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Ground Penetrating Radar Analysis of an Emergent Mid-Pleistocene Estuarine Shoreline Complex, Chesapeake Bay, Maryland, USA.

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ABSTRACT

In northeastern Dorchester County, Maryland, 100 and 250 MHz ground penetrating radar surveys were used to define the east-west trending, linear Parsonsburg Sand deposit as a stranded estuarine shoreline complex, composed of three distinct highstand successions emplaced during climate-driven sea level cycles during the mid Pleistocene. These deposits form a broad ridge with 5 meters of relief, rising from their contact with the Kent Island Formation at + 10 m MSLto ~ + 14 m MSLalong the crest. The thin (<5 m) highstand deposits are cut into the underlying Pliocene Beaverdam and/or Miocene Pensauken Formations and overtop one another, attaining modern elevations of + 12 m, + 11 m, and + 14 m MSL, in succession. Radar facies and lithologic data were used to identify transgressive and highstand components of these deposits, as well as backbarrier, shoreface, and nearshore facies and structures which can be traced into their equivalent bay bottom facies in the adjacent Kent Island Formation. These data correlate well with similar regional and global coastal deposits of marine oxygen isotope stage 11 age.

ADDITIONALINDEXWORDS: *barrier island, GPR, highstand, sea level*

INTRODUCTION

Investigations of Cenozoic sea level change in the mid-Atlantic coastal plain of North America often rely upon scarp and terrace morphology to identify individual highstand successions representative of the landward extent of distinct marine transgressive events. In the absence of such clear geomorphic relationships, the complex record of climate-induced Pleistocene sea-level fluctuations (IMBRIE *et al*., 1984; SHACKLETON, 1987) is difficult to interpret in an area where subsurface exposures are rare. No clear escarpments, suggestive of wave-cut paleoshorelines, have been mapped on the eastern margin of Chesapeake Bay in Dorchester County, Maryland (OWENS and DENNY, 1986), where a broad platform slopes gently from MSL at the bay edge, to ~ + 10m MSL, 40 km inland. The platform is overlain by the late Pleistocene age, bay bottom sediments (OWENS and DENNY, 1979) of the Kent Island Formation. In several locations on the platform are surficial deposits of the Parsonsburg Sand. This unit of uncertain, late Pleistocene age, is suspected of having multiple origins (DENNY *et al*., 1979), from estuarine to fluvial to eolian. In the central and northeastern sections of the platform are several subtle, linear, roughly bay margin-parallel, topographic highs within these two units.

In the study presented here, 100 and 250 MHz ground penetrating radar and lithologic evidence were used to delineate three distinct highstand successions within an east-west trending, linear Parsonsburg Sand deposit in northeastern Dorchester County. Suspected of stemming from mid Pleistocene sea level fluctuations (local and global correlation), the deposits within this shoreline complex define a barrier island-style morphology for paleoshorelines in this area, rather than the wave-cut style seen along escarpments elsewhere in the mid-Atlantic (OWENS and DENNY, 1979; MIXON, 1985; NEWELL *et al*., 2000). These data also confirm that in this location, the Parsonsburg Sand and Kent Island Formation are coeval, representing shore and offshore (bay bottom) deposits of equivalent sea level cycles.

STUDYAREA

Dorchester County lies on Maryland's Eastern Shore, on the west side of the Delmarva Peninsula, within the Atlantic Coastal Plain physiographic province. Most of the land surface within the county lies within 10 meters of MSL, in a ~ 40 km-wide, gently bayward-sloping platform, bounded on the north and southeast by the Choptank and Nanticoke Rivers, respectively, and by the Chesapeake Bay to the west. Upland surfaces of 15+ m MSL are restricted to the extreme northeast part of the county.

The Quaternary sediments of the broad platform bordering Chesapeake Bay in Dorchester County consist primarily of the late Pleistocene-age Kent Island Formation (Figure 1) and the overlying Holocene salt marsh (not shown in Figure 1). The Kent Island Formation is characterized as interbedded silt, clay, and sand, deposited as bay bottom sediments of a larger, late Sangamon to middle Wisconsin-age, ancestral Chesapeake Bay (OWENS and DENNY, 1979; 1986). The unit is silty where it overlies the marine sediments of the Miocene Chesapeake Group, and sandy where it overlies the coarser fluvial to shelf to marine sediments of the late Miocene and middle to late Pliocene Pensauken Formation and Beaverdam Sand, respectively (OWENS and DENNY, 1979; 1986). These latter units are exposed in the northeastern upland part of the county (Figure 1).

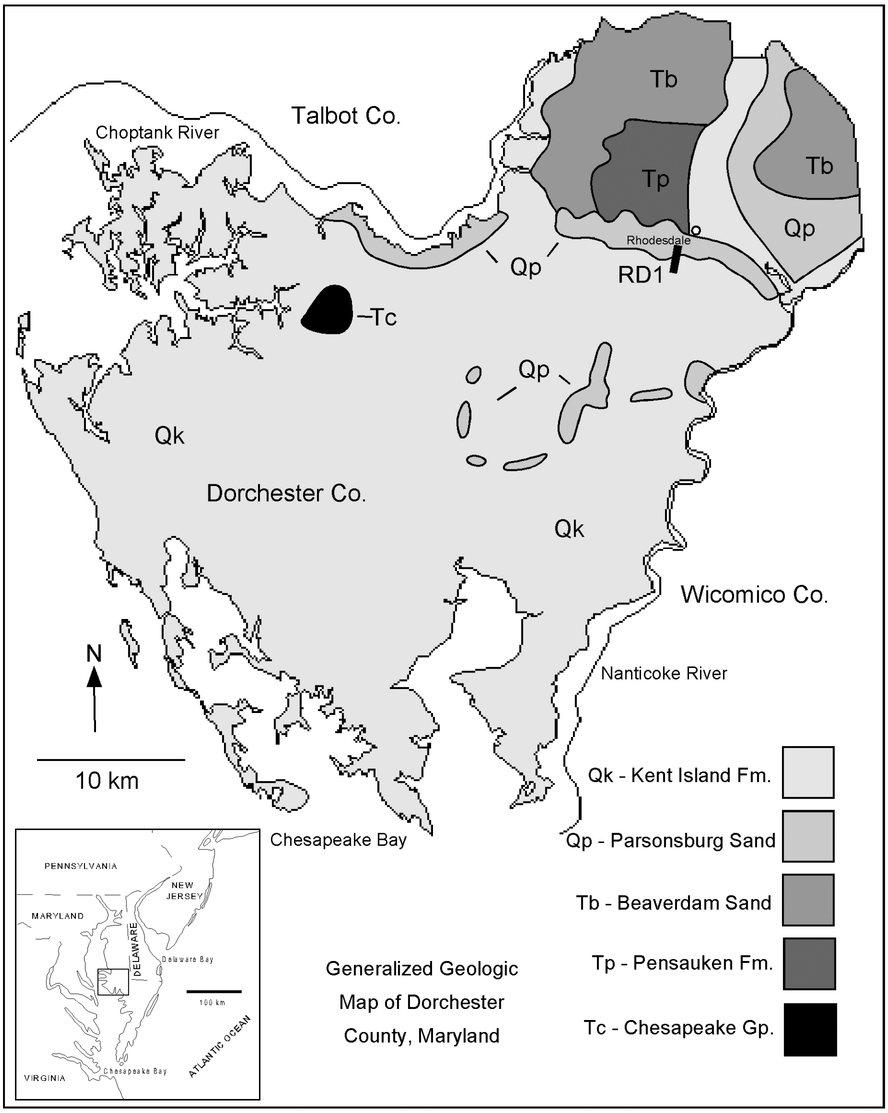

Figure 1. Generalized geologic map of Dorchester County, Maryland, showing outcrop pattern of upper Cenozoic deposits (Holocene salt marsh and alluvium omitted). Inset map shows location of Dorchester County in mid-Atlantic region. Study area (RD1) is located in northeastern section of the county. Adapted from OWENS and DENNY (1986) onto Maryland Geological Survey county map datum.

Another Pleistocene-age unit, the Parsonsburg Sand (Figure 1), is characterized as loose, light colored quartz sand that discontinuously mantles stream valleys, and appears as sand ridges and dunes, in several locations along the Delmarva Peninsula (SIRKIN *et al*., 1977; DENNY *et al*., 1979). The origin of this unit is complex, with possible eolian to fluvial to estuarine depositional characteristics, depending on locality. These variations suggest that the Parsonsburg Sand is the result of the reworking of previous deposits, in different sedimentary environments, at different times (OWENS and DENNY, 1986). The age of the unit has been estimated to be as young as late Wisconsin where it flanks modern river valleys, and as old as late Pliocene where it appears to be fresh exposures of older units (OWENS and DENNY, 1986). The Cenozoic geologic history of the region is further summarized in OWENS and DENNY (1979; 1986).

The prominent east-west trending linear Parsonsburg Sand deposit in northeast Dorchester County (Figure 1), forming a broad ridge with 4-5 meters of relief, was chosen for evaluation as a possible Pleistocene paleoshoreline. Several assumptions regarding the nature of this deposit and possible sea level history of the area were made in this site selection. If the Parsonsburg Sand is the result of the reworking of previous deposits, then this roughly bay margin-parallel sand ridge might be the location of a previous bay shoreline, cut into the older, sandy Pensauken Formation or Beaverdam Sand. This deposit of Parsonsburg Sand also forms the eastern limit of Pleistocene-age deposits mapped in the county, and falls roughly on strike with escarpments in the Kent Island Formation in adjacent areas of the Delmarva Peninsula (OWENS and DENNY, 1979; 1986). Finally, the contact between the Parsonsburg Sand and the Kent Island Formation, at this location, presented an opportunity to firmly establish the latter unit as a bay bottom deposit, in direct relation to a suspected paleoshoreline deposit.

METHODS

A combination of ground penetrating radar (GPR) systems were used in transects across the linear Parsonsburg Sand and adjacent Kent Island Formation deposits near Rhodesdale, Maryland (Figure 1), to establish the subsurface geometry of their internal depositional sequences. The stratigraphic framework revealed in these profiles was used to determine ideal locations for hand-auger borings. The combination of radar-derived and lithologic stratigraphic sections allowed for the delineation of individual highstand successions, and the identification and interpretation of backbarrier, shoreface, and nearshore sedimentary structures and facies. Age estimates of the highstand successions identified in this study were derived from elevation and sequence correlation with other regional and global coastal highstand deposits.

Ground Penetrating Radar

Several researchers have summarized the underlying principles of GPR operation, including ULRIKSEN (1982), DANIELS (1989), and HUGGENBERGER (1993). GPR has been successfully used in coastal applications to locate and identify sedimentary structures (LEATHERMAN, 1987; JOL and SMITH, 1991, 1992a, 1992b; MEYERS *et al*., 1994; BRIDGE *et al*., 1995; JOL *et al*., 1996) and buried paleochannels (WYATT and TEMPLES, 1996; O'NEAL and MCGEARY, in press). Recent coastal stratigraphic studies conducted using GPR in the mid-Atlantic region include MCGEARY *et al*. (1994), SOTSKY (1995), DALY (1997), O'NEAL (1997), and O'NEAL and MCGEARY (in press).

Two GPR systems were used in this study. For overall subsurface stratigraphy, a 1000-volt, digital bistatic pulseEKKO 100 unit was used with 100 MHz antennas, at a separation distance of 1 meter, and step increments of 0.25 meters in a common-offset profile mode. Common-midpoint gathers were obtained to derive a radar-wave velocity of 0.1 m/ns, used for accurate depth plotting of stratigraphic profiles. This process is described by ANNAN and COSWAY (1992, 1994). Each vertical trace was stacked 16 times with a sampling rate of 800 picoseconds. The pulseEKKO data was processed and plotted with Win EKKO Pro software (v. 1.1), using a dewow filter and automatic gain control. Topographic correction of the radar sections was performed with data acquired through level transit surveying.

For reconnaissance and detailed subsurface imaging, a 250 MHz, broad band Noggin system was used. This fixed-separation, bistatic system operates as a tow-behind model, and was used in continuous collection mode with a step size equivalent to 0.1 meters. Preset user-specified values of radar wave velocity, stacking, and collection intervals were selected to match those of the pulseEKKO system used in this study.

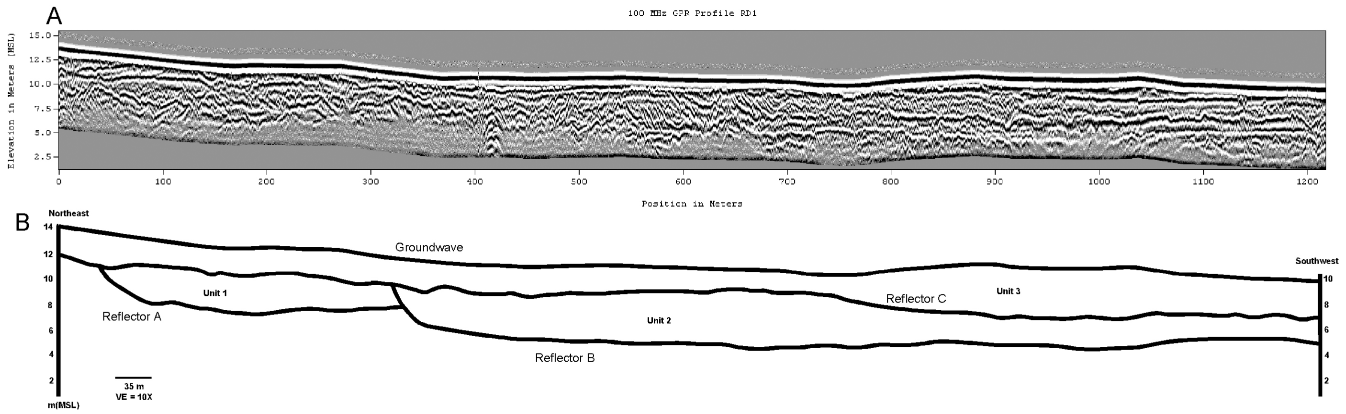

Figure 2. (A) 100 MHz ground penetrating radar profile RD1, collected across Parsonsburg Sand and Kent Island Formation near Rhodesdale, Maryland. (B) Interpretive section of profile RD1, showing major reflectors A, B, and C, unconformably separating highstand units 1, 2, and 3.

RESULTS

The 100 MHz GPR profile RD1 (Figure 2A) was collected along an agricultural access lane west of Rhodesdale, Maryland. Extending south-southwest for a distance of 1215 meters, the profile begins at a surface elevation of +14 m MSL on the crest of a low, broad ridge of the Parsonsburg Sand (Figure 1). The profile continues down a gentle slope (bayward), perpendicular to the sand ridge, crossing into the Kent Island Formation at an elevation of +10 m MSL, at a point 750 meters along the profile. The remaining 465 meters of the profile is characterized by relatively flat terrain, punctuated by two low ridges normal to the profile direction, at points 880 and 1150. The profile ends at an elevation of 9.75 m MSL.

Figure 2B is an interpretation of radar section RD1, depicting the strongest and/or most laterally extensive (major) reflectors. The upper two strong reflectors record the airwave and groundwave arrivals directly from the transmitting to receiving antennas, and do not represent the underlying stratigraphy. Three primary reflectors, labeled A, B, and C are visible nearly continuously across the profile. Little information is recorded below reflectors A and B, marking the limit of radar wave depth penetration in this area and/or a significant change in lithology of the underlying sediments. Smaller, generally bayward-dipping reflectors are also seen throughout the profile, recording small scale sedimentary structures and bedding planes.

Reflector C is the most continuous of the major reflectors, starting at +12 m MSL in the northeast, and may be traced at 1 to 2 meters below land surface to an elevation of +7 m MSL in the southwest. Reflector B is truncated by reflector C above, at point 320, where it dips steeply to +7 m MSL before tracing a gently undulating path to +5 m MSL at the southwest end of the profile. Reflector A is truncated from above by reflector C at point 30 (+11.5 m MSL), and at its southwest end by reflector B at point 340 (+8.5 m MSL). Together, these three reflectors define three separate sedimentary sequences, labeled units 1, 2, and 3 on Figure 2B.

In a sea-level highstand depositional framework, major reflectors exhibiting characteristics of an overall seaward (bay) slope (consistent inset into older units landward and/or truncation by younger units seaward, and overall lateral continuity), may be interpreted as unconformities separating highstand deposits of distinct sea level cycles. In a siliciclastic setting of fairly uniform sand on sand deposition, the high-energy environment of an active shoreline eroding into and overtopping underlying sediments during a rise in sea level often produces an unconformable transgressive ravinement surface (TRS), characterized by coarse sediment deposition (NUMMEDAL and SWIFT, 1987).

Using the radar record RD1 as a guide, hand-augered boreholes RDA1 through RDA14 were obtained to verify major reflectors A, B, and C as representing unconformities. Shown in Figure 3, each borehole that penetrated the location of a major reflector encountered a gravel or gravelly sand deposit at the appropriate depth. Together with the characteristics of the major reflectors, these lithologic data suggest that reflectors A, B, and C each represent a distinct TRS, separating three highstand successions of separate sea level cycles, units 1, 2, and 3, in decreasing age order (Figures 2B and 3).

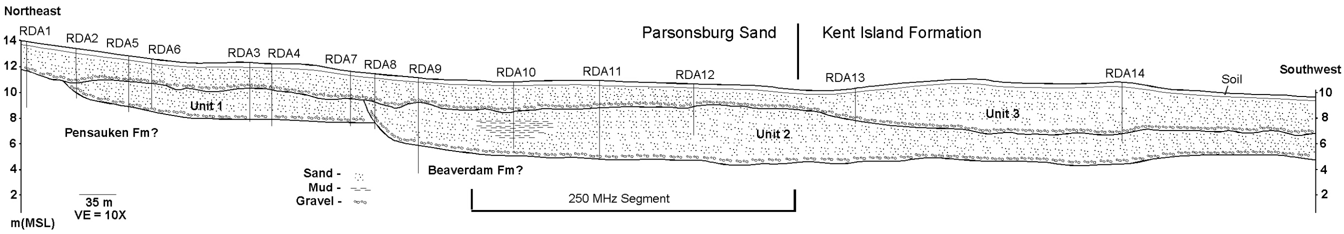

Figure 3. Lithostratigraphic cross section of radar profile RD1 showing three successive highstand units within the Parsonsburg Sand and Kent Island Formation near Rhodesdale, Maryland. These highstand units cut into Miocene Pensauken and/or Pliocene Beaverdam Sand below. Hand-augered borehole locations are shown with numerical designation RDA. Location of 250 MHz GPR segment of profile RD1 is identified within unit 2.

As shown in Figure 3, unit 1 exists entirely within the Parsonsburg Sand deposits at this location, while units 2 and 3 are clearly continuous in lithologic and radar sections (Figure 2A) across the Parsonsburg Sand/Kent Island Formation contact. Hand-augered boreholes that penetrated below units 1, 2, and 3 all encountered more compacted sediments of lithologies differing from either the Parsonsburg Sand or the Kent Island Formation. Boreholes RDA1-5 encountered coarse, feldspathic sands consistent with published descriptions of the Miocene Pensauken Formation (OWENS and DENNY, 1979; 1986), while boreholes RDA7, 8 and 9 penetrated into stiff, sandy clays matching descriptions of subunits within the Pliocene Beaverdam Sand (OWENS and DENNY, 1979; 1986). Either or both of these units possibly underlie the study site as mapped by OWENS and DENNY (1986), and are herein treated as undifferentiated for the purposes of this study.

DISCUSSION

Paleoshoreline Morphology

The radar- and borehole-derived lithologic section in Figure 3 reveals units 1, 2, and 3 as separate sea-level highstand successions of nearly uniform sand deposition, with the exception of a 2 meter-thick section of interbedded sands and muds in unit 2, augered in RDA10 at point 480 (Figure 2A). Adjacent to this location surrounding point 600, several steeply bayward dipping minor reflectors may be seen in profile RD1 (Figure 2A). Further investigation of these features in the 250 MHz subsection of GPR profile RD1 revealed the sedimentary structures shown in Figure 4.

The fine scale reflectors (bedding planes) of this radar record, combined with the lithologic data obtained from boreholes RDA10, 11, and 12, clearly define the cross sectional profile of a stranded estuarine shoreline within unit 2. The bayward dipping sands of the shoreface sampled in RDA11 are composed predominately of quartz, with a heavy mineral concentration higher than surrounding sands. Northeast of the shoreface, borehole RDA10 encountered the interbedded sands and muds of a backbarrier lagoon or marsh, while a small foreshore bar may be seen southwest of RDA12. Together these structures and lithologies suggest that this stranded highstand deposit was a low, estuary-margin, barrier island-type shoreline, in contrast to the wave-cut shorelines seen in adjacent sections of the Chesapeake Bay. Though no other internal barrier structures were encountered in this study, the overall morphology of the linear Parsonsburg Sand deposit investigated in this study (Figure 1) suggests that unit 1 (youngest) was deposited in a barrier island setting as well. In contrast to the wave-cut shorelines of more open coasts seen elsewhere in the Chesapeake Bay (OWENS and DENNY, 1979; MIXON, 1985), this barrier island shoreline morphology suggests that during times of inundation, the broad platform of Dorchester County between the Choptank and Nanticoke Rivers forms a shallow embayment where tidal and wave energies are altered, allowing the construction of migrating barrier shorelines behind the leading edge of estuarine transgression.

Age Estimates

No datable organic material was found in sediments of the Parsonsburg Sand or Kent Island Formation, in samples obtained during this study. This is a common problem in dating Atlantic Coastal Plain sediments, and has been reported previously in these two units in Dorchester County (OWENS and DENNY, 1979). OWENS and DENNY (1986) report a radiocarbon age of >42,000 years from a peaty unit beneath the Kent Island Formation in the northwest part of the county, inland from the Choptank River, placing the age of this unit as late Pleistocene (late Sangamon to middle Wisconsin).

A middle Pleistocene age estimate is herein proposed for the three highstand units within the Parsonsburg Sand and Kent Island Formations identified in this study on the basis

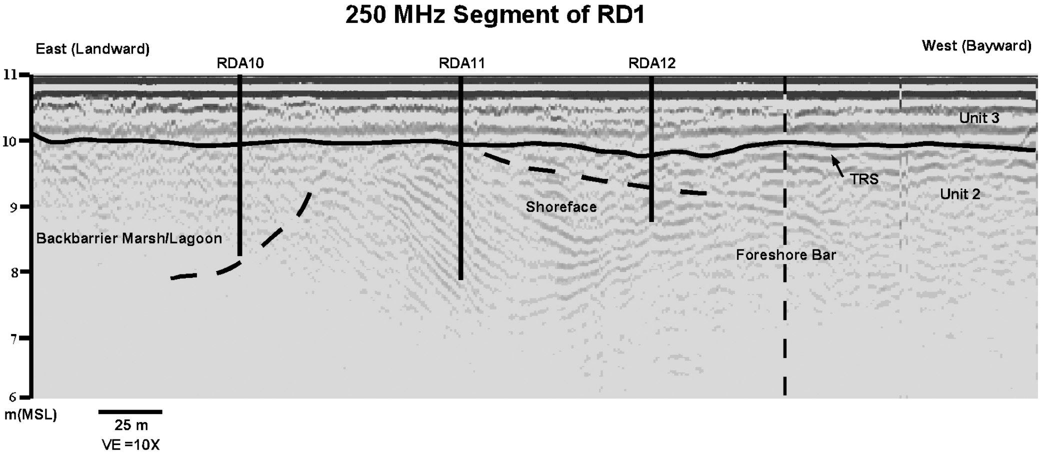

Figure 4. 250 MHz segment of radar profile RD1 showing backbarrier, shoreface, and foreshore structures of a stranded mid-Pleistocene barrier island-style shoreline within highstand unit 2. The upper section of unit 2 has been removed along the TRS (reflector C) incised during the sea level high of unit 3 time.

of elevation and sequence correlation with other regional and global coastal successions. Although the current elevation of these highstand successions is not likely to accurately reflect eustatic sea levels at the time of their deposition (uplift, subsidence, compaction, etc.), the overall tectonic stability of the study area during the Pleistocene allows for their interpretation as reasonable estimates of local, relative sea level. As such, the uppermost deposits of unit 1 infer a sea level of + 12 m MSL, while those of unit 2 infer a sea level of + 11 m MSL. Both of these estimates are minima, as the younger unit 3 has overtopped and removed their upper deposits during the transgression leading to a sea level high of + 14 m MSL at that time.

A comparison of these Pleistocene sea levels with those inferred from other coastal deposits is shown in Table 1. In the tectonically stable carbonate platform of the Bahamas, HEARTY and KAUFMAN (2000) have correlated a succession of inset and overtopped marine deposits to multiple highstands within the overall high sea level cycle equivalent to marine oxygen isotope stage (MIS) 11, at approximately 400 ka. Though not attributed to multiple highstands, comparable high sea levels are recorded for coastal deposits in Argentina (ROSTAMI *et al*., 2000), Hawaii (HEARTY *et al*., 1999), and Delaware (RAMSEY, 1993, 1997). Also in the Delaware Bay area, O'NEAL and MCGEARY (in press) have identified an MIS 11-equivalent succession of highstand deposits comparable to those in the Bahamas, within the Cape May Formation of southern New Jersey. The MIS 11 sea levels inferred from these regional and global records fit well in elevation and sequence (the youngest event is the highest) with the succession of highstand deposits identified in this study.

Table 1. Comparison of MIS 11 Highstand Elevations above MSL

MIS Stage	**[a]Bahamas [c]Hawaii**	**[b]Argentina**	**[d]Delaware**	**[e]New Jersey**	**This Report**
Early 11?	+2m			+12m	+12m
Mid 11?	+7m			+6m	+11m
Late 11?	+20m	+20m	+14m	+16m	+14m

[a]HEARTY and KAUFMAN (2000)
[b]ROSTAMI *et al*. (2000)
[c]HEARTY *et al*. (1999)
[d]RAMSEY (1993; 1997)
[e]O'NEAL and MCGEARY (in press)

CONCLUSIONS

Ground penetrating radar and hand-auger borings were successfully used to identify three middle Pleistocene-age highstand successions deposited during three distinct transgressions of + 12 m, + 11 m, and + 14 m MSL, within the overall high sea level cycle of MIS 11. The barrier island-style shorelines of these three sea level events are preserved as a barrier complex within the linear ridge of Parsonsburg Sand in northeastern Dorchester County, Maryland. The equivalent offshore facies of the younger two units (2 and 3) are preserved in the sandy deposits of the adjacent Kent Island Formation. The lithology of these deposits suggests a sandy tidal flat to shallow, sandy bay bottom environment of deposition. As the sedimentary environments of highstand units 2 and 3 identified herein may be traced continuously from their paleoshoreline positions to their offshore equivalents, the Parsonsburg Sand and Kent Island Formation are coeval at this location.

LITERATURE CITED

ANNAN, A.P. and COSWAY, S.W., 1992. Ground Penetrating Radar Survey Design. *SAGEEP Annual Meeting*, Chicago.

ANNAN, A.P. and COSWAY, S.W., 1994. GPR Frequency selection. *Proceedings of the 5th International Conference on GPR*, 747-760.

BRIDGE, J.S. ALEXANDER, J. COLLIER, R.E.L., and GAWTHORPE, R.L., 1995. Ground-Penetrating Radar and Coring Used to Study the Large-Scale Structure of Point-Bar Deposits in Three Dimensions. *Sedimentology*, 42, 839-852.

DALY, J.F., 1997. *Ground-Penetrating Radar Investigation of Holocene and Pleistocene Spit Complexes in Southeastern Delaware. Newark, Delaware*: University of Delaware, M.S. thesis.

DANIELS, J.J., 1989. Ground Penetrating Radar. *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*. Society of Engineering and Mineral Exploration Geophysicists, 2, 62-142.

DENNY, C.S. OWENS, J.P. SIRKIN, L.A. and RUBIN, M., 1979. The Parsonsburg Sand in the central Delmarva Peninsula, Maryland and Delaware. *U.S. Geological Survey Professional Paper* 1067-B, pp. B1-B16.

HEARTY, P.J. and KAUFMAN, D., 2000. Whole-Rock Aminostratigraphy and Quaternary Sea-Level History of the Bahamas. *Quaternary Research*, 54, 163-173.

HEARTY, P.J. KINDLER, P. CHENG, H. and EDWARDS, R., 1999. The Kaena Highstand on O'ahu, Hawai'I: Further Support for Partial Antarctic Ice Collapse during Marine Isotope Stage 11. *American Geophysical Union, Fall Meeting, Programs with Abstracts*.

HUGGENBERGER, P., 1993. Radar Facies: Recognition of Facies Patterns and Heterogeneities within Pleistocene Rhine Gravels, NE Switzerland. *Geological Society of America Special Publication* 75, 163-176.

IMBRIE, J. HAYS, J.D. MARTINSON, D.G. MCINTYRE, A.; MIX, A.C., and others, 1984. The Orbital Theory of Pleistocene Climate: Support from a Revised Chronology of the Marine dO^{18} Record. *In* BERGER, A.L. IMBRIE, J. HAYS, J.D. KUKLA, G. and SALTZMAN, B. (eds) *Milankovitch and Climate, Part I.* Dordrecht (Reidel), 269-305.

JOL, H.M. and SMITH, D.G., 1991. Ground Penetrating Radar of Northern Lacustrine Deltas. *Canadian Journal of Earth Science*, 28, 1939-1947.

JOL, H.M. and SMITH, D.G., 1992a. Geometry and Structure of Deltas in Large Lakes: a Ground Penetrating *Radar Overview. Geological Survey of Finland Special* Paper 16, pp. 159-168.

JOL, H.M. and SMITH, D.G., 1992b. Ground Penetrating Radar: Recent Results. *Canadian Society of Exploration Geophysics Recorder*, 27, 15-20.

JOL, H.M. SMITH, D.G. and MEYERS, R.A., 1996. Digital Ground Penetrating Radar (GPR): a New Geophysical Tool for Coastal Barrier Research (Examples from the Atlantic, Gulf and Pacific Coasts, U.S.A.). *Journal of Coastal Research*, 12, 960-968.

LEATHERMAN, S.P., 1987. Coastal Geomorphological Applications of Ground Penetrating Radar. *Journal of Coastal Research*, 3, 397-399.

MCGEARY, S. SOTSKY, J. and KRANTZ, D.E., 1994. Ground-Penetrating Radar Imaging of Pleistocene Stratigraphy on the Margin of Delaware Bay. *Geological Society of America Annual Meeting, Abstracts with Programs*, A-305.

MEYERS, R.A. SMITH, D.G. JOL, H.M. and HAY, M.B., 1994. Internal Structure of Pacific Coast Barrier Spits Using Ground Penetrating Radar. Proceedings of the *5th International Conference on GPR*, 843-854.

MIXON, R.B., 1985. Stratigraphic and Geomorphic Framework of Uppermost Cenozoic Deposits in the Southern Delmarva Peninsula, Virginia and Maryland. *U.S. Geological Survey Professional Paper 1067-G*, pp. G1-G53.

NEWELL, W.L. POWARS, D.S. OWENS, J.P. STANFORD, S.D. and STONE, B.D., 2000. Surficial Geological Map of Central and Southern New Jersey. *U.S. Geological Survey Miscellaneous Investigations Series Map I-2540-D*.

NUMMEDAL, D. and SWIFT, D.J.P., 1987. Transgressive Stratigraphy at Sequence Bounding Unconformities; Some Principles Derived from Holocene and Cretaceous examples. *In:* NUMMEDAL, D. (eds.), *Sea-Level Fluctuations and Coastal Evolution*.

Society of Economic Paleontologists and Mineralogists Special Publication 41, 241-259.

O'NEAL, M.L., 1997. *Ground Penetrating Radar Analysis of Composite Quaternary Coastal Terraces on the Northern Margin of the Delaware Bay*. Newark, Delaware: University of Delaware, Ph.D. thesis.

O'NEAL, M.L. and MCGEARY, S., in press. Late Quaternary Stratigraphy and Sea Level History of the Northern Delaware Bay Margin, Southern New Jersey, USA: a Ground Penetrating Radar Analysis of Composite Quaternary Coastal Terraces. *Quaternary Science Reviews*.

OWENS, J.P. and DENNY, C.S., 1979. Upper Cenozoic Deposits of the Central Delmarva Peninsula, Maryland and Delaware. *U.S. Geological Survey Professional Paper 1067-A*, pp. A1-A28.

OWENS, J.P. and DENNY, C.S., 1986. *Geologic Map of Dorchester County*. Maryland Geological Survey.

RAMSEY, K.W., 1993. *Geologic Map of the Milford and Mispillion River Quadrangles*. Delaware Geological Survey Geologic Map Series No. 8.

RAMSEY, K.W., 1997. Geology of the Milford and Mispillion River Quadrangles.*Delaware Geological Survey Report of Investigations* No. 55, pp. 40.

ROSTAMI, K. PELTIER, W.R. and MANGINI, A., 2000. Quaternary Marine Terraces, Sea-Level Changes and Uplift History of Patagonia, Argentina: Comparisons with Predictions of the ICE-4G (VM2) Model of the Global Process of Glacial Isostatic Adjustment. *Quaternary Science Reviews*, 19, 1495-1525.

SHACKLETON, N.J., 1987. Oxygen Isotopes, Ice Volume and Sea Level. *Quaternary Science Reviews*, 6, 183-190.

SIRKIN, L.A. DENNY, C.S. and RUBIN, M., 1977. Late Pleistocene Environment of the central Delmarva Peninsula. *Geological Society of America Bulletin*, 88, pp. 139-142.

SOTSKY, J.M., 1995. *Ground-Penetrating Radar Imaging of Quaternary Stratigraphy in Delaware*. Newark, Delaware: University of Delaware, M.S. thesis.

ULRIKSEN, C.P.F., 1982. *Application of Impulse Radar to Civil Engineering*. Switzerland: Lund University, Ph.D. thesis.

WYATT, D.E. and TEMPLES, T.J., 1996. Ground-Penetrating Radar Detection of Small-Scale Channels, Joints and Faults in the Unconsolidated Sediments of the Atlantic Coastal Plain. *Environmental Geology and Water Sciences*, 27.