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Digital Ground Penetrating Radar (GPR): A New Geophysical Tool for Coastal Barrier Research (Examples from the Atlantic, Gulf and Pacific Coasts, U.S.A.)

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ABSTRACT

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Although digital ground penetrating radar (GPR) is still in its infancy, results indicate that it will soon become one of the most significant geophysical instruments for coastal barrier studies. GPR can infer stratigraphic trends, and therefore directions of progradation and/or aggradation, delineate sedimentary facies, and determine depth to the fresh-brackish water interface in shallow freshwater conditions (*i.e.*, Galveston Island). Internal structure of barriers consisting of sand, broken shell fragments and boulder-gravel in Georgia, Florida, Texas, Oregon and Washington States are illustrated using GPR. Seaward dipping reflections (1–23°) from paleo-beach surfaces occur to depths of 12 m. Severe signal loss is noted on all barriers at approximately the level of the low tide. Gulf Coast barriers have thin freshwater lenses (<4 m), below which brackish water attenuates electromagnetic energy. In contrast, the best results are from high wave energy and high tidally-influenced (3.7 m) Pacific clastic sand and barriers with paleo-beach dips of 1–2° to 12 m deep. A boulder-gravel beach at Seaside, Oregon, has good results with inclined reflections of 23° to 12 m deep. Shelly beaches at Anastasia Island, Florida exhibit semi-continuous seaward inclined reflections (3–6°) to depths of 6 m.

ADDITIONAL INDEX WORDS: *Barrier island, geophysics, coastal stratigraphy, coastal sediments.*

INTRODUCTION AND BACKGROUND

Acquisition of subsurface stratigraphic information of modern barriers has been restrained over recent decades because of limited funds available for research and development. Drilling and geophysical systems for deep stratigraphy acquisition has been motivated by high profitability in the exploration for hydrocarbons and minerals. Development of drilling and geophysical systems for shallow stratigraphy has been driven by the less profitable environmental and geotechnical industries (ROMIG, 1993). A stratigraphic acquisition system is needed with high resolution (dm scale) that is affordable, portable, robust, and time and cost effective. Recent developments in ground penetrating radar (GPR) technology have made such a system available. GPR is a high resolution geophysical instrument useful for assessing stratigraphy and paleogeomorphology of barriers. Earlier analog GPR systems, which were revolutionary at the time of their introduction (early 1980's) are now bulky and lack basic acquisition parameters and post-processing capabilities (*i.e.*, scaling changes, topography corrections). Digital GPR systems have dealt with these problems. The digital system has the advantage of high fidelity (better signal-to-noise ratio) and, equally important, the capability to record, process, and store data digitally. This latter feature allows data to be processed with sophisticated seismic processing software.

Barrier islands, spits and strandplains are elongate bodies of coarse grained sediments (usually sand), transported and deposited by longshore drift and wave processes. North American examples can be found along the Atlantic Coast and Gulf of Mexico and along isolated segments of the Pacific Coast, Gulf of St. Lawrence and the Arctic Coast (Alaska).

Over the last several decades, there has been an increasing interest in the stratigraphy and sedimentology of barriers, spits, and strandplains. Early interest was motivated by the need for depositional models for oil and gas exploration (BERNARD *et al.*, 1962; BYRNE *et al.*, 1959; GOULD and MCFARLANE, 1959; HAYES and KANA, 1976; HAYES, 1979; HOYT and HENRY, 1965; KRAFT, 1971, 1978; MCCUBBIN, 1982; REINSON, 1984). Recently, rapid urbanization of barriers has initiated additional research to enable coastal communities to better plan and mitigate sustainable freshwater supplies, sewage and garbage disposal, and better understand long term erosion and depositional problems. Therefore, to better understand the dynamics and nature of barrier systems, new and different methodologies must be applied to keep pace with this growing demand for information.

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Although pioneering studies provided the basis for understanding the origin and dynamics of barriers (FISK, 1959; BERNARD *et al.*, 1962; HOYT, 1967; KRAFT, 1971; HAYES, 1979), the internal structure and stratigraphic trends are inferred, not fully documented. Recently, the development and application of GPR to stratigraphic and geomorphic problems has shown promise (ULRIKSEN, 1982; LEATHERMAN, 1987; BERES and HAENI, 1991; JOL and SMITH, 1991; SMITH and JOL, 1992). Limited studies carried out in the late 1980's established that analog GPR could detect sedimentary structures within barriers (LEATHERMAN, 1987; FITZGERALD *et al.*, 1992; VAN HETERN *et al.*, 1994); while more recently, digital GPR clearly demonstrated its full potential on the Willapa Bay Barrier of Washington State (JOL *et al.*, 1994; MEYERS, 1994; MEYERS *et al.*, 1994).

Our primary objective is to establish the effectiveness of digital GPR for data acquisition in the assessment of barrier stratigraphy from a variety of depositional settings (Atlantic, Gulf and Pacific Coasts) with different sediment compositions (sand, shell fragments and boulder-gravel). A secondary objective is to show how GPR can be used to determine the depth and delineate the fresh/brackish groundwater contact in coasts that have a shallow lens of fresh groundwater.

METHODOLOGY

Digital GPR profiles are similar in appearance to seismic profiles, except that GPR data are acquired by using transient electromagnetic (EM) energy reflection. A short pulse of high frequency EM energy, usually in the 10 to 1,000 megahertz (MHz) range, is transmitted into the ground. Some of the energy is reflected back to the surface from the contacts between different subsurface lithologies, including such changes as sediment grain size (facies change contacts), mineralogy, density, bedrock contact, and water content (Figure 1; MOORMAN *et al.*, 1991; DAVIS and ANNAN, 1989). This effect enables the subsurface stratigraphy and ground moisture conditions to be inferred from the character of the radar return signals. The resolution of GPR at 100 MHz (assuming a velocity of 0.1 m/ns; ns = nanosecond = 10^{-9} seconds) is approximately 25 to 50 cm which is approximately 10 times greater than conventional high-resolution shallow seismic which is between 3–5 m (JOL, 1988). GPR theory and methodology are adequately explained elsewhere (ANNAN and DAVIS, 1976; ULRIKSEN, 1982; DANIELS *et al.*, 1988; DAVIS and ANNAN, 1989).

We used a pulseEKKO® IV radar system in reflection survey mode with antennae frequencies of 50, 100 and 200 MHz and either a 400 v or 1,000 v transmitter. At each site, prior to a decision being made for the complete survey, we test all antennae frequencies. In this paper, we provide the dataset obtained with the antennae that we believe best illustrates the stratigraphy of each site. Traces at each surface location (0.5 or 1.0 m intervals) were digitized at a sampling time interval of 800 picoseconds and vertically stacked 64 times. Profiles were processed and plotted using pulseEKKO® IV (version 4.0) software. The depth scales of the profiles are based on an average near-surface velocity

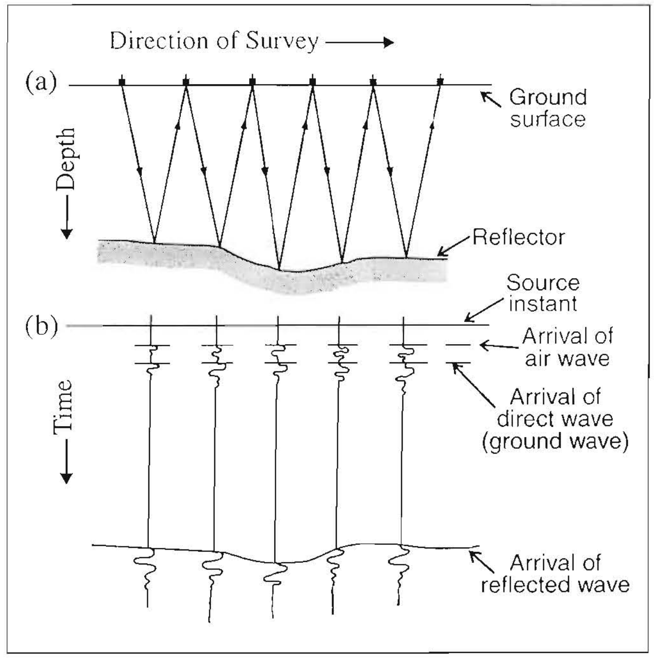

Figure 1. Ground penetrating radar profiling procedure. (a) The step-like procedure involves repetitive moves of both the transmitter and receiver at a constant spacing. (b) Five schematic GPR traces, showing the arrival of air-wave and ground-wave pulses and a lower reflected wave from a subsurface reflector (JOL and SMITH, 1991).

determined from common mid-point (CMP) surveys at each site (for additional information on CMP surveys see JOL and SMITH, 1991).

RESULTS AND INTERPRETATION

The studied sites include: Jekyll Island, Georgia; Anastasia Island, Florida; Galveston, Mustang, and Padre Islands, Texas; Netarts, Bay Ocean, Nehalem, Seaside, and Clatsop barriers, Oregon; and Willapa and Ocean Shores barriers, Washington (Figure 2). From this extensive data base, selected radar profiles are presented. For the sake of clarity, the horizontal scale of all profiles is distance in meters, while the vertical scale is shown as both two-way travel time in (nsec) and depth in meters (m). It should be noted that all profiles are vertically exaggerated. The two uppermost continuous reflections in all profiles represent air wave and ground wave arrivals respectively and are not part of the stratigraphic data.

Jekyll Island (Georgia—Atlantic Coast)

Jekyll Island is located 13 km southeast of Brunswick, Georgia, and consists of fine grained sand. The 200 MHz profile shows seaward dipping reflections, typical of most barriers studied to date. The profile is oriented northwest-to-southeast (perpendicular to shore) and is located on a level playing field 400 m northeast of the University of Georgia field station laboratories. Inclined reflections dipping south-

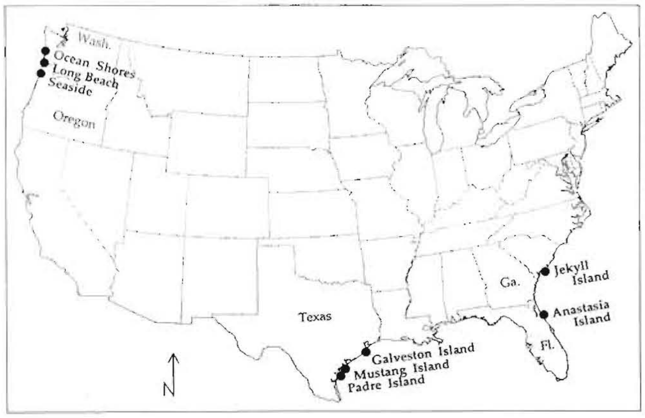

Figure 2. Location map of 8 GPR sites studied along the Atlantic, Gulf and Pacific coasts of the United States.

east at 1–2° indicate seaward paleo-progradation of the shoreface. The third nearly continuous horizontal reflection is from the freshwater table. The inclined wavy-like deeper reflections may represent preservation of offshore bars. An erosional contact (interpreted as sand to silt), at 20 m (horizontal scale) and 5 m deep, shows 2 m of strata with steeper inclined reflections that may represent a lithofacies change and possibly a tidal inlet channel-fill.

Figure 4 (100 MHz) perpendicularly intersects Figure 3 southwest from trace 70, and this profile indicates horizontal stratigraphy along the depositional strike. However, two distinct radar facies join at approximately 3.0–3.5 m deep. We interpret the continuously inclined upper facies to represent the beachface. The lower radar facies, between 3.0–3.5 to 7.0 m, is interpreted as offshore bars and tidal inlet-fill.

Anastasia Island (Florida—Atlantic Coast)

Anastasia Island, located southeast of St. Augustine, northeast Florida, consists of coarse grained sand from broken shells. Eastward dipping radar reflections indicate large scale gently inclined strata (Figure 5). This 50 MHz line is from an abandoned west-to-east road (perpendicular to shore), located 2 km northwest of St. Augustine Beach. The freshwater table was at-or-near the surface (<1 m). Semi-continuous, inclined reflections dipping at 3 to 6° to a depth of at least 6 m indicate a seaward paleo-progradation of the coast. This paleo-shoreface is steeper than that at Jekyll Island (Figure 4) which has inclined reflections of 1–2° in fine sand. The ability of GPR to measure the angle of inclination of paleo-beachface surfaces can be used to infer grain size (steeper slopes are associated with coarser grained sediments; PETHICK, 1984). The importance of the profile is to show that radar can perform reasonably well in coarse grain broken shelly material which is typical of the eastern Florida coast. But, the absence of vacant land suitable for radar profiling, free of buildings, power lines and other cultural structures is a major problem in these continuously urbanized coasts.

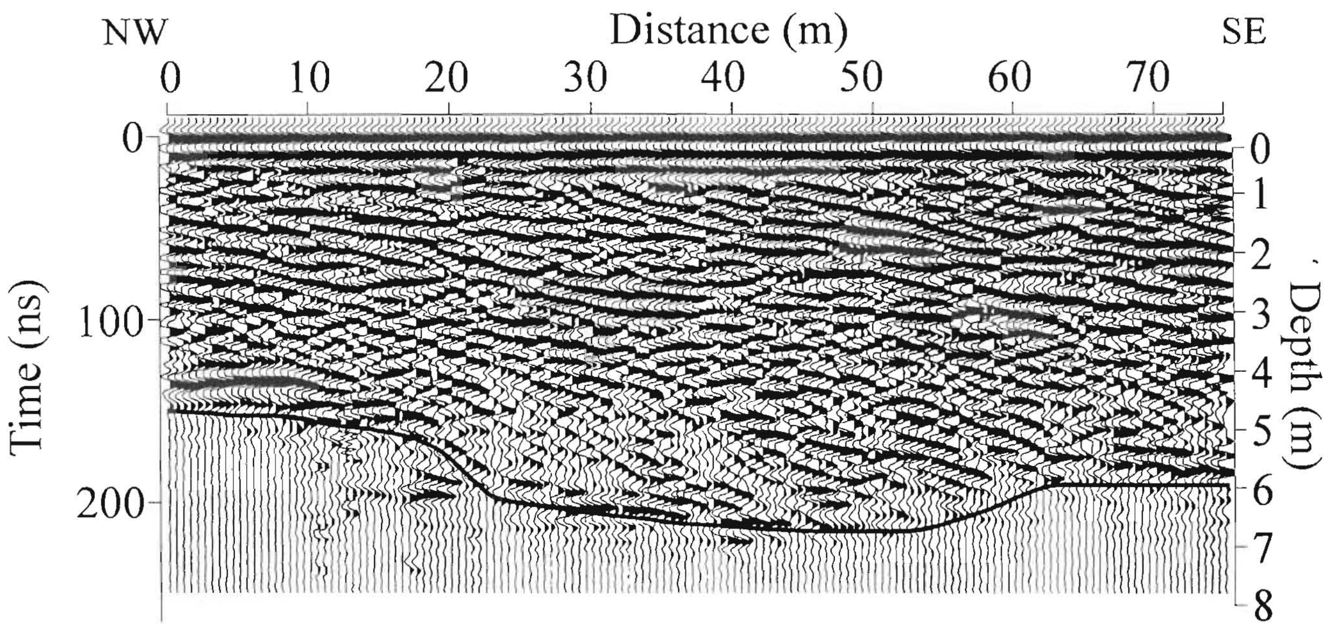

Figure 3. GPR profile (200 MHz) from Jekyll Island, Georgia, showing inclined reflections dipping seaward which represent paleo-beach surfaces and offshore bars. The stratigraphically lower 2 m of reflections (20–75 m) may represent a tidal inlet-fill. Solid line shows the erosional contact (sand to silt) or possibly a fresh-brackish water contact.

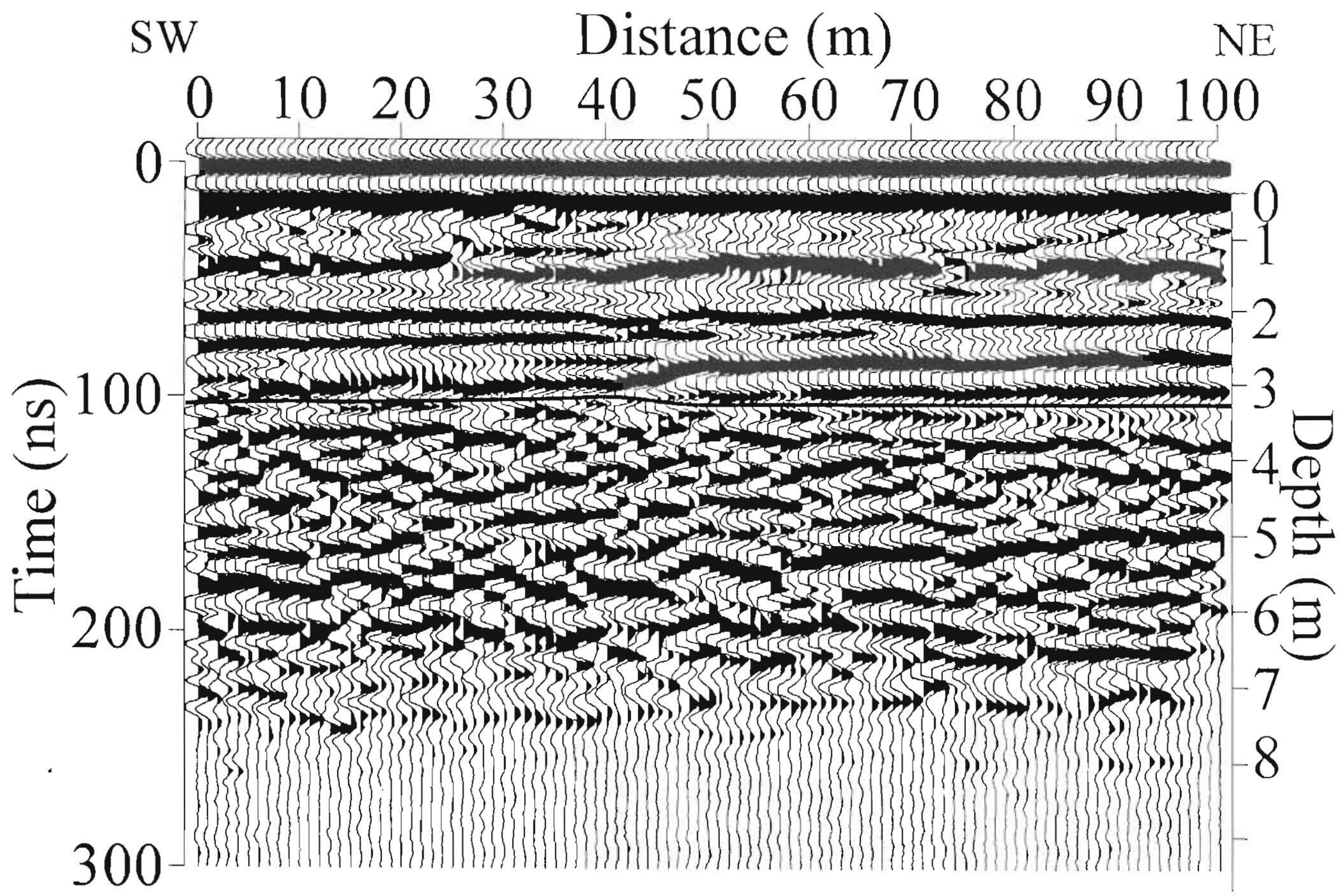

Figure 4. GPR profile (100 MHz) along the barrier axis of Jekyll Island, Georgia, shows horizontal reflections (extending southwest from Figure 3 at 70 m). The absence of dips suggests that the island was neither accreting northeastward nor southwestward at the time of deposition.

Galveston Island (Texas—Gulf Coast)

The first profile (100 MHz) from Galveston Island was shot along 8-Mile Road (northwest to southeast; Figure 6) in an attempt to verify the pioneering interpretation of seaward dipping shoreface structure proposed by BERNARD *et al.* (1962). Galveston Island consists of fine grained sand and contains a shallow water table at mid-island (1.5 m deep—3rd reflection). The semi-continuous radar reflections are dipping seaward at approximately 1–2° extending to a depth of about 5.5 m. This angle of inclination is the same as the angle of radar reflections at Jekyll Island. Below 5.5 m, the radar signal is attenuated by either an increase of silt sized sediment, structureless burrowed sediment or possibly brackish water.

The second profile from Galveston Island (100 MHz, Figure 7) shows horizontal reflections, then signal attenuation by brackish water below 2.75 m (depth to brackish water confirmed by the golf course head groundskeeper, *Personal Communication,* 1994). This site was shot on a northwest-to-southeast golf course fairway at Lafitte's Cove Golf Course, near the mid-barrier. The upper horizontal reflection (1.6 m) may represent vertical accretion strata from washover storms or eolian processes. The lower reflections are ringing (geophysical noise). Data from both Mustang and Padre Islands are similar to Figure 8, with very shallow radar penetration, but the available data does suggest vertical accretion bedding within the freshwater lens (<3 m in tested locations).

Figure 6 shows reflections extending down to 5.5 m; the additional 3 m of data are possible to acquire because the surface elevation is approximately 3 m higher than the surface in Figure 7 (*i.e.,* a thicker sedimentary pile above the brackish water table). The surficial sedimentary structures in Figure 6 are most likely attributable to beach progradation during storm and post-storm events (MEYERS, 1994). To explain these structures, MEYERS (1994) suggests an erosional phase during high magnitude storms which concentrate either heavy minerals or slightly coarser grained sediments as a lag. This erosional phase is followed by lateral accretion of sediment during summer low wave intensity periods. Figure 7 from Lafitte's golf course shows an absence of inclined strata and the horizontal strata could be interpreted as a washover similar to that shown by MCCUBBIN (1982, p. 269).

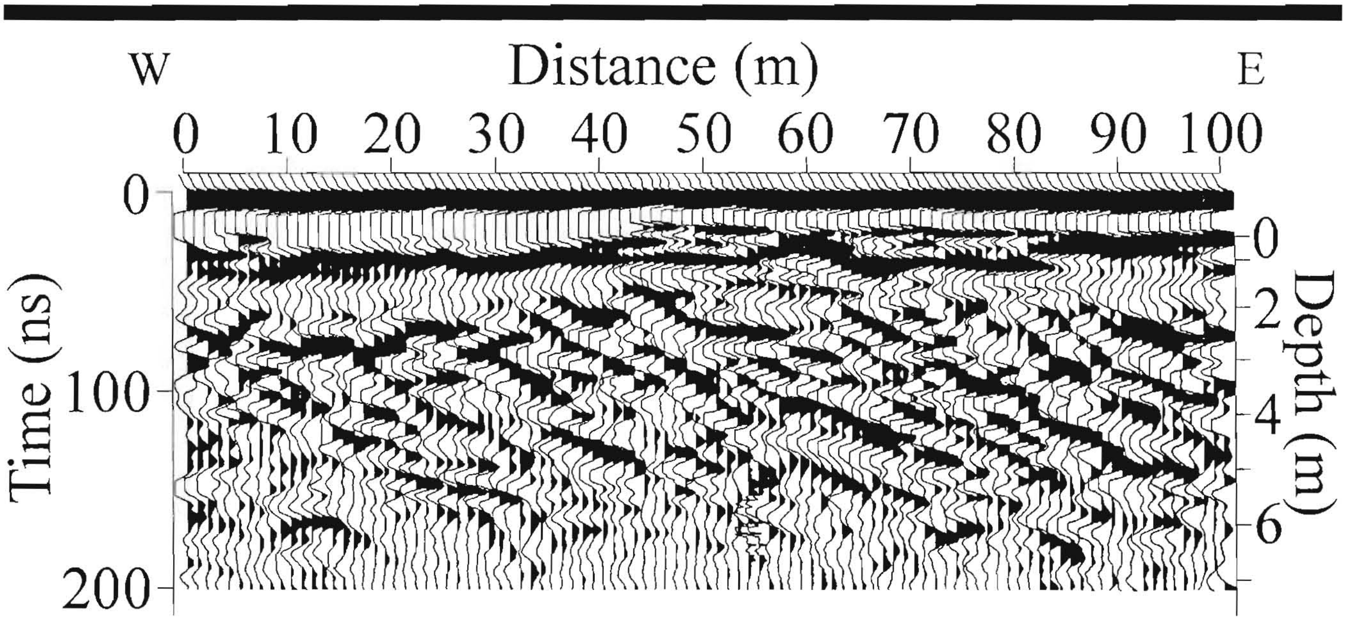

Figure 5. GPR profile (50 MHz) from Anastasia Island, Florida, (broken shell material) showing seaward dipping inclined reflections. The profile is from an abandoned road 2 km northwest of St. Augustine Beach.

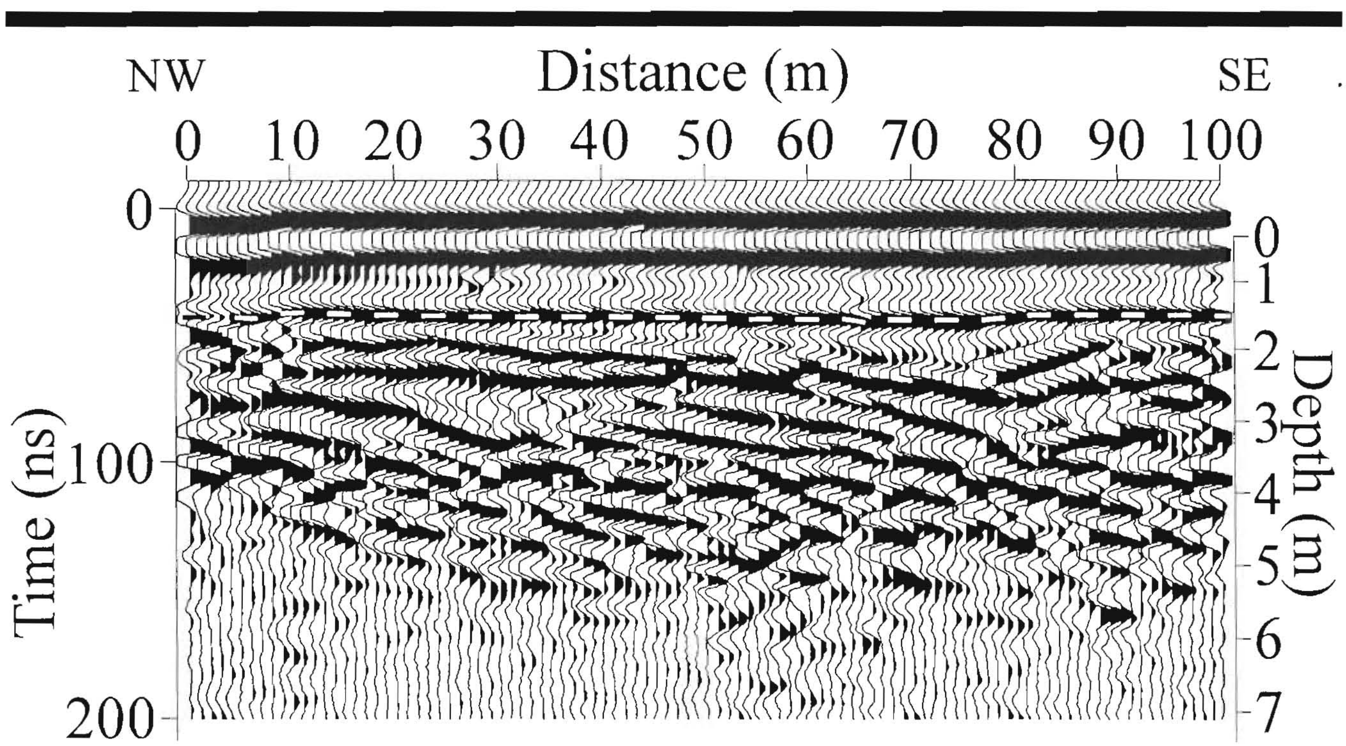

Figure 6. GPR profile (100 MHz) from mid-Galveston Island, Texas, along 8-Mile Road shows inclined reflections dipping toward the Gulf of Mexico, verifying the depositional interpretations in the "classic drill core profile" of BERNARD *et al.* (1962). Dashed line shows the water table.

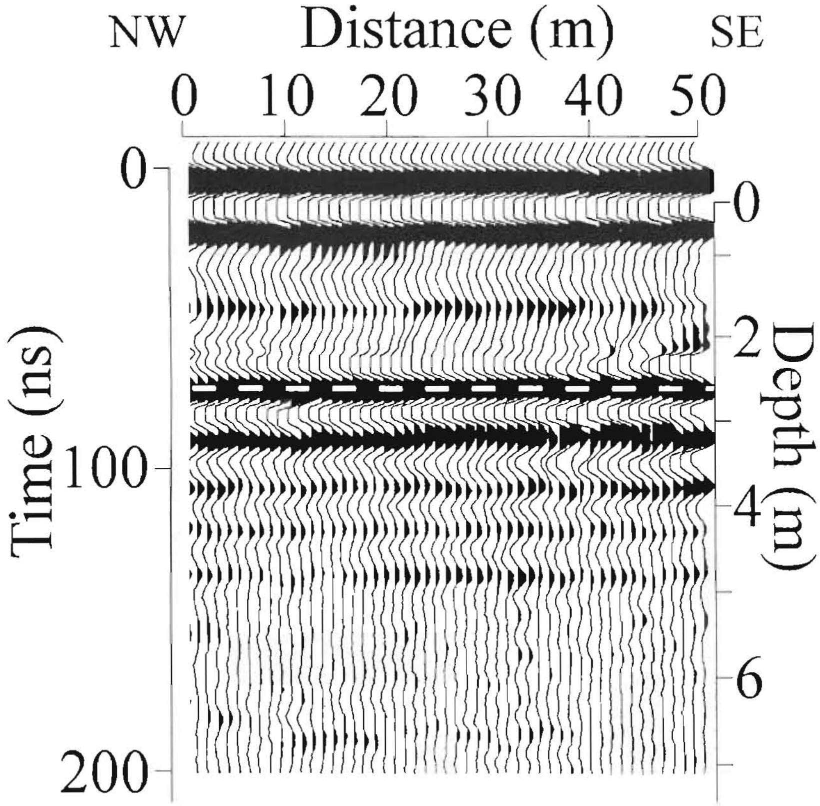

Figure 7. GPR profile (100 MHz) from Galveston Island, Texas, showing horizontal stratigraphy and a loss of signal below 2.75 m, the depth to brackish water (head groundskeeper, Lafitte's Cove Golf course, *personal communication*, 1994). The dashed line shows the water table. Profiles from Mustang and Padre Islands were similar.

Seaside Stranplain (Oregon—Pacific Coast)

The coast at Seaside, Oregon consists of a raised boulder-gravel strandplain (RANKIN, 1983) with a relatively steep beachface. This poorly sorted boulder gravel was derived from the nearby Tillamook headland (RANKIN, 1983). The west-to-east (perpendicular to shore) profile (100 MHz) ends at the boardwalk near the north end of the Tides Motel (Figure 8). The radar reflections show inclined boulder-gravel strata dipping up to 23° to a depth of 11 m and this is interpreted as paleo-beach surfaces, probably deposited during storms. The loss of signal below the somewhat prominent reflection at 200 nsec may be due to intrusion of salt water and/or a bedrock contact. Again, a single drill hole would verify the cause and GPR could then map the entire area. Over the 50 m of profile, the freshwater table, represented by the prominent, nearly continuous horizontal radar reflection is 5.5 m below the surface.

Willapa Barrier (SW Washington—Pacific Coast)

The Willapa barrier is a modern, active barrier spit consisting of fine grained sand derived from the mouth of the Columbia River via longshore transport (BALLARD, 1964). It is 38 km long by 2–3.5 km wide and is influenced by a 3.7 m tidal range and high-energy waves (MEYERS, 1994). The 6 m thick facies of shingle-like reflections dip toward the ocean at approximately 1–2° and this pattern represents a history of progradation since 4500 BP (100 MHz, Figure 9). These prominent and continuously inclined reflections are interpreted as major storm depositional bedding surfaces in which offshore bars are not preserved, contrasting with the inferred offshore bars in the Jekyll Island profile (Figure 3). Profiles along the depositional strike show horizontal, nearly continuous reflection patterns similar to those in Figure 4. The radar facies below 6 m shows discontinuous reflections and loss of radar signal returns which may indicate a lithofacies change, possibly due to bioturbation destroying primary sedimentary structures. Abundant water well data verify the absence of brackish water or silt in the upper 30 m of the barrier.

Ocean Shores Barrier (Washington—Pacific Coast)

Located 26 km west of Aberdeen, Washington, the barrier protects the northwest sector of Grays Harbor from the Pacific Ocean. The barrier consists of fine grained sand transported from the Columbia River by longshore currents (PETERSON and PHIPPS, 1992). The GPR profile, (100 MHz) from the back barrier (Figure 10), shows a lower radar facies of steeply inclined (2–8°) reflections steepening eastward

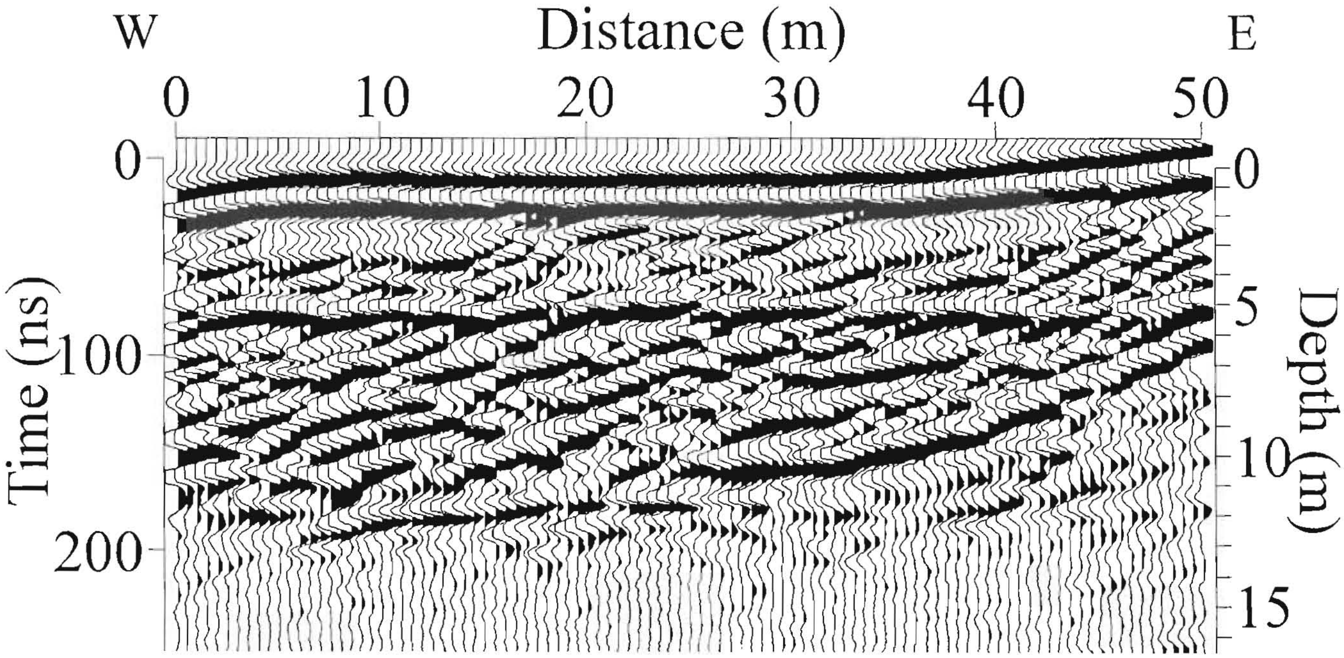

Figure 8. GPR profile (100 MHz) from Seaside, Oregon, of a raised boulder-gravel beach showing inclined reflections dipping seaward. Note the water table at 5.5 m and paleo-beach surfaces inclined to 23° angle.

into the harbor; this may represent a washover fan deposit in the early evolution of the barrier spit. The change in slope angle from west (2°) to east (8°) is similar to a conceptual diagram of washover fans (McCubbin, 1982). Above the washover foresets (between traces 73 and 150 m) and located between the surface and 5 m deep, the continuous horizontal reflections represent vertical accretion from storm washover events during sea level rise through the mid-Holocene. Farther west (between traces 0 and 73 m), reflections dip seaward, inclined at 1–2°. These reflection patterns are similar in angle to those from the Willapa, Galveston and Jekyll Barriers.

DISCUSSION

A GPR comparison of sandy barriers shows a range of radar reflection patterns and depths of penetration, affected by storm wave and tidal energy, sediment grain size and mineralogy. Pacific sandy barriers yield the highest quality datasets (Figures 9 and 10), which consist of continuous, prominent reflections to a depth of 12 m, as compared to less prominent reflections from Jekyll and Galveston Islands. Other beach materials such as boulder-gravel (Figure 8) and shell fragments (Figure 5) provide discernible radar stratigraphy, but are generally of a lower quality than clastic sand dominant systems. However, boulder-gravel deposits did allow one of the deepest penetrations for GPR in our study.

Pacific and Atlantic barriers receive 1.5–2.0 m of precipitation annually with moderate amounts of evaporation which result in thick (30–60 m) freshwater lenses (Meyers, 1994). This compares to lower precipitation and higher evaporation rates for Texas barriers where freshwater lenses are 1–4 m thick. The brackish-saline water near the surface at Galveston, Padre and Mustang Islands severely limits the usefulness of radar for stratigraphic studies. However, if the depth at which signal loss due to brackish water can be verified by drilling a single hole, then GPR can be used to map the freshwater lens in a barrier. Therefore, GPR provides a time efficient, cost effective and non-destructive means for coastal groundwater studies (seasonal changes, drawdown characteristics due to water extraction, and salt water intrusion).

All the radar data from the barriers investigated indicate a dominance of seaward progradation rather than downdrift accretion. The Willapa barrier was the most extensively studied and the 35 line kilometers of GPR also show a predominantly seaward progradation (Meyers, 1994); other barriers need rigorous investigation with GPR to indicate their long term progradation patterns.

CONCLUSIONS

We believe that GPR is presently the most promising device available for subsurface investigations of coastal sedimentary and groundwater environments. Shallow seismic does not provide the needed resolution for detailed stratigraphy. Leatherman (1985) noted "conventional seismic surveying has been found to be useless on barrier islands and detailed stratigraphic correlations are difficult based on borehole data". Vibracoring provides the only inexpensive point source data, but has a very limited depth of penetration in barriers. Six m was achieved by repeatedly reinserting the core tube into the same hole; an additional meter of core was

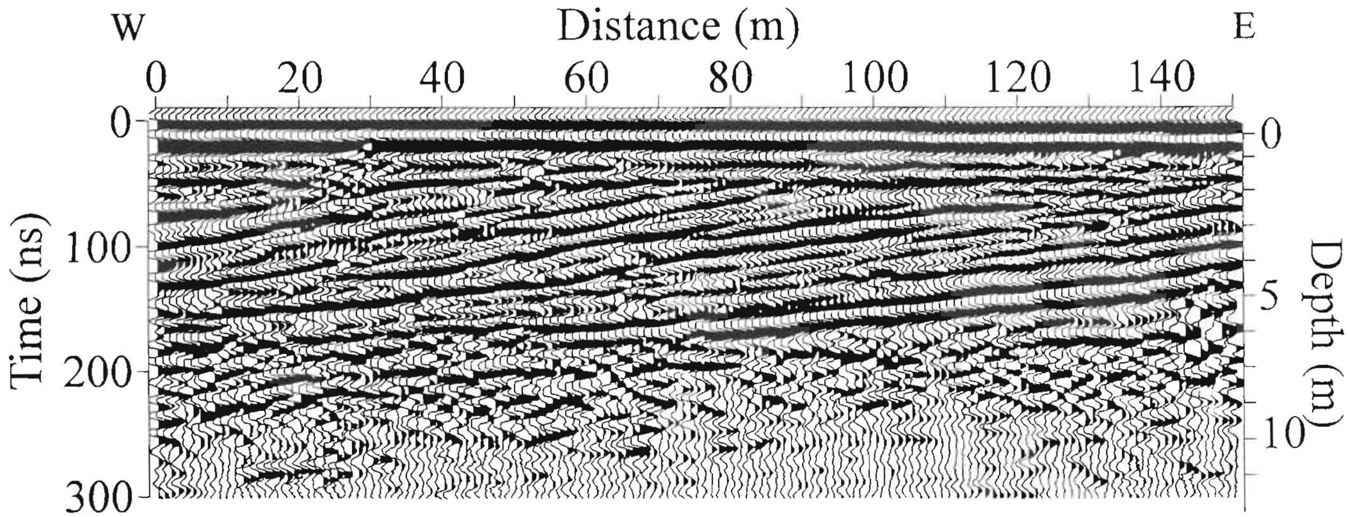

Figure 9. GPR profile (100 MHz) from the Willapa barrier spit, Washington showing 1–2° inclined reflections dipping seaward. The absence of offshore bars, contrary to Jekyll Island, is attributed to reworking of the beach surface by severe winter storm waves (MEYERS, 1994).

recovered with each attempt. Rotary auger and trenching is limited due to sediment collapse because of shallow groundwater tables. Geophysical wireline logging is limited due to little change in sediment grain size and this method also requires existing wells. Apart from GPR, no other shallow subsurface data-acquisition system with comparable resolution and continuity of data is presently available.

GPR can be used effectively on coastal barriers, spits and strandplains composed of clean coarse sediments (little to or no clay or silt) with reasonably thick freshwater aquifers. These are important requirements since the GPR signal is attenuated in brackish/saline groundwater and silt/clay conditions. GPR results can infer sedimentary facies and directions of paleo-deposition. Previous tests have shown that radar facies compare well with structural facies (JOL and SMITH, 1991; SMITH and JOL, 1992; HUGGENBERGER, 1993). Dip angle of inclined reflections may be associated with grain size of sediments (1–2° in fine sand, 3–6° in coarse sand to granules of broken shells, and up to 23° in boulder-gravel), as well as wave energy. Paleo-directions and patterns of pro-

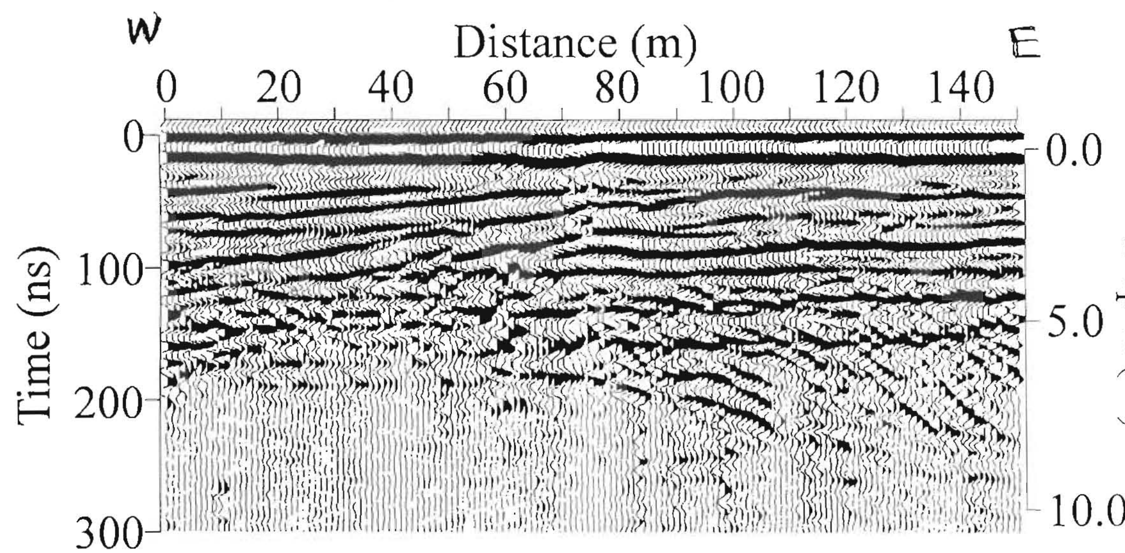

Figure 10. GPR profile (100 MHz) from the back barrier at Ocean Shores, Washington. Lowermost eastern steeply dipping strata are probable washover foreset beds. Upper facies of horizontal reflections east of 73 m are interpreted as vertical accretion bedding deposited as part of the original spit sand mass. Farther west shingle-like seaward beach accretion beds are indicated by prominent continuous inclined reflections.

gradation and aggradation in barriers can be useful in planning coastal communities and navigational facilities. Finally, GPR can be used to accurately delineate and map the subsurface fresh-brackish water contact beneath some sandy coasts for a fraction of the cost and time as compared to conventional drilling.

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