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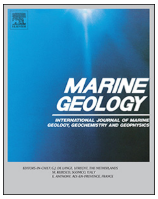

Seismic stratigraphic framework of the continental shelf offshore Delmarva, U.S.A.: Implications for Mid-Atlantic Bight Evolution since the Pliocene

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ABSTRACT

Understanding how past coastal systems have evolved is critical to predicting future coastal change. Using over 12,000 trackline kilometers of recently collected, co-located multi-channel boomer, sparker and chirp seismic reflection profile data integrated with previously collected borehole and vibracore data, we define the upper (< 115 m below mean lower low water) seismic stratigraphic framework offshore of the Delmarva Peninsula, USA. Twelve seismic units and 11 regionally extensive unconformities (U1-U11) were mapped over 5900 km^2 of North America's Mid-Atlantic continental shelf. We interpret U3, U7, U9, U11 as transgressive ravinement surfaces, while U1,2,4,5,6,8,10 are subaerial unconformities illustrating distinct periods of lower sea-level. Based on areal distribution, stratigraphic relationships and dating results (Carbon 14 and amino acid racemization estimates) from earlier vibracore and borehole studies, we interpret the infilled channels as late Neogene and Quaternary courses of the Susquehanna, Potomac, Rappahannock, York, James rivers and tributaries, and a broad flood plain. These findings indicate that the region's geologic framework is more complex than previously thought and that Pleistocene paleochannels are abundant in the Mid-Atlantic. This study synthesizes and correlates the findings of other Atlantic Margin studies and establishes a large-scale Quaternary framework that enables more detailed stratigraphic analysis in the future. Such work has implications for inner continental shelf systems tract evolution, the relationship between antecedent geology and modern coastal systems, assessments of eustacy, glacial isostatic adjustment, and other processes and forcings that play a role in passive margin evolution.

1. Introduction

Seismic stratigraphic analysis provides a framework for understanding the depositional and erosional history of an area and defines the antecedent geology over which modern coastal processes act (Vail and Mitchum Jr., 1977; Belknap and Kraft, 1985). Knowledge of an area's shallow geology is required to correctly interpret and predict shelf and coastal change (Johnson et al., 2017; Warner et al., 2017). Throughout the Quaternary period a series of sea-level lowstands and highstands associated with glacial-interglacial cycles occurred (e.g., Spratt and Lisiecki, 2016). During sea-level lowstands large rivers continued across many continental shelves, likely to the present-day shelf edges (Twichell et al., 1977; Tesson et al., 2015; Yoo et al., 2017). Where present, such remnant channels and their associated fill sequences can form dominant components of an area's geologic framework and may exert controls on modern shorelines (e.g., Foyle and Oertel, 1997; Posamentier, 2001; Mallinson et al., 2005; Baldwin et al., 2006; Green, 2009; Mallinson et al., 2010a; Thieler et al., 2014; Zhuo et al., 2015).

The Delmarva Peninsula is a 220-km-long headland, spit and barrier island complex located in the central Mid-Atlantic Bight (Fig. 1). The Peninsula is bounded by Chesapeake Bay, North America's second largest estuary, and Delaware Bay. Several geophysical studies have documented regional stratigraphy and paleochannels in Chesapeake Bay and the Delmarva inner continental shelf, however the local extents and variations in seismic frequencies used in the studies, in addition to the disappearance of several of the original datasets, have inhibited the correlation of Quaternary stratigraphy across the region (e.g., Sheridan et al., 1974; Colman and Mixon, 1988; Toscano et al., 1989; Chen et al., 1995; Oertel and Foyle, 1995; Nebel, 2013; Krantz et al., 2015) (Fig. 2). Thus, the stratigraphic relationships and relative ages of the paleochannels have not been resolved and the overall evolution of the Delmarva continental shelf remains uncertain (Hobbs III, 2004; Oertel et al., 2008). In this study, we interpret over 12,000-trackline kilometers of newly collected multichannel boomer, sparker and chirp seismic reflection data collected over 5900 km^2 of the continental shelf

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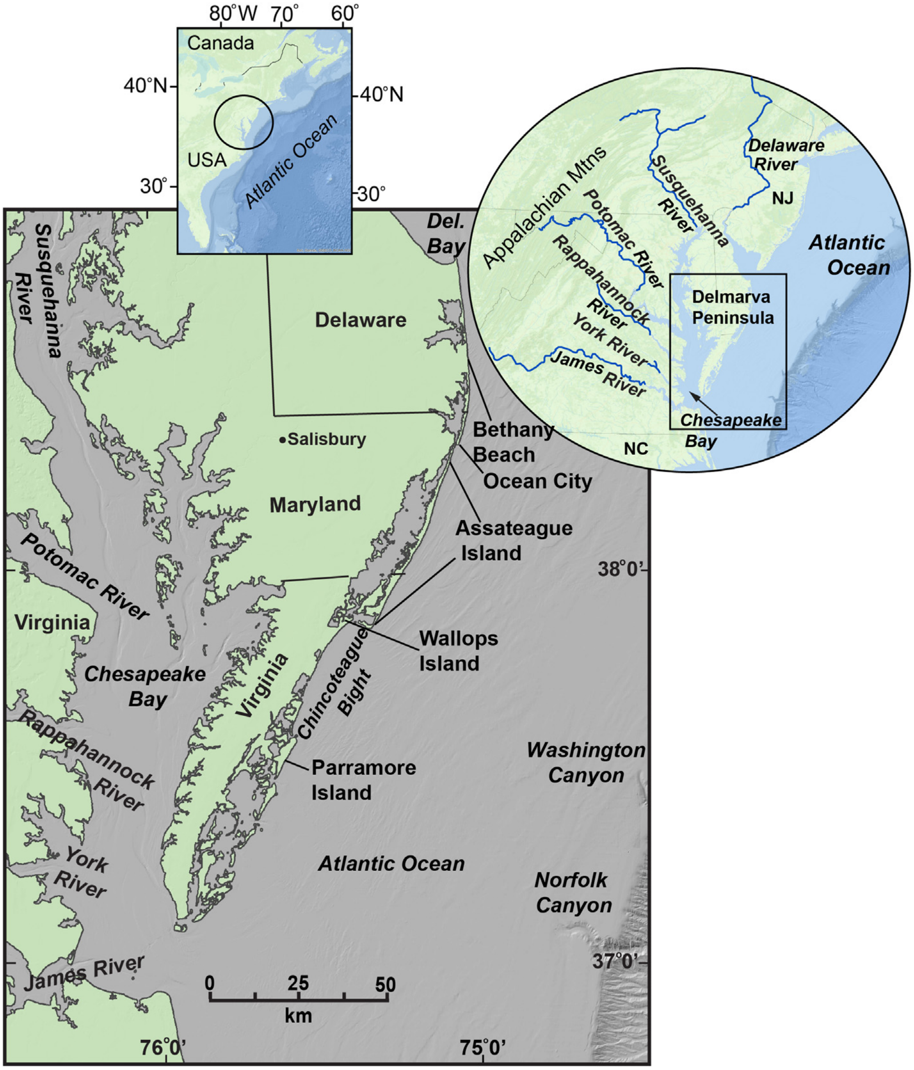

Fig. 1. Map of the Delmarva Peninsula region. Inset of the Atlantic Margin of North America indicates the position of the circular inset. The circular inset of the Mid-Atlantic Bight illustrates the position of the study area, major mountain ranges, rivers and water bodies and locations named in the text, NC = North Carolina, NJ = New Jersey. Hill-shaded relief is from Andrews et al. (2016) and the U.S. Coastal Relief Model NOAA, 1999.

of the Delmarva Peninsula, to resolve the character, distribution and geometry of seismic sequences (Fig. 3). Because character of any one seismic unit can vary substantially over the study area, we primarily rely upon the regionally-extensive unconformities that have broadly-consistent characters to define the geologic framework. We incorporate the geologic findings from previous onshore, estuarine and continental shelf borehole and geophysical studies to ground truth our interpretations (Shideler et al., 1972; Owens and Denny, 1979; Mixon, 1985; Toscano et al., 1989; Colman et al., 1990; Ramsey, 1999; Mattheus et al., 2020a, 2020b; McFarland and Beach, 2019)(Fig. 2). The resulting geologic framework lays the foundation for understanding patterns of margin evolution likely active on many mid-latitude, passive-margin settings.

2. Regional setting

2.1. Geologic background

The Delmarva Peninsula is located within the Atlantic Margin tectonic downwarp known as the Salisbury Embayment (Klitgord et al., 1988). Coastal Plain beds of Mesozoic and Cenozoic age characterize the regional stratigraphy with the Cretaceous beds occurring ~400–750 m below sea level (Olsson et al., 1988; Miller et al., 2017) while the Bethany Beach, Delaware core shows that Miocene strata occur at 35.8 m below sea level (Miller et al., 2002; Browning et al., 2006). Within Chesapeake Bay near the southern tip of the Delmarva Peninsula, an impact crater occurs through upper Eocene to Lower Cretaceous sediments 1.5–2.0 km below sea level (Poag et al., 1994). Several studies indicate that accommodation space and ground water salinity trends resulting from the impact crater have influenced regional Quaternary deposition and hydrology (e.g., Powars and Bruce, 1999; Gohn et al., 2008; Krantz et al., 2015). These structural underpinnings have resulted in a thick and well-preserved sedimentary record (Miller et al., 2017).

During the Quaternary and, at least part of the Neogene, present-day Chesapeake Bay and the Delmarva Peninsula were the drainage ways for several of the larger, east-flowing rivers of the central Appalachian region including the Delaware, Susquehanna, Potomac, Rappahannock, York and the James (Mixon, 1985) (Fig. 1). Throughout the Quaternary a coastline similar to the present existed in the region with modifications mainly associated with the prograding spit of the southern Delmarva peninsula which occurred during major interglacial sea-level high stands (Colman and Mixon, 1988; Mixon, 1985; Ramsey, 1992) (Fig. 3). The southern megaspit is a 2–60 m thick mantle of unconsolidated sand, gravel, silt, clay and peat of Quaternary age that unconformably overlies consolidated Neogene sand and clay-silt

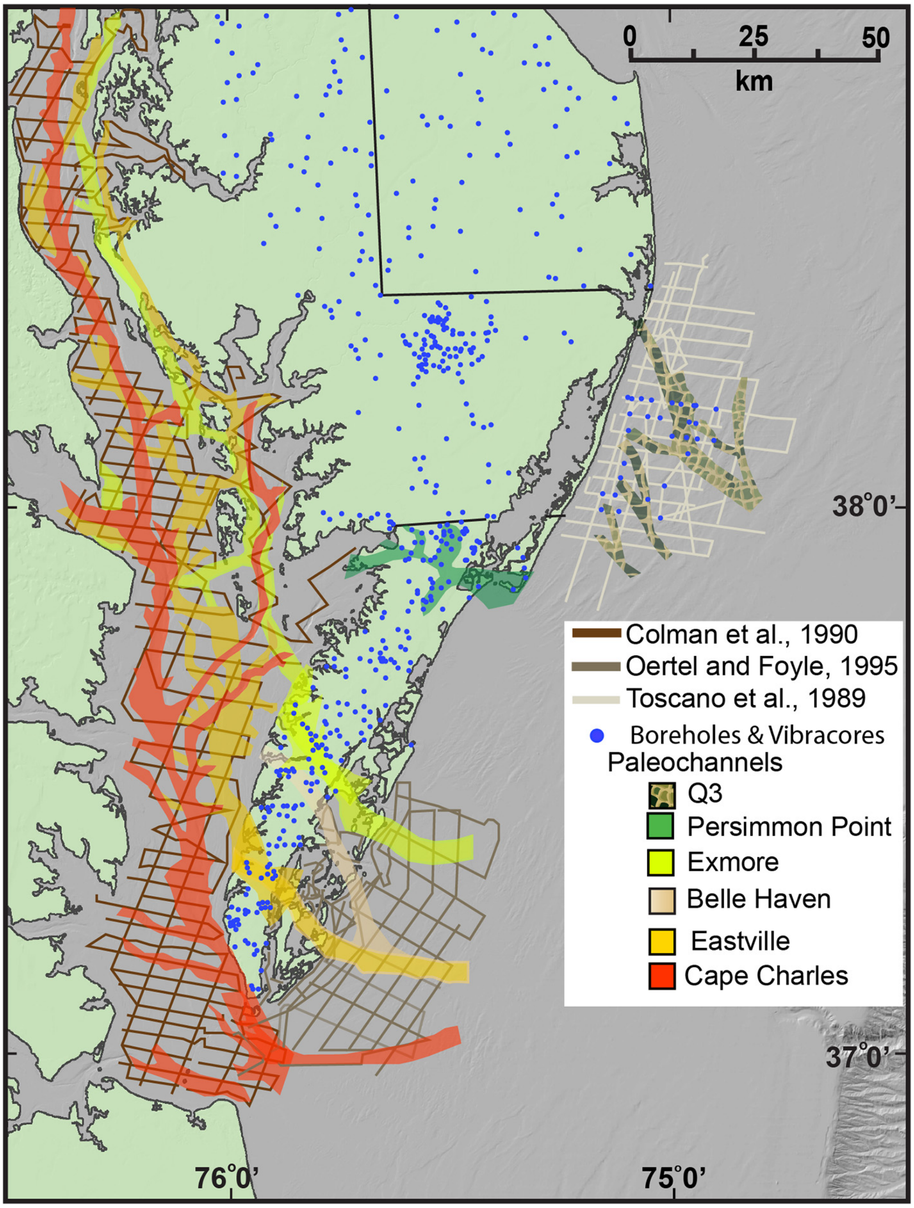

Fig. 2. Map of the study area showing the tracklines, borehole and vibracore locations as well as the interpreted paleochannels of previous regional studies. Geophysical surveys reported in Toscano et al. (1989), Colman et al. (1990), and Oertel and Foyle (1995) primarily collected single-channel, boomer source seismic reflection profile data. Terrestrial boreholes are from Hansen (1966), Owens and Denny (1979), Mixon (1985) and McFarland and Beach (2019). Offshore vibracores are from Toscano et al. (1989). Tracklines and Interpreted paleochannels are from Colman et al. (1990), Toscano et al.'s (1989) figure 26, Oertel and Foyle's (1995) Figs. 4 and 5. Seismic data used in Colman et al. (1990) are available in Colman (1987) and Colman (1986).

(Mixon, 1985). The progradation of the southern Delmarva Peninsula during the Quaternary pushed the Susquehanna and smaller river systems south to the present-day configuration (Colman et al., 1990; Foyle and Oertel, 1997).

2.2. Previous works

Hobbs III (2004) provides a thorough overview of the geologic history of Chesapeake Bay based on numerous Coastal Plain (e.g., Klitgord et al., 1988; Groot, 1991; Groot and Jordan, 1999), Delmarva Peninsula (e.g., Mixon, 1985; Ramsey, 1992), Chesapeake Bay (Colman and Hobbs III, 1988; Colman and Mixon, 1988; Colman et al., 1990) and continental shelf studies (Oertel and Foyle, 1995). Much of the insight into the region's Quaternary seismic stratigraphy came from an effort in the late 1980's. The U.S. Geological Survey (USGS) working with state geologists from Virginia and Maryland collected ∼2600 km of boomer and 3.5 kHz seismic data in Chesapeake Bay (Fig. 2) (Colman and Hobbs, 1987). They identified Holocene and Pleistocene deposits using those seismic data as well as boreholes collected as part of the Chesapeake Bay Tunnel project (Table 1) (Colman and Mixon, 1988; Colman and Mixon, 1988; Mixon et al., 1989). Later, Colman et al. (1990) mapped three paleochannels within Chesapeake Bay and across the southern Delmarva Peninsula using the geophysical data and borehole data (Mixon, 1985; Colman and Mixon, 1988). Following the conventions of the borehole studies in the area (Mixon, 1985; Colman and Mixon, 1988) that used town names, Colman et al. (1990) referred to the distinct paleochannels as the 'Exmore', 'Eastville' and 'Cape Charles.' They interpreted the paleochannels to be remnants of the ancient Susquehanna River. Stratigraphic relationships, Carbon 14, Uranium-series and amino acid racemization (AAR) dating estimations suggest that these paleochannels were formed during significant sea-level lowstands that occurred around 400 or 200 ka (Marine Isotope Stage -MIS 12 or 8, Exmore paleochannel), 150 ka (MIS 6, Eastville paleochannel) and 18 ka (MIS 2, Cape Charles paleochannel) when the ancient river likely continued to the shelf edge (Colman and Hobbs III, 1988). Following those and other efforts (e.g., Shideler et al., 1984), Oertel and Foyle (1995) used boomer seismic reflection profile data to map seismic sequences on the inner continental shelf offshore of the southern Delmarva Peninsula. They identified paleochannels as a major component of the Quaternary stratigraphy and interpreted them to be correlative to those identified by Colman et al. (1990) (Table 1). However, Oertel and Foyle (1995) hypothesized that smaller river

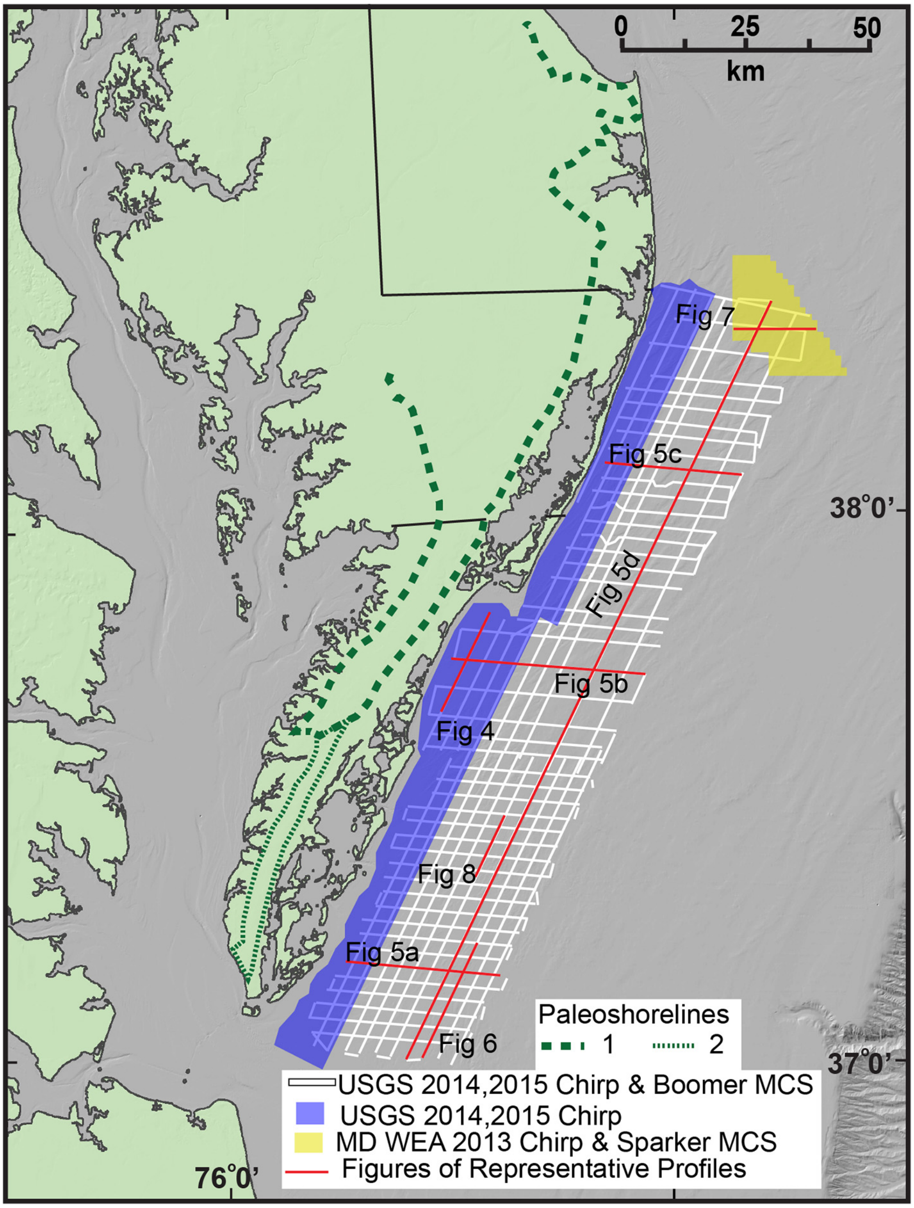

Fig. 3. Map of the study area showing locations and types of seismic reflection profile data interpreted in this study. Locations of seismic profile data tracklines are plotted as lines while areas of dense (200 m or less apart) trackline spacing are designated as polygons. Onshore green lines represent paleoshorelines: Dashed (1) line represents the Quaternary shoreline at either ~200 ka (Marine Isotope State (MIS) 7) or ~ 400 ka (MIS11) (Colman and Mixon, 1988; Ramsey, 2010). Stipled (2) line represents the Quaternary shoreline at ~100 ka (MIS 5) (Colman and Mixon, 1988; Mixon, 1985). Red lines denote other figure locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

systems as well as the Susquehanna River played a role in forming the paleochannels (Oertel and Foyle, 1995; Foyle and Oertel, 1997). Upon further analysis of the seismic data Foyle and Oertel (1997) reported that transgressive deposits largely filled the paleochannels and characterized the stratigraphy of the southern Delmarva shelf. Recently, McFarland and Beach (2019) analyzed the geophysical logs, geologists' logs of sediment core and drill-cutting lithologies, and other ancillary data from 205 boreholes to construct the hydrogeologic framework of the southern Delmarva peninsula. Using published maps of the top Tertiary beds (Mixon, 1985; Powars, 2011) and analysis of new borehole data, McFarland and Beach (2019) mapped the Eastville, Exmore Paleochannels as well as an additional paleochannel, Persimmon Point paleochannel near Wallops Island, Virginia (Fig. 2).

In addition to the work off of the southern Delmarva Peninsula, Shideler et al. (1972) and Toscano et al. (1989) collected 268 and 580 km of geophysical data on the inner continental shelves of southern Virginia and Maryland to define the Quaternary geologic framework. Both studies used boomer (400–200 joule) seismic reflection profiles, vibracore data (Fig. 2), faunal analysis and Carbon 14 dating, while the Maryland study also incorporated AAR age estimation (Toscano et al., 1989). Those studies identified stratigraphic units ranging from the late Neogene to the modern day, with some units containing evidence of paleochannels. The work of Toscano et al., (1989) largely corroborate the onshore borehole studies conducted by Hansen (1966) and Owens and Denny (1979). In the northern portion of the Delmarva Peninsula numerous vibracore and borehole samples have been collected on the inner continental shelf and onshore (Owens and Denny, 1979; Owens and Minard, 1979; McKenna and Ramsey, 2002; Ramsey and McKenna, 2009; Mattheus et al., 2020a, 2020b) and Quaternary/Late Neogene geologic units are well-constrained onshore (Ramsey, 1999, 2010).

3. Methods

3.1. Data types and acquisition

In 2014 and 2015 the USGS conducted geophysical surveys offshore the Delmarva Peninsula aboard the 132′ M/V *Scarlett Isabella* (Pendleton et al., 2015a; Sweeney et al., 2015). Seismic reflection profile data were collected using two systems during the surveys. Multichannel seismic (MCS) data were collected using an Applied Acoustics S-Boom ‘boomer’ source operated between 200 and 400 joules and a 100-m long Geometrics GeoEel 16-channel streamer (50-m active

Table 1
Seismic stratigraphic units and major unconformities identified in this study compared to those of other seismic studies.

This study	Shideler et al., 1972	Colman and Mixon, 1988; Colman et al., 1990	Toscano et al., 1989	Oertel and Foyle, 1995	Foyle and Oertel, 1997	Mattheus et al., 2020b
Qmn	D	Qhe	Q5		Sequence I	Qns, Qfs, Qsl, Qss, Qls, Qets
U11	R3		A1	Hr	R-2	
Qcch		Qc	Q3		Sequence I	
U10			M3	Hb	SR-3	
Q2	C		Q2		Sequences II and III	Qsi
U9	R2		M2	Ptr	R-6	
Qe		Qe			Sequence IV	
U8				Pel	SR-9	
Q1			Q1			
U7			M1			
Qx		Qx			Sequences V and VI	
U6				Pxl	SR-10 and SR-11	
Qbd			T1			Tbd
U5						
Qpp						
U4						
T2	B					
U3	R1		B1			
Tchy						
U2						
Tchb						
U1						
T1	A	TM				

section with 3.125-m channel spacing). Geometrics CNT-1 software was used for MCS data acquisition. We collected chirp seismic data using an EdgeTech Geo-Star FSSB sub-bottom profiling system and a catamaran-mounted SB-0512i towfish (0.5–12 kHz). Chesapeake Technologies' SonarWiz software versions 5.00.015 and 5.06.0058 were used for chirp data acquisition. We collected MCS data at 3-or 6-km line spacing concurrently with chirp data. In addition, in the nearshore, chirp data were collected in shore-parallel lines every 200 m (Fig. 3). We processed all seismic reflection profile data using scripts within SIOSEIS and Seismic Unix (Pendleton et al., 2015a; Sweeney et al., 2015).

We also examined other seismic reflection profile data recently collected in the region. In 2013 to characterize the Maryland Wind Energy Area (Fig. 3), Coastal Planning & Engineering, Inc., a CB&I Company, collected chirp subbottom data using an Edgetech SB-0512i towfish, and MCS data using a Geometrics GeoEel 24-channel streamer with a sparker source. These data were collected in north-south lines every 150 m with crossing lines every 900 m (Coastal Planning and Engineering, 2014). We interpreted all seismic reflection profile data in Kingdom Suite software version 2015 and projected and integrated with other geospatial data in ArcGIS 10.3.1 and Global Mapper 19. A comprehensive description of acquisition parameters, processing steps and, in the case of USGS's efforts, the seismic reflection data themselves, are included in Pendleton et al. (2015a), Sweeney et al. (2015) and Coastal Planning and Engineering (2014).

3.2. Seismic stratigraphic mapping

We digitized seismic stratigraphic horizons in Kingdom Suite (KS) 2D/3DPAK version 2015 software in the two-way travel time domain. We converted horizons from two-way travel time to depth by building stratigraphic models with KS Dynamic Depth Conversion (DDC). We corrected stratigraphic horizons to mean lower low water (MLLW) tide datum with DDC by calculating the difference between the uncorrected sea floor horizon that we digitized in KS and a composite MLLW bathymetric grid created from data collected by the USGS (Pendleton et al., 2015a; Sweeney et al., 2015), National Oceanic Atmospheric Administration (NOAA) (Pendleton et al., 2015b) and Coastal Planning and Engineering, 2014. We used constant interval velocities of 1500 m/s for the water column, 1650 m/s for Quaternary seismic stratigraphic units, and 1750 m/s for Neogene units. We derived these velocities from semblance analysis of selected USGS 2014 and 2015 MCS data.

4. Results

4.1. Delmarva continental shelf stratigraphy

We identify 11 regionally continuous acoustic reflections that define boundaries between 12 distinct seismic stratigraphic units in the upper ~100 m of the seafloor (Tables 1, 2; Figs. 4-8). Our identification of units and unconformities align with the observations made by Shideler et al. (1972), Colman and Mixon (1988), Toscano et al. (1989) Colman et al. (1990), Oertel and Foyle (1995), Foyle and Oertel (1997) and Mattheus et al. (2020b) (Tables 1, 2).

Unit T1- The basal unit in this study, T1 generally consists of planar seaward dipping beds and occurs over the entire study area (Figs. 4–8). The unit can contain concave reflections suggesting paleochannels, however these reflections are often discontinuous and difficult to map across survey lines. Unit T1 typically underlies a high-amplitude, low-relief, seaward-dipping, regionally-extensive reflection (U3), though the unit may also underlie concave, high-relief unconformities associated with fluvial incision (U1, U2). At its most shallow expression the unit occurs within 30 m of the seafloor.

Unconformity 1 (U1)- Occurring from 38 to 112-m below MLLW in the present-day Chincoteague Bight, are broad laterally extensive (15–50 km width) high-amplitude concave reflections (Figs. 4, 5) that can be mapped across survey lines and deepen in the seaward portion of the survey area. In shore-parallel profiles, the concave reflections exhibit maximum 7-m relief. These deep concave reflections vary in amplitude and can be discontinuous. U1 is the base of Unit Tchb.

Unit Tchb- The unit overlying U1 contains discontinuous concave reflections of variable amplitude that are conformable in places (Fig. 4). Horizontal bedding is also present within the unit.

Unconformity 2 (U2)-Unconformity 2 is characterized by a series of high-amplitude, concave reflections that deepen seaward. U2 occurs in the northern, middle and southern portions of the study area and is truncated broadly by Unconformity 3 and shoreward by younger fluvial unconformities (Figs. 4, 5, 6).

Unit Tchy- Overlying the U-shaped reflections of U2, Unit Tchy's

Table 2
Interpretations of seismic stratigraphic units and major unconformities.

Unit	Interpretation
Qmn	The highstand systems tract (HST) that includes sand bodies, ridges and the modern sandy shoreface
U11	The most recent transgressive ravinement surface (TRS) of the MIS2-MIS1 sea-level rise. U11 is the seafloor in many places
Qcch	The transgressive systems tract (TST) since the Last Glacial Maximum (LGM). It fills the Cape Charles paleochannel and other channels eroded during and since the LGM. A tidal ravinement surface is within, or at the base of Qcch. Tidal or back-barrier deposits exist above the tidal ravinement surface.
U10	Subaerial unconformity (SU) formed during the last sea-level lowstand at the LGM during MIS 2 (~18 ka). U10 in the southern portion of the study area is the base of the Cape Charles paleochannel, ancestral bed of the Susquehanna River. Along Assateague Island and underneath present-day Chincoteague Bight U10 was formed by what were likely tributaries that flowed into the Cape Charles paleochannel. In the northern-most portion of the study area U10 was formed by small higher-order streams that drained south-eastward. Shoreward and along the flanks of paleochannels, U10 merges with, or is modified by a tidal ravinement surface. This composite unconformity forms the base of Qcch.
Q2	Quaternary age HST characterized by estuarine and marine sediments that are not channel fill. They overlie U9 and underlie U10 or genetically related tidal ravinement surface, U11, or the seafloor.
U9	Pleistocene-age TRS, merges with other unconformities in some locations, including U7.
Qe	The TST filling the Eastville paleochannel, tributaries and drainage networks following the MIS 6 (~150 ka) lowstand. Genetically related with Q2.
U8	U8 is the SU formed during the Pleistocene MIS 6 (~150 ka) sea-level lowstand. U8 in the southern portion of the study area is the base of the Eastville paleochannel, ancestral bed of the Susquehanna River, and a tributary to that major river, likely the ancestral York and/or James rivers. In the northern portion of the study area U8 forms the base of likely tributaries that flow into the Eastville paleochannel. In the northernmost portion of the study area, the Maryland Wind Energy Area, U8 defines a broad drainage network that flows south eastward.
Q1	Pleistocene age HST characterized by shelf and estuarine sediments that are not paleochannel fill. These appear generally massive, though at some locations conformable and laminar. Directly overlie U7. Absent in the southern portion of the study area.
U7	A Pleistocene-age TRS. Merges with U9 at certain locations
Qx	The TST filling the Exmore and Belle Haven paleochannels. Deposited during the Pleistocene following the sea-level lowstand either associated with MIS 12 (~400 ka) or MIS 8 (~200 ka). Genetically related with Q1.
U6	The SU that forms the base of the Exmore paleochannel, an ancestral bed of the Susquehanna River, and the base of the Belle Haven paleochannel, an ancestral tributary to the Susquehanna River, likely the ancestral Rappahanock River. This regressive unconformity was formed during a Pleistocene sea-level lowstand during either MIS 12 (~400 ka) or MIS 8 (~200 ka).
Qbd	A lowstand system tract (LST) that is broadly distributed and relatively unconfined by organized fluvial channels across the inner shelf of Maryland and extending into northern Virginia. Internal hummocky seismic facies suggest Qbd consists of amalgamated channel fill. Qbd is interpreted to be a braided fluvial and deltaic plain. The upper boundary of Qbd is a TRS (U7) associated with a younger TST (Qx).
U5	A broadly-distributed SU formed during a period of lower sea level in the Pleistocene by a relatively unconfined braided drainage network. Underlies Qbd.
Qpp	The TST filling the Persimmon Point and Ocean City paleochannels. Deposited during the Pleistocene.
U4	A SU is the base of the Persimmons Point and Ocean City paleochannels, formed by the Susquehanna, Potomac and possibly other, rivers. This subaerial unconformity was formed during a sea-level lowstand during the Pleistocene.
T2	HST Coastal Plain marine sediments deposited during the Pliocene. The base (subaerial unconformities) of many Quaternary paleochannels and transgressive ravinement surfaces (U7 and U9) form the upper boundary of this unit.
U3	TRS within the Pliocene.
Tchy	TST deposited in paleochannels during the Pliocene. U3 forms the upper boundary offshore. Tchy can be truncated by Quaternary unconformities shoreward.
U2	A SU formed during a lower sea level during the Pliocene.
Tchb	TST fill deposited above Pliocene paleochannels.
U1	SU formed during a period of lower sea level during the Pliocene, or a high-amplitude reflection indicative of a broader lowland.
T1	HST deposited during the later Neogene

seismic character consists of conformable, draped reflections, reflections indicative of large (2-km wide) parallel and tangential clinoforms and chaotic, discontinuous reflections (Figs. 4, 5, 6). Unconformity 3 truncates Tchy as do younger fluvial unconformities shoreward.

Unconformity 3 (U3)–U3 is a high-amplitude, low-angle, seaward dipping reflection. The reflection occurs at 24–95 m below MLLW throughout the entire study area (Figs. 4–8). The surface is locally incised by the basal unconformities of younger paleochannels. Though regionally extensive, U3 is not always resolved due to geologic disruptions (e.g. paleochannels), noise, or multiples within the seismic reflection data. U3 is not resolved in chirp data.

Unit T2 –Above the continuous, high-amplitude, regional unconformity U3, T2 is characterized by slightly seaward-dipping planar beds (Figs. 5–8). Also present are smaller channel features generally less than 5 km in width and exhibiting less than 10 m of relief. These smaller channel complexes cannot be mapped across survey lines. Unit T2 is usually incised by the basal unconformities of large channel complexes (U4, U5, U6, U8). Unit T2 can also be upwardly bound by extensive, low-relief unconformities, U7 and U9.

Unconformity 4 (U4)- Spanning much of the area under present day Chincoteague Bight as well as discrete portion of the study area by Ocean City, MD, Unconformity 4 produces a series of high-amplitude concave reflections that deepen seaward (Figs. 4, 5, 9). U4 occurs from 18 to 76 m below MLLW with the unconformity exhibiting up to 15 m of relief in shore-parallel profiles.

Unit Qpp- Unit Qpp overlies Unconformity 4 and is characterized by sub-parallel bedding, clinoforms, chaotic and discontinuous reflections (Figs. 4, 5). Qpp can underlie Unconformities U5, U7, U8, U9, and U10.

Unconformity 5(U5)- U5 is a high-amplitude reflection that is continuous over the entire northern portion of the study area, but absent south of Chincoteague Bight (Figs. 5,6,9). Seaward dipping, U5 occurs between 25 and 80 m below MLLW and exhibits irregular undulations on the order of 5 m (Figs. 5, 7). U5 incises T2 and Qpp.

Unit Qbd—Present in the northern portion of the study area offshore of Delaware, Maryland and Chincoteague Bight VA, Unit Qbd consists of discontinuous hummocky reflections underlain by U5 (Figs. 5, 7). Many of the internal reflections are concave and channel-like, but few structures can be traced across survey lines. The unit thickens seaward to a maximum of 29 m, then is truncated by younger sequences. Qbd is upwardly bound by U6, U7, and U8.

Unconformity 6 (U6)- U6 is characterized by two series of high-amplitude, U-shape reflections that deepen seaward and are mapped from the nearshore to the seaward extent of the survey area (Figs. 5, 8, 9). Found between 28 and 74 m below MLLW, there are greater than 30-m relief across the base of the widest (~20 km) concave high-amplitude reflections observed in shore-parallel seismic reflection profiles. The southern series of U6 is smaller (4–10 km wide) and exhibits less relief (maximum 15 m).

Unit Qx- The seismic character within Unit Qx is indicative of long (2.5 km wide), parallel and tangential low-angle clinoforms, conformable fill, and chaotic and discontinuous reflections (Fig. 8). Qx underlies the unconformities U7 or U8, while U6 forms its lower boundary. Structures within Unit Qx in the smaller, southern series of concave reflections (Fig. 5) are generally characterized by horizontal, to sub-

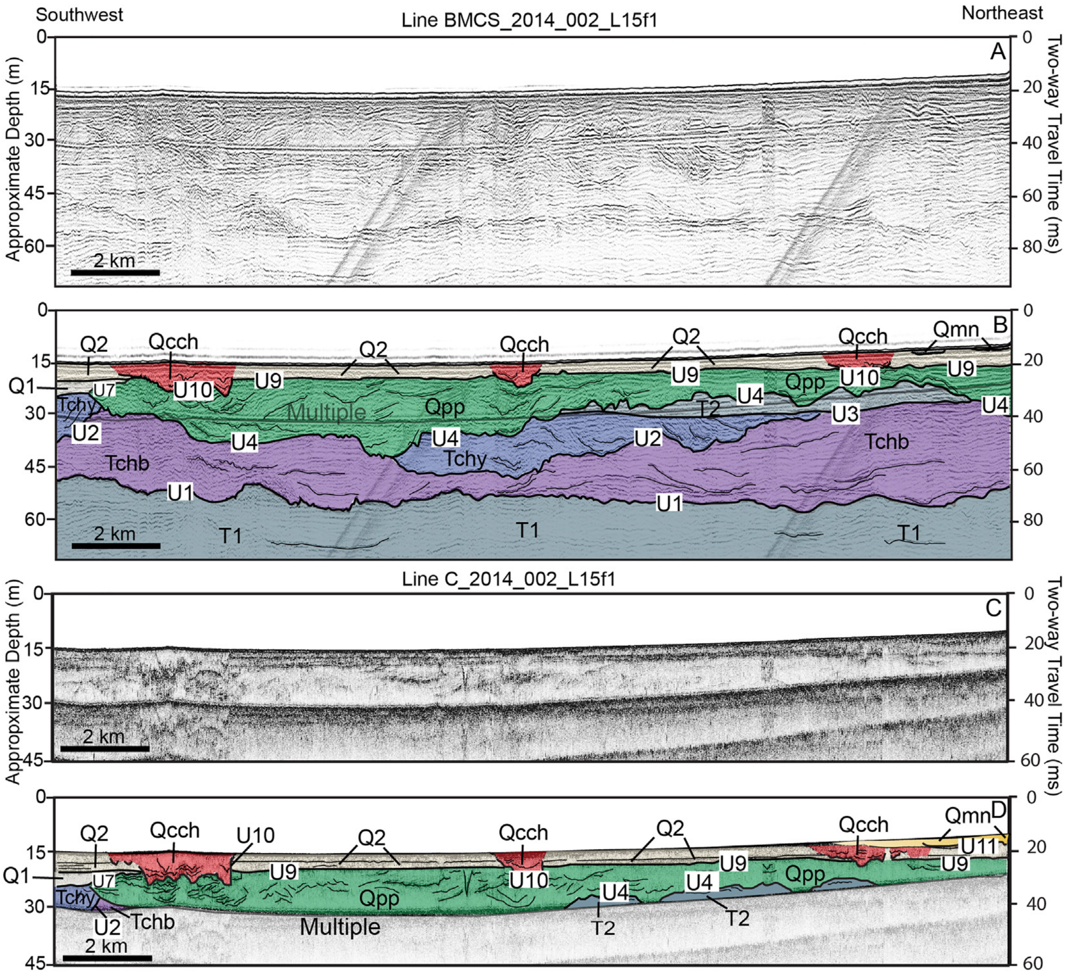

Fig. 4. Shore parallel, coincident Boomer (a) and chirp (c) seismic reflection profiles and interpretations (b, d) containing the deeper principle stratigraphic units and unconformities of Chincoteague Bight. Tertiary and Quaternary paleochannnels (U1, U2, U4, U10) and fill sequences (Tchb-purple, Tchy-blue, Qpp-dark green, Qcch-red) dominate the area's stratigraphy. Prominent in the upper ~45 m of the profile are the remnants of the Wallops paleochannel (U4, Qpp-dark green), interpreted to be the earliest Quaternary expression of the Susquehanna River and indication of a sea level lowstand. See Table 2 for descriptions of units and major unconformities. See Fig. 3 for location. Depth conversions in the figure are based on sound velocity of 1500 m/s in both water and sediment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

horizontal internal reflections.

Unconformity 7 (U7)- A regionally-continuous, low-relief, seaward-dipping, high-amplitude reflection, U7 truncates Units Qx, Qbd and Qpp (Figs. 5–7). In some locations, it merges with U9 (Figs. 5, 8). The reflection occurs 18–52 m below MLLW. U7 is absent in the southern portion of the survey area.

Unit Q1—Resolved in the chirp data, Unit Q1 directly overlies U7 and exhibits a range of seismic facies indicative of laminar bedding to massive deposition (Figs. 5, 7, 8). Unit Q1 occurs only above U7 and is absent in the southern portion of the study area. U8 or U9 form its upper boundary.

Unconformity 8 (U8)- U8 is a high-amplitude, concave reflection preserved both in the northern and southern portions of the study area (Figs. 5,6, 7, 9) between 20 and 80 m below MLLW. It is truncated by U9. In the northern portion of the study area, in the Maryland Wind Energy area (Figs. 3, 7), U8 is a continuous surface that exhibits small channel features with an east-southeast orientation. Offshore of Maryland and northern Virginia U8 occurs as several series of relatively broad (2–20 km wide), concave reflections (Fig. 5) that are mapped the full length of Assateague Island and trend south-south east (Fig. 9). The series of concave reflections appear to converge in the seaward portion of the study area.

In southern Delmarva two series of sub-parallel, large U-shaped reflections occur near the shoreline and merge ~20 km offshore. U8 in southern Delmarva exhibits greater than 20 m of relief in shore-parallel seismic profiles (Figs. 5, 6).

Unit Qe – Unit Qe directly overlies U8. In the northern portion of the study area Qe is characterized by conformable horizontal and concave reflections in places, sub-horizontal and unconformable and discontinuous reflections in others. In the southernmost portion of the study area Qe is characterized by parallel, tangential, horizontal, sub-horizontal, conformable and discontinuous reflections (Fig. 6). Over much of its extent Unit Qe is truncated by Unconformity 9. It is also locally truncated by Unconformity 10, and crops out at the seafloor, particularly in the northern most portion of the study area.

Unconformity 9 (U9)- U9 is a regionally extensive, high-amplitude, low-relief reflection that truncates the fill of many Quaternary paleochannel complexes (Figs. 4–8). Generally planar and seaward dipping, U9 occurs 14–43 m below MLLW over the entire survey area and, in certain locations, merges with U7.

Unit Q2- Unit Q2 overlies U9 and is upwardly bounded by U10, U11, or the seafloor (Figs. 4–8). Its seismic character includes planar beds, channel structures, acoustically massive units and opaque zones interpreted to reflect the presence of natural gas.

Unconformity 10 (U10)- U10 is a high-amplitude, high-relief concave reflection, locally truncated by U11 or the seafloor and occurs

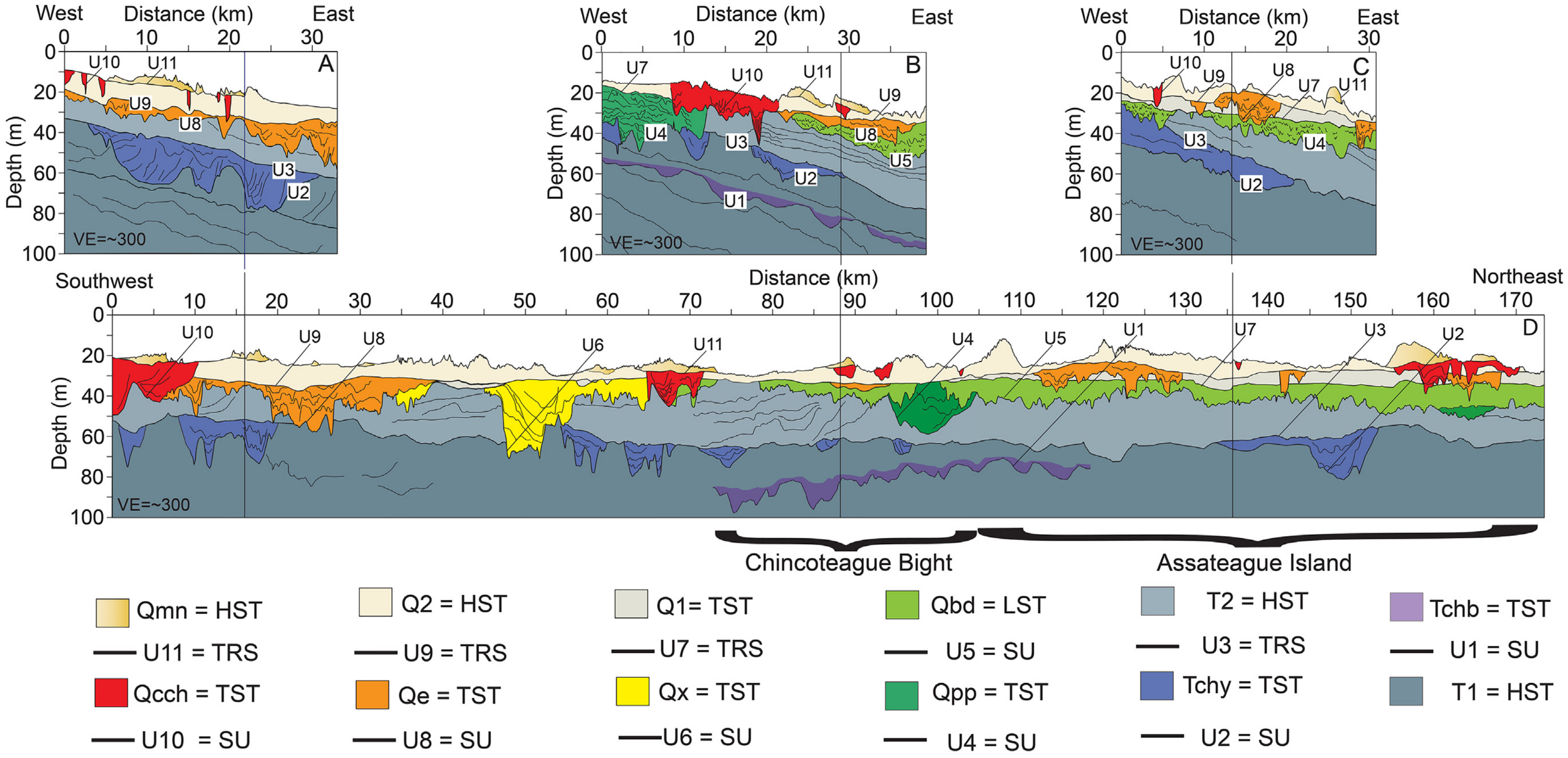

Fig. 5. Representative cross sections showing regional geologic framework of the study area. Cross Section A illustrates the framework along a shore-perpendicular W-E –trending transect in the southern most portion of the study area. Cross Section B illustrates the framework along a shore-perpendicular W-E –trending transect in the middle portion of the study area off of present day Chincoteague Bight. Cross Section C illustrates the framework along a shore-perpendicular W-E –trending transect in the northern portion of the study area offshore of Assateague Island. Cross section D illustrates the structure along a shore-parallel SSW-NNE-trending transect. Crosse section D shows Quaternary iterations of the Susquehanna River: Persimmon Point and Ocean City paleochannels (Qpp-dark green, U4 base), Exmore and Belle Haven paleochannel (Qx-yellow, U6 base), Eastville paleochannel (Qe-orange, U8 base) and Cape Charles paleochannel (Qcch-red, U10 base, southern end of profile). Unit Qbd (light green, U5 base) is widespread in the northern portion of the study area offshore of Assateague Island. SU = subaerial unconformity; TRS = transgressive ravinement surface; HST = high systems tract; LST = low systems tract; TST = transgressive systems tract. See Fig. 3 for transect locations. See Table 2 for complete unit and unconformity definitions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

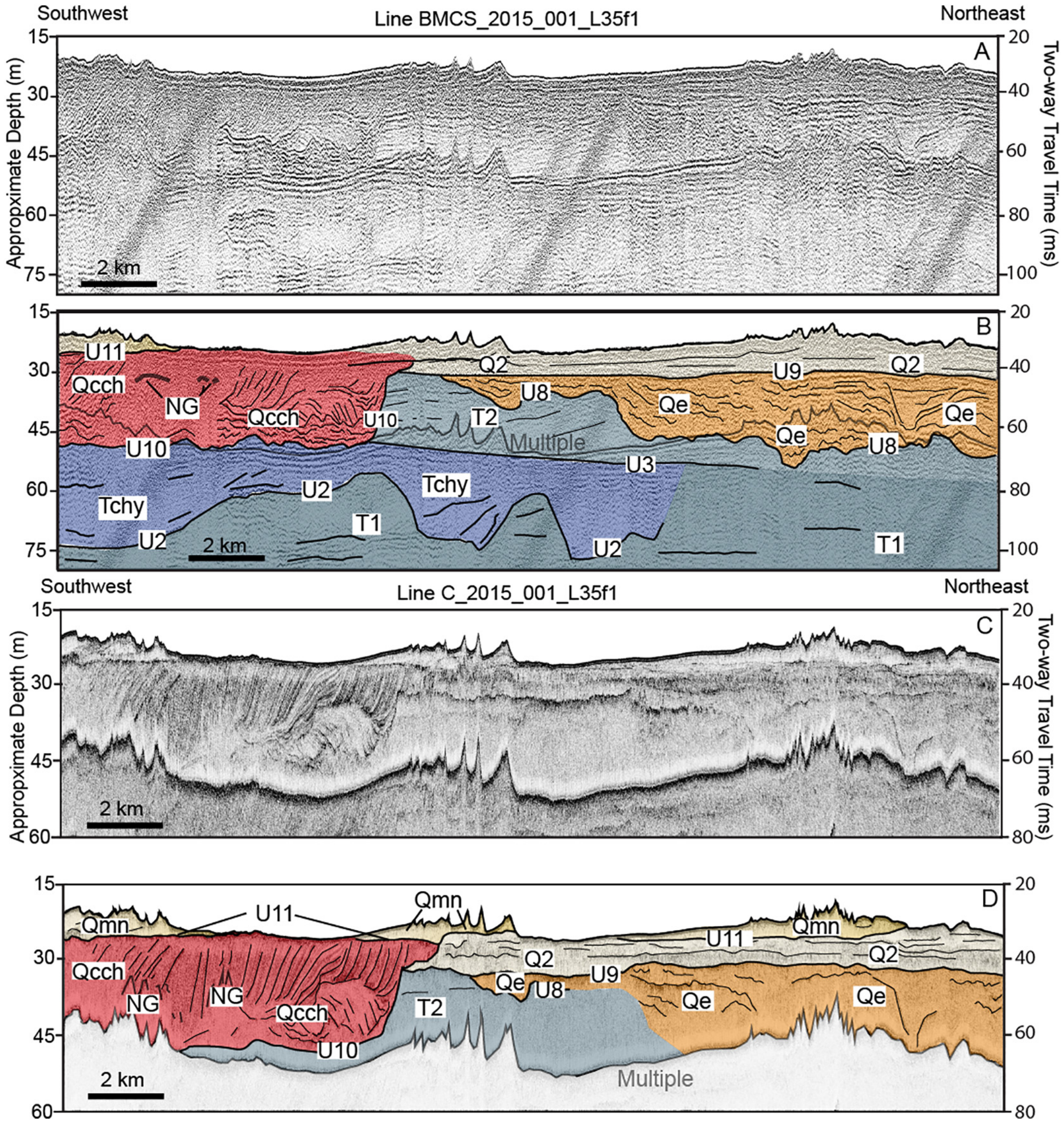

Fig. 6. Shore parallel, coincident boomer (a) and chirp (c) seismic reflection profiles and interpretations (b, d) containing the principle stratigraphic units and unconformities associated with southern Delmarva. U8 and unit Qe (orange) denote the Eastville paleochannel, the ancestral Susquehanna River, present in the northern end of the profile. U10, the base of the Cape Charles paleochannel, cuts into Coastal Plain sediments and U9, the transgressive unconformity that truncates the fill (Qe-red) of the Eastville paleochannel (U8). Boomer data resolve remnants of the ancient York River deeper in the sediment column (a, b). See Table 2 for descriptions of units and major unconformities. See Fig. 3 for location. Depth conversions in the figure are based on sound velocity of 1500 m/s in both water and sediment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

throughout the study area (Figs. 4, 5, 6, 9) 3–6 m below MLLW. U10 reflections are abundant in the nearshore and exhibit relief on the order of 3–8 m. Although some of the nearshore expressions of U10 can be mapped in a general seaward direction, in other locations the series of concave U10 reflections are mapped parallel with the shoreline.

Along Assateague Island and under Chincoteague Bight (Figs. 1, 4, 5), U10 is a mappable series of concave reflections that converge offshore and then continue south-south east. In southern Delmarva U10 is two series of large (~10 km-wide) U-shaped reflections that occur and appear to merge ~30 km offshore (Figs. 5, 6). These reflections deepen seaward and can exhibit greater than 23 m of relief in shore-parallel seismic reflection profiles.

Unit Qcch- Unit Qcch directly overlies U10 and occurs throughout the study area. It is truncated by U11 or crops out at the seafloor (Figs. 5, 6). The unit exhibits a variety of internal reflections ranging from large (~10-m long) parallel and tangential clinoforms, horizontal or u-shaped conformable beds, to discontinuous returns. The large clinoforms record spit progradation, sometimes in multiple directions (Fig. 6). Acoustic attenuation interpreted as natural gas is abundant within this unit.

Unconformity 11 (U11)- U11 is the uppermost, high-amplitude reflection clearly resolved in the chirp data and occasionally in the boomer data (Figs. 5, 6). The reflection occurs 8–35 m below MLLW, is generally planar and can appear serrated. It often intersects the modern seafloor.

Unit Qmn- Most abundant in the nearshore, Unit Qmn is the uppermost unit resolved in the chirp data, and occasionally in the boomer data. Unit Qmn overlies U11 and is upwardly bounded by the modern seafloor. This acoustically transparent unit forms most bathymetric highs, or shoals on the inner shelf (Figs. 5, 6).

5. Discussion

5.1. Seismic stratigraphy interpretations and integration with earlier studies

Corroborating earlier studies, the 12 units and 11 unconformities

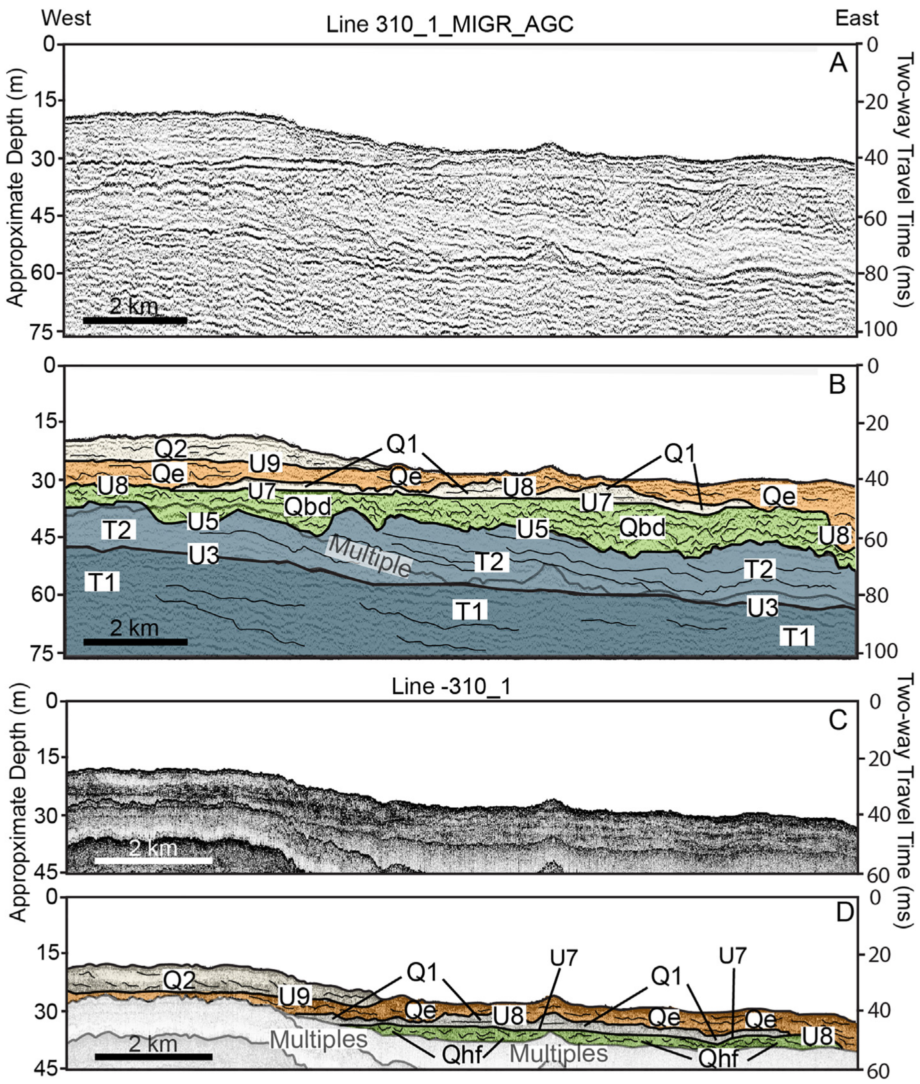

Fig. 7. Shore perpendicular, coincident sparker (a) and chirp (c) seismic reflection profiles and interpretations (b, d) containing the principle stratigraphic units and unconformities of offshore Maryland. Visible in the sparker data, the hummocky fill characteristic of Qbd (light green) overlies the high amplitude reflection indicative of U5. U5 truncates the seaward dipping Coastal Plains bed (T2-gray blue). Also visible is the broad concave reflection characteristic of U8 in the northern portion of the study area. See Table 2 for descriptions of units and major unconformities. See Fig. 3 for location. Depth conversions in the figure are based on sound velocity of 1500 m/s in both water and sediment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that make up our seismic framework indicate a series of transgressions and regressions occurring since the Pliocene (Tables 1, 2). Using reflection character, distribution, geometry and the sequence stratigraphic terminology of (Catuneanu et al., 2009; Catuneanu et al., 2011) we interpret unconformities either as transgressive ravinement surfaces or subaerial unconformities. These major unconformable surfaces bound units which correspond to distinct systems tracts (Miller et al., 2018) (Table 2, Fig. 5). Unconformities U3, U7, U9, U11 are high-amplitude, low-angle, seaward-dipping unconformities that each extend over a significant portion of the study area. Based on these characteristics we interpret those unconformities as transgressive ravinement surfaces formed by wave erosion during shoreline transgression (e.g., Swift, 1975; Zecchin et al., 2018). Because U1, U2, U4, U5, U6, U8, U10 are broad U-shaped structures that incise underlying strata we interpret these as subaerial unconformities formed from fluvial erosion as sea-level retreated during regression (Vail and Mitchum Jr., 1977; Catuneanu et al., 2009).

We estimate the age of transgressive and regressive periods based on the findings and methods of previous regional studies (Mixon, 1985; Colman and Mixon, 1988; Toscano et al., 1989; Colman et al., 1990). Colman et al. (1990) robustly constrained the fluvial signature associated with the two most recent sea-level lowstands using C14, Uranium-series, AAR estimates and stratigraphic positioning. They hypothesized that older paleochannels were incised during similar magnitude sea-level events earlier in the Quaternary. Following that example, we compare our stratigraphic framework to Quaternary and Pliocene eustatic sea-level curves (e.g., Raymo et al., 2011; Spratt and Lisiecki, 2016) to estimate the timing of the transgressive-regressive cycles evident in the stratigraphic record. Please note that our age estimates are more speculative earlier in the geologic record.

5.1.1. *Tertiary*

Based on hundreds of published onshore and estuarine borehole results (Hansen, 1966; Owens and Denny, 1979; Mixon, 1985; Colman and Mixon, 1988; Johnson and Berquist Jr., 1989; Mixon et al., 1989; McFarland and Beach, 2019; Powars, 2011) we interpret the deepest units (T1-T2) and unconformities (U1-U3) to have been deposited and formed during the Late Tertiary Period, or Neogene Period. The seaward dipping planar beds exhibited by units T1 and T2 are highly suggestive of bedding deposited during the Miocene or Pliocene Epochs in a marine shelf setting (Olsson et al., 1988). Since the Pliocene did not have significant sea-level lowstands (Raymo et al., 2011) the suggestions for channels and channel fill in the deeper units (U1, U2, Tchy, Tchb), and a transgressive ravinement surface (U3) are perplexing. There could be issues with our age inferences or discrepancy between eustatic and relative sea level in this region during that period. It is also possible that the slightly concave and undulating shape of U1 (~70–120 km along Fig. 5D) may be indicative of a broader lowland at that point in the Neogene (Olsson et al., 1988; Miller et al., 2017).

Onshore and estuarine borehole studies indicate Neogene-aged

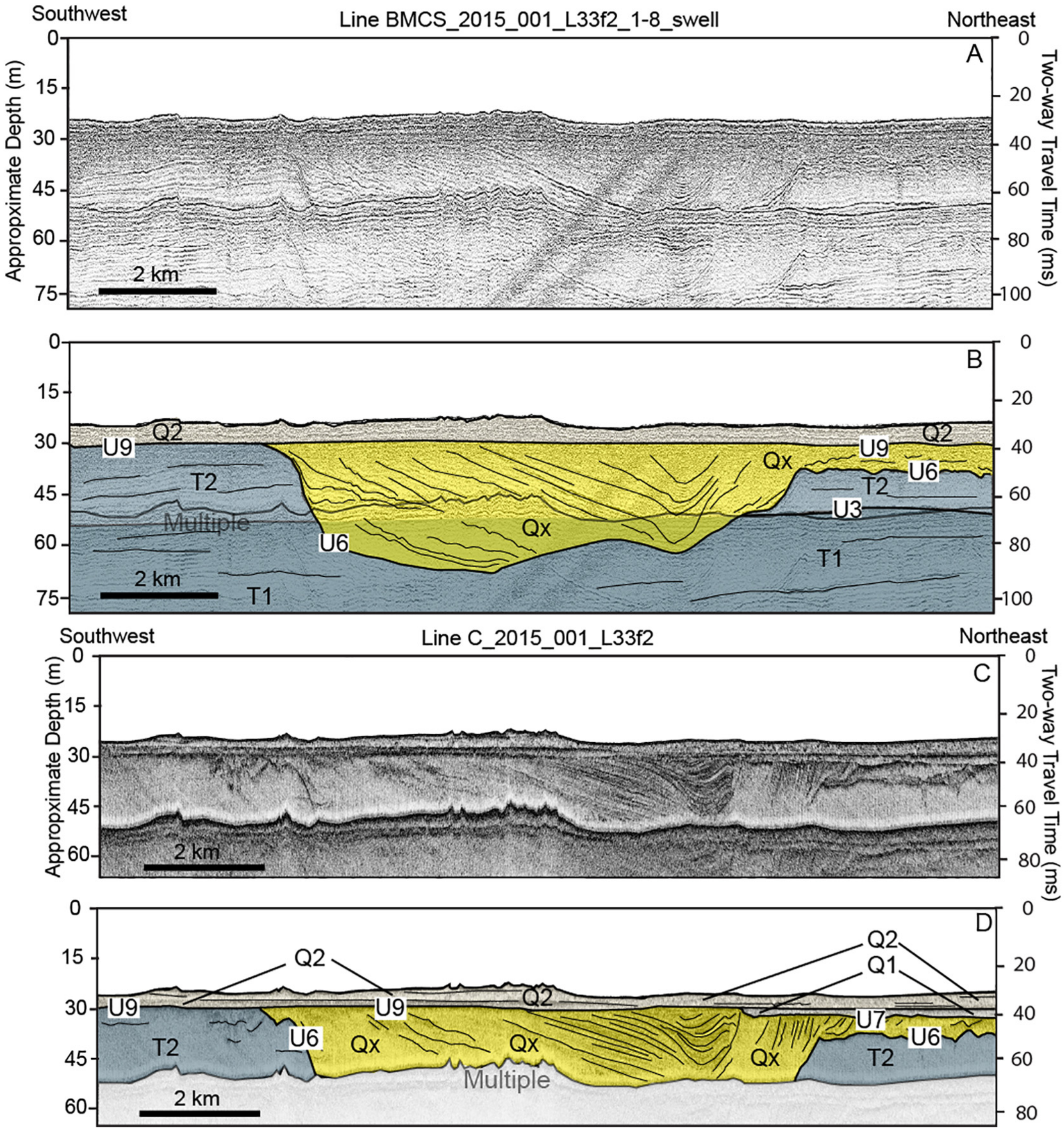

Fig. 8. Shore parallel, coincident boomer (a) and chirp (c) seismic reflection profiles and interpretations (b, d) containing the principle stratigraphic units and unconformities associated with the Exmore paleochannel. Exhibiting over 30 m of relief between its thalweg and interfluves, the Exmore paleochannel (U6) provided accommodation space for the deposition of extensive clinoforms (Qx-yellow). See Table 2 for descriptions of units and major unconformities. See Fig. 3 for location. Depth conversions in the figure are based on sound velocity of 1500 m/s in both water and sediment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sediments occur within 5–69 m of sea level and are often incised by Pleistocene-age paleochannels (Owens and Denny, 1979; Mixon, 1985; Mixon et al., 1989; McFarland and Beach, 2019). Thus, adjacent regional geological and geophysical studies have interpreted Neogene-aged sediments below large Pleistocene-aged paleochannels (Colman and Hobbs III, 1988; Colman and Mixon, 1988; Oertel and Foyle, 1995; Foyle and Oertel, 1997; Krantz et al., 2015). These observations and interpretations correspond well to the Quaternary-Tertiary boundary depths that we interpret offshore (Fig. 9B). We find the top of the Tertiary surface ranges from 14 to 80 m below MLLW, with the deepest values corresponding to the base of Quaternary paleo drainage pathways. The shallowest occurrence of the Tertiary is at the southern edge of Chincoteague Bight. That location is unique in our study area because it doesn't coincide with any major Quaternary paleochannels (Fig. 9A). Instead, the southern edge of Chincoteague Bight has persisted as an interfluve over the course of several transgressive-regressive cycles.

5.1.2. *Quaternary*

The first indication of a Quaternary sea-level lowstand is U4 (Fig. 10A). Found at Chincoteague Bight and offshore of Ocean City, U4 occurs as two discrete, deep channels (Figs. 4, 9A, 10A). Mixon (1985), McFarland and Beach (2019) and Krantz et al. (2015) each found indications of a deep paleochannel onshore and in the nearshore in the Chincoteague Bight region. Mixon's (1985) borehole distribution was sparse in that area, so he interpreted merely a depression in the Quaternary-Tertiary boundary near the Halwall borehole (his structure map Fig. 9), and not a paleochannel. Collecting additional boreholes in northern Virginia during the 2000's, Powars (2011) and McFarland and Beach (2019) fully resolved a Quaternary paleochannel onshore. Krantz et al.'s (2015) nearshore chirp survey offshore of Wallops Island clearly resolved a large paleochannel, which they interpreted to be Pleistocene in age (Wikel, 2008; Krantz et al., 2015). The size, stratigraphic positioning and location of those previous observations of a paleochannel and paleochannel fill correspond with our unconformity U4 and unit Qpp observed off of Chincoteague Bight (Figs. 4,5,9).

Hansen (1966) observed a Pleistocene paleochannel in Salisbury,

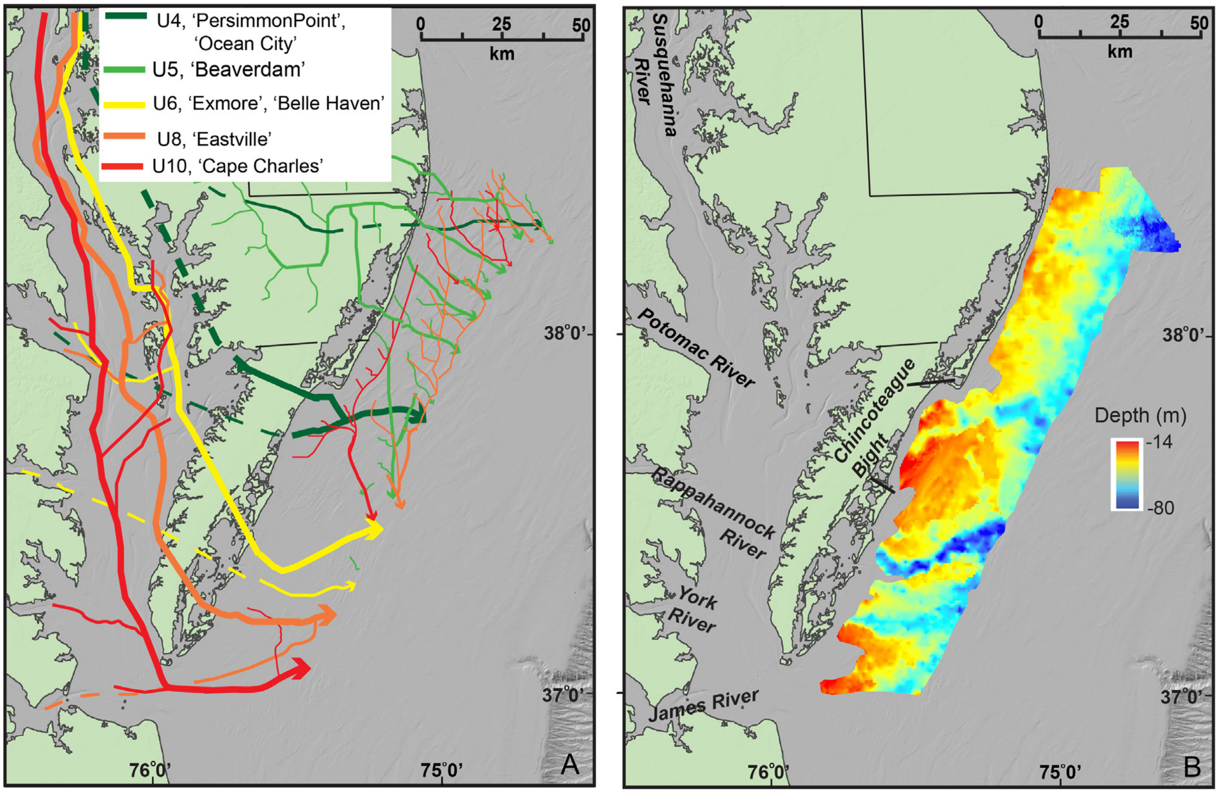

Fig. 9. A. Simplified vectors of Quaternary paleodrainage pathways are overlain on the modern shoreline. Paleochannels on land and inside Chesapeake Bay are from Owens and Denny (1979), Hansen (1966), McFarland and Beach (2019) and Colman et al. (1990). Solid lines offshore are from this study. Dashed lines indicate hypothesized pathways. B. Gridded seismic stratigraphic horizon composed of U4, U5, U6, U7, U8, U9, U10 shows the depth to the top of Tertiary-age sediments overlain on the present shoreline with modern rivers labeled. C. The Quaternary(Q)/Tertiary(T) surface reflects the courses of the Susquehanna River and tributaries beginning in Chincoteague Bight and south where the Persimmon Point, Exmore, Belle Haven, Eastville and Cape Charles paleochannels cut into Tertiary sediments. In the northern portion of the study area unconformities U4 and U5, associated with Ocean City paleochannel and Beaverdam fluvial plain, eroded the lows of the Q/T surface.

Maryland in a series of boreholes collected for hydrology. He found a "Red Gravelly" Facies of the Salisbury Formation, interpreted as Pleistocene channel fill, unconformably overlying Tertiary-aged sediments of the Yorktown Formation. Hansen (1966) reported the "Red Gravelly" Facies to be overlain by the Beaverdam Facies. The "Red Gravelly" Facies and underlying unconformity, occur at comparable depths and latitude to Qpp and U4 that we identify offshore of Ocean City, Maryland (Figs. 2, 5, 9). We interpret U4 as the base of ancestral fluvial beds of the Susquehanna, Potomac and, possibly, other rivers. Unit Qpp is the transgressive systems tract (TST) sequence deposited in the Persimmon Point and Ocean City paleochannels during the Pleistocene.

Incising and overlying unit Qpp and Tertiary Unit T2, U5 and Qbd are each the most unique unconformity and unit in this study (Figs. 5, 7). U5's undulating character and broad distribution are suggestive of erosion during a sea-level fall that did not go beyond the shelf edge (Posamentier and Allen, 1999). Therefore, we interpret U5 as a subaerial unconformity formed by a diffuse drainage network, during a period of lower sea level in the Pleistocene (Fig. 10B). Qbd fills the channel system carved by U5. A thick and widespread unit, Qbd is characterized by hummocky and channel-like internal reflections and we interpret the unit as a lowstand system tract (LST) indicative of a fluvial and deltaic plain environment.

Other studies conducted in New Jersey, Delaware and Maryland offer potential insights into U5 and Qbd. Uptegrove et al. (2012) using boomer seismic reflection data imaged a remarkably similar unconformity and unit 130 km north of our study area on the New Jersey continental shelf. However, based on limited AAR data they interpreted that unit (named MIS 5 cbms) to be significantly younger than our interpretation of Qbd. They interpreted unit MIS 5 cbms as sediments that were deposited as the shoreline advanced landward and/or bayward and coastal channels migrated during Marine Isotope Stage 5. Moving south, a comparison of our results with recent chirp and vibracore studies in Delaware by Mattheus et al. (2020a) and the Maryland borehole study of Owens and Denny (1979) suggests that Unit Qbd may be equivalent to their Beaverdam Formation. The onshore depths and spatial distribution of Owen and Denny's (1979) map of the base of the Beaverdam Formation (their Fig. 10) correspond well to our offshore mapping of U5 (Figs. 9, 10B). The Beaverdam Formation consists primarily of fine to coarse sand with interbeds of fine silty sand to sandy and clayey silt and is interpreted to have been deposited in fluvial to estuarine environments (Ramsey, 1999). Though initially interpreted to be Quaternary in age, Owens and Denny (1979) and then later Groot et al. (1990) interpreted the Beaverdam to have been deposited in the Late Tertiary based on the presence of palynomorphs in fine-grained sediments that indicated a warmer climate. We interpret Units Qbd and Qpp to be Pleistocene in age based on the underlying fluvial unconformities (U4, U5) associated with the units that incise stratified dipping beds characteristic of the Coastal Plain. The recent chirp work conducted in Delaware cannot resolve the base of the Beaverdam (Mattheus et al., 2020a, 2020b), thus making it challenging to fully integrate their stratigraphic framework with our study. The seismic facies within their unit interpreted as Beaverdam has the same hummocky internal character that we observe in the unit Qbd, however better constraining the timing and geologic significance of Unit Qbd will require additional research.

Incising Qbd is the unconformity U6. Our observations of U6 and unit Qx correlate spatially with the Exmore paleochannel and channel fill identified by Colman et al. (1990) and Oertel and Foyle (1995)

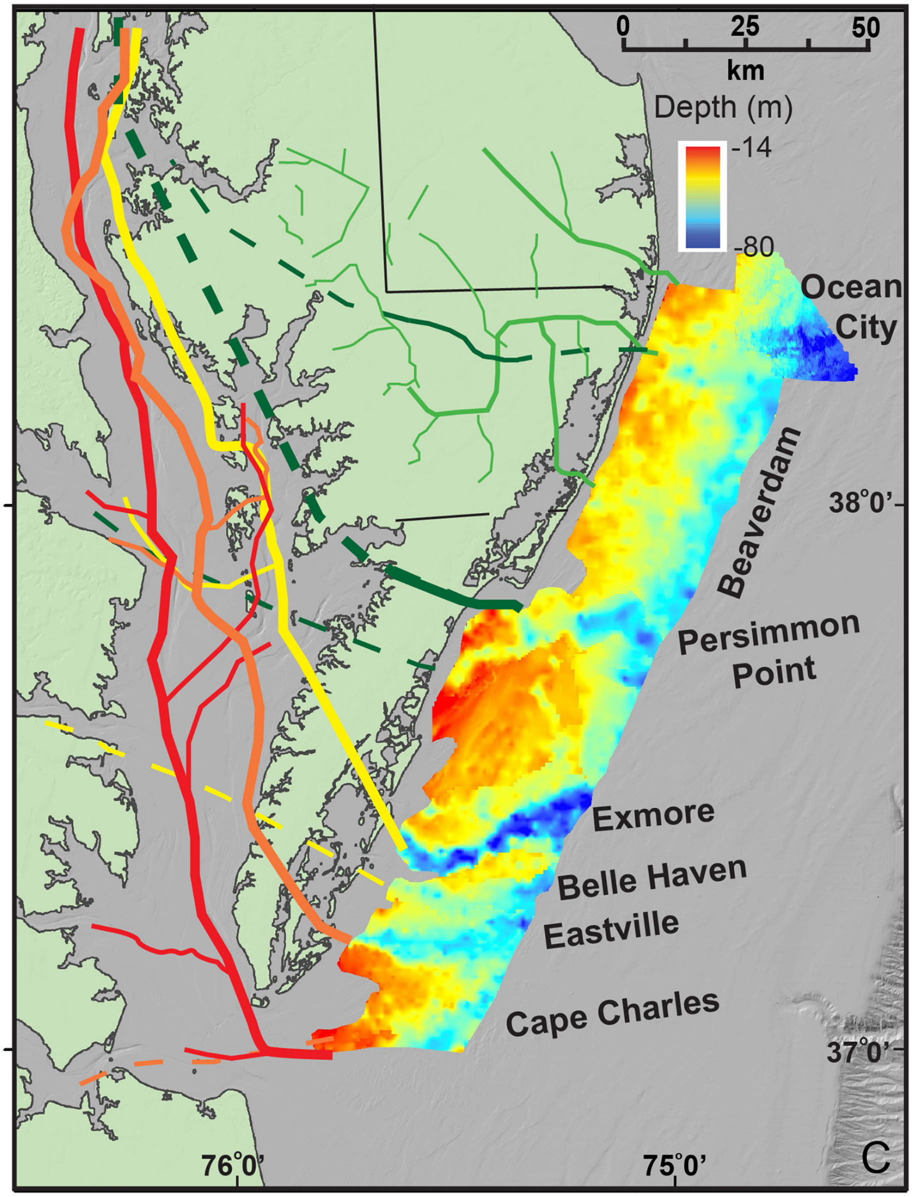

Fig. 9. (*continued*)

(Figs. 2 and 9). We agree with their interpretation that the unconformity represents an incised valley of the ancestral Susquehanna River and tributaries that developed during a lowstand either at MIS 8 or MIS 12 (Fig. 10D). Unit Qx is the TST that fills subaerial unconformity U6.

We also find evidence for another paleochannel that appears to be coeval with the Exmore paleochannel, which we interpret as the incised valley of the ancestral Rappahannock River (Figs. 5 and 9). Oertel and Foyle (1995) identified a paleochannel in a similar area which they referred to as the "Belle Haven" paleochannel (Fig. 2). Although Oertel and Foyle (1995) identified the Belle Haven paleochannel, they were conflicted with its relationship to other paleochannels, writing that the Belle Haven was both a tributary to, and incised by the Eastville paleochannel. We concur that the channel fill of the Belle Haven (Unit Qx) is indeed incised by the Eastville paleochannel (U8). We observe the transgressive ravinement surface (TRS) U7 to truncate the Belle Haven, just as it does the Exmore paleochannel (Fig. 8), thus we interpret that the Belle Haven and the Exmore are coeval. Neither Colman et al. (1990), Mixon (1985) nor McFarland and Beach (2019) identified the Belle Haven in seismic profiles collected in Chesapeake Bay or in borehole data collected on the southern Delmarva Peninsula. The absence of evidence for the Belle Haven paleochannel in those two studies is likely due to erosion caused by the spatially coincident Eastville and Cape Charles paleochannels within the Chesapeake Bay, and the dearth of boreholes collected where we would expect the Belle Haven to occur on the southern Delmarva Peninsula (Mixon, 1985; Colman et al., 1990).

Following the U6 sea-level lowstand (Fig. 10D) and subsequent transgression marked by the TRS U7 and highstand systems tract (HST) Q1 (Figs. 10E, 5) the Delmarva seismic stratigraphy shows evidence for two additional sea-level lowstands (U8, Fig. 10F; U10, Fig. 10H) and highstands (U9, Fig. 10G; U11, Fig. 10I). In agreement with previous studies (Shideler et al., 1972; Toscano et al., 1989), we interpret Units Q1, Qe, Q2 and Qcch to contain estuarine and shelf sediments deposited during Pleistocene and early Holocene transgressions (Qe, Qcch) and highstands (Q1, Q2). Toscano et al. (1989) sampled unit Q2 and, based on AAR analysis, estimated the Unit's age as MIS 5.

In the southern portion of the study area, our observations of U8 spatially correspond with those made by Colman et al. (1990) in Chesapeake Bay and Oertel and Foyle (1995) on the inner shelf (Figs. 2, 9),

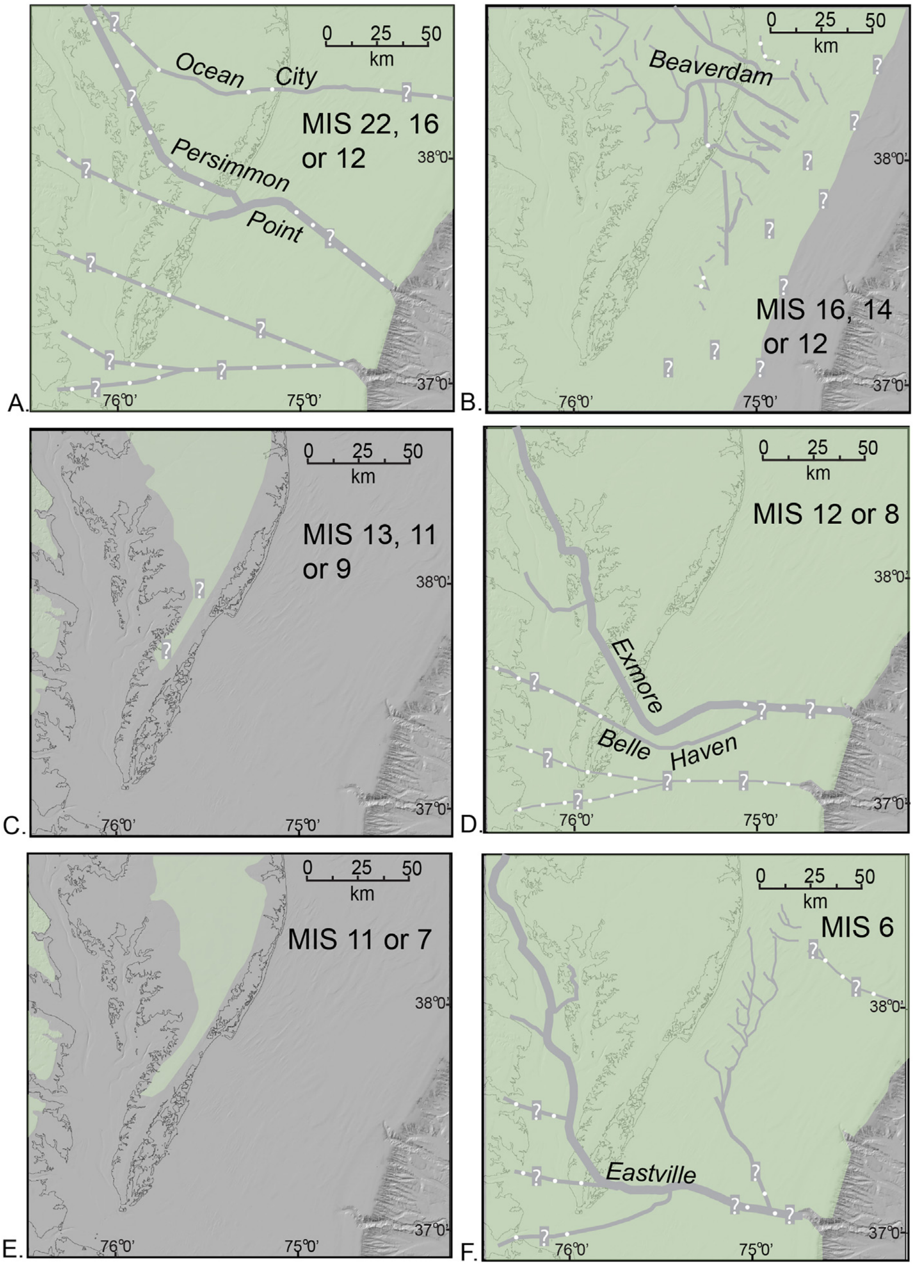

Fig. 10. Panels A-I illustrate the evolution of the Delmarva Peninsula and continental shelf since the Late Pleistocene. The outline of the present-day Delmarva Peninsula overlies a hillshaded-relief map of the Mid-Atlantic Bight region, while light green represents land and gray represents submerged areas. Offshore solid gray lines are paleodrainage pathways mapped in this study. Drainage pathways are named, and estimated MIS labeled. Question marks and white dashes denote speculated drainage pathways or highstand sea-level positions. A. Sea-level lowstand associated with U4. Onshore position of the Ocean City paleochannel comes from Hansen (1966). Onshore position of the Persimmon Point paleochannel comes from McFarland and Beach hydrogeologic borehole study (2019). B. Lower sea level associated with U5. Onshore location of the Beaverdam paleodrainage comes from Owen and Denny (1979). C. Hypothesized Middle Pleistocene sea level highstand. D. Sea-level lowstand associated with U6. Location of the Exmore paleochannel onshore and inside the Chesapeake Bay come from Mixon stratigraphic borehole study (1985) and Colman et al. (1990) respectively. E. Sea-level highstand position from Mixon (1985). F. Sea-level lowstand associated with U8. Location of the Eastville paleochannel onshore and inside the Chesapeake Bay come from Mixon (1985) and Colman et al. (1990) respectively. G. Sea-level highstand position from Mixon (1985). H. Sea-level lowstand associated with U10. Location of the Cape Charles paleochannel onshore and inside the Chesapeake Bay come from Mixon (1985) and Colman et al. (1990) respectively. I. Present-day configuration of Chesapeake Bay (CB) and the Delmarva Peninsula with modern rivers labeled. SR = Susquehanna River, PR = Potomac River, RR = Rappahannock River, YR = York River, JR = James River. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

we therefore interpret U8 as the ancestral bed of the Susquehanna River, developed at the MIS 6 lowstand (Fig. 10F). We also find evidence offshore of a tributary to the ancient Susquehanna, likely the ancient York and, or James Rivers (Figs. 9, 10F). In the northern portion of the study area where Toscano et al., (1989) reported paleochannels (Fig. 2) U8 indicates higher-order streams that had a NW-SE orientation (Fig. 9). We hypothesize that those streams fed into the Eastville paleochannel near the present-day mid-to-outer shelf (Fig. 10F). In the northern most portion of the study area in the Maryland Wind Energy Area (Fig. 3), U8 suggests a broad regional drainage network that drained southeastward (Figs. 9, 10F).

Our observations of U10, in the southern portion of the study area,

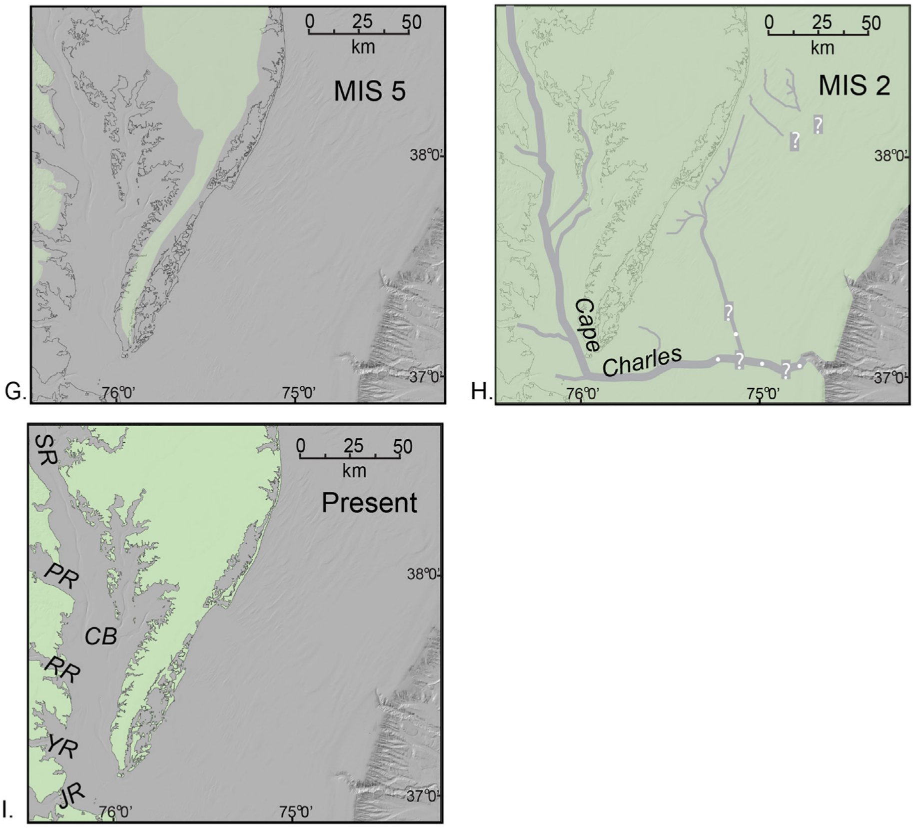

Fig. 10. (*continued*)

spatially correspond with those made by Colman et al. (1990) in Chesapeake Bay and Oertel and Foyle (1995) on the inner shelf (Figs. 2, 9). Therefore, we interpret U10 as the incised valley of the ancestral Susquehanna River in the southern portion of the study area, developed at the MIS 2 lowstand (Fig. 10H). Seaward of present-day Maryland and Chincoteague Bight, streams and rivers converged in a N-S flow direction (Fig. 9). We hypothesize that this tributary merged with the Cape Charles toward the present mid-to-outer shelf (Fig. 10H). In the most northern portion of the study area, similar to the earlier U8 drainage pattern in the Wind Energy Area, our observations of U10 suggest that the area drained southeastward. The unit that fills U10 channels is unit Qcch. Previous studies that sampled the unit or reported age estimates found it to be younger than 18 ka (Toscano et al., 1989; Colman et al., 1990). This unit represents the TST of the most recent sea-level rise.

We note that maps of U8 and U10 offshore of Maryland do not correspond precisely to the paleochannels identified by Toscano et al. (1989) (our Fig. 2, after their Figure 26). We attribute these discrepancies to relatively coarse survey line spacing, lack of high-resolution chirp data and the short sampling depth of vibracores in the earlier study. As Toscano et al. (1989) wrote, their map of paleochannels is actually an amalgamation of three unconformities (their M3, M2, M1) that they interpreted to be entirely filled with sediments deposited since the LGM (their unit Q3; our unit Qcch; Table 1). Based on cross-cutting relationships evident in our high-resolution seismic study we know that the channel systems combined in that figure were formed at different times and most have channel fills that pre-date the LGM. We think that much of what Toscano et al. (1989) mapped in that figure are paleochannels coeval with the Eastville Paleochannel, and thus filled with Qe. Recent reviews of the Toscano et al. (1989) cores suggest that they indeed penetrated the Qe unit, and analysis of shells for AAR data may make it possible to conclusively reconcile these interpretations (Wehmiller et al., 2019).

U11 is the most recent TRS in the study and is overlain by Qmn. Based on acoustic character, distribution and previous regional coring and sampling studies (Shideler et al., 1972; Field, 1980; Toscano et al., 1989; Pendleton et al., 2017a; Pendleton et al., 2017b; Pendleton et al., 2019) we interpret Unit Qmn as a HST consisting of the modern sandy shoreface and shelf, sand bodies and ridges.

5.2. Regional evolution: preservation and erosion

In general, TSTs and HSTs are well- preserved over much of the study area. This high degree of preservation may, at least in part, be the reason for the comparable depths of channel incision at progressively shallower stratigraphic positions over time that characterizes this shelf (Fig. 5D). However, preservation of HSTs is not uniform throughout the region's shallow stratigraphy. For instance, there is no evidence for TRSs and related HSTs in the stratigraphic record between the subaerial unconformities U4, U5, U6, whereas they are evident elsewhere (e.g, U3, T2, U7, Q1, U9, Q2, U11, Qmn). We presume a sea-level highstand (Fig. 10C) preceded the sea-level lowstand associated with U6 (Exmore and Belle Haven paleochannels) (Fig. 10D) and possibly the lower sea-level indicated by U5 (Fig. 10B). We interpret the lack of preserved wave-ravinement surfaces as evidence of extreme erosion on the shelf during Pleistocene glacial and interglacial cycles. Oertel and Foyle (1995)'s model of spit progradation, channel shifting and channel filling for the Chesapeake Bay entrance illustrates a mechanism for how a TRS may be eroded in the course of sea-level fluctuations by repeated channel migration and incision.

We also observe abundant evidence of younger paleochannels eroding older units. In the southern portion of the study area we see several iterations of an ancient York and, or James river in the stratigraphic record (Figs. 5, 9a). These findings corroborate Oertel and Foyle's (1995) model of channel diversion and shifting of the Susquehanna. As the southern Delmarva Peninsula prograded south (Figs. 10C, E, G), the Susquehanna River captured the Potomac (Fig. 10D), Rappahanock and the York (Fig. 10F) and finally, the James rivers (Fig. 10H). Colman et al.'s (1990) map of the successive iterations of paleochannels in the Chesapeake Bay does not resolve the Potomac, Rappahanock, York or James rivers continuing toward the shelf edge independently of the Susquehanna River (Fig. 2). This is likely a result of the younger iterations of the Susquehanna, with their successively larger drainages, eroding the underlying stratigraphic records of the regional rivers.

5.3. Broader implications

Regional Quaternary framework studies, such as this, have a host of broader implications including: linking adjacent regional frameworks (e.g., Yoo et al., 2016); where applicable, better constraining glacio isostatic adjustment in margin evolution (e.g., Barnhardt et al., 1995; Todd and Shaw, 2012); and resolving the role of antecedent geology in modern coastal processes (e.g., Schwab et al., 2017). Though each of these topics warrants its own focused and detailed analysis, our framework establishes a context in which we can examine them in brief below.

5.3.1. Regional architecture and glacial isostatic adjustment

The Delmarva continental shelf's geologic framework is analogous to those of New Jersey and North Carolina (Fig. 1). Both of those shelves host complexly cut and filled Quaternary sequences (Carey et al., 2005; Mallinson et al., 2005; Mallinson et al., 2010a; Mallinson et al., 2010b; Uptegrove et al., 2012; Miller et al., 2013; Thieler et al., 2014). Uptegrove et al. (2012) report Quaternary sequences greater ~20 m thick on the New Jersey inner shelf. Using the extensive datasets from Integrated Ocean Drilling Program (IODP) Expedition 313 (Mountain et al., 2010), Miller et al. (2013) found minimal Holocene sediments and a thinning of the Pleistocene sequences to 3–10 m thickness on the middle shelf. An exception to thin Pleistocene sequences were those sequences found within incised valleys, interpreted as the ancestral Hudson shelf valley. Thieler et al., 2014 and Mallinson et al.'s (2010a) geologic framework studies show a similar, though much thicker (> 60 m) Quaternary sediment package existing to the south in Albemarle Bay and the inner continental shelf of North Carolina. They map the depth to Tertiary to −5-95 m below present sea level (Thieler et al. (2014) their Fig. 3A), comparable to the depths that we interpret in Delmarva (Fig. 9B). Mallinson et al. (2010b) and Thieler et al. (2014) map several paleochannels, including those of the ancestral Roanoake, Nuese, Tar rivers and Pamlico Creek that were incised during the sea level lowstand associated with the Last Glacial Maximum (MIS 2).

Though Uptegrove et al. (2012) interpret MIS 3 sediment in the New Jersey inner continental shelf (their unit MIS 3 ecbr), in the mid continental shelf Miller et al. (2013) revised the interpretation of sediments previously identified as MIS 3 (Sheridan et al., 2003; Carey et al., 2005) to MIS 5 (their units Up2, Up3). In Delmarva (Toscano et al., 1989, this study) and North Carolina (Mallinson et al., 2010b; Thieler et al. (2014)) the youngest Pleistocene highstand sediments (Q2-Toscano et al., 1989; SSU V-Mallinson et al., 2010a) are also interpreted as MIS 5. Miller et al. (2013) concluded that on the mid-Atlantic continental shelf only some of the peak Pleistocene sea-level events are preserved.

Several onshore studies in Albemarle Bay North Carolina, southern Virginia and Chesapeake Bay (Parham et al., 2007; Scott et al., 2010; Parham et al., 2013; Dejong et al., 2015) have identified MIS 3 deposits using optically stimulated luminescence methods. These studies invoke glacial isostatic adjustment (GIA) in response to the Laurentide Ice sheet to explain MIS 3 deposits at elevations significantly higher than predicted by global mean sea level (Railsback et al., 2015). Using those OSL dates and others as sea-level indicators, Pico et al. (2017) modelled the rheologic and ice conditions necessary to accommodate a local sea-level highstand at MIS 3. A comprehensive review and reconciliation of Mid-Atlantic geochronology data and sea-level indicators is outside the scope of this study. However, the availability of well-mapped Quaternary frameworks across the Mid Atlantic (Mallinson et al., 2010a; Uptegrove et al., 2012; Miller et al., 2013; Thieler et al. (2014); Mattheus et al., 2020b; this study) presents an opportunity. The cited offshore geologic studies span hundreds of kilometers over 4 degrees of latitude and could be examined for stratigraphic evidence of the latitudinal variability in GIA predicted by Pico et al. (2017) during MIS-3, or GIA related to earlier glacial cycles. Such a study would test the model and provide greater understanding of ice sheet and continental shelf dynamics.

5.3.2. The role of antecedent geology

Although a thorough quantitative assessment of antecedent topographic controls is also beyond the scope of this manuscript, the Delmarva geologic framework appears to exert controls on large-scale geomorphic characteristics similar to that of North Carolina (Mallinson et al., 2010a; Thieler et al. (2014)). The modern coastline is offset at the southern end of Assateague Island with adjacent Wallops Island occurring 7-km westward of Assateague Island (Fig. 1). This offset initiates Chincoteague Bight (Fig. 1, Fig. 9) where the barrier islands in that region and to the south have high rates (> − 18 m/yr) of long-term shoreline change and exhibit patterns of widespread retreat, in contrast to the relatively stable shoreline of Assateague Island to the north (Hapke et al., 2010; Himmelstoss et al., 2010). The offset in the present-day shoreline and shoreline retreat patterns also coincides with significant changes in the Quaternary stratigraphy. Beginning in Chincoteague Bight with the Persimmon Point paleochannel (Figs. 5d, 9) and continuing south, the stratigraphy is dominated by deeply incised valleys (U4, U6, U8, U10) and valley fills (Qpp,Qx, Qe, Qcch) of the ancestral Susquehanna River (Fig. 5d). This is distinct from the shallow stratigraphy in the north which is characterized by the broad fluvial flood plain deposits of Qbd and more abundant HSTs (Q1, Qmn) (Fig. 5d). Based on the spatial correspondence of shoreline change patterns and changes in Quaternary stratigraphy, we hypothesize that the antecedent geology exerts a first order control on the modern configuration and behavior of the Delmarva Peninsula's coastline. This control may relate to the lithologic composition or consolidation properties of the valley fills, or the dearth of Qbd, Q1, Qmn in the southern portion of the study area. Several studies have outlined the role underlying topography and slope of ravinement surfaces can play in barrier island and sand ridge dynamics with steeper and rougher surfaces generally associated with slower rates of barrier island migration and more likely to host sand bodies (Belknap and Kraft, 1985; Fruegaard et al., 2015; Fruegaard et al., 2018; Durán et al., 2018; Raff et al., 2018). It is possible that the Quaternary stratigraphy of southern Delmarva sets up conditions where mobile sand is less likely to accumulate, and thus the shoreline is setback and retreats rapidly. Of course, many processes contribute to coastline dynamics and more analysis is required to resolve the role of shallow stratigraphy.

6. Conclusions

Using over 12,000 trackline kilometers of new subbottom and seismic reflection profile data we define the upper seismic stratigraphic framework offshore of the Delmarva Peninsula, USA. We identify 12 system tracts bounded by 11 regional unconformities. Our framework builds upon and reconciles many of the earlier, smaller-scale seismic and litho stratrigraphic investigations in the area. Corroborating the results of earlier studies, we find that erosion and deposition related to paleodrainage and sea-level history dominate the region's Quaternary stratigraphy. Our study shows that more paleochannels exist on the continental shelf than previously mapped and that the drainage history and related stratigraphy of the Mid-Atlantic Bight are significantly more complex than previously indicated. In addition, our geologic framework fills a spatial gap between other established Mid-Atlantic frameworks. These findings show that high-resolution, regional scale (hundreds of kilometers) mapping efforts can reconcile observations from disparate studies and are required to accurately resolve an area's Quaternary history. Further examination of the seismic stratigraphy presented here could elucidate the roles of GIA, antecedent geology and other processes that contribute to the evolution of the U.S. Atlantic margin and many other mid-latitude passive margins.

Data availability

For a comprehensive description of acquisition parameters, processing steps and, in the 2014 and 2015 USGS seismic reflection data please refer to Pendleton et al. (2015a) https://doi.org/10.5066/F7MW2F60 and Sweeney et al. (2015) https://doi.org/10.5066/F7P55KK3. Data from the Maryland Wind Energy Area are available by request from the state or the Bureau of Ocean Energy Management (BOEM). Seismic data used in Colman et al. (1990) are available in Colman (1987) https://cmgds.marine.usgs.gov/fan_info.php?fan=1987-027-FA and Colman (1986) https://cmgds.marine.usgs.gov/fan_info.php?fan=1986-022-FA.

Declaration of Competing Interest

None

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References

Coastal Planning & Engineering, Inc. a C.B. &I. Company, 2014. Maryland Energy Administration High Resolution Geophysical Resource Survey Final Report of Investigations. Maryland Energy Administration, pp. 109.

Andrews, B.D., Chaytor, J.D., ten Brink, U.S., Brothers, D.S., Gardner, J.V., Lobecker, E.A., Calder, B.R., 2016. Bathymetric terrain model of the Atlantic margin for marine geological investigations (ver. 2.0, May 2016): U.S. Geological Survey Open-File Report 2012-1266. pp. 12.

Baldwin, W.E., Morton, R.A., Putney, T.R., Katuna, M.P., Harris, M.S., Gayes, P.T., Driscoll, N.W., Denny, J.F., Schwab, W.C., 2006. Migration of the Pee Dee River system inferred from ancestral paleochannels underlying the South Carolina Grand Strand and Long Bay inner shelf. Geol. Soc. Am. Bull. 118, 533–549.

Barnhardt, W.A., Gehrels, W.R., Belknap, D.F., Kelley, J.T., 1995. Late Quaternary Relative Sea-Level Change in the Western Gulf of Maine - evidence for a Migrating Glacial Forebulge. Geology 23, 317–320.

Belknap, D.F., Kraft, J.C., 1985. Influence of antecedent geology on the stratigraphic preservation potential and evolution of Delaware's barrier systems. Mar. Geol. 63, 235–262.

Browning, J.V., Miller, K.G., McLaughlin, P.P., Kominz, M.A., Sugarman, P.J., Monteverde, D., Feigenson, M.D., Hernandez, J.C., 2006. Quantification of the effects of eustacy, subsidence, and sediment supply on Miocene sequences, mid-Atlantic margin of the United States. Geol. Soc. Am. Bull. 118, 567–588.

Carey, J.S., Sheridan, R.E., Ashley, G.M., Uptegrove, J., 2005. Glacially-influenced late Pleistocene stratigraphy of a passive margin: New Jersey's record of the North American ice sheet. Mar. Geol. 218, 155–173.

Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.S.C., Macurda, B., Martinson, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., Winker, C., 2009. Towards the standardization of sequence stratigraphy. Earth Sci. Rev. 92, 1–33.

Catuneanu, O., Galloway, W.E., Kendall, C.G.S.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence Stratigraphy: Methodology and Nomenclature. Newsl. Stratigr. 44 (3), 173–245.

Chen, Z., Hobbs III, C.H., Wehmiller, J.F., Kimbell, S.M., 1995. Late Quaternary paleochannel systems on the continental shelf, south of the Chesapeake Bay Entrance. J. Coast. Res. 11, 605–614.

Colman, S.M., 1986. Field Activity Details for Field Activity 1986-022-FA. https://cmgds.marine.usgs.gov/fan_info.php?fan=1986-022-FA.

Colman, S.M., 1987. Field Activity Details for Field Activity 1987-027-FA. https://cmgds.marine.usgs.gov/fan_info.php?fan=1987-027-FA.

Colman, S.M., Hobbs, C.H., 1987. Quaternary Geology of the Southern Virginia Part of the Chesapeake Bay. U.S. Geological Survey Miscelaneous Field Investigastions. (Map MF-1948-A).

Colman, S.M., Berquist Jr., C.R. and Hobbs III, C.H. (1988) Structure, age and origin of the bay-mouth shoal deposits, Chesapeake Bay, Virginia. Mar. Geol. 83, 95–113.

Colman, S.M., Mixon, R.B., 1988. The record of major Quaternary sea-level changes in a large coastal plain estuary, Chesapeake Bay, eastern United States. Palaeogeogr. Palaeoclimatol. Palaeecol. 68, 99–116.

Colman, S.M., Halka, J.P., Hobbs III, C.H., Mixon, R.B., Foster, D.S., 1990. Ancient channels of the Susquehanna River beneath Chesapeake Bay and the Delmarva Peninsula. Geol. Soc. Am. Bull. 102, 1268–1279.

Dejong, B.D., Bierman, P.R., Newell, W.L., Rittenour, T.M., Mahan, S.A., Balco, G., Rood, D.H., 2015. Pleistocene relative sea levels in the Chesapeake Bay region and their implications for the next century. GSA Today 25, 4–10.

Durán, R., Guillén, J., Rivera, J., Lobo, F.J., Muñoz, A., Fernández-Salas, L.M., Acosta, J., 2018. Formation, evolution and present-day activity of offshore sand ridges on a narrow, tideless continental shelf with limited sediment supply. Mar. Geol. 397, 93–107.

Field, M.E., 1980. Sand bodies on coastal plain shelves: Holocene record of the U.S. Atlantic inner shelf off Maryland. J. Sediment. Petrol. 50, 505–528.

Foyle, A.M., Oertel, G.F., 1997. Transgressive systems tract developement and incised-valley fills within a Quaternary estuary-shelf system: Virginia inner shelf, USA. Mar. Geol. 137, 227–249.

Fruegaard, M., Møller, I., Johannessen, P.N., Nielsen, L.H., Andersen, T.J., Nielsen, L., Sander, L., Pejrup, M., 2015. Stratigraphy, evolution, and controls of a Holocene transgressive – regressive barrier island under changing sea level: Danish North Sea coast. J. Sediment. Res. 85, 820–844.

Fruegaard, M., Johannessen, P.N., Nielsen, L.H., Nielsen, L., Møller, I., Andersen, T.J., Piasecki, S., Pejrup, M., 2018. Sedimentary architecture and depositional controls of a Holocene wave-dominated barrier-island system. Sedimentology 65, 1170–1212.

Gohn, G.S., Koeberl, C., Miller, K.G., Reimold, W.U., Browning, J.V., Cockell, C.S., Horton, J.W.J., Kenkmann, T., Kulpecz, A.A., Powars, D.S., Sandford, W.E., Voytek, M.A., 2008. Deep drilling into the Chesapeake Bay Impact Structure. Science 320, 1740–1745.

Green, A.N., 2009. Palaeo-drainage, incised valley fills and transgressive systems tract sedimentation of the northern KwaZulu-Natal continental shelf, South Africa, SW Indian Ocean. Mar. Geol. 263, 46–63.

Groot, J.J., 1991. Palynological evidence for late Miocene, Pliocene, and early Pleistocene climate changes in the middle U.S. Atlantic Coastal Plain. Quat. Sci. Rev. 10, 147–162.

Groot, J.J., Jordan, R.R., 1999. The Pliocene and Quaternary Deposits of Delaware: Palynology, Ages, and Paleoenvironments. Report of Investigations No. 58. Delaware Geological Survey, pp. 36.

Groot, J.J., Ramsey, K.W., Wehmiller, J.F., 1990. Ages of the Bethany, Beaverdam, and Omar formations of southern Delaware. Delaware Geological Survey Report of Investigations 47, 22.

Hansen, D., 1966. Pleistocene Stratigraphy of the Salisbury Area, Maryland and its Relationsip to the Lower Eastern Shore: A Subsurface Approach, Maryland Geological Survey Report of Investigations no 2. Maryland Geological Survey.

Hapke, C.J., Himmelstoss, E.A., Kratzmann, M.G., List, J.H., Thieler, E.R., 2010. National assessment of shoreline change: Historical shoreline change along the New England and Mid-Atlantic coasts. In: U.S. Geological Survey Open-File Report 2010-1118, pp. 57.

Himmelstoss, E.A., Kratzmann, M.G., Hapke, C.J., Thieler, E.R., List, J.H., 2010. The national assessment of shoreline change: A GIS compilation of vector shorelines and associated shoreline change data for the New England and Mid-Atlantic Coasts. U.S. Geological Survey Open-File Report 2010-1119 available only online at. https://pubs.usgs.gov/of/2010/1119.

Hobbs III, C.H., 2004. Geological history of Chesapeake Bay, USA. Quat. Sci. Rev. 23, 641–661.

Johnson, G.H., Berquist Jr., C.R., 1989. Geology and Mineral Resources of the Brandon and Norge Quadrangles, Virginia. Publication 87. Virginia Division of Mineral Resources, Charlottesville, pp. 28.

Johnson, S.Y., Hartwell, S.R., Sorlien, C.C., Dartnell, P., Ritchie, A.C., 2017. Shelf evolution along a transpressive transform margin, Santa Barbara Channel, California. Geosphere 13.

Klitgord, K.D., Hutchinson, D.R., Schouten, H., 1988. U.S. Atlantic continental margin; Structural and tectonic framework. In: Sheridan, R.E., Grow, J.A. (Eds.), The Atlantic Continental Margin. Geological Society of America, Boulder, CO, pp. 19–56.

Krantz, D.E., Hobbs III, C.H., Wikel, G.L., 2015. Coastal processes and offshore geology. In: Bailey, C. (Ed.), The Geology of Virginia. College of William and Mary, pp. 44.

Mallinson, D., Riggs, S., Thieler, E.R., Culver, S., Farrell, K., Foster, D.S., Corbett, D.R., Horton, B., Wehmiller, J.F., 2005. Late Neogene and Quaternary evolution of the northern Albemarle Embayment (mid-Atlantic continental margin, USA). Mar. Geol. 217, 97–117.

Mallinson, D.J., Culver, S.J., Riggs, S.R., Thieler, E.R., Foster, D.S., Wehmiller, J.F., Farrell, K.M., Pierson, J., 2010a. Regional seismic stratigraphy and controls on the Quaternary evolution of the Cape Hatteras region of the Atlantic passive margin, USA. Mar. Geol. 268, 16–33.

Mallinson, D.J., Smith, C.W., Culver, S.J., Riggs, S.R., Ames, D., 2010b. Geological characteristics and spatial distribution of paleo-inlet channels beneath the outer banks barrier islands, North Carolina, USA. Estuar. Coast. Shelf Sci. 88, 175–189.

Mattheus, C.R., Ramsey, K.W., Tomlinson, J.L., 2020a. The evolution of Coastal Plain incised paleovalleys over multiple glacio-eustatic cycles: insights from the Inner Continental Shelf of Delaware. J. Sediment. Res In Press.

Mattheus, C.R., Ramsey, K.W., Tomlinson, J.L., 2020b. Geologic Map of Offshore Delaware. Geologic Map Series No. 25. Delaware Geological Survey.

McFarland, E.R., Beach, T.A., 2019. Hydrogeologic Framework of the Virginia Eastern Shore: U.S. Geological Survey Scientific Investigations Report 2019–5093. (26 p., 13 pl).

McKenna, K.K., Ramsey, K.W., 2002. An Evaluation of Sand Resources, Atlantic Offshore, Delaware, Report of Investigations No. 63. Delaware Geological Survey, Newark, Delaware, pp. 43.

Miller, K.G., McLaughlin Jr., P.P., Browning, J.V., Bensen, R.N., Sugarman, P.J., Hernandez, J.C., Ramsey, K.W., Baxter, S.J., Feigenson, M.D., Aubrey, M.-P., Monteverde, D., Cramer, B.S., Katz, M.E., McKenna, T.E., Strohmeir, S.A., Pekar, S.F., Uptegrove, J., Cobbs, G., Cobbs III, G., Curtain, S.E., 2002. Bethany Beach Site Report, Proceedings of the Ocean Drilling Program, Initial Reports, Leg 174AX (supplement). Ocean Drilling Program, College Station, Texas p. 1–85., p. 85.

Miller, K.G., Sugarman, P.J., Browning, J.V., Sheridan, R.E., Kulhanek, D.K., Monteverde, D.H., Wehmiller, J.F., Lombardi, C., Feigenson, M.D., 2013. Pleistocene sequence stratigraphy of the shallow continental shelf, offshore New Jersey: Constraints of Integrated Ocean Drilling Program Leg 313 core holes. Geosphere 9, 74–95.

Miller, K.G., Browning, J.V., Sugarman, P.J., Monteverde, D.H., Anreasen, D.C., Lombardi, C., Thornburg, J., Fan, Y., Kopp, R.E., 2017. Lower to Mid-Cretaceous sequence stratigraphy and characterization of CO2 storage potential in the Mid-Atlantic U.S. Coastal Plain. J. Sediment. Res. 87, 609–629.

Miller, K.G., Lombardi, C.J., Browning, J.V., Schmelz, W.J., Gallegos, G., Mountain, G.S., Baldwin, K.E., 2018. Back to basics of sequence stratigraphy: early Miocene and Mid-Cretaceous examples from the New Jersey paleoshelf. J. Sediment. Res. 88, 148–176.

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. 59.

Mixon, R.B., Berquist Jr., C.R., Newell, W.L., Johnson, G.H., Powars, D.S., Schindler, J.S., Rader, E.K., 1989. Geologic Map and Generalized Cross Sections of the Coastal Plain and Adjacent Parts of the Piedmont, Virginia. U.S. Geological Survey Miscellaneous Investigations Series Map I-2033 1:250,000.

Mountain, G.S., Proust, J.-N., McInroy, D., Cottterill, C., Scientists, E., 2010. Initial Report: Proceedings of the International Ocean Drilling Program, Expedition 313, College Station, Texas.

Nebel, S.H., 2013. Reconstructing the Origin and History of Buried Channel-Fill Sequences Offshore of Cedar Island, Virginia, Department of Geological Sciences. Univesity of Delaware, Newark, DE, pp. 241.

NOAA, 1999. U.S. Coastal Relief Model-Southeast Atlantic. National Geophysical Data Center.

Oertel, G.F., Foyle, A.M., 1995. Drainage displacement by sea-level fluctuation at the outer margin of the Chesapeake Seaway. J. Coast. Res. 11, 583–604.

Oertel, G.F., Allen, T.R., Foyle, A.M., 2008. The influence of drainage hierarchy on pathways of barrier retreat: an example from Chincoteague Bight, Virginia, U.S.a. Southeast. Geol. 45, 179–201.

Olsson, R.K., Gibson, T.G., Hansen, H.J., Owens, J.P., 1988. Geology of the Northern Atlantic Coastal Plain: Long Island to Virginia. In: Sheridan, R.E., Grow, J.A. (Eds.), The Atlantic Continental Margin. Geological Society of America, Boulder, CO, pp. 87–106.

Owens, J.P., Denny, C.S., 1979. Upper Cenozoic deposits of the central Delmarva Peninsula, Maryland and Delaware. US Geological Survey Professional Paper 1067-A, pp. 32.

Owens, J.P., Minard, J.P., 1979. Upper Cenozoic sediments of the lower Delaware Valley and the northern Delmarva Peninsula, New Jersey, Pennsylvania, Delaware, and Maryland. U.S. Geological Survey Professional Paper 1067-D, pp. 54.

Parham, P.R., Riggs, S.R., Culver, S.J., Mallinson, D.J., Wehmiller, J.F., 2007. Quaternary depositional patterns and sea-level fluctuations, northeastern North Carolina. Quat. Res. 67, 83–99.

Parham, P.R., Riggs, S.R., Culver, S.J., Mallinson, D.J., Rink, W.J., Burdette, K., 2013. Quaternary coastal lithofacies, sequence development and stratigraphy in a passive margin setting, North Carolina and Virginia, USA. Sedimentology 60, 503–547.

Pendleton, E.A., Brothers, L.L., Thieler, E.R., Danforth, W.W., Parker, C.E., 2015b. National Oceanic and Atmospheric Administration hydrographic survey data used in a U.S. Geological Survey regional geologic framework study along the Delmarva Peninsula. U.S. Geological Survey Open-File Report 2014–1262, pp. 18. https://doi.org/10.3133/ofr20141262.

Pendleton, E.A., Brothers, L.L., Sweeney, E.M., Thieler, E.R., Foster, D.S., 2017a. Sediment Texture and Geomorphology of the Sea Floor from Fenwick Island, Maryland to Fisherman's Island, Virginia, U.S. Geological Survey Data Release.

Pendleton, E.A., Brothers, L.L., Thieler, E.R., Sweeney, E.M., 2017b. Sand ridge morphology and bedform migration patterns derived from bathymetry and backscatter on the inner-continental shelf offshore of Assateague Island, USA. Cont. Shelf Res. 144, 80–97.

Pendleton, E.A., Sweeney, E.M., Brothers, L.L., 2019. Optimizing an inner-continental shelf geologic framework investigation through data repurposing and machine learning. Geosciences 9, 231.

Pendleton, E.A., Ackerman, S.D., Baldwin, W.E., Danforth, W.W., Foster, D.S., Thieler, E.R., Brothers, L.L., 2015a. High-resolution geophysical data collected along the Delmarva Peninsula, 2014, USGS Field Activity 2014-002-FA (ver. 3.0, December 2015): U.S. Geological Survey data release. Available online. https://doi.org/10.5066/F5067MW5062F5060.

Pico, T., Creveling, J.R., Mitrovica, J.X., 2017. Sea-level records from teh U.S. mid-Atlantic constrain Laurentide Ice Sheet extent during Marine Isotope Stage 3. Nat. Commun. 8, 15612.

Poag, C.W., Powars, D.S., Poppe, L.J., Mixon, R.B., 1994. Meteoroid mayhem in Ole Virginny: source of the North American tektite strewn field. Geology 22, 691–694.

Posamentier, H.W., 2001. Lowstand alluvial bypass systems: Incised vs. unincised. AAAP Bull. 85, 1771–1793.

Posamentier, H., Allen, G.P., 1999. Siliciclastic Sequences Stratigraphy—Concepts and Applications. SEPM (Society for Sedimentary Geology, Tulsa, OK.

Powars, D.S. (2011) Middle and late Pleistocene geology of the Eastern Shore of Virginia and relationships ot the Chesapeake Bay impact structure with impact debris core display: 41st Virginia Geological Field Conference, Wachapreague, Virginia, October 29-30, 2011. 15–35.

Powars, D.S., Bruce, T.S., 1999. The Effects of the Chesapeake Bay Impact Crater on the Geological Framework and Correlation of Hydrogeologic Units of the Lower York-James Peninsula, Virginia, Professional Paper 1612. pp. 82.

Raff, J.L., Shawler, J.L., Ciarletta, D.J., Hein, E.A., Lorenzo-Trueba, J., Hein, C.J., 2018. Insights into barrier-island stability derived from transgressive/regressive state changes of Parramore Island, Virginia. Mar. Geol. 403, 1–19.

Railsback, L.B., Gibbard, P.L., Head, M.J., Voarintsoa, N.R.G., Toucanne, S., 2015. An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. Quat. Sci. Rev. 111.

Ramsey, K.W., 1992. Response to Late Pliocene climate chang: Middle Atlantic Coastal Plain, Virginia and Delaware. In: Fletcher IIIC.H., Wehmiller, J.F. (Eds.), Quaternary Coasts of the United States: Marine and Lacustrine Systems. Society for Sedimentary Geology, SEPM Tulsa, Oklahoma.

Ramsey, K.W., 1999. Cross section of Pliocene and Quaternary deposits along the Atlantic Coast of Delaware. Miscellaneous Map Series No. 6. Delaware Geological Survey.

Ramsey, K.W., 2010. Report of Investigations No. 76: Stratigraphy, Correlation, and Depositional Environments of the Middle to Late Pleistocene Interglacial Deposits of Southern Delaware. Delaware Geological Survey.

Ramsey, K.W., McKenna, K.K., 2009. In: Survey, D.G. (Ed.), Delaware Offshore Geologic Inventory Dataset. Delaware Geological Survey, Newark.

Raymo, M.E., Mitrovica, J.X., O'Leary, M.J., DeConto, R.M., Hearty, P.J., 2011. Departures from eustasy in Pliocene Sea-level records. Nat. Geosci. 4, 328–332.

Schwab, W.C., Baldwin, W.E., Warner, J.C., List, J.H., Denny, J.F., Liste, M., Safak, I., 2017. Change in morphology and modern sediment thickness on the inner continental shelf offshore of Fire Island, New York between 2011 and 2014: Analysis of hurricane impact. Mar. Geol. 391, 48–64.

Scott, T.W., Swift, D.J.P., Whitticar, G.R., Brooke, G.A., 2010. Glacioisostatic influences on Virginia's late Pleistocene coastal plain deposits. Geomorphology 116.

Sheridan, R.E., Dill, C.E.J., Kraft, J.C., 1974. Holocene sedimentary environment of the Atlantic inner shelf off Delaware. Geol. Soc. Am. Bull. 85, 1319–1328.

Sheridan, R.E., Ashley, G.M., Miller, K.G., Waldner, J.S., Hall, D.W., Uptegrove, J., 2003. Offshore-onshore correlation of upper Pleistocene strata, New Jersey coastal plain to continental shelf and slope. Sediment. Geol. 134, 197–207.

Shideler, G.L., Swift, D.J.P., Johnson, G.H., Holliday, B.W., 1972. Late Quaternary stratigraphy of the inner Virginia continental shelf: a proposed study section. Geol. Soc. Am. Bull. 83, 1787–1804.

Shideler, G.L., Ludwick, J.C., Oertel, G.F., Finkelstein, K., 1984. Quaternary stratigraphic evolution of the southern Delmarva Peninsula coastal zone, Cape Charles, Virginia. Geol. Soc. Am. Bull. 95, 489–502.

Spratt, R.M., Lisiecki, L.E., 2016. A Late Pleistocene sea level stack. Clim. Past 12, 1079–1092.

Sweeney, E.M., Pendleton, E.A., Ackerman, S.D., Andrews, B.D., Baldwin, W.E., Danforth, W.W., Foster, D.S., Thieler, E.R., Brothers, L.L., 2015. High-Resolution Geophysical Data Collected along the Delmarva Peninsula 2015, U.S. Geological Survey Field Activity 2015–001-FA (ver. 3.0, May 2016): U.S. Geological Survey Data Release P. Available online: https://doi.org/10.5066/F5067P5055KK5063.

Swift, D.J.P., 1975. Barrier-island genesis: evidence from the Central Atlantic Shelf, Eastern U.S.A. Sediment. Geol. 14, 1–43.

Tesson, M., Posamentier, H., Gensous, B., 2015. Compound incised-valley characterization by high-resolution seismics in a wave-dominated setting: example of the Aude and Orb rivers, Languedoc inner shelf, Gulf of Lion, France. Mar. Geol. 367, 1–21.

Thieler, E.R., Foster, D.S., Himmelstoss, E.A., Mallinson, D.J., 2014. Geologic framework of the northern North Carolina, USA inner continental shelf and its influence on coastal evolution. Mar. Geol. 348, 113–130.

Todd, B.J., Shaw, J., 2012. Laurentide Ice Sheet dynamics in the Bay of Fundy, Canada, revealed through multibeam sonar mapping of glacial landsystmes. Quat. Sci. Rev. 58, 83–103.

Toscano, M.A., Kerhin, R.T., York, L.L., Cronin, T.M., Williams, S.J., 1989. Quaternary Stratigraphy of the Inner Continental Shelf of Maryland, Report of Investigations No. 50. Maryland Geological Survey, pp. 119.

Twichell, D.C., Knebel, H.J., Folger, D.W., 1977. Delaware River: evidence for its former extension to Wilmington Submarine Canyon. Science 195, 483–485.

Uptegrove, J., Waldner, J.S., Stanford, S.D., Monteverde, D., Sheridan, R.E., Hall, D.W., 2012. Geology of the New Jersey Offshore in the vicinity of Barnegat Inlet and Long Beach Island. New Jersey Geological and Water Survey Geologic Map Series GMS 12–13.

Vail, P.R., Mitchum Jr., R.M., 1977. Seismic stratigraphy and global changes of sea level, part I: Overview. In: Payton, C.E. (Ed.), Seismic Stratigraph–Applications to Hydrocarbon Exploration. The American Association of Petroleum Geologists, Tulsa, OK, pp. 51–52.

Warner, J.C., Schwab, W.C., List, J.H., Safak, I., Liste, M., 2017. Inner-shelf Ocean dynamics and seafloor morphologic changes during Hurricane Sandy. Cont. Shelf Res. 138, 1–18.

Wehmiller, J.F., Brothers, L.L., Foster, D.S., Ramsey, K.W., 2019. Southern Delmarva Barrier Island Beaches: Linking Offshore and Onshore Units Using Racemization Geochronology to Infer Sediment Sources during Shoreline Migration. Paper 13–5. Geological Society of America, SE Sectional meeting, Charleston SC.

Wikel, G.L., 2008. Variability in geologic framework and shoreline change: Assateague and Wallops Islands, Eastern Shore of Virginia, School of Marine Science. In: The College of William and Mary in Virginia, pp. 210.

Yoo, D.-G., Lee, G.-S., Kim, G.-Y., Kang, N.-K., Yi, B.-Y., Kim, Y.-J., Chun, J.-H., Kong, G.-S., 2016. Seismic stratigraphy and depositional history of late Quaternary deposits in a tide-dominated setting: an example from the eastern Yellow Sea. Mar. Pet. Geol. 73, 212–227.

Yoo, D.-G., Kim, K.-J., Lee, G.-S., Kang, N.-K., Yi, B.-Y., Kim, G.-Y., Chang, S.-W., Kim, H.-J., 2017. Seismic stratigraphic reconstruction of Plio-Quaternary depositional sequences on the continental shelf of Korea Strait. Quat. Int. 459, 116–132.

Zecchin, M., Catuneaunu, O., Cauffau, M., 2018. Wave-ravinment surfaces: Classification and key characteristics. Earth Sci. Rev. 188, 210–239.

Zhuo, H., Wang, Y., Shi, H., He, M., Chen, W., Li, H., Wang, Y., Yan, W., 2015. Contrasting fluvial styles across the mid-Pleistocene climate transition in the northern shelf of the South China Sea: evidence from 3D seismic data. Quat. Sci. Rev. 129, 128–146.