Report to the Texas Coastal Coordination Council: CMP Cycle 14 Final Report: Mapping and Coring of the Inner shelf of Galveston Island-post Hurricane Ike

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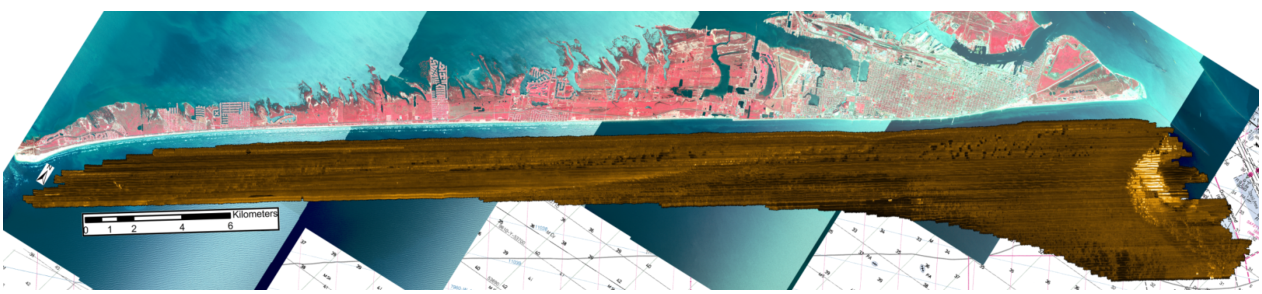

A REPORT OF THE COASTAL COORDINATION COUNCIL PURSUANT TO THE NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION AWARD No. NA09NOS4190165

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Contents

1.0 INTRODUCTION

The seabed of the inner shelf of Galveston Island was mapped through a series of CMP projects (Cycles 5, 6, 9, and 10), all conducted prior to Hurricane Ike. Hurricane Ike struck Galveston Island as a Category 2 storm based on wind velocities and a Category 4 storm based on storm surge. The eye of the storm passed directly over the eastern half of the island with a storm surge as high as 14 feet on the eastern end of the island and 8 feet on the western end. The study reported here was funded to investigate the impact of the seabed off of Galveston Island due to Hurricane Ike. To conduct this study, a series of geophysical cruises were conducted (September 25th-29th 2010 and December 15th -19th 2010), where the seabed was imaged using a Benthos C3D bathymetric side scan (purchased from CMP Cycle 12 funds) and CHIRP seismics. In addition, through supplemental CMP funding, a series of 23 submersible vibra cores and 15 grab samples were collected. In addition to the geophysical mapping, a series of beach profiles were collected the week prior to Hurricane Ike and the week immediately after Hurricane Ike to assess changes to beach profiles due to the storm. During the course of the geophysical survey, a series of offshore bars were identified which had not been seen in the previous surveys. Supplemental CMP funding was acquired to sample these bars and also the area between the bars to assess sediment changes on the seabed across the study site. In addition to the ability to document the extent of erosion due to Hurricane Ike, this project also added to our overall understanding of the morphodynamics of Galveston Island.

2.0 Background

2.1 Geologic Setting

Galveston Island is a barrier island situated on the southeast Texas Quaternary coastal plain, approximately 80 km southeast of Houston (GIARDINO et al., 2000). It is part of an almost continuous barrier island chain that runs down the Northwestern coast of the Gulf of Mexico (GIARDINO et al., 2000). Galveston Island extends over 40 km from the Bolivar Roads mouth of Galveston Bay to San Luis Pass. It began formation during the Holocene low stand of sea level over 6,000 years ago as a sand bar (COLE and ANDERSON, 1982). Overtime the island accreted both seaward and southwestward and formed the modern island. For most of its history, the Galveston barrier island system was prograding seaward, however, over the past 50 years, it has been in a state of retreat, moving landward at an average rate of 3 m/y (ANDERSON, 2002; SIRIGAN and ANDERSON, 1994).

The retreat of the island in the early 1900's has been influenced by several anthropogenic obstructions and physical processes, including: the damming of the Trinity and Brazos rivers, construction of the Galveston seawall system and the dredging of the Houston Ship Channel. These have all altered sediment dispersal patterns and reduced the sediment supply to the island (HAYES, 1967).

The Galveston Island South Jetty is a 7.6 km long and was constructed at the eastern end of the island at Bolivar Roads inlet in the late 1800's. The South Jetty and its counter -part, the 10.6 km North Jetty on Bolivar Peninsula has caused a large accretion of sand on the eastern end of the island. After the devastating effects of the Hurricane of 1900, which killed over 6,000 residents of Galveston Island, the Army Corps of Engineers constructed a 16 km long Seawall and groin system. These have further contributed to the alteration of sediment supply by causing a system of erosion and accretion, and an overall sediment deficiency in the region.

Sediment supply in this region of the Gulf of Mexico is also influenced by hurricanes. These short term, high-energy events affect the Texas shoreline on average every 1.5 years, and a storm that causes substantial erosion to this area occurs about every six years (SIRINGAN and ANDERSON, 1994). Galveston typically has southeasterly winds in the summer months and short periods of northerly winds in the winter (WHITE et al., 1985). Average significant wave size and tidal range are 2.1 m and 45-50 cm, respectively, however during hurricanes wind direction changes and wave heights can reach wave height of up to 7 m (RODREGUIEZ and ANDERSON, 1999).

In other coastal settings such as North and South Carolina, it is not only the sediment supply, sea level rise, short and long term events that are the major factors influencing barrier island morphology, but the geological framework as well (HARRIS et al., 1995; RIGGS et al., 1995). In North Carolina, Riggs et al. showed that the barrier island features were controlled by the Pleistocene, Tertiary and Cretaceous sediments upon which the barrier island system was perched (RIGGS, et al., 1995). They divided the system into two distinct regions, which controlled various aspects of the modern shoreface. The modern shoreface north of Cape

Lookout is composed of a sequence that filled the depositional basin, while the shoreface south of Cape Lookout was composed of antecedent units that crop out along the shelf, with only a thin veneer of modern sediment (RIGGS, et al., 1995). The antecedent sequences are cut by an old drainage system (RIGGS, et al., 1995). This created fluvial valleys filled with modern sediment, which are separated from the antecedent outcropping units (RIGGS, et al. 1995). These two distinct regions create nonheadland and headland systems, which influence composition of sediments on the beach, shoreline retreat rates, and the morphology of the barrier island (RIGGS, et al., 1995). In South Carolina, at Folly and Kiawah Islands, Harris et al. (2005) conducted a study to define the influences of geologic framework on evolution of the coastal zone. They concluded that out of the five geologic regions identified by seismic studies, three units directly influence the barrier island evolution by controlling the stratigraphic highs and lows of the system (HARRIS et al., 2005). Furthermore, it was stated that the magnitude of influence depends on the depth and competence of the antecedent geologic unit.

In the Galveston area, several studies have been conducted to establish the basic geology offshore of the region (Figure 1). According to Rodriguez et al. (2001), the geology of the inner shelf of the east Texas coast is composed of three distinct sedimentary facies progressing offshore: the Upper, Proximal Lower, and the Distal Lower Shoreface. The Upper Shoreface consists of 80 to 100% fine to very fine sands and extends approximately 1.5 to 2 km offshore (RODERIGUEZ et al., 2001; SIRINGAN and ANDERSON, 1994; ROBB et al., 2003). Surface sediments in this region have a modal size of 3 to 3.25 phi (RODRIGUEZ et al., 2001) The Proximal Lower Shoreface is composed of very fine sands and medium to thickly interbedded mud layers (10-50 cm), with a silt and clay content ranging from less than 30% to over 60% at the central portions of the island (RODRIGUEZ et al., 2001). The Distal Lower Shoreface contains predominately muddy sediment and thin to medium bedded sand layers (3-20 cm) with 55 to 75% silt and clay content (RODRIGUEZ et al., 2001; SIRINGAN and ANDERSON, 1994). Sands within the Proximal and Distal Lower Shoreface have a modal size of 2.5 to 3.0 phi. More recently Robb et al., (2003) have identified a fourth geologic facies offshore of Galveston Island; a Modern Mud Unit. The Modern Mud Unit incises antecedent shoreface units and contains at least 60% silt and clay (ROBB, et al., 2003; Figure 1).

Radioisotope age dating was conducted by Robb et al. (2003) using ^{137}Cs and 210Pb to establish a geochronology at a study site offshore of the Galveston Island between 25th and 68th streets (East End) and offshore of Pirates Beach (West End). The base of the Modern Mud Layer dates to 2660 ybp and the most recent mud layer has formed in the last 22 and 57 years (ROBB et al., 2003).

At the base of the modern stratigraphic sequence lies the Pleistocene aged Beaumont Clay (BC) (SIRINGAN & ANDERSON, 1994; Figure 1). It was formed during the Pleistocene highstand of sea level as clays and silts were deposited from the Trinity and Brazos rivers far from shore. Over time, sea level fell as the Wisconsin Ice age began. During this time, the rivers formed large deltas that cut into the BC unit and extended through our study area and to the southeast (COLE and ANDERSON, 1982; BLUM and PRICE, 1998). The resulting valley fill and alluvial plain formation provided the sands from which the formation of Galveston Island began (COLE and ANDERSON, 1982).

During the Wisconsin transgression, sea level rose, the regional sand bodies were transported landward, and Galveston Island began to emerge. Since the BC has a shear strength of 1 kg/cm^2, it has a high resistance to erosion, and served as a base upon which the modern island lies.

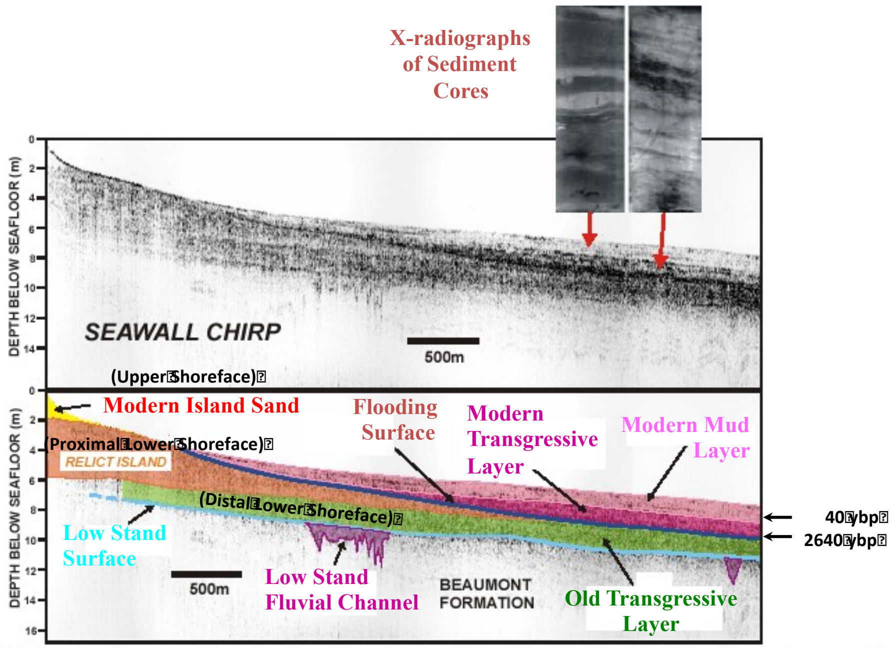


FIGURE 1: Geology of the Shoreface and inner continental shelf off of Galveston Island originally developed for CMP Cycle 5 data and published in Robb et al. (2003)

The upper BC boundary is marked by a sharp increase in shear strength and a transition to mottled orange and green clay and often the presence of calcareous nodules is observed (BERNARD, 1959). This Pleistocene sequence lies deeper towards the eastern end of the island near the ancestral incised Trinity River valley and becomes shallower towards the western portion of the island. (WHITE et al., 1985; BERNARD et al., 1970). This westward shallowing of the hard, consolidated, indurated BC corresponds with the thickness of overlying sand and mud, resulting in the thinning of the Holocene sediment towards the western end of Galveston Island. As expected, the amount of sand also decreases with the distance offshore towards the island's sand toe; which, on the western end of the island pinches out at approximately 1.5 km offshore (ROBB et al., 2003; FIGURE 1).

The seaward extent of the island toe is also the depth of closure (RODRIGUEZ, et al., 1999; SWIFT, et al., 1985). The depth of closure is the depth below the wave base, where the waves will actively be stirring the sediment. It is here that there is a change from sand dominated to a mud dominated sediment regime. Consequently, there is also a change in slope at this point, since coarser sediment will form a steeper slope while finer sediment will create a shallower slope.

Studies quantifying beach erosion rates on Galveston Island have been conducted by Morton (1985) and more recently by Gibeaut (2006). Long-term beach erosion has occurred on the West End of the island. Rates were up to 4 m/y from just west of the end of the Galveston Seawall to Bermuda Beach (MORTON and PAINE, 1985; GIBEAUT, 2006). Erosion is significantly enhanced after hurricanes, increasing rates to 6 m/y just past the end of the Seawall and towards the western most end of the island. (MORTON and PAINE, 1985).

2.2 Study Site

This study focuses on the nearshore region of Galveston Island from the South Jetty to San Louis Pass between the 3-10 meter isobaths which varies in the range of 4-6 km offshore of Galveston Island (FIGURE 2). To determine the location, volume, and characteristics of the sediments the study implemented side scan sonar, swath bathymetry, and both gravity and submersible vibra-coring. In addition to this study others have been conducted in the same region with less coverage the most recent of which was CMP Cycle 10 which this study uses as a comparison to Identify changes in the offshore sediments (FIGURE 3). The offshore geology has been well established both in previous CMP studies as well as other scientists such as Anderson 2007 and Rodriguez et al. 1999; the focus for this study was on upper range of sediments especially those which potentially could be recently deposited during large storm events.

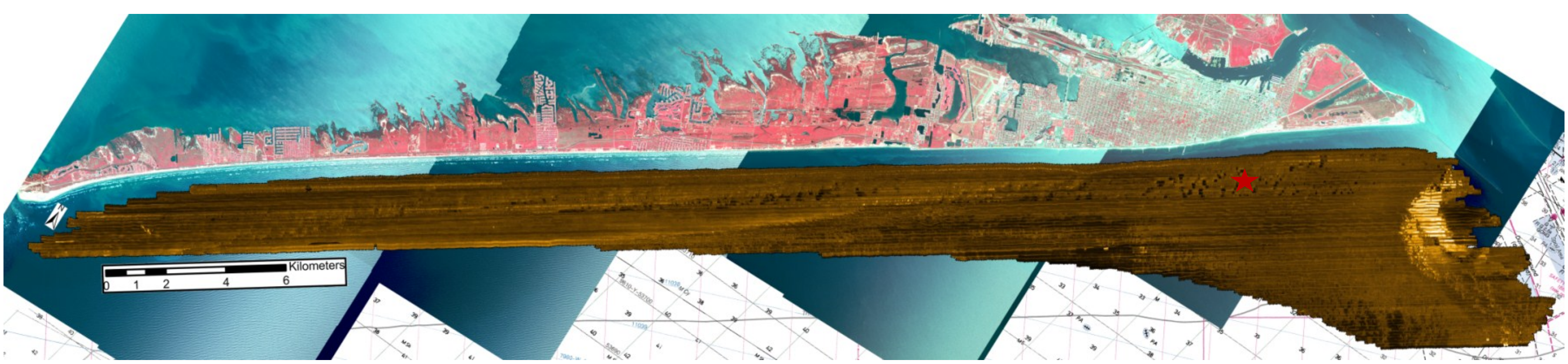


FIGURE 2: Side Scan Sonar Map of the study site along Galveston Island Texas

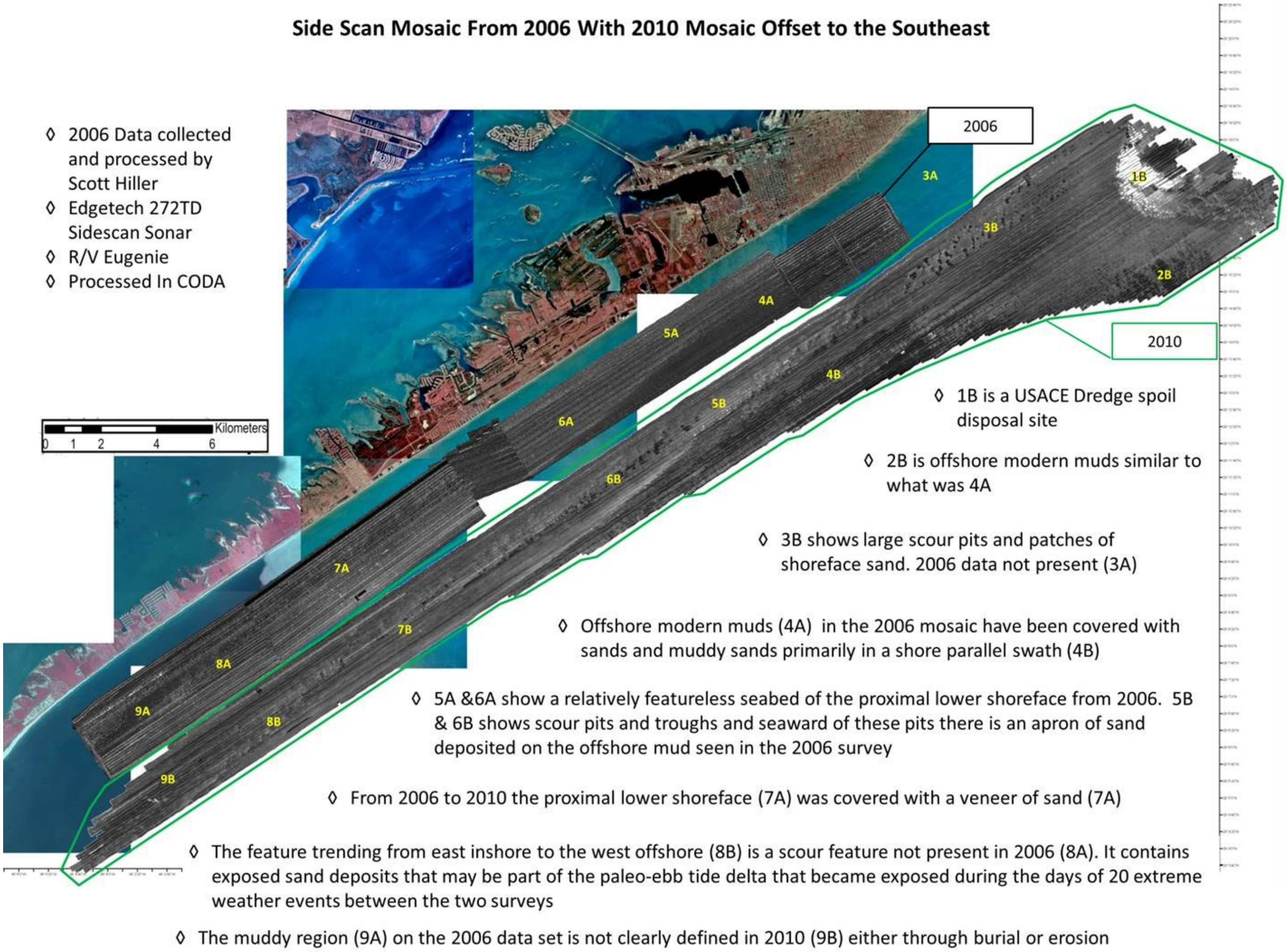


FIGURE 3: Offset comparison of the CMP Cycle 10 survey in true location and CMP Cycle14 survey offset to the Southeast by 4km. Annotations mark the same location between the two surveys

2.3 Hurricane Ike

2.3.1 General Storm Details

Hurricane Ike made landfall on the upper Texas coast on September 13 at 2:10 am CTD (07:10 UTC) as a very intense Category 2 (Saffir-Simpson Hurricane Scale) with winds of 175 km/h (110 mph) and a central pressure of 952 mbar (Wikipedia.com, 2008). According to a National Hurricane Center (NHC) advisory, at 2:00am CTD, the hurricane winds extended 443 km (275 miles) across the storm path and 190 km (120 miles) along its path (FIGURE 4). At its peak, on September 5, Ike was a Category 4 hurricane with maximum sustained winds of 230 km/hr (145 mph) and a pressure of 935 mbar, making it the most intense storm in the 2008 Atlantic Hurricane season. Hurricane Ike is also estimated to have been the third most costly storm in US history, with estimated damages of $27 billion and a loss of US lives estimated to be 82 dead and 202 missing (Wikipedia.com, 2008).

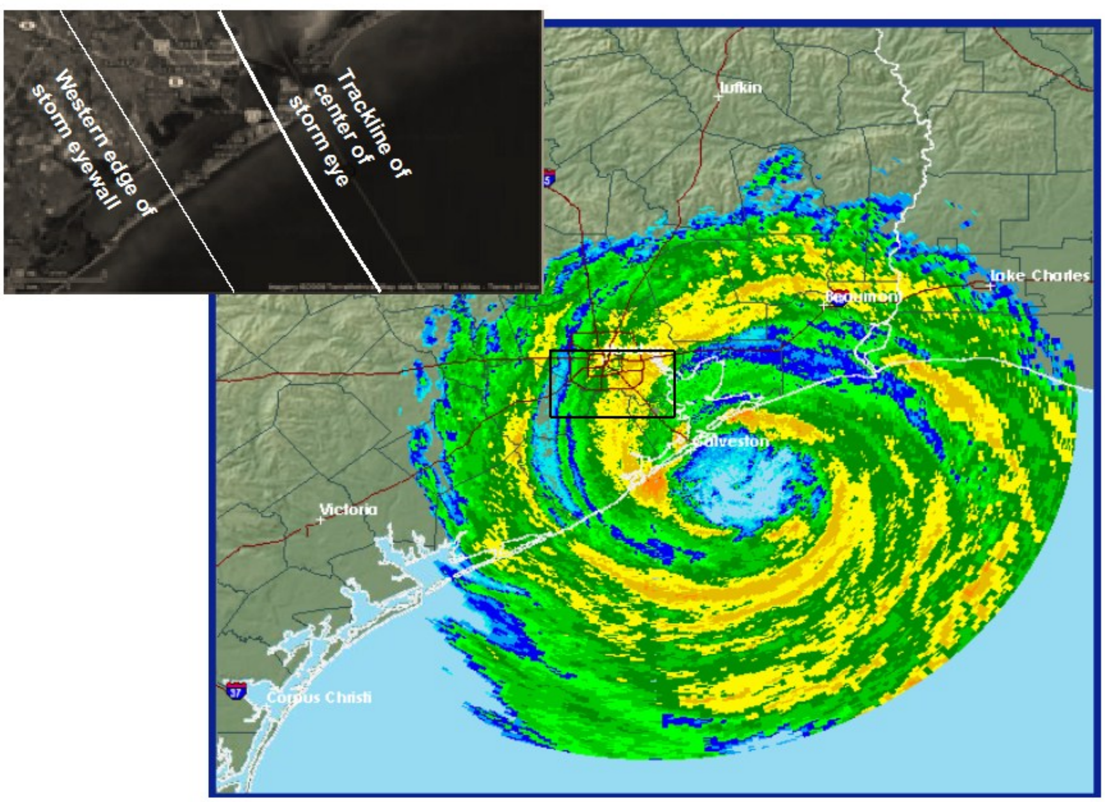
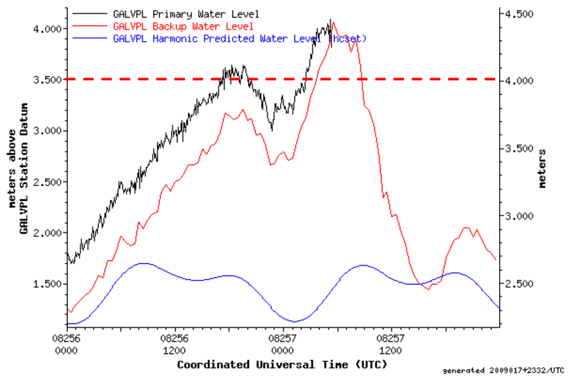


Figure 4. A) Hurricane Ike shortly before landfall, Houston/Galveston Radar, September 13, 1:07am (http://en.wikipedia.org/wiki/Hurricane_Ike). B) Map showing location of the trackline of the center of the storm eye and the western edge of the storm eyewall overlayed on a Google Earth® image of Galveston Island and the neighboring coast (http://earth.google.com).

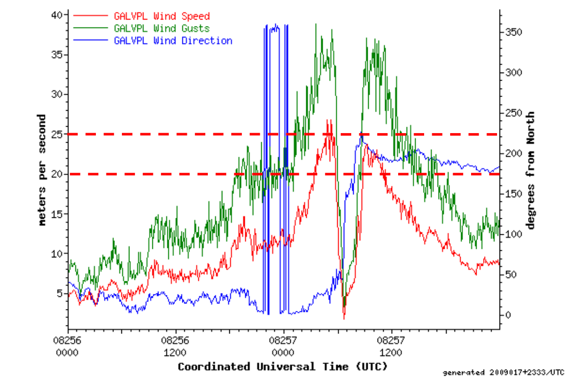
2.3.2 Specific Storm Details as related to Galveston Island

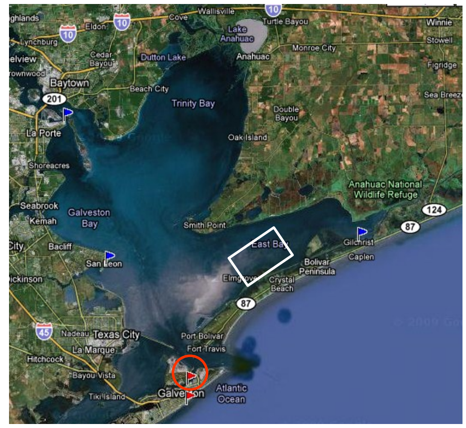
Galveston Island has a 16 km (10 mile) long seawall, 5.2 m (17 feet) high that was constructed after the devastating 1900 Hurricane that destroyed much of the City of Galveston. Along with the construction of the seawall, much of the city was raised, with the area proximal to the seawall having the same elevation (5.2 m) and sloping towards the bay to reach a less than a meter above sea level. The 29.5 km (18.25 miles) of island west of the seawall is referred to as the Westend and is not protected by the seawall. The storm surge from Hurricane Ike rose to approximately 4 m over the course of approximately 33 hours prior to making landfall (FIGURE 5), with winds primarily out of the south. The storm surge rose from both the bay and Gulf sides of the island. Although heavily pounded by waves, the storm surge never reached above the seawall. For the over 10 hours prior to the storms landfall, the storm surge was higher than 3.5 m and winds were in excess of 20 m/s (40 mph). As the eye of the storm passed, the wind velocity dropped from over 40 m/s to 2 m/s and rotated 180^{o} so that it was out of the north. The passage of the backside of the eyewall explosively hit with gusts as high as 40 m/s for nearly 4 hours and maintained gusts in excess of 25 m/s for an additional 8 hours (FIGURE 5). The bayside of the island is far less protected than the Gulf side of Galveston Island. There are extensive older water front neighborhoods with bulkheaded canals and a few with natural wetland interfaces. The explosive surge of the backside of the storm resulted in entire bay front neighborhoods and business being completely destroyed. In addition, the storm surge ripped through much of the interior of Galveston Island from the bayside to the Gulf side. Much of the storm surge receded very rapidly. FIGURE 6 is an infrared LandSat image with storm surge values posted on it. Note that the area in red is the area where the vegetation is dead, indicating inundation from seawater, and extends nearly 10 km into the mainland directly across from much of Galveston Island. Also note that all of the Westend was flooded as was much of the City of Galveston.

Galveston Island Pier 21- TCOONS Station- Water Levels and Harmonic Predicted Water Level (tide)- Sept. 12-13, 2008



Galveston Island Pier 21- TCOONS Station- Wind Speed, Gusts and Direction-Sept. 12-13, 2008



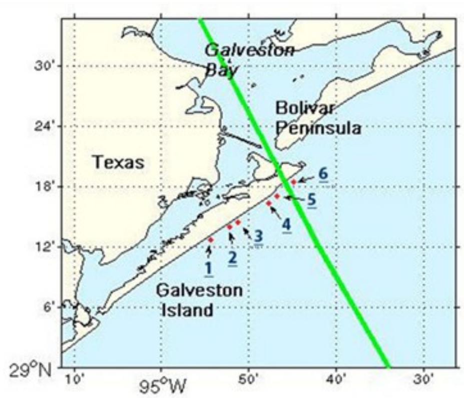


Data obtained from the Texas Coastal Ocean Observation Network, Division of Nearshore Research, Conrad Blucher Institute for Surveying and Science, Texas A&M University-Corpus Christi.

Figure 5. TCOONS water level and meteorological data from the Galveston Island Pier 21 Tidal station showing the Hurricane Ike conditions before, during and after the passage of the eye of the storm.

Figure 6. The yellow line delineates the approximate landward extent of dead vegetation as a result of Ike surge inundation (Courtesy of the U.S. Army Corps of Engineers)

FIGURES 7-10 are from the USGS showing the impact of select sections of the beach with oblique aerial photographs from pre- and post-Ike, showing the impact at each site. Included is also an inset map showing the location of each photoset. During the week prior to Hurricane Ike making landfall, Robert Webster, with the TAMUG Coastal Geology Laboratory conducted a series of beach profiles from the back of the dune to wading depth to establish base-line pre-storm conditions. Within a week of the storm making landfall, he repeated these profiles. FIGURE 11 contains a summary of his results (unpublished), showing both horizontal distance the tow of the beach moved (landward) and the vertical change (loss of elevation) of the beach across the transect. As FIGURE 11 shows, in general, both the vertical and horizontal changes decrease to the west



http://www.srh.noaa.gov/hgx/projects/ike08/images/galveston_westend1/IMG_9269.JPG

http://coastal.er.usgs.gov/hurricanes/ike/photo-comparisons/galveston.html

FIGURE 7
Location 1: Oblique aerial photography of Galveston, TX, on September 9, 2008 (top) and September 15, 2008, two days after landfall of Hurricane Ike (bottom). Yellow arrows mark features that appear in each image. Evidence of inundation here includes eroded beach face, sand deposited inland of the shoreline, and distressed vegetation. However, the coastal-change impacts were less severe here than on the Bolivar Peninsula, located northeast of landfall. [larger version]

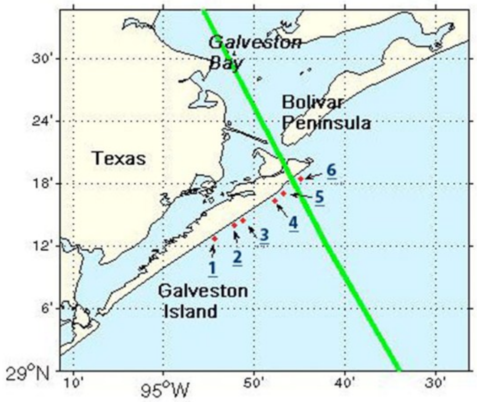
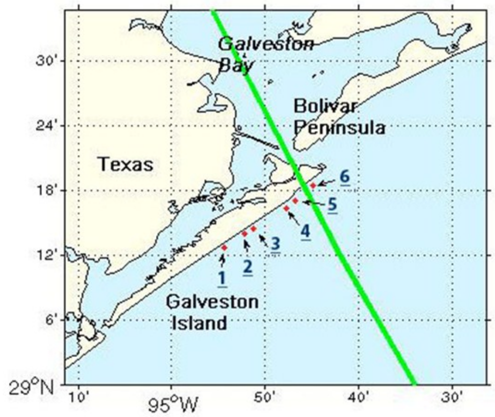


FIGURE 8

Location 2: Oblique aerial photography of Galveston, TX, on September 9, 2008 (top) and September 15, 2008, two days after landfall of Hurricane Ike (bottom). Yellow arrows mark features that appear in each image. Hurricane impacts include the breaching of a narrow spit and erosion of the Gulf-front beach.

http://coastal.er.usgs.gov/hurricanes/ike/photo-comparisons/galveston.html



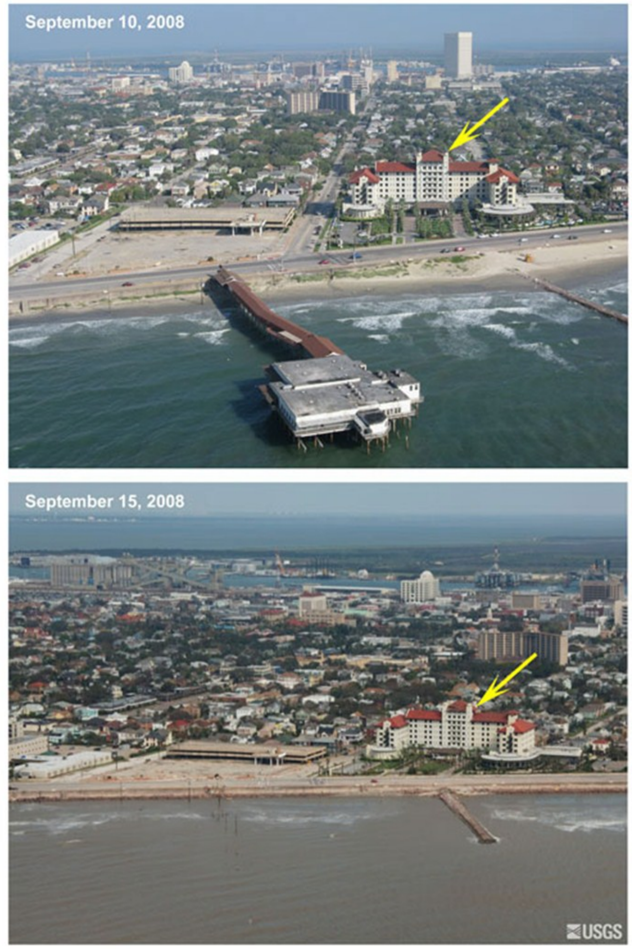


FIGURE 9

Location 5: Oblique aerial photography of Galveston, TX, on September 9, 2008 (top) and September 15, 2008, two days after landfall of Hurricane Ike (bottom). Yellow arrows mark features that appear in each image. Hurricane-induced waves and surge destroyed the historic Balinese Room and pier, and eroded adjacent beaches.

http://coastal.er.usgs.gov/hurricanes/ike/photo-comparisons/galveston.html

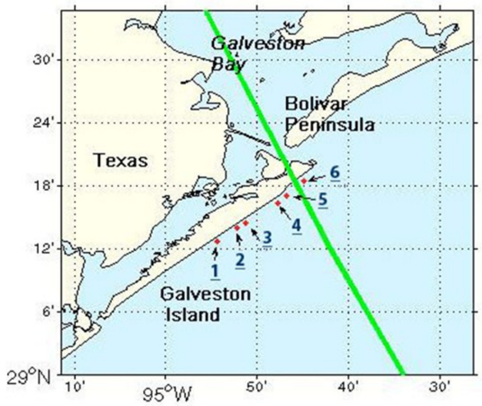


FIGURE 10

Location 6: Oblique aerial photography of Galveston, TX, on September 9, 2008 (top) and September 15, 2008, two days after landfall of Hurricane Ike (bottom). Yellow arrows mark features that appear in each image. Hurricane-induced waves and surge destroyed a small walkway. Coastal-change impacts include beach and dune erosion, and the removal of considerable dune vegetation. This location is on the right-hand side of the hurricane track and likely experienced the strongest winds, highest surge, and waves.

http://coastal.er.usgs.gov/hurricanes/ike/photo-comparisons/galveston.html

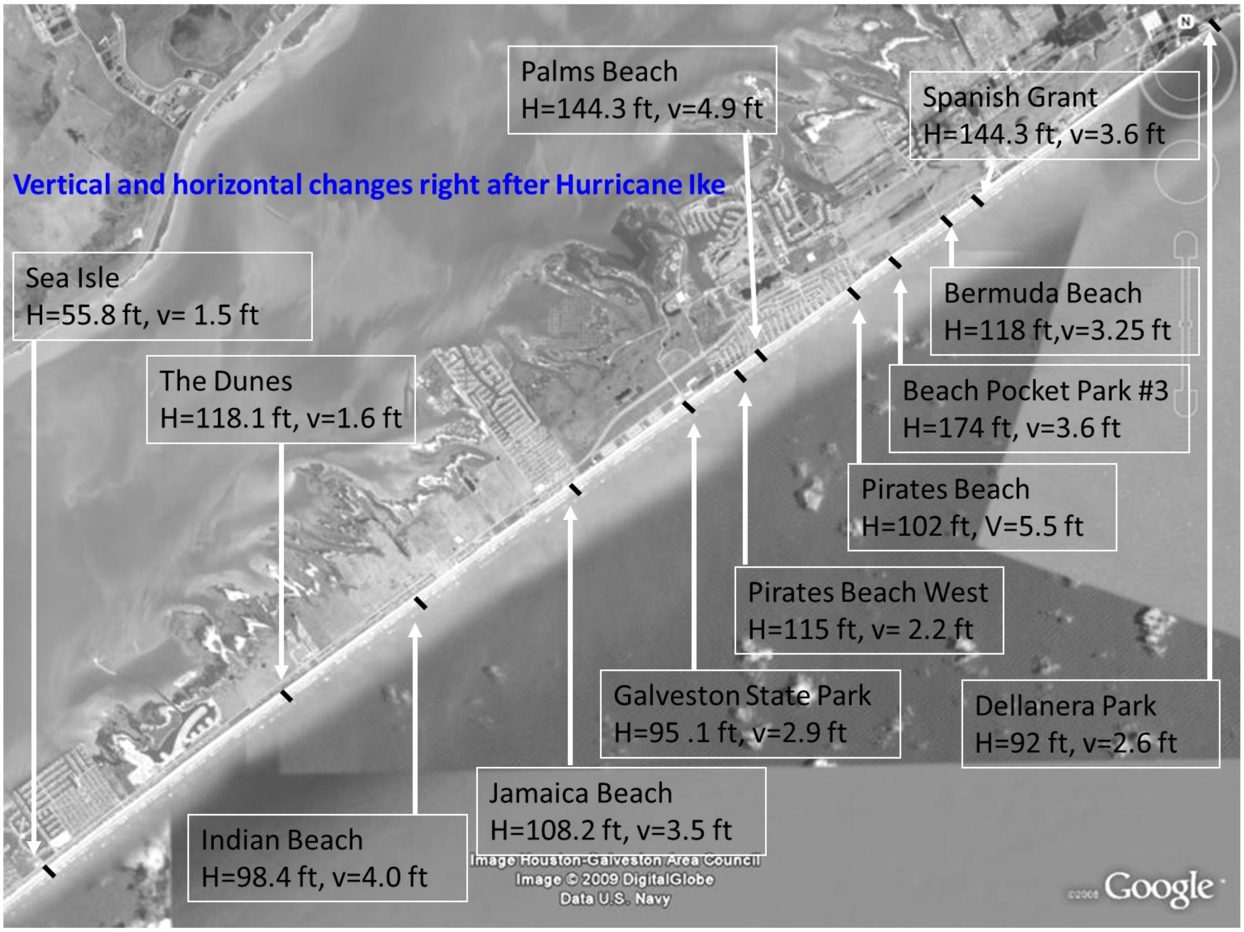


Figure 11. Comparisons of beach surveying profiles collected the week prior to and within one week after the landfall of Hurricane Ike (Sept. 13, 2008). Note, this is unpublished data courtesy of Robert Webster.

2.4 Post Hurricane Ike Beach and Bathymetric Profile Changes

During the week prior to Hurricane Ike Robert Webster, a technician affiliated with the TAMUG Coastal Geology Laboratory and TAMUG conducted a series of quick beach profiles along the beaches to the west of the Seawall (Galveston's Westend) to document the conditions of the beach immediately prior being hit by Hurricane Ike. He was able to return to Galveston the week immediate after Hurricane Ike and he resurveyed the same profiles. Figure (11) shows a summary of the data he collected, showing the horizontal retreat of the profiles as well as the average vertical difference (Unpublished data courtesy of Robert Webster). As the figure shows, in the eastern half of his study area, there was initially a 174 ft (53 m) retreat of the beach, with up to 5.5 ft (1.7 m) vertical change. Not that the changes decrease to the west past the western end of the extent of the western eyewall of the storm.

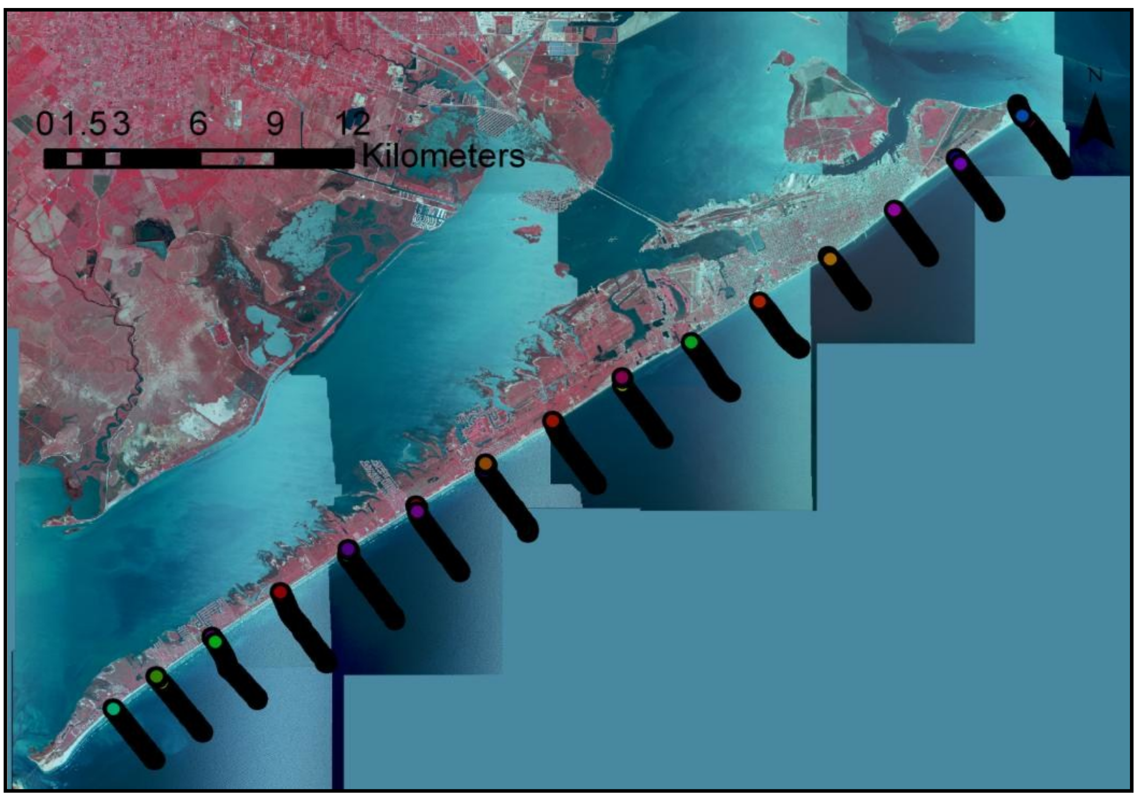
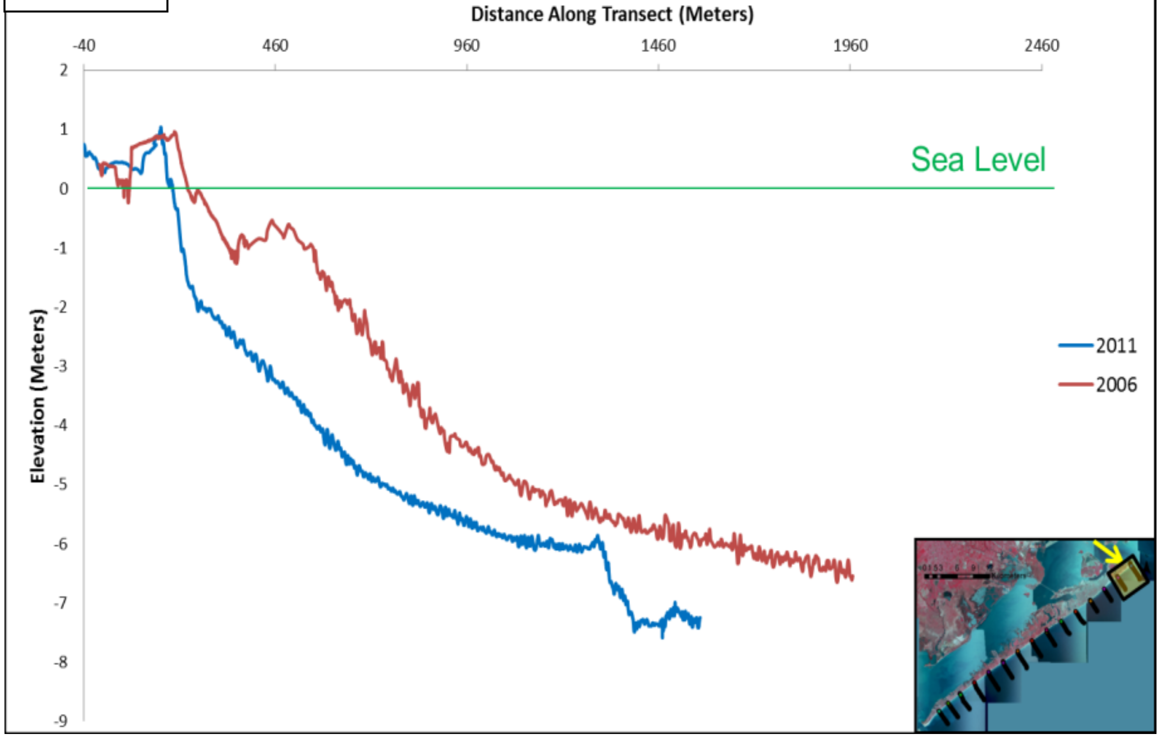


Figure 12. Location of profile transects on Galveston Island. Each transect is spaced 3.2 km (2 miles) apart.

During the summer of 2006 the TAMUG Coastal Geology Laboratory, with funding from CMP Cycle 10 conducted a series of beach profiles along the upper Texas coast, extending from the crest of the dune (or top of Seawall) to a distance of 3.2 km (2 miles) off shore. The survey extended from High Island to the northern Freeport Jetty, with each survey spaced 3.2 km (2 miles. During the summer of 2011 the Galveston Island profiles were re-surveyed to determine total change between 2006 and 2011 (Figure 12). Figure 13 shows an example of the comparisons between the 2006 and 2011 beach profiles. In an effort to determine total shore face volume changes between 2006 and 2011, maps were generated with extrapolations between survey lines and the 2011 surface was subtracted from the 2006 surface to show total change (Figure 14). It was estimated that there was a total volume loss between the 2006 and 2011 surfaces of 79 million m^3 (103 million cubic yards).

Figure 13



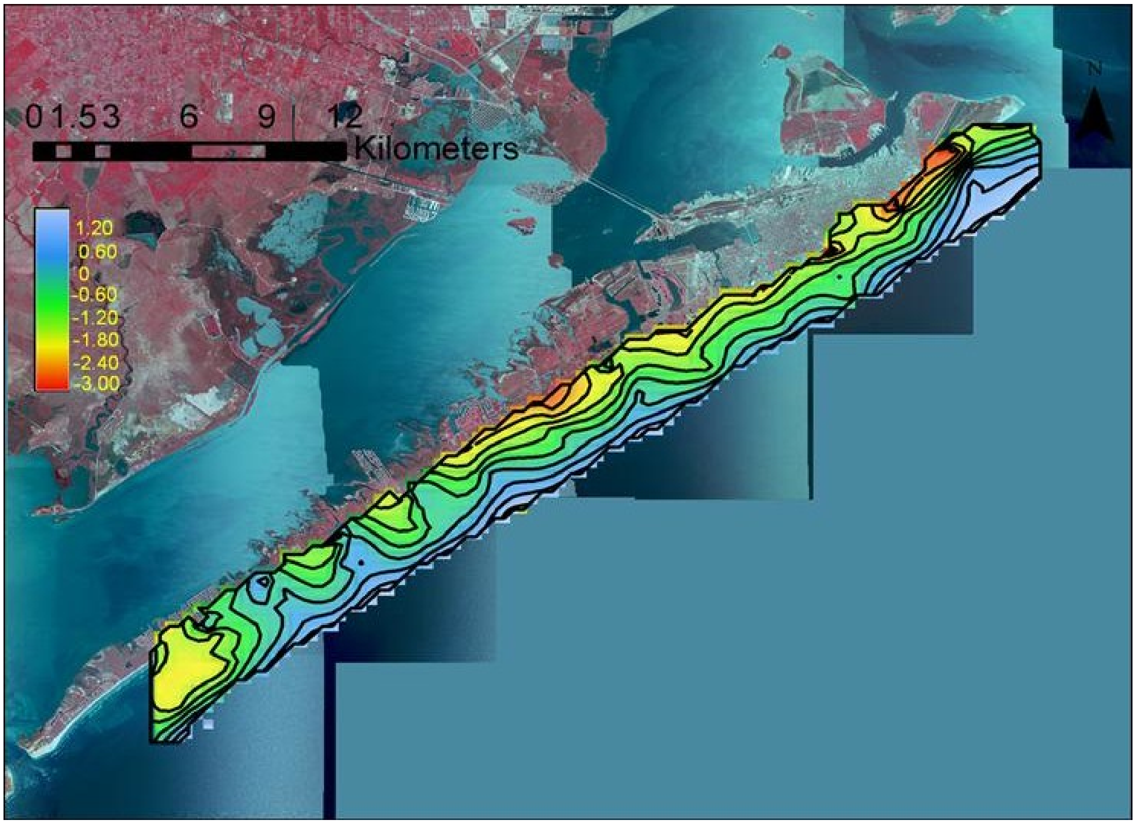


Figure 14. Elevation change between the summers of 2006 and 2011. Blue represents deposition little net change. Transition from green to yellow to red represents higher degrees of erosion.

3.0 Materials and Methods

3.1 Geophysical Surveys

3.1.1 Survey Design

The Galveston Shelf Survey, conducted in September and December of 2010, extended from near the Galveston Jetties in the east to near San Luis Pass in the west. The survey was conducted aboard the NOAA FGBNMS R/V Manta in water depths from the 3 m to 10 m isobath based on NOAA nautical charts. Survey lines were plotted parallel to the shore using Hypack® 2009a Coastal Oceanographic software. Lines spacing was 100 meters giving 200% coverage for the side scan data and approximately 60% coverage for the bathymetry data. The total length of the surveys was 1922 km (1194 miles). Survey data was collected in the WGS 1984 datum and projected into UTM Zone 15 North coordinates. The horizontal and vertical data are in meters. The bathymetric data was corrected to mean low water (MLW) using NOAA tide station 8771450 located on Pier 21 in Galveston, TX which is in the shipping channel on the bay side of the study site marked with a red star in FIGURE 2.

3.1.2 Data Collection

Side scan sonar (SSS) and bathymetric data were collected concurrently using a Teledyne Benthos® C3D-LPM High-Resolution Side-Scan Sonar Bathymetric System. This sonar utilizes two transducers operating at a frequency of 200 kHz coupled with a six hydrophone array receiver collect the SSS data, and bathymetric data is computed by the sonar using the computed Angle of Arrival Transient Imaging (CAATI) algorithm. The sonar was pole-mounted to the bow of the vessel, position of the vessel was determined using a Hemisphere® Vector differential GPS and ship motion data was determined using a SG Brown TSS® DMS3-05 motion reference unit to correct the bathymetric data collected. Periodic casts with an Odom® Sound Velocity Probe were conducted to collect sound velocity data throughout the water column to also correct bathymetric data. Sonar data was acquired using Hypack® Hysweep 2009a software.

3.1.3 Data Processing

Bathymetric data was processed using Hypack® Hysweep 2009a software, where tidal, ships motion, and sound velocity data were integrated to correct the raw bathymetric soundings. SSS data was processed using Chesapeake Sonar Wiz.Map® software to create and export SSS mosaics.

3.2 Sediment Data

3.2.1 Sediment Core Collection

Sediment cores were collected from both study areas in September of 2011 aboard the NOAA FGBNMS R/V Manta, 22 from the Galveston Shelf Study (FIGURE 2). The cores were 7.62 cm (3 in) in diameter and on average 1 m of sediment were recovered. These cores were collected using a pneumatic submersible vibra-core rig deployed off the stern of the vessel. Cores were stored upright and refrigerated until analyzed. Surface sediment grab samples were also collected from both study areas.

3.2.2 Sediment Analysis

Cores were cut lengthwise, photographed, and visual descriptions of the sediment lithology were recorded. One-half of the core was archived for future reference and one-half processed for water content and grain size analyses. Water content sample data will be used for ancillary analyses. This data is not provided in this report. Cores were sub-sampled for every lithological unit as determined by visual analysis in sections ranging from 1 – 5 cm thick depending on the unit for the length of the core, and placed into labeled whirl-pak bags until analyzed.

Sediments samples were analyzed in the lab for grain size distributions using a Malvern Mastersizer 2000® laser particle diffractometer. Sediment samples were homogenized, and an approximately 3-5 g aliquot was placed in a 100 ml glass jar. Ten milliliters of a 5.5-g/L sodium hexametaphosphate solution was added to the jar as a dispersant. The sediment with dispersant was sonicated for 30 min. at a temperature of approximately 25°C at a frequency of 40 kHz. After sonication, samples were wet-sieved through a 2 mm sieve into a 250 ml glass jar, and material larger than 2 mm was placed in a pre-weighed aluminum dish, dried for at least 24 hours, and then weighed. The sample slurry in the 250 ml glass jar was filled with de-ionized water to a volume of exactly 200 ml then placed on a stir plate. While the slurry was stirring, a representative 10 ml aliquot was removed by a pipette and placed in a pre-weighed aluminum dish and dried for at least 24 hours then weighed. After the 10 ml aliquot was removed, the slurry was pipetted into the Malvern Mastersizer 2000® until a pre-determined level of obscuration was reached. At this point the instrument made three measurements and averaged the three results. The instrument determined percent composition of sand, silt and clay of the samples, and from the 10 ml aliquot that was removed and the material excluded during the wet-sieving process the percentage of material greater than 2 mm was calculated. In total the fraction of gravel, sand silt and clay were determined for each sample, as well as the mean grain size of the sand fraction.

4.0 Results

4.1 Galveston Island Shelf Side Scan Sonar

The sides scan sonar shows several zones of unique backscatter characteristics. Darker zones are due to lower backscatter or more absorption of the signal where lighter toned areas are places with a higher backscatter or more reflection of the signal. The intensity of the backscatter in this survey was ground truthed using an average over the top 5 centimeters of sediment from each core site. The results of that ground truthing show that the areas of higher backscatter had higher sand content and lower return areas had lower percentages of sand. Using these interpretations, the surface expressions of the facies identified in Figure 1 were delineated, including the Modern Island, Proximal Lower shoreface, and Modern Offshore Mud Facies.

The East end of the survey proximal to the South Jetty of Bolivar Roads has the highest sand content in the surface sediment of the entire survey area (Red triangle in Figure 15). The bright patch on the sides scan is part of a bathymetric low. The surface sand percentage decreases with distance from this zone and is shown to be part of a thin (less than 5cm) veneer over the offshore modern muds identified by the CMP Cycle 10 study.

There is a long bright feature extending from the 3m isobath offshore from 61st street offshore in a southwesterly direction to beyond the survey depth at the "G" core transect (Offshore of Terramar). This feature is a sandbar identified in Figure 20 as numbers 1, 5, and 6 which contains a large amount of sand in the surface sediments and is not present in the CMP Cycle 10 survey (Figures 3 & 16).

To better visualize relative percentages of sand in the upper 5 centimeters the intensity of the return after ground truthing was assigned a range of sand percentages and then displayed in a false color map (Figure 15). Due to the range in percentages of sand found in the core samples and the correlating range of intensities the range for each color is large. This data is farther simplified in Figure 16 to show the regions of greater than 70% sand sized material in the top 5cm.

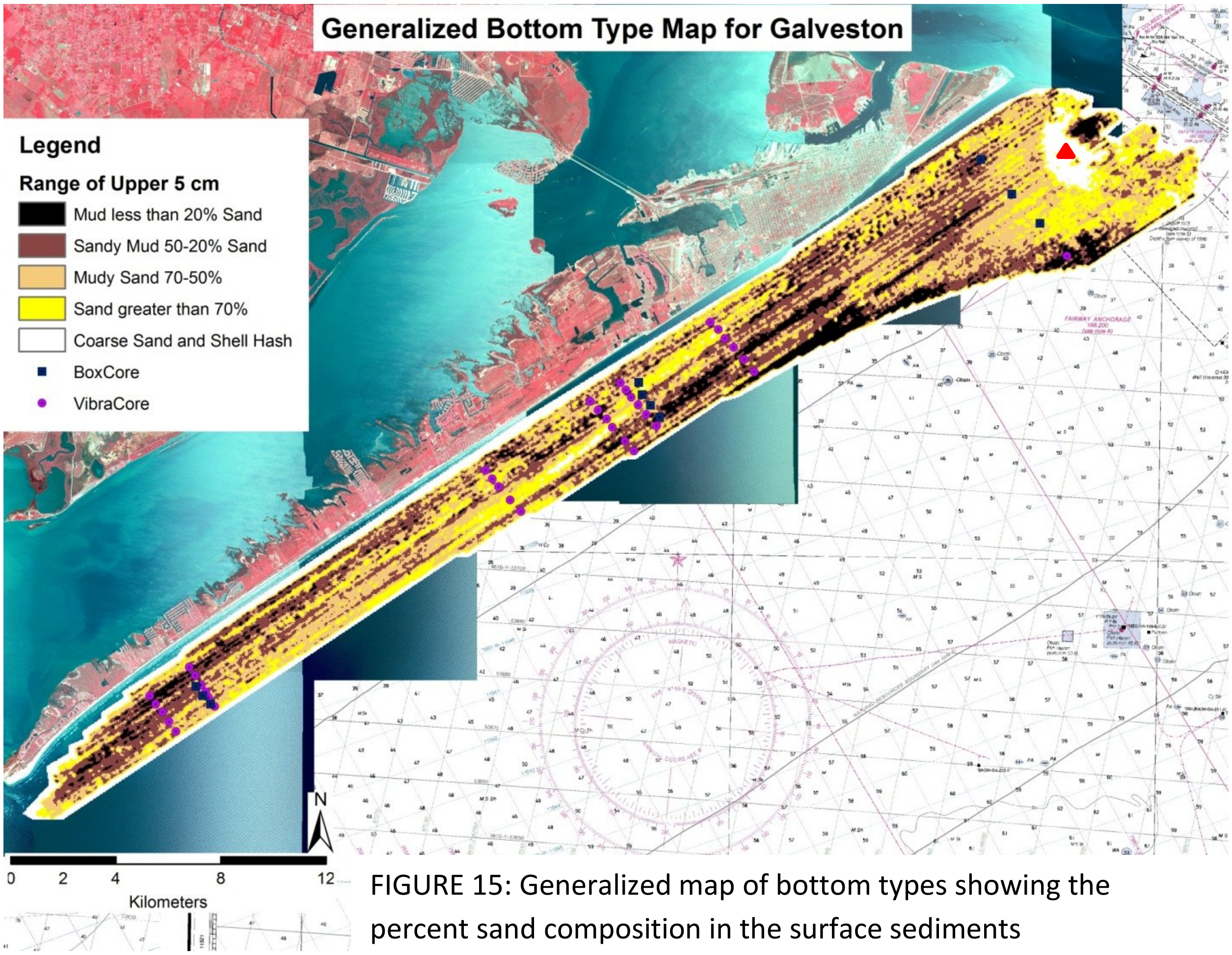


FIGURE 15: Generalized map of bottom types showing the percent sand composition in the surface sediments

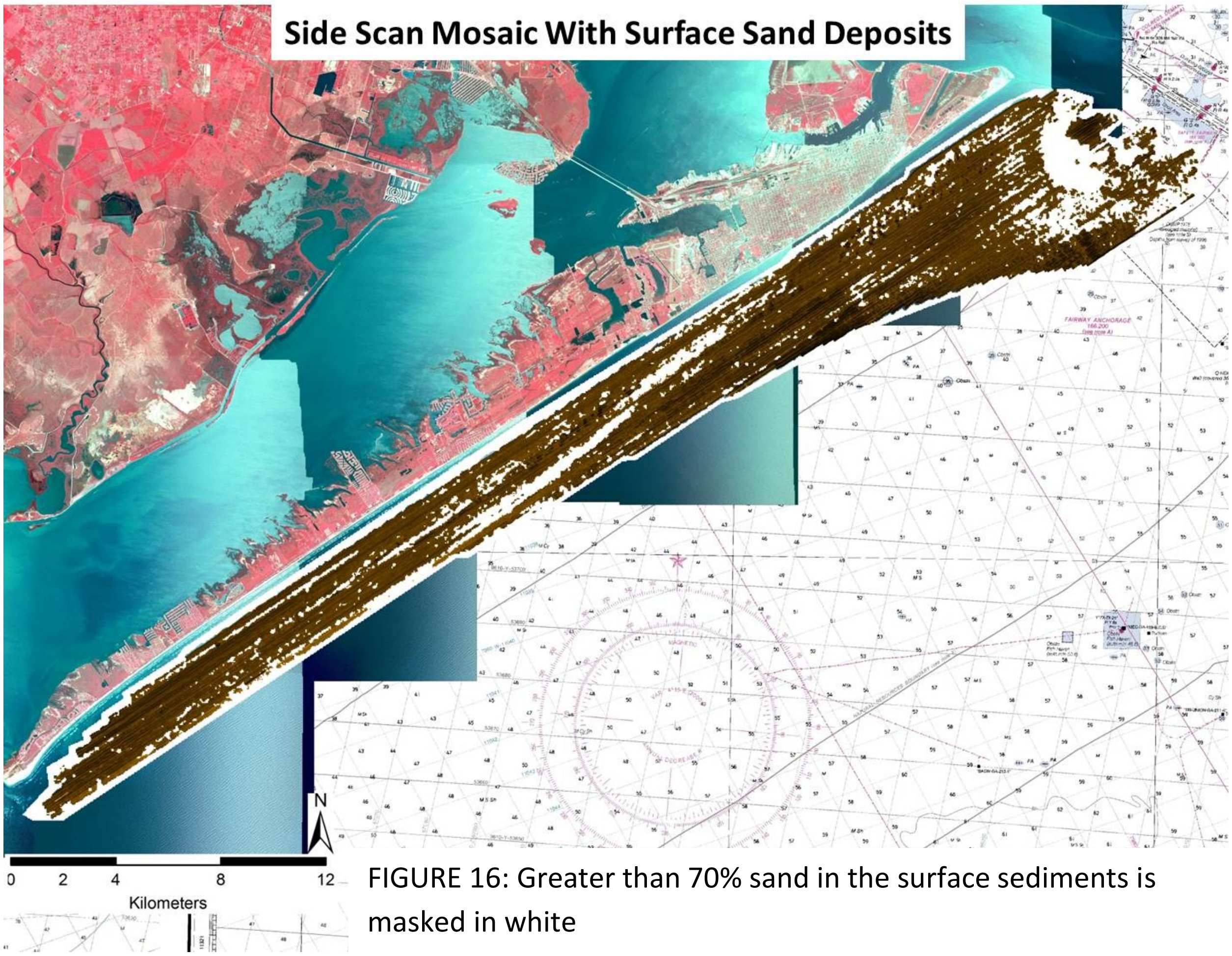


FIGURE 16: Greater than 70% sand in the surface sediments is masked in white

4.2 Sediment Analysis

In order to accurately visualize, analyze the study site, and produce estimates for sand volumes, cross-sectional profiles were generated (Figures 17-21). There is an individual profile for each core sample transit and the physical description of each core has an arrow indicating its respective location relative to the first core in each transit. The vertical scale on the left side of each figure shows the bathymetric depth in meters. The horizontal scale is the distance in meters to the first core in each profile.

The average slope for the profiles ranges from 0.012 for the GSE transect to 0.381 for the GSH transect (Figures 17 and 19). In general the slopes are shallow (0.012-0.077) in the middle section of the survey and increase to steeper angles at both the east and west ends (0.365). In addition to the general slope change the profiles have ridges and troughs which are part of a large set of sandbars troughs throughout the majority of the survey. These large scale sandbars represent almost 10% of the total surveys surface area. Using the bathymetric profiles, patterns in the side scan data, and the depth of sand for these features from the sediment cores surface sand volume estimates were generated for each distinct sandbar (Figure 22). The appendix contains the individual profiles with the depths of sand indicated on them along with the respective core descriptions.

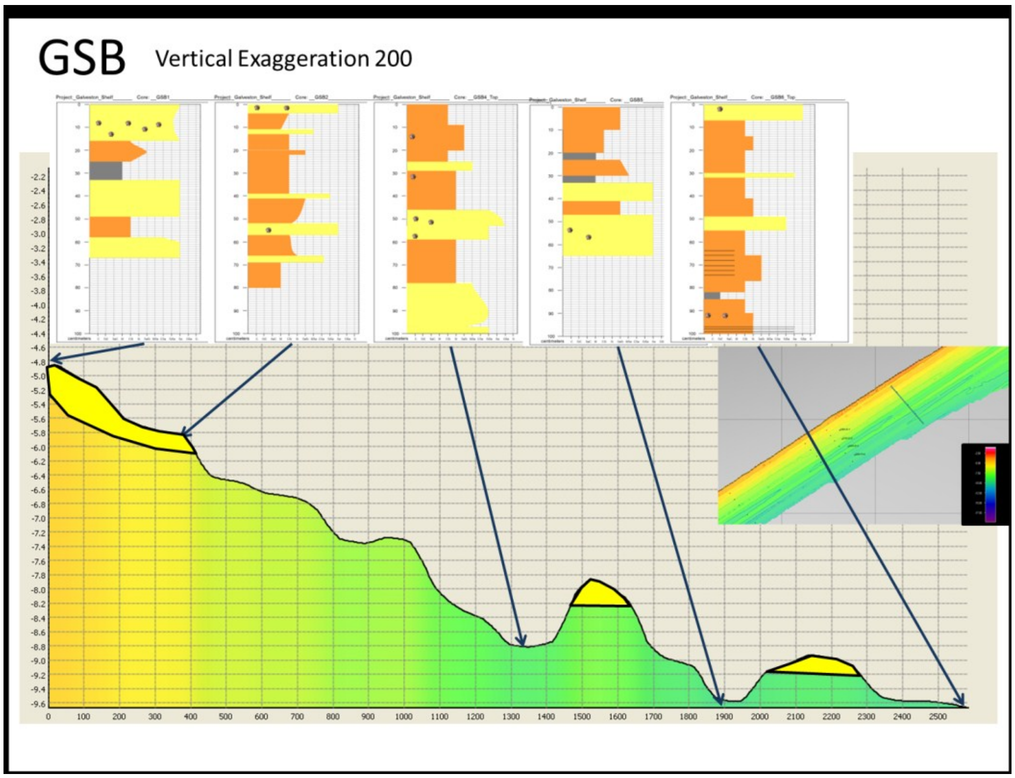


FIGURE 17: Cross-shelf profile with sand bars masked in yellow and arrows showing core locations

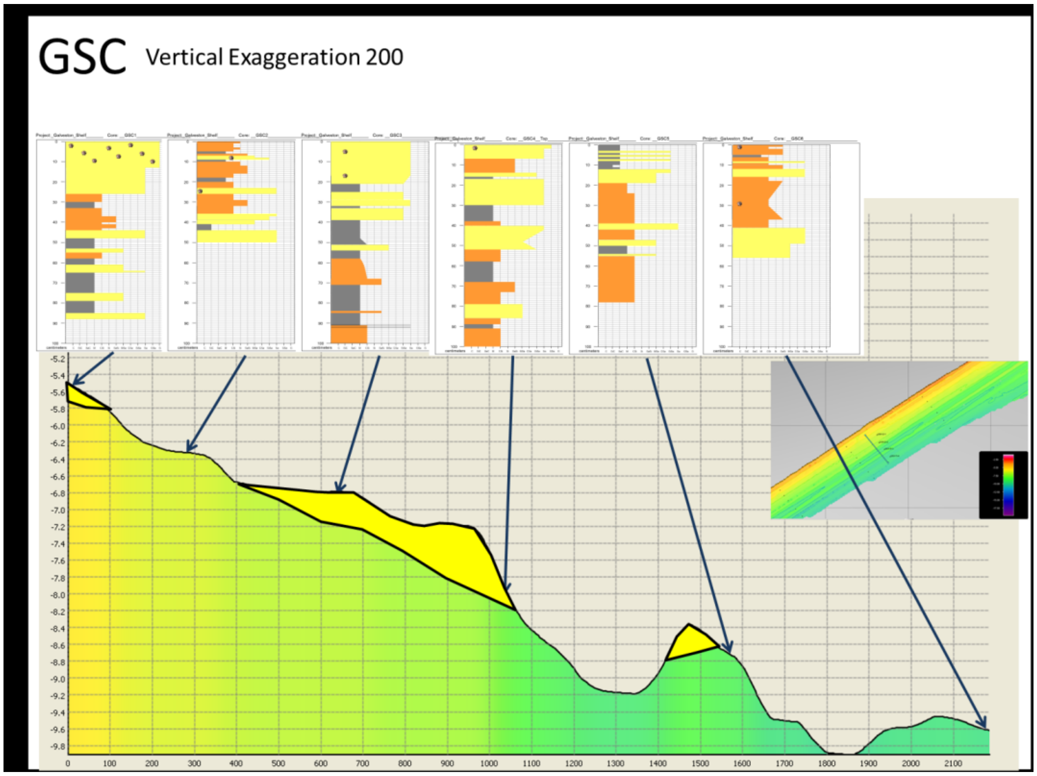


FIGURE 18: Cross-shelf profile with sand bars masked in yellow and arrows showing core locations

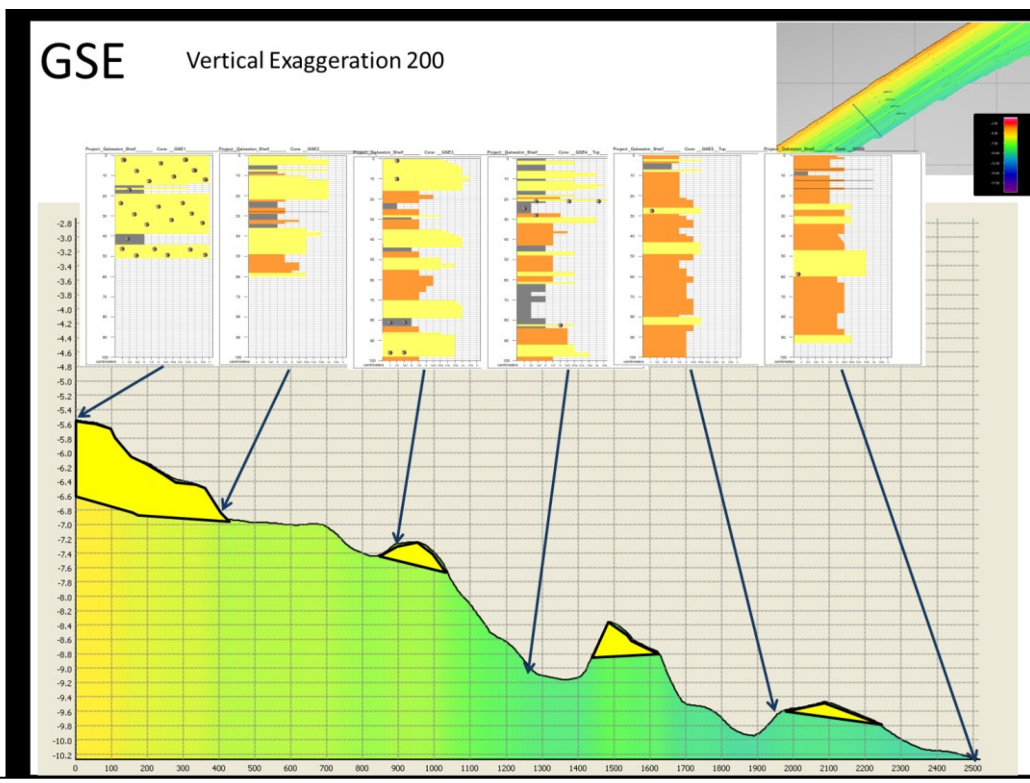


FIGURE 19: Cross-shelf profile with sand bars masked in yellow and arrows showing core locations

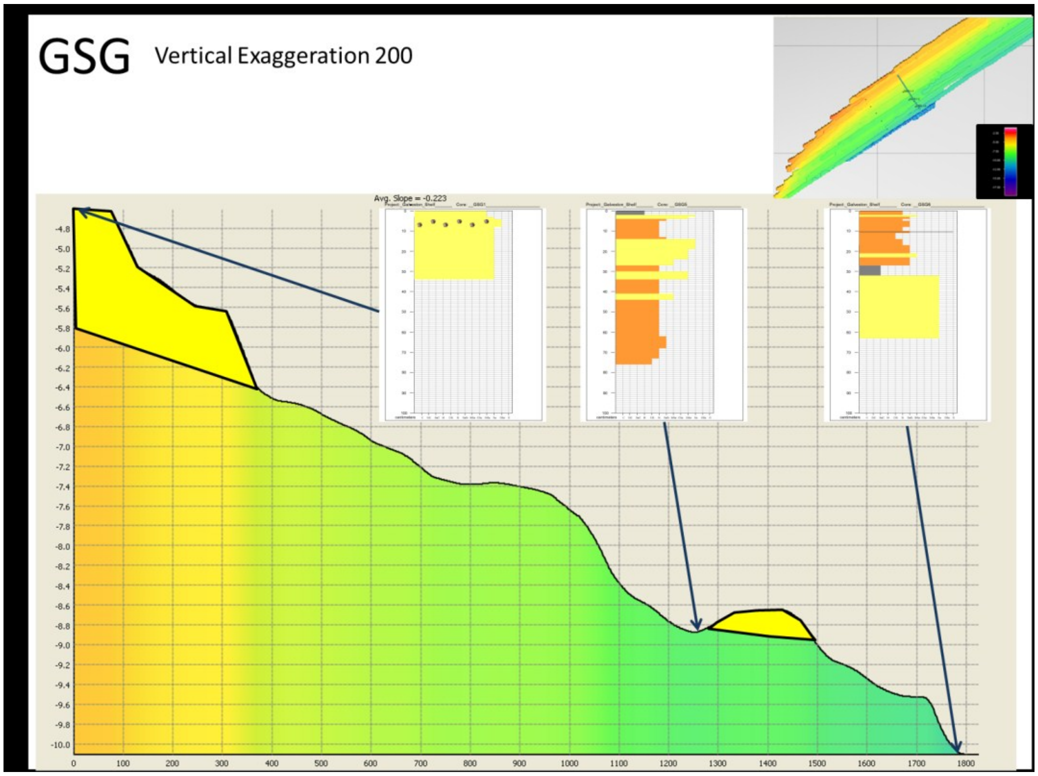


FIGURE 20: Cross-shelf profile with sand bars masked in yellow and arrows showing core locations

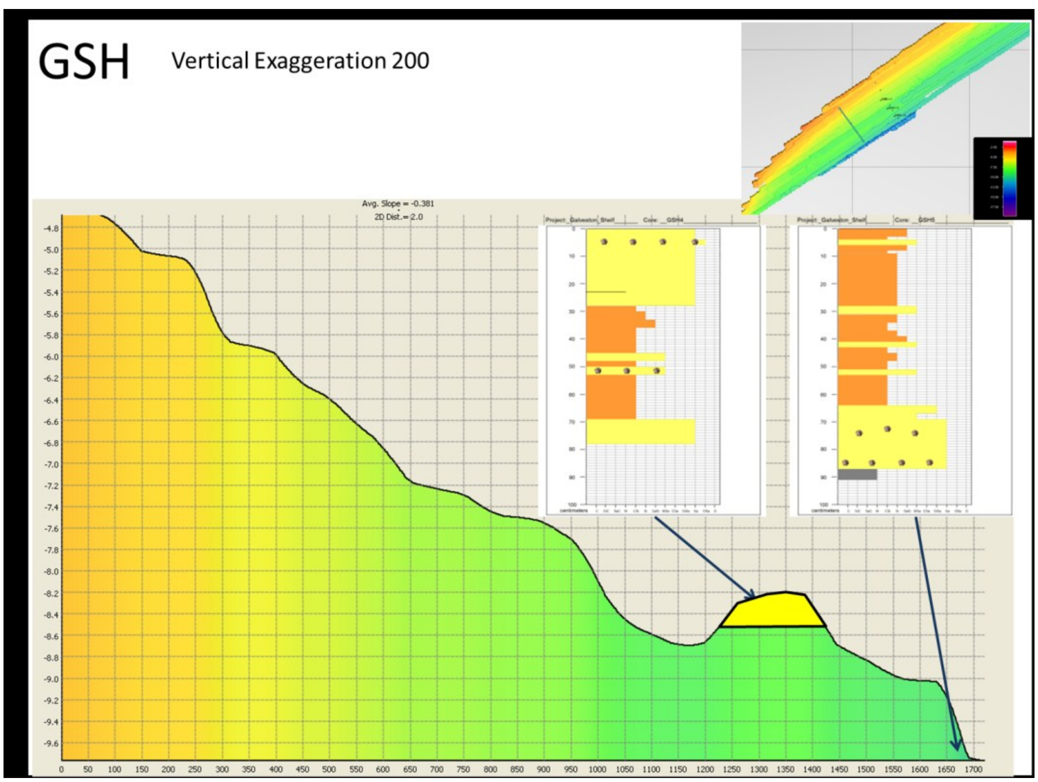
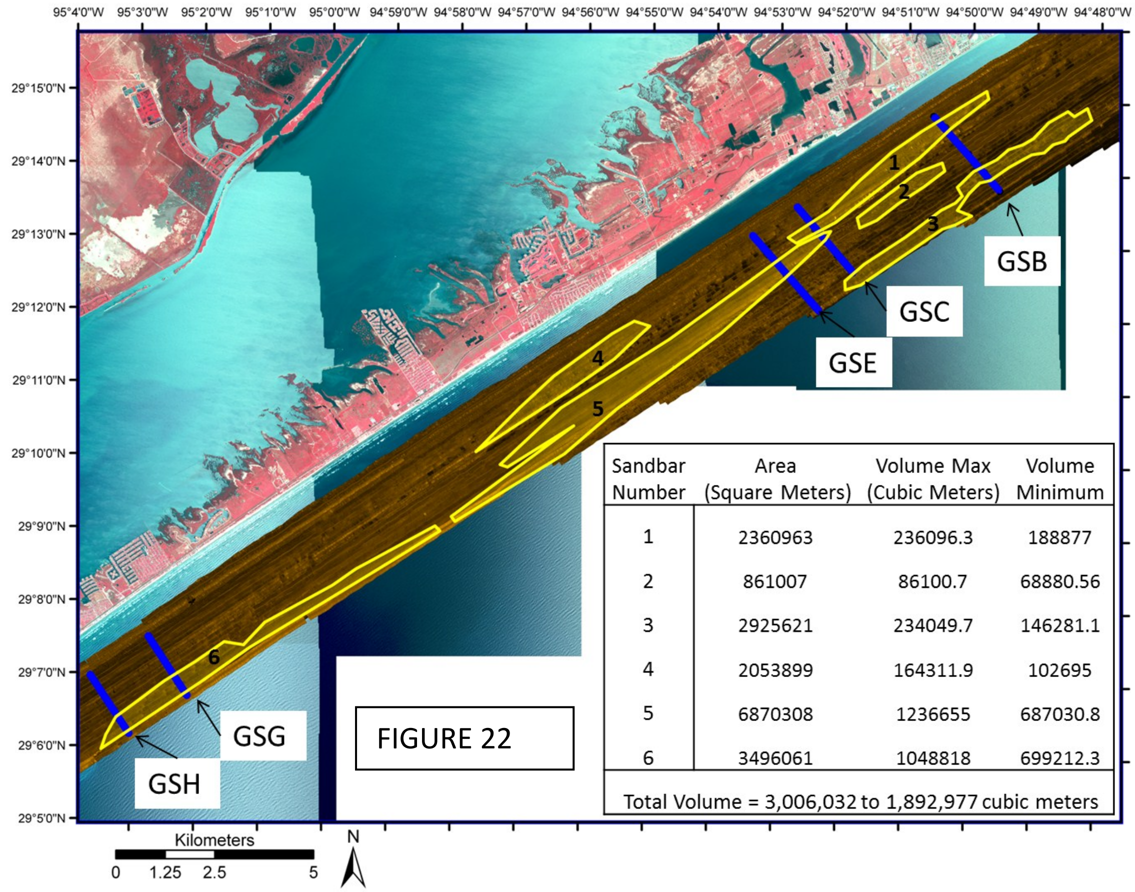


FIGURE 21: Cross-shelf profile with sand bars masked in yellow and arrows showing core locations



Sandbar Number	Area (Square Meters)	Volume Max (Cubic Meters)	Volume Minimum
1	2360963	236096.3	188877
2	861007	86100.7	68880.56
3	2925621	234049.7	146281.1
4	2053899	164311.9	102695
5	6870308	1236655	687030.8
6	3496061	1048818	699212.3
Total Volume = 3,006,032 to 1,892,977 cubic meters			

FIGURE 22

When only considering the upper half meter of sediment throughout the survey area, sand content generally followed a trend of reduction of sand with distance from Galveston Island. In order to identify the trends and the anomalies in sand distribution Figures 23 -25 were generated. Figures 23-25 characterize the east, middle, and west zones of the survey and they display the net amount of sediments in the sand size range within the upper 50cm (20in) with isobaths every 5cm overlaying the side scan base map. The isobaths were generated using a kriging interpolation between the known data points. The mean net sand thickness is 18cm with a range from 0-44cm. When calculated across the survey area of $1.27x10^5$ m^2 ($1.52x10^5 yd^2$), the volume is $2.3x10^7$ m^3 ($3x10^7$ yd^3). Figures 26 and 26.1-26.3 show the bathymetry for the full study site with zoomed in maps of the Northern, Middle, and Southern portion of the survey.

Figure 23 in a shore normal transect shows a rapid decrease in sand volume close to shore and a steady low content of sand seaward that with one small increase at the last core (GS-B-6). This pattern is similar to the general trend of a steady decrease in net sand in the upper 50cm with distance from Galveston Island along a shore normal transect seen throughout the survey site but with a more rapid decrease in sand content within the first kilometer from the shore.

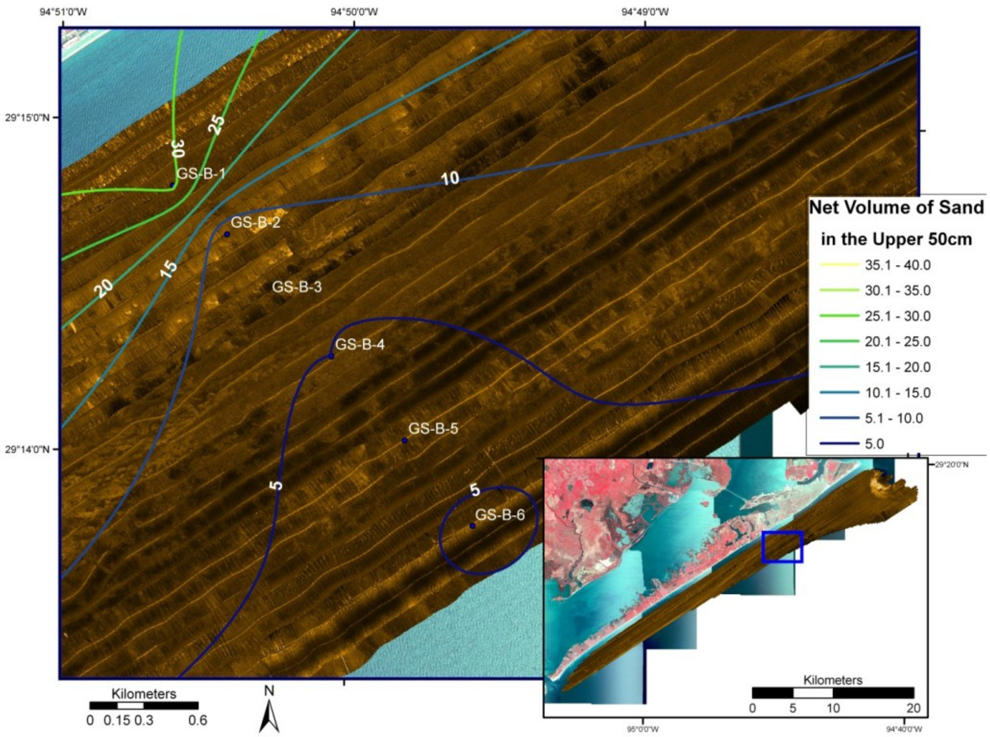


FIGURE 23: Net sand content in upper 50cm of each sample site for the North end of the survey.

The region North of here at the GS-A transect was unable to be used for this net sand analysis as the high sand percentages in that region prevented successful coring to the depths needed for accurate analysis. However the surface grab samples and the side scan trends seen elsewhere in this survey suggest that the regions of high surface sand percentages also have more net sand with depth.

The middle section of the survey, shown in Figure 24, shows the continued general trend of a steady decrease in net sand in the upper 50cm with distance from Galveston Island along a shore normal transect particularly noticeable for the GS-E transect. The GS-C transect captures the unique surface feature at GS-C-4 of a sandy bar extending from north of the middle of the survey nearshore, to offshore at the southern extent of the survey out to beyond the survey depth. This transect also captured the very low return patches scattered along the survey. The GS-E-2 core is on the edge of one of these muddy features and can be seen in the decrease in net sand there. GS-C-2 is directly on one of these features and only has 5cm of sand within the upper 50cm of the core.

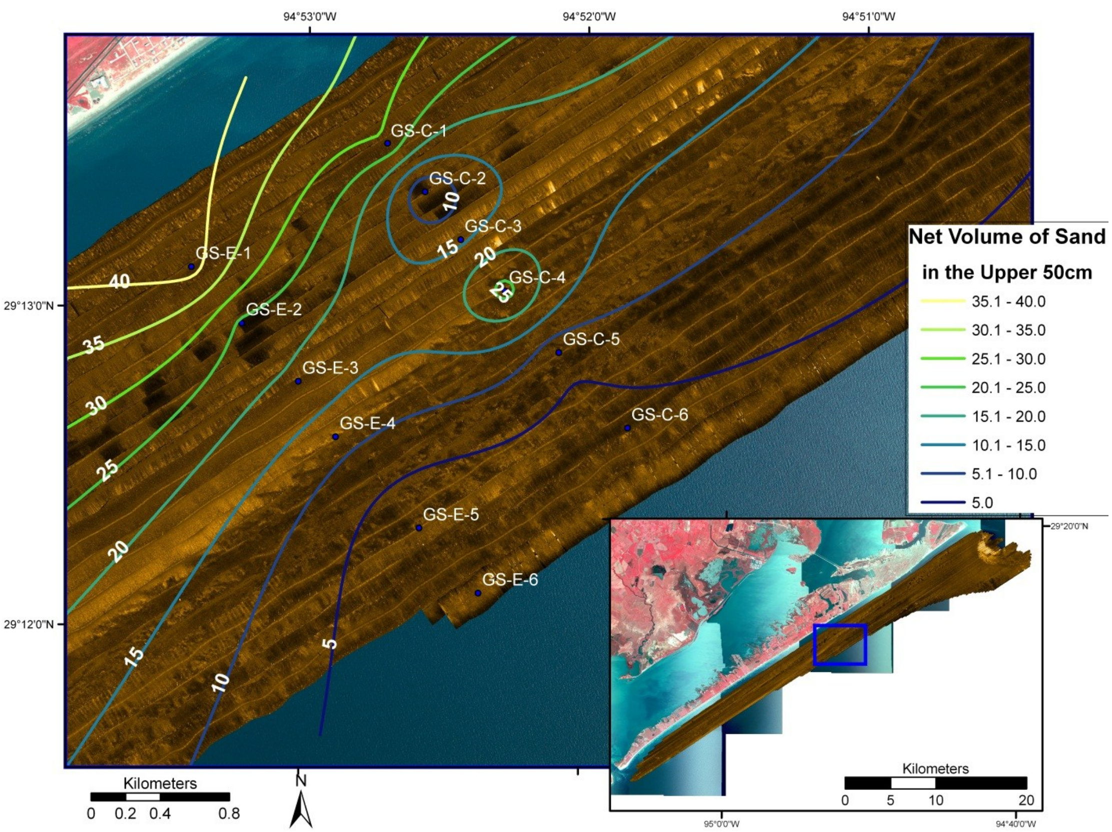


FIGURE 24: Net sand content in upper 50cm of each sample site for the middle region of the survey.

The western region of the survey contains the GS-G and GS-H transects (Figure 25). Both of these transects have the same general trend of a steady decrease in net sand in the upper 50cm with distance from Galveston Island along a shore normal transect, however both GS-G and GS-H have higher net sand values at the offshore end than the rest of the survey. This is particularly evident at GS-H-4 and GS-G6 where the net sand values extend out towards these points.

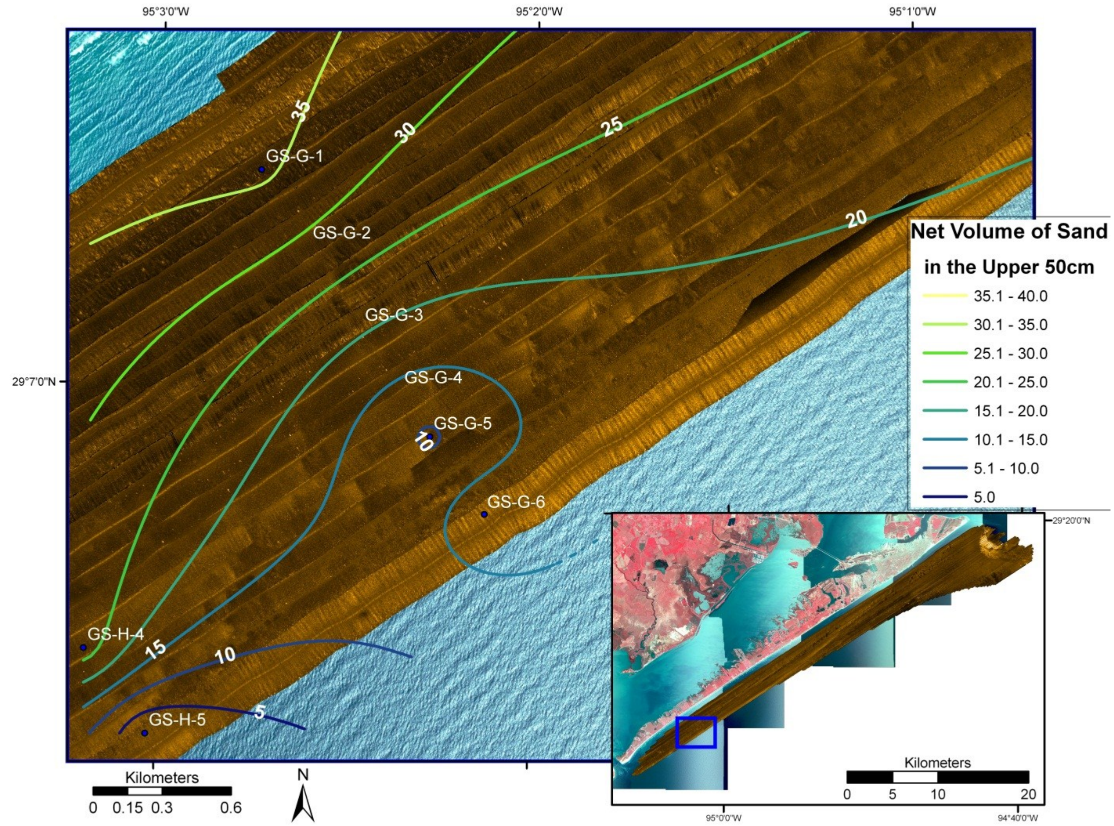


FIGURE 25: Net sand content in upper 50cm of each sample site for the Southern end of the survey.

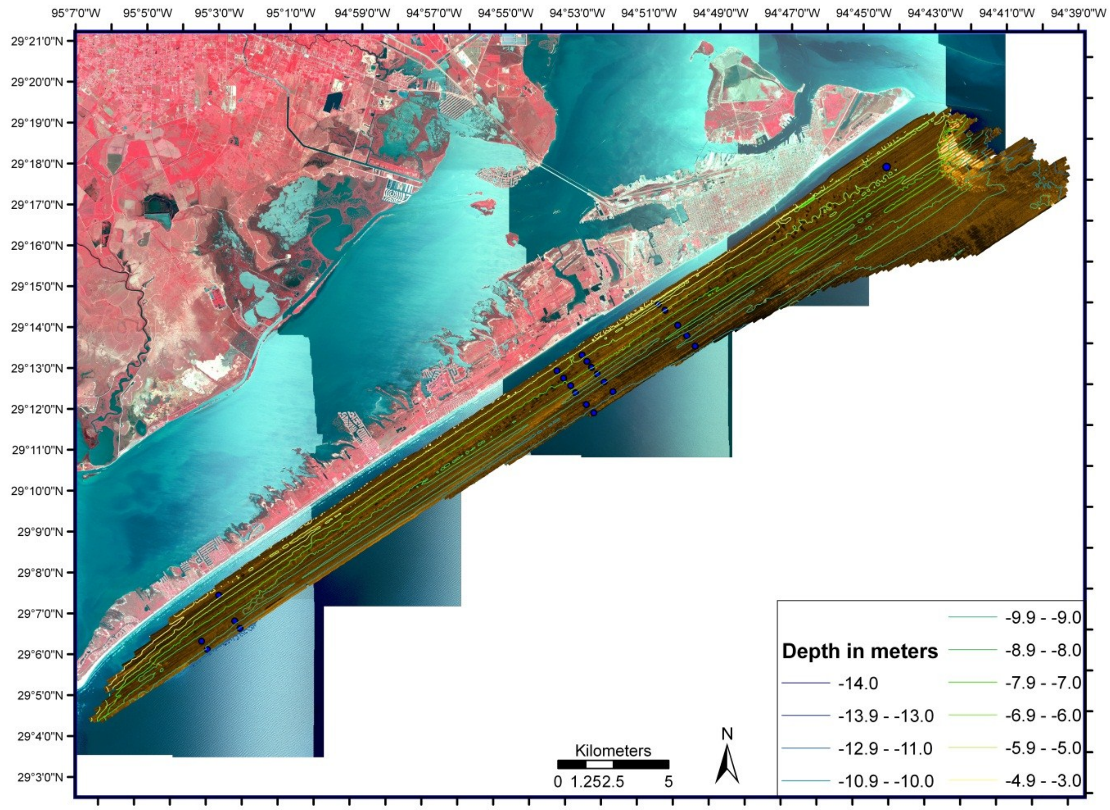


FIGURE 26: Bathymetry of the survey area. Core locations designated with blue circles.

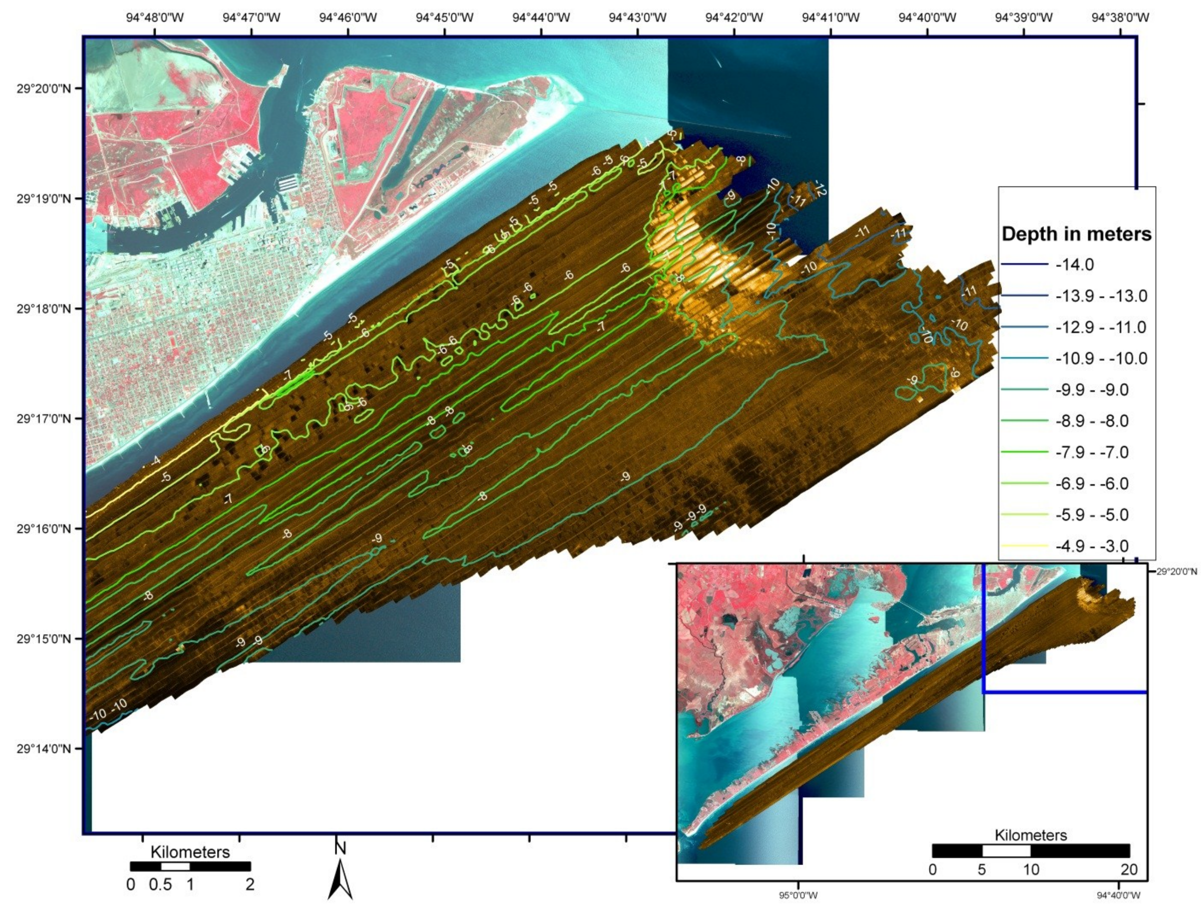


FIGURE 26.1: Bathymetry of the east end of the survey area.

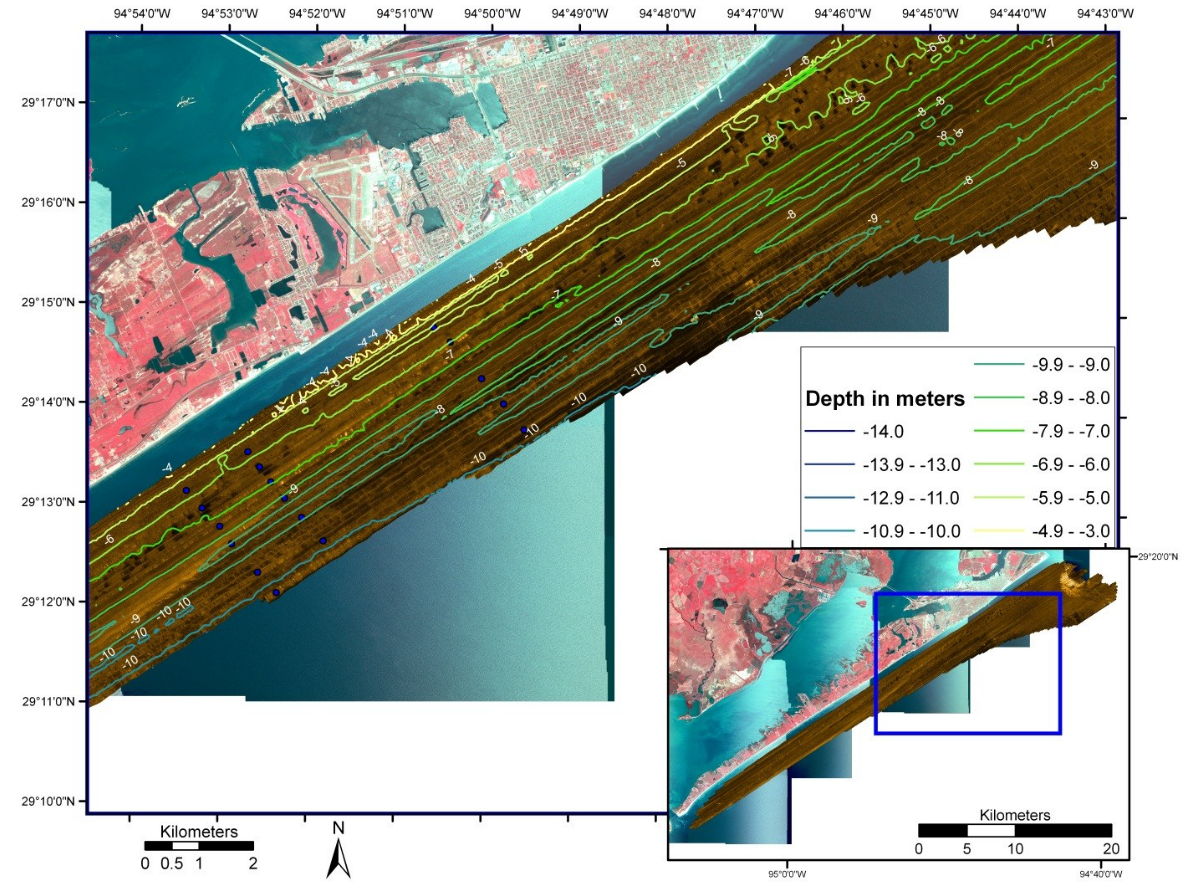


FIGURE 26.2: Bathymetry of the seawall section of the survey area.

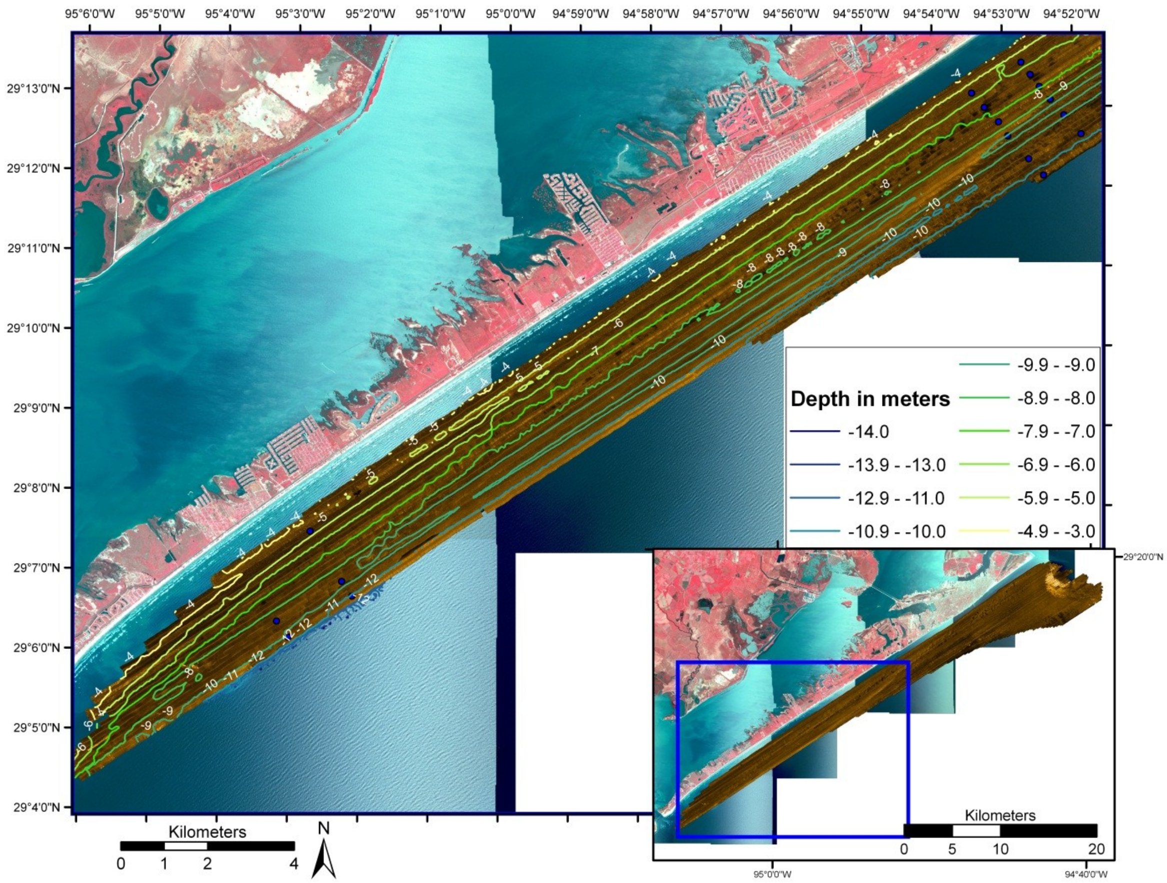


FIGURE 26.3: Bathymetry of the west end of the survey area.

5.0 Discussion and Conclusions

When comparing the pre- and post- Ike shore face and inner shelf of Galveston Island significant changes in both sediment type distribution and bathymetric changes were identified. Unpublished beach profiling collected immediately pre- and post- Ike reveal post Ike shoreline retreat for the beaches of the portion of Galveston Island west of the Seawall (Figure Webster beach data) to have retreated from 53 m (174 ft) to 16.8 m (55 ft), with an average retreat of 30.5 m (100 ft). Comparisons of total volume changes of the beach and shoreface from surveys conducted 2006 and 2011 estimate a total volume loss of 79 million m^3 (103 million cubic yards). The only major storm event to have occurred during this time period is Hurricane Ike. The shoreline retreat rates depicted in Figure (Webster's beach data) capture the immediate impact directly after the storm, prior to any natural recovery of the beach. The 2011 volume change shows the volume change both after three years of natural beach recovery as well as the added volume of beach nourishment material (less than 0.1% of total change), also note that the area across which the estimate was made does not include the western most 6 km (3.7 miles) and likely is an underestimate of the overall volume loss, but at least provides a reasonable working estimate.

When comparing the pre- to post- Hurricane Ike side scan sonar data, the post-Hurricane Ike survey reveals extensive scour troughs and pit across the study area suggesting extensive erosion as well as broad deposition of a relatively thin layer (18 cm average thickness) across much of the study area. In addition to the thinner sand, six large sand bars identified in Figure 22 contain an estimated total between 1.9 - 3 million m^3 of sand. The reason for the large range is the surface area of these sandbars is quite large so a few centimeter difference in depth of the surface sand deposit results in a large volume change. The higher estimate is produced using the actual depth of surface sand measured for each sand bar from a physical sample located within each sand bar. The lower estimate used a shallower assumed average depth of sand for each feature to compensate for volume changes from tapering at the edges of each sandbar. The resulting volume of surface sands is distributed over 10% of the total survey area. These new sand layers reveal sand further out on the shelf than was found in the pre-Ike surveys.

In addition to the sand bars, overall, there is a large deposit of sand off of the eastern end of the island, proximal to the South Jetty, indicating extensive offshore sand transport from East Beach. Unfortunately, the sand created a hard seabed in this area and the box-cores and vibra-cores were not able to recover cores long enough for complete computation of the volume of sand present in that area. Based off of the trends seen in the rest of the survey in the side scan, physical samples, and bathymetry, it seems like the USAE dredge deposit site (located in this region, as noted above) has been physically sorted removing much of the finer sediments (mud) leaving sand behind in a bathymetric low. This site covers an area of 4,038,914 m^2 making it almost twice as large as the biggest sand bar (#1 Figure 22) or roughly 2% of the entire survey area. Although none of the physical samples in this area fully penetrated the surface sand layer one core recovered was 15cm deep. Assuming uniform coverage of at least 15 cm the USAE dredge deposit site contains at least 605,837 m^3 (792,405 y^3) of sand (likely a gross under estimate).

The total volume of new sand sitting on the seabed in the upper 50 cm of the seabed is estimated to be between 1.9×10^6 and 3.0×10^6 m^3 (2.5×10^6 and 3.9×10^6 cubic yards). Most of the change in the beach profiles between 2006 and 2011 occurred within the nearshore, sand dominated portion of the profile. If we assume the sediment lost was all sand, then the volume of offshore sand deposited due to Hurricane Ike is between 2.4% and 3.8% of volume eroded. Likely, this is an overestimate because a portion of the sediment eroded was likely mud rather than sand, but at least it provides a rough estimate of total eroded sediment. This begs the question, where did all of the sand go. We are currently not to the point of being able to provide a detailed budget, however, we can make some basic observations, which are:

1) although the entire section of Galveston Island west of the Seawall was submerged, there does not appear to have been significant beach-to-bay transport of sand. Immediately after the storm, overwash deposits of sand extended landward of the shore 200-300 m for the normal mean water mark.
2) Both the flood and ebb tidal delta of San Luis Pass likely have expanded since Hurricane Ike, suggesting an additional storage area
3) Offshore of the study area- Goff et al. (2010) conducted a small study of Bolivar Roads and Bolivar Peninsula and reached the conclusion that much of the sediment eroded due to Hurricane Ike was transported offshore of the normal "depth of closure." Likely, much of the sand is dispersed offshore of the study site, perhaps even in additional offshore bars.

6.0 References

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7.0 Appendix

Core Description Key

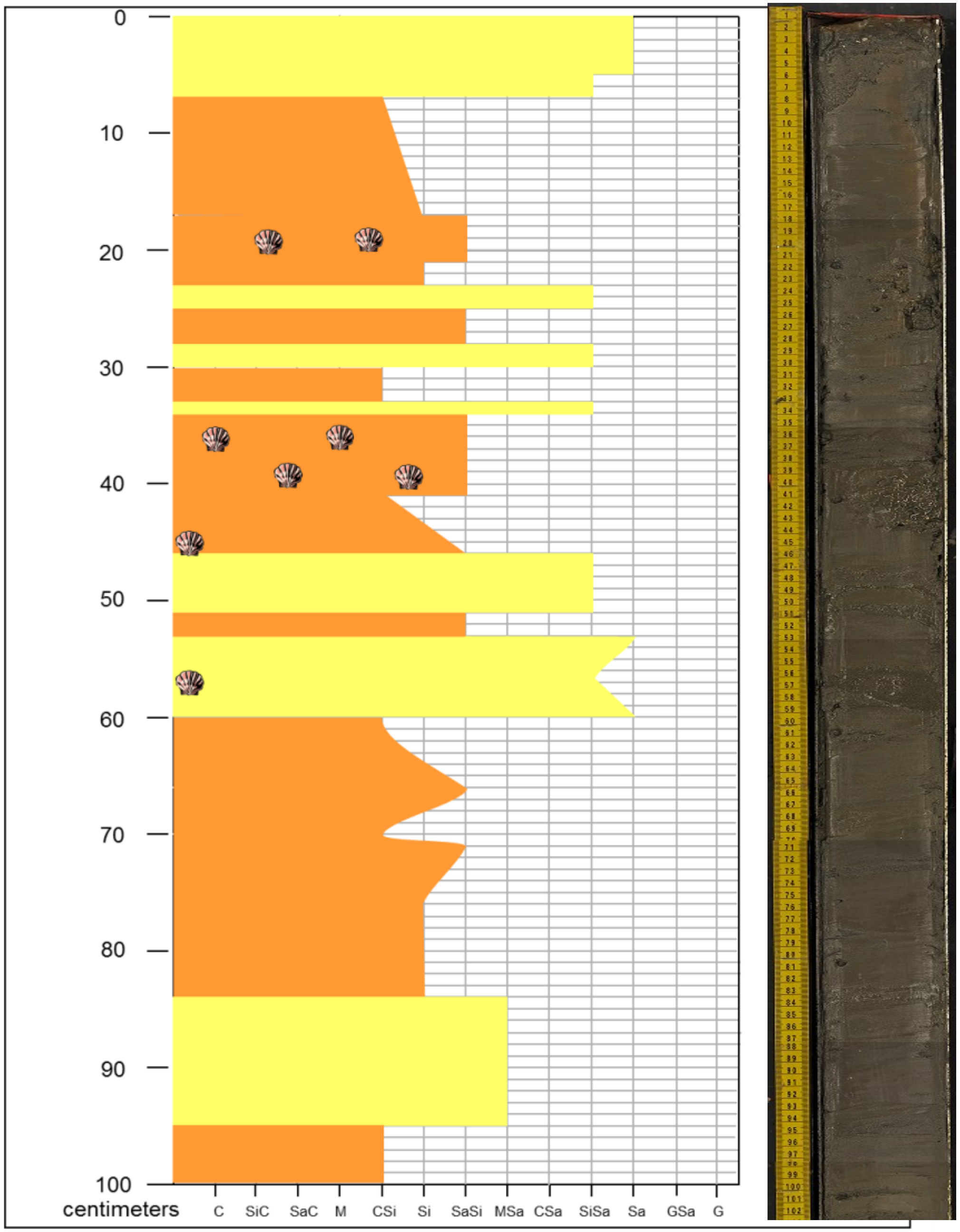
Sediment Grain Size

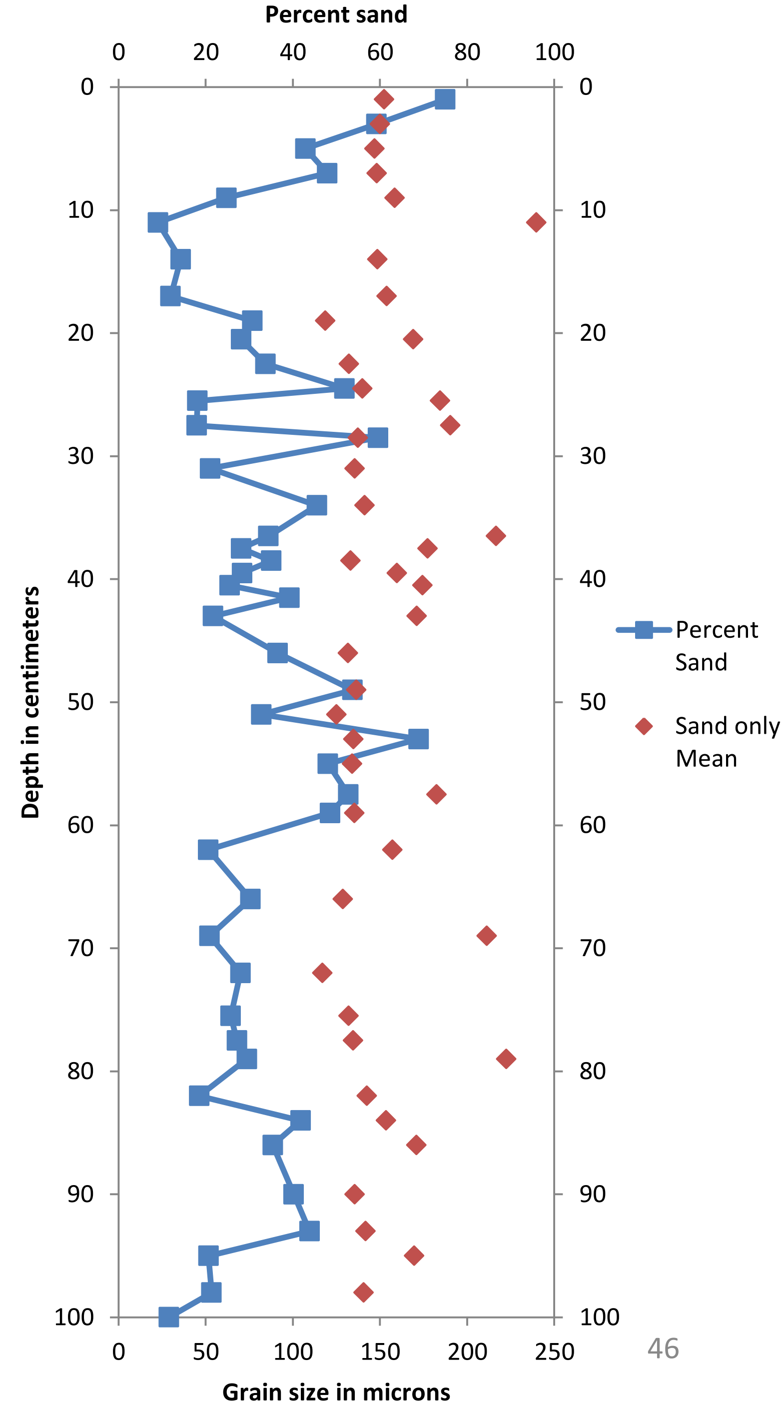
Clay Dominated						Silt Dominated						Sand Dominated					
C	"Clay"	Clay comprises more than two-thirds of sediment	M	"Mud"	Near equal portions silt and clay with little sand	CSi	"Clayey-Silt"	Silt dominates with clay comprising a significant fraction	MSa	"Muddy-Sand"	Near equal portions mud and sand	CSa	"Clayey-Sand"	Sand dominates with clay comprising a significant fraction	G	"Gravel"	Gravel comprises more than two-thirds of sediment
SiC	"Silty-Clay"	Clay dominates with silt comprising a significant fraction				Si	"Silt"	Silt comprises more than two-thirds of sediment				SiSa	"Silty-Sand"	Sand dominates with silt comprising a significant fraction			
SaC	"Sandy-Silt"	Clay dominates with sand comprising a significant fraction				SaSi	"Sandy-Silt"	Silt dominates with sand comprising a significant fraction				Sa	"Sand"	Sand comprises more than two-thirds of sediment			
												GSa	"Gravely-Sand"	Sand dominantes with gravel comprising a significant fraction			

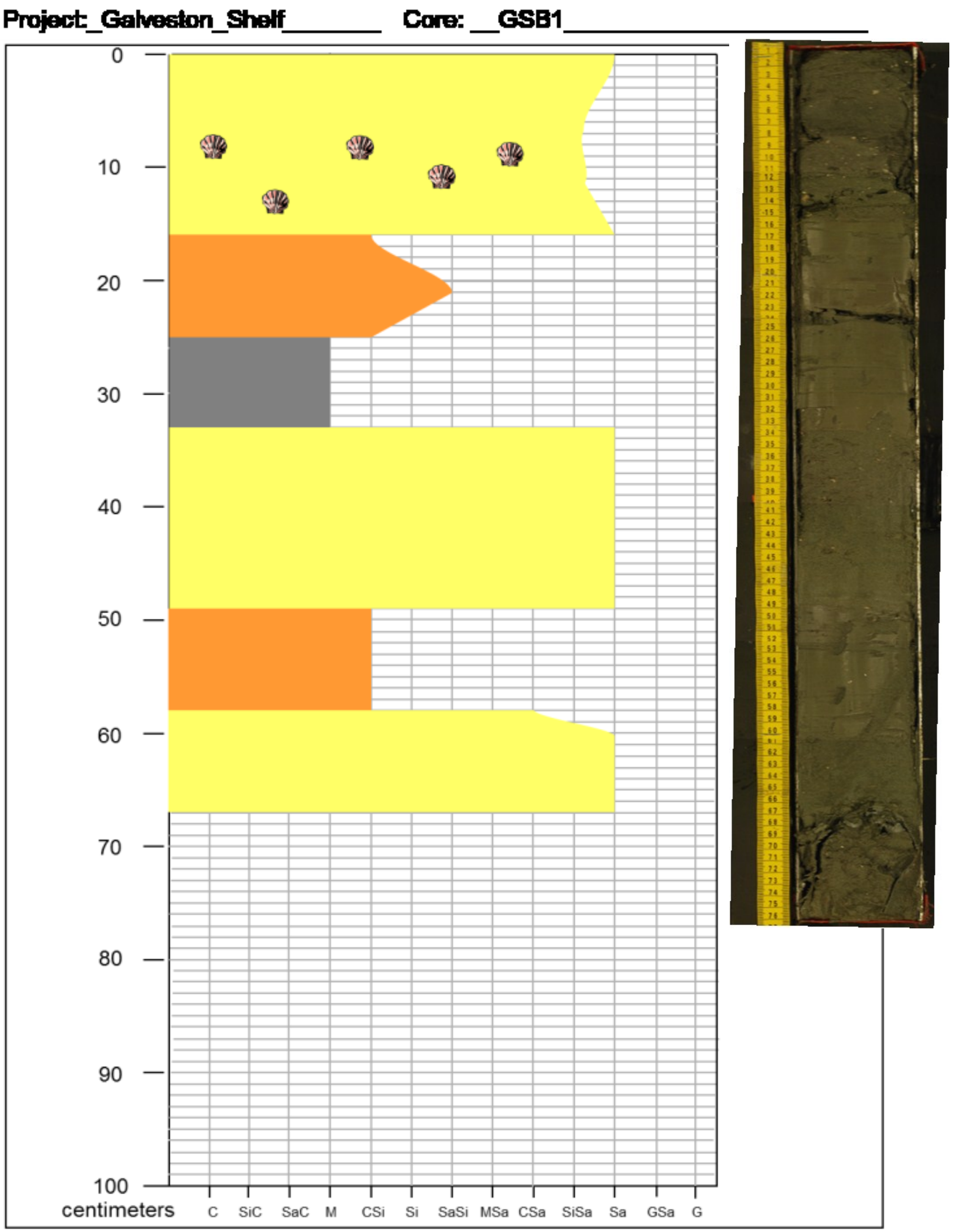
Sediment Color Key

Galveston Shelf Cores: Size-based Color			Brazos Delta Cores: Observed Color		
	-	Clay Dominated		-	Grey
	-	Silt Dominated		-	Grey-Brown
	-	Sand Dominated		-	Brown
	-	Shells/ Shell Fragments		-	Red-Brown
				-	Red

Project:_Galveston_Shelf________ Core: __GSA1__________________



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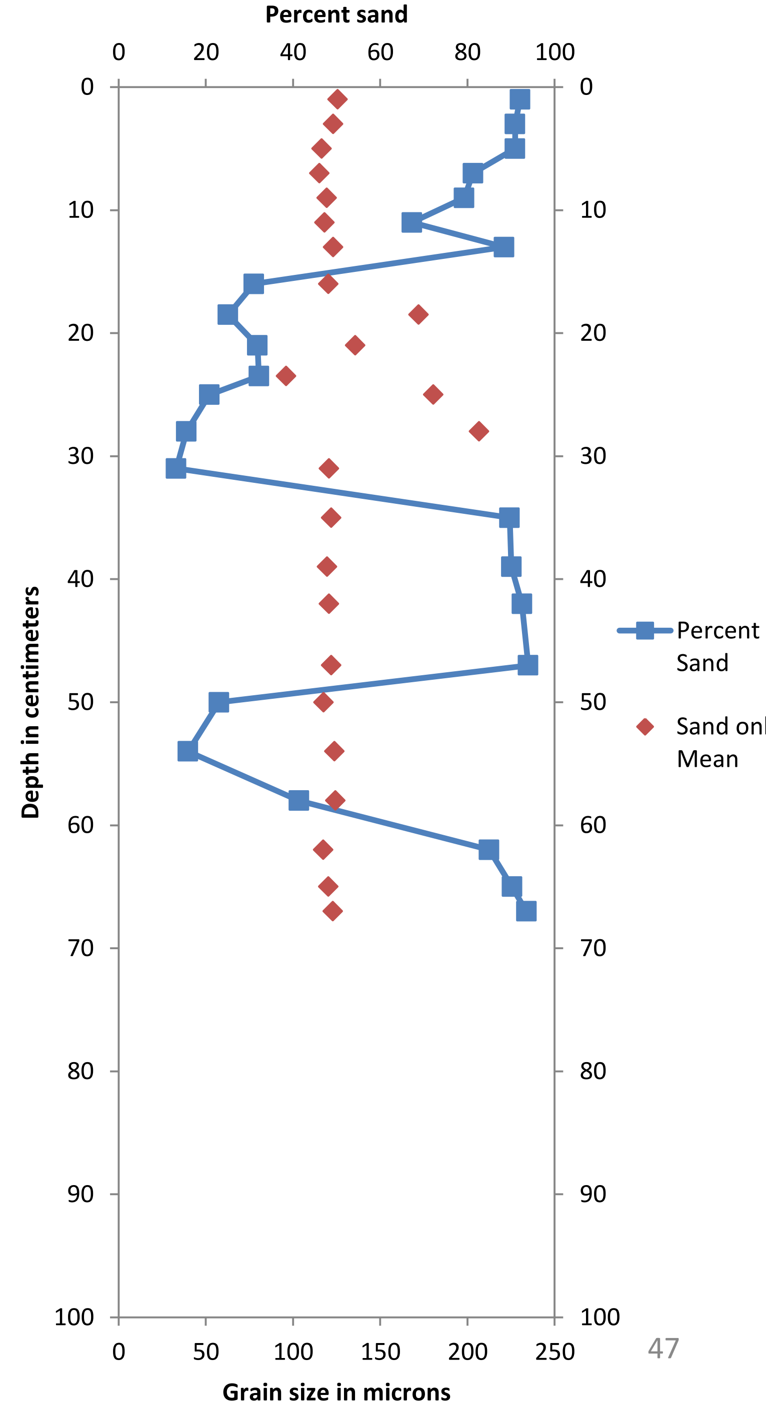
Percent sand
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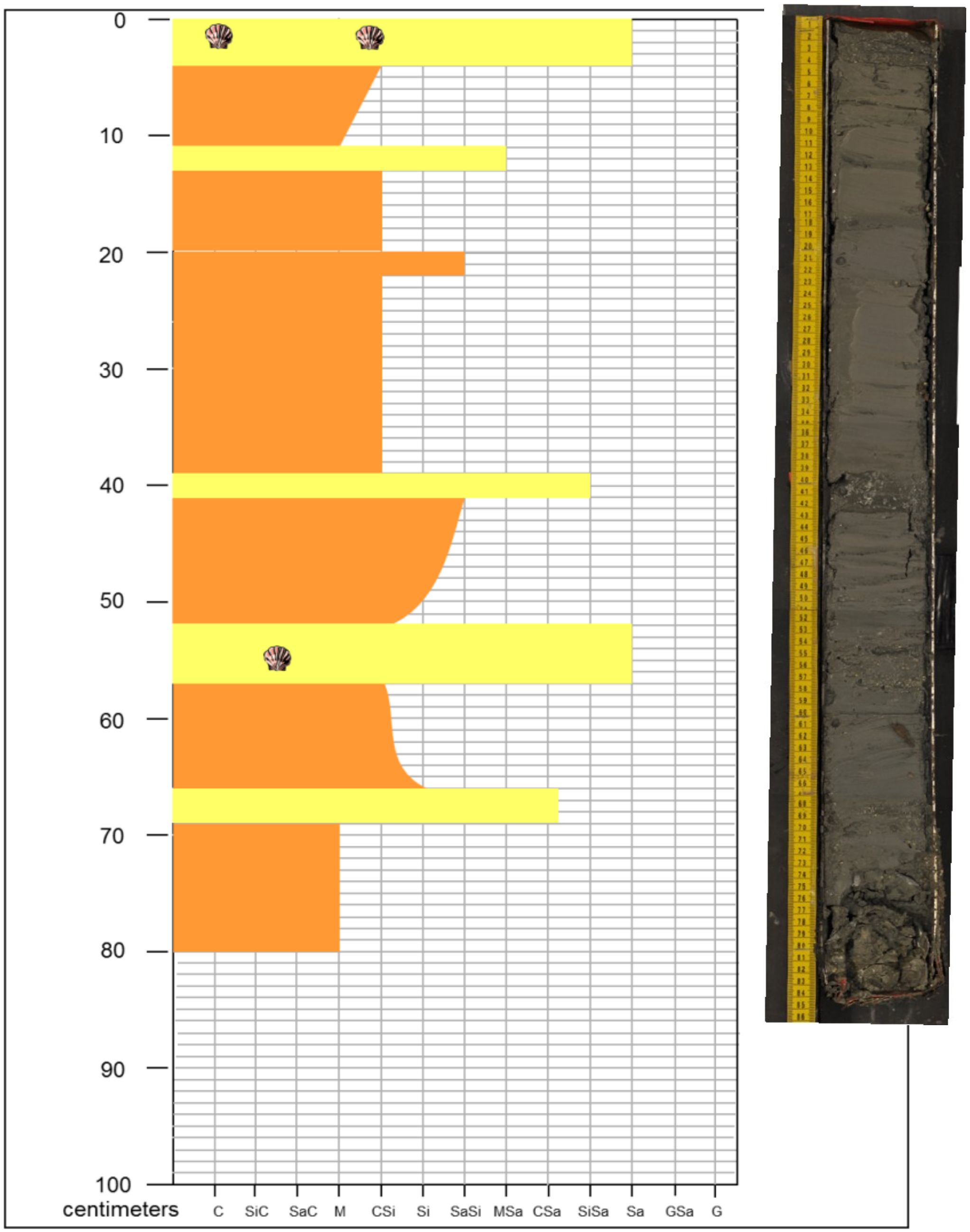
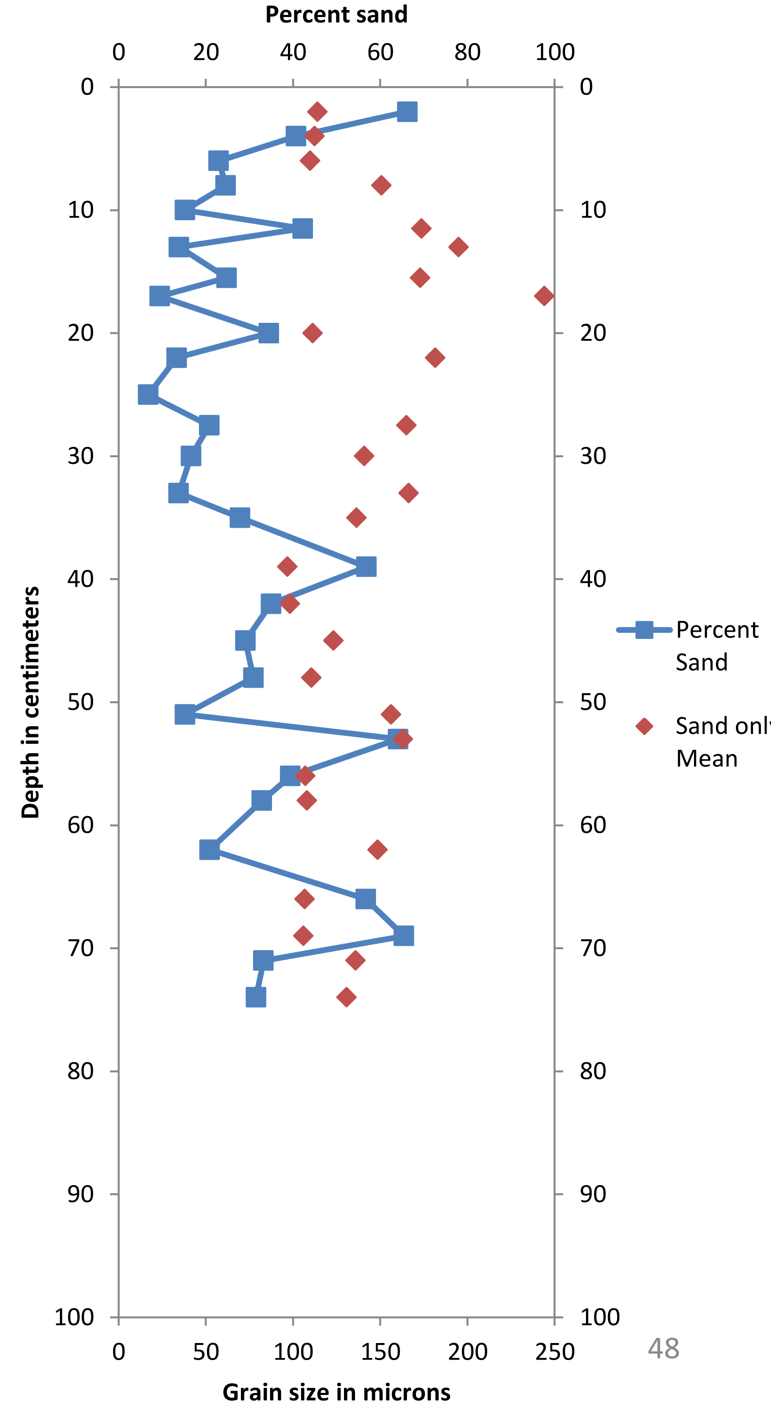
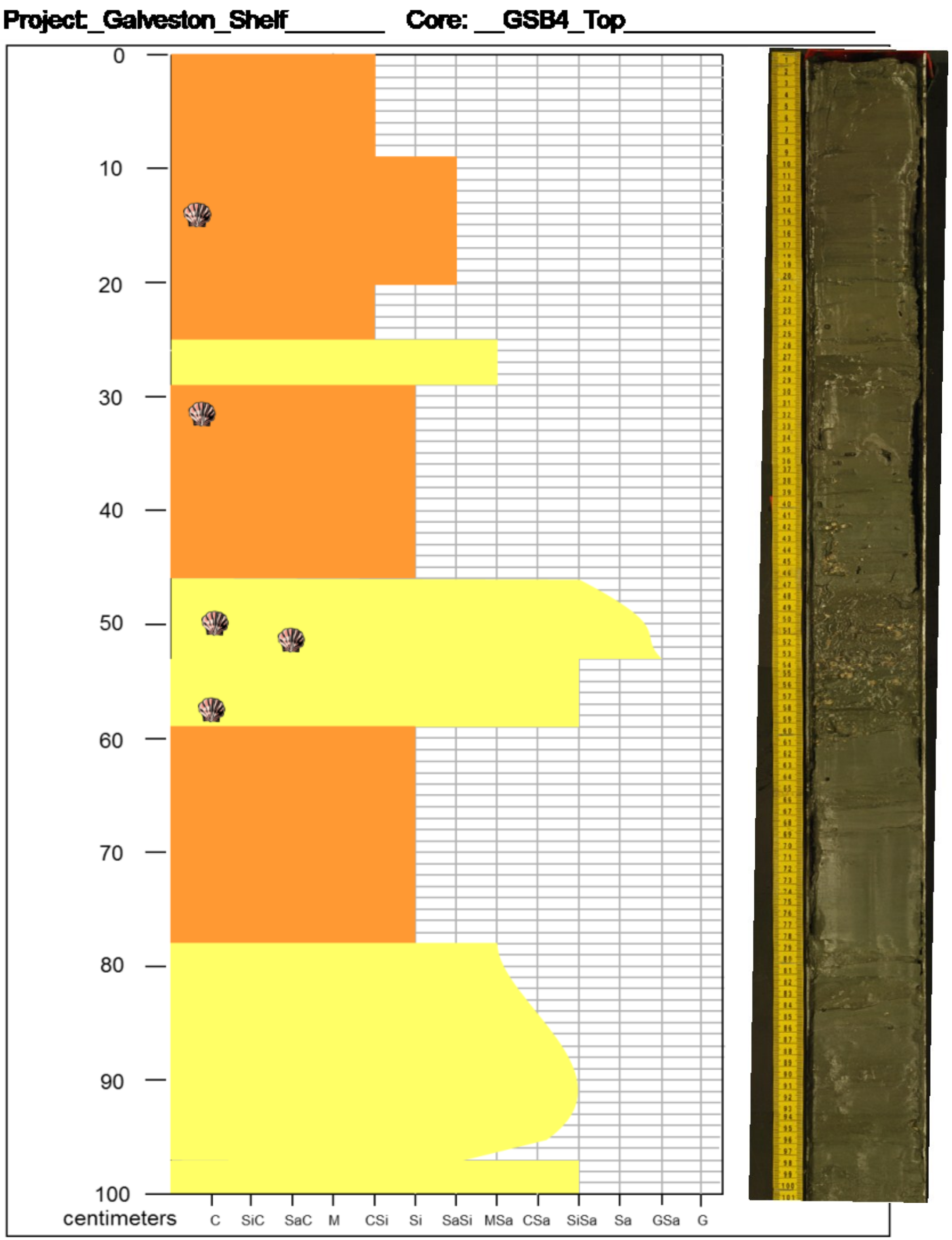
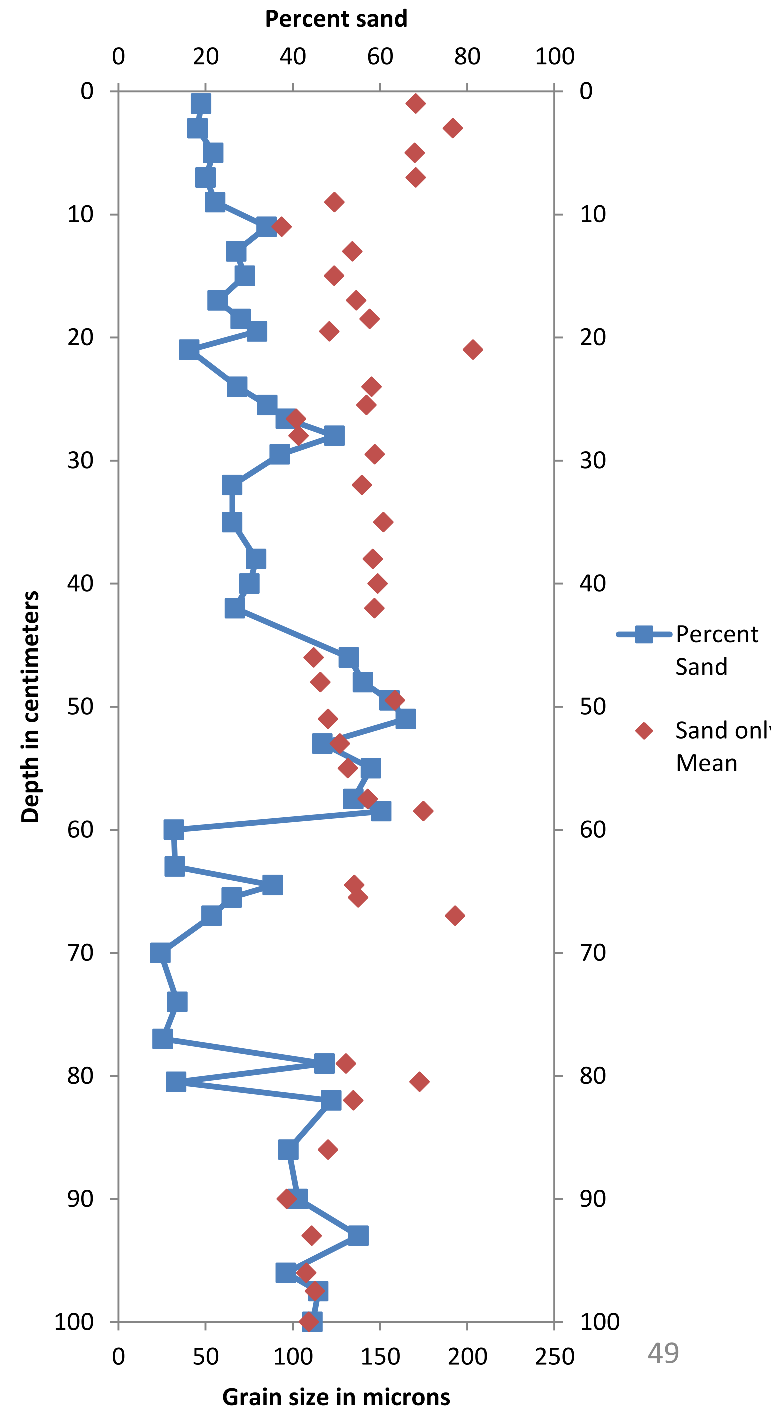
250
Grain size in microns

Project:_Galveston_Shelf________ Core: __GSB2_________________________

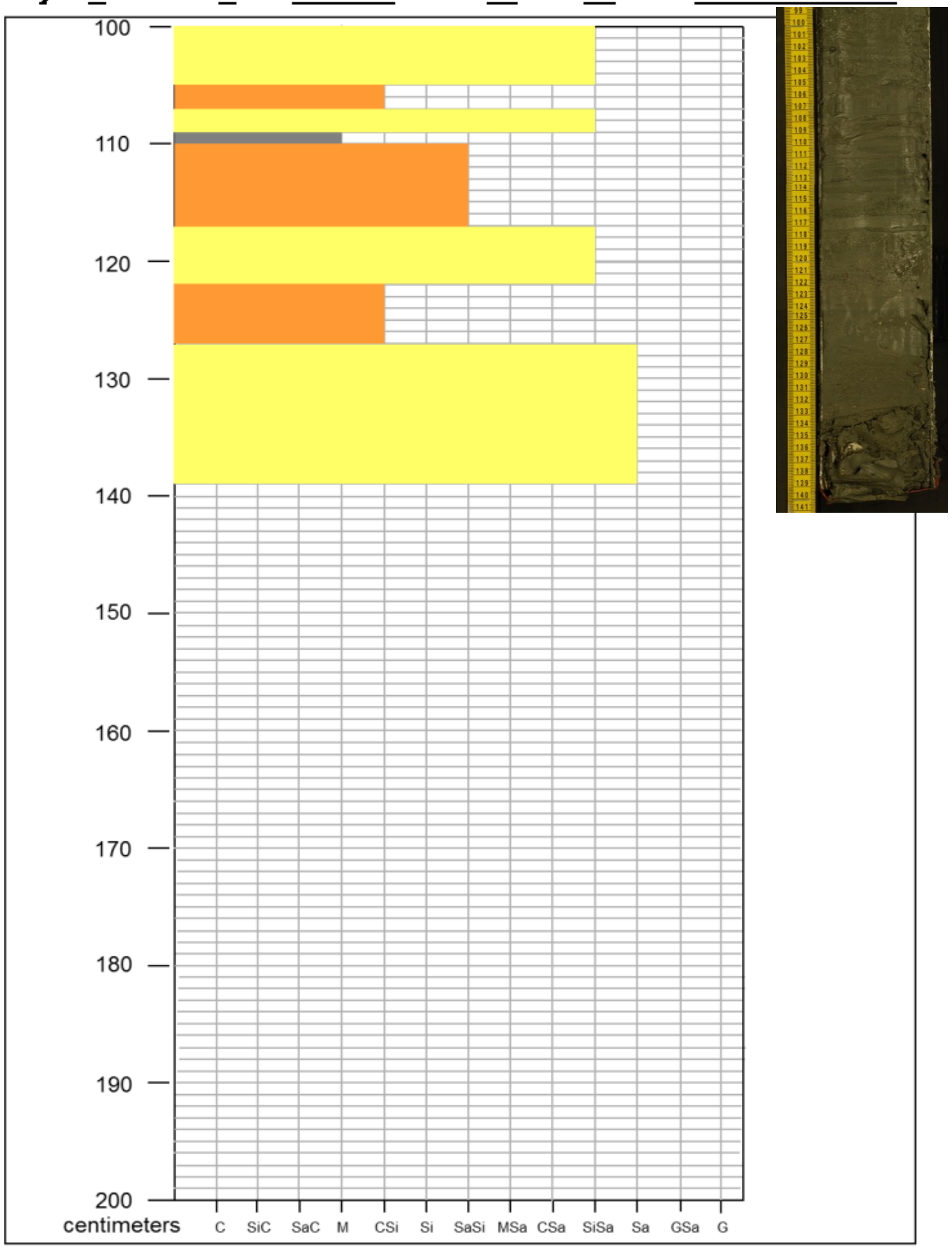


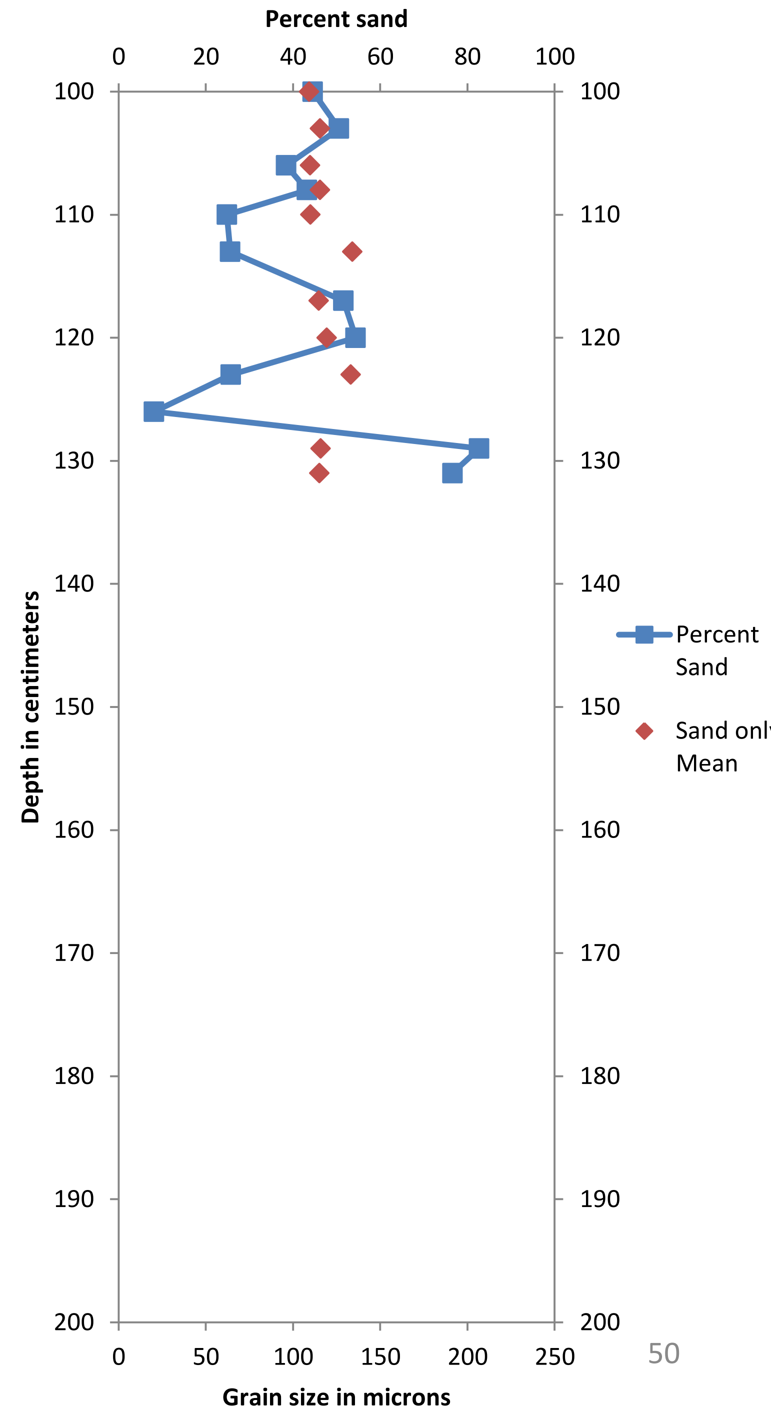


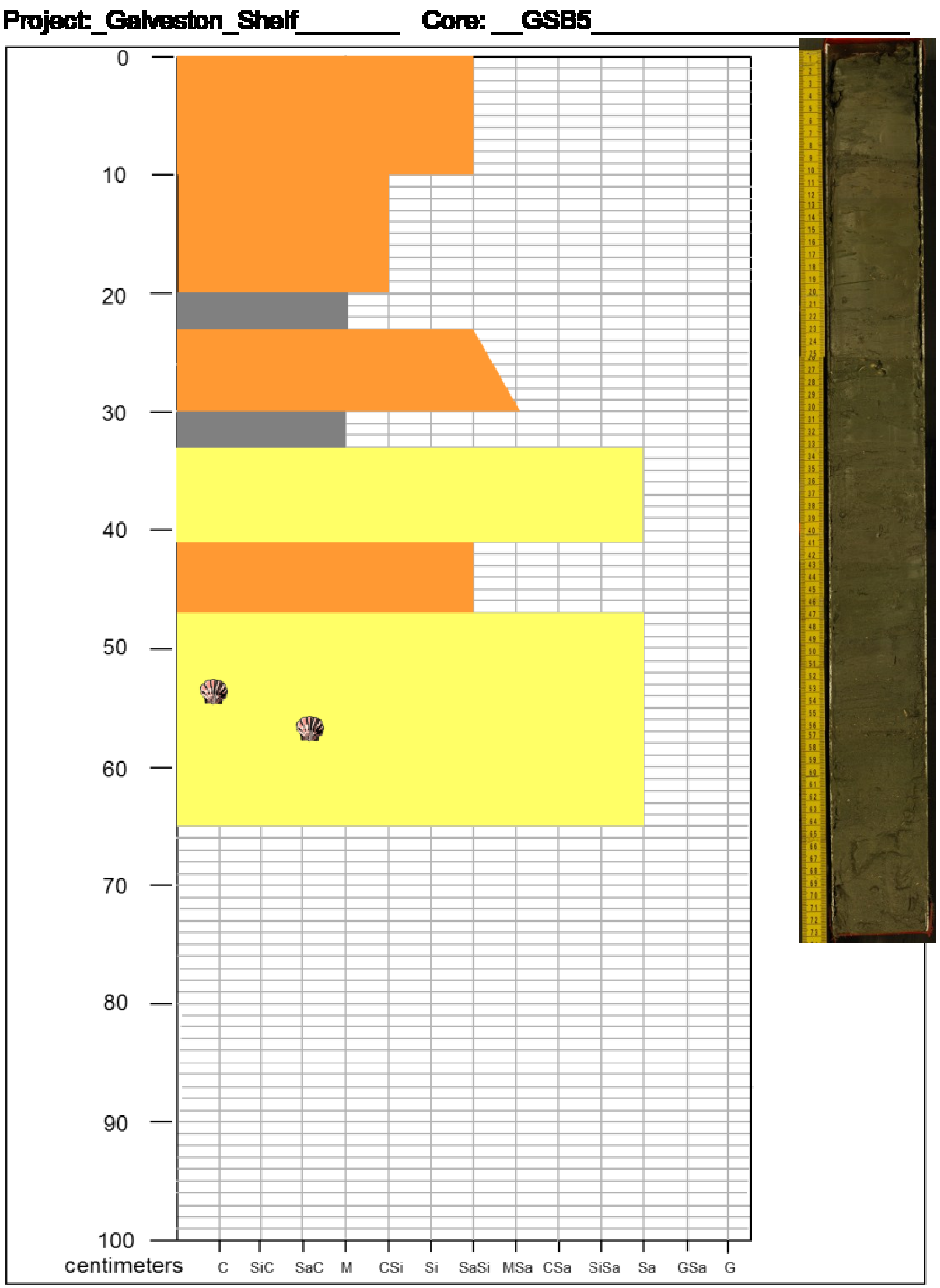

Project_Galveston_Shelf
Core: __GSB4_Top
0
10
20
30
40
50
60
70
80
90
100
centimeters
C
SiC
SaC
M
CSi
Si
SaSi
MSa
CSa
SiSa
Sa
GSa
G

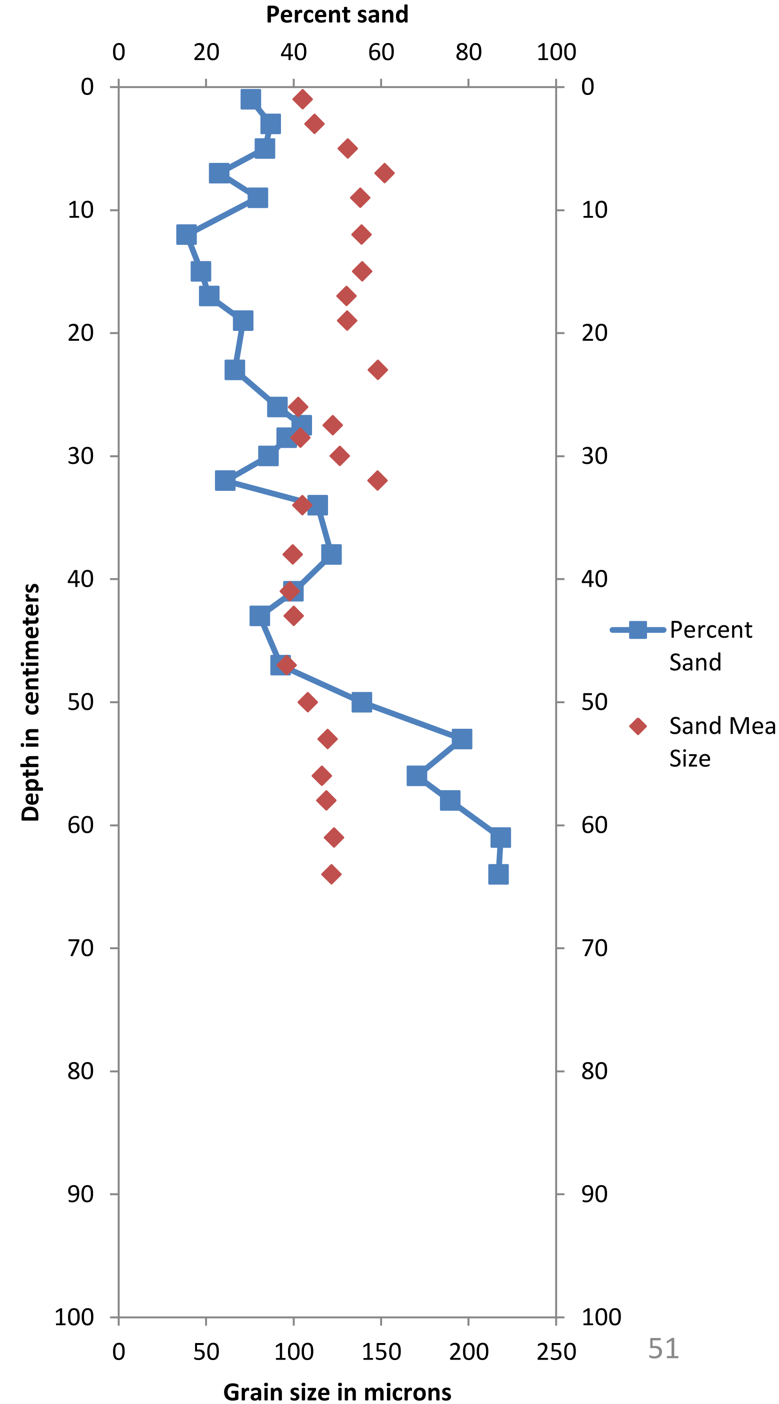

Percent sand
0
20
40
60
80
100
Depth in centimeters
0
10
20
30
40
50
60
70
80
90
100
Percent Sand
Sand only Mean
0
50
100
150
200
250
Grain size in microns

Project:_Galveston_Shelf________ Core:__GSB4__Bottom________________

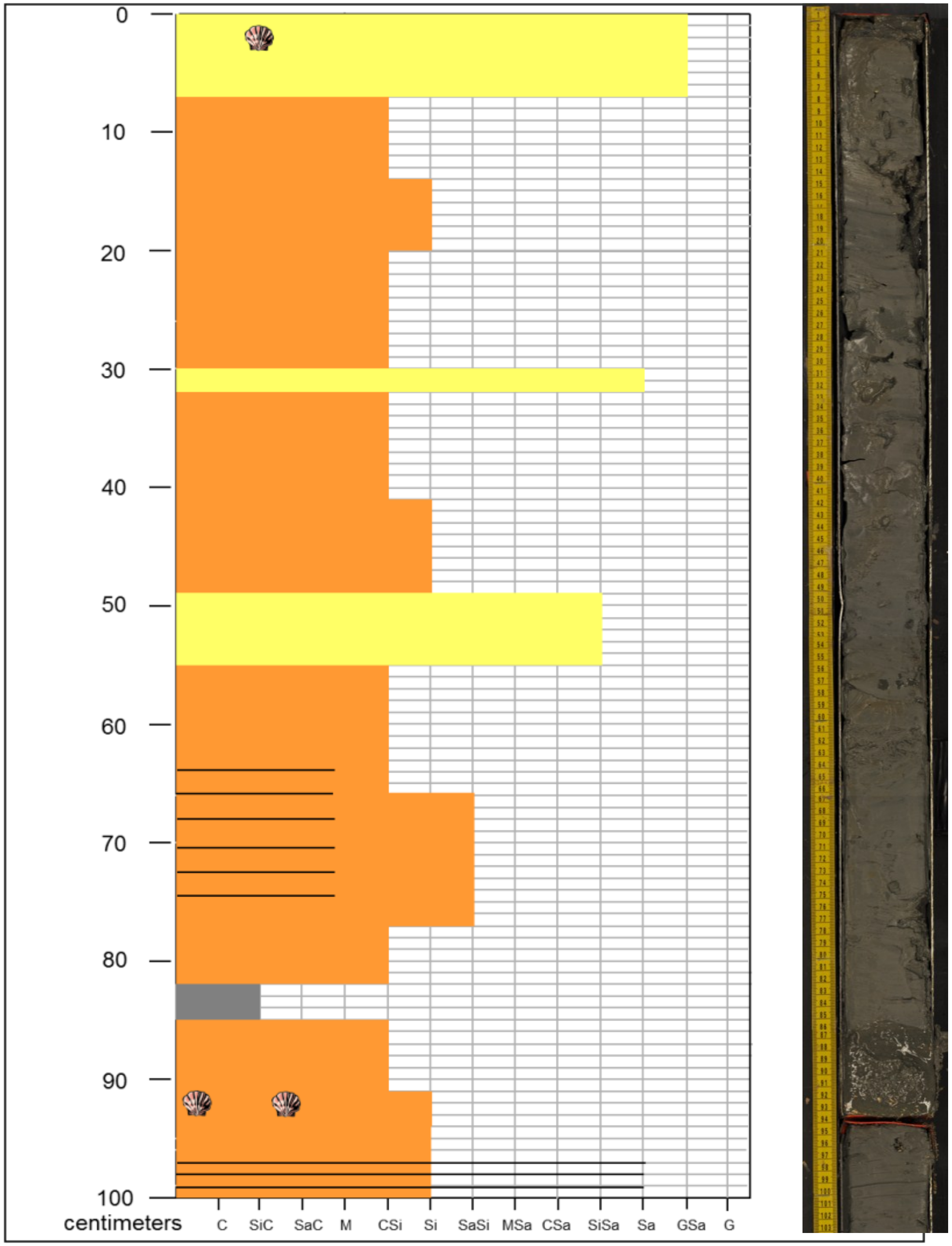


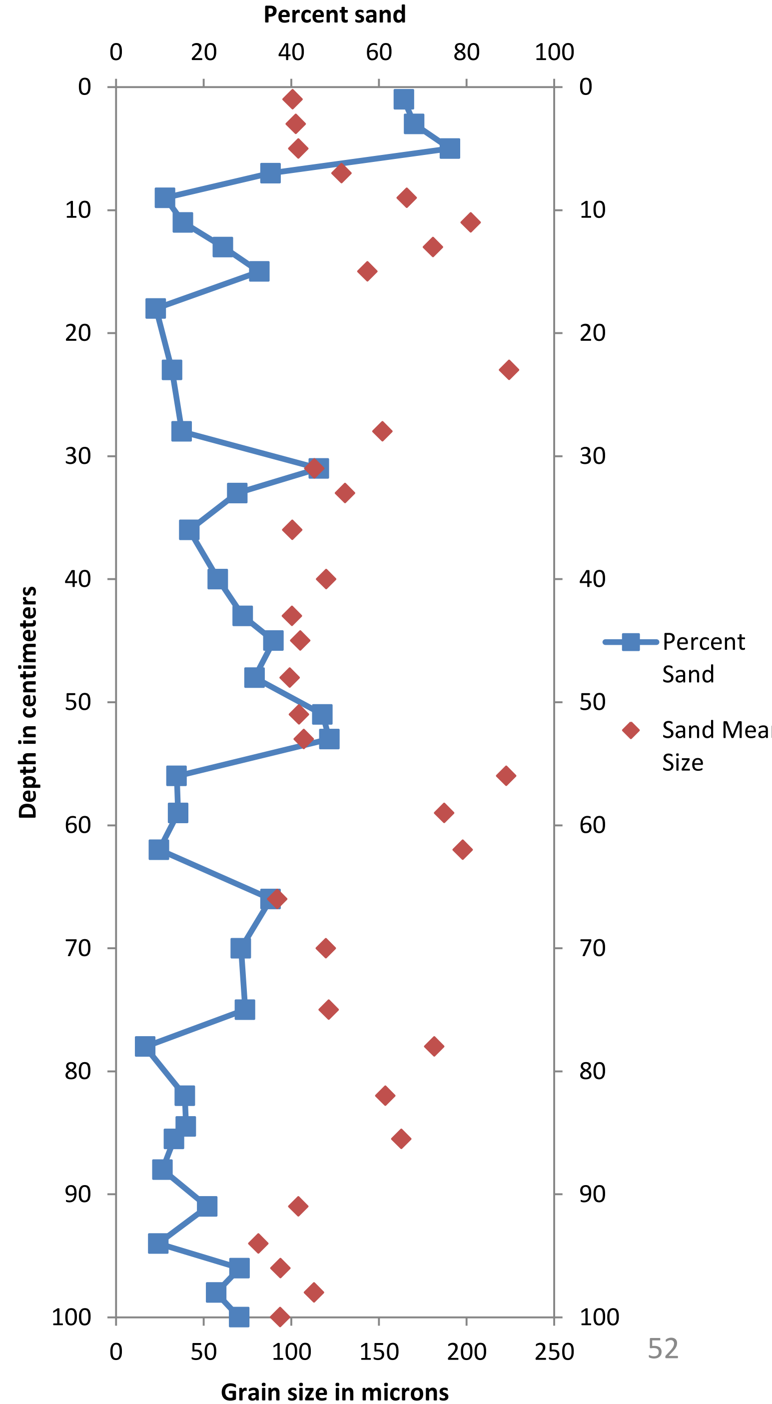


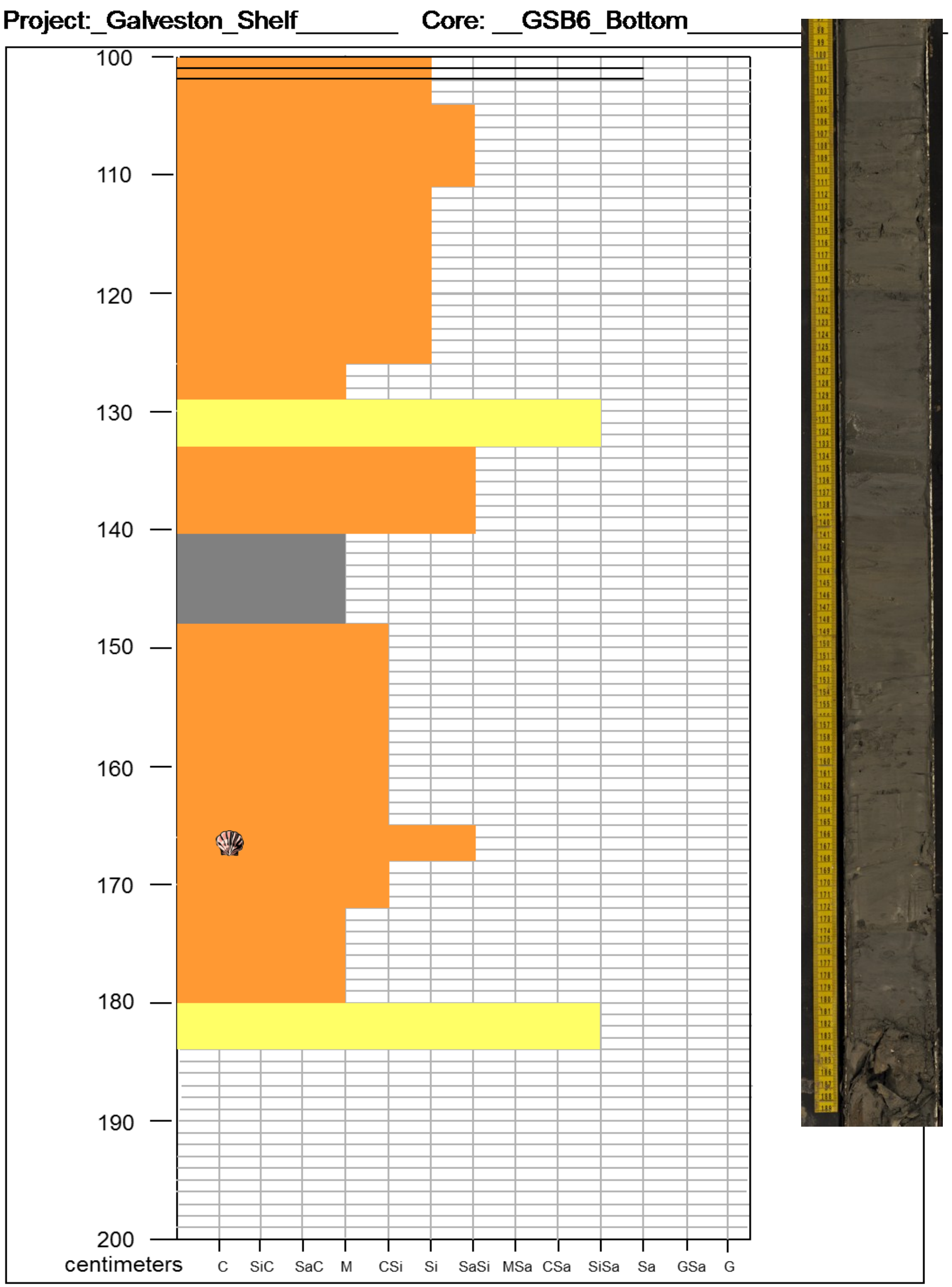

Project: Galveston Shelf
Core: GSB5
0
10
20
30
40
50
60
70
80
90
100
centimeters
C
SiC
SaC
M
CSi
Si
SaSi
MSa
CSa
SiSa
Sa
GSa
G

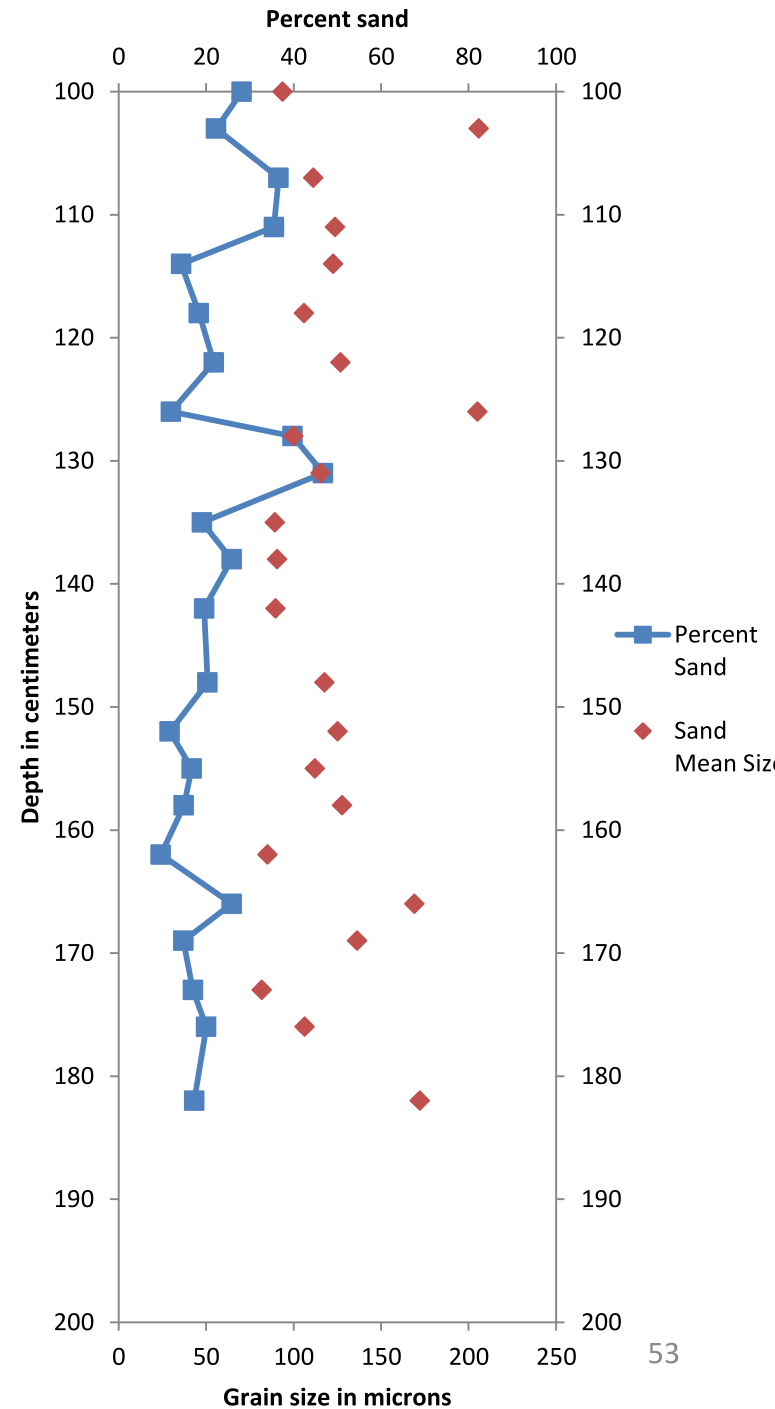

Percent sand
0
20
40
60
80
100
Depth in centimeters
0
10
20
30
40
50
60
70
80
90
100
Percent Sand
Sand Mean Size
0
50
100
150
200
250
Grain size in microns

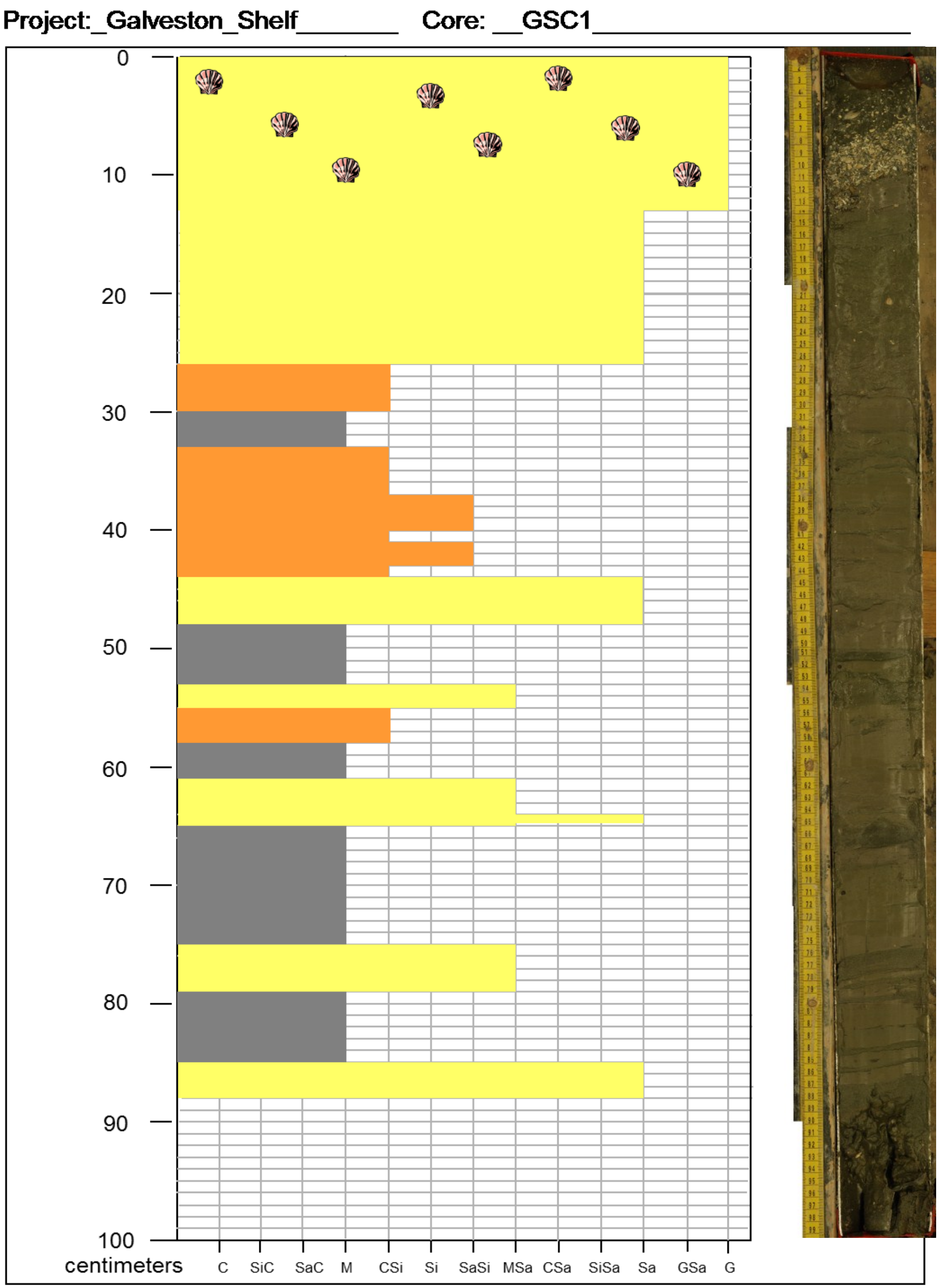
Project:_Galveston_Shelf_______ Core: __GSB6_Top__________________

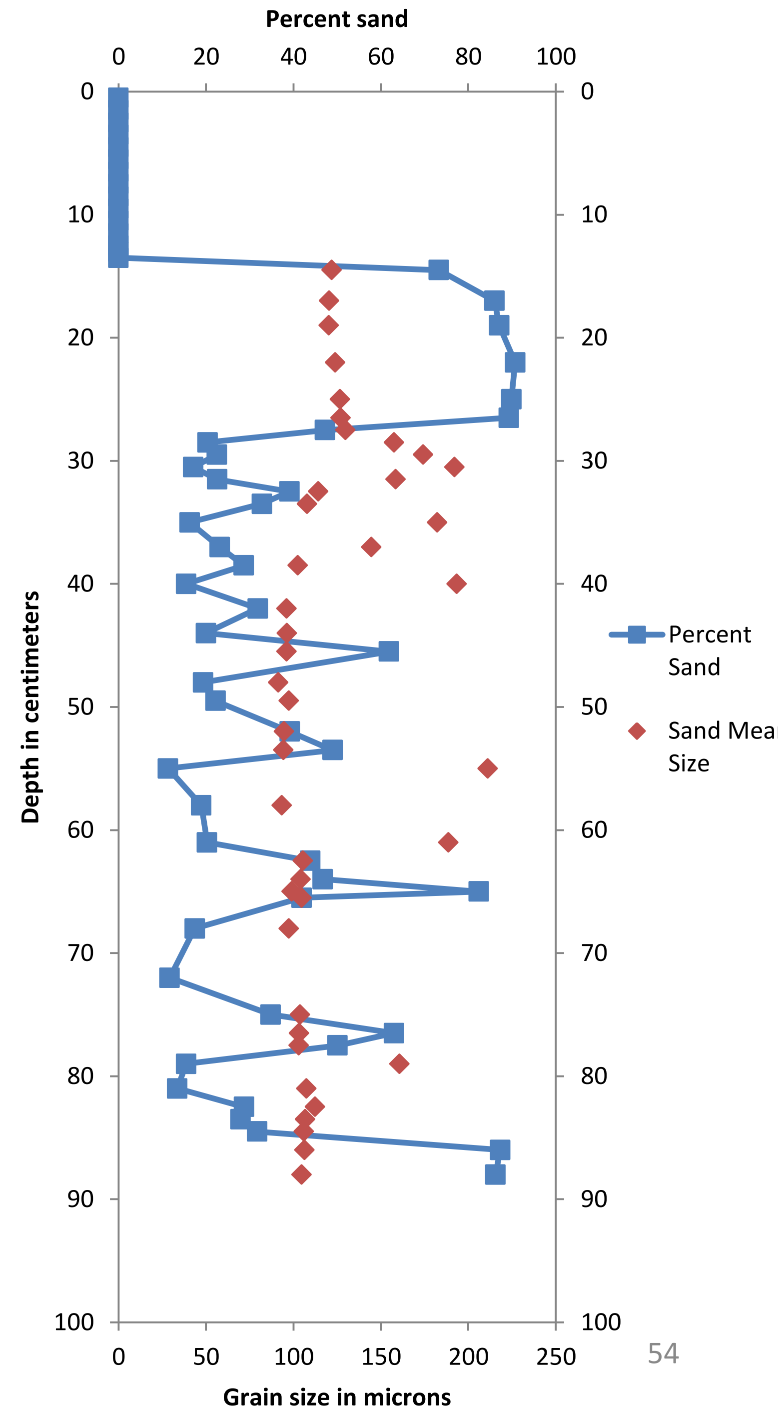




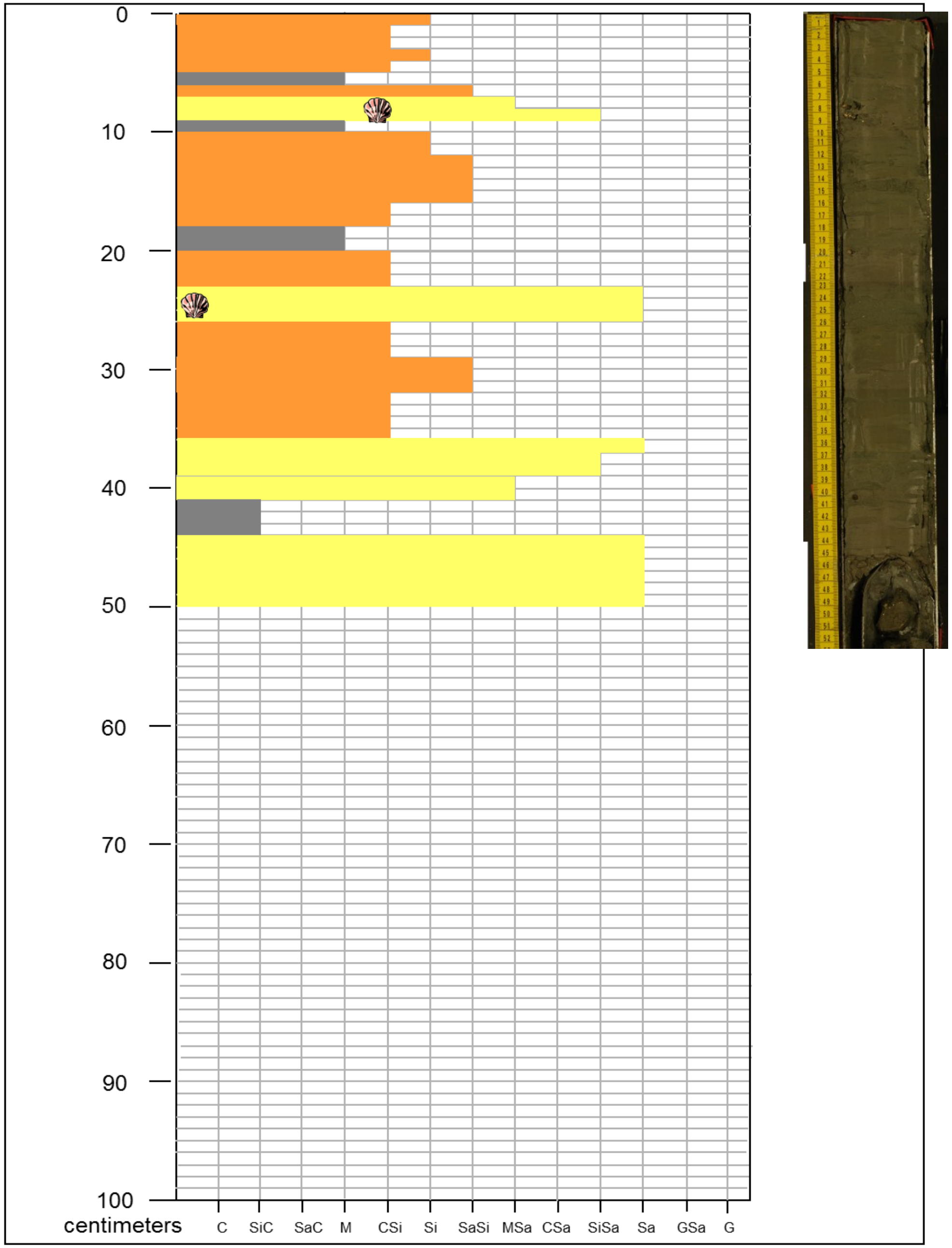

Project:_Galveston_Shelf________ Core: __GSB6_Bottom
100
110
120
130
140
150
160
170
180
190
200
centimeters
C SiC SaC M CSi Si SaSi MSa CSa SiSa Sa GSa G

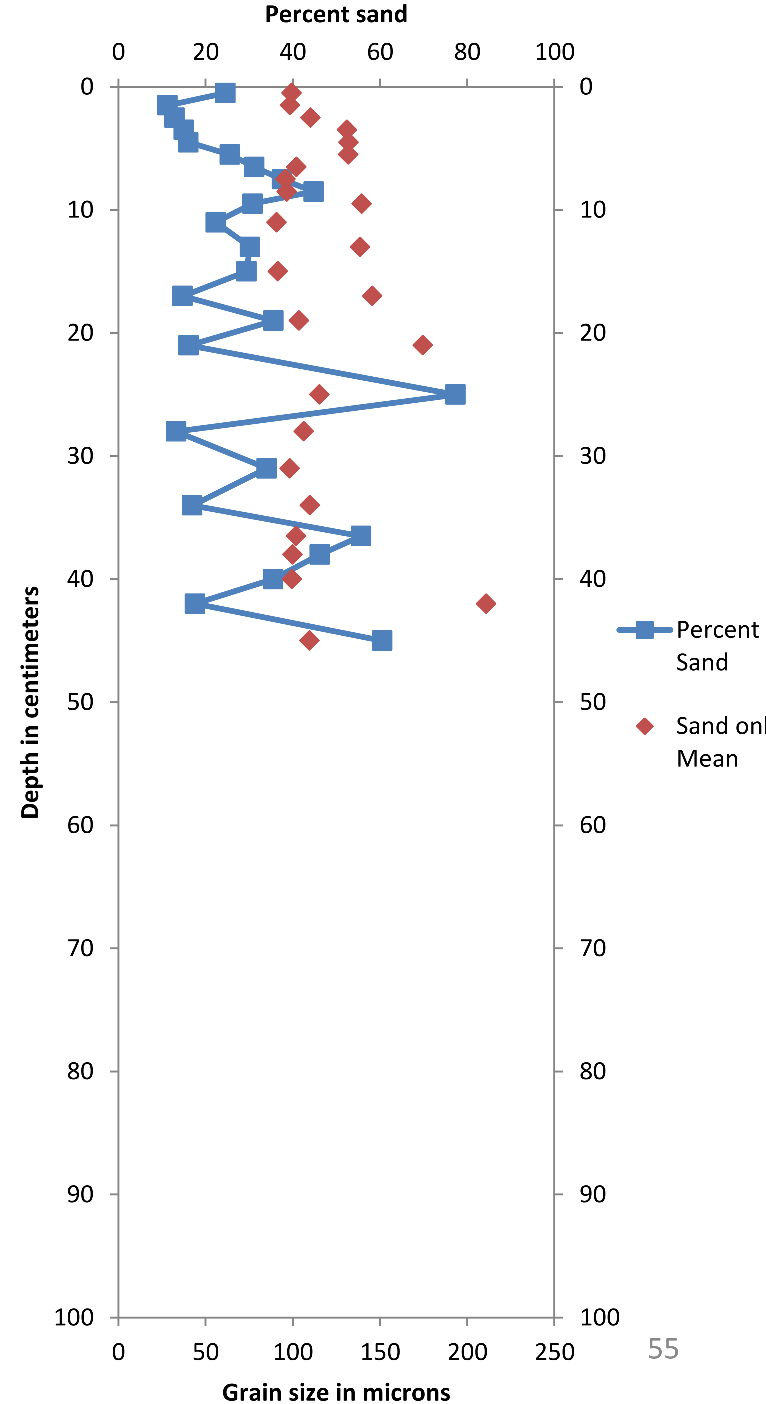

Percent sand
0 20 40 60 80 100
Depth in centimeters
100 110 120 130 140 150 160 170 180 190 200
0 50 100 150 200 250
Grain size in microns
Percent Sand
Sand Mean Size

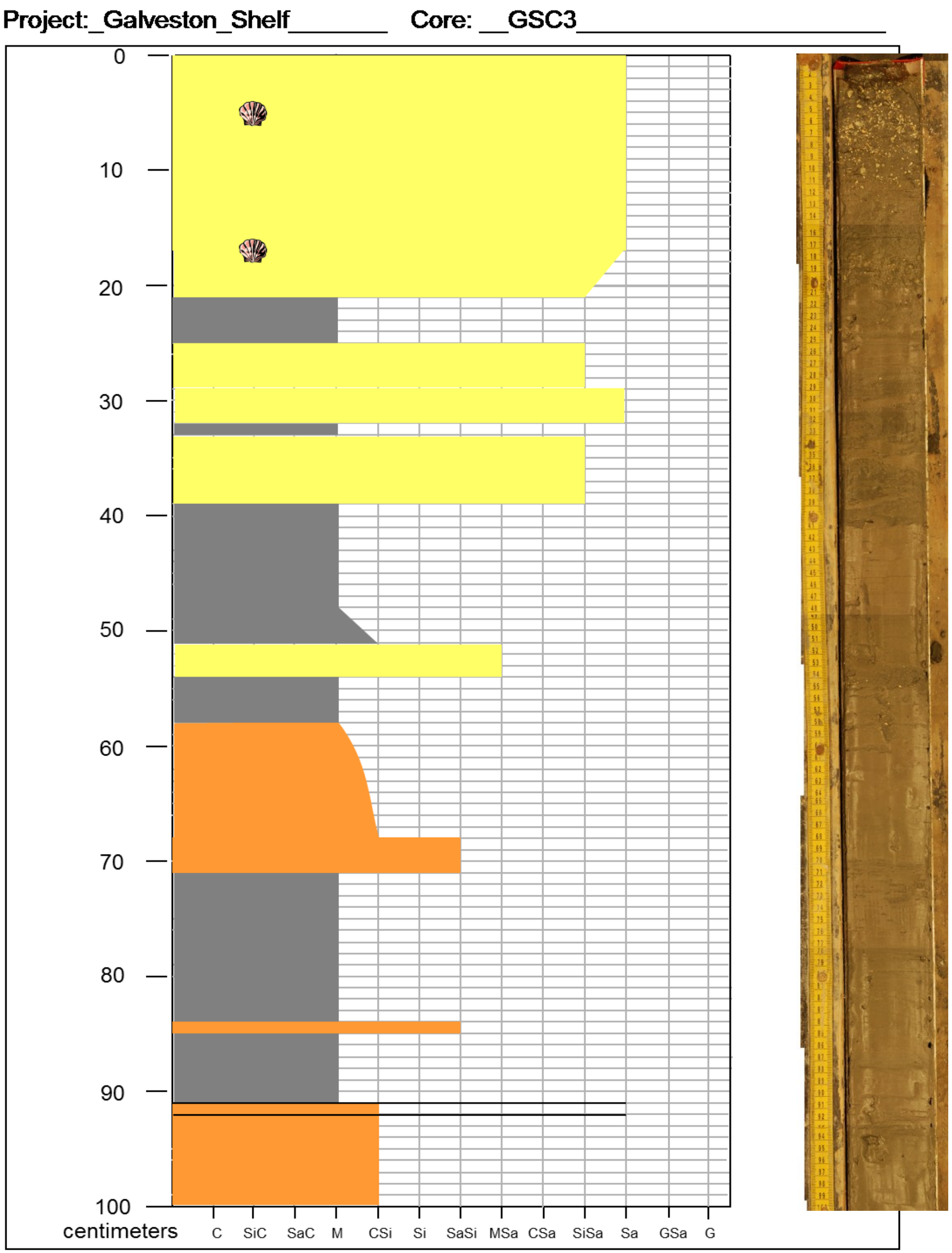

Project:_Galveston_Shelf________
Core: __GSC1___________________
0
10
20
30
40
50
60
70
80
90
100
centimeters
C
SiC
SaC
M
CSi
Si
SaSi
MSa
CSa
SiSa
Sa
GSa
G

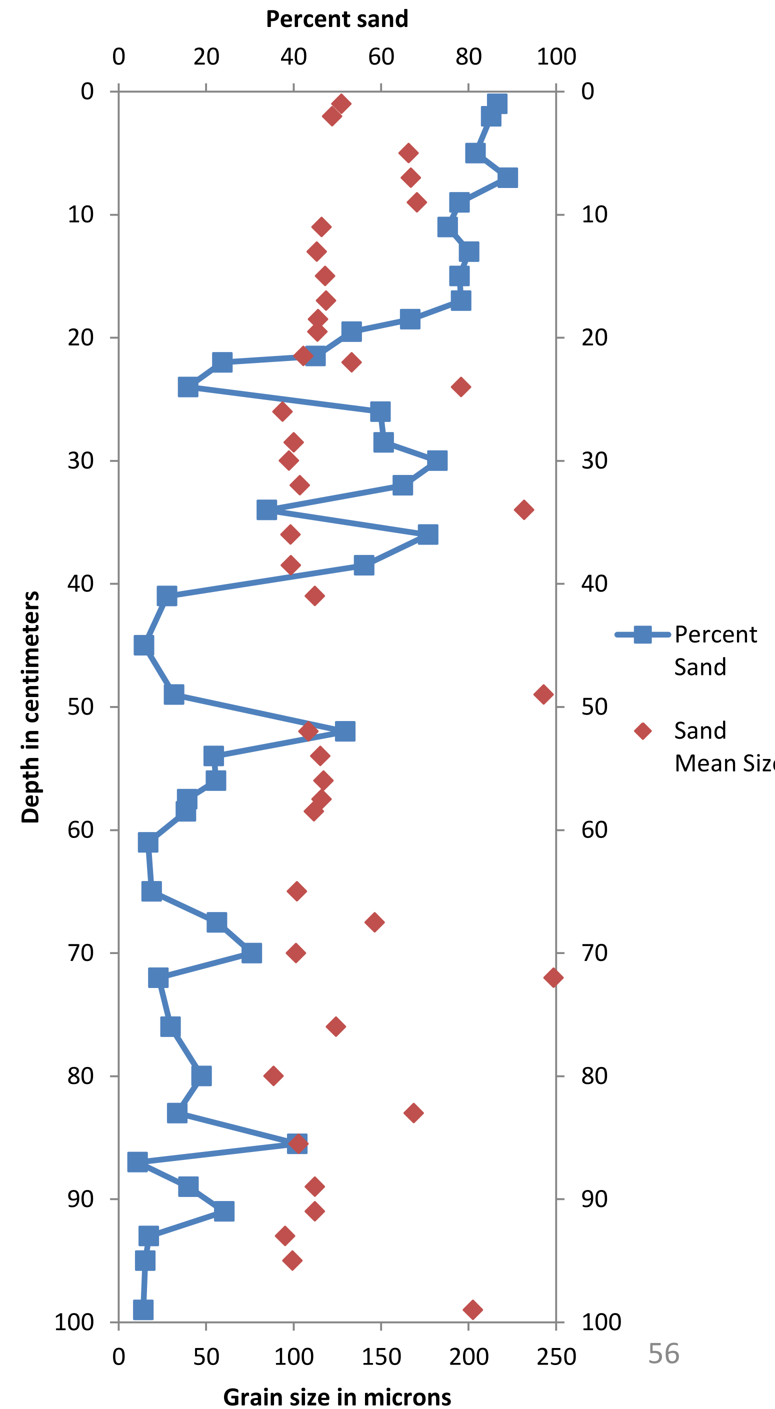

Percent sand
0
20
40
60
80
100
Depth in centimeters
Percent Sand
Sand Mean Size
0
50
100
150
200
250
Grain size in microns

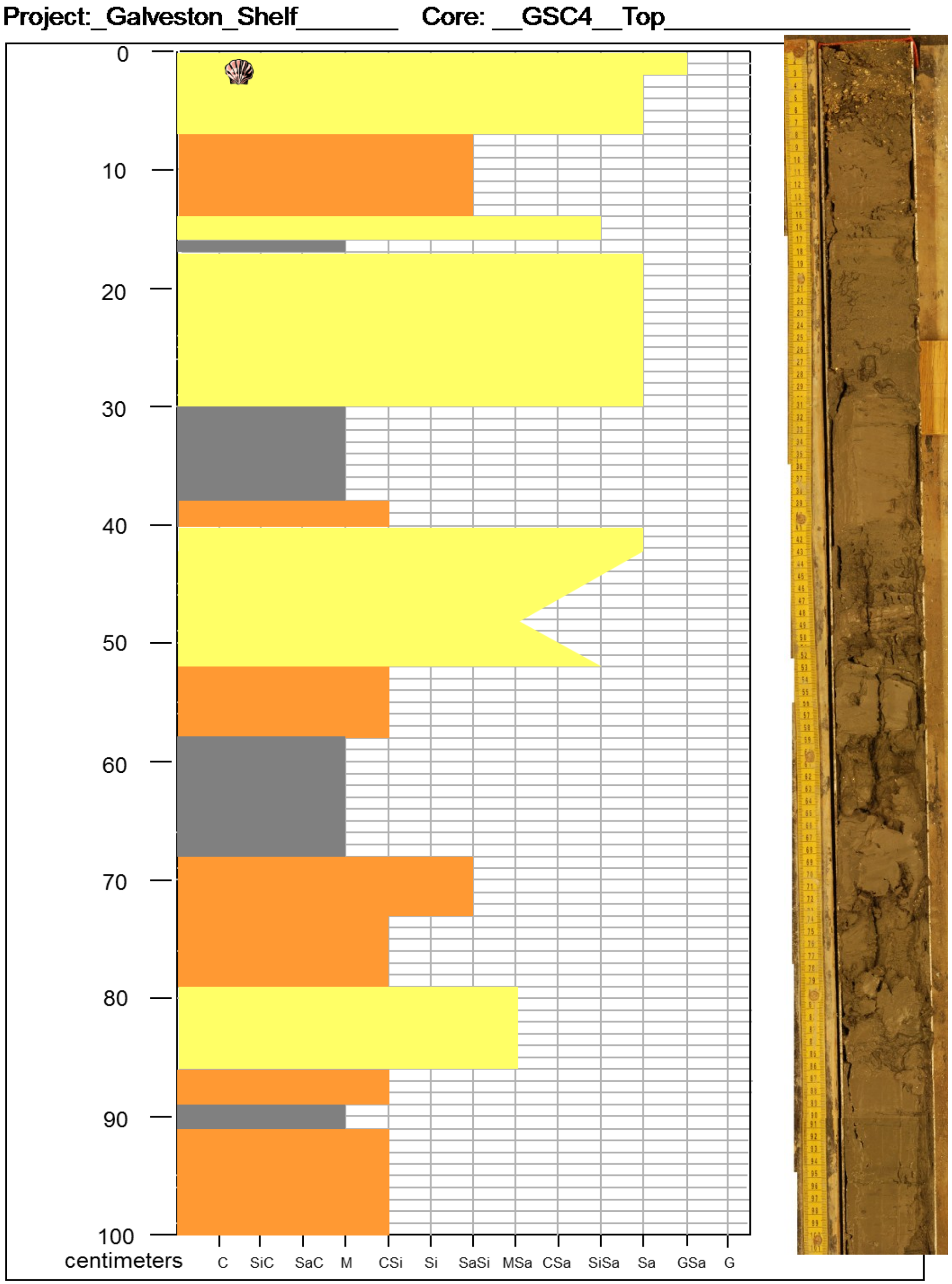
Project:_Galveston_Shelf________ Core: __GSC2________________________

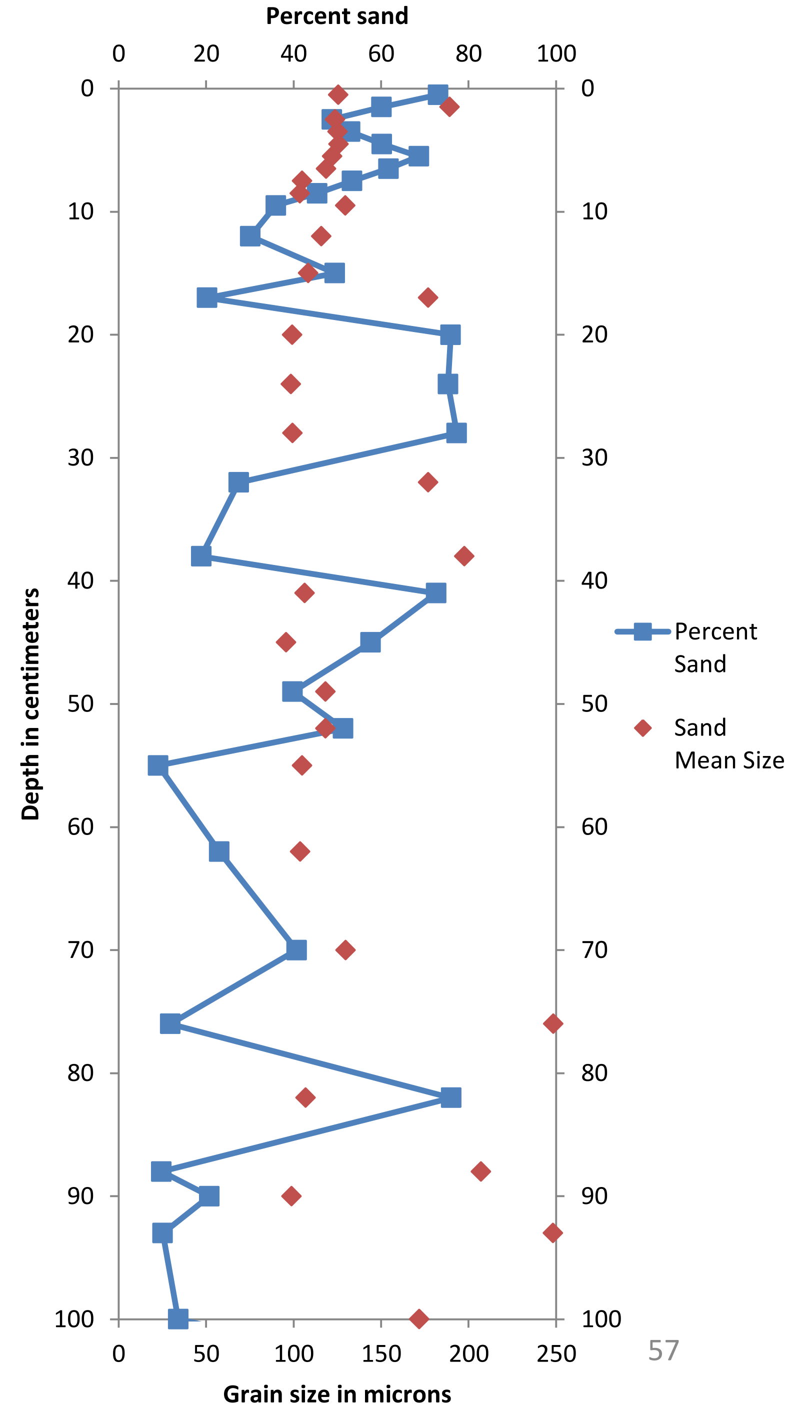




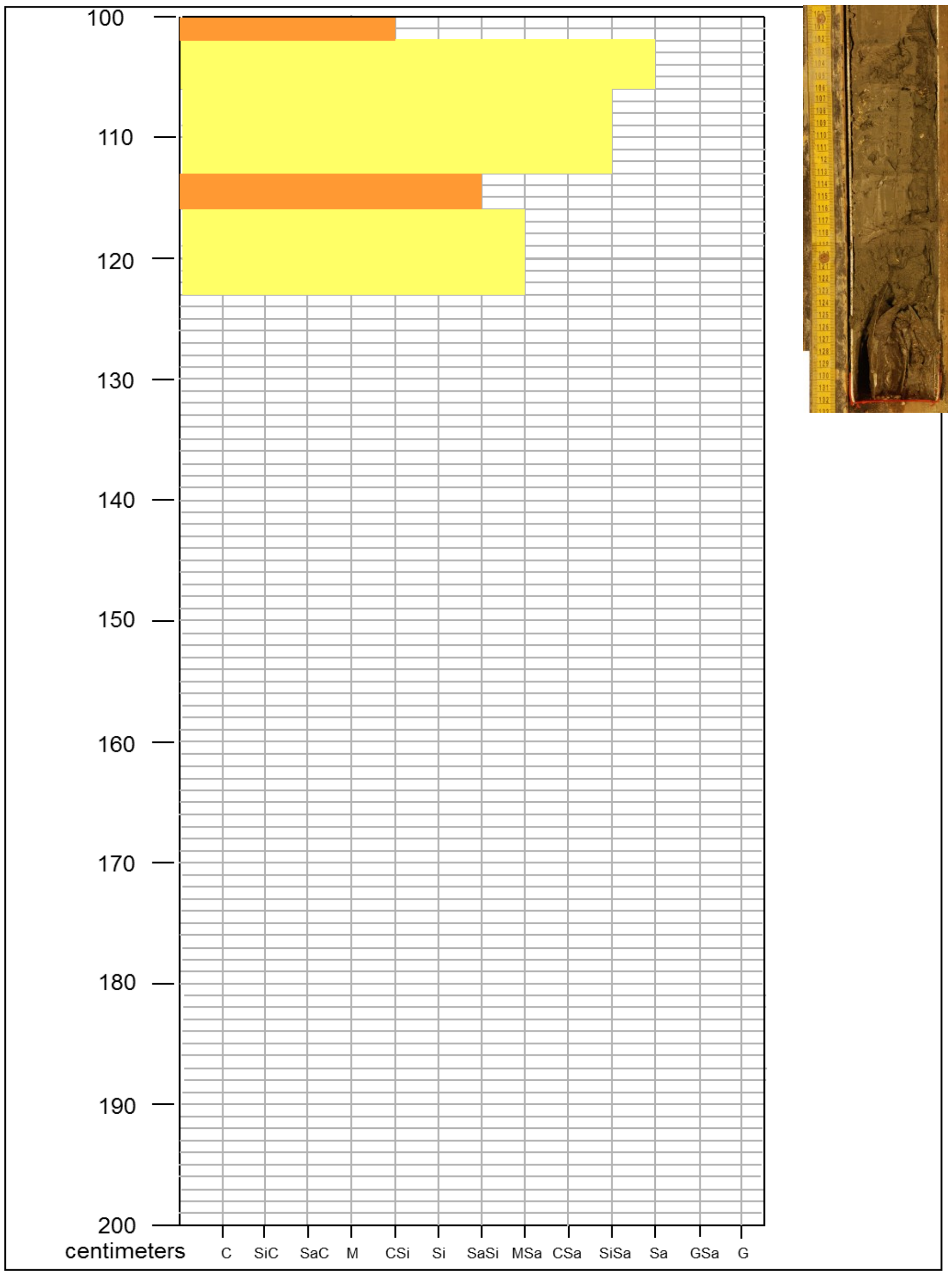

Project:_Galveston_Shelf________ Core: __GSC3___________________________
0
10
20
30
40
50
60
70
80
90
100
centimeters
C SiC SaC M CSi Si SaSi MSa CSa SiSa Sa GSa G

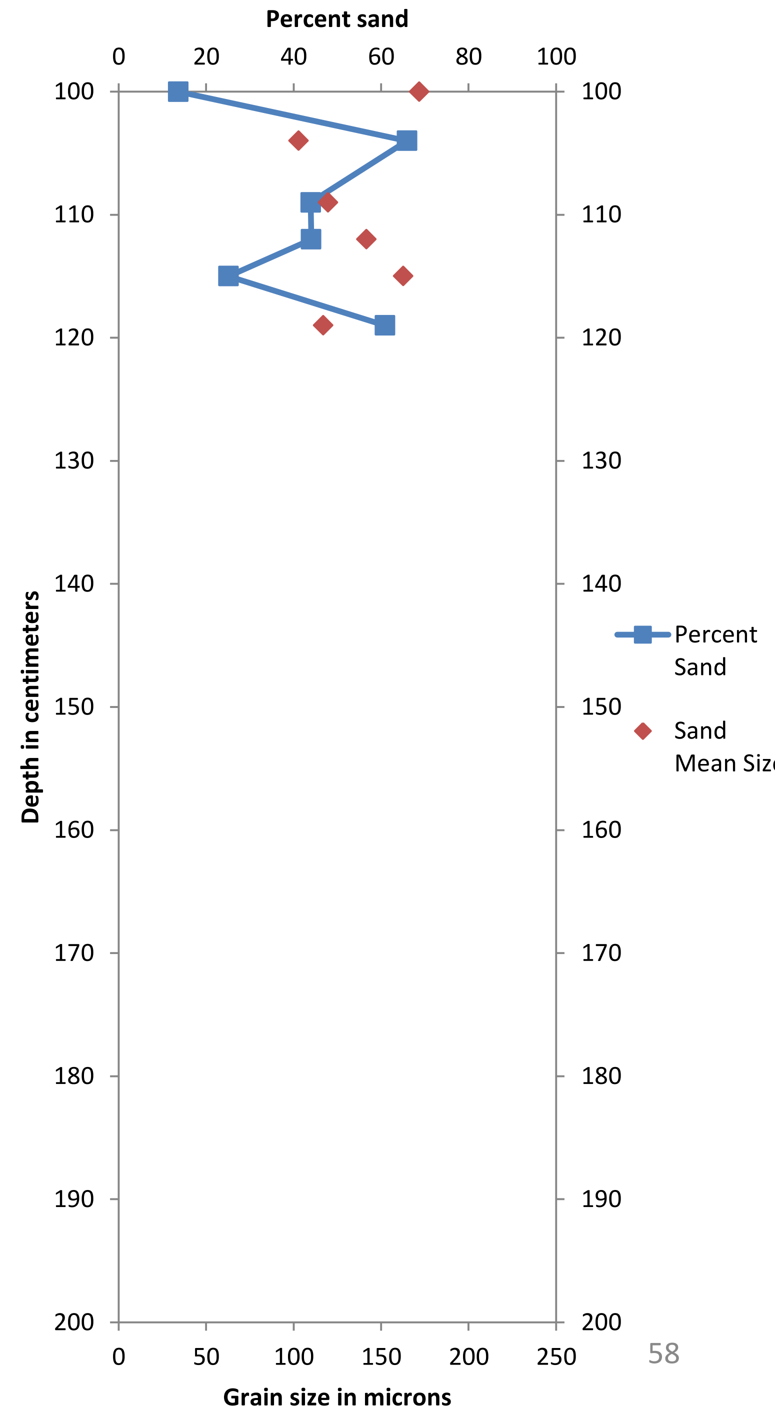

Percent sand
0 20 40 60 80 100
Depth in centimeters
0 10 20 30 40 50 60 70 80 90 100
Percent Sand
Sand Mean Size
0 50 100 150 200 250
Grain size in microns

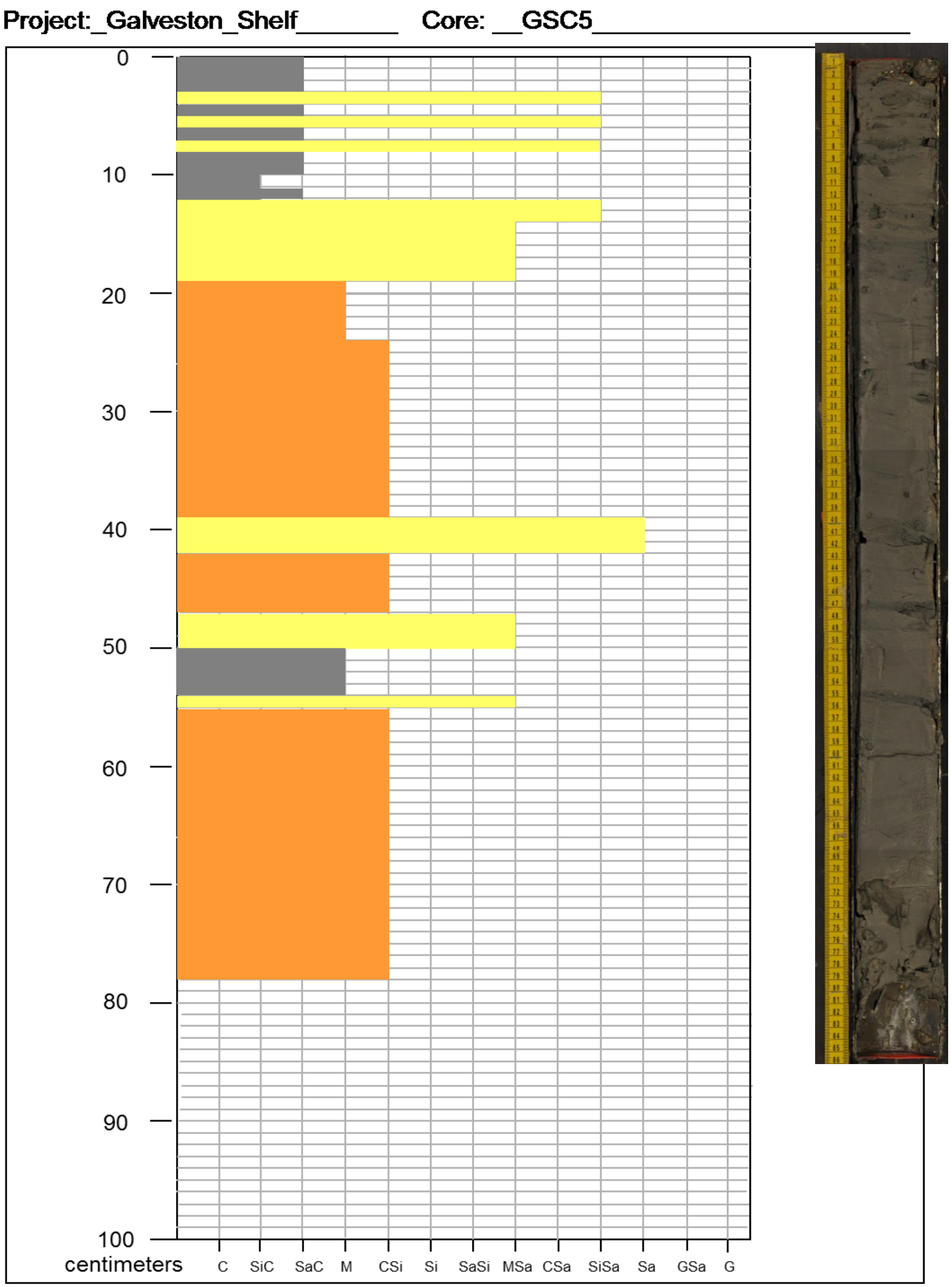

Project:_Galveston_Shelf________ Core: __GSC4__Top______________
0
10
20
30
40
50
60
70
80
90
100
centimeters
C SiC SaC M CSi Si SaSi MSa CSa SiSa Sa GSa G

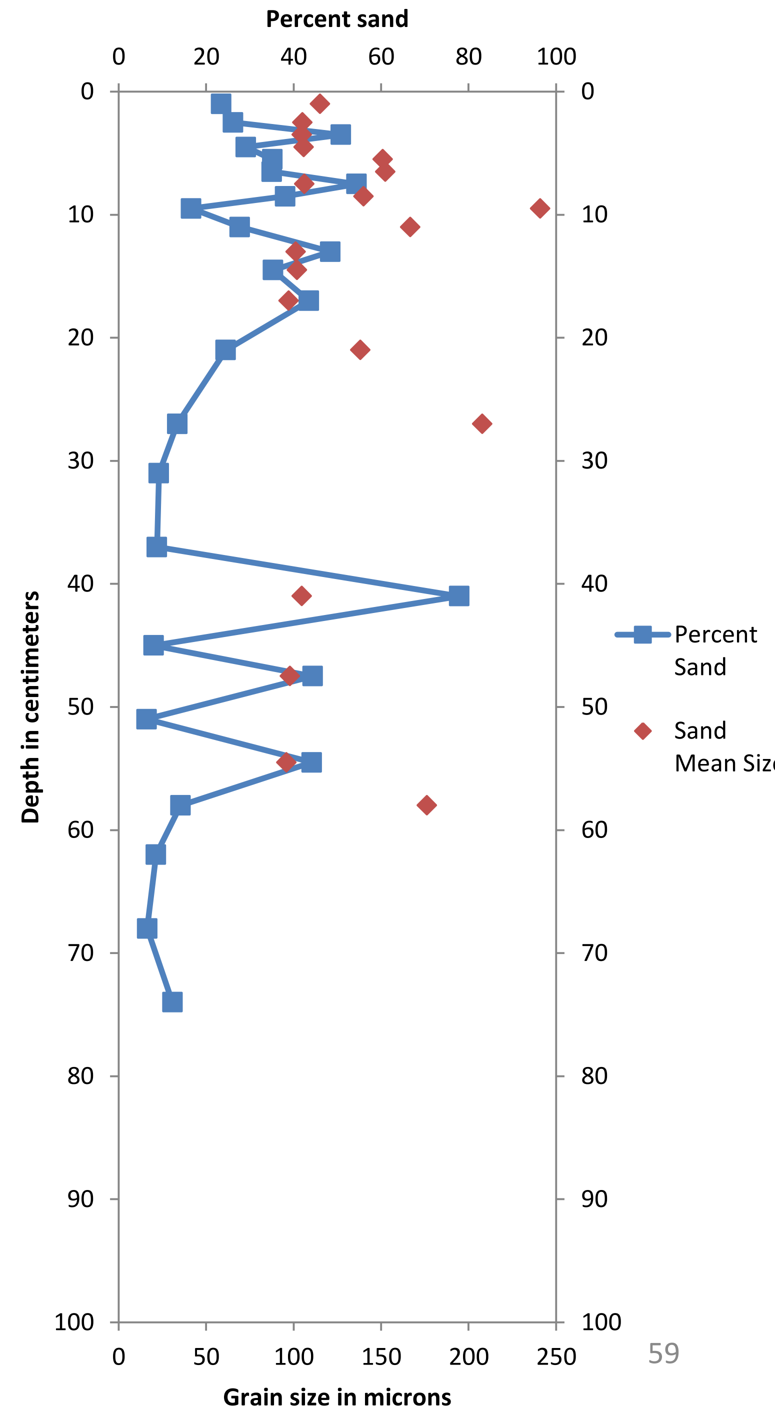

Percent sand
0 20 40 60 80 100
Depth in centimeters
0 10 20 30 40 50 60 70 80 90 100
Percent Sand
Sand Mean Size
0 50 100 150 200 250
Grain size in microns

Project:_Galveston_Shelf_______ Core: __GSC4__Bottom______________

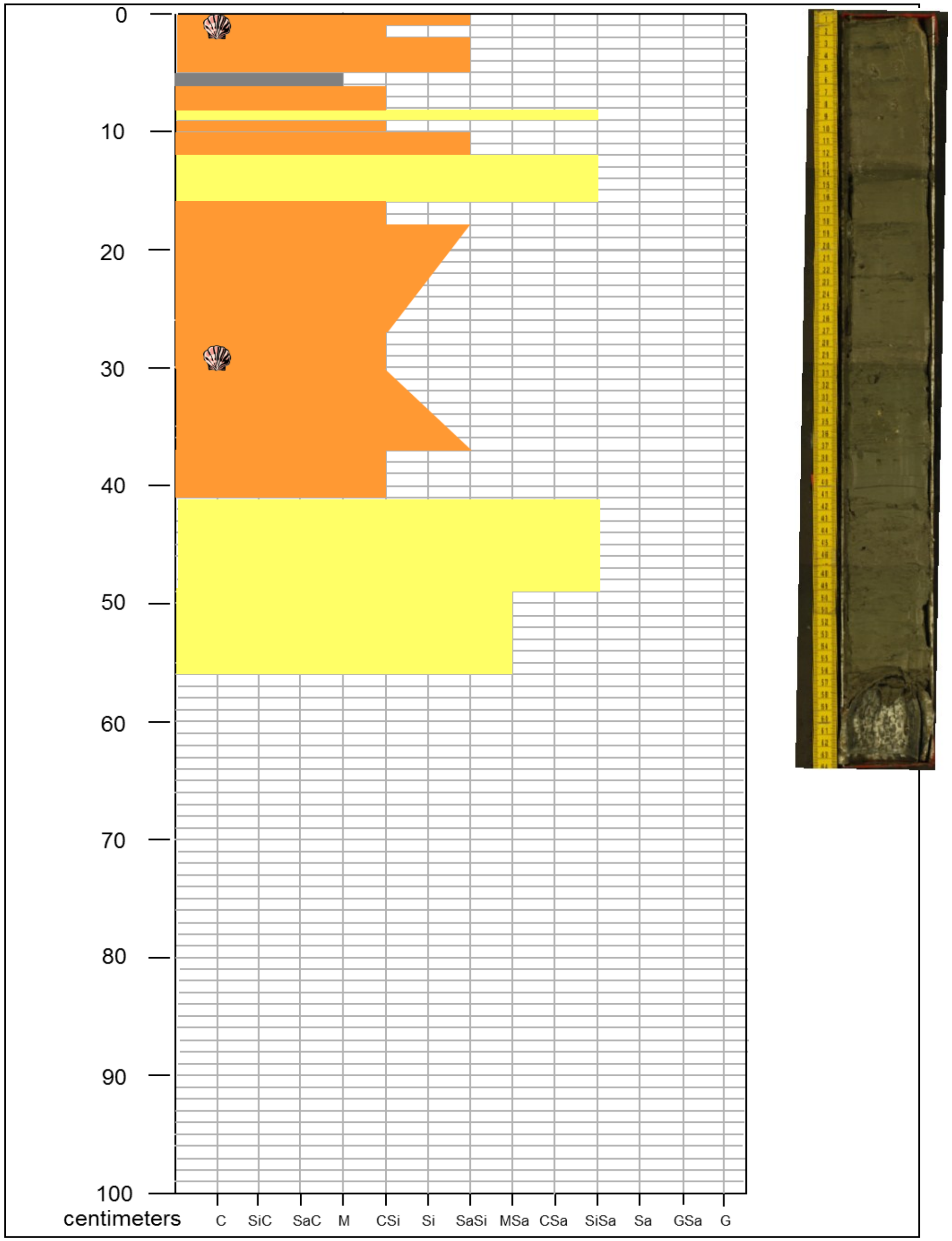


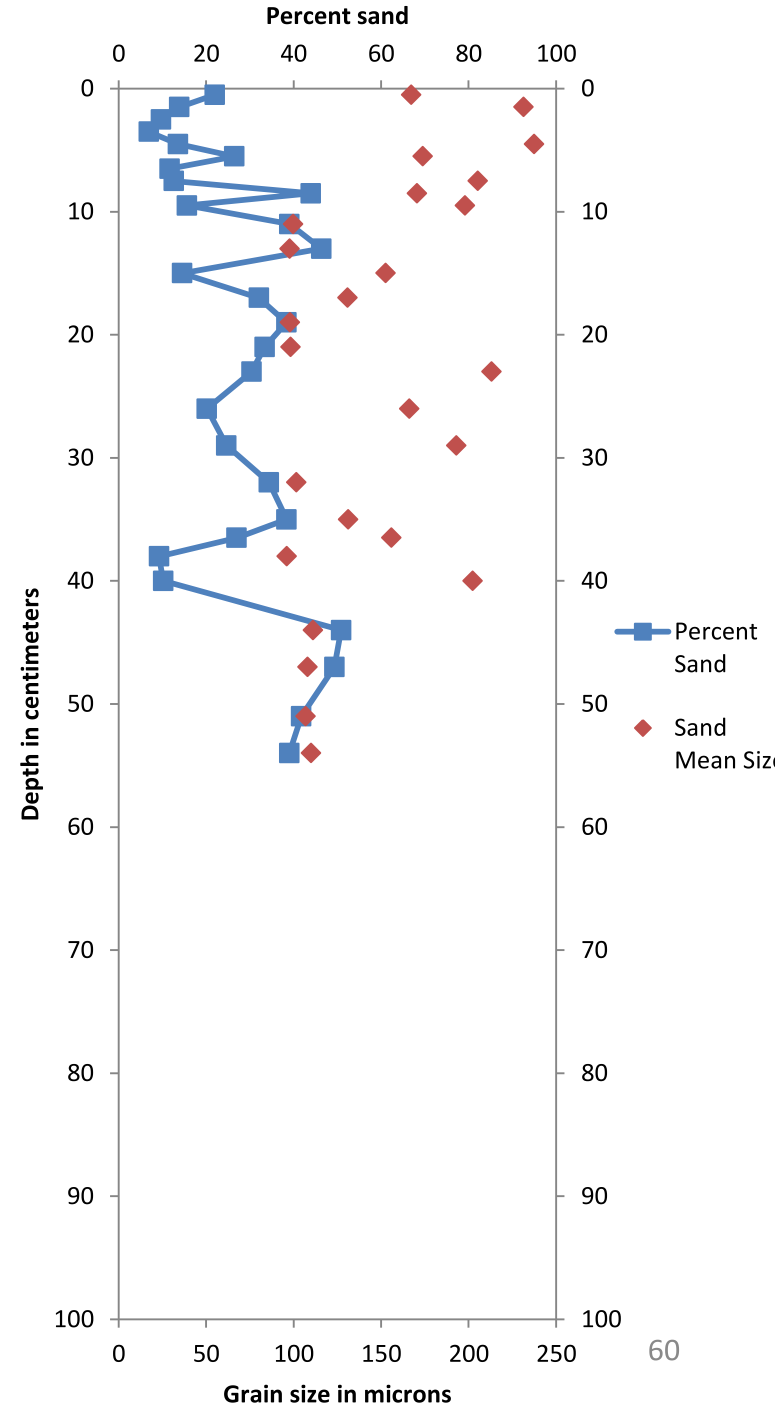



Project:_Galveston_Shelf________
Core: __GSC5________________________
0
10
20
30
40
50
60
70
80
90
100
centimeters
C
SiC
SaC
M
CSi
Si
SaSi
MSa
CSa
SiSa
Sa
GSa
G

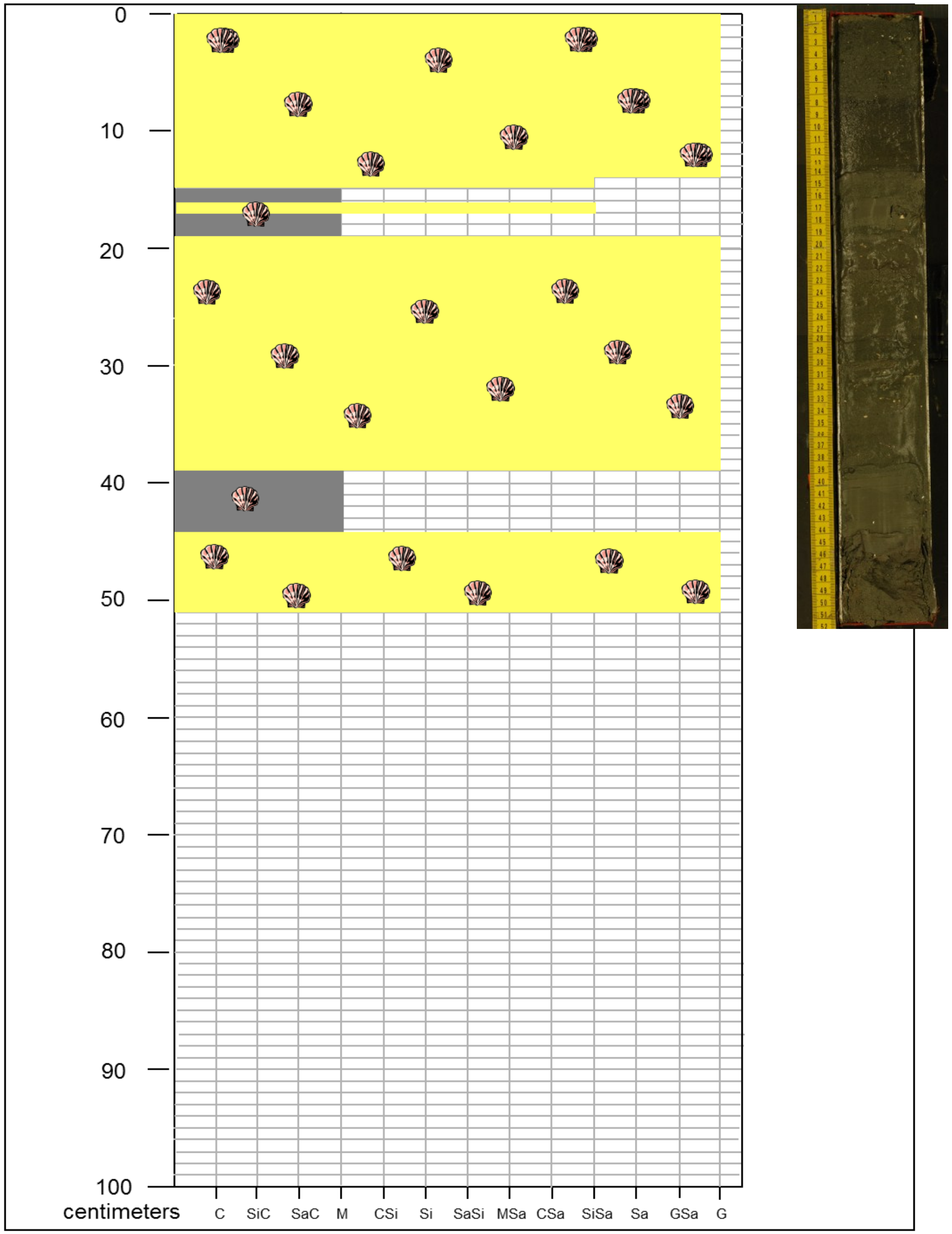

Percent sand
0
20
40
60
80
100
Depth in centimeters
Percent Sand
Sand Mean Size
0
50
100
150
200
250
Grain size in microns

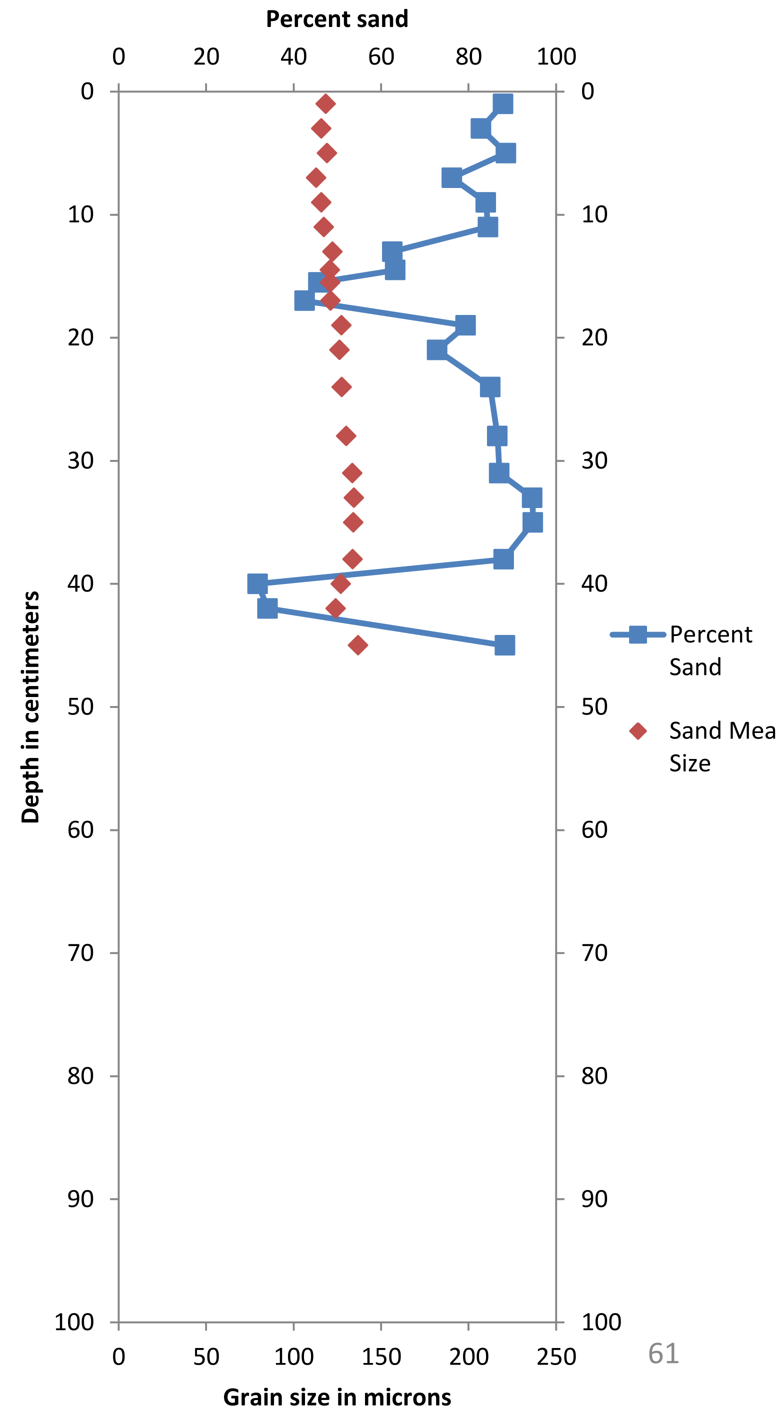
Project:_Galveston_Shelf________ Core: __GSC6______________________



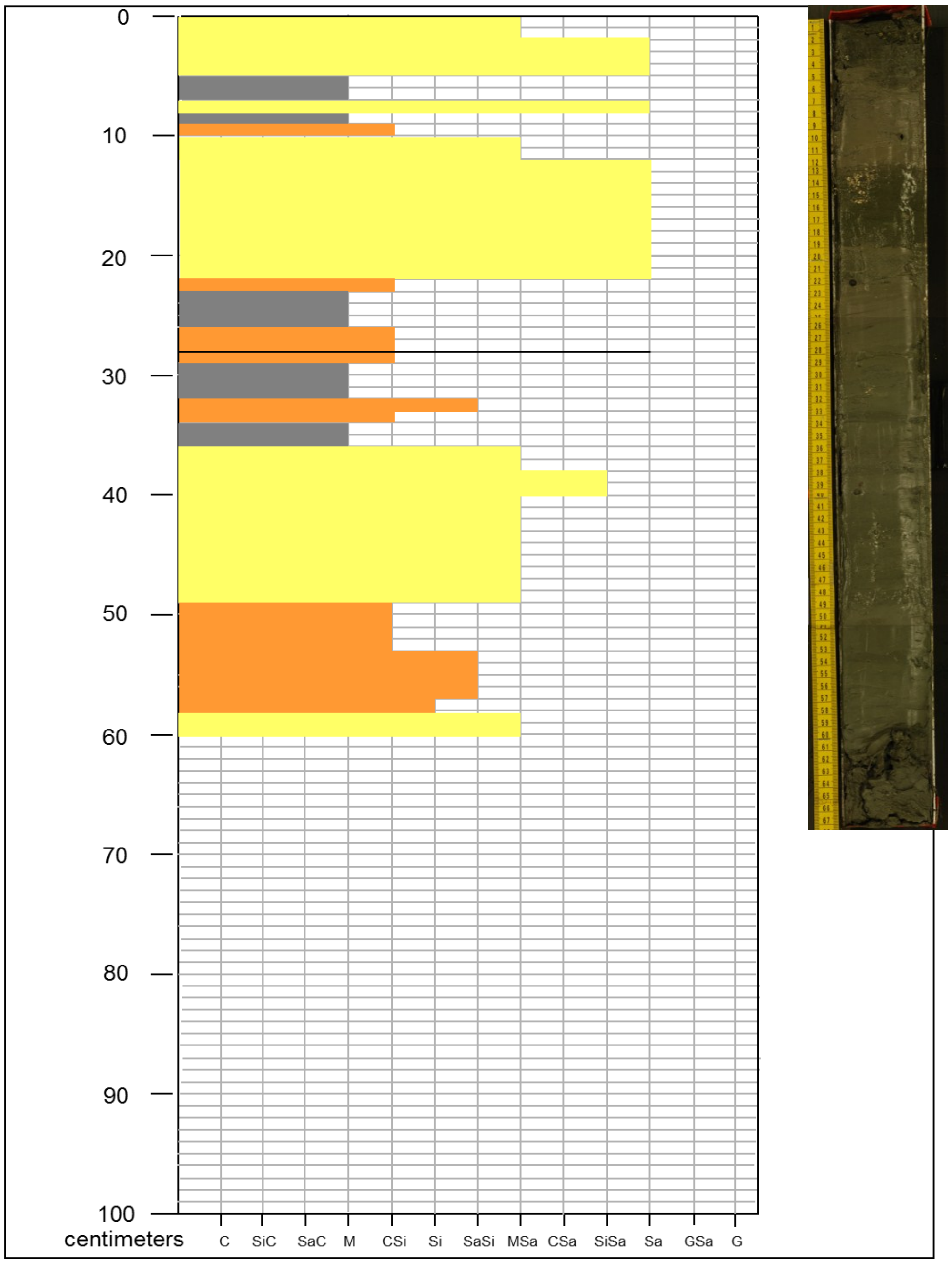


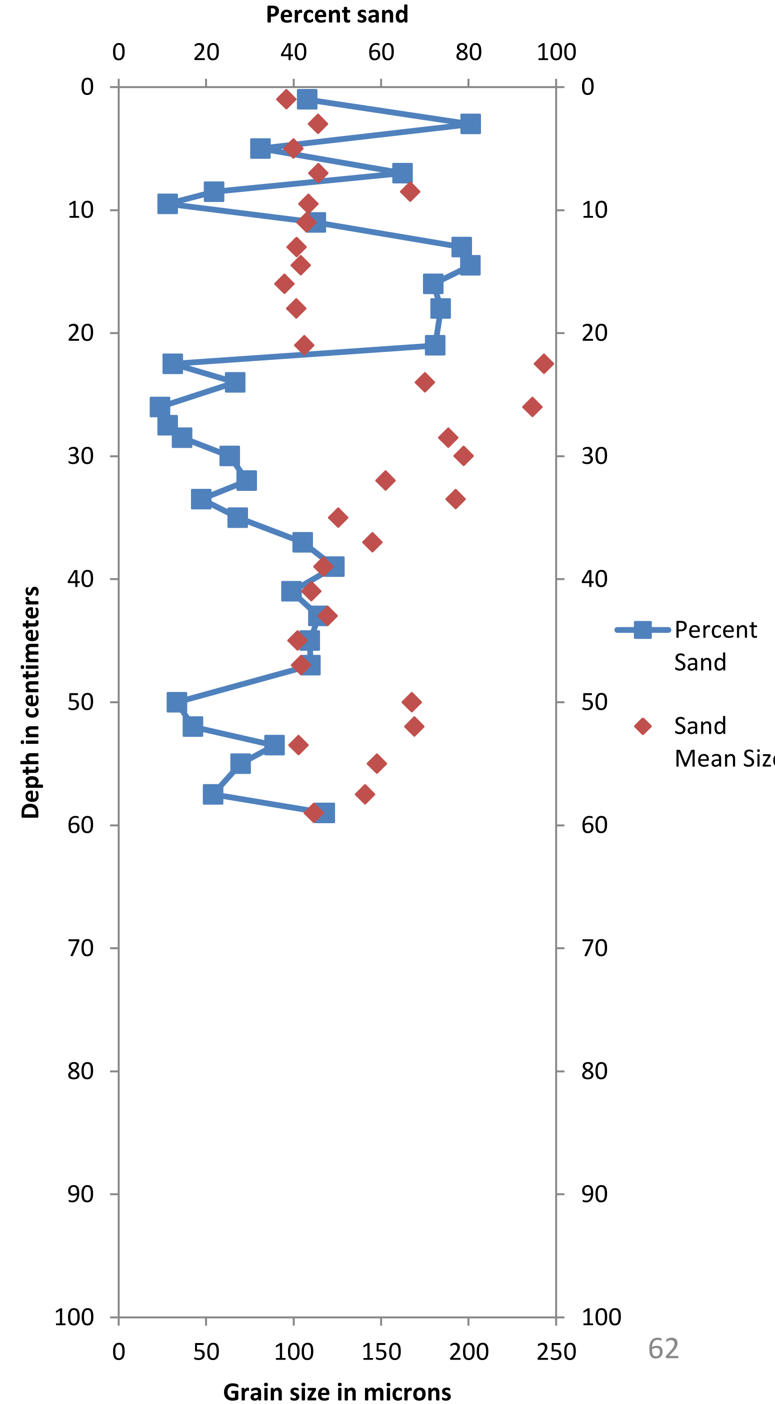
Project:_Galveston_Shelf________ Core: __GSE1________________________

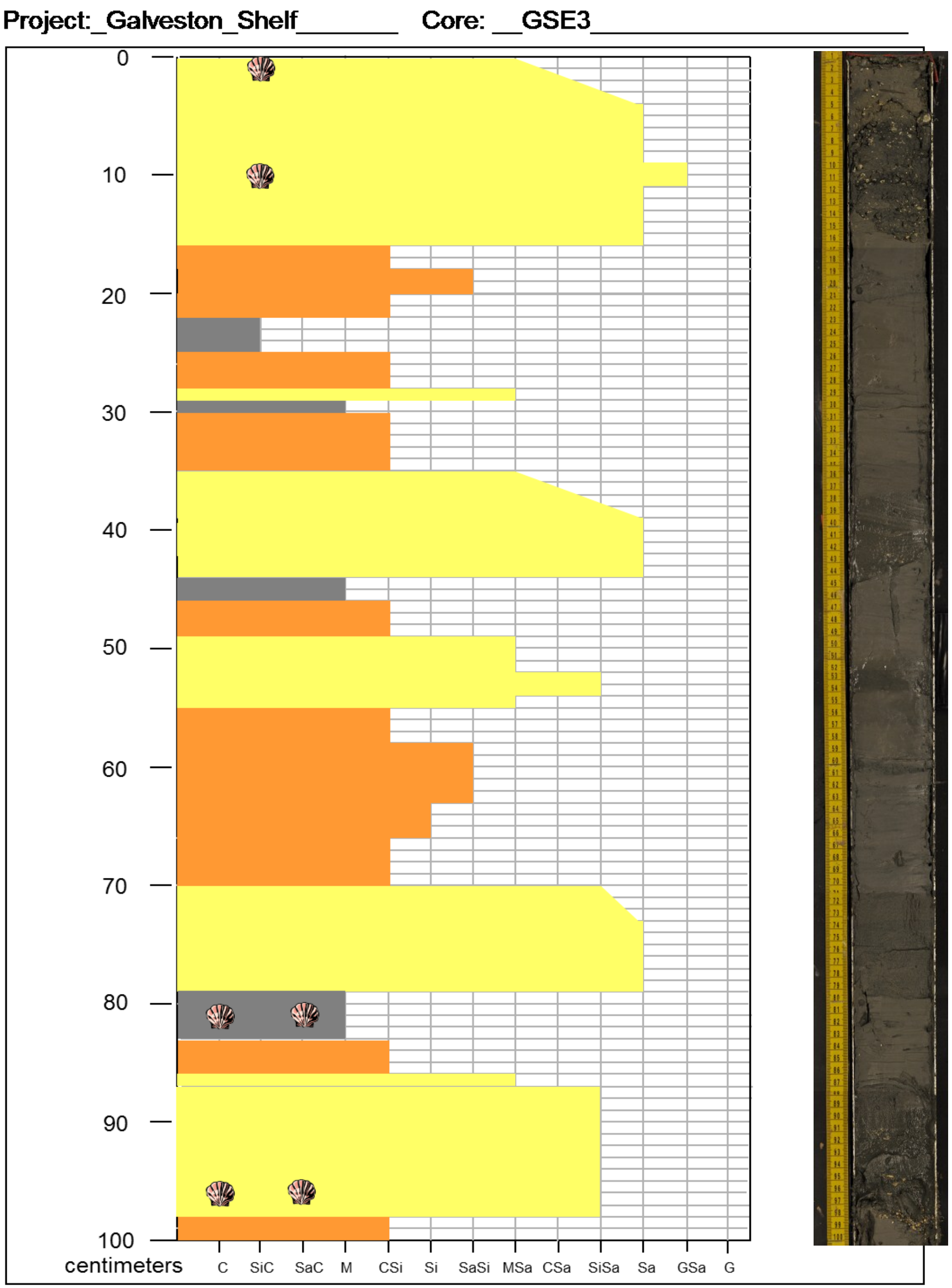




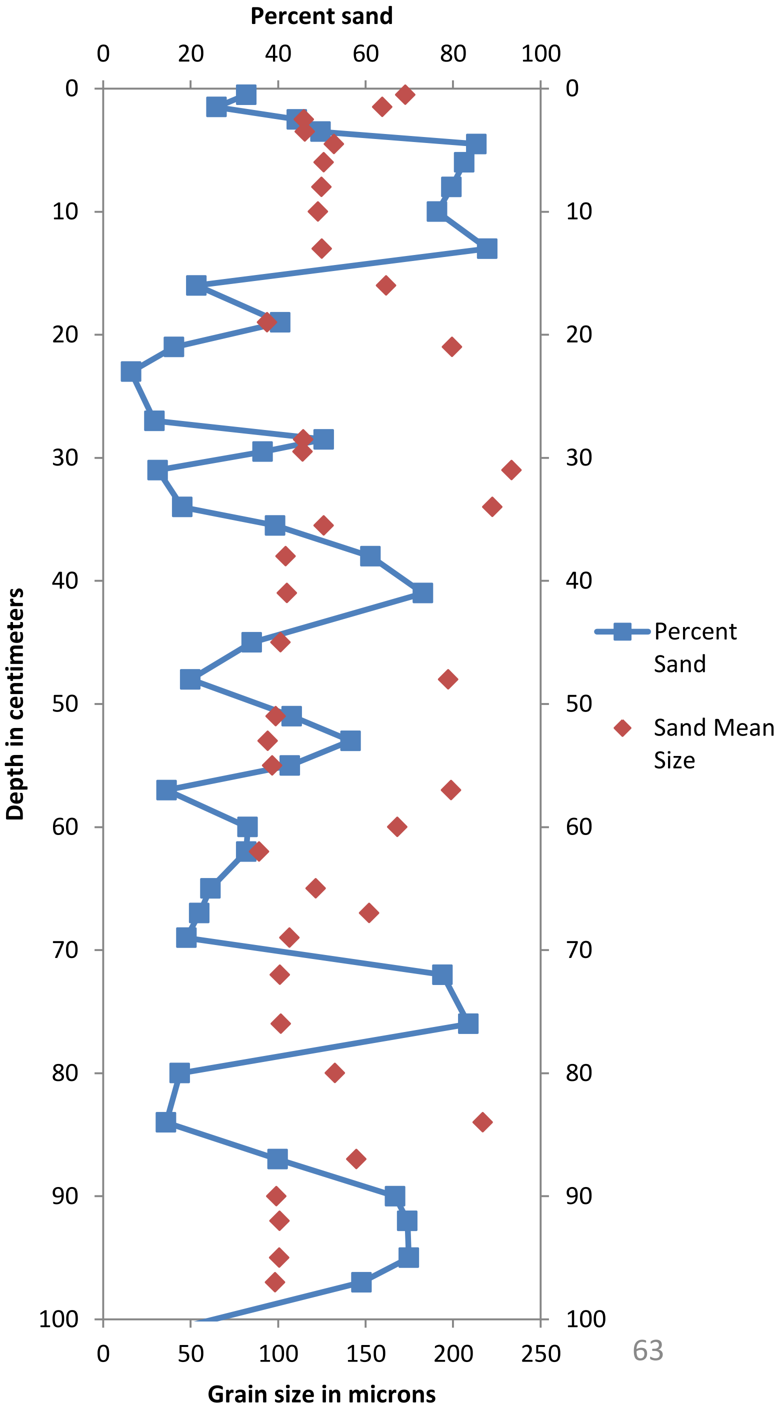
Project:_Galveston_Shelf________ Core: __GSE2_________________________



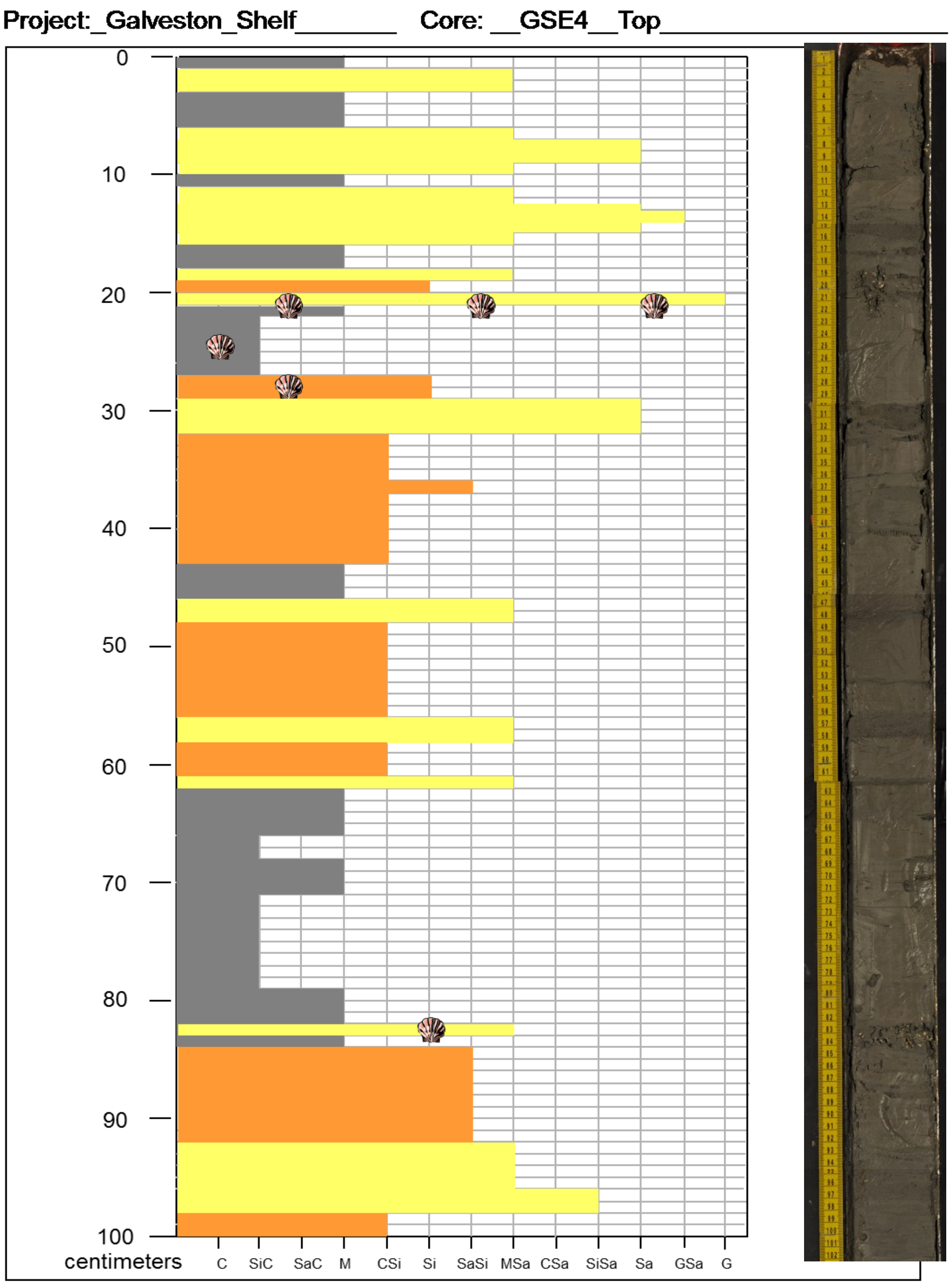


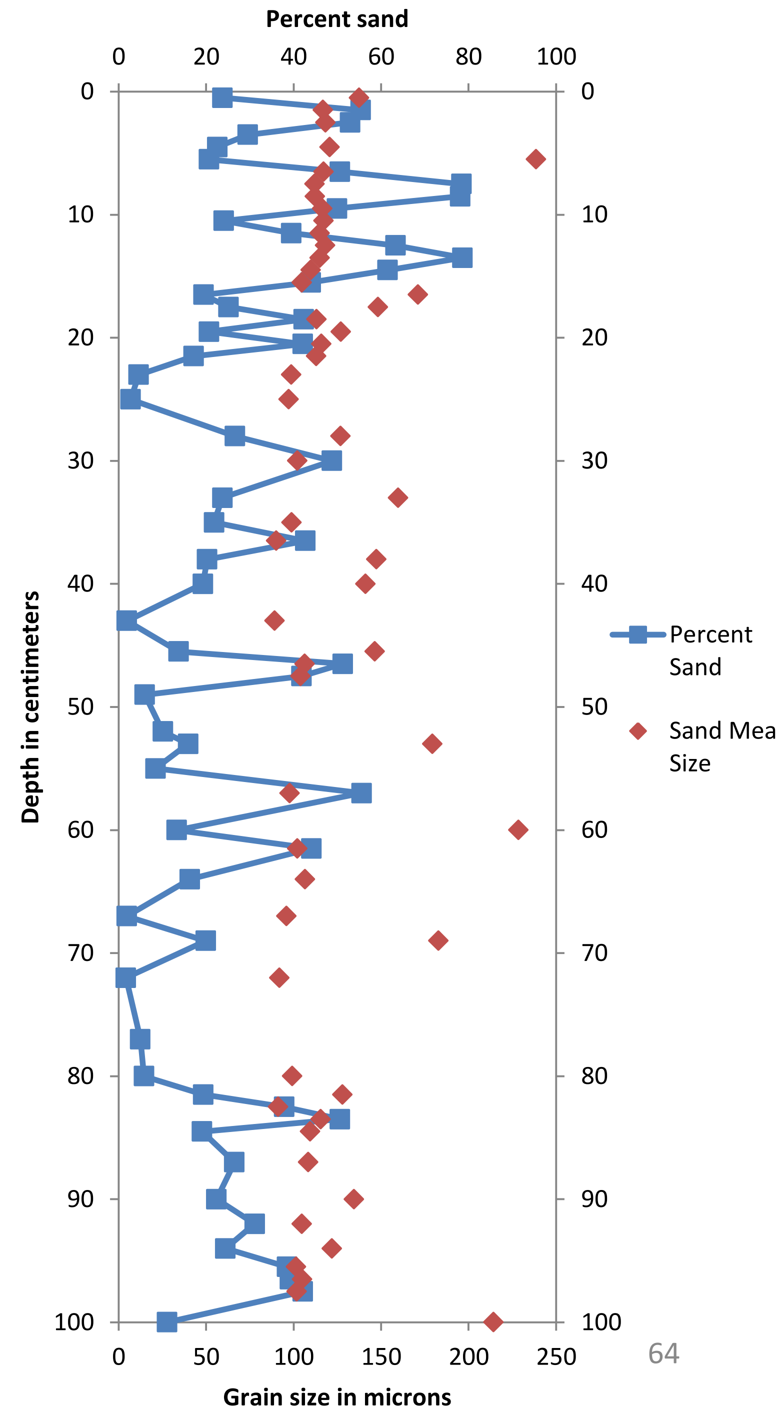


Project:_Galveston_Shelf________
Core: __GSE3________________________
0
10
20
30
40
50
60
70
80
90
100
centimeters
C
SiC
SaC
M
CSi
Si
SaSi
MSa
CSa
SiSa
Sa
GSa
G

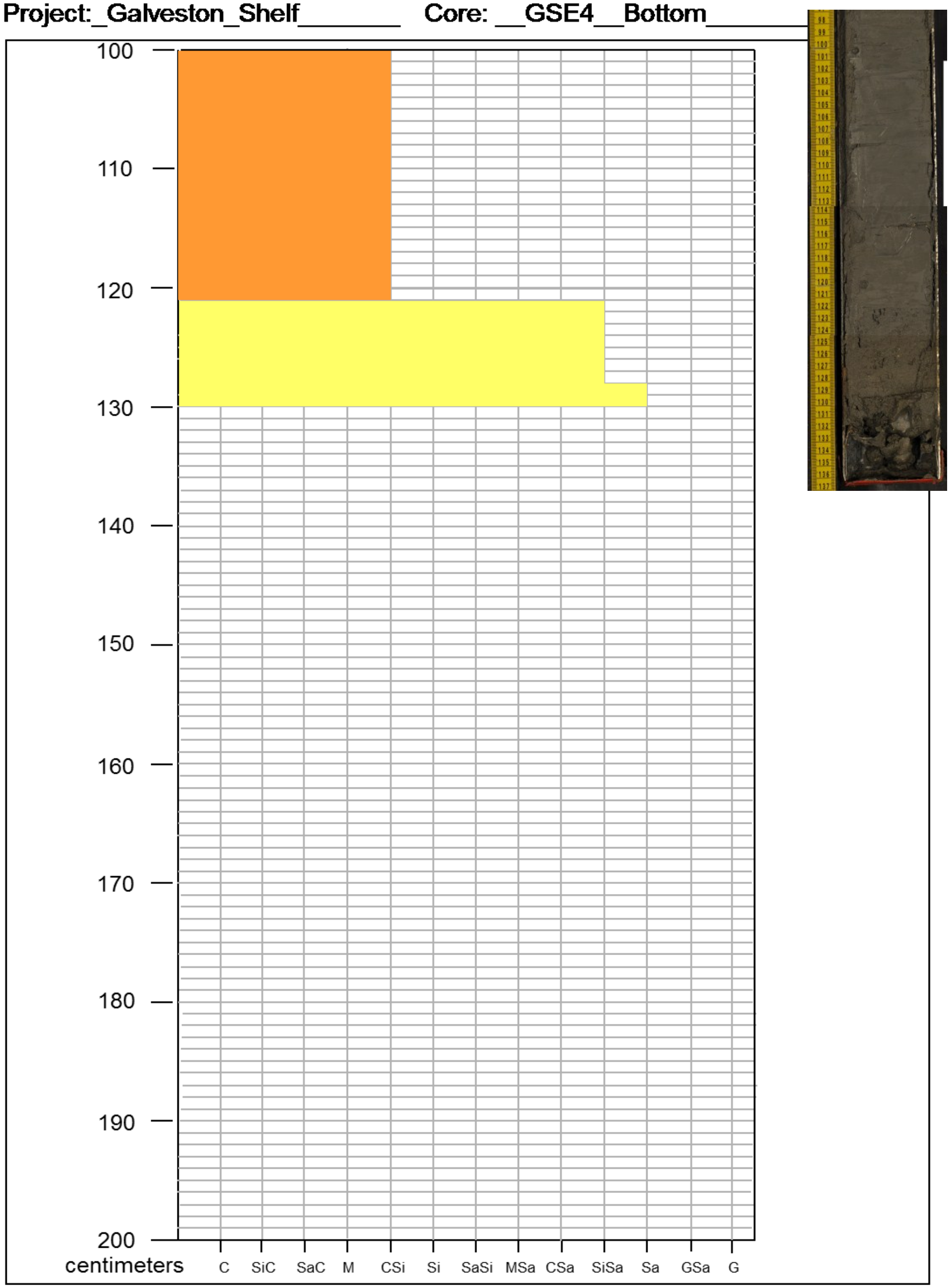


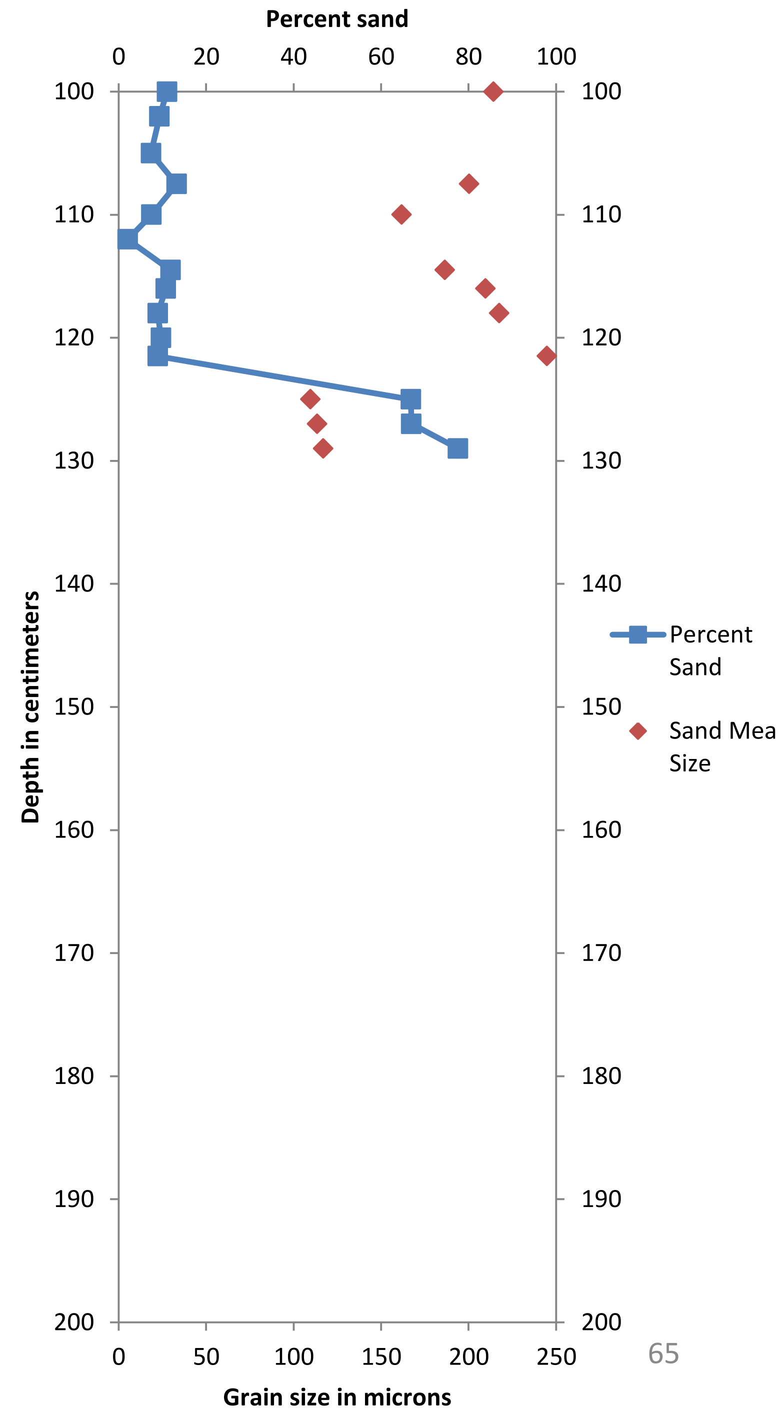
Percent sand
0
20
40
60
80
100
Depth in centimeters
Grain size in microns
0
50
100
150
200
250
Percent Sand
Sand Mean Size

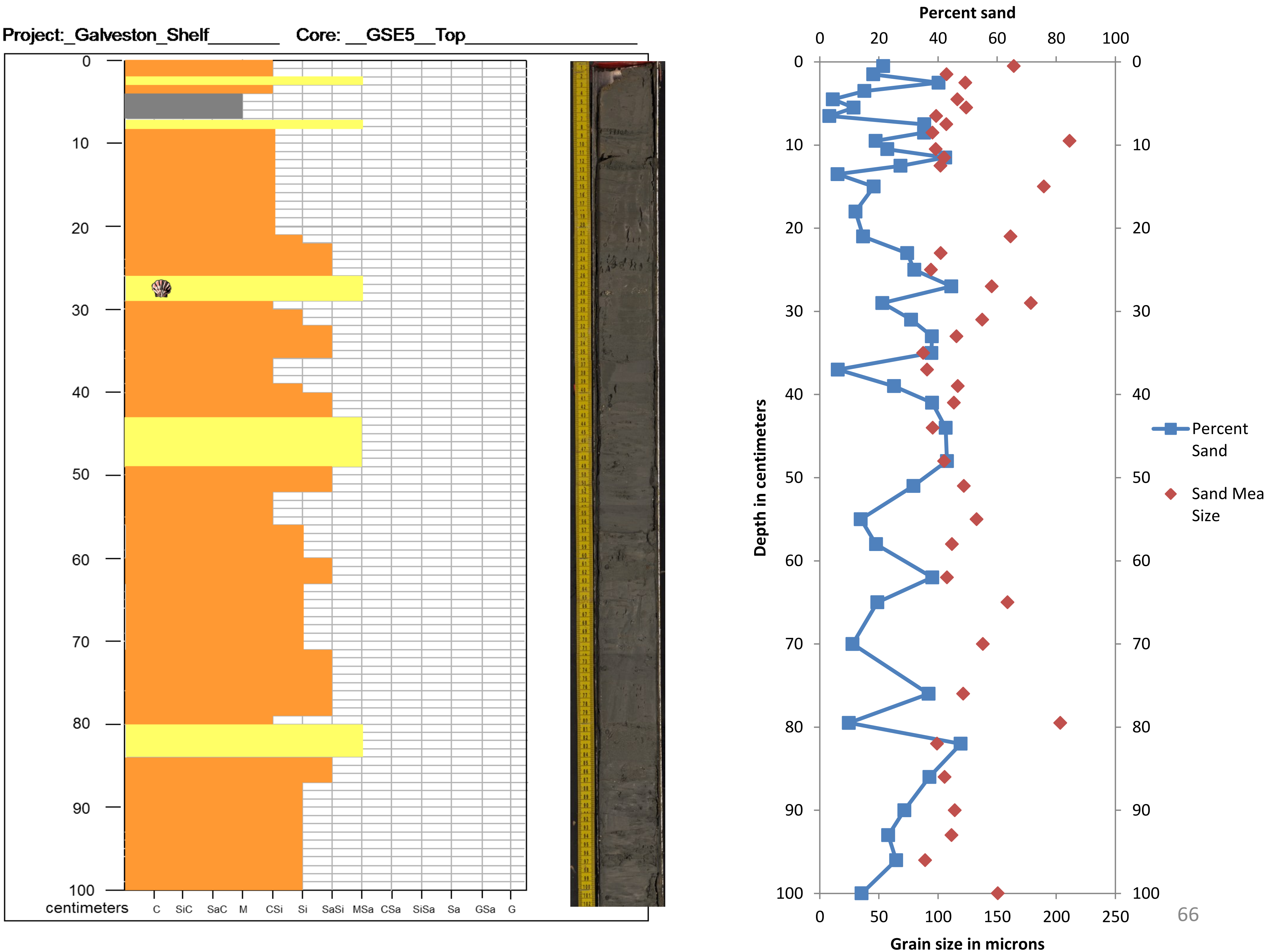

Project:_Galveston_Shelf_______
Core: __GSE4__Top___
0
10
20
30
40
50
60
70
80
90
100
centimeters
C
SiC
SaC
M
CSi
Si
SaSi
MSa
CSa
SiSa
Sa
GSa
G


Percent sand
0
20
40
60
80
100
Depth in centimeters
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
Grain size in microns
Percent Sand
Sand Mean Size

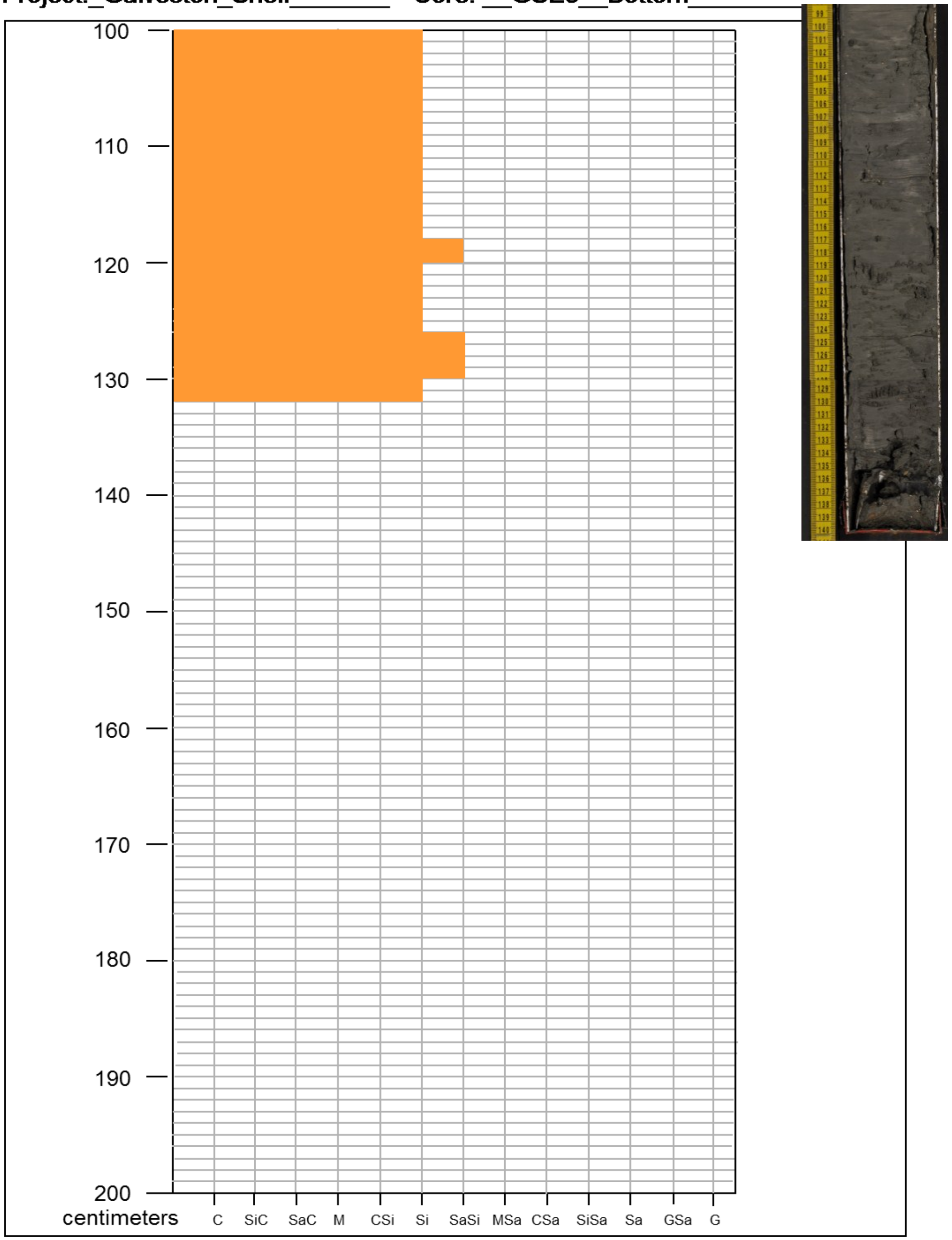
Project:_Galveston_Shelf________ Core: __GSE4__Bottom__________

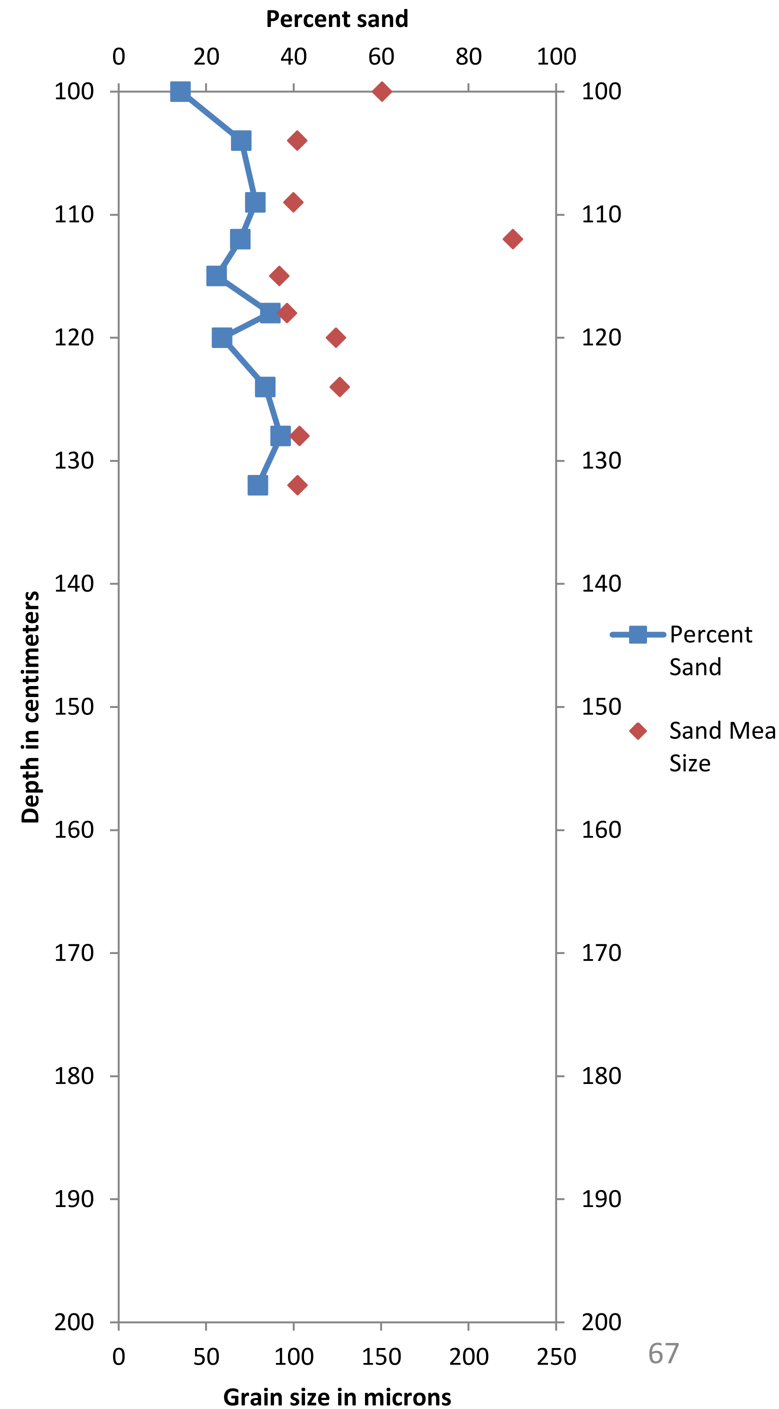


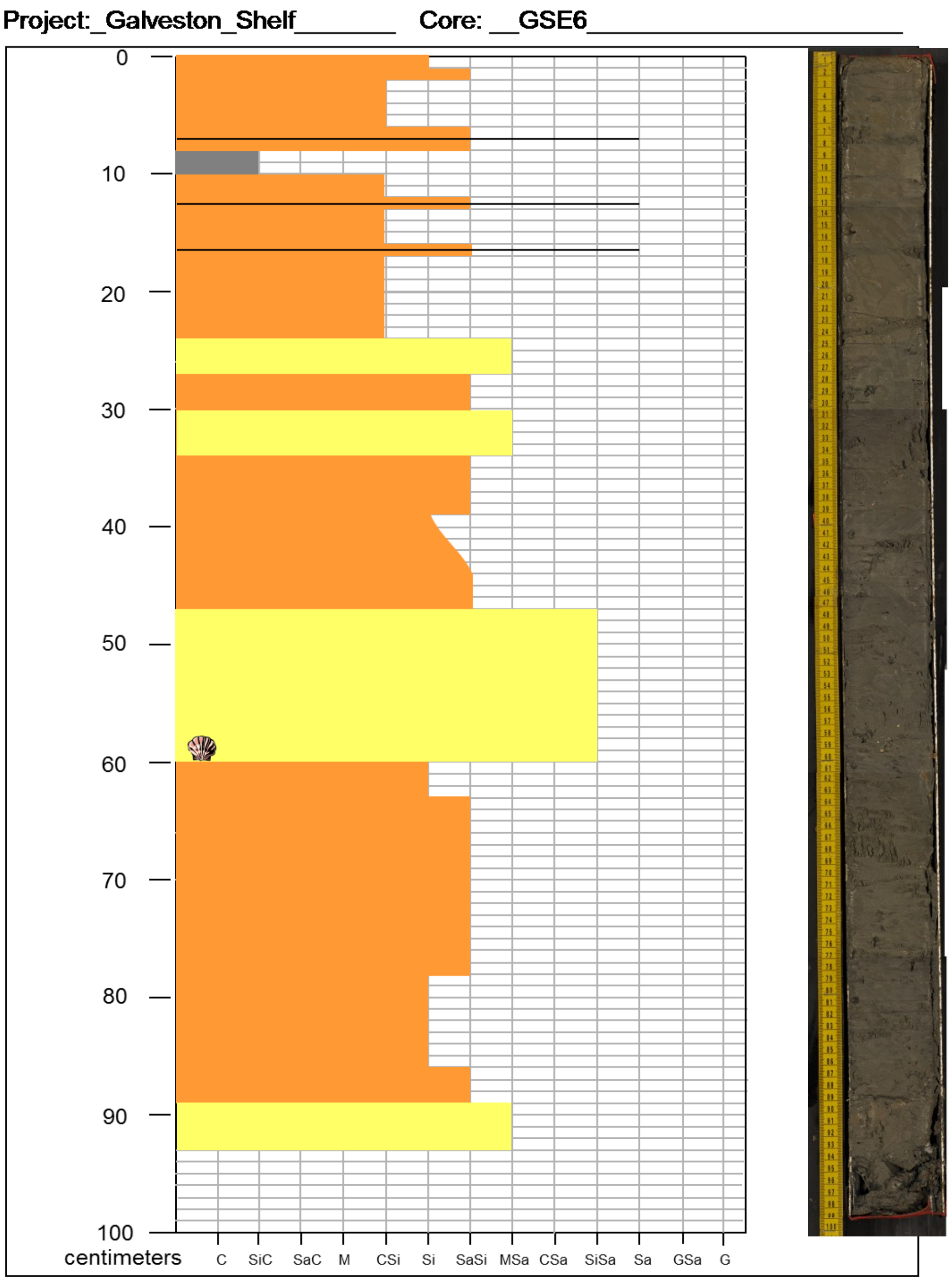



Project:_Galveston_Shelf________ Core: __GSE5__Top__________________
0
10
20
30
40
50
60
70
80
90
100
centimeters
C SiC SaC M CSi Si SaSi MSa CSa SiSa Sa GSa G
Percent sand
0 20 40 60 80 100
Depth in centimeters
Percent Sand
Sand Mean Size
0 50 100 150 200 250
Grain size in microns

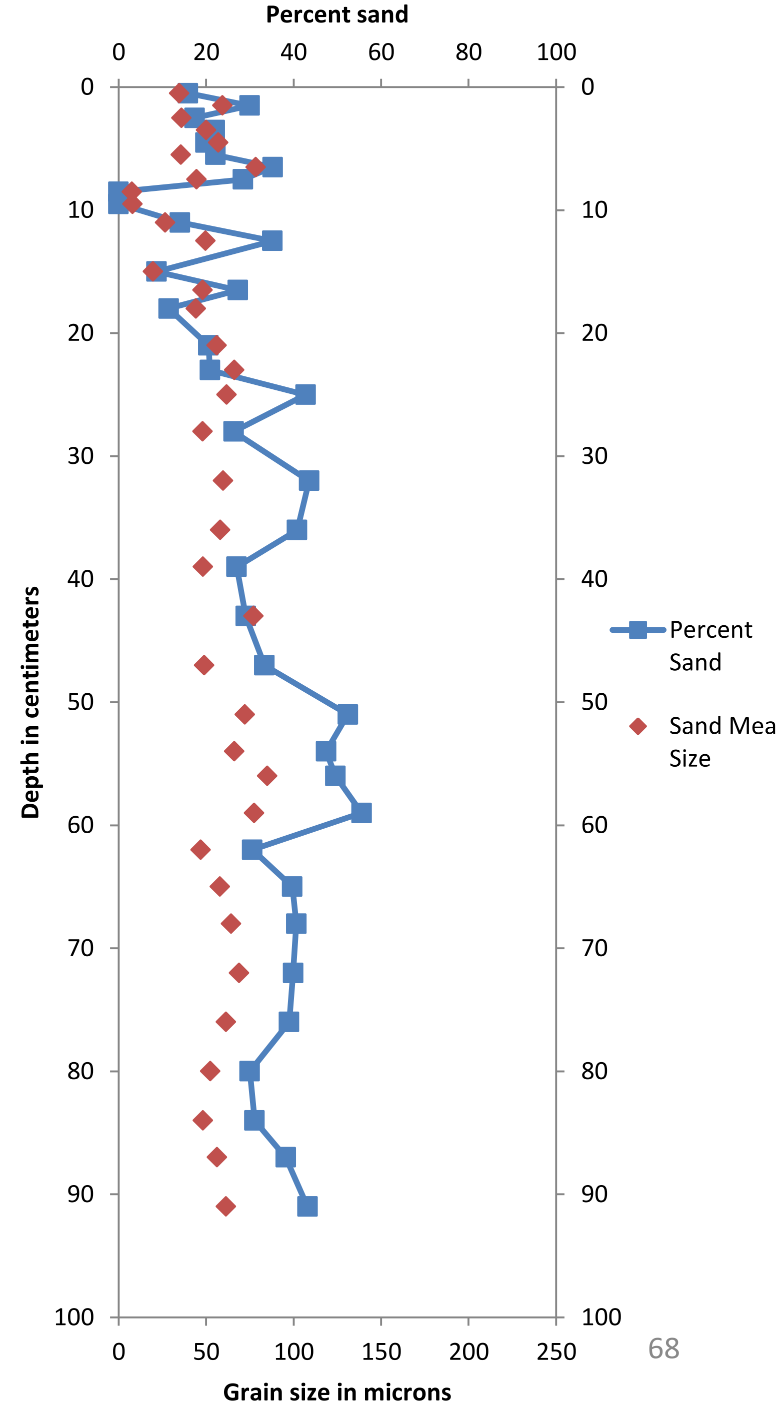
Project:_Galveston_Shelf_______ Core: __GSE5__Bottom_________





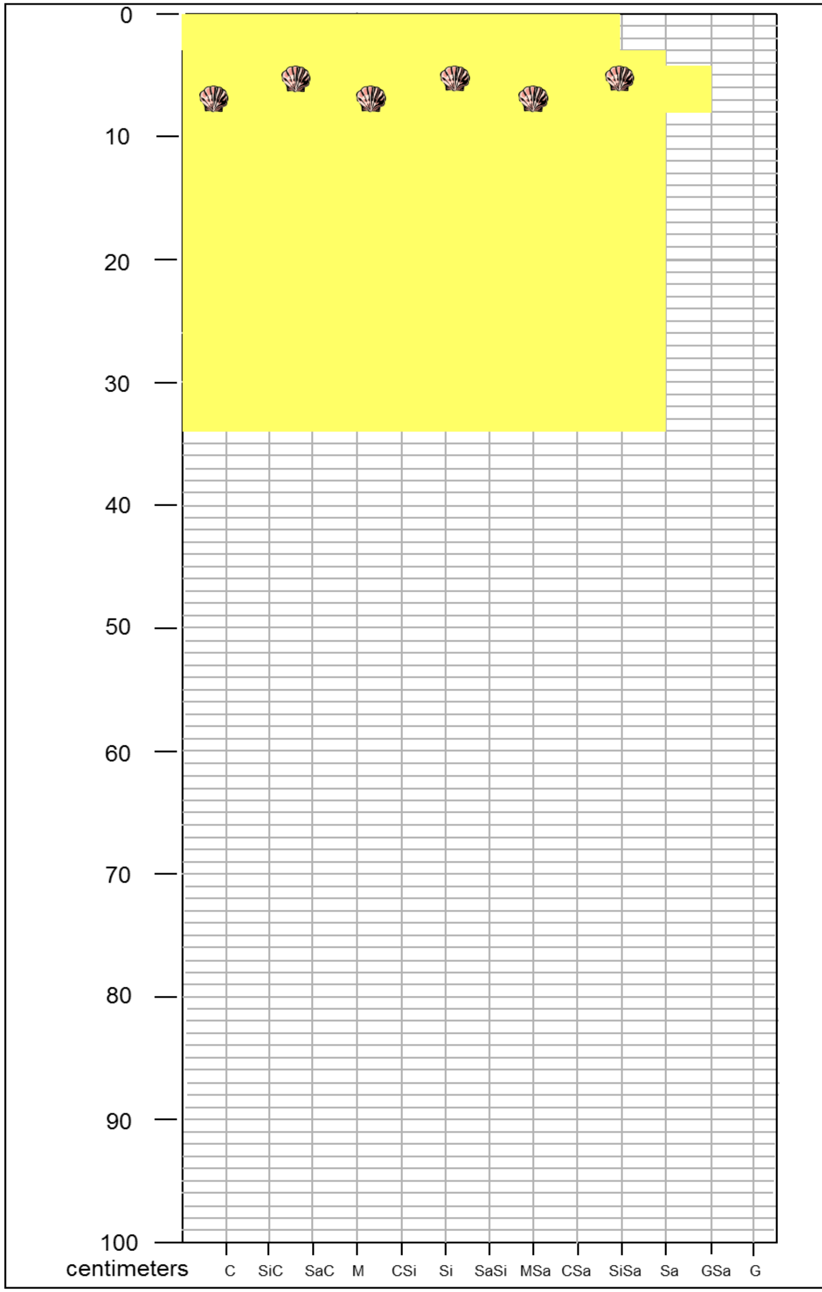


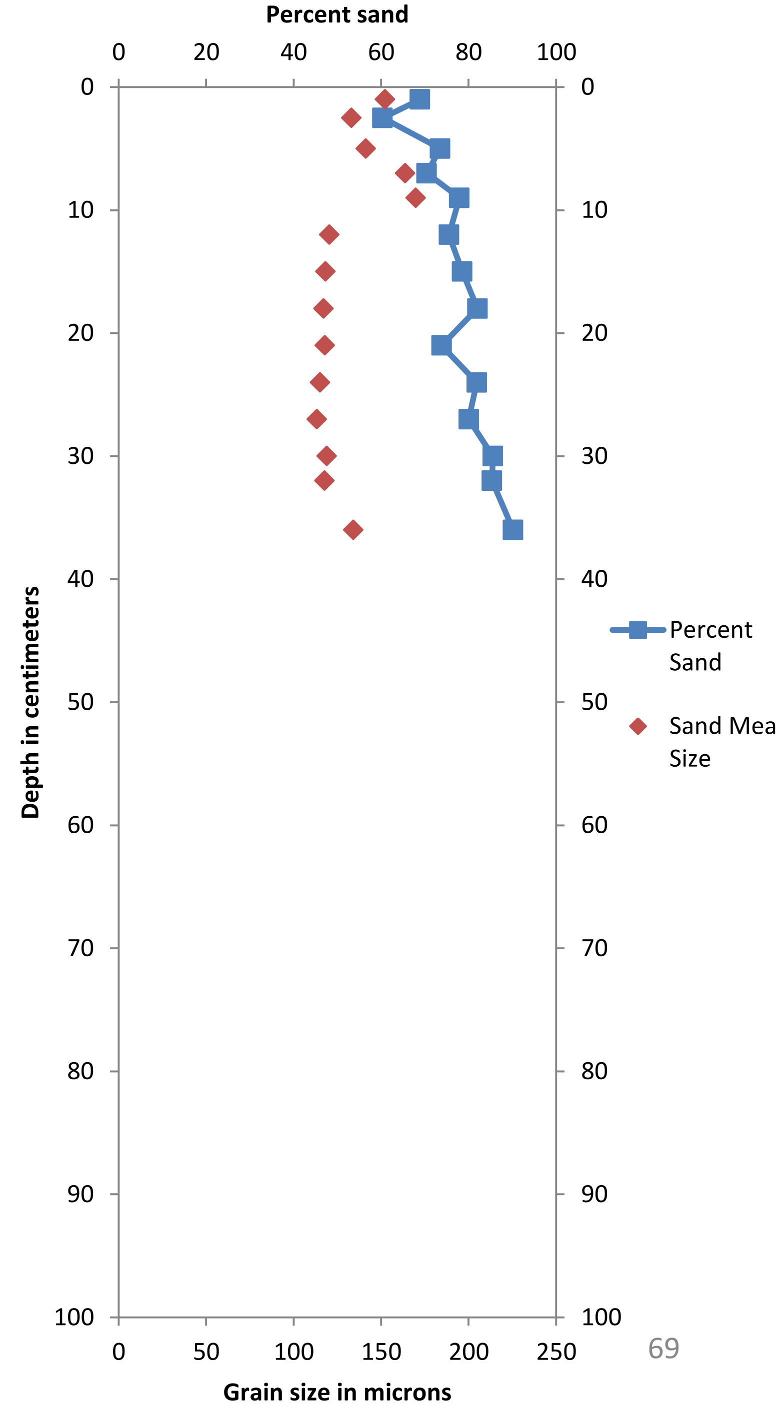
Project:_Galveston_Shelf________ Core: __GSE6__________________
0
10
20
30
40
50
60
70
80
90
100
centimeters
C SiC SaC M CSi Si SaSi MSa CSa SiSa Sa GSa G



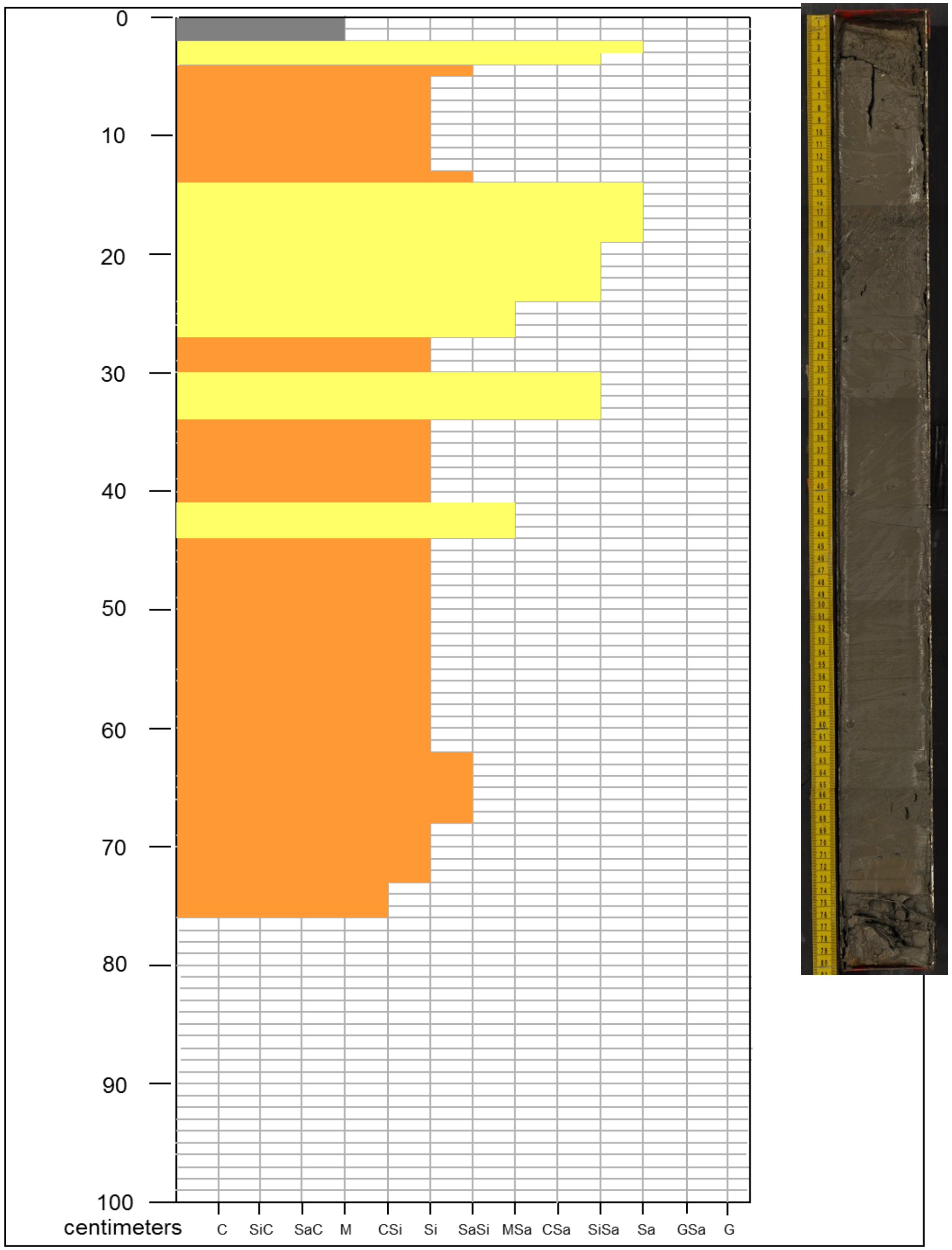
Percent sand
0 20 40 60 80 100
Depth in centimeters
0 10 20 30 40 50 60 70 80 90 100
Percent Sand
Sand Mean Size
0 50 100 150 200 250
Grain size in microns

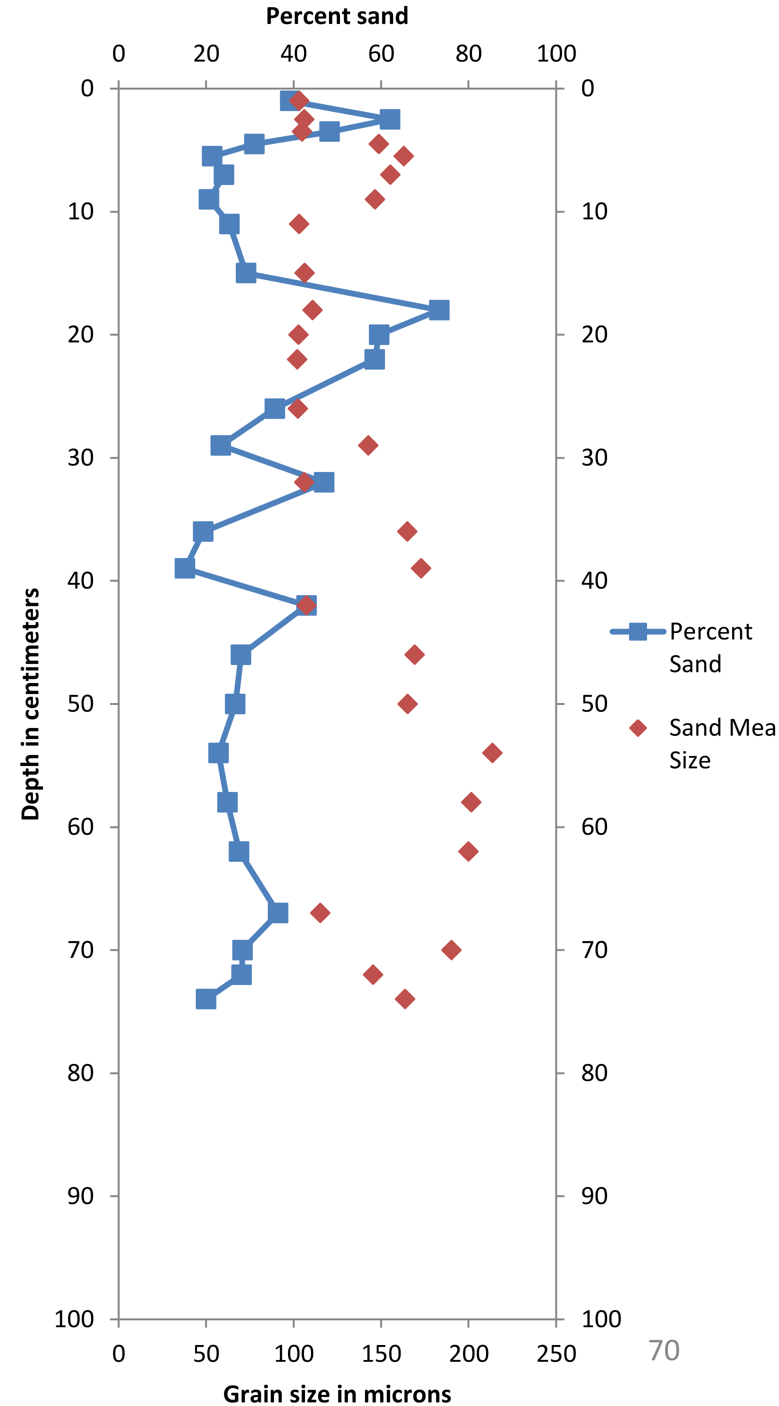
Project:_Galveston_Shelf________ Core: __GSG1_____________________



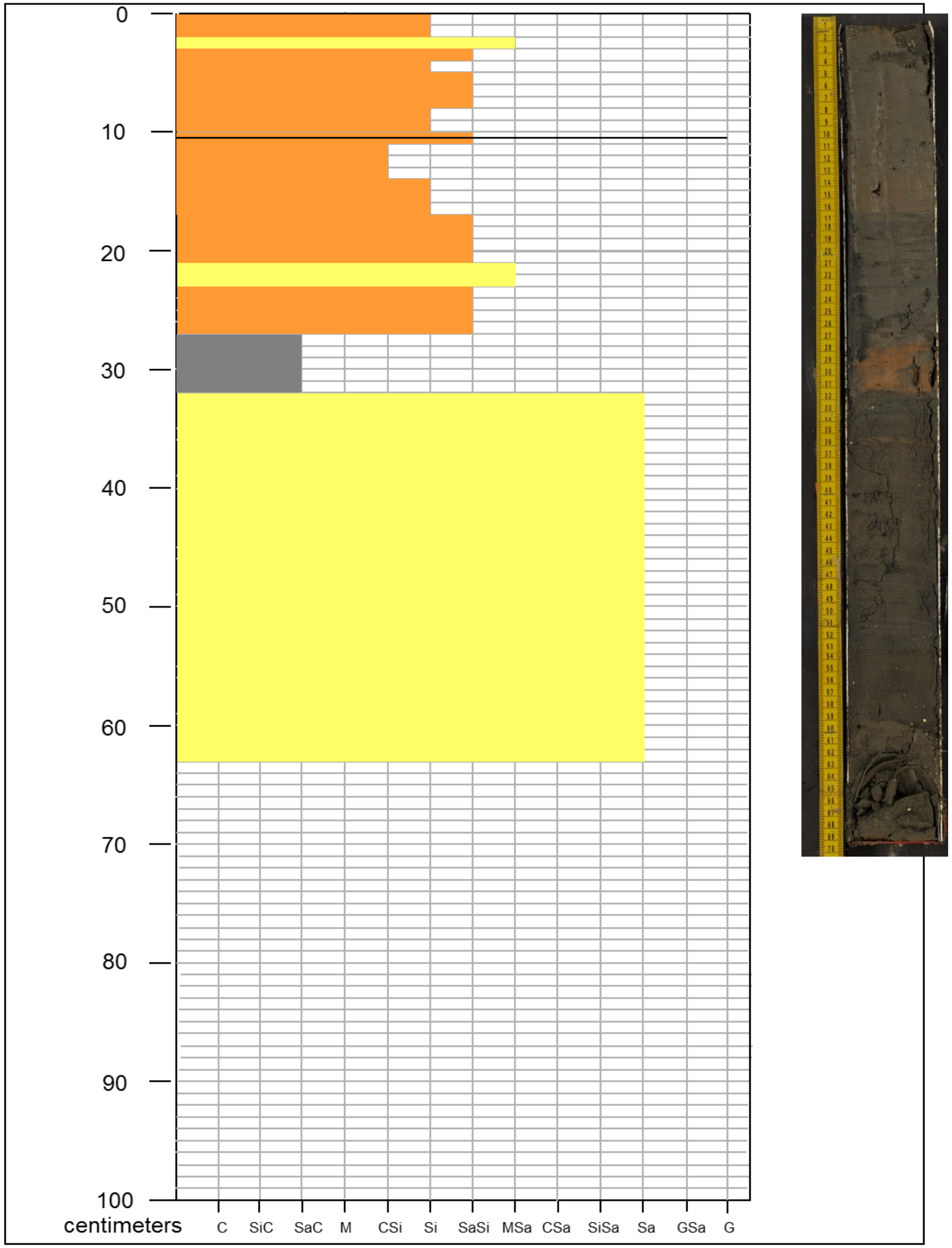


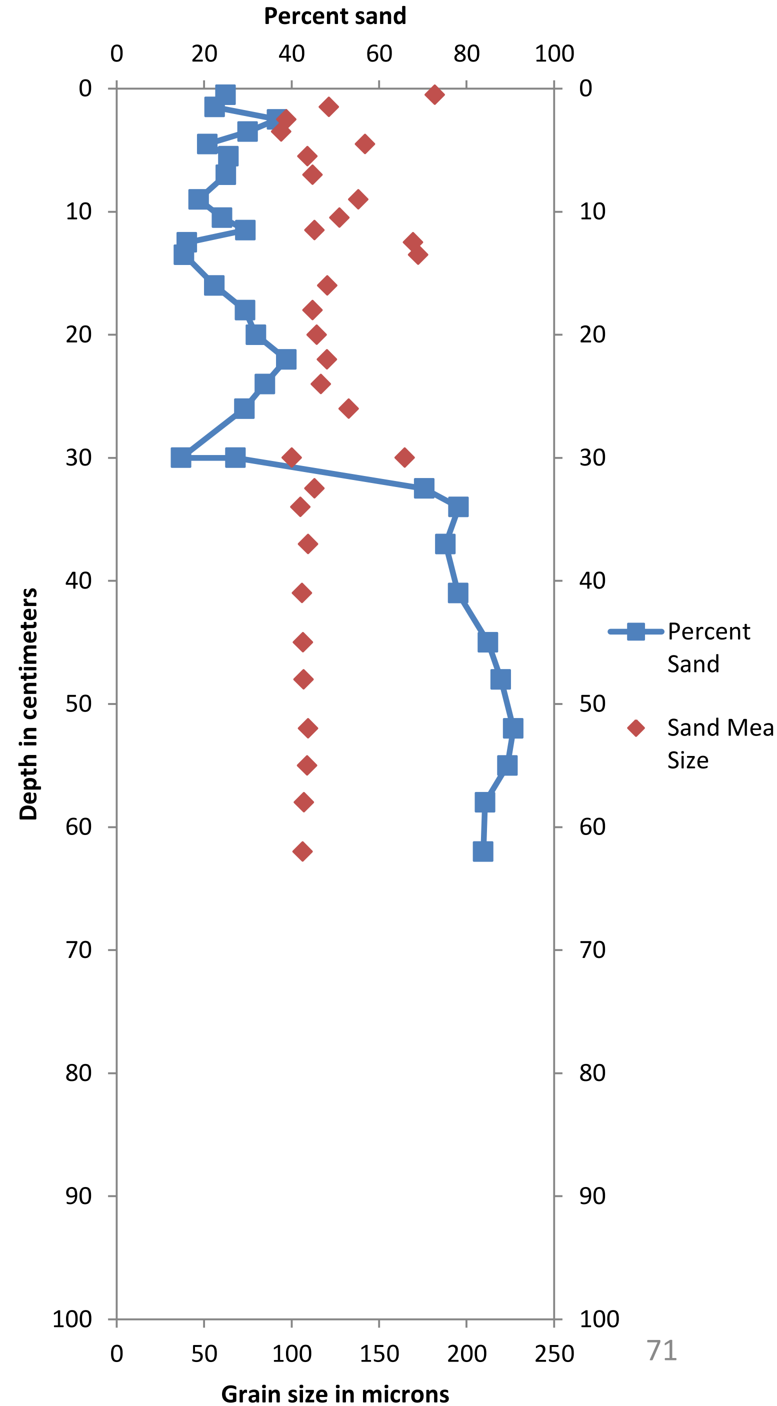
Project:_Galveston_Shelf_______ Core: __GSG5____________________



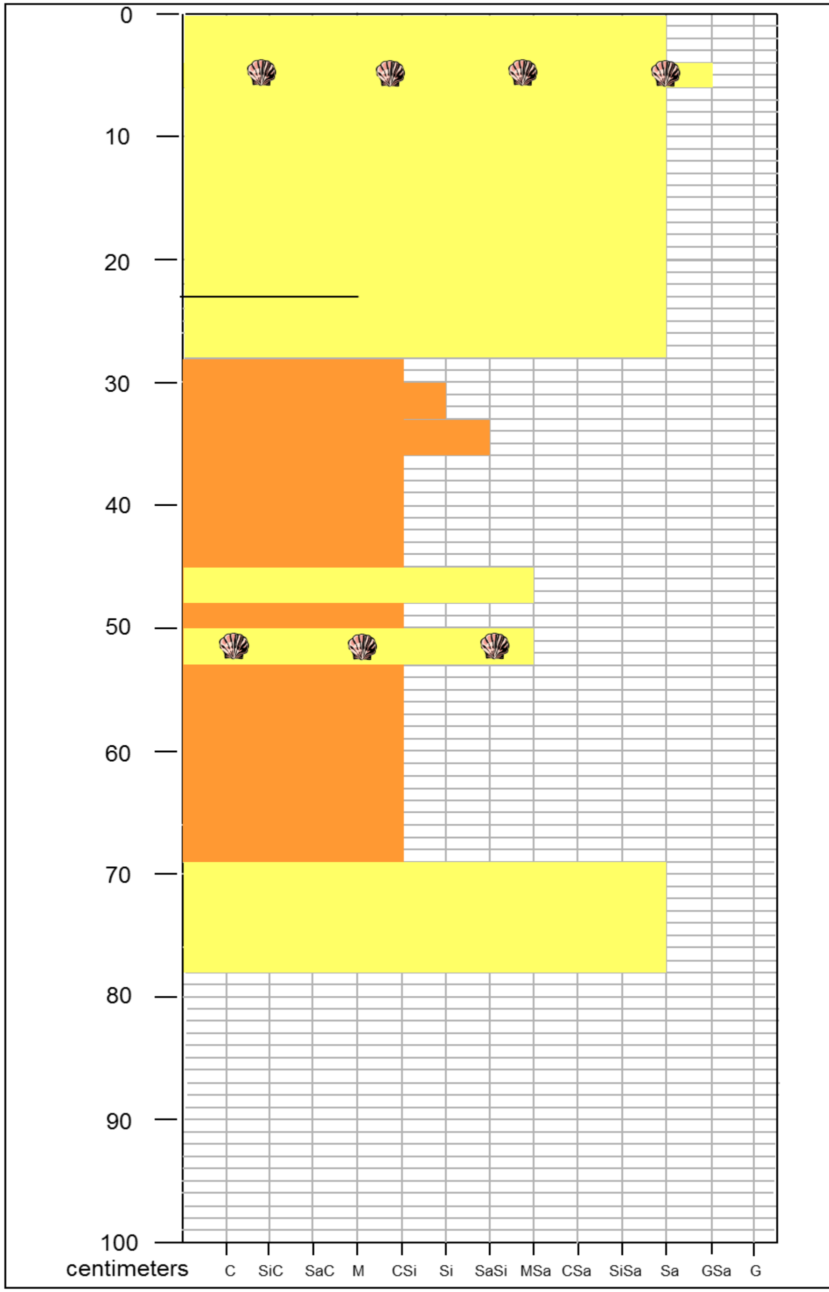


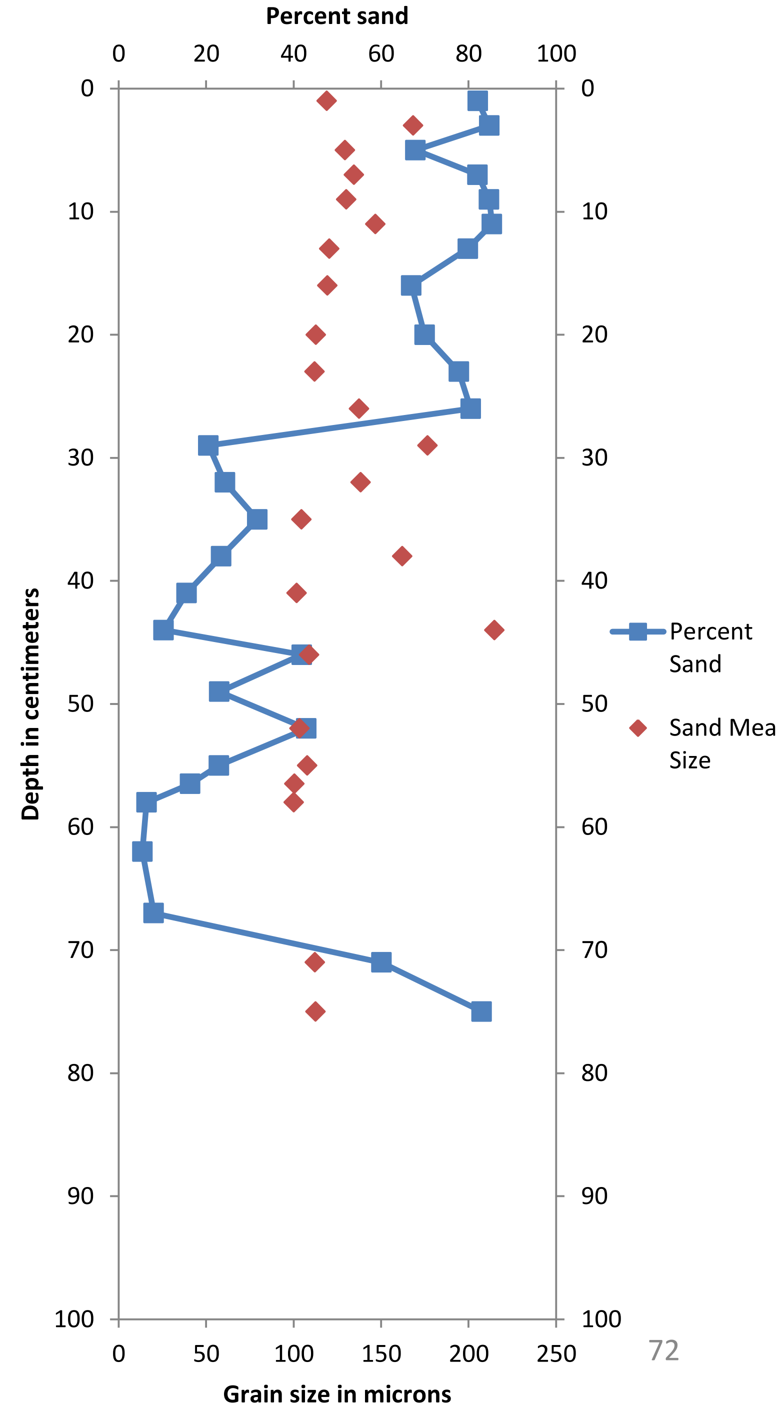
Project:_Galveston_Shelf_______ Core: __GSG6____________________

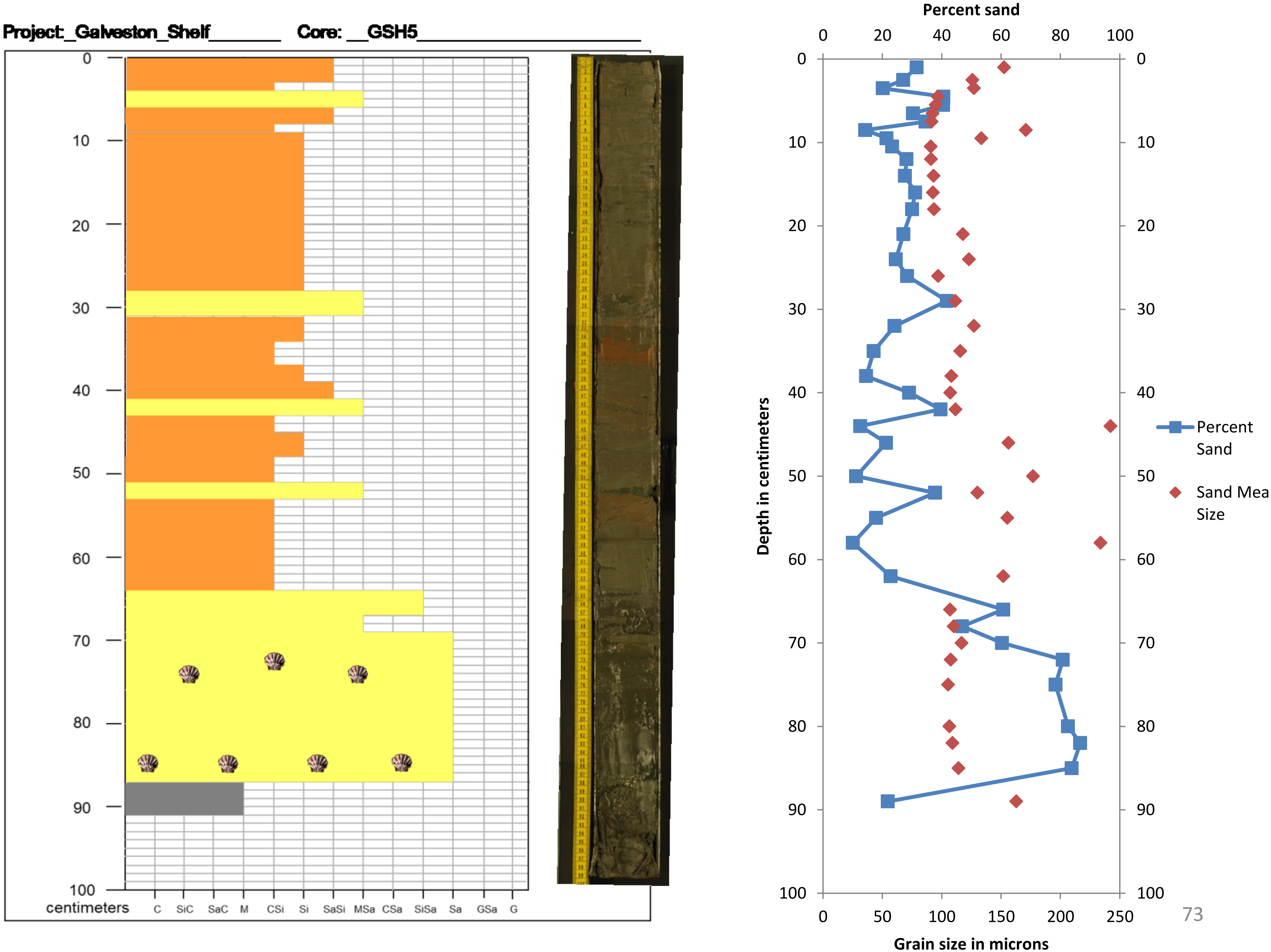




Project:_Galveston_Shelf________ Core: __GSH4___________________________






Project:_Galveston_Shelf
Core: __GSH5
0
10
20
30
40
50
60
70
80
90
100
centimeters
C
SiC
SaC
M
CSi
Si
SaSi
MSa
CSa
SiSa
Sa
GSa
G
Percent sand
0
20
40
60
80
100
Depth in centimeters
Percent Sand
Sand Mean Size
0
50
100
150
200
250
Grain size in microns