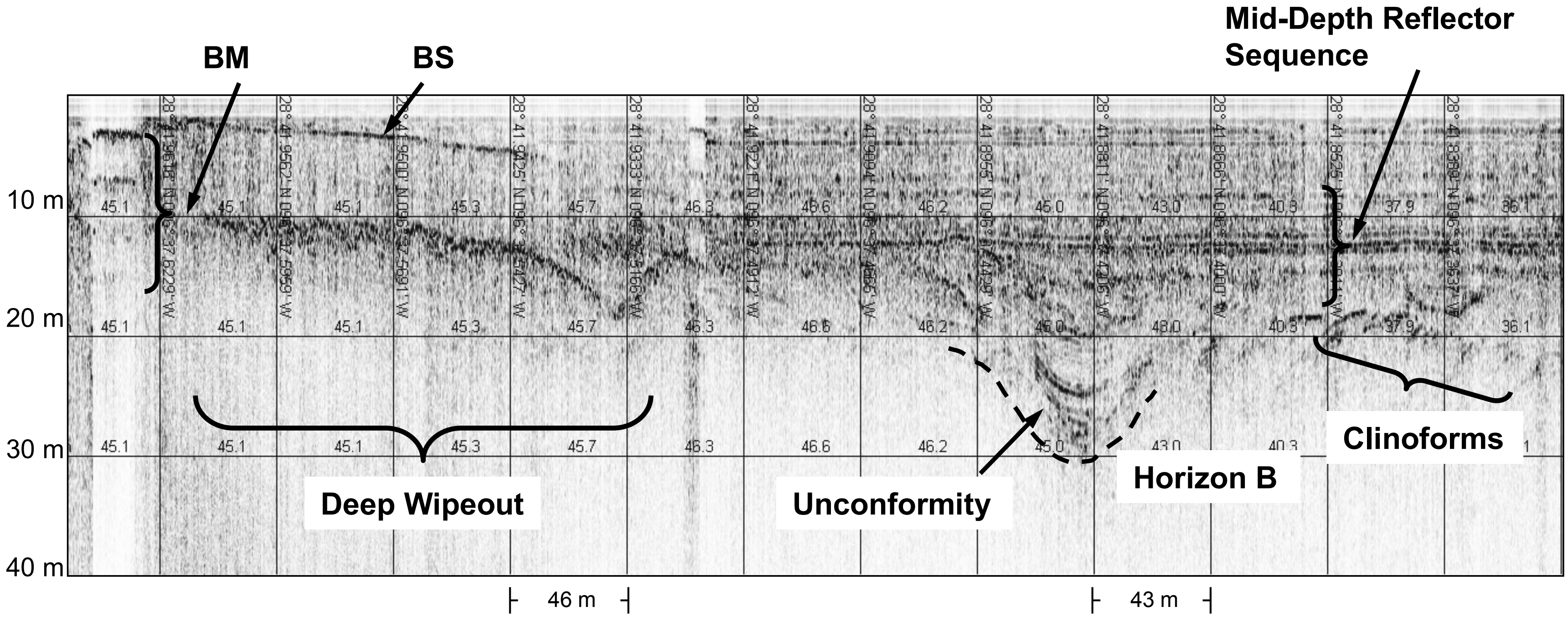

Figure 11. Chirp sonar profile showing relationships between deep reflectors. Note how buried strong seems to continue from the buried multiples and deep wipeout grades to a mid-depth reflector sequence.

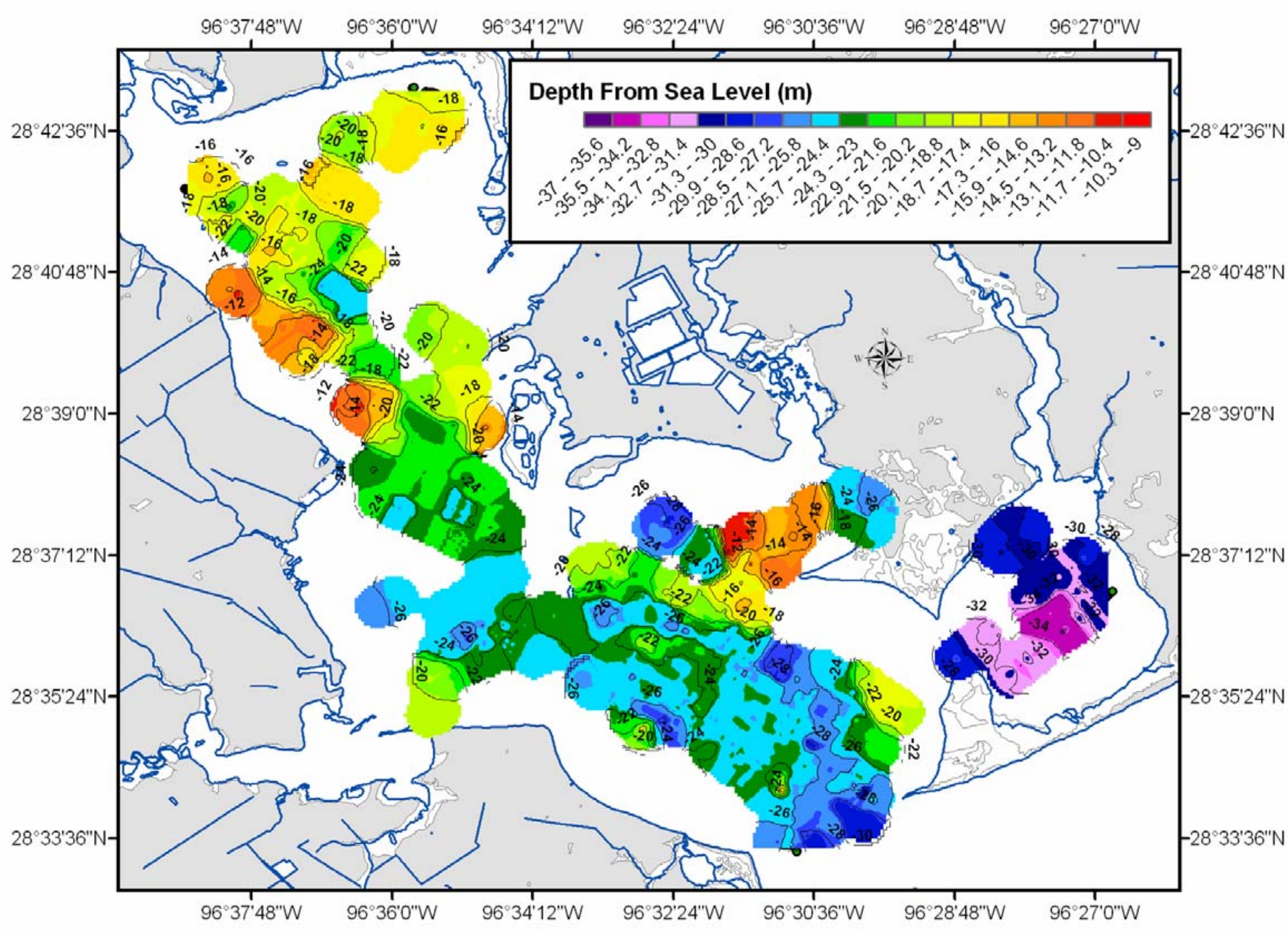

Figure 12a. Distribution and depth of subbottom reflector A. Map shows contour of reflector A in the bay. Contour interval is 2 m. Depth is measured from sea level.

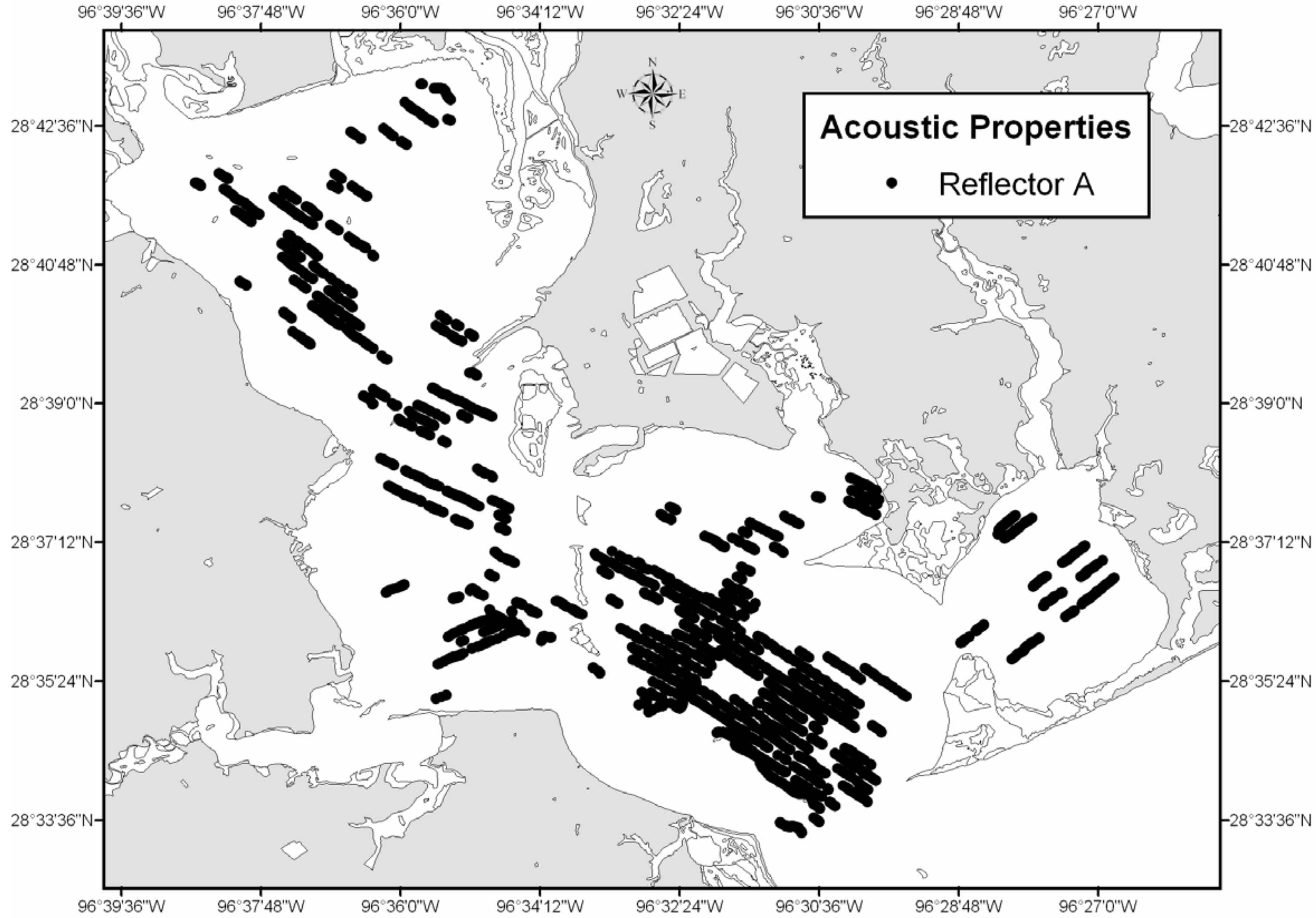

Figure 12b. Data points of reflector A. Map shows location of reflector A data points used to make contour map in Figure 12a.

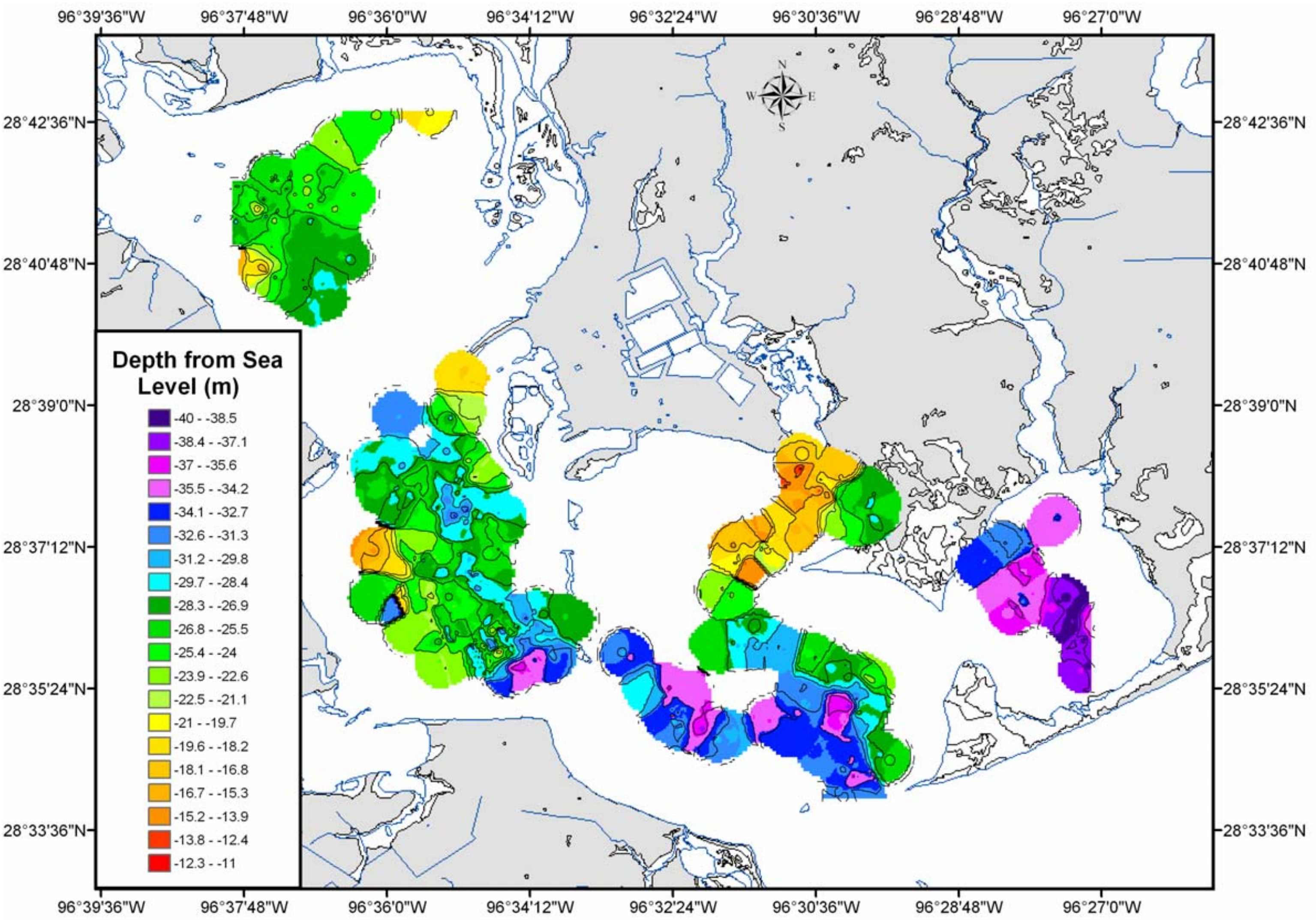

Figure 13a. Map of distribution and depth of subbottom horizon B. Contour interval is 2 m. Depth is measured from sea level.

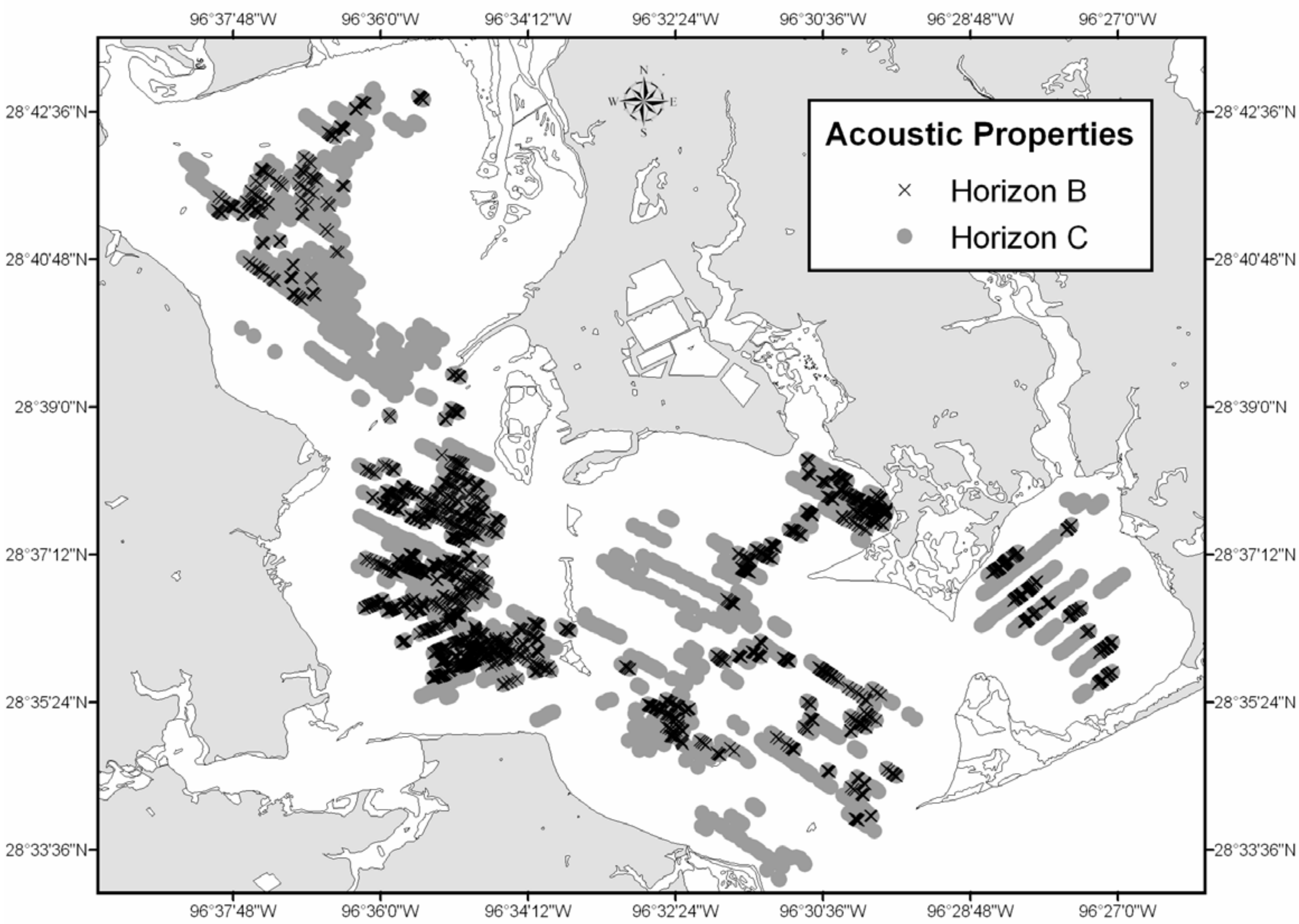

Figure 13b. Data points of horizons B and C. Map shows location of horizon B and C data points used to make contour map in Figure 13a.

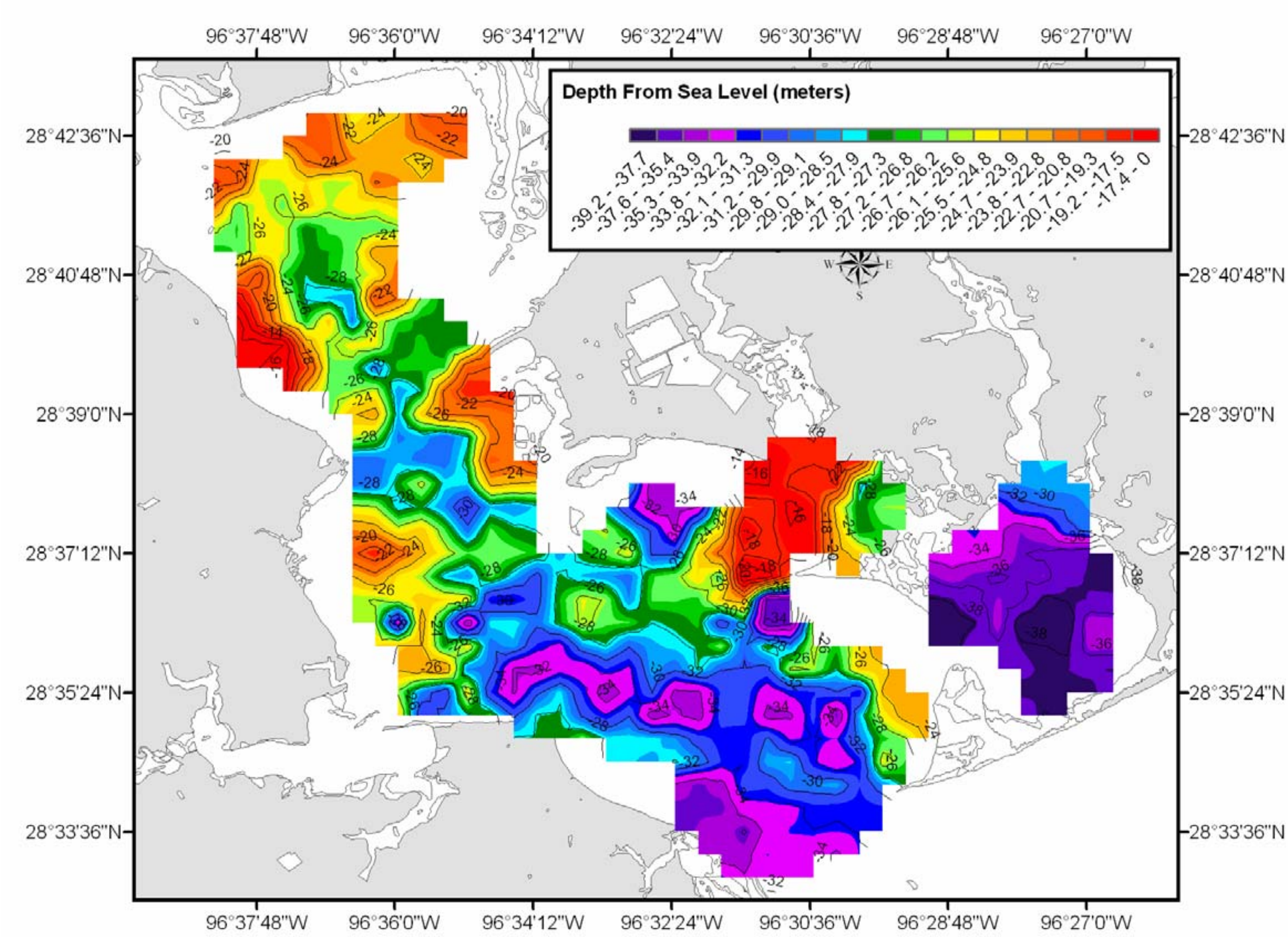

Figure 14. Contour map of depth of combined horizons C and B. Depths measured from sea level.

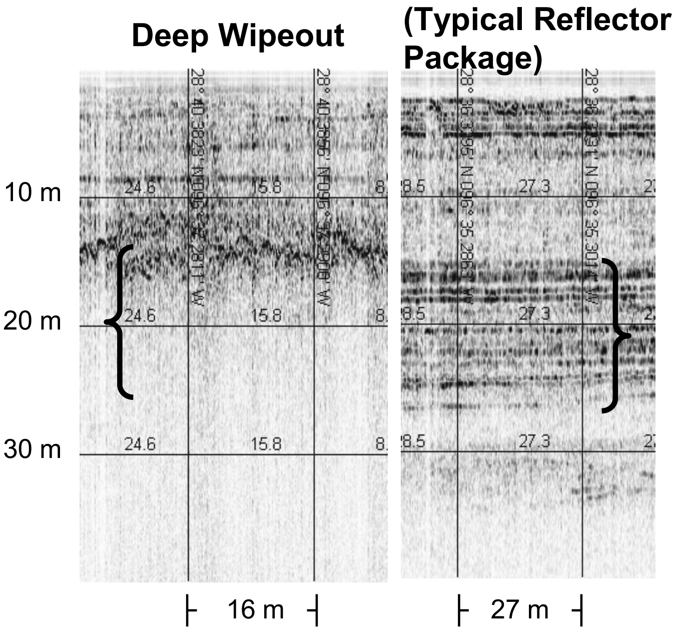

Figure 15. Chirp sonar profiles comparing deep wipeout to normal, undisturbed stratigraphy.

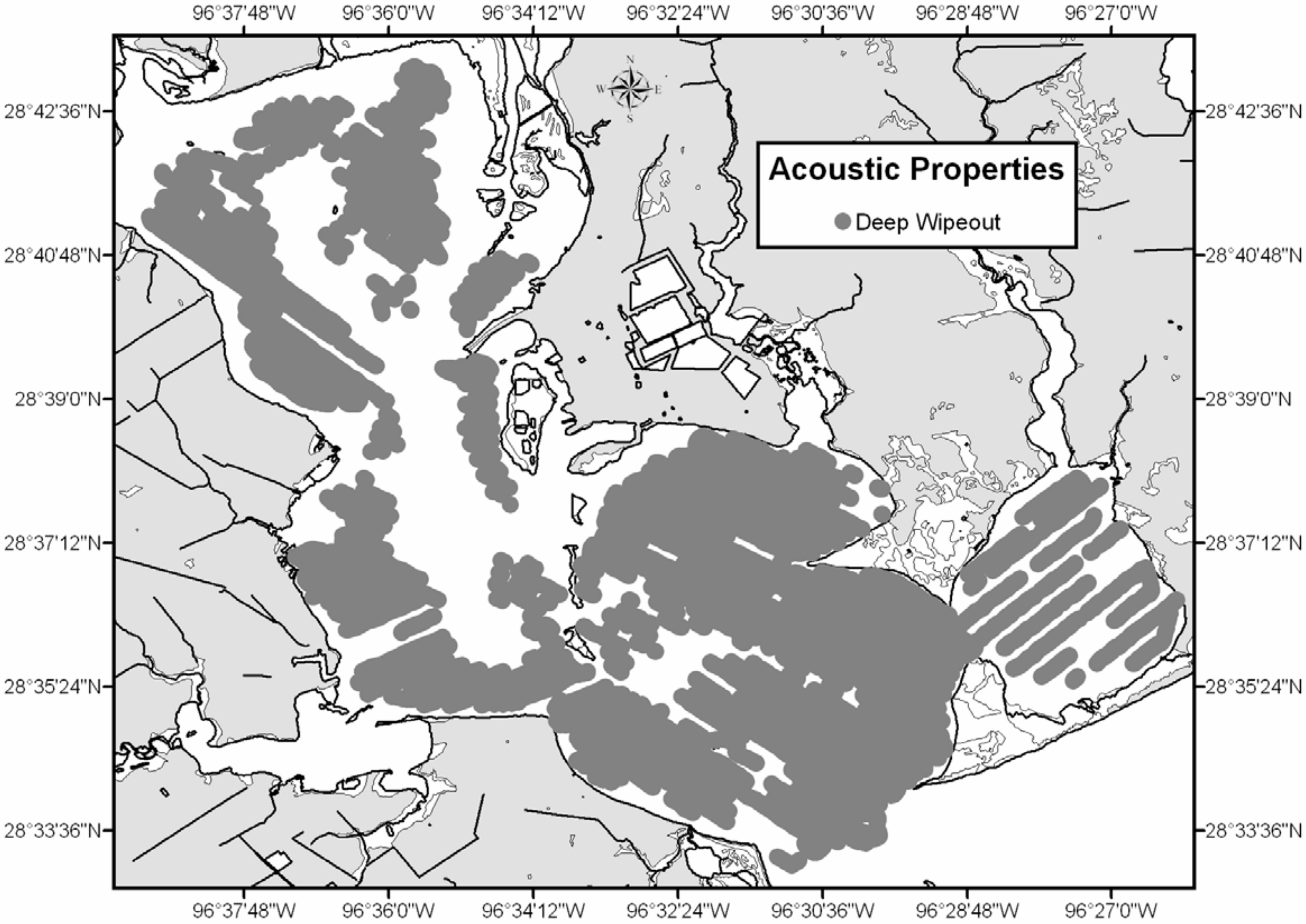

Figure 16. Map showing occurrence of deep wipeout between 10-30 m depth.

Clinoforms

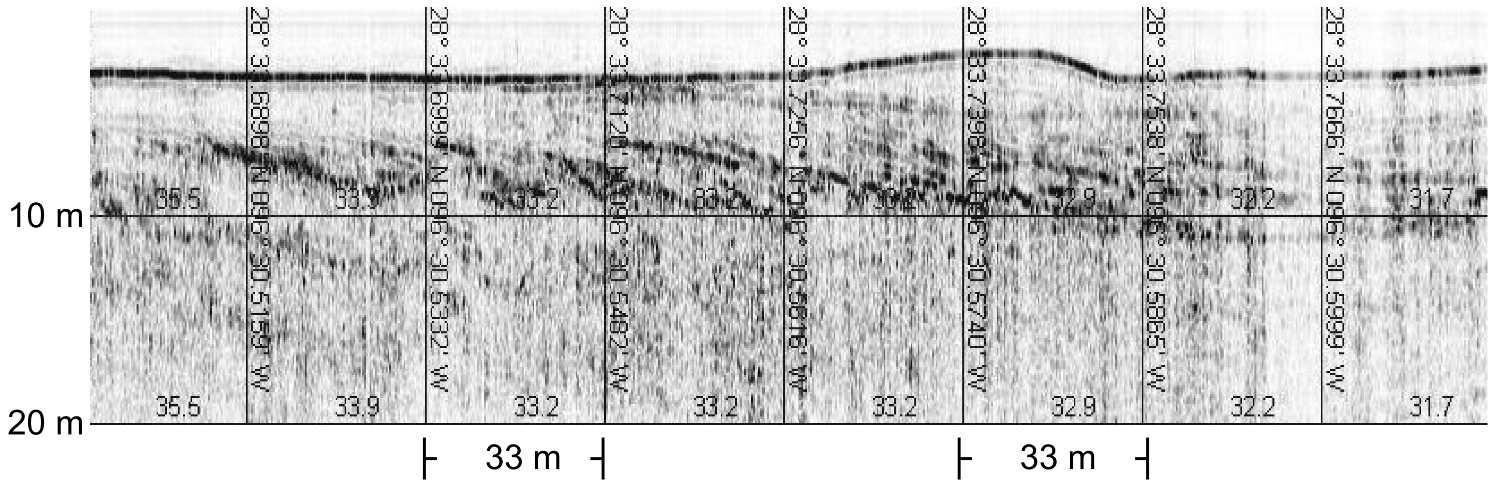

Figure 17. Chirp sonar profile showing example of clinoforms.

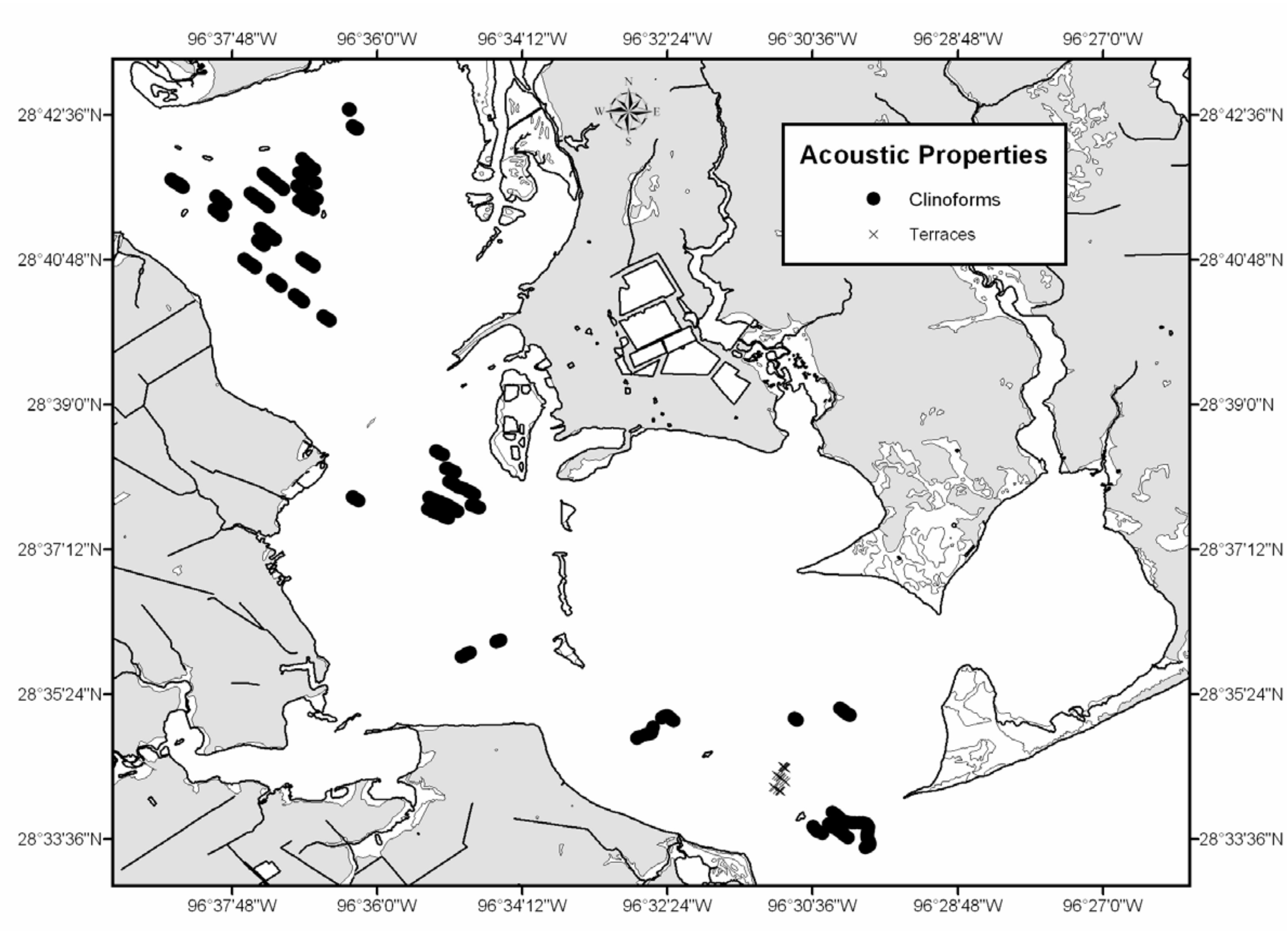

Figure 18. Map showing distribution of clinoforms and terraces in Lavaca Bay.

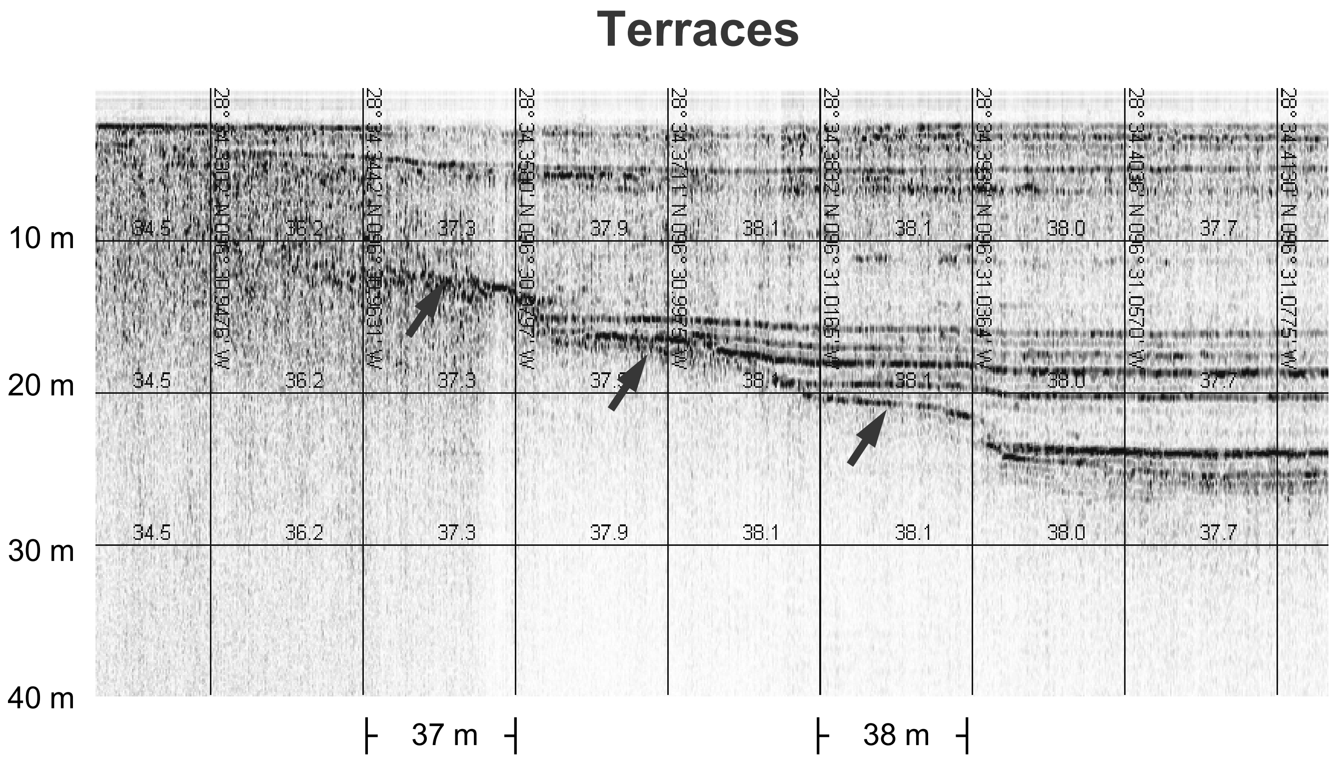

Figure 19. Subbottom profile showing example of terraces in Lavaca Bay.

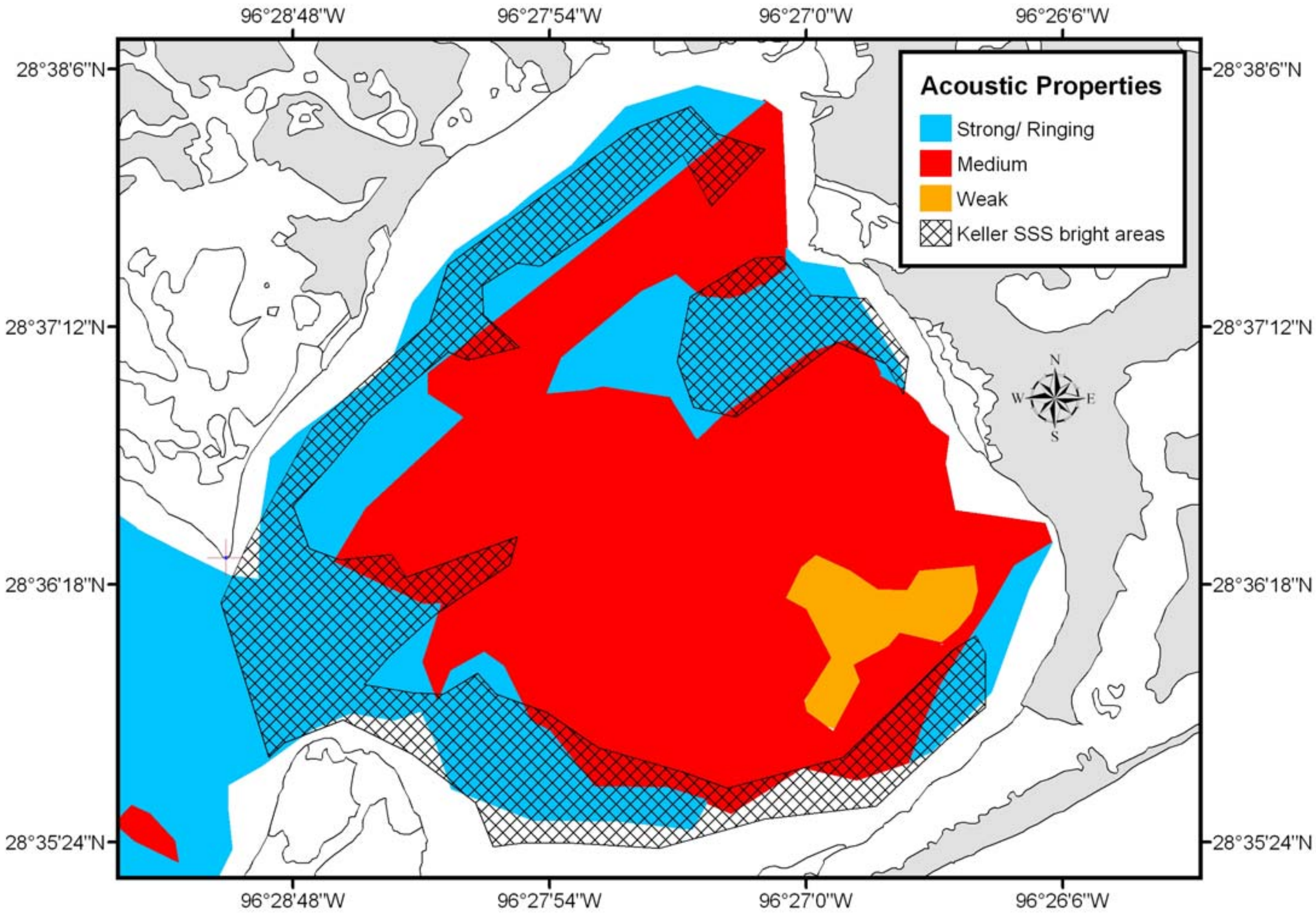

Figure 20. Comparison of surface reflection strength with strong return areas of side-scan sonar. Areas of strong return observed with side-scan (Bronikowski 2004) are shown by hachures.

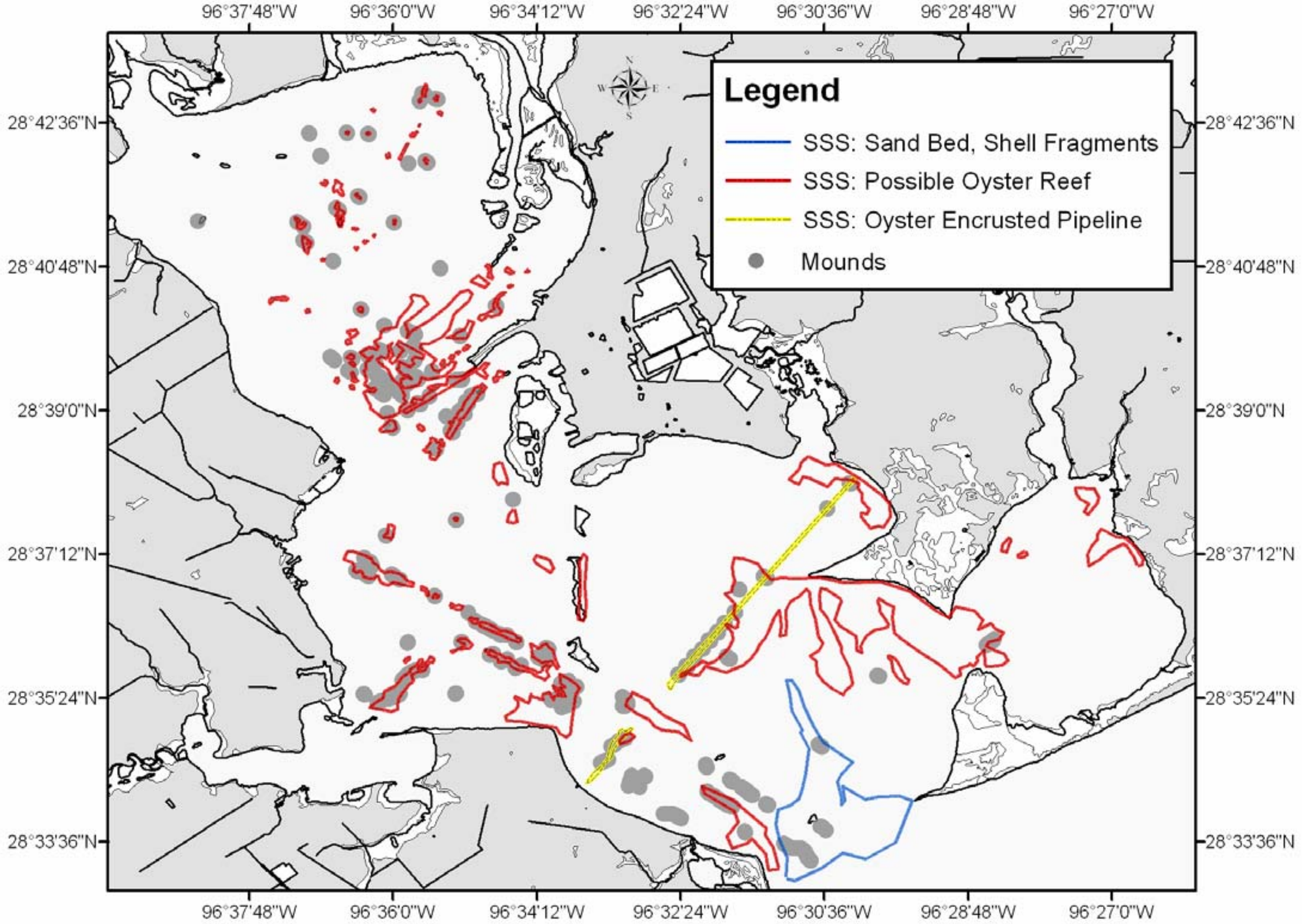

Figure 21. Comparison of areas interpreted as sand, shell, reef, and pipeline from side-scan sonar images and areas interpreted as mounds. Map shows comparison of distribution of oyster reefs in side-scan sonar and subbottom profiler data. Side scan sonar data outlines areas in red, blue, and yellow; subbottom data are green dots. Side-scan sonar outlines from Bronikowski (2004).

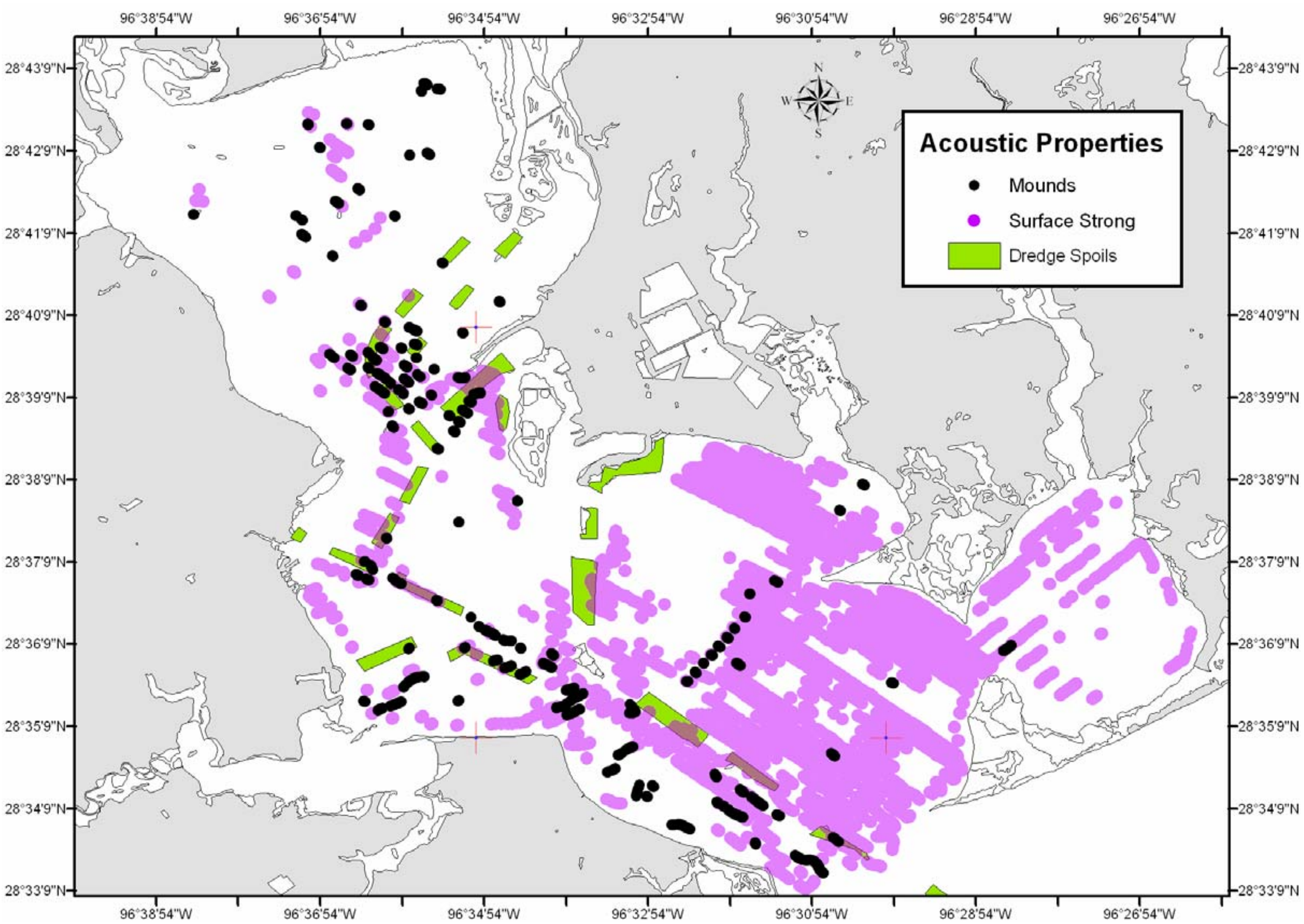

Figure 22. Comparison of mounds, strong surface reflectors, and dredge spoils. Figure shows base map with outlines of dredge spoil areas. Distribution of surface strong reflectors and mounds was overlaid in order to observe pattern of mounds relative to weak and strong reflectors.

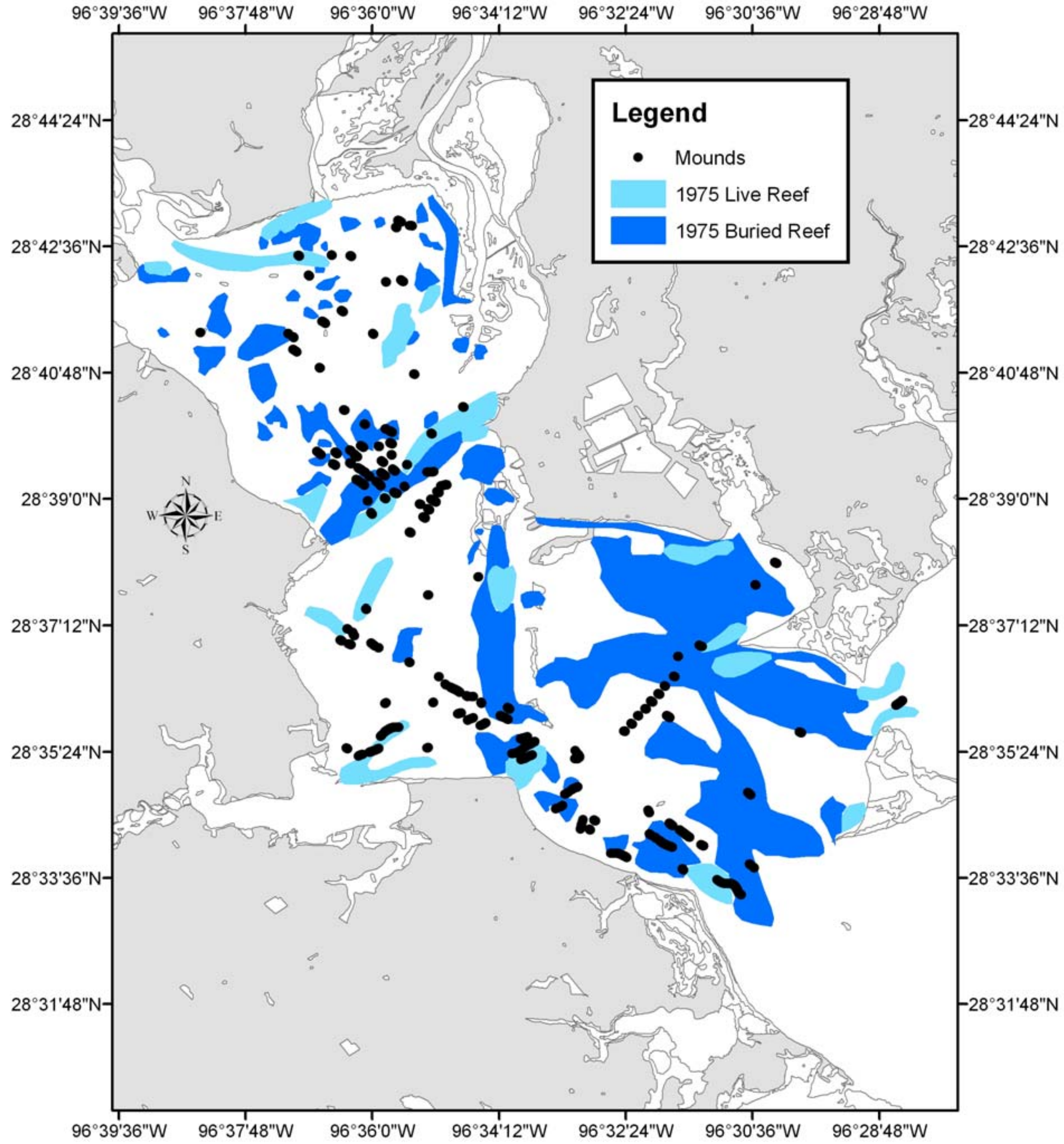

Figure 23. Map showing distribution of mounds and outline of live and buried oyster reefs in 1975 (modified from Byrne 1975).

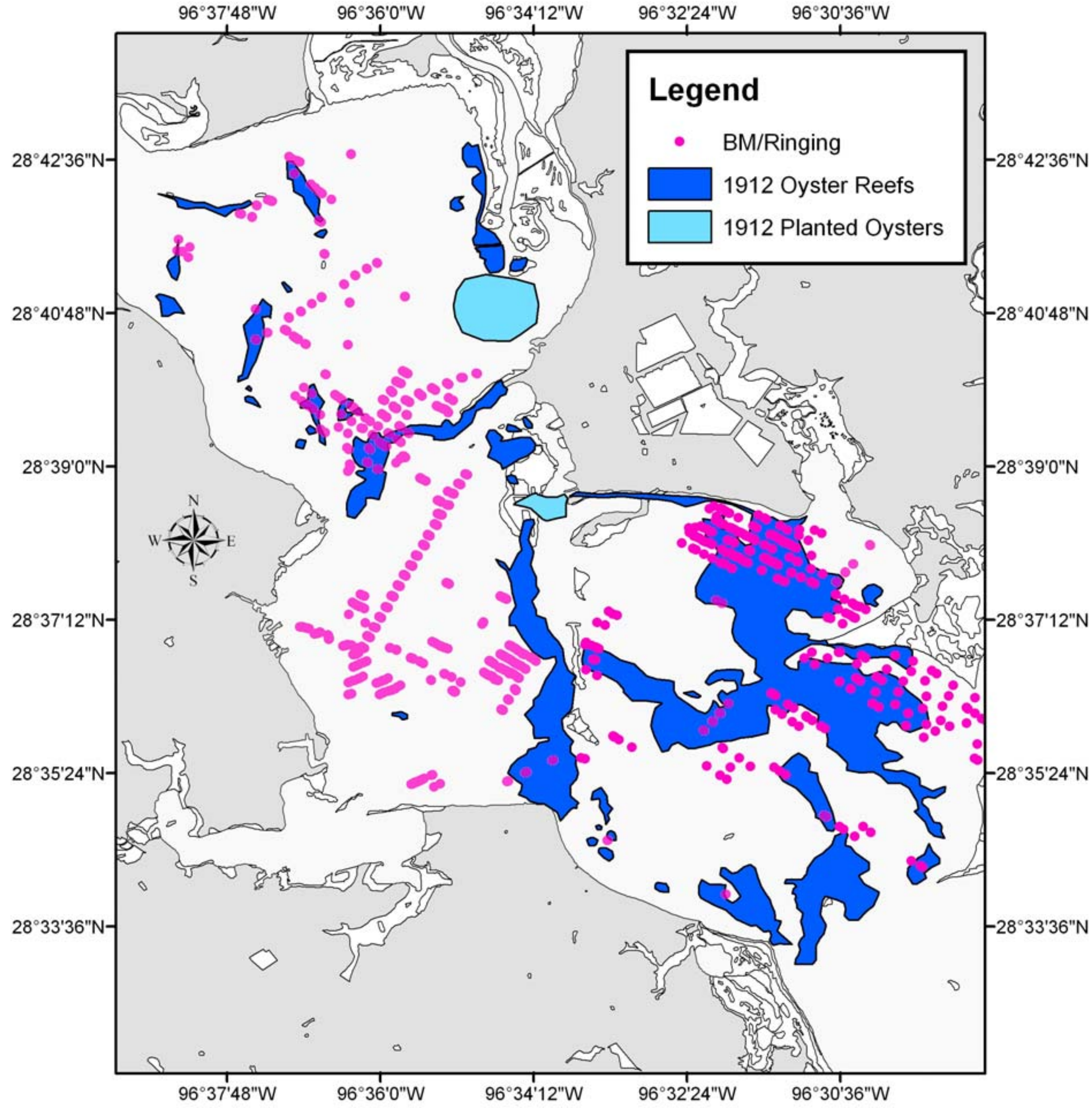

Figure 24. Map showing distribution of buried multiples (BM)/ringing signature and outline of the major oyster reefs in 1912 (modified from U.S. Bureau of Fisheries 1912).

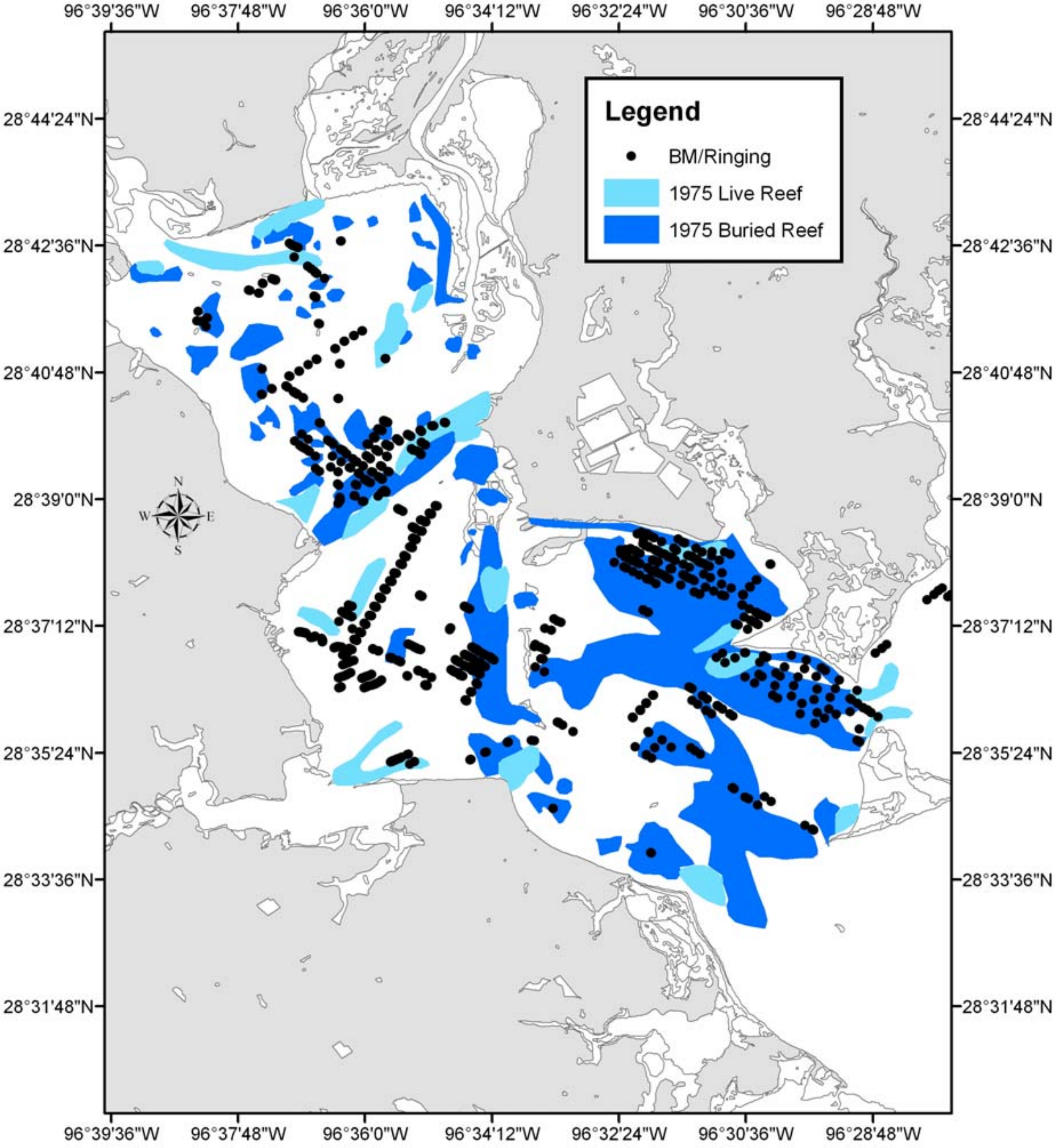

Fig. 25. Map showing distribution of buried multiples (BM)/ringing signature and outline of live and buried oyster reefs in 1975 (modified from Byrne 1975).

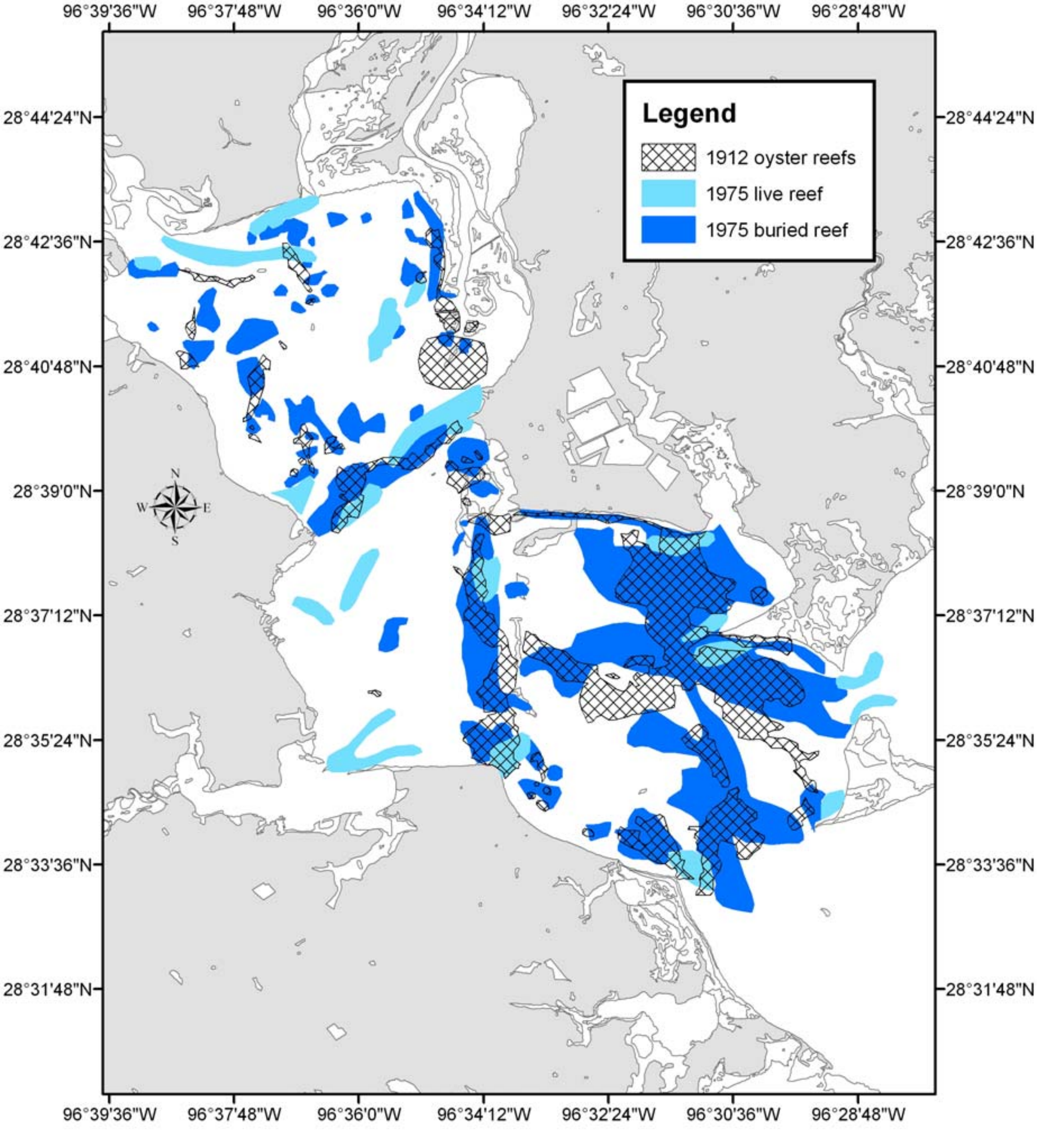

Fig 26. Map showing distribution oyster reefs in 1912 (U.S. Bureau of Fisheries 1912) and outline of live and buried oyster reefs in 1975 (modified from Byrne 1975).

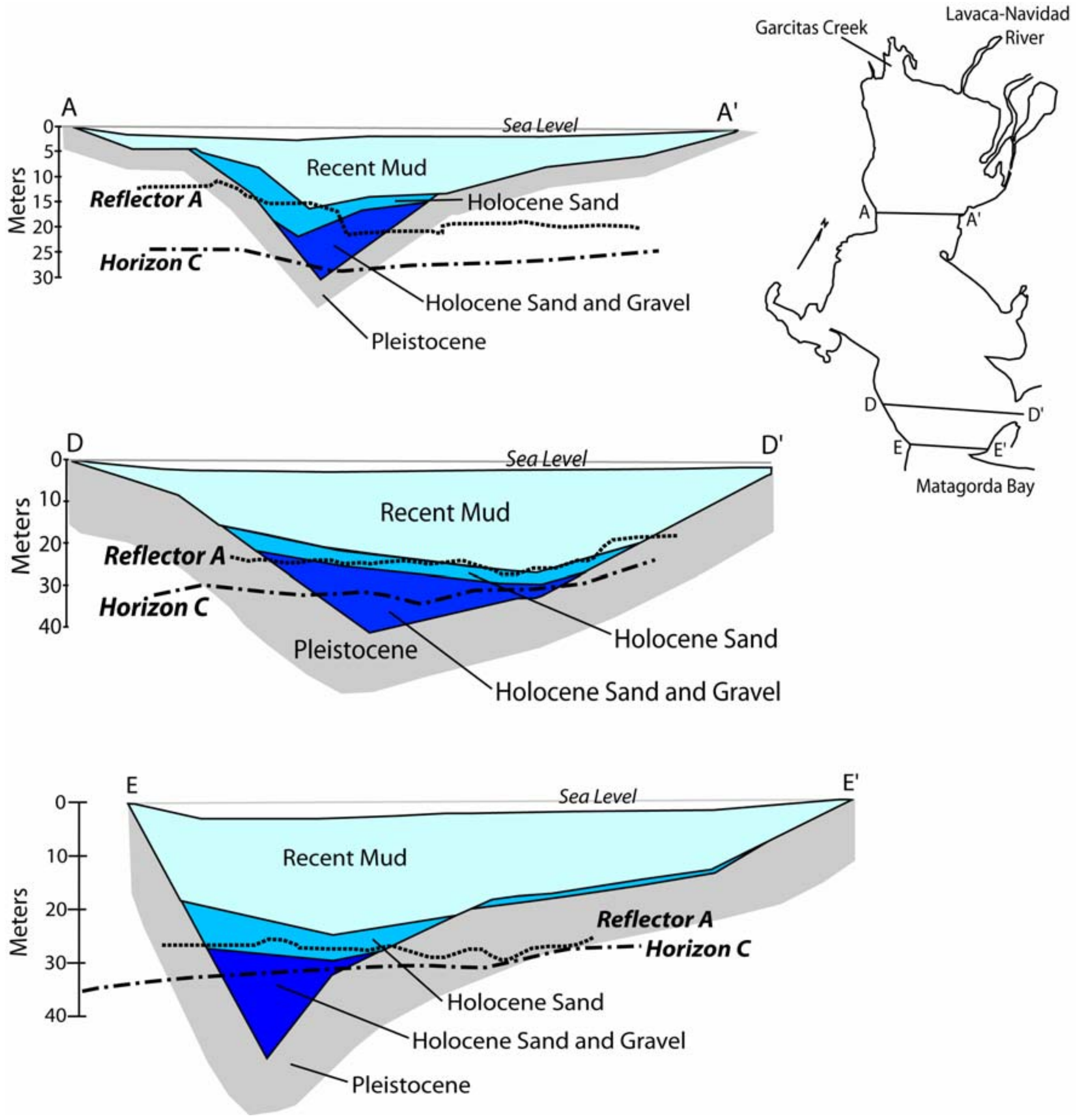

Figure 27. Correlation of reflector A and horizon C to three of Byrne's (1975) cross sections. Colored cross sections and location map modified from Byrne (1975).

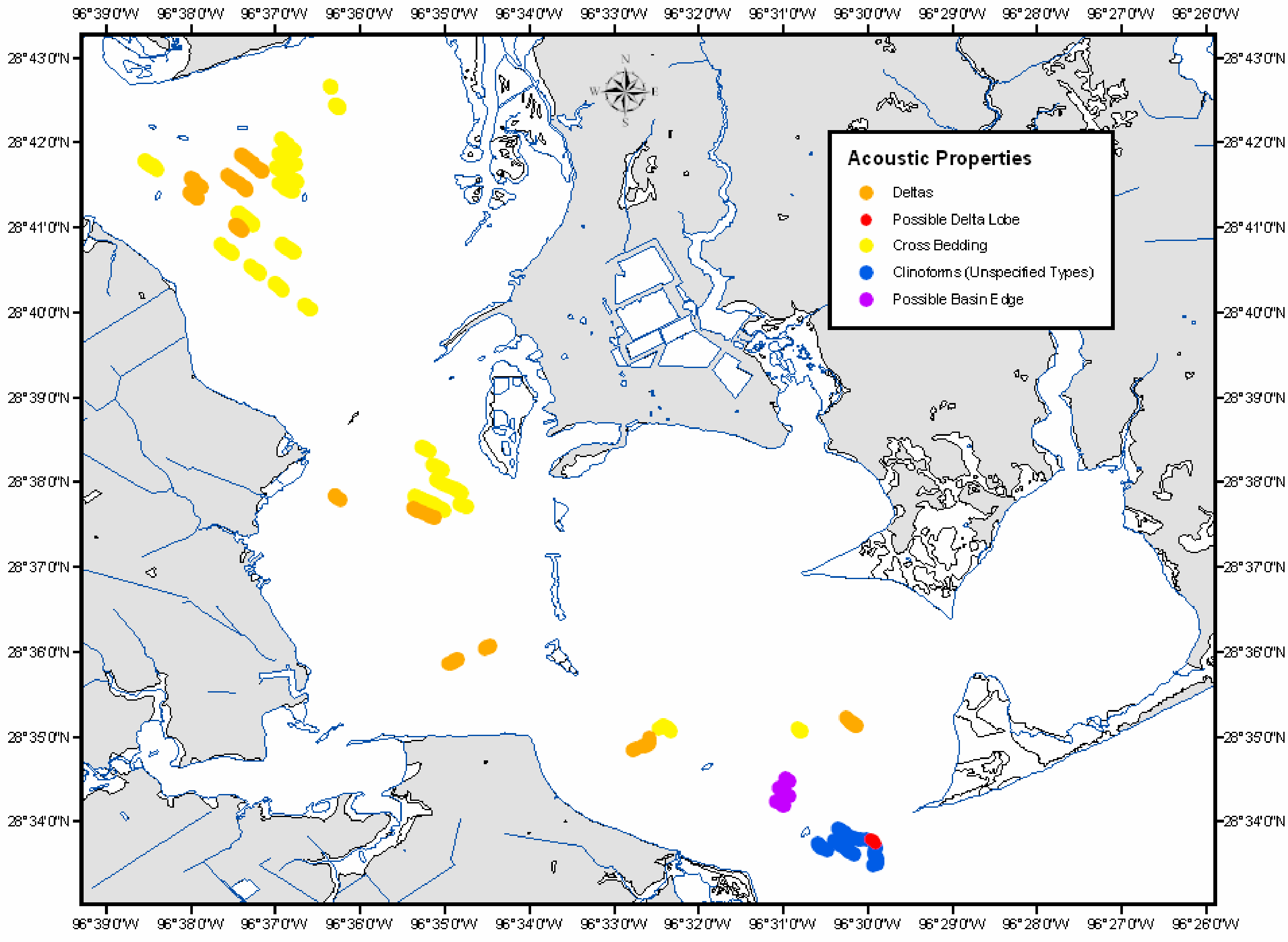

Figure 28. Lavaca Bay underlying structures. Map shows interpretation of clinoforms and location of possible basin edge in Lavaca Bay.

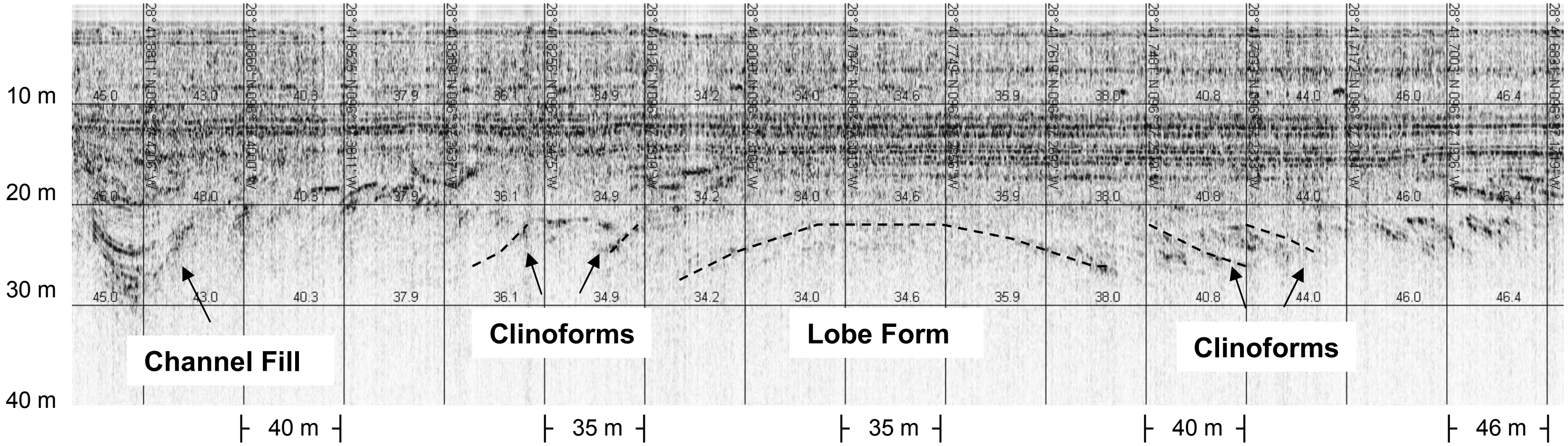

Figure 29. Subbottom profile showing cross section features of a delta lobe near Garcitas Creek.

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