ALONGSHORE VARIATION IN DEPTH OF ACTIVATION: IMPLICATIONS FOR OIL RESIDENCE TIME ON PENSACOLA BEACH, FLORIDA

A Thesis

by

PEGGY ELIZABETH FLORES

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Chair of Committee,	Chris Houser
Committee Members,	Mark Everett
	John R Giardino
Head of Department,	Michael Pope

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ABSTRACT

The Deepwater Horizon Oil Spill in 2010 released approximately 5 million barrels of oil into the Gulf of Mexico just as the nearshore and beach profile were recovering from winter storms. As a consequence, oil mats and tar balls were trapped at depth within the beach and nearshore profile. Excavation of this buried oil during subsequent storms creates the potential for the contamination of adjacent beaches and the degradation of marine ecosystems, which can in turn negatively impact local economies that depend on fisheries and tourism. The potential for oil burial and persistence is dependent on three things: the physio-chemical nature of the oil as it reaches the nearshore environment, the pre-existing morphology of the beach and nearshore, and the evolution of that morphology after the oil is deposited. The depth at which the oil is buried is also dependent on the beach profile during the time of the spill. The purpose of this study is to characterize the alongshore variation in depth of activation on a Deepwater Horizon impacted section of Pensacola Beach, Florida with regards to the implications of oil residence time. Ground- Penetrating Radar (GPR) surveys were conducted along two parallel 1-km transects adjacent to the swash zone and the dunes. Additional cross- shore transects were completed every 150 m from the base of the dunes to the top of the swash zone. Sediment cores were taken at the crossing points of the alongshore and cross-shore transects, to calibrate the GPR surveys and complete an elemental analysis for the identification of storm layers and the presence of buried oil. Results will show implications for oil residence time with regards to the evolution of the beach envelope.

DEDICATION

To my family and friends.

Thank you for always being there for me.

This manuscript is dedicated to my grandmothers;

Jean Payne Alfrey and Lindell Cope Burgess

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NOMENCLATURE

DIS	Digital Image Scanner
EM	Electromagnetic
FEDP	Florida Department of Environmental Protection
GOM	Gulf of Mexico
GPR	Ground Penetrating Radar
IODP	Integrated Oceanic Drilling Program
MHz	Megahertz
SOM	Submerged Oil Mats
SRB	Surface Residue Patty
XRF	X-Ray Fluorescence

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1. INTRODUCTION

In 2010, the Deepwater Horizon oil spill released approximately 4.9 million barrels of oil into the Gulf of Mexico just as the nearshore and beach profile were recovering from winter storms (Graham et al., 2016). As a consequence, oil mats and tar balls were trapped at depth within the beach and nearshore profile. Excavation of this buried oil during subsequent storms creates the potential for the contamination of adjacent beaches and the degradation of marine ecosystems, which can in turn negatively impact local economies that depend on fisheries and tourism. There are several examples of past oil spills that even after many years the effects of the oil are still being felt. In 1989, ~257,000 barrels of oil spilled into Prince William Sound, Alaska when the Exxon Valdez ran aground. The Valdez spill occurred during strong winds and a spring tide, allowing oil to be trapped along the upper-beach and seep deep into the sediment (Carls *et al*., 2001), where it remained trapped for many years and some oil is still coming to the surface. Similar to the Exxon Valdez spill, storm waves during the release of oil from the Prestige Tanker in northwestern Spain and the (intermediate) morphology of the nearshore and beach resulted in the partial and variable burial of oil, leading to the sporadic remobilization of 10,000 tons of oil over the course of 4 years (Gonzalez *et al*., 2009).

The residence time of oil is dependent on many factors. One of the factors being the use of dispersants during cleanup efforts. Emergency responders used multiple methods including skimming, burning and applying nearly two million gallons of dispersant. Dispersants are chemicals used during an oil spill to break up oil slicks and to limit floating oil from reaching delicate ecosystems (Graham et al., 2016). The dispersants were used on the surface of the water and for the first time in US history dispersants were injected about one mile below the sea surface (Graham et al., 2016). Very little is known about the effects of dispersants but recent findings are suggesting that dispersants can act as a lubricating agent for oil helping it to penetrate sediment at a much greater depth (Zuijdgeest and Huettel, 2012). The potential for oil burial and persistence is also dependent on other four things: the physio-chemical nature of the oil as it reaches the nearshore environment, the pre-existing morphology of the beach and nearshore, and the evolution of that morphology after the oil is deposited (Owens, 1985; Gonzalez et al., 2009). The longer oil remains on the beach, the more it changes chemically and physically in a way that promotes burial, and the more variable the beach and nearshore profile. In this respect, the sequence of wave activity and beach evolution that occurs over the course of an oil spill and the subsequent evolution of both oil and the beach leads to stratified layers of oil, oiled sands and clean sands (Pardue et al., 2014).

The variability of beach states is dependent on the frequency and magnitude of storm events and the length of time that the beach is able to recover following each storm. In general, dissipative beaches (characterized by frequent storm waves and/or smaller sediment) exhibit a relatively small beach envelope (Wright and Short, 1984), but relatively large depth of disturbance in the nearshore and across the beach (Sherman et al., 1993). Intermediate beaches are characterized by relatively large beach envelopes and sediment activation, and therefore, exhibit the greatest potential for oil to be regularly exhumed and moved to greater depth. Reflective beaches (fewer storm waves and/or larger sediment) exhibit a relatively large variability in the beach envelope both horizontally and vertically in response to the post-storm recovery of the beach through the seaward development a berm (Houser and Barrett, 2010). The horizontal and vertical variability of dissipative, intermediate and reflective beaches observed by Wright and Short (1984) is presented in Figure 1. In short, the depth that oil is buried and therefore persists is dependent on the amount of time that the oil remains on the surface and the variability of the beach profile that is in turn dependent on the morphology of the beach and nearshore system.

The purpose of this study is to characterize the alongshore variation in depth of activation on a Deepwater Horizon impacted section of Pensacola Beach, Florida with regards to the implications of oil residence time. Ground- Penetrating Radar (GPR) surveys were conducted along two parallel 1-km transects adjacent to the swash zone and the dune. Additional cross- shore transects were completed every 150 m from the base of the dune to the top of the swash zone. Sediments cores were taken at the crossing points of the alongshore and cross-shore transects, to calibrate the GPR surveys and complete an elemental analysis for the identification of storm layers. The cores were also analyzed for the presence of buried oil.

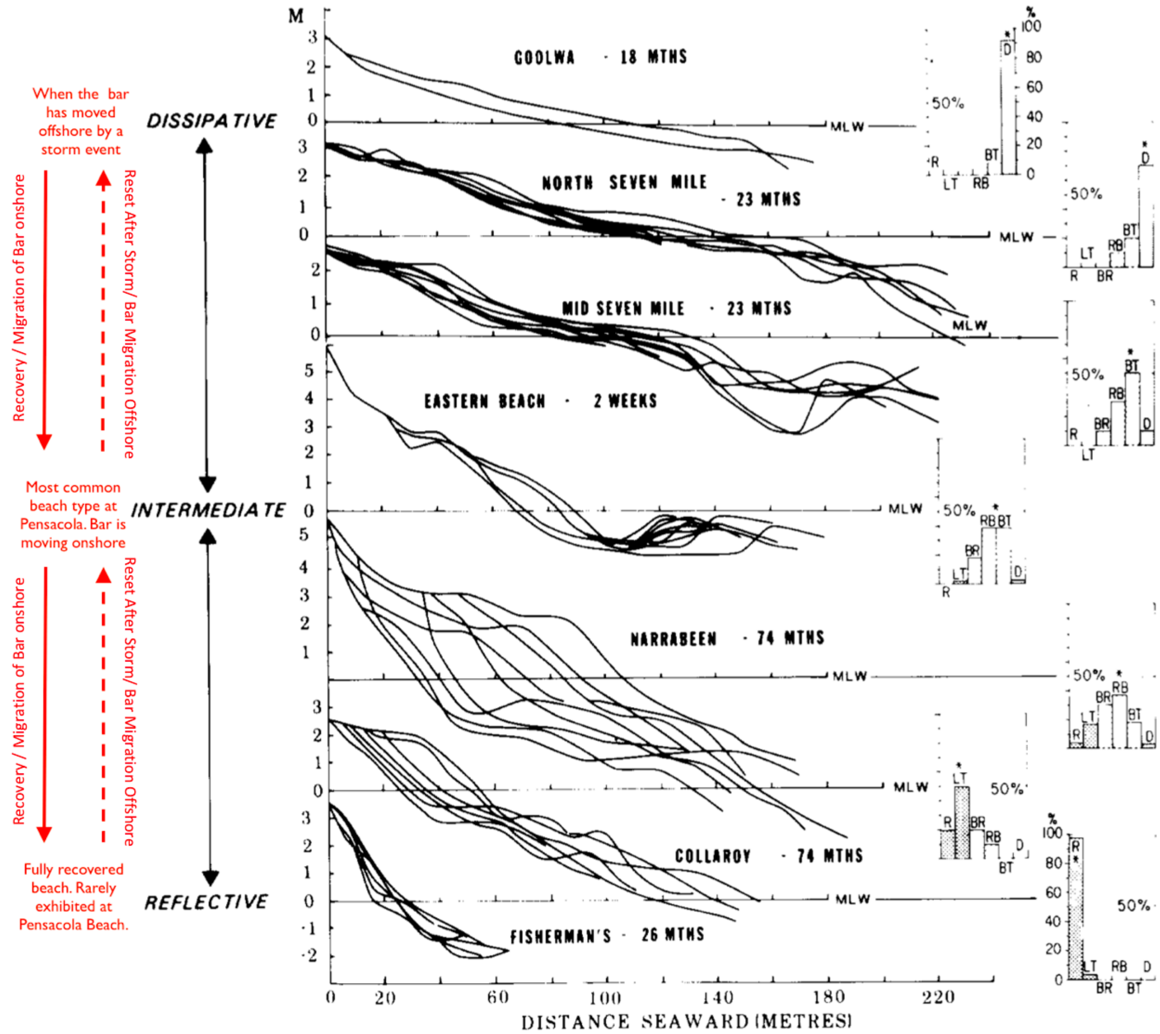

Figure 1: Vertical and horizontal profile variability for dissipative, intermediate and reflective beaches Modified from Wright and Short (1984).

2. BACKGROUND

2.1 Previous Oil Spills/ Historic Oil Spills

There are hundreds of oil rigs with tanker ships running back and forth transporting oil to refineries in the Gulf of Mexico (GOM). With numerous oil rigs, pipelines, and shipping channels in the GOM (Figure 2) there is a strong potential for an oil spill to occur and contaminate beaches, degrade marine ecosystems, and/or negatively impact local economies that depend on fisheries and tourism. Oil spills are not only hazardous to the economies of affected areas but also to the ecosystems including coastal wetlands that provide vital services including storm protection, water quality enhancement, faunal support, carbon sequestration and fisheries habitat (Mendelssohn, et al. 2012). A species living on the surface of the water will be affected first and species that live in the subsurface are more protected until the oil begins to sink and penetrate the sediment. Oil that persists after a spill and is later exhumed by a storm can cause commercial fisheries to suffer direct losses from product mortality, possible harvesting closures due to clean up and loss of market demand due to fear of exposure to toxins (Chang and Demes, 2014). If commercial fishing decreases there will be direct losses to businesses that depend on commercial fishers such as marinas, docks, processors, and distributors (Sumaila, et al. 2012). There are numerous historic examples of oil spills that have impacted coastal environments around the world but the Deepwater Horizon oil spill is the most recent and one of the largest oil spills in U.S. history. The impact of this oil spill has been tremendous and seems that it will be felt for many years after the spill.

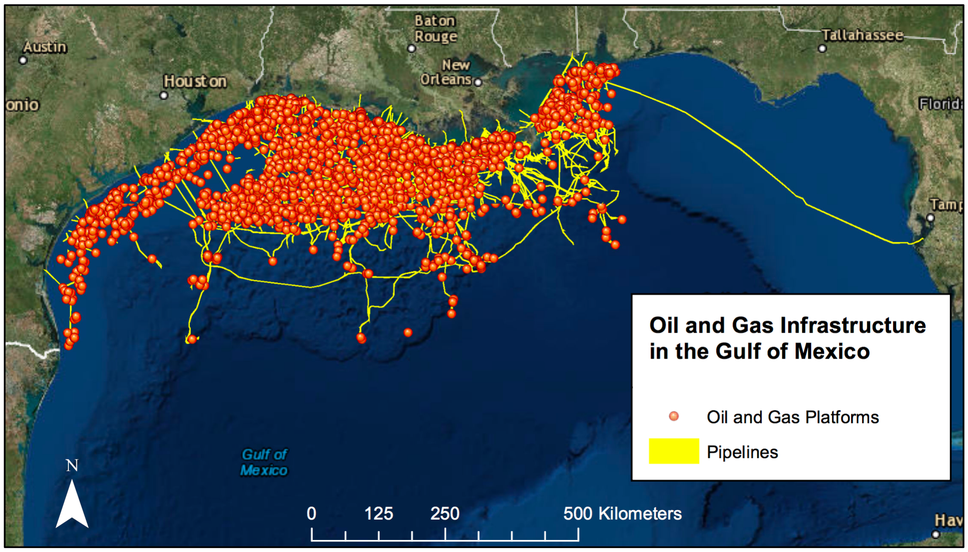

Figure 2: Map of oil and gas platforms and pipelines present in the Gulf of Mexico. Data Obtained from ESRI Online.

On April 20th, 2010, a blowout occurred on the BP Deepwater Horizon oil rig (Table 1). The blowout resulted in 4.9 million barrels of oil being spilt into the Gulf of Mexico over a three-month period of time (Read, 2011). The spill occurred roughly 50 miles off the shore of Louisiana but Louisiana was not the only coastal area to be impacted (Maung-Douglass et al., 2015). The oil washed up on the coast of four states and covered nearly 1,100 miles of coastline, as seen in Figure 3 (Graham et al., 2015). The Deepwater Horizon oil spill was regarded as one of the worst oil spills of all times and the media was quick to compare it to the Exxon Valdez oil spill (Read, 2011). In comparison, the Exxon Valdez released a lot less oil than the Deepwater Horizon but the Deepwater Horizon occurred in an environmentally sensitive area and was covered by the media 24 hours a day just like the Exxon Valdez (Read, 2011). At the time of the spill, the nearshore and beach profile were recovering from winter storms and as a

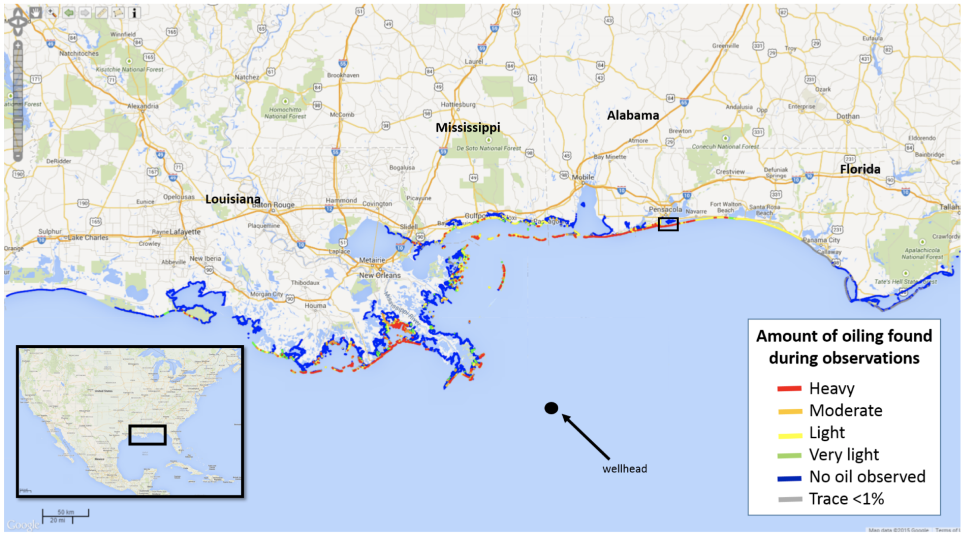

Figure 3: Amount of oiling from Heavy (red) to no oil (blue) on the Gulf Coast (Modified from Graham et al., 2015).

consequence, oil mats and tar balls were trapped at depth within the beach and nearshore profile making clean-up efforts much more difficult.

In 1974, the supertanker *Metula* ran aground near the First Narrows in the strait of Magellan, Chile spilling 53,000 tons of oil (~378,000 barrels of oil) (Gundlach, 1997 and Wang et al., 2001). The oil spilt by *Metula* oiled nearly 250 km of coastline (Wang et al., 2001). Only the ferry landing areas (60-80 km of coastline) were cleaned of oil. The rest of the oil was left to weather naturally because it was a very remote area (Gundlach, 1997 and Wang et al., 2001). With the oil being left on the sand surface to weather naturally some was able to break down on the surface but most of it migrate deep into the beach profile (Gundlach, 1997 and Wang et al., 2001). As a result, an extensive mat was not exposed for several years and in parts of the backshore, was not exposed for at least 10 years because it had been deposited on a lower elevation storm profile (Baker *et al.,* 1993; Gundlach, 1997). As of 2010, it was reported that majority of the area was beginning to show signs of a full recovery. Researchers are looking it for a case study of what happens if you allow the oil to weather and break down on its own versus newer methods of using dispersants, burning it, or cleaning it off the surface (Tracy, 2010).

In 1989, ~250,000 barrels of oil spilled into Prince William Sound, Alaska when the Exxon Valdez ran aground (Table 1). The Exxon *Valdez* is considered a small oil spill in terms of the amount of oil that was spilled into the Prince William Sound, but because it occurred in an environmentally sensitive area and the media ran new stories on a 24-hour cycle, the nation was more informed about the Exxon Valdez (Read, 2011). As a result, it is regarded by the public as one of the most damaging spills in United States history (Read, 2011). The Valdez spill occurred during strong winds and a spring tide, allowing oil to be trapped along the upper-beach and seep deep into the sediment (Carls *et al*., 2001), where it remained trapped for many years. Maximum oil concentrations were found throughout Prince William Sound 3-6 years after the spill, but 25 years after later oil continues to be remobilized within PWS by storms capable of eroding the beach down to the spill layer (Xia and Boufadel, 2011). The rate of natural hydrocarbon weathering and biodegradation were much slower than expected following the Exxon Valdez, with oil remaining trapped deep in the sediment column or beneath dense mussel beds (Carls et al., 2001). Six years after the oil spill the amount of oil measured in the mussel beds began to drop but it seemed to persist for decades (Carls et al., 2001).

Similar to the Exxon Valdez spill (Table 1), the *Prestige* oil tanker ran aground ~130 nautical miles off the Western coast of Spain in November 2002 spilling 77,000 tons (~550,000 barrels) of oil into the Atlantic Ocean (Albaiges et al., 2006). Storm waves during the release of the oil and the (intermediate) morphology of the nearshore and beach resulted in the partial and variable burial of oil, leading to the sporadic remobilization of 10,000 tons of oil over the course of 4 years (Gonzalez *et al*., 2009). The burial of oil was promoted by "*an exceptional sequence*" of high-energy storm events altering the intermediate beach profile. While much of the oil in the upper sediment had degraded after 4 years, a large storm event eroded the beach and exposed oil that was deeply buried or had been advected lower on the profile.

Table 1: Each oil spill discussed broken down by date, amount spilled, location, beach type, impact, and present day impacts.

Oil Spill	Date	Amount Spilled	Location	Beach Type	Impact	Present Day Impacts
Metula Supertanker	August 9th, 1974	~378,000 barrels	First Narrows in the Strait of Magellan, Chile	Intermediate Morphology. Remote Area.	250 km of oiled coastline. Extensive oil mats formed and were present until the early 2000's.	Most of the oil mats have broken up and are no longer present.
Exxon *Valdez*	March 24th, 1989	~250,000 barrels	Prince William Sound, Alaska	Intermediate Morphology Very Rocky.	~2,100 km of oiled coastline. Occurred during strong winds and a spring tide, allowing oil to be trapped along the upper-beach and seep deep into the sediment. Impacted marine ecosystems, tourism, and fisheries.	Some oil still trapped in the sediment. Takes large scale storms to exhume it.
Prestige Oil Tanker	November 13th, 2002	~550,000 barrels	Western Coast of Spain	Intermediate Morphology	300 km of oiled coastline. The intermediate morphology of the nearshore and beach resulted in the partial and variable burial of oil, leading to the sporadic remobilization. Caused a suspension of offshore fishing for 6 months after the spill.	As recent at 2006 oil mats and tar balls were still being found. Oil still remains in the wrecked ship which could split open and release more oil.
BP Deepwater Horizon	April 20th, 2010	~4,900,000 barrels	Gulf of Mexico, 42 miles southeast of Venice, Louisiana	Intermediate Morphology	~1,800 km of oiled coastline. Occurred in April as the nearshore and beach profile was recovering from the winter storms, trapping the oil mats and tar balls at depth within the sediment. Impacted marine ecosystems, tourism, and fisheries.	Oil mats and tar balls are still being discovered on Gulf Coast beaches.

2.2 Beach Variability

The variability of beach states is dependent on the frequency and magnitude of storm events and the length of time that the beach is able to recover following each storm. In general, dissipative beaches (characterized by frequent storm waves and/or smaller sediment) exhibit a relatively small beach envelope (Wright and Short, 1984), but relatively large depth of disturbance in the nearshore and across the beach (Sherman et al., 1993). Intermediate beaches are characterized by relatively large beach envelopes and sediment activation, and therefore, exhibit the greatest potential for oil to be regularly exhumed and moved to greater depth. Reflective beaches (fewer storm waves and/or larger sediment) exhibit a relatively large variability in the beach envelope both horizontally and vertically in response to the post-storm recovery of the beach through the seaward development of a berm (Houser and Barrett, 2010). Figure 1 shows the beach profile envelopes of temporal variation of several beaches with bar graphs showing the corresponding variability and modal state (Wright & Short, 1984). The most spatially and temporally dynamic beach forms are associated with intermediate beaches (Wright & Short, 1984). In short, the depth that oil is buried and therefore persists is dependent on the amount of time that the oil remains on the surface and the variability of the beach profile that is in turn dependent on the morphology of the beach and nearshore system. At Pensacola beach, the beach is constantly trying to achieve a fully recovered state. Anytime a storm happens, the beach resets and has to move through all the stages in order to try to reach the fully recovered state. At Pensacola, when the beach is fully recovered is exhibits a reflective state. When the bar is pushed off shore by a storm event, the beach is dissipative. The most common beach type exhibited at Pensacola is the intermediate state which is the most complex morphology.

Sediment reworking directly by waves and currents, and the migration of bedforms can lead to the burial of heavier objects, even if there is not a net change in the elevation of the sediment surface (Gallagher *et al.,* 2007). As a bedform migrates across the beachface (at high tide), heavier oil will fall to the low point of the bedform trough before subsequently being buried by the passage of the following bedform crest (Gallagher and Holman, 2002). As a consequence, heavier oil could become mixed into the sediment over the course of a tidal cycle, with the potential for burial greater when the surf and swash zones are most turbulent. Results of Karunarathna *et al.* (2012) suggest that the swash zone is the most morphodynamically active region and therefore has the greatest potential for oil burial and persistence, particularly during winter months when storms are more common. The behavior of the swash zone is attributed to the welding of the innermost bar to the foreshore which creates a shallow nearshore terrace (Houser & Barrett, 2009). As a result, this led to faster uprush velocity which promoted the landward advection of sediments picked up from the shallow terrace (Houser & Barrett, 2009). In all cases, the range of beach states is dependent on the frequency and magnitude of tropical storms and hurricanes; the greater the frequency of storm events the narrower the distribution, since the beach does not have the opportunity to recover.

2.3 Residence Time

The potential for oil burial and persistence of oil is dependent on four things: 1.) the physio-chemical nature of the oil as it reaches the nearshore environment, 2.) the pre-existing morphology of the beach and nearshore, 3.) the evolution of that morphology after the oil is deposited, and 4.) the use of dispersants (Owens, 1985; Gonzalez et al., 2009; Graham et al, 2015). The longer oil remains on the beach, the more it changes chemically and physically in a way that promotes burial, and the more variable the beach and nearshore profile. In this respect, the sequence of wave activity and beach evolution that occurs over the course of an oil spill and the subsequent evolution of both oil and the beach leads to stratified layers of oil, oiled sands and clean sands (Pardue et al., 2014).

2.3.1 Physio- Chemical Nature of the Beach and Nearshore

The point of deposition on the beach is controlled by the physio-chemical composition at the time that it reaches the beach. Oil that is less dense than seawater floats on the surface and is deposited on surface sediment with the swash uprush, while oil that is heavier than seawater exhibits varying degrees of mixing with the sediment. Oil that is lighter than the sediment is deposited on the bottom and moves along the bed in a manner analogous to fine sand, with the sediment typically deposited at high tide. In other words, lighter oil deposited along the upper-beach and in the backshore, has the potential to be buried several meters within the beach, nearshore, and/or within the backshore and dune (Gonzalez et al., 2009). The lighter oil from the deepwater horizon oil spill that made it to the shallow nearshore zone was subject to enhanced dispersion by the breaking of waves by breaking down and mixing oil parcels throughout the shallow water column (Zuijdgeest and Huettel, 2012). This natural dispersion was enhanced by the application of dispersants leading to the relatively rapid advection of the oil into permeable sands to be buried and persist for several years.

The transition from light to heavy oil is a result of weathering and biodegradation. As the oil develops a similar settling velocity to the sediment, it will be mixed with the sand to form tar-balls and behave similar to medium to coarse sand in response to waves and currents. Heavier oil is difficult to move and tends to be found trapped in submerged parts of the beach and quickly buried to the depth of sediment activation (Sherman *et al.,* 1993; Gallagher *et al*., 2007). This heavier oil undergoes further weathering through a slow emulsification in which the small droplets are either advected deeper into the sediment or adsorbed to the sand grains (Pardue et al, 2014). Adsorption is limited on beaches with large seasonal profile variability and on beaches where strong tidal-induced groundwater flows moves sediment to the groundwater table (Zuijdgeest and Huettel, 2012). The highest concentrations of oil are found in the deeply buried anoxic and low-nutrient layers of the beach profile, where there is an absence of mechanical abrasion by waves and currents (Bernabeu *et al.,* 2009). An adequate supply of oxygen and nutrients with water flowing through the sand column in the upper sediment promotes biodegradation by microorganisms (Daling *et al.,* 2002; Wang and Fingas, 2003), and photo-oxidation when exposed at the surface (Pardue et al, 2014).

2.3.2 Pre-existing Morphology and Morphology After Deposition

The potential for burial depends on the beach and nearshore state at the time that the oil reaches the beach. If an oil spill happens during a low-profile state such as a "storm" or "winter" beach when the sediment is temporarily stored in the innermost bar(s), oil can be trapped as the beach recovers and accretes through the landward migration of the bar (Wright and Short, 1984) as observed during the Prestige tanker spill (Gonzalez *et al.*, 2009). The oil would not be exhumed until the next storm capable of eroding the beach down to the level at which the oil was deposited or to the level at which the oil has been advected through the sediment. Exhumed oil is not necessarily removed from the beach and can be moved further landward with the swash or elevated storm surge, seaward with the backwash and undertow, re-deposited at the same location or buried to a greater depth that is dependent on the depth of disturbance of the swash or waves (Gonzalez *et al*., 2009). In contrast, oil that is deposited after the beach has completely recovered will remain at or near the surface meaning that it has a relatively short residence time (at the surface) but is also easier to clean (Pontes *et al.,* 2013). However, if the oil reaches a beach and is not immediately cleaned it can end up within the backshore and dune or buried several meters (Gonzalez *et al.,* 2009), and the more it changes chemically and physically in a way that promotes burial and a longer residence time (Figure 4).

2.3.3 Use of Dispersants

The residence time of oil at depth is dependent on many factors. One of the factors being the use of dispersants during cleanup efforts. Emergency responders used multiple methods including skimming, burning and applying nearly two million gallons of dispersant. Dispersants are chemicals used during an oil spill to break up oil slicks and to limit floating oil from reaching delicate ecosystems (Graham et al., 2015). For the Deepwater Horizon oil spill dispersants were used on the surface of the water and for

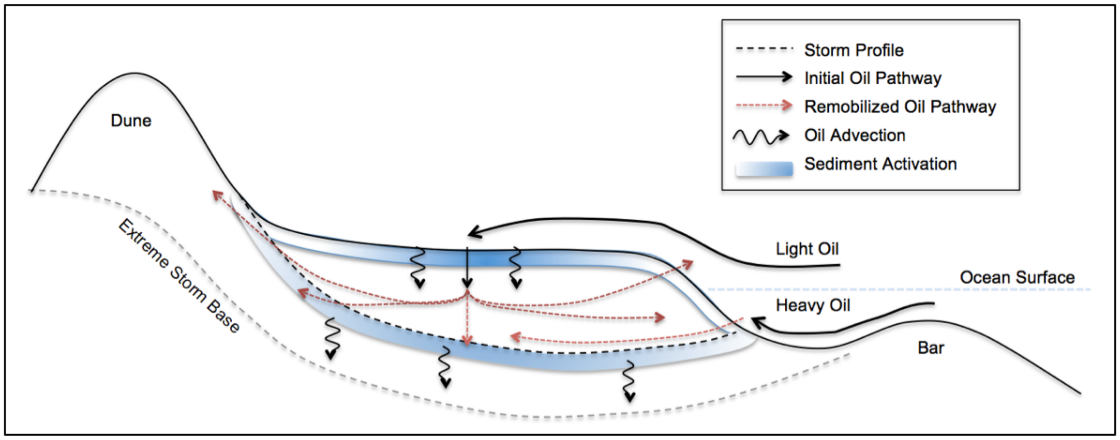

Figure 4: Schematic showing pathways of light and heavy oil on a beach environment. Oil tends to get incorporated in the upper layer of sediment through sediment activation by waves and currents, and eventually moves downwards through the profile through advection, physio-chemical weathering to a heavier state and/or deepening of the beach profile. The longer the oil remains on the beach, the greater the potential for it to be buried at depth or further landward.

the first time in US history, dispersants were used below the sea surface (Graham et al., 2015). The effects of dispersants have not been studied in depth but recent findings suggest dispersants can act as a lubricating agent, helping oil to penetrate sediment at a much greater depth (Zuijdgeest and Huettel, 2012).

3. STUDY SITE DESCRIPTION

The focus of this study is a 2.5 km section of Pensacola beach on Santa Rosa Island in Northwest Florida (Figure 5). Formed during the Holocene, Santa Rosa Island is the second longest barrier island in the Gulf of Mexico (Houser, Hapke, & Hamilton, 2008). This barrier island originated from the erosion of a central Pleistocene "core" and longshore distribution of sediments (Otvos, 1982), with sediment derived from a Pleistocene age headland east of Destin, Florida (Kwon, 1969; Stone, 1991; Stone et al., 1992; Stone and Stapor, 1996). Comparing the beach sand to the grain size and mineralogy of Pleistocene sediments proves that the sand is likely from the reworking of the older Pleistocene sediments (Hsu, 1960) as well as from late Pleistocene coastal and dune sand ridge bluffs near Panama City and Destin (Stone et al, 2004; Houser, 2012). The grain size and mineralogy is not consistent with being transported by the Apalachicola River as previously thought (Hsu, 1960, Houser, 2012). Subsequent landward transgression of the island during the Holocene draped a trailing sheet of sand over the Pleistocene surface and then storm waves and currents reshaped the original surface (Parker et al, 1992, McBride and Byrnes, 1995; Houser, 2012).

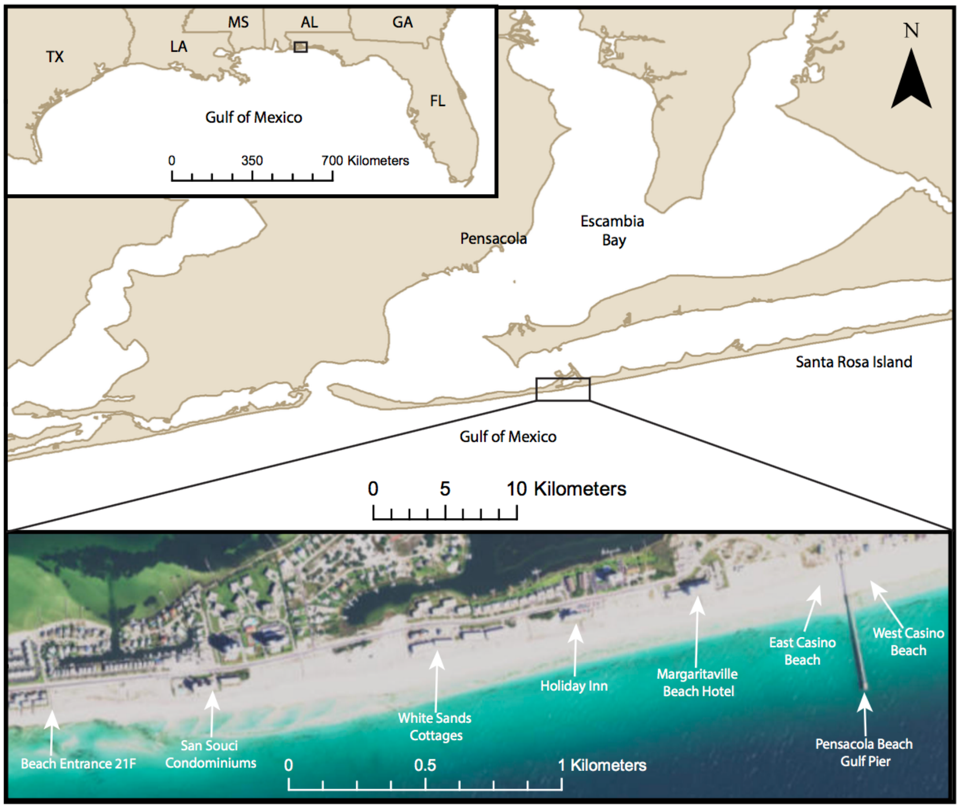

Figure 5: Santa Rosa Island is a narrow Holocene age barrier island in Northwestern Florida. The study site location begins at Beach Entrance 21F and ended at Pensacola Beach Gulf Pier.

As a result of island transgression, the offshore bathymetry of Santa Rosa island is dominated by ridges and swales (Houser, 2012). It includes a shore oblique shelf, shore face ridges, and swales which lie on Holocene age shelf-edge lobes (Houser, 2012). The ridges are shore-attached and extend ~1700 m offshore to the southeast and are 25° from shore normal and they appear to terminate at ~15m of depth (Houser, 2012). Although these ridges are part of a much larger field of ridges, the shore connected ridges are the only ones that affect wave transformation during extreme storms. (Houser et al., 2011a, 2011b). The ridges are typically located seaward on the widest portion of the island with a cuspate feature on the back-barrier shoreline, while the swales are seaward on the narrow portions of the island and are more prone to wash over and breaching (Houser, 2012). As a consequence of swales, the shoreface profile is steep which causes the outermost bar closer to shore in turn causing transverse bar and rip morphology (Wright and Short, 1984, and Houser, 2012). This beach and nearshore state reduce the exchange of sediment to dune which causes small discontinuous dunes. The beaches in front of the ridges are less steep and relatively dissipative which produces larger dunes (Houser, Hapke, & Hamilton, 2008; Houser, 2012).

This study site was chosen because it was one of the areas that was heavily oiled during the Deepwater Horizon oil spill (Graham et al., 2015). Although clean-up efforts were thought to have cleaned up majority of the oil, some is still being remobilized. A 1250-pound tar ball that was discovered near Pensacola Beach Florida in February 2014 (FDEP Beach Monitoring Report, 2014). In November of 2015, the main data collection occurred for this thesis. During this time of year, the beach would be transitioning into a winter beach profile, which means the berms and dunes erode because of increased wave height due to storms. The result of an eroded berm and dunes is a flatter more gently sloping beach. While running the experiments multiple surface residual patties (SRPs) and one submerged oil mat (SOM) were discovered. SRPs are defined by Graham et al., (2015) as a 4 in. to 3 feet piece of oil that is made up of pieces of sand, shell, and other materials bound by oil that have washed up on shore. These SRBs had a strong fuel smell when broken apart. A SOM is defined as mixed oil and sediment ranging in size from a few centimeters to a few meters that have been buried in the sediment (Dalyander et al., 2014). SOMs require a high magnitude event in order to exhume the oil from the sediment. The SOM was discovered in the swash zone (Figure 6), and similarly to the SRBs the tar mat has a very strong fuel smell when broken apart. The tar mat and SRBs were likely exhumed due to the more storm dominated profile that Pensacola Beach was experiencing at the time of data collection.

Figure 6: Top Row: Tar mat found in swash zone on Pensacola Beach November 2015. Bottom Row: Surface Residual Patties (SRP) found in study area November 2015.

4. METHODOLOGY

This study involves ground penetrating radar (GPR), coring, X-ray fluorescence (XRF) analysis, and grain size analysis. GPR is a very versatile, high resolution method used to image near surface structures using electromagnetic (EM) waves that typically range from 10Mhz to 1Ghz (Sharma, 1997, Everett, 2013). GPR is similar to seismic, both methods use reflection of energy from underground features to identify different structures within the subsurface (Sharma, 1997). Although GPR and seismic are similar in principle, GPR produces an image with much higher vertical resolution but the site-specific applications are very different (Davis and Annan, 1989, Sharma, 1997, Everett, 2013). GPR cannot penetrate into a medium that has a high electrical conductivity whereas this is a good medium to perform seismic (Sharma, 1997). GPR is used to image many different features including soil stratigraphy, erosional surfaces, bedrock depth, and detecting water tables (Davis and Annan, 1989, Weymer et al, 2015). GPR emits short pulses of EM radiation that propagate through the medium from the transmitter (T_x) and are reflected back and detected by the receiver (R_x) when the wave encounters a distinct change in dielectric properties in the medium (Neal, 2004, Weymer et al, 2015). For this study, GPR was chosen because it is non- invasive, economical, and produces a high-resolution image of subsurface features.

4.1 GPR Acquisition

A Sensors and Software PulseEKKO PE100® was used in this study to collect the GPR profiles using the 200 MHz and 500 MHz antennas using standard methods

(Bailey and Bristow, 2000; Neal and Roberts, 2000; Bristow et al., 2000; Bristow and Bailey, 2001; Knight, 2001; Neal, 2004; Weymer, 2012). The 200 MHz antennae were chosen because it provides subsurface images at a higher vertical resolution but at the expense of depth of penetration and the 500 MHz antennae was chosen because it will provide an even higher vertical resolution than the 200 MHz antennae but will still lack in depth of penetration (Davis and Annan, 1989; Sharma, 1997). A total of 20 GPR transects were taken but only 19 of them were able to be used, 7 of those lines are alongshore and 12 are cross shore (Line 16 was not used). The transects were first run by the 200 MHz antennae and then the 500 MHz antennae followed the same path so the transect grid is the same for both. For the 200 MHz transects a step size of 0.050 m was chosen and for the 500 MHz transects a step size of .020 m was used. The operating mode was set to automatically collect as the wheel on the GPR system turned. The antennae were constantly in contact with the ground to minimize ground- air coupling and the antennae was towed on the beach in a slow controlled manner to prevent skips. A GPS unit set to automatically collect data points was carried at all time during the GPR data collection in order to record the path and the topography that the GPR encountered as it was towed (Figure 7, Figure 8, Figure 9, &Figure 10).

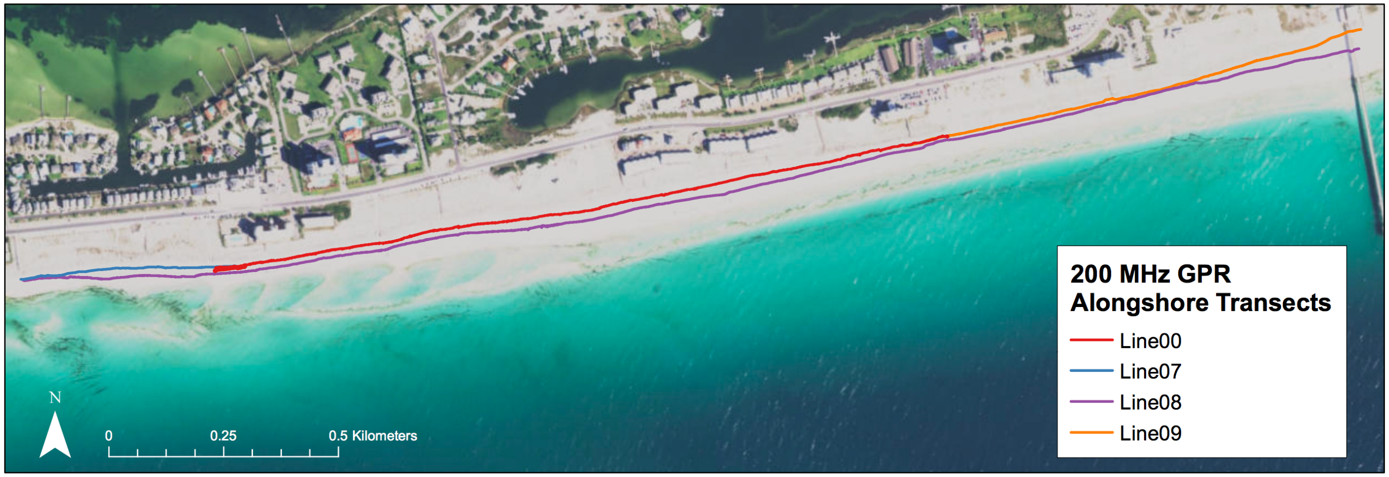

Figure 7: Map showing the path of the 200 MHz alongshore GPR transects.

Figure 8: Map showing the path of the 200 MHz alongshore GPR transects with corresponding 200 MHz cross-shore transects.

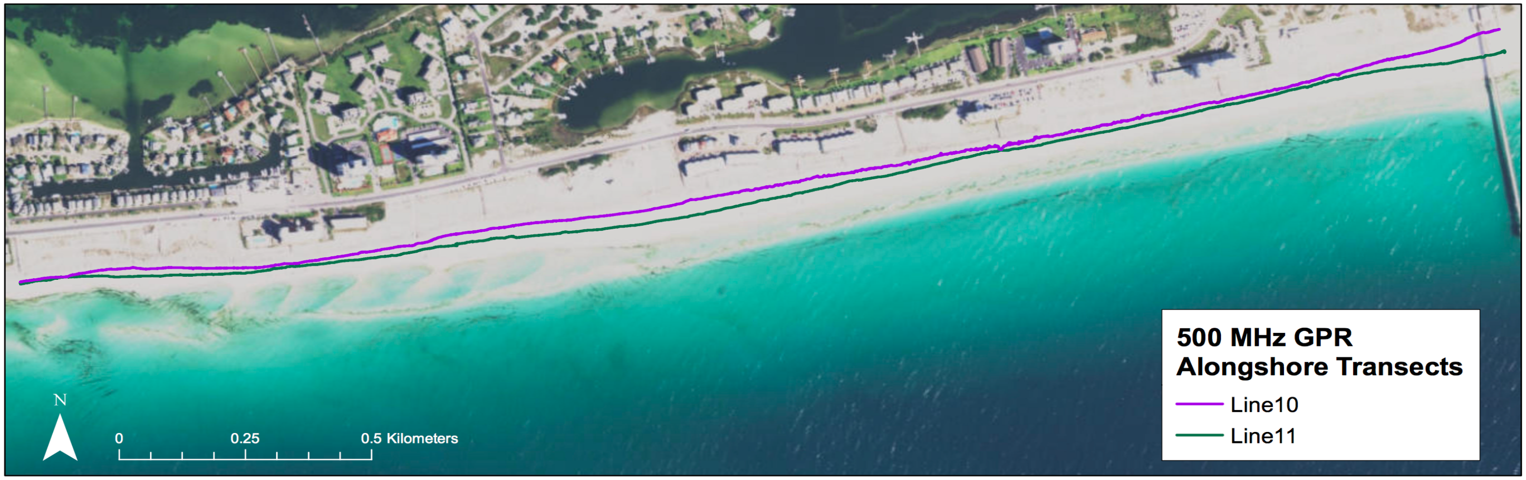

Figure 9: Map showing the path of the 500 MHz alongshore GPR transects.

Figure 10: Map showing the path of the 500 MHz alongshore GPR transects with corresponding 500 MHz cross-shore transects.

4.2 GPR Processing

The transects were processed using the software EKKO_Project developed by Sensors and Software. In order to keep the data accurate, minimal processing was done. Only three filters were applied, Dewow, Background Subtraction and Migration. The Dewow function removes unwanted low frequency signals while keeping the high frequency signals (Everett, 2013). The background subtraction filter removes any unwanted ground clutter of antenna ringing in the radar sections which produces a better visualization of shallow reflectors (Everett, 2013). Migration was applied “to undo the effects that the finite-velocity wave propagation bestows on measured time sections” (Everett, 2013). After the filters were applied, a topographic correction was applied to the cross-shore transects. The alongshore transects were not topographically corrected because the variation in Z height is so small it won’t make a difference in the data EKKO_Project requires a topographic file with the .top extension. The topographic files used contained 2 variables: the distance on the transect and the elevation or Z value. In order to calculate the Z value for all the traces GPS points were taken on each cross shore transect and then put into matlab where it interpolated the elevation for traces that were lacking a Z value. For each cross-shore transect a topographic file was imported shifting the traces up or down to reflect the true topography of the beach.

4.3 Coring

A total of fourteen cores were taken from the study site for x-ray fluorescence and grain size anaylsis. The location of each core was at the intersection of an alongshore and cross shore GPR transect with the exception of core 05 which was taken in the middle of a cross shore transect. The process for taking each core was to take a 3-inch diameter PVC pipe and hammer it into the ground (Figure 11). Once it was as deep as it could go, the top sand surface would be marked and then the top would be filled with paper or sand and capped. Once the top was capped the core was dug out of the ground and the bottom sand surface was marked and filled like the top. Each core was duck taped to ensure that no movement within the core would happen. A GPS location of each core was recorded (Figure 12&Figure 13).

Figure 11: Modified Coring system created using 3- inch diameter PVC pipe and Sledge hammer.

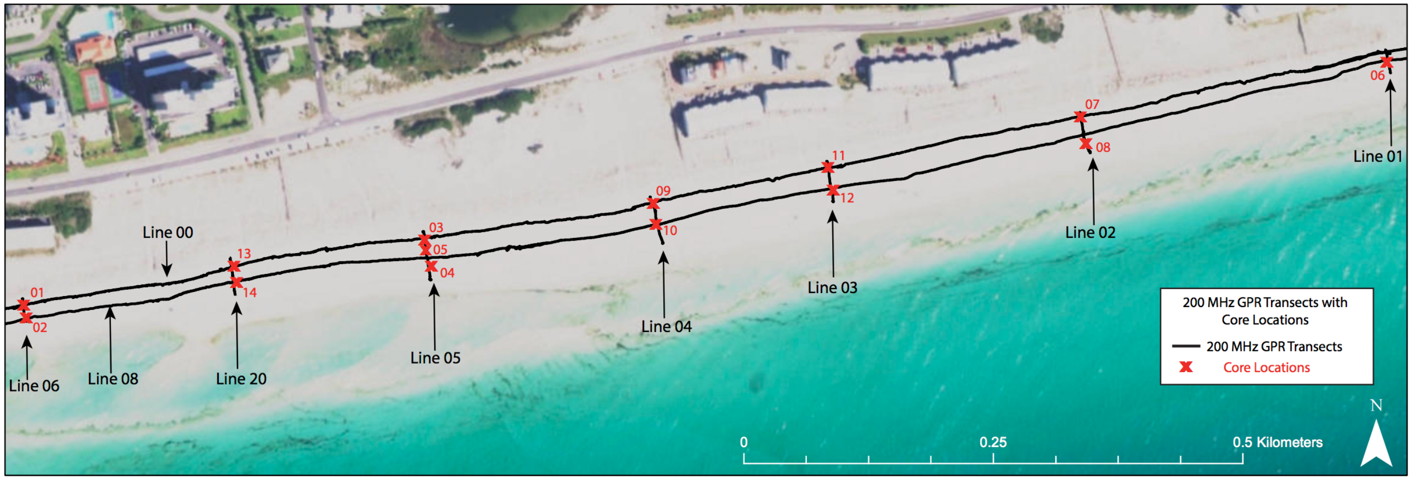

Figure 12: Location of cores with respect to the 200 MHz GPR Transects.

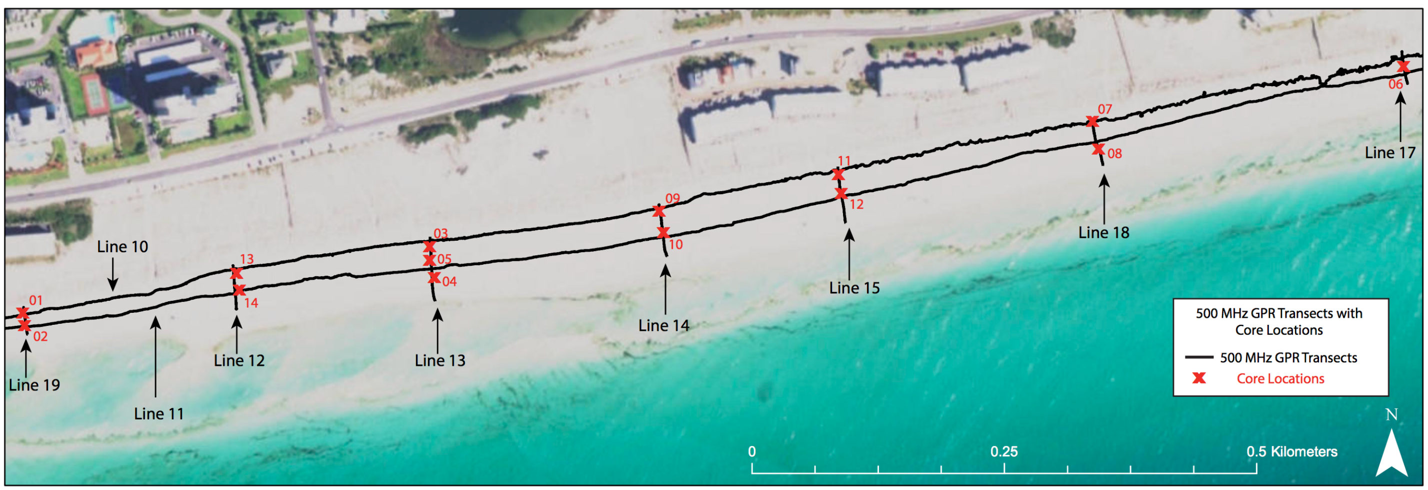

Figure 13: Location of cores with respect to the 500 MHz GPR Transects.

4.4 Core Processing and XRF

The fourteen cores were stored in a climate controlled storage unit until they were split and taken to the Integrated Oceanic Drilling Program (IODP) Faculty on the Texas A&M University Campus for analysis. Once they were cut, fishing line was used to split them into working and archive halves. The working halves were ruined during the splitting process so the archive halves were immediately wrapped in plastic wrap and taken to IODP for scanning on the digital image scanner (DIS) and XRF Core Scanner. The DIS took a high-resolution image of the archive half before it was prepped and run on a Avaatech XRF Core Scanner™ for elemental analysis. The settings used for the core scanner are: 9kV energy, 0.250mA, 6s scan time, with no filter at a 1 cm resolution. Certain sections of the core were skipped such as the top and bottom of the core because they were filled with sand or paper during the coring process. The 9kV spectrum scans for 15 lighter elements (Mg, Al, Si, P, S, Cl, Ar, K, Ca, Ti, Cr, Mn, Fe, Rh, and Ba) which were recorded as depth vs counts.

4.5 Grain Size Analysis

A Horiba Camsizer was used to collect grain size measurements. The Camsizer digitally images and analyzes thousands of particles of sand from each sample for the grain size and average sphericity. Each core was sampled at 10 cm intervals skipping the portions of core that were not scanned by the XRF. The cores were also sampled at areas where the XRF detected high counts of calcium, each location was recorded. The detection limits were selected from Wentworth grain size scales ranging from 0.05 – 0.1 mm and the distributions were recorded at 10^{th}, 50^{th}, and 90^{th} percentile. Once each sample was run through the Camsizer, the percent retained for each grain size was imported into GRADISTAT™ to calculate mean grain size (ϕ), sorting or standard deviation (σ), skewness (*Sk*), and kurtosis (*K*). These four grain size parameters can be calculated using many different equations (Folk, 1966).

The mean grain size (ϕ) reflects the overall average sediment size. Sorting (σ) is the range of sizes for a given sample. A sample that is well sorted and has a small standard deviation suggests sediment transport has taken place. In coastal environments, a poorly sorted sand is indicative of a beach deposit and well sorted sand is commonly found in the dunes. Skewness (*Sk*) measures the distribution of symmetry within a sample. If the sample is positively skewed this indicates the addition of fine grains transported by wind or coarse grains being removed by water. Kurtosis (*K*) is the measure of "tailedness" which looks at the sorting of the central part of the curve and the sorting of the tails. If the central part of the curve is well sorted then it is called Leptokurtic and if the tails are well sorted then it is called Platykurtic.

For the purpose of this study the mean grain size is calculated using the following equation from Folk and Ward (1957):

$$\boldsymbol{\mu} = \frac{\phi 16 + \phi 50 + \phi 84}{3} \qquad (1)$$

Sorting was determined by:

$$\boldsymbol{\sigma} = \frac{\phi 84 - \phi 16}{4} + \frac{\phi 95 - \phi 5}{6.6} \qquad (2)$$

Skewness was calculated using:

$$\boldsymbol{Sk} = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)} \qquad (3)$$

Kurtosis was calculated using:

$$\boldsymbol{K} = \frac{\phi 95 - \phi 5}{2.44x(\phi 75 - \phi 25)} \qquad (4)$$

5. RESULTS

5.1 XRF and Grain Size Analysis Results

Grain size statistics, and XRF results are shown in the following section to demonstrate a relationship exists between calcium spikes from the XRF analysis and the four grain size parameters: mean grain size (ϕ), sorting or standard deviation (σ), skewness (*Sk*), and kurtosis (*K*). In some of the cores there is a spike in calcium around 100 cm as depth and the mean grain size increases. The sorting value also increases at that depth which suggests poor sorting, negative skewness, and increase in kurtosis. In a few cores, there is an increased calcium value but the mean grain size does not increase, this could be because the Camsizer was not set to measure any grain size over 1mm. The increase in Ca counts and mean grain size around 100 cm is most likely indicative of a storm layer. In many of the cores there is also an increase in calcium, mean grain size, and sorting near 60 cm. The characteristics of this spike are similar to those of the 100 cm spike, which means this could be a storm layer as well. It should also be noted that some of the plots show a spike in grain size but no change in calcium counts which could be caused by the narrow sampling window of the x-ray beam on the XRF. Those layers can be observed visually on the core photos.

5.1.1 Backbeach Cores

Core 01 was taken in front of the San Succi Condominiums at the intersection point of alongshore and crossshore GPR transects. It reached a depth of 130 cm and was located in the center of an offshore bathymetric swale. Figure 14 shows a calcium spike, increase in grain size, poor sorting, negative skewness and decreased kurtosis near 60 cm. At 115 cm below the surface there is a calcium spike, poor sorting, negative skewness and increased kurtosis. The grain size does not increase but this is likely because the grains were larger than 1 mm and the Camsizer was not set to measure them. The grain size change can be seen in Figure 15. Just below the red line that is drawn on the image there is an increase in grain size and it becomes poorly sorted. The layer of larger grains extends from about 115 cm to 117 cm

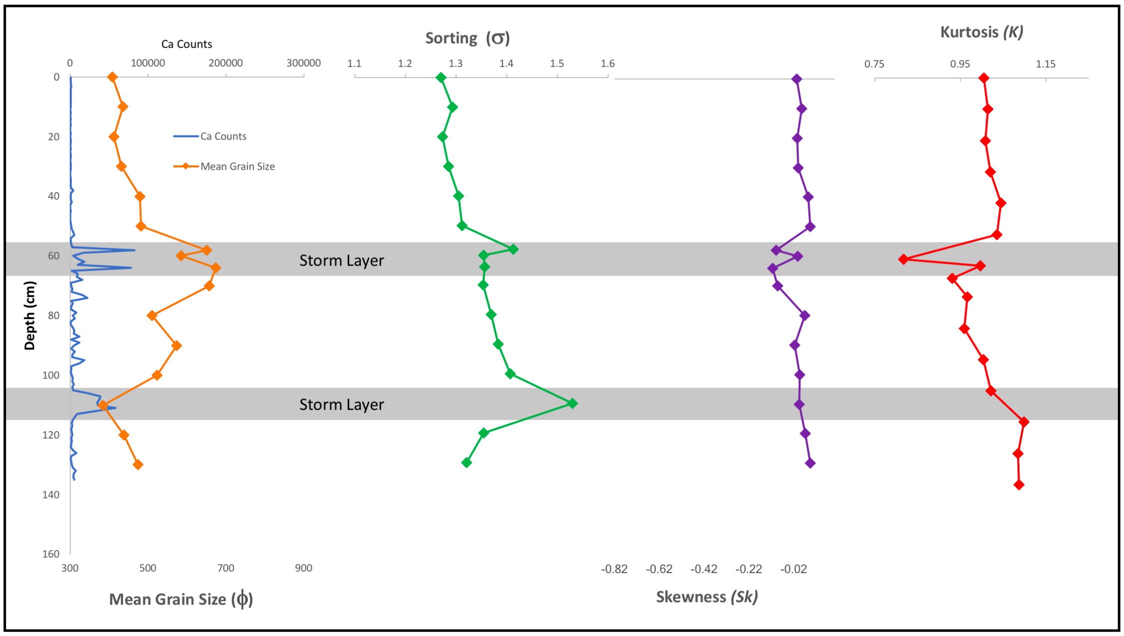

Figure 14: Core 01 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

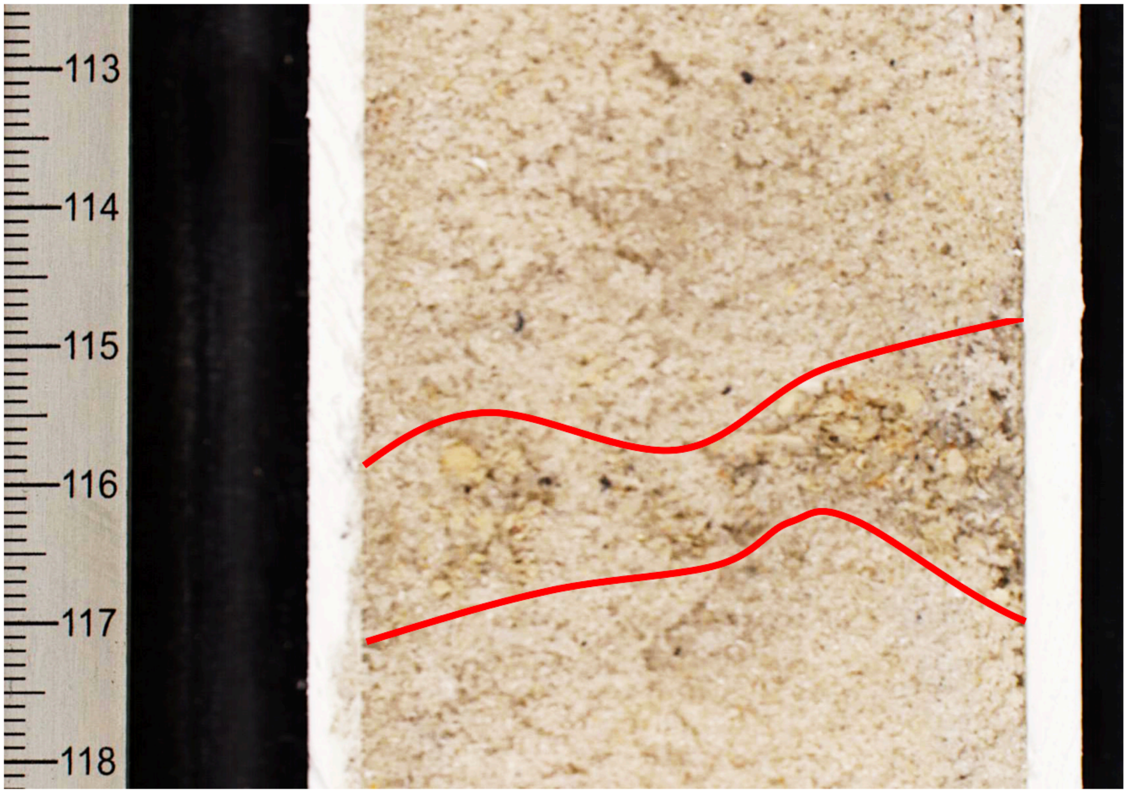

Figure 15: Storm layer at 115 cm. The mean grain size in Figure 14 does not show grain size increase but the core photos show a grain size change.

Core 13 (Figure 16) is to the east of core 01 on the same backbeach alongshore GPR line but is at the next intersection point of the crossshore GPR transects. Similar to core 01, two storm layers are identified at about 55cm and 100 cm in depth. There is also a third storm layer at ~140 cm below the surface which shows a major increase in calcium, poor sorting, negative skewness, and increased kurtosis. Core 01 does not reach deep enough for the third layer to be identified.

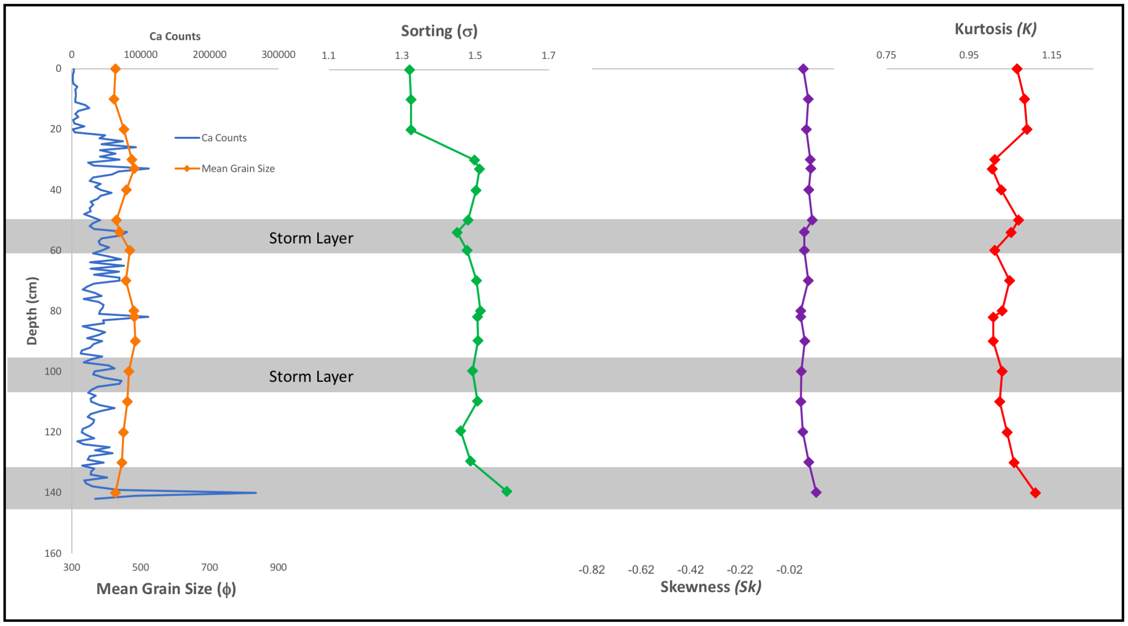

Figure 16: Core 13 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

Just east of core 13 is core 03 (Figure 17). This core was taken at an intersection point between the backbeach alongshore GPR line and another one of the crossshore GPR transects. It is almost in the middle between the San Succi Condominiums and White Sands Cottages. The two storm layers identified in core 01 and 13 are once again prevalent. The first is around 50 cm and the second is around 105-110 cm. The second shell layer has shifted deeper in the profile and 10 cm in the vertical, because the cores are in a swale which would cause this area to be lower lying.

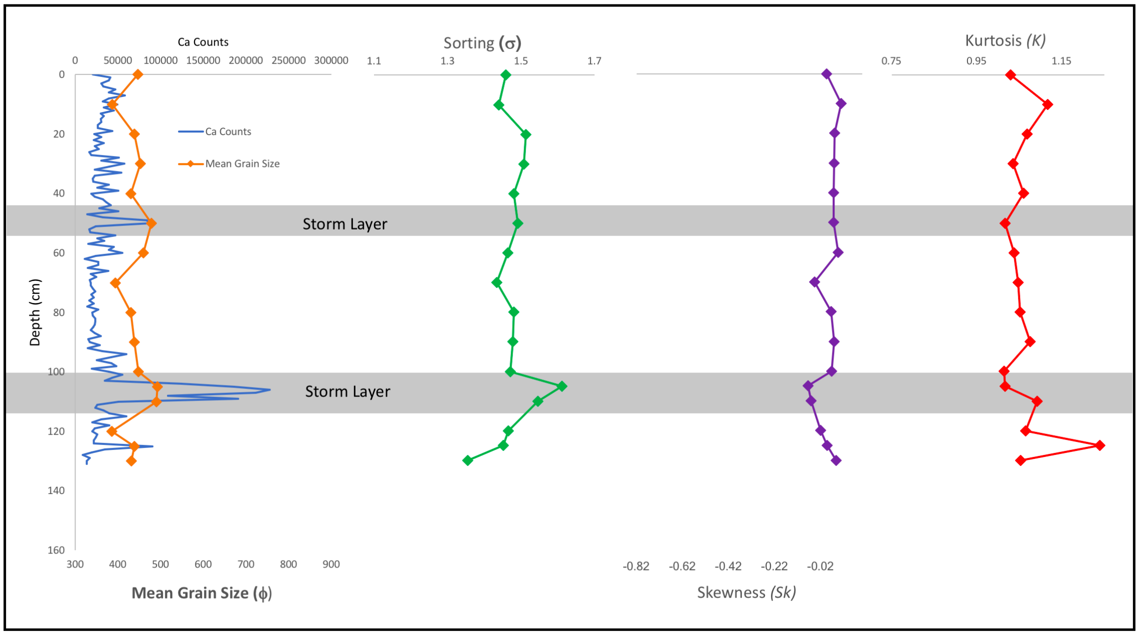

Figure 17: Core 03 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

Core 05 was taken in the middle of the beach between core 03 and 04 on the same crossshore GPR line. This core was the only core that was taken in the middle of the beach between the two alongshore GPR lines. The plot shows an increase in grain size, poor sorting and negative skewness around 50 cm depth but no calcium spike which could be caused by the narrow sampling window of the XRF. The calcium spike at 115 cm is accompanied by increased grain size, poor sorting, and negative skewness. The increases at 50 cm and 115 cm depth are a continuation of the storm layers identified in the previous cores.

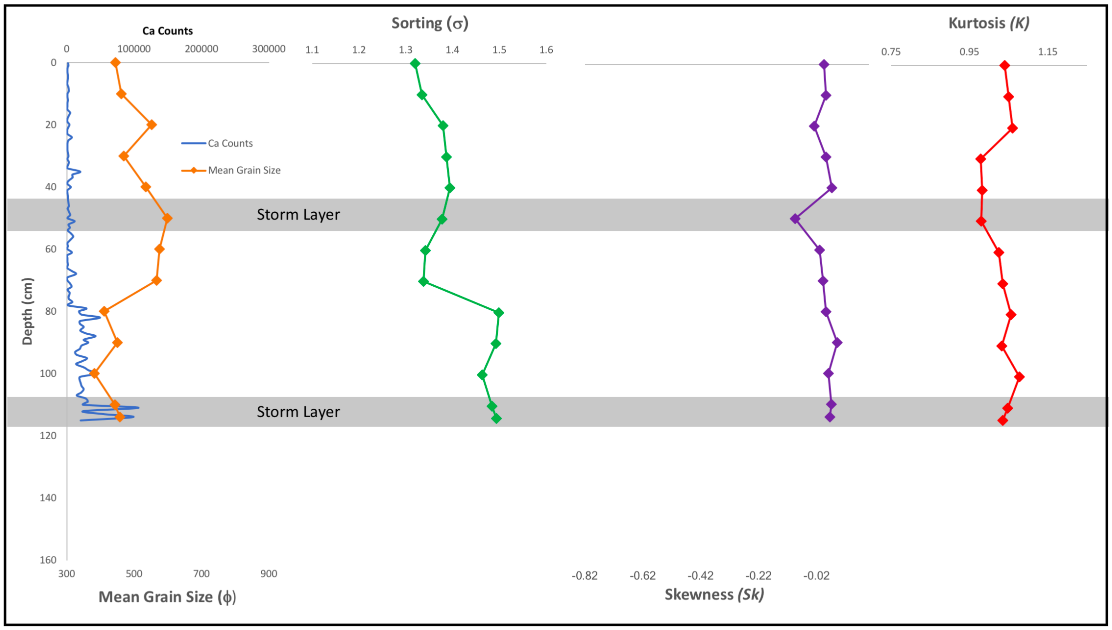

Figure 18: Core 05 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

Further east core 09 was taken just before the White Sands Cottages property line at the intersection point between the backbaeach alongshore and one of the crossshore GPR transects. Figure 19 shows storm layers at about 60 cm and 110 cm. These storm layers are at similar depths to the other cores and show the same characteristic grain size parameters. The storm layer at 110 cm is slightly deeper in depth which likely corresponds to a low in that portion of the beach at the time of deposition.

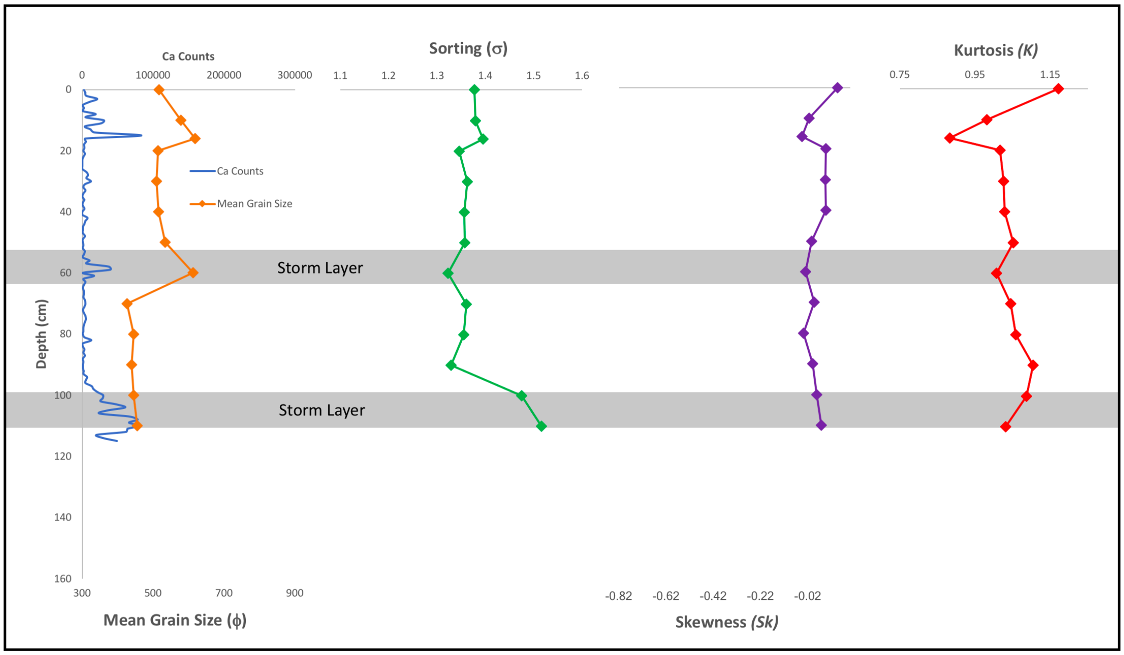

Figure 19: Core 09 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

Core 11 is east of core 09 and is located away from the base of the dune in front of the second building in the White Sands Cottages at the meeting point of the backbeach alongshore and one of the crossshore GPR transects. The first storm layer is identified at 55 cm and the second storm layer is at about 90 cm (Figure 20). These two layers are slightly shallower when compared to the other cores.

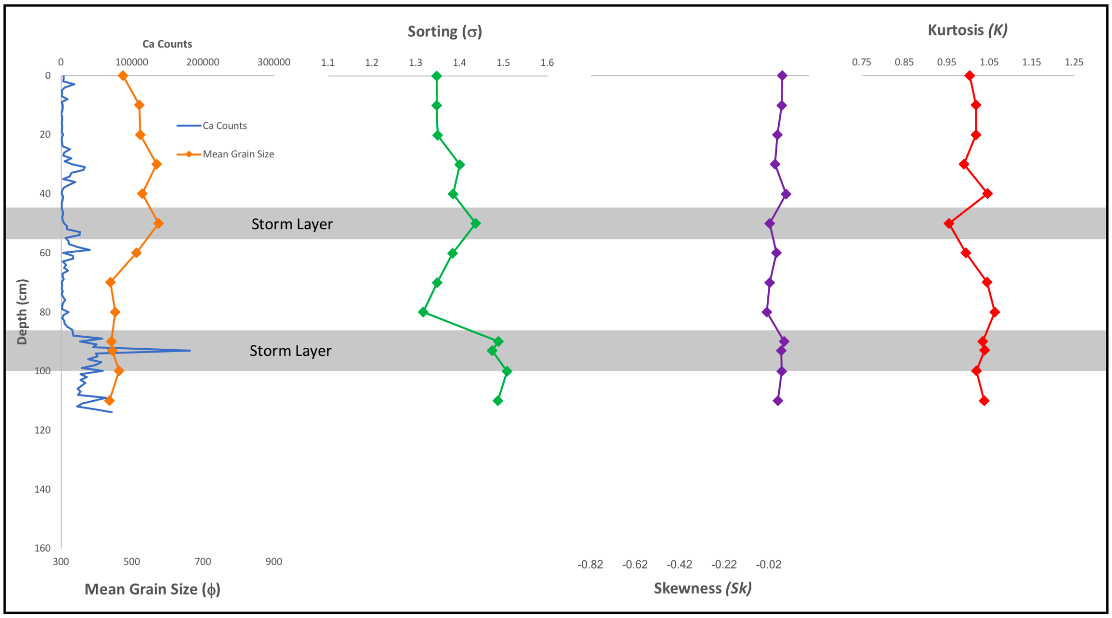

Figure 20: Core 11 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

The last core in the backbeach is core 07. It was taken away from the base of the dune at the end of the White Sands Cottages property line. This spot was chosen because it is the intersection point of two GPR lines. Figure 21 shows the characteristic grain size parameters of storm layers at depths of ~60 cm and 105 cm. These depths are the same as core 01.

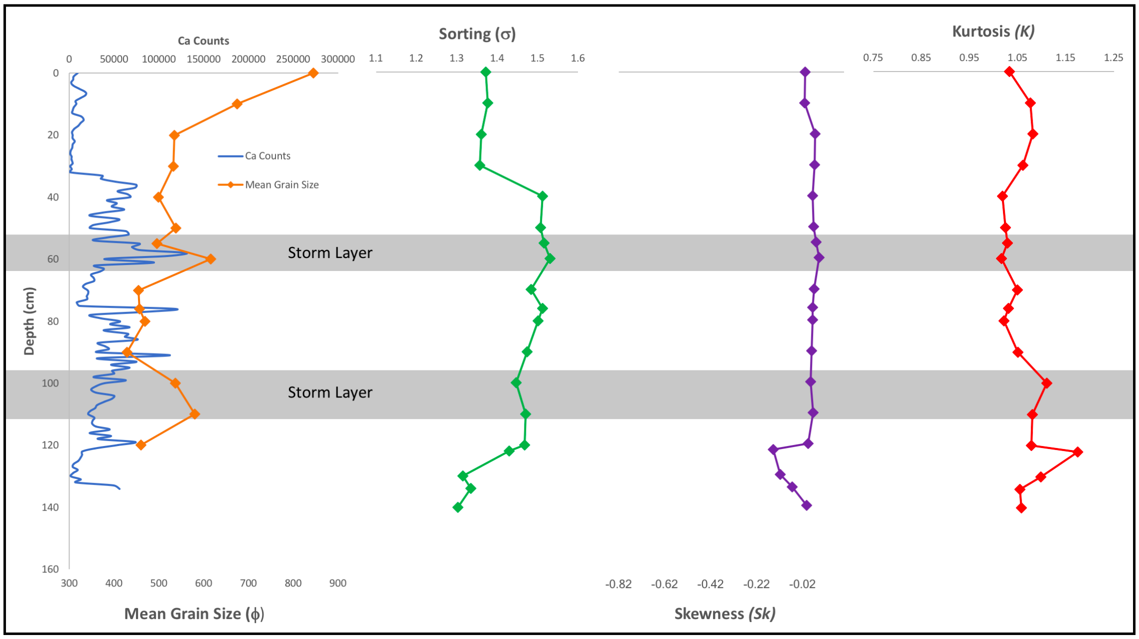

Figure 21: Core 07 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

5.1.2 Forebeach Cores

Core 02 is on the same cross shore transect as core 01 but is taken at the intersection of the forebeach alongshore transect. Core 02 showed very similar trends in grain size parameters as core 01, the only difference is the first storm layer is shallower at about 45-50 cm below the surface whereas core 01 was at a depth of 60 cm (Figure 22). This is likely due to a berm that was present causing this area to be slightly higher than the back beach. The second layer identified is between 100 cm and 110 cm which again is just slightly shallower than the second layer in core 01.

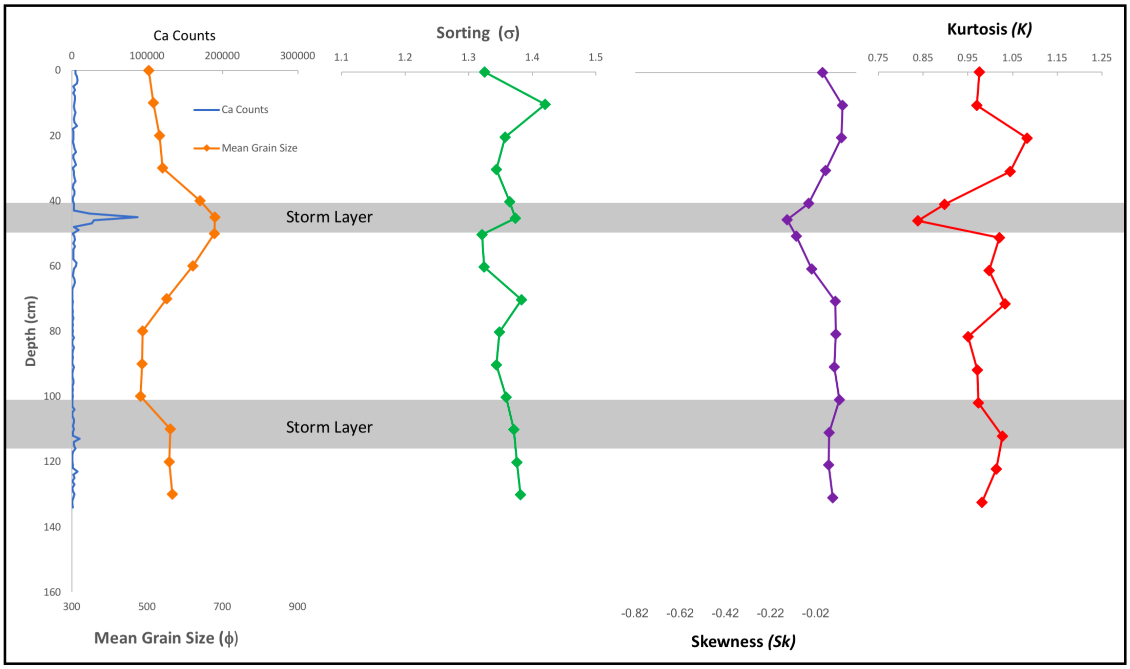

Figure 22: Core 02 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

Core 14 is east of core 02 and it located at the intersection point of the forebeach alongshore transect and the same crossshore GPR transect that core 13 is located on. Figure 23 exhibits only one of the previous identified storm layers which is at ~105 cm depth. The grain size parameters are the same as previously identified storm layers.

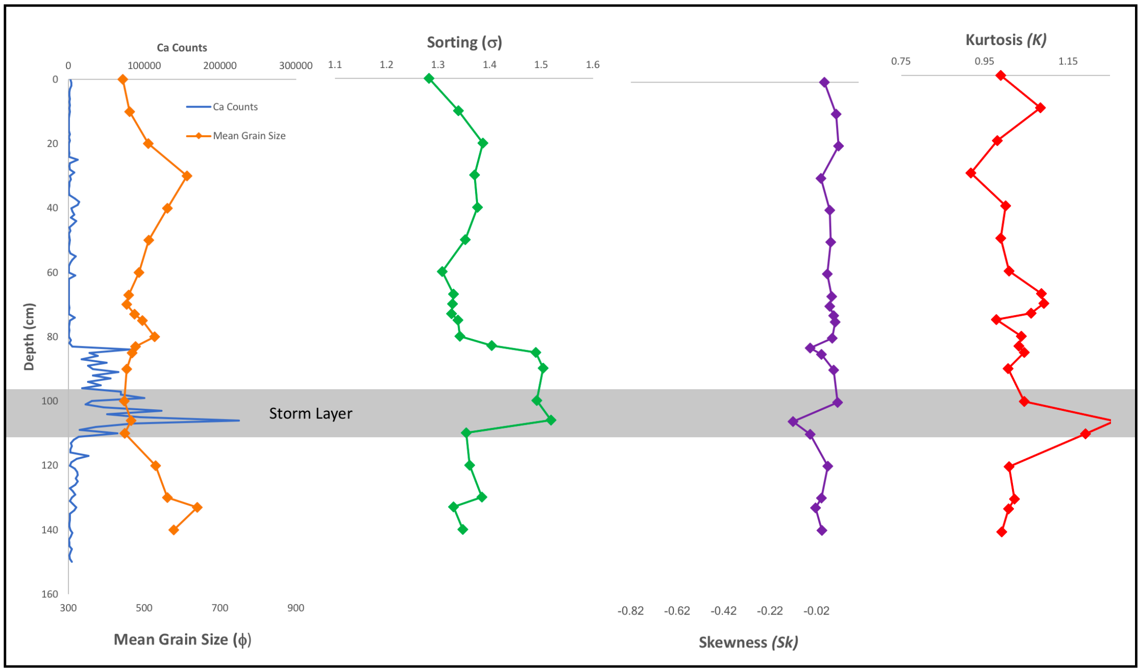

Figure 23: Core 14 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

Core 04 is located east of core 14 and is on the same crossshore GPR line as Core 03 and 05. This core was taken at the intersection point of the near forebeach alongshore GPR line and the crossshore GPR transect. Figure 24 shows the characteristic grain size parameters of storm layers at 58 cm, 100 cm, and 135 cm. The first two layers are likely the continuation of the layers previously identified and the third layer is identified in a few of the previous cores, but many of the cores do not reach deep enough to identify this layer in all of the cores.

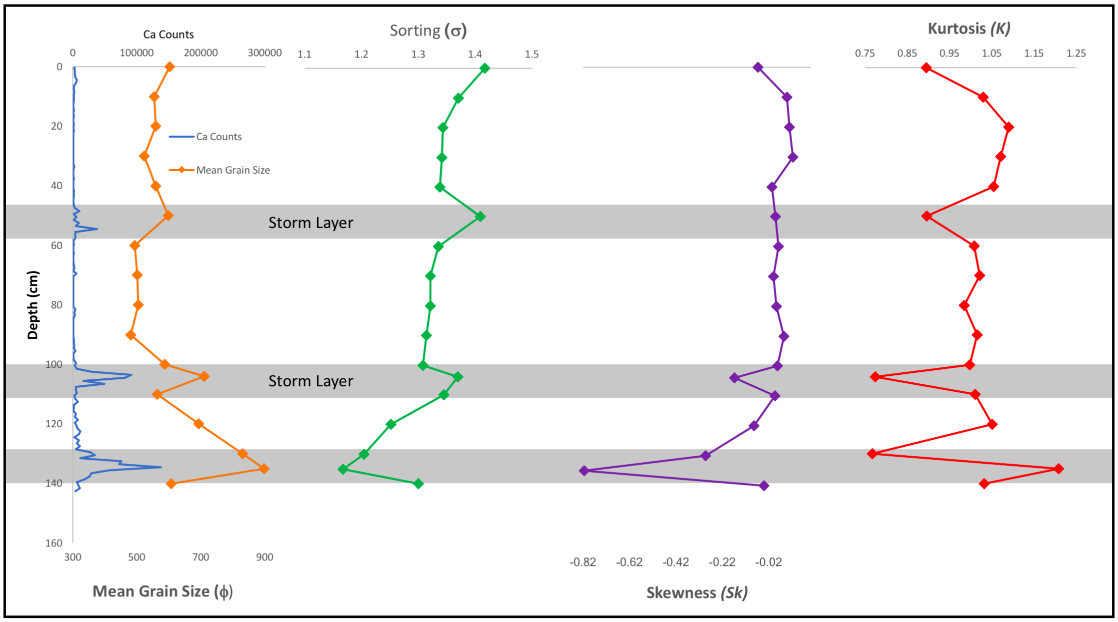

Figure 24: Core 04 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

The next core taken was core 10, this core was taken to the east of core 04 and on the same crossshore GPR line as core 09 but at the intersection of the forebeach alongshore GPR transect. Two storm layers are identified at ~60 cm and ~125 cm (Figure 25). These two layers are shifted deeper than previous cores had shown, this could be the result of the swale getting slightly deeper.

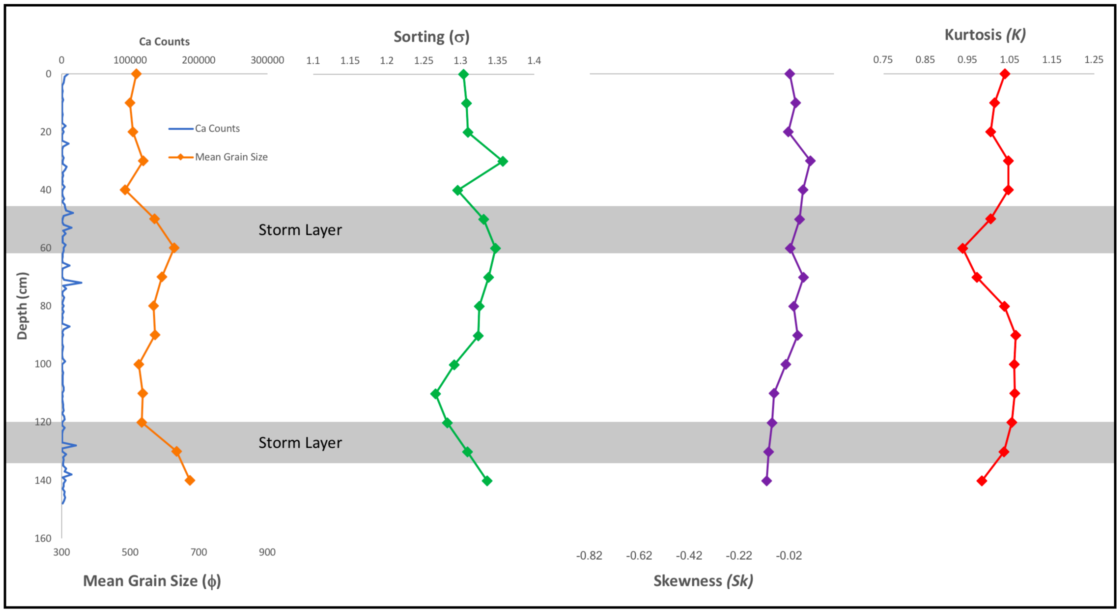

Figure 25: Core 10 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

Just east of core 10, core 12 was taken at the intersection point of the forebeach alongshore GPR transect and the crossshore transect that contains core 11. Two storm layers are identified at depths of 60 cm and 105 cm. The grain size parameters from this core (Figure 26) are similar to previous cores and the depths seem to correspond to a continuation of the storm layers previously identified.

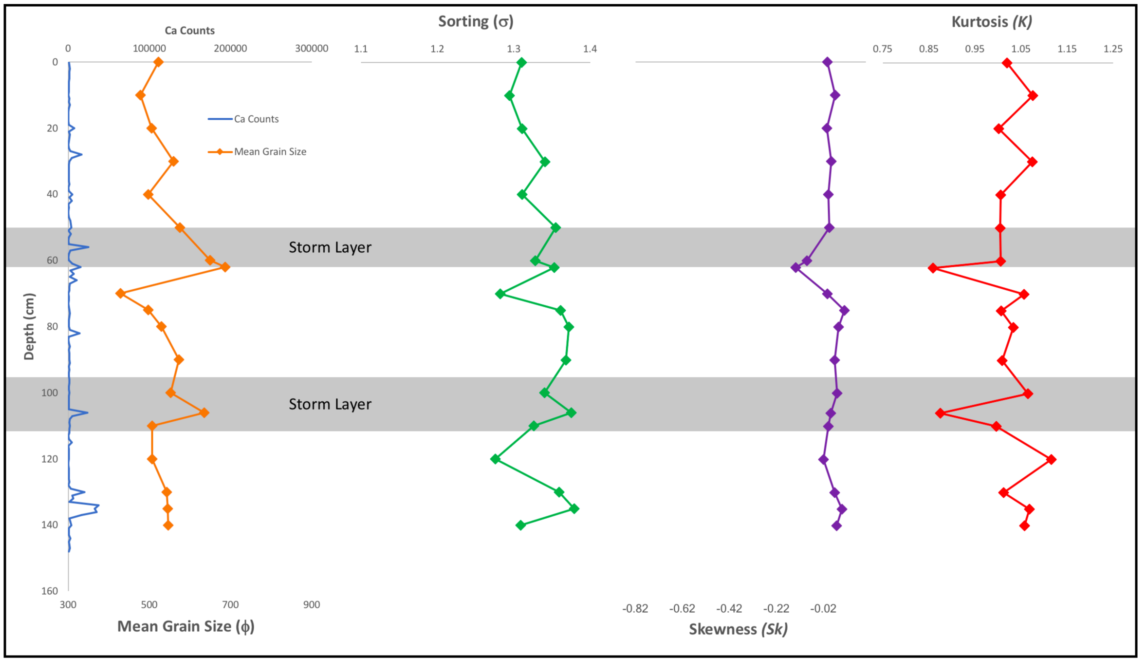

Figure 26: Core 12 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

Core 08 is located east of core 12 on the near swash alongshore GPR transect. It was taken at the intersection of the forebeach alongshore GPR transect and the crossshore GPR line containing core 07. Two storm layers have been identified at ~55cm and 110 cm (Figure 27). These depths are consistent with previous cores and the storm layer seems to be shifting shallower in depth which could be the result of getting closer to the offshore bathymetric ridge which causes a high in the beach.

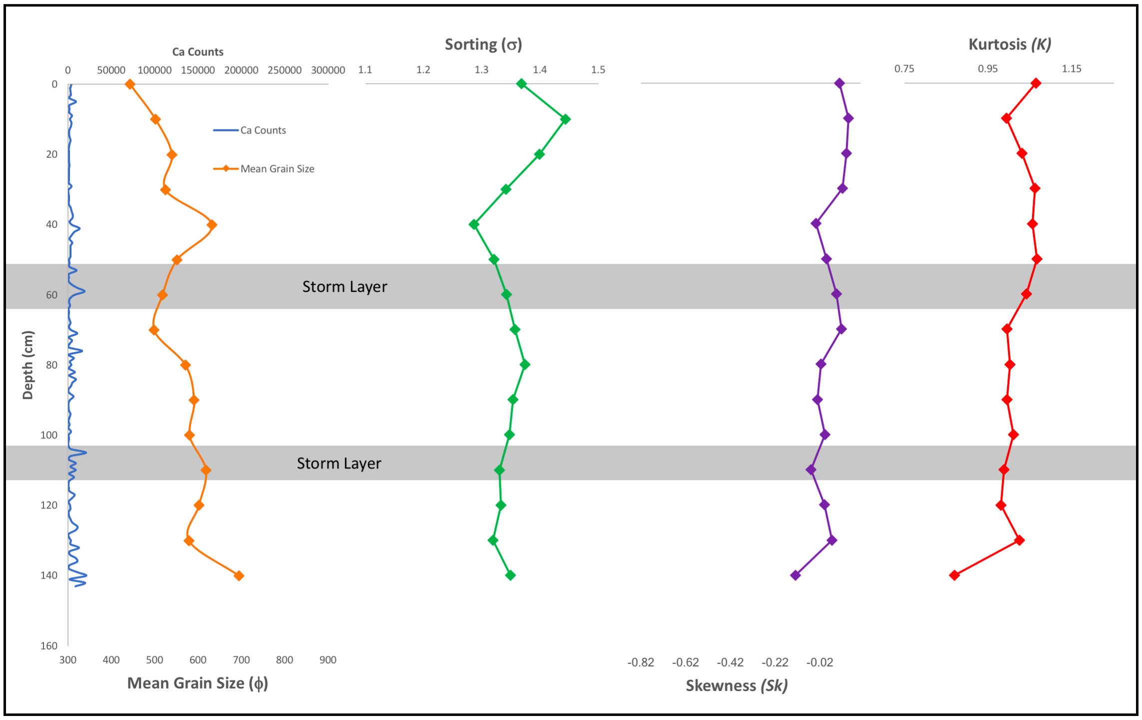

Figure 27: Core 08 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

The last core taken near the swash is core 06. It is located at the intersection point of the forebeach alongshore GPR line and a crossshore transect. There were no other cores taken on this crossshore GPR line and is the core furthest to the east and closest to ridge. Two storm layers were identified in Figure 28. The first is at a depth of ~45-50 cm and the second is at a depth of ~100-105cm. These layers are shallower than in previous cores which could be the result of being so much closer to the ridge and the beach beginning to rise.

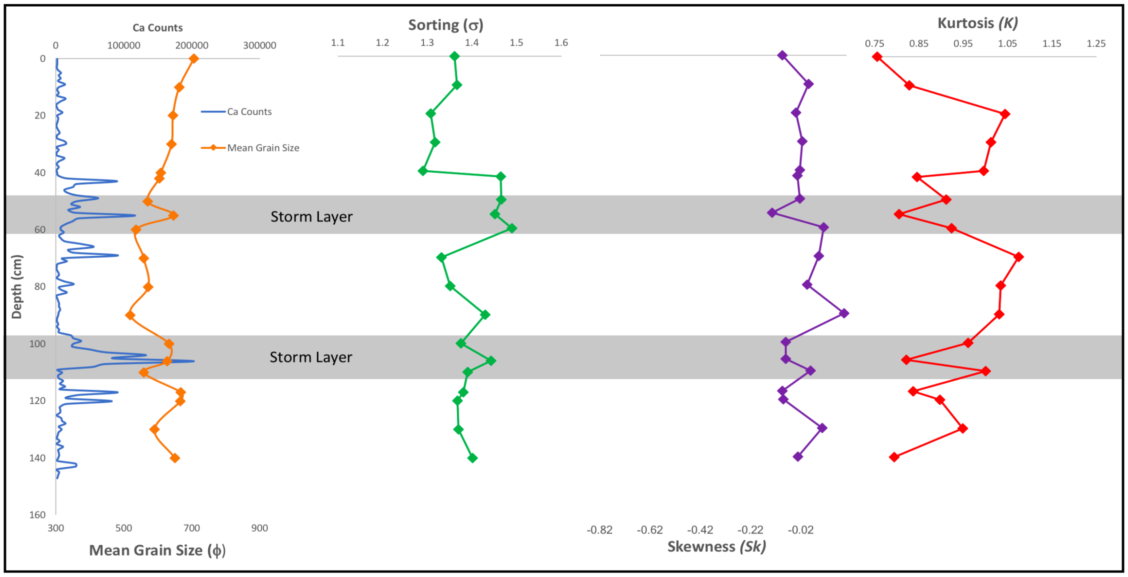

Figure 28: Core 06 plot showing shell layers, XRF Calcium Counts, and grain size parameters.

5.2 GPR Results

5.2.1 Backbeach Alongshore GPR Analysis

The first set of GPR transects was taken using the 200 MHz attena in the backbeach where this is relatively no elevation change (+/- 1 meter). The first line in this set (Line 07) begins at beach entrance 21F (A) and ends near the San Succi Condominiums (A') (Figure 29) and is 370 m long. The first 90 m is slightly attenuated (the signal is weakened) which could likely be caused by frequent and deep cleaning of machines because this is an entrance to the beach. Although slightly washed out, some structure can be seen. After the first 90 m, a long horizontal reflector that continues through the entire line at a depth of 1-1.5 m is very visible and corresponds with the depth of the storm layers in the cores.

The second line (Line 00) is 1.31km long, beginning at the San Succi (B) and ending at the Holiday Inn (B') (Figure 29). The horizontal reflector extends the entire length of the line, and is at the same depth as the storm layers identified in the cores. In the GPR line the horizontal reflector varies in depth from 1m to 1.5m with an alongshore variation. Where it is shallower at the start and finish of the line and the reflector is deeper in the middle of the transect.

The third line (Line 09) in this series extends from the Holiday Inn (C) to the Pier (C') for a total of 825 m (Figure 29). the horizontal reflector is present in this line as well but it slightly deeper than the last two. The reflector is present at a depth of about 1.5m but towards the end of the line (~750-800m horizontal) it goes as deep as 2.5m below the surface.

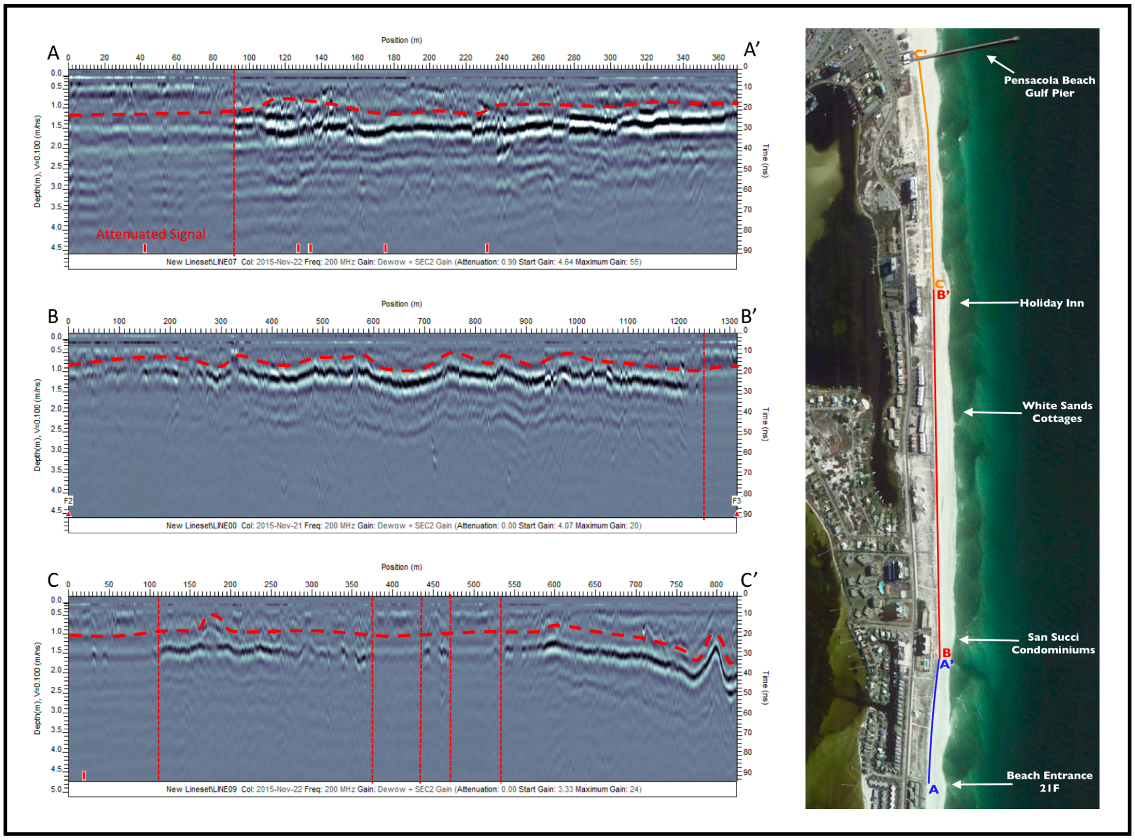

Figure 29: Backbeach 200 MHz Alongshore GPR Transects. Line 07 (blue) extends 370m from A to A'. Line 00 (red) extends 1.31km from B to B'. Line 09 (orange) extends 825m from C to C'.

A single 500 MHz GPR transect that was taken on the same path as the 200 MHz lines (Figure 30). It had to be broken into two parts because the software could not be process the line as a whole. It was split into two almost equal parts the first part being 1.2 km in length and the second being 1.21 km in length. There is little to no change in elevation so this line was not topographically corrected. The first 100 m is washed out similar to the 200 MHz line in part A. After the washed-out part there is also a horizontal reflector that is present from about 1 m to 1.5 m depth. It is continuous through the entire line. The horizontal reflector identified in part A is also present in part B starting at a depth of 1 m and continuing for the entire line. At the beginning of part B there it starts a 1m depth and dives to 1.5 m in depth within 50 meters and then comes back up to about 1m in depth and holds that depth for the rest of the line. The dip seen at the position 1200- 1250m on the horizontal matches to a similar dip in the second line at the position 830 m in Figure 29. The horizontal reflector seen in this line also corresponds to the storm layer that is identified in the cores and in Figure 29.

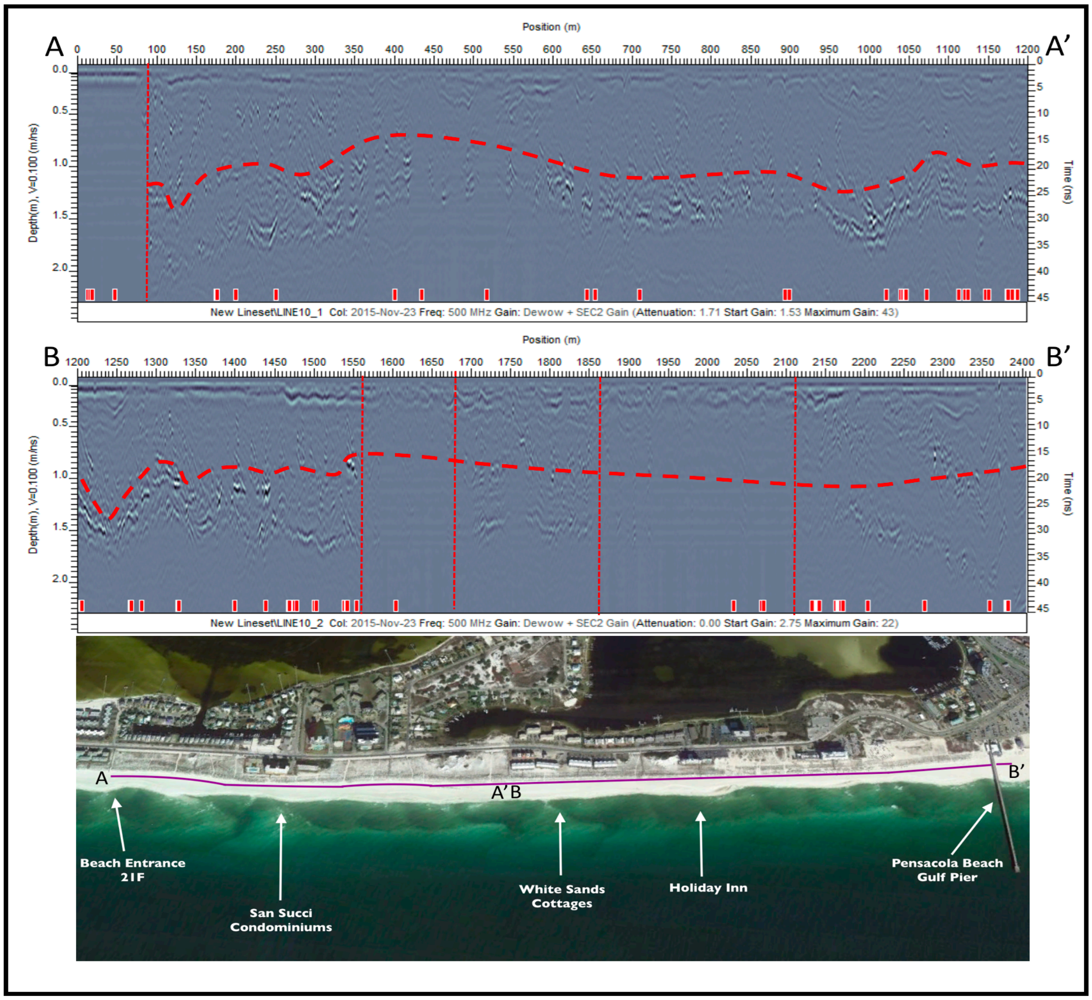

Figure 30: Backbeach Alongshore 500 MHz GPR Transect. This line had to be broken into two parts to be processed. A.) First half of Line 10 which extends 1.2km. B.) Second half of Line 10 which extends 1.21 km.

5.2.2 Forebeach Alongshore GPR Analysis

This line (line 08) was taken as one continuous line beginning at the beach entrance 21F and ending at the Pensacola Beach Gulf Pier. It extends a total of 2.41km and runs nearly parallel to the backbeach alongshore transect. This line was taken near the top of the swash zone where the sand is not wet to ensure that the salt water would not attenuate the signal. Figure 31 shows that the line is very washed out, there are areas that show a horizontal reflector for ~100-150m and then there is another washout. The small horizontal reflectors that are present in Figure 31 show up at a depth of about 1m which corresponds to the storm layer present in the cores along the same line. There should be a continuous reflector present in this like because the cores in the forebeach have the same storm layers' present as the cores in the back beach. There is likely more moisture in the forebeach that is attenuating the signal ever 100m or so, causing the reflector to only show up in certain parts of the line. The extra moisture is likely the result of the difference in wave set up causing swash with a higher elevation..

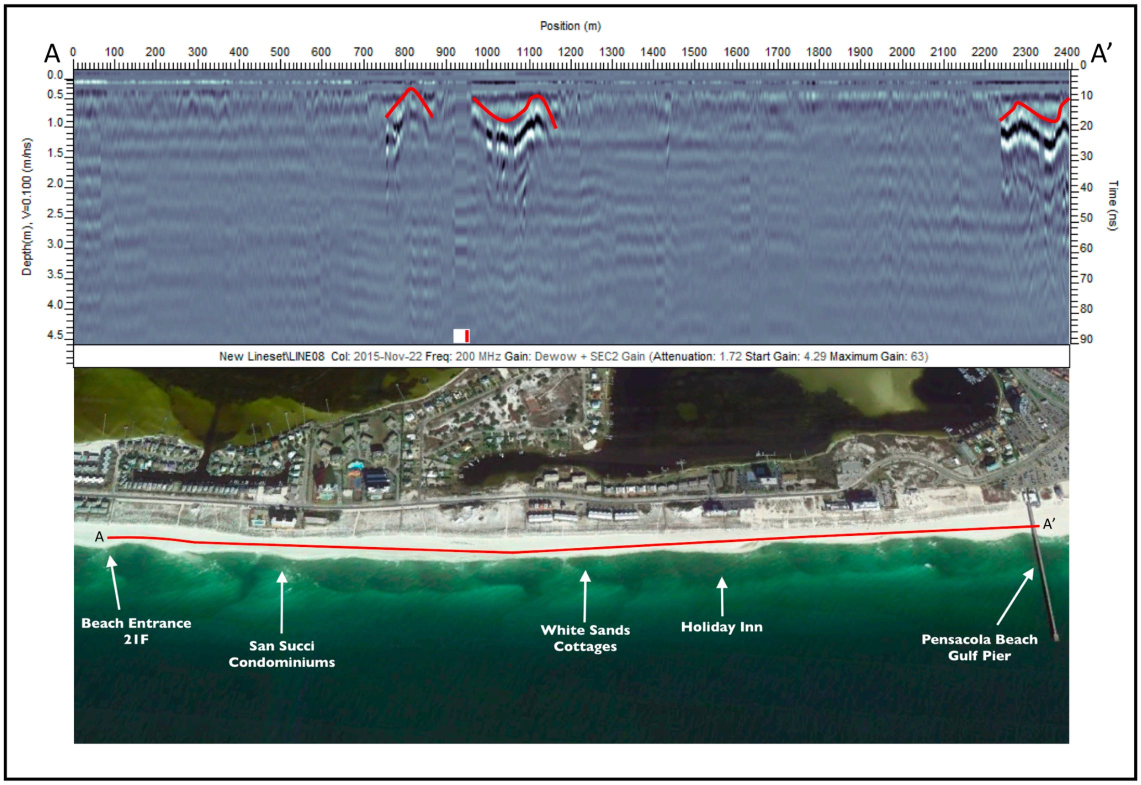

Figure 31: 200 MHz forebeach Alongshore GPR Transect. This line is 2.41 km in length beginning at beach entrance 21F and ending at the Pensacola Beach Gulf Pier.

A GPR trasnect was shot using the 500 MHz antenna and was taken on the same path as the line in Figure 31. It began at beach entrance 21F and ended at the Pensacola Beach Gulf Pier. It was shot in the opposite direction of line 08 in Figure 31 so it had to be reversed when the lines were processed. Similar to the lines in Figure 30 it had to be broken into two parts. It was originally shot as one continuous line, but the program could not process the entire line so it was split into two almost equal parts. Part A of the line is 1.21 m long and part B of the line is 1.2 m long. This line is also very washed out in the sub surface. In Figure 32, some structure can be seen in the upper half meter but other than that only pieces of a horizontal reflector shows through. The horizontal reflectors are at a depth of about 1m – 1.5m. There is moisture attenuating the signal causing the reflector to only show up in certain parts of the line.

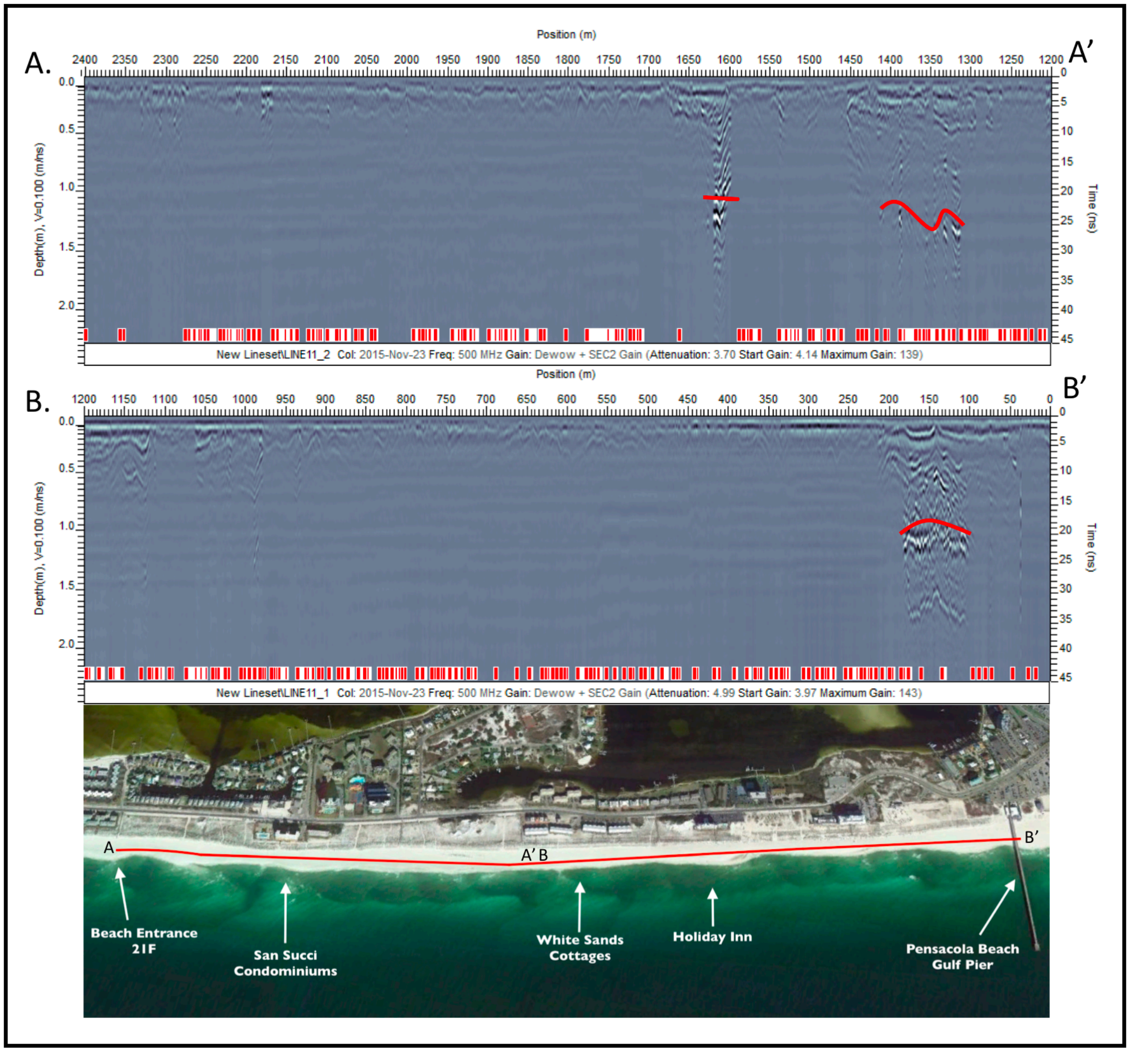

Figure 32: 500 MHz forebeach alongshore GPR transect. This line begins at beach entrance 21F and ends at the Pensacola Beach Gulf Pier. It is a total length of 2.41km.

5.2.3 Crossshore GPR Analysis

The first set of GPR transects was taken with the 200 MHz antenna. This set consists of 7 different transects. These lines were topographically corrected because there is a variation in height from start to finish. Line 06 was taken crossshore in front of the San Succi condominiums. Line 06 had to be reversed during processing because it was taken from the swash towards the dune. Figure 33 presents line 06 some structure can be identified as beach deposits and a storm surface. Moving seaward the line becomes washed out and this is likely due to the salt water trapped in the sand.

Moving east of line 06 is Line 20, this line was taken from the dune to the swash zone and did not have to be reversed. More beach deposits and a storm surface can be seen. The storm surface is at a depth of about 1m- 2m. It is deeper in the dune than it is towards this swash. This is likely because sand has been deposited as the dune builds back following the storm.

The next line (line 05) is between the San Succi Condominiums and The White Sands Cottages. It had to be reversed because it was originally taken from the swash to the dune. A strong horizontal reflector is at a depth of about 1.5 m to .5 m and persists through the entire line. Towards the swash the signal somewhat weaken as a result of the salt water.

Line 04 is on the property line of the White Sands Cottages and like previous lines, it had to be reversed because it was originally shot starting at the swash zone and ending at the dune. This line has a very strong horizontal reflector that is at a depth of about 1m. This horizontal reflector is likely a storm surface because it is at a depth that has been previously identified as a storm layer using the alongshore GPR lines and the cores.

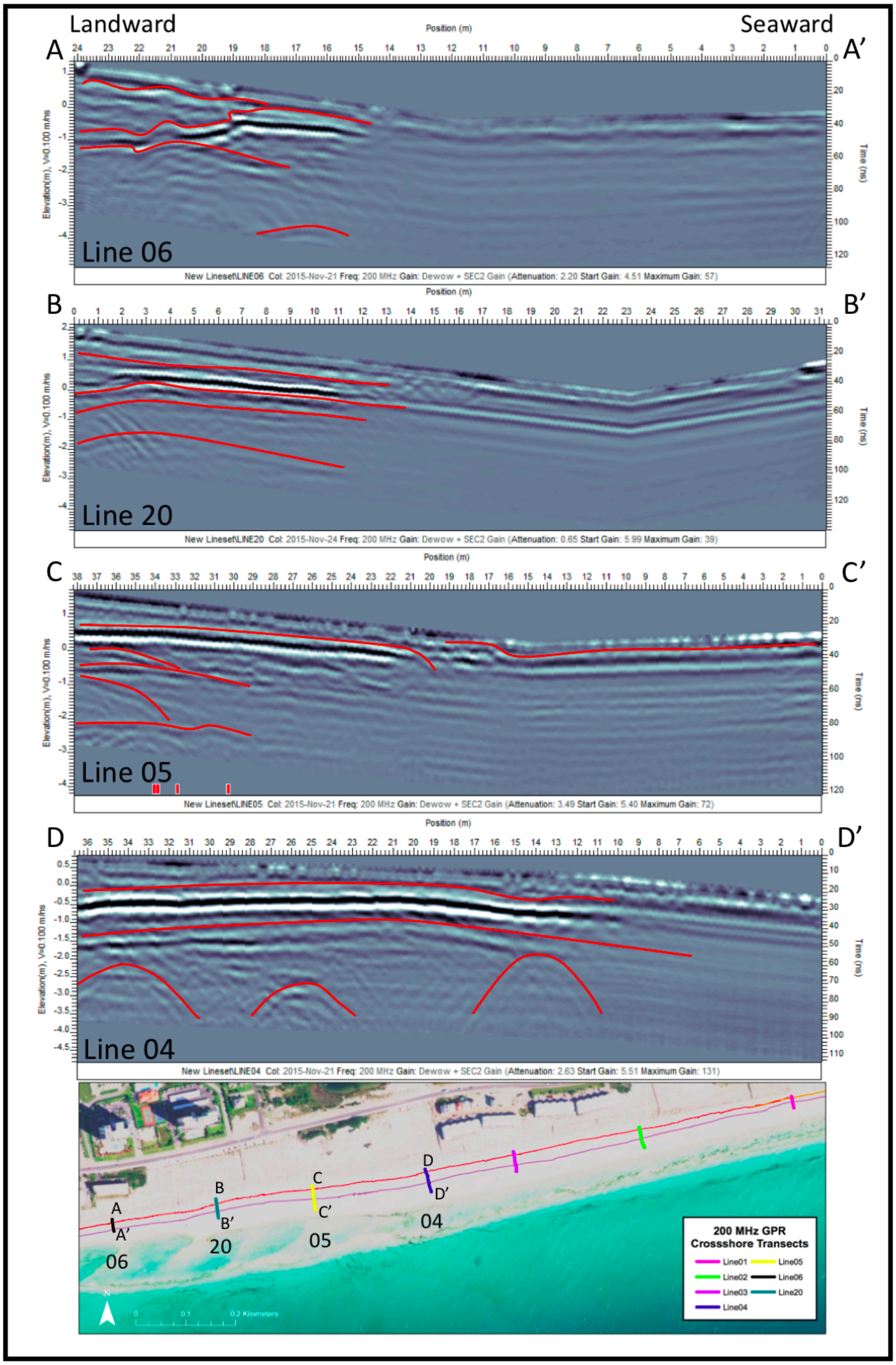

Figure 33: The first four 200 Mhz crossshore GPR transects.

Line 03 is the east of line 04 and the direction has been reversed. This line has several strong horizontal reflectors. The first reflector is at a depth of ~1m and is continuous through the entire line. The second is at a depth of ~1.4-1.5m and only extends about 11m from the beginning of the line in Figure 34. These horizontal reflectors are storm layers or initial post storm accretion layers.

Line 02 is at the end of the White Sands property line. This line is 31 meters in length and was shot from swash to dune so the during processing it had to be reversed. Once again there are strong horizontal reflectors that are storm layers or initial post storm accretion layers.

Line 01 is the final 200 MHz crossshore transect. It has a total length of 19m and had to be reversed during processing because it was taken from the swash towards the dune. At a depth of about 100cm depth there is a strong horizontal reflector that is a storm surface.

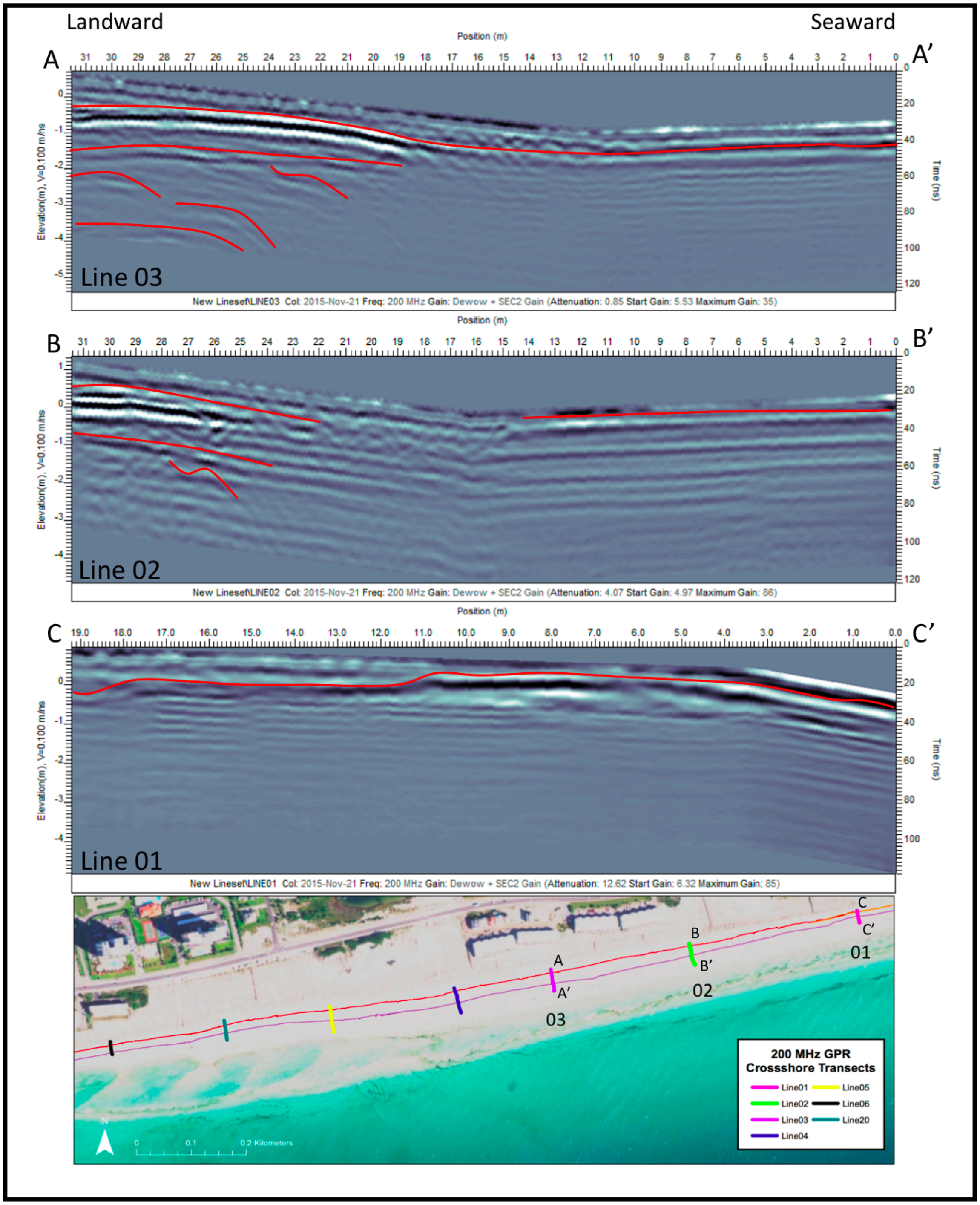

Figure 34: The last three 200 MHz crosshore GPR transects.

This set of GPR transects is taken on the same path as the 200 MHz crossshore GPR lines but was taken with the 500 MHz antenna (Figure 35). All of the lines in this set of GPR transects had to be topographically corrected because there is variation in height from the backbeach to the forebeach. The 500 MHz lines don't penetrate as deep as the 200 MHz line but they show the subsurface structure at a much higher resolution.

The first line (line 19) is taken in front of the San Succi and is on the same path as line 06 in the 200 MHz GPR lines and extends ~22 m. There are 3 defined horizontal reflectors which correspond to the depths where storm layers are present in the cores on this line.

Moving east to line 12 which is ~35m in length and has multiple horizontal reflectors at similar depths as line 19. These reflectors are also storm layers. The first layer is at ~50cm depth, the second is at ~100 cm and the third layer is at ~140 cm depth. All three of these depths correspond to similar depths as core 13 which was taken on this line.

Line 13 is further east and located right in the between the San Succi Condominiums and the White Sands Cottages. This line has a total length of 52 meters. Three horizontal reflectors are seen in this line at similar depths as the previous lines but these lines are slightly dipping seaward. These reflectors are likely post storm accretion layers and are dipping because there was recent bar welding at this location.

The next line (line 14) is at the edge of the White Sands Cottages and extends ~42 meters. This line has similar characteristics as line 13. There are post storm accretion layers that are dipping because of recent bar welding.

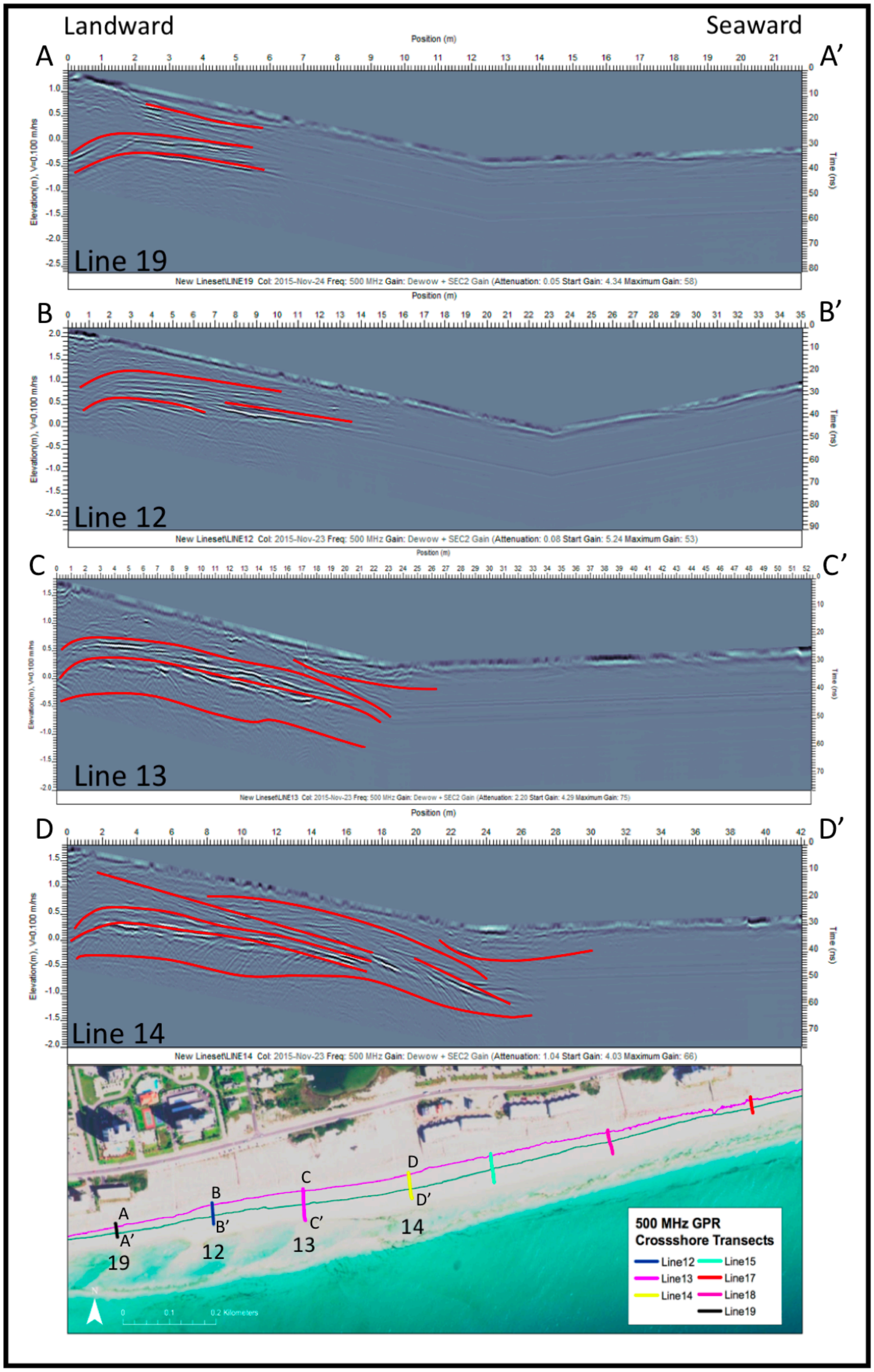

Figure 35: The first four 500 MHz crossshore GPR transects.

Line 15 was shot from dune to swash in front of the second building in the White Sands Cottages complex and is ~44 meters in length (Figure 36). This line shows dipping horizontal reflectors that begin dipping seaward about 18 meters into the line. These layers are dipping because of recent bar welding to the shore.

Line 18 is located at the eastern edge of the White Sands cottages complex and is ~25 meters in length. This line shows fully horizontal layers that do not dip. This is likely because the bar did not weld to shore in this section of the beach. The horizontal reflectors identified in this line correspond to the same depths of storm layers that have been identified in the cores.

The last line in this set of GPR transects is line 17. It is the eastern most line and is ~38 meters in length. Line 17 has horizontal dipping reflectors which are storm layers that are dipping because the bar welded to the shore line.

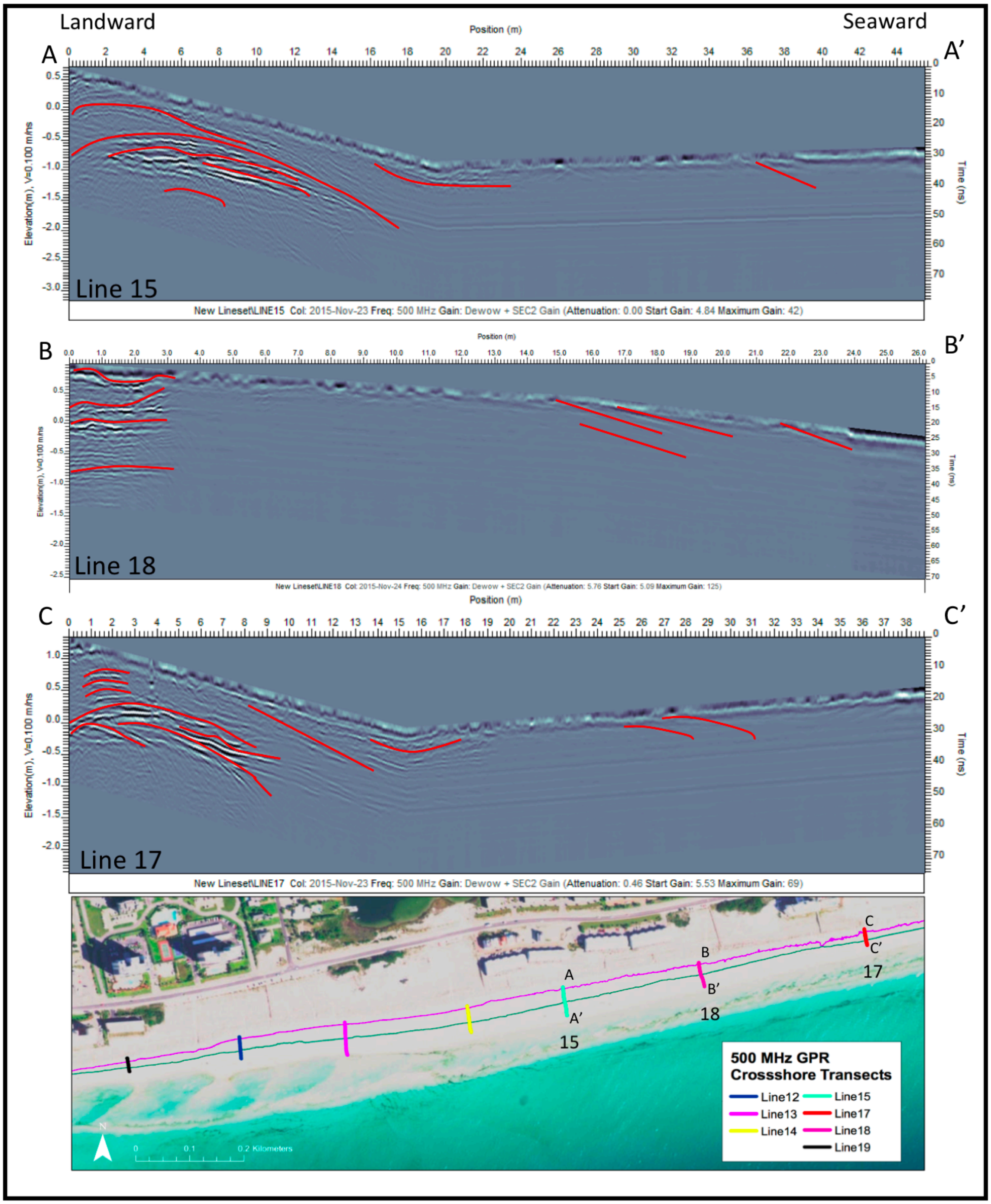

Figure 36: The last three 500 MHz crossshore GPR transects.

6. DISCUSSION

This study utilizes GPR, coring, XRF scanning, and grain size analysis to demonstrate the alongshore variation in the depth of activation of a 2.5 km section of Santa Rosa Island in northwest Florida. This section of beach was chosen because of its complex beach and nearshore morphology (offshore ridges and swales and transverse bar and rip nearshore morphology because of the ridges and swales) and this section of beach was heavily oil by the Deepwater Horizon oil spill. Results from the recent study suggest the depth of activation varies along the this stretch of beach, which in turn suggests that as oil is deposited on this beach it is not going to be at a uniform depth along the beach. There are areas where the oil is deeper in the profile and in other areas it is shallow and close to the surface, depending on the nearshore and beach morphology at the time of burial, which can influence future emergence.

The depth at which oil is deposited affects how oil breaks down and how much and when the oil is exhumed in the future. If the oil is deposited at a greater depth it is going to take a high magnitude storm (not frequent) to exhume the oil whereas, if the oil is deposited at shallower depth it will take a much smaller magnitude storm (which are more frequent). The physio-chemical composition of the oil at the time of deposition is going to control where the oil is deposited on the beach (Gonzalez et al., 2009). Less dense oil that floats on the seawater surface is going to be deposited on surface sediments with the swash uprush, while oil that is heavier than seawater exhibits varying degrees of mixing with the sediment (Gonzalez et al., 2009). Oil that is lighter than the sediment is deposited on the bottom and moves along the bed in a manner analogous to fine sand, with the sediment typically deposited at high tide. In other words, lighter oil tends to be deposited along the upper-beach and in the backshore has the potential to be buried several meters within the beach, nearshore, and/or within the backshore and dune (Gonzalez et al., 2009). The lighter oil from the Deepwater horizon oil spill that made it to the shallow nearshore zone was subject to enhanced dispersion by the breaking of waves by breaking down and mixing oil parcels throughout the shallow water column (Zuijdgeest and Huettel, 2012). Dispersants applied during cleanup enhanced this natural dispersion leading to the relatively rapid advection of the oil into permeable sands and for the oil to be buried and persist for several years (Zuijdgeest and Huettel, 2012).

The alongshore variation in the depth of activation at Pensacola Beach is visible in the grain size and XRF data. All of the storm layers identified in the cores are at similar depths but not necessarily at the exact same depths, they vary slightly alongshore because of the offshore ridge and swale bathymetry on Santa Rosa Island. The storm layers are important because they are an area that will trap the oil. When the storm layer is deposited, oil will likely be remobilized and it is typically redeposited which can mean it will be exposed and cleaned up or it can be reburied and potentially at an even deeper depth. There is a swale centered on the San Succi Condominiums and one ridge at Fort Pickens Gate (just east of Beach Entrance 21F) and another ridge at the Pensacola Beach Gulf Pier (Figure 37). The ridges and swales produce bathymetric highs and lows and as a result force an alongshore variation in the beach state (Houser et al., 2011a, 2011b). The swales produce a steep shoreface which forces the bar closer to shore and as a result

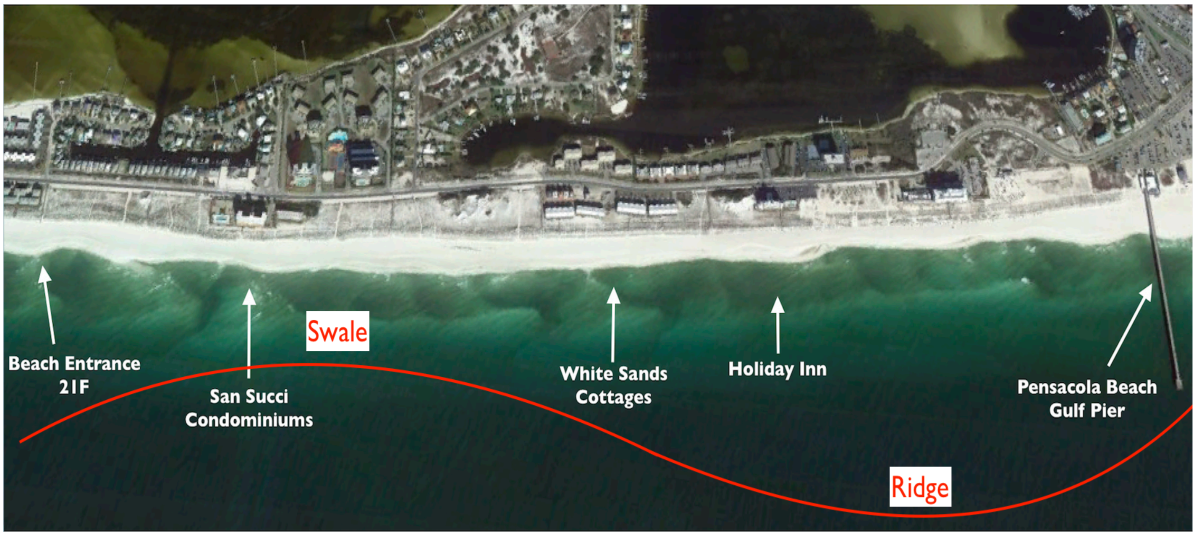

Figure 37: Ridge and swale topography is typical of Santa Rosa Island. In the study area, there is a swale centered on the San Succi Condominiums and two ridges; one ridge at Fort Pickens Gate (east of beach entrance 21F) add the other ridge is centered on the Pensacola Beach Gulf Pier. (Location of ridge and swale from Houser, 2012)

creates the transverse bar and rip morphology common to Pensacola Beach. Landward of the ridges the shore face is not as steep and exhibits a relatively dissipative nearshore. Although Pensacola Beach works through different beach states depending on the location of the bar. If a storm occurs, the beach will likely begin to change states (Wright and Short, 1984, Short, 1985). After a storm, the bar that was once located nearshore will likely be moved offshore (Sallenger Jr, Holman, and Birkemeier, 1985; Short, 1985). When this occurs, the beach will change from the intermediate or reflective state and become dissipative. As the bar begins to move back on shore, the beach state will change again reverting back to an intermediate state. Once the bar is fully welded to the shoreline again the beach will be back to its reflective state (Short, 1985).

As a result of the ridges and swales, the storm layers get slightly deeper moving away from the San Succi and towards the White Sands Cottages. Figure 38 shows the elevation at which the top of the core is located relative to the other cores in the backbeach, the Ca counts vs mean grain size plots have also been adjusted to show the alongshore variation in depth of storm layers. The forebeach cores show a similar trend as the backbeach cores (Figure 39). The storm layers move deeper in the swale and then begin to rise as the cores move closer towards the ridge. When oil is deposited on this beach it is likely going to be trapped deeper in the profile where a swale occurs and shallower where a ridge occurs.

A hard shell layer is identified in the 200 MHz GPR crossshore at a depth of about 1-1.5 meters. This hard-shell layer is the storm layer previously identified in the cores. Above the hard shell layer, there are more horizontal reflectors and those reflectors are alternating between berm development and the migration of the bar (Davidison- Arnott, 2010). In the 200 MHz lines the signal gets slightly attenuated towards the swash zone because of the presence of moisture in the sand. The presence of moisture in the sand means that the water table is likely penetrating into this portion of the beach and that is why the signal is attenuating in parts and not in others. The 500 MHz crossshore lines show the hard shell layer and alternating berm development and movement of the bar on shore at much greater detail. These lines also show areas where the bar welded to the shore. Santa Rosa Island exhibits transverse bar and rip morphology. In the 500 MHz transects horizontal reflectors that are dipping seaward indicate the bar has welded to the shore in these locations. The lines that do not exhibit bar welding show an alongshore

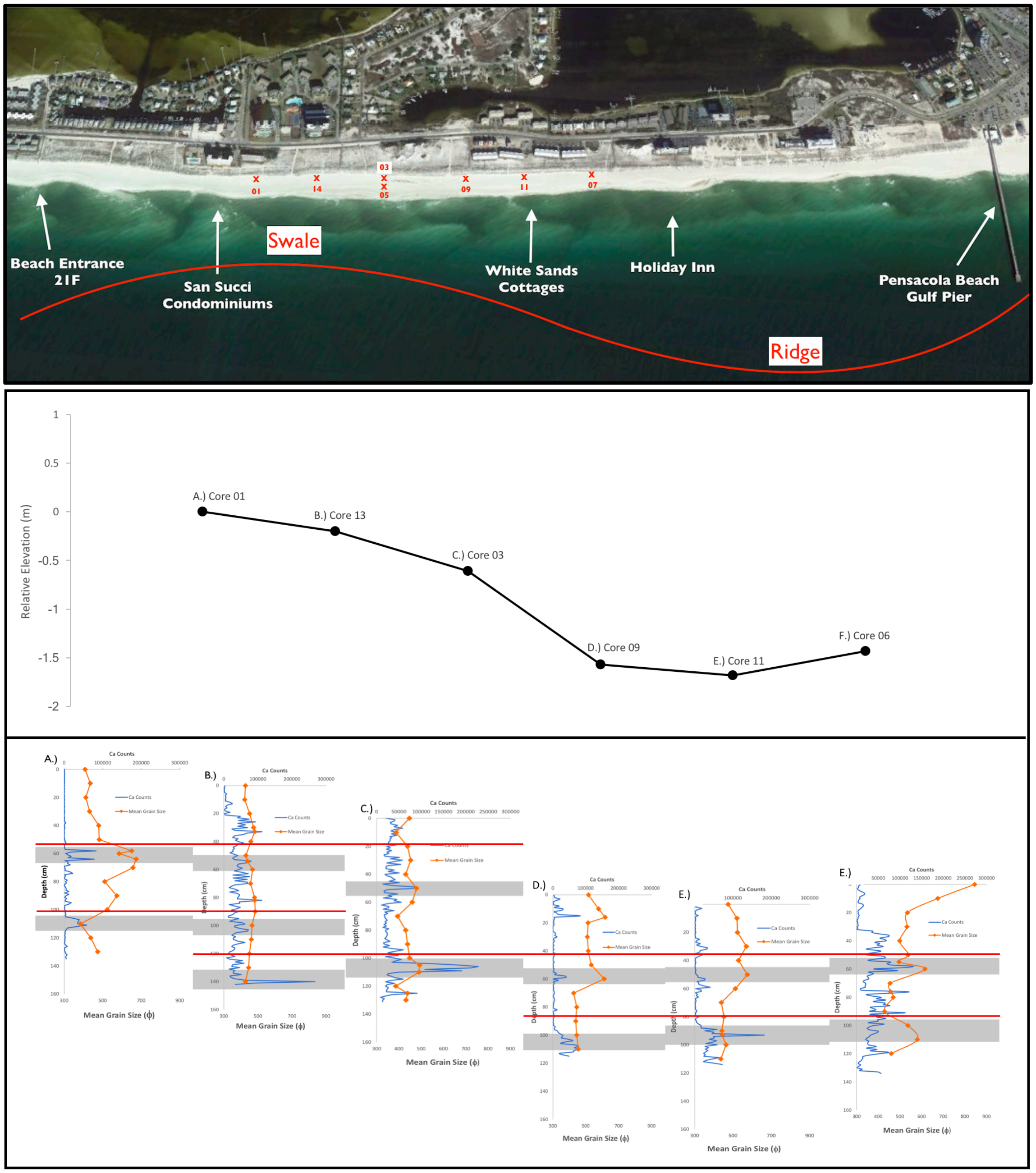

Figure 38: Backbeach cores Ca counts vs Mean Grain Size lined up with Alongshore elevation profile for reference. A.) Core 01 B.) Core 13 C.) Core 03 D.) Core 09 E.) Core 11 F.) Core 07. The storm layers are marked with red lines.

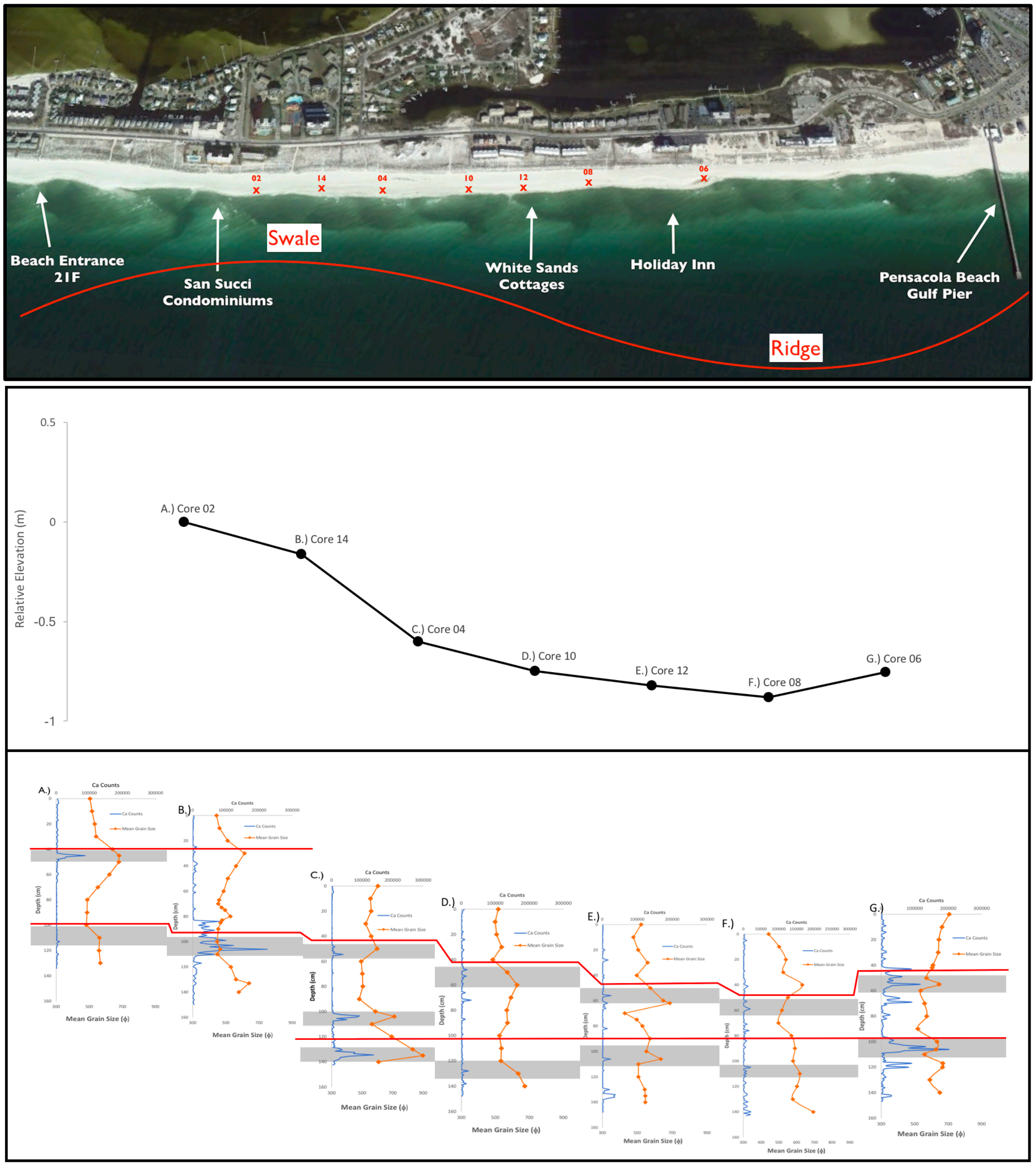

Figure 39: Forebeach cores Ca counts vs Mean Grain Size lined up with alongshore elevation profile. A.) Core 02 B.) Core 14 C.) Core 04 D.) Core 10 E.) Core 12 F.) Core 08 G.) Core 06. The storm layers are marked with red lines.

alongshore redistribution of sediments from the adjacent bar welding so the reflectors are just simple swash laminae. The lines where swash laminae are present would be where a rip channel would occur (Wright and Short, 1984).

In Figure 40, the locations of 500 MHz GPR transects are labeled in red on a Google Earth image from November 2013. This image was chosen because these GPR transects were taken in November of 2015 so the morphology of the beach in November should be similar from year to year. Line 19 and line 12 show no bar welding in the GPR line and this is because the bar has welded to the offshore ridge as shown in Figure 40. In line 13 the bar is beginning to weld to the shore. Line 14 and 15 exhibit bar welding in the GPR lines and in the google earth image the bar can be seen clearly welded to the shore. Between line 14 and 15 there is a rip channel present. Line 18 does not show bar welding and in the google earth image there is a rip channel directly in front of the location of the line. The next line (line 17) shows the bar welded to the shore once again and between line 18 and 17 there are two rip channels present.

Figure 40: Locations of 500 MHz crossshore GPR lines. The areas where the bar welded to shore are labeled as well as the rip channel.

Figure 41 shows the forebeach alongshore 200 MHz GPR transect with the location of four of the 500 MHz crossshore GPR transects labeled. The four transects that are labeled on this figure are the ones that exhibit bar welding. In Figure 41 after line 13 the signal becomes attenuated which would be expected because a rip channel would occur next to an area where the bar is welded to the shore and the water would be able to penetrate deeper into the forebeach attenuating the signal (washing out the structure). The horizontal reflector picks up again after about 100 meters and continues until just after line 14. Line 14 also showed bar welding and in the google earth image a rip channel occurs just to the east which would explain the signal becoming attenuated just after line 14. Line 15 and 17 are in highly attenuated areas and do not show much structure. This is because the bar welds to the shore just in front of line 15 and then there are 4 rip channels that occur before line 17.

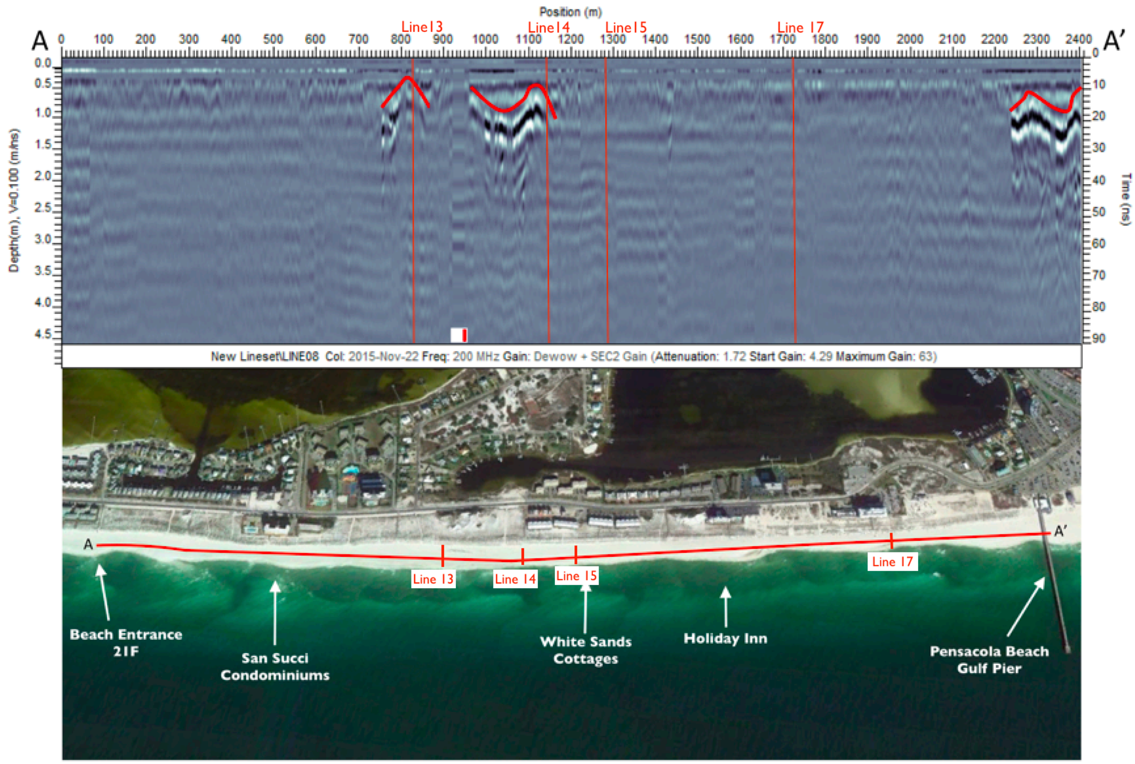

Figure 41: 200 MHz alongshore forebeach GPR transect with the location of four of the 500 MHz crossshore GPR transects.

As noted, the swash zone is the most morphodynamically active region and has the greatest potential for oil burial (Karunarathna *et al.*, 2012). This increases with transverse bar and rip morphology. As oil is deposited on the beach it could easily be trapped in a rip channel or where the bar welded to the shore. If the oil is trapped in a rip channel this will cause the oil to breakdown completely different because the salt water that is penetrating into the forebeach will cause the oil to change both chemically and physically making the oil penetrate to an even greater depth (Gonzalez *et al.*, 2009). Not only will the oil move deeper into the sediment it will also be much more difficult to exhume from the profile.

In the swale, the oil is going to be trapped much longer because the type of event that has to take place in order to exhume the oil is going to be a low frequency, high magnitude event. The longer oil remains on the beach, the more it changes chemically and physically in a way that promotes burial, and the more variable the beach and nearshore profile. In this respect, the sequence of wave activity and beach evolution that occurs over the course of an oil spill and the subsequent evolution of both oil and the beach leads to stratified layers of oil, oiled sands and clean sands (Pardue et al., 2014). Oil deposited on a ridge will likely be shallower and easier to exhume because a high frequency, low magnitude event is going to be able to remobilize the oil. It is also important to note that oil deposited in the backbeach is going to take longer to exhume versus oil that is deposited in the forebeach. Although it is likely that oil will be deposited in the forebeach because the forebeach/ swash zone is the most morphodynamically active region and has the greatest potential for oil burial and persistence particularly during winter months when storms are more common (Karunarathna *et al.,* 2012).

6.1 Time of Deposition

Another very important factor to consider is the time of year the oil was deposited. In the case of the Deepwater Horizon the oil was deposited on the beach as it was recovering from Winter beach meaning that the sediment was temporarily stored in the innermost bar(s) and had begun moving back on shore through landward migration of the bar(s). During this time, the oil was getting trapped in the accreting sediment and worked its way deeper into the profile (Wright and Short, 1984). The oil will not be able to be exhumed until a storm of great enough magnitude to erode the beach down to the level at which the oil was deposited or to the level at which the oil has been advected through the sediment. Oil that is exhumed is not always removed from the beach and can actually be moved further landward by the swash or elevated storm surge or further seaward with the backwash and undertow. It then can be re-deposited at the same location or buried at a greater depth which is dependent on the depth of disturbance of the swash or waves (Gonzalez *et al*., 2009). In contrast, oil that is deposited after the beach has completely recovered will remain at or near the surface meaning that it has a relatively short residence time (at the surface) but is also easier to clean (Pontes *et al.,* 2013).

The depth at which oil is deposited is going to depend spatially (storm events and evolution of beach) and temporally (morphology of beach at time of deposition) for each beach that it comes in contact with. At Pensacola Beach, the oil is deposited at different depths because of the alongshore variation and therefore reemerges at different times. For other beaches the oil could be deposited deep and uniform across the beach or with considerable variability causing the reemergence to of the oil to vary quite a bit. Overall the burial and persistence of oil is going to depend on the beach it is deposited on, the beach state and the subsequent evolution of the beach after the oil has made it to land.

6.2 Future Work

For future scientists, this study could be used as a building block to take and apply to beaches all along the gulf coast and anywhere in the world where there is a risk of oil spill. This type of study has never been done in a way that can be taken and applied to other beaches. Most study only focus on one type of beach and only when an oil spill occurs. Understanding the morphology of beaches along the Gulf of Mexico could help all spill managers and coastal city managers be prepared for when another oil spill occurs. A scientist could also try to identify oil in sand. I was able to see the storm layers in GPR but could never identify oil in the sand. This could be done relatively easy because a storm layer is going to have a higher dielectric constant if it is just water and it will have a relatively low dielectric response if it is oil. This would be something that could be tested in a controlled study area and then used on areas like Pensacola to help remove all oil that remains trapped in the sediment.

This study can help assess the areas that need to be focused on the most and the areas that may see some affects but cleanup will not be as difficult. If a future spill manager knows approximately where the oil is going to make landfall and he/she has an idea of the morphology of the beach, they will know where to send their resources to maximize clean up and reduce the amount of oil that is trapped and later remobilized.

To further clarify and prove the finding, this study would need to expand by taking crossshore GPR transects along the entire beach and not just the seven crossshore transects that were taken. More cores would need to be taken at the intersection points of the crossshore and alongshore GPR transects. Another thing that could be added would be to sample the tar mat and tar balls found in on the beach and bring them back to Texas A&M for chemical analysis to see if it was from the Deepwater Horizon. The dispersants used have a unique chemical signature making them easier to identify through analysis. Lastly, it would have be very interesting to go back a year later and collect data on the beach in the same way compare one year to the next. It would be very interesting to see what changed in a year and in light of the recent hurricanes (Irma and Harvey) it would be very interesting to go back to Pensacola and take data on the beach or at least see if some new oil was reactivated after the storms and if there was oil reactivated, I would like to know how much was now present.

7. CONCLUSION

This study demonstrates that through the use of GPR and coring there is an alongshore variation in depth of activation which could cause oil to become trapped at depth and persist longer. As a result of the oil being deposited at different depths along the beach, the oil will be exhumed at different times depending on storm events. This study also demonstrates that the depth at which oil is deposited can vary greatly from beach to beach because it depends on storm events, morphology of beach at the time of deposition and the subsequent evolution after. In the case of Pensacola Beach, the ridge and swale bathymetry cause the variation in depth that the oil is trapped along the beach. The swale causing oil to be trapped at a greater depth and the ridge causing oil to be trapped shallower.

The ridge and swale bathymetry forces the transverse bar and rip morphology which also causes further small scale variations in oil burial and persistence. Depending on the beach state at the time of oil deposition will determine the depth at which the oil is trapped and if it will be able to be exhumed easily. The areas where the bar is welded to shore will allow for the oil to be trapped in because the bar is constantly working to build the berm between storms and then welding the bar to shore. The oil in this area will be tougher to exhume because until a big enough storm occurs the beach will keep adding sediment. The rip channels allow for oil to get trapped much easier and the salt water identified in these channels will change the oil chemically and physically quicker promoting deeper burial.

Pensacola Beach will likely have oil remobilized for many years to come. The oil is trapped very deep in some parts of the beach and not as deep in others, there is not one single depth that the oil is deposited at. Simply cleaning up the beach after the oil is remobilized it not going to fully clean this beach and clean-up efforts are going to have to continue for many years to come costing a lot of time and money. In order to do a more thorough job, geophysical assessments need to be run along the beach in order to identify the depth at which the oil persists. This is why some oil is remobilized after a small storm or when the beach is in winter profile after extensive clean-up efforts. The oil that is trapped deep in the profile is going to take a huge storm to exhume and since the Deepwater Horizon oil spill, no major storms have impacted this portion of Florida coast.

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