OCS Study
BOEM 2016-056

Virginia Ocean Geophysical Survey Phase II Analyses Offshore Virginia Wind Energy Area

US Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs

FUGRO

BOEM Bureau of Ocean Energy Management

Virginia Department of Mines Minerals and Energy

Virginia Ocean Geophysical Survey
Phase II Analyses
Offshore Virginia Wind Energy Area

Authors

Sean M. Sullivan
Kevin R. Smith
Dave M. Sackett

Prepared under BOEM Cooperative Agreement
M15AC00002
and Virginia Department of Mining, Minerals, and Energy
C13-6030
by
Fugro Consultants, Inc.
101 West Main Street
Suite 350
Norfolk, Virginia 23510

US Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs
June, 2016

BOEM
Bureau of Ocean Energy Management

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Funding was provided by the US Department of the Interior, Bureau of Ocean Energy Management, Washington, DC, under Cooperative Agreement M15AC00002. This project was part of a cooperative agreement with the Commonwealth of Virginia, Department of Mines, Minerals, and Energy and was jointly funded with contributions from Fugro Consultants, Inc. This report has been technically reviewed by BOEM and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the US Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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CITATION

Sullivan, S.M., Smith, K.R. and D.M. Sackett. 2016. Virginia Ocean Geophysical Survey Phase II Analyses: Offshore Virginia Wind Energy Area. US Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Herndon. OCS Study BOEM 2016-056. 39 pp.

FUGRO CONSULTANTS, INC.

350 World Trade Center
Norfolk, Virginia 23510
Tel: (757) 625-3350

June 30, 2016
Project No. 04.81150002

Commonwealth of Virginia
Department of Mines, Minerals and Energy
Washington Building, 8th Floor
1100 Bank St.
Richmond, Virginia 23219-3638

Attention: Mr. Al Christopher, Director, Division of Energy, Virginia DMME

Subject: Virginia Ocean Geophysical Survey, Phase II Analyses, Offshore Virginia Wind Energy Area

Dear Mr. Christopher:

Fugro Consultants, Inc. (Fugro) is pleased to present the results of the "Virginia Ocean Geophysical Survey, Phase II Analyses, Offshore Virginia Wind Energy Area" study. The study was completed in response to, and is compliant with, the requirements of the Department of Mines, Minerals and Energy's (DMME) Request for Proposals (RFP) # 14DE01, dated February 4, 2014. This study made use of existing seismic reflection data collected across the offshore Virginia Wind Energy Area (WEA) in 2013 by Fugro under contract to DMME and the U.S. Department of Interior's Bureau of Ocean Energy Management (BOEM) in order to provide further analyses related to data acquisition, data processing and seismic interpretation.

The original concept for the Fugro 2013 geophysical survey, as authorized by DMME Agreement Number: C13-6030 on March 2013 using both DMME "seed money" and BOEM "matching funds", was to conduct a regional geophysical survey and perform a geologic evaluation of the Virginia Outer Continental Shelf (OCS) WEA. The 2013 seismic reflection data were acquired using state-of-the-art technology designed for shallow subsurface studies. An EdgeTech 3200 sub-bottom (Chirp) profiler was utilized to image the shallow subsurface while deeper-penetrating multichannel seismic data were acquired using a dual plate boomer seismic source combined with a 32-channel Geo-Eel streamer. The hydrophone array of the Geo-Eel streamer consisted of 16 channels with 1.56 meter-group-intervals (mgi), trailed by 16 channels with 3.125 mgi. The streamer's geometry allowed the data to be processed with either 16 channels at 1.56 mgi or 24 channels at 3.125 mgi.

After initially processing two survey lines with both 16 channels at 1.56 mgi and 24 channels at 3.125 mgi, it was determined that in order to best meet the objectives of the original study, the remainder of the data would be processed using 24 channels at 3.125 mgi. This decision was based on the need to properly map the seismic horizon corresponding to the base of the late Pleistocene unconformity (as required by BOEM), which lies up to 22 meters below the seafloor. Processing the data with fewer channels at shorter group intervals (i.e., 16 channels at 1.5625 mgi) results in an ability to increase the resolution/definition of near-seafloor conditions, while processing the data utilizing 24 channels at 3.125 mgi (i.e., more channels at longer group intervals) increases the ability to image the deeper portion of the subsurface. While presenting the survey results to DMME and BOEM, Fugro discussed the opportunity to process the WEA data set at 16 channels at 1.56 mgi data to increase the resolution of the shallow subsurface data for enhanced geological and paleogeographic (historical landforms) definition.

The additional processing and interpretation will supplement and expand the prior interpretation. Moreover, the additional processing and data analyses will be used to evaluate different hydrophone-streamer configurations and seismic data processing techniques that affect the interpretation of paleo-landforms in support of marine archeological resource assessments and geologic interpretation for support of site characterization and engineering studies. The initial Atlantic OCS wind farm geophysical surveys have relied primarily upon Chirp data to support marine archaeological assessments. However, the early geophysical surveys indicate that the Chirp signal penetration is often limited to shallow depths and often does not reach the late Pleistocene unconformity or is inconclusive due to limited signal penetration. Imaging the late Pleistocene unconformity and providing high resolution data to aid interpretation of paleo-landforms is important for marine archaeological resource assessments. The Phase II of this study evaluates different hydrophone configurations and processing techniques that (we believe) will be able to mitigate the limitations of the Chirp signal penetration in the Atlantic OCS.

The results of Phases I and II of the Virginia Ocean Geophysical Survey hope to provide adequate analyses of the subsurface so that future scientific and engineering research conducted on the OCS will help to promote, plan and further the goals of safe, economic and responsible commercial development of offshore renewable energy.

Sincerely,

FUGRO CONSULTANTS, INC.

Sean Sullivan
Geologist

Kevin Smith, P.G. (CA)
Senior Engineering Geologist

David M. Sackett, P.G. (VA)
Vice President, Principal Geologist

Copy Submitted: Dr. Mary Boatman, BOEM (PDF Copy)

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1.0 OVERVIEW

1.1 PROJECT DESCRIPTION

During 2013, Fugro Consultants, Inc. (Fugro) conducted a regional marine geophysical survey for the Virginia Department of Mines, Minerals and Energy (DMME) and the U.S. Department of Interior, Bureau of Ocean Energy Management (BOEM) in the designated Wind Energy Area (WEA) on the Outer Continental Shelf (OCS) offshore southeastern Virginia. The survey and reporting conducted in 2013 comprise Phase I of the Virginia Ocean Geophysical Survey. The primary purpose of Phase I was to advance the state of knowledge relative to the geologic and subsurface conditions in the WEA.

One of the key sources of data collected during the 2013 survey was the two-dimensional (2D), multichannel seismic reflection data. The multichannel seismic data were acquired using multichannel hydrophone streamer with two different group intervals. The front 16 channels had a group interval of 1.56 meters and were trailed by 16 channels at 3.125 meter group interval (mgi). Altogether, the streamer could be treated as 24-channels at 3.125-mgi. After conducting a preliminary assessment of the data, it was decided to process and interpret the 3.125-mgi data.

During the course of the study, it was identified that the 1.56-mgi data set would provide value in imaging the upper 50-feet and provide improved resolution over the 3.125-mgi data in the shallow subsurface.

Interpretation of the geophysical data relative to archaeological or cultural resources, and benthic habitat was not part of the scope of work. Seafloor targets and/or magnetometer anomalies that could be of archaeological significance are noted and that information was provided to BOEM for their consideration and interpretation.

Phase II of the Virginia Ocean Geophysical Survey utilized previously collected seismic data acquired within the offshore Virginia Wind Energy Area (WEA) in order to determine which seismic survey designs and processing steps provide the best imaging of the subsurface as needed for future site characterization studies and marine archaeological research. Additionally, the present study also identified key paleo-landforms along the Virginia Outer Continental Shelf (OCS) that could be used by archaeologists and geoscientists to reconstruct past environments along the U.S. Atlantic Margin. While this study was not conducted to meet the Bureau of Ocean Energy Management's (BOEM) recommendations described in "Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585" (BOEM, 2015a) and "Guidelines for Providing Archaeological and Historic Property Information Pursuant to 30 CFR Part 585" (BOEM, 2015b), this project provides an understanding of how a regional/reconnaissance-scale (i.e., primary lines spacing greater than 150 meters) seismic survey can be utilized to help inform the collection of more detailed (i.e., smaller-scale) surveys for both site characterization and archaeological site identification on the Atlantic OCS.

1.2 PURPOSE OF STUDY

Section 388 of the Energy Policy Act of 2005, granted the Department of the Interior the ability to grant leases along the Outer Continental Shelf in support of the production, transport or transmission of energy from sources other than oil and gas (O&G). In 2009, President Barack Obama announced the final regulations for the OCS Renewable Energy Program resulting in numerous lease sales within areas predetermined by BOEM, known as Wind Energy Areas

(WEAs) from 2009 to the present. On September 4 2013, Virginia Electric and Power Company (dba Dominion Virginia Power) won the first commercial wind energy lease in Virginia. The leased areas covered the entire Virginia WEA, stretching over 450 km^2 and 20 OCS blocks (Figure 1). The seismic data acquired by Fugro in 2013 and used in this report were collected as part of a regional geophysical survey for the Virginia Department of Mines, Minerals and Energy (DMME) and BOEM (Figure 2). The purpose of the geophysical survey and the resulting geologic evaluation was to advance the state of knowledge relative to the geologic and subsurface conditions in the WEA in order to promote, plan and further the goals of safe, economic and responsible future commercial development of the WEA (Fugro, 2013b).

With 15 years of experience dedicated to the production and transmission of energy from offshore wind turbines, the European community has led the world in the development of offshore renewable resources. While the United States is comparatively young, considerable progress occurring over the last decade has produced a knowledgeable community of scientists, engineers and businessmen prepared to cultivate a more robust offshore renewable energy industry operating along the East Coast. Installation of five steel jacket foundations in 2015 at the Block Island Wind Farm site, located within Rhode Island's state waters, marked the completion of the first offshore construction season devoted to offshore wind energy in the U.S. (Deepwater Wind, 2015). If the announced schedule for Block Island Wind Farm is maintained, 2016 will see installation of submarine cables in the spring, construction of five offshore wind turbines in the summer and the site will be in-service and generating power by the end of the fourth quarter (Deepwater Wind, 2015).

Since 2009, eleven commercial leases have been awarded by on the Atlantic OCS by BOEM's Office of Renewable Energy Programs (OREP) (BOEM, 2016). Presently, lease sales for offshore renewable energy on the Atlantic OCS are in the planning stages for North Carolina, South Carolina and New York.

The transmission and production of energy derived from offshore renewable resources on the U.S. OCS have yet to be realized. Authorities at both the State and Federal level realize that in order to foster a thriving industry, more data needs to be collected, more research projects will need funding (such as the current study) and the policies created to regulate this new industry will likely need to be adjusted as the industry progresses. The purpose of this study is provide current and future lessees with a case study to use as an example on methods to evaluate geological conditions in the marine environment and how geophysical data can be utilized to perform site characterization studies necessary for the development of offshore renewable energy facilities on the Outer Continental Shelf of the United States.

1.3 COORDINATE SYSTEM, DATUMS AND UNITS OF MEASUREMENT

The horizontal coordinate system used during the survey is Universal Transverse Mercator (UTM) Zone 18 North, North American Datum 1983 (NAD83), meters. Elevations in this report are referenced to Mean Lower Low Water (MLLW) and are in meters. The tidal corrections are based upon the observed water levels reported from National Oceanic and Atmospheric Administration's (NOAA) tidal monitoring station No. 8651370 located at Duck, North Carolina. That tidal reference proved to provide a better reference, based on our evaluation of consistency of water depths at primary-tie line intersections than did data corrections based on the NOAA's tidal station No. 8638863 located at the Chesapeake Bay Bridge Tunnel, Virginia. During prior

NOAA multibeam surveys in the WEA, NOAA also used the measured tide data for tidal corrections of their water depth measurements from station No. 8651370 located at Duck, North Carolina.

1.4 REPORT FORMAT

The report includes the following sections.

1. Overview
2. Introduction
3. Study Methodology
4. Discussion and Results
5. Conclusions
6. References

The report text is followed by various figures that support the descriptions provided in the report text. Figures are numbered sequentially and the list of tables and figures are presented in the table of contents.

1.5 AUTHORIZATION

Phase II of the Virginia Ocean Geophysical Survey is funded by the Virginia Department of Mines, Minerals and Energy and the U.S. Department of the Interior Bureau of Ocean Energy Management. Fugro's authorization for this study is provided by DMME Agreement Number: C13-6030, dated March 2013.

1.6 LIMITATIONS

Fugro Consultants, Inc. has prepared Phase II of the Virginia Ocean Geophysical Survey for the Commonwealth of Virginia's Department of Mines, Minerals and Energy and the Department of the Interior's Bureau of Ocean Energy Management, solely to provide an evaluation of high-resolution geophysical acquisition and processing techniques suited to meet the needs of offshore renewable energy development. Two sub-bottom datasets collected by Fugro in 2013 were analyzed to determine how resolution and penetration depth is affected by specific acquisition and processing techniques and how these parameters influence the ability to interpret paleo-landforms. In preforming our professional services, we have used that degree of care and skill ordinarily exercised, under similar circumstances, by reputable professional engineers and geologists currently practicing in this or similar localities. No other warranty, express or implied, is made as to the content of this report. Fugro makes no claim or representation concerning any activity or conditions falling outside its specified purposes to which this report is directed.

2.0 INTRODUCTION

2.1 PAST AND PRESENT GEOLOGIC PROCESSES IN THE MID-ATLANTIC REGION

The same fluvial, tidal and marine processes that have shaped the present Mid-Atlantic coastline were also responsible for creating and modifying sedimentary environments that are currently buried below the Atlantic seafloor. The position of the various paleo-landforms (e.g., barrier islands, incised valleys) preserved beneath the Continental Shelf record a geologic history of multiple glacial-interglacial cycles with associated sea-level adjustments that have come to characterize the Quaternary Period. Identification of these paleo-landforms is important, not only for reconstructing past geological events but also because they provide insight into former environmental conditions that could have been favorable areas of activity by pre-contact North American's.

2.1.1 The Mid-Atlantic Coast

The Mid-Atlantic region is a loosely defined region that generally lies between New England and the South Atlantic States. For this report, we identify the Mid-Atlantic coast as extending from south of the glacial region offshore southern Massachusetts to central North Carolina, based on similar geologic processes. The northern margin of the Mid-Atlantic, as discussion herein, is approximately coincident with the Late Wisconsin Last Glacial Maximum's southern extent and associated glacial outwash plain. The islands of Nantucket, Martha's Vineyard, and Long Island represent the approximate moraine that is inferred to represent the south glacial limit. Glacial processes in the New England region resulted in paleolandforms (e.g. moraines, glacially carved valleys, and outwash plains) that are significantly different from non-glaciated areas to the south. We provide the following discussion about the current Mid-Atlantic coast and geomorphology since this modern analog is inferred to be representative of the Holocene depositional environments that transgressed across the shelf and created the shallow paleolandfroms researched in this study.

The present configuration of the Mid-Atlantic coast of the United States can be divided into distinct sections (Massachusetts-Rhode Island; Long Island; New Jersey; the Delmarva Peninsula; and Virginia-North Carolina) that correspond to a repeating pattern of barrier-fronted coastal compartments separated by estuaries each defined by unique landscape elements (Fisher, 1967; Oertel and Kraft, 1994). The four elements that comprise each Mid-Atlantic coastal compartment, listed from north to south, are:

1. A cuspate spit located along the southern tip of each estuary's mouth,
2. An eroding headland,
3. Barrier spits and long linear barrier islands, and
4. Short tide-dominated barrier islands with numerous inlets occurring north of the estuary which defines the start of another coastal compartment.

Swift et al. (1986) showed that each of these compartments share similarities with respect to geomorphology, sediment transport and sediment accumulation.

All four elements defined above are present along the Virginia coast starting in the north with the tide-dominated barrier island segment of the Delmarva coastal compartment. This tide-dominated segment includes thirteen barrier islands of Virginia's Eastern Shore including all barriers between Wallops Island in the north and Fishermans Island located near the northern margin of Chesapeake Bay. South of Chesapeake Bay, the Virginia-North Carolina coastal compartment begins where the northward progradation of the Cape Henry spit was accreted along the Virginia Beach mainland. Lagoons are generally absent along the linear, land-attached coastline of Virginia Beach until approximately 20 kilometers (km) south of Cape Henry, near Sandbridge, beach separation from the mainland at North Bay creates a long barrier spit that is a continuous landform until reaching North Carolina's Oregon Inlet approximately 65 miles to the south. From Sandbridge, Virginia to Cape Lookout, North Carolina, the transport of sediment by tidal energy is minimal and wave-dominated landforms such as long, linear barrier islands and barrier spits characterize this portion of the Virginia-North Carolina coastal compartment (Hobbs et al., 2008).

The Late Pleistocene geologic evolution of the Mid-Atlantic offshore region is depicted in Figures 3 and 4. During the Wisconsin Last Glacial Maximum (approximately 25,000 to 15,700 years before present), the Continental Shelf became exposed during sea level lowering and channels delivered sediment to large canyons at the present shelf break (e.g., Duncan et al., 2000; Nordfjord et al., 2005). Holocene transgression of the shoreline across the exposed Continental Shelf led to the infilling of former fluvial channels and valleys with an upward-deepening succession of lagoonal and estuarine muds; estuaries, lagoons, shoreface barriers, and nearshore shores/oblique ridges (Figure 3). The modern seafloor on the Continental Shelf reflects the reworking of former pre-Holocene deposits by marine transgression. Much of the present shelf is covered by a thin veneer of Holocene-age sediments. These sediments were reworked and winnowed from oblique shoreface ridges and have obscured the location of former drainage systems that were infilled during transgression (Figures 3 and 4).

Presently, much of the Mid-Atlantic Shelf is characterized as a storm-dominated shelf where the regional sediment transport is alongshore in a southwesterly direction. Reinson (1992) described Chesapeake Bay as a shore-parallel, partially-closed, wave-dominated estuary. Regardless of the classification, Chesapeake Bay differs from an idealized tide-dominated estuary illustrated in Figure 5. Tide-dominated estuaries commonly form along macrotidal (tidal range greater than 4 meters) coasts but are also found along coasts with smaller tidal ranges where the tidal prism is large and/or wave energy is low (Dalrymple et al., 1992).

As described above, the main depositional environments along the present Mid-Atlantic shoreline are dominated by barrier-island systems and estuaries. Table 2.1-1 highlights sedimentary characteristics of the main depositional environments present along the Outer Banks of North Carolina. While this table is specific to the Outer banks of North Carolina, the depositional environments represented are present in barrier island systems throughout the Mid-Atlantic region.

Both barrier-island and estuarine systems have a well-defined organization with transitions between sub-environments occurring in predictable locations in relation to the distance from the shoreline dominated by marine processes (Figure 5). Classification of both barrier island systems and estuaries are based on the relative influence of wave or tidal action (Dalrymple et al., 1992; Davis, 1994). Distinct trends in sediment distribution and the formation of specific geomorphologic landforms help define these coastal systems as being wave-dominated, mixed-energy or tide-dominated.

At the mouths of estuaries and along tidal inlets of barrier island systems, tidal currents exert their greatest influence transporting sediment landward during flood conditions and then seaward during receding ebb tides. Ebb and flood tidal flows occur twice a day along the Mid-Atlantic region as the tides are semi-diurnal. Tidal channel inlets of barrier island systems allow the exchange of water and sediment to occur between the marine environment and lagoonal systems. In wave-dominated barrier systems, ebb-tidal deltas are generally small or non-existent while flood-tidal deltas are typically large (Davis, 1994). Wave-dominated estuaries are composed of a marine sand body composed of barrier, washover, tidal inlet and tidal delta deposits. Estuaries have a net landward movement of sediment in their most seaward extension.

In mixed-energy systems, barrier island systems are influenced significantly by both waves and tides. The formation of seaward protruding ebb-tidal deltas causes wave refraction and the reversal of longshore current direction down drift of the ebb delta causing sediment trapping along this portion of the ebb-tidal delta (Davis, 1994). Shoal retreat massifs formed at the estuary mouths as the shoreline system transgressed across the shelf (Swift et al., 1977). Today, relict shoal retreat massifs can be observed on the seafloor and they illuminate the transgressive path of many large estuary mouths (Figure 6).

Table 2.1-1. Sedimentary Characteristics of Major Depositional Environments along the Outer Banks of North Carolina

Depositional environment	Lithology	Shells and Organics	Sedimentary structures	Large-scale features
Overwash and foreshore	Clean, moderately sorted, fine to medium sand	Whole and abraded shells in layers; variable assemblage (low diversity)	Horizontal and planar laminations	Caps inlet and barrier sequences
Shoreface	Well-sorted, fine to medium sand and silt	Abundance of sand-sized shell material; *Gemma gemma*, *Arcopecten* sp., *Olivelia* sp.	Cross-bedded (upper half) and burrowed (lower half) sequence	Coarsening-upward sequence: increase in mud content towards base
Backbarrier (estuary, tidal flat, salt marsh)	Well-sorted, fine to medium silty sand and sandy clay	Organic-rich: *Spartina* sp., and other plant material; *Ensis* sp., *Crassostrea* sp., *Crepidula* sp. (mollusks)	Burrowed, thin parallel clay laminations	Capped by salt marsh; increasing mud and organic content upwards
Flood-tidal delta	Moderately sorted, medium to coarse silty sand	Coarse shell fragments common: echinoderm fragments common	Gently dipping cross-laminae; burrowed	Interbedded with backbarrier facies; cyclic fining-upward sequences
Inlet margin	Clean, well-sorted, fine to medium sand	Mollusks rare; low diversity	Planar and horizontal laminations	Caps fining-upward inlet sequence
Inlet channel	Moderately sorted, medium to coarse sand and shell; pebble sand common	Mixed mollusk assemblage of shelf and backbarrier sps., shells common and abraded	Cross-bedded (trough and planar?)	Thickset unit of inlet sequence; fines upward
Inlet floor	Poorly sorted, coarse to pebbly sand and shell	Large, worn and abraded shell fragments common	Rip-up clasts; graded bedding	Basal scour lag

Source: Moslow and Heron (1994)

2.1.2 The Outer Continental Shelf of the Mid-Atlantic

The Virginia Wind Energy Area lies approximately 40 km southeast of the entrance to Chesapeake Bay, the largest estuary in the contiguous United States. Estuaries, as defined by Dalrymple et al. (1992) are the seaward portion of a drowned valley system influenced by tidal, wave and fluvial processes and contain sedimentary deposits of both marine and fluvial origin. Several shelf-valley complexes traverse the Mid-Atlantic OCS and are believed to represent large estuarine systems that infilled former river valleys while migrating landward during Late Pleistocene/Holocene transgression (Figure 6; Swift et al., 1980).

Those former shelf-valley complexes are buried beneath surficial sand ridges or thin sedimentary cover and preserved in the subsurface and can be delineated on bathymetric maps where they often appear as surficial channels/valleys or as broad, smooth, featureless bathymetric lows (Swift et al., 1980; Duane and Stubblefield, 1988).

Multibeam bathymetry and side scan sonar (or backscatter intensity) data collected by NOAA in 2011 and 2012 cover the entire Virginia WEA area (Figures 7 and 8). These high-resolution data sets were very useful in the interpretation of present and past geologic processes affecting the Virginia WEA. The bathymetry data reveal a seafloor with complex morphology and bedforms that suggest they are mobile.

In general, the water depth within the WEA increases from west to east with minimum and maximum water depths of approximately 18 to 41 meters MLLW. The shallowest water depths exist on the crests of the sand ridges (the dominant seafloor features) along the northwestern and western regions of the WEA (Figure 7). These areas are separated by a low lying and low relief swale areas.

The northwest area of the WEA has an irregular seafloor with sandwave bedforms superimposed along broad shoals. The water depth varies from approximately 18 meters on the shoals to 28 meters in the adjacent troughs. Sandwave bedforms (e.g., dunes) in this area are generally of lower relief and extent, with crest-to-trough height varying from approximately 1 to 3 meters. In the central and southern areas of the WEA, the seafloor consists of sand ridges that may represent shoal retreat massifs superimposed on a broader, shallow water region (Figure 7 and 8).

The ancestral Susquehanna River and Virginia Beach shelf valleys are located to the north and south of the Virginia WEA, respectively (Figure 9; Swift et al., 1973). The Susquehanna River shelf valley extends from the mouth of Chesapeake Bay in an easterly direction and curves to the north around the WEA and is inferred to connect to the head of Norfolk Canyon (Figure 6). The infilled paleo-valley system located in the northeastern corner of the WEA that was interpreted using seismic data during the Phase 1 of this study (Fugro, 2013b) likely was part of the ancestral Susquehanna drainage system that connected to Norfolk Canyon (Figures 9 and 10). The Virginia Beach shelf valley, which is located to the south of the WEA, extends from the Atlantic Ocean Channel (AOC) and runs shore parallel until changing direction to the east-normal offshore the False Cape area (Figure 6).

Within both shelf valley areas, the seafloor generally appears to be relatively flat and featureless, but broad areas with topographic relief are located to the north of these two shelf valleys (Figure 6). These topographic highs are the Virginia Beach and Susquehanna shoal-retreat massifs. Their positions mark the former positions of estuary mouths where littoral drift converges on one or both sides of the estuary to create levee-like highs that are preserved on the seafloor as the estuary mouth moves landward during transgression (Swift 1973; Swift et al., 1980).

2.2 PREHISTORIC ARCHAEOLOGY ON THE CONTINENTAL SHELF

BOEM requires detailed information concerning the nature and location of historic properties that may be affected by offshore renewable energy development in order to fulfill Section 106 of the National Historic Preservation Act (NHPA) (36 CFR § 800) and the National Environmental Policy Act (NEPA). While scholars have long acknowledged that focused research on the continental shelf could significantly advance our understanding of human prehistory, those presently underwater areas remain largely unexplored by archaeologists due mainly to difficulties in funding and the ability to access submerged lands. For this reason, previous archaeological studies (e.g., CEI, 1977) of the OCS have largely focused on defining methodologies to help identify archaeologically significant sites while focused archaeological investigation on the OCS is very rare. Chance finds of archaeological artifacts on the OCS through dredging or fishing activities have led to the collection of more culturally-significant material than by discoveries as part of an archaeological research investigation (Flatman and Evans, 2014).

Determining the preservation potential and probability of discovering prehistory archaeological sites is beyond the scope of this project and is better-suited to an archaeology-focused study, but there are several topics that have been noted in previous studies that warrant some discussion for the present study (e.g., CEI, 1977; Lowery and Martin, 2009; TRC Environmental Corporation, 2012; Evans et al., 2014). Besides the cost and challenges of conducting underwater research, Bailey (2014) lists the generally held belief that destruction and disturbance of underwater sites due to inundation as the largest obstacle faced by submerged prehistoric archaeologists. While former sea level positions provide an approximate location to look for prehistory North American coastal communities, various oceanographic and geologic processes can influence the ability to preserve these sites. For example, the rate of relative sea level rise during marine transgression is of considerable significance (Lowery and Martin, 2009; TRC Environmental Corporation, 2012).

Barrier islands migrate landward either by shoreface retreat or in-place drowning and abandonment (Figure 11; Swift et al., 1975). During slow sea-level rise, sediment is often reworked by wave- and current-action, so that the preservation of paleo-landforms and potential archaeological sites will also be modified. While it can be assumed that during slow sea-level rise humans would more likely occupy coastal regions given the likelihood of increased productivity and proximity to food sources (Lowery and Martin, 2009; TRC Environmental Corporation, 2012). During higher rates of sea level rise, preservation of paleo-landforms is more likely to occur.

2.3 BOEM'S RECOMMENDATIONS FOR HIGH-RESOLUTION GEOPHYSICAL SURVEYS

Prior to conducting a site assessment survey, BOEM recommends that lessees and applicants participate in a pre-survey coordination meeting to discuss the survey's scope and objectives (BOEM, 2015a; 2015b). The purpose of this meeting is to ensure that the data acquired will allow BOEM to properly analyze the potential impacts on physical, biological, cultural, and socioeconomic resources, as well as the seafloor and sub-seafloor conditions near the proposed areas of construction, installation and operation. BOEM performs this impact analysis when reviewing the developer's submitted Site Assessment Plan (SAP), Construction and Operations Plan (COP), or General Activities Plan (GAP). The lessee's plans must be approved by BOEM prior to the commencement activities that could impact the OCS environment such as the installation of oceanographic and/or meteorological monitoring equipment, construction of wind turbines, and the installation of transmission cables. To best inform present and future companies interested in pursuing renewable energy resource on the U.S. OCS, BOEM has published recommended guidelines for the collection, use and dissemination of data for site characterization studies (BOEM, 2015a) and archaeological/historical property identification surveys (BOEM, 2015b). The collection and interpretation of high-resolution seismic data is integral to both of these surveys.

3.0 STUDY METHODOLOGY

Seismic data acquired in 2013 by Fugro was reprocessed and reinterpreted for Phase II of the Virginia Ocean Geophysical Survey. The goal of Phase II is to provide insight on methods to optimize the design, collection, processing and interpretation of seismic data for future site characterization and archaeological studies required as part of offshore wind energy development on the Atlantic OCS. A significant product of the present study is the "Paleo-Landform Catalog" that was created to be used to inform the general public, researches and industry members with representative interpreted seismic sections of numerous landforms likely to be encountered in the subsurface over much of the Atlantic OCS. In order to put these landforms into a regional context, a Relative Sea Level (RSL) curve was used to reconstruct past shoreline positions on the VA OCS covering the 20,000-year time span starting with the Last Glacial Maximum (LGM) and extending into the present.

3.1 SEISMIC DATA ACQUISITION AND PROCESSING

3.1.1 Data Acquisition: Fugro 2013 Survey

The sub-bottom seismic data presented in this report were collected in 2013 by Fugro as part of a high-resolution geophysical (HRG) survey aboard the vessel, *Tiki XIV* (Fugro, 2013b). Multibeam, side scan sonar, and magnetometer data were also collected during the survey along regional survey tracklines (Figures 2 and 12; Fugro, 2013b). Operations for the survey were conducted in accordance with the parameters, requirements, and mitigation procedures defined by the Final Environmental Analysis (BOEM, 2012b) for the Mid-Atlantic OCS.

Seismic data was collected over the Virginia WEA using two different, but complimentary seismic systems providing Fugro (2013b) with a more detailed understanding of subsurface conditions within the surveyed area (Fugro, 2013b). A high-resolution Chirp sub-bottom profiler provided detailed information of the shallow subsurface. Chirp signal penetration was generally limited to up to about 5 meters below the seafloor (e.g., Figure 13). That limited level of Chirp signal penetration is typical for much of the sandy seafloor environments on the Mid-Atlantic OCS. A medium penetrating, multi-channel boomer system was collected over the same tracklines as the Chirp data (Figure 2) and the record length was 500 milliseconds (which corresponds to subsea depths of approximately 400 to 500 meters).

A total of approximately 880 line-km of seismic data were acquired during the 2013 survey. The track-lines surveyed during the Virginia Ocean Geophysical Survey consist of three distinct sub-surveys (Figure 2; Fugro, 2013b), including:

1. A reconnaissance-scale regional grid totaling 635 line-km and collected over the entire Virginia WEA (100 and 200 series survey lines),

2. A site characterization-scale grid consisting of 35 line-km surveyed over two southern aliquots designated as a potential Research Lease No. 1 meteorological tower (300 and 400 series survey lines) and
3. Regional tie-lines (line series 500 and 600) extending 210 line-km connecting the WEA to the Chesapeake Light Tower (CLT) and the mouth of Chesapeake Bay (Fugro, 2013b).

The orientation and optimization of survey lines collected during the 2013 Fugro Virginia WEA survey was chosen so that primary lines would be collected perpendicular to the axes of a regional, buried paleo-channel systems that run across the Mid-Atlantic OCS (Figure 6). The survey line plan was developed with the use of Fugro's prior experience and the results of the "Geoscience-focused Desktop Study, Virginia Offshore Wind Energy Area, Virginia Outer Continental Shelf" (Fugro, 2013a and 2013b). The primary lines (line number series 100) within the WEA are oriented northeast-southwest and sub-parallel to regional isobaths (Figures 2 and 7). The tie-lines (line number series 200) were collected perpendicular to the primary lines, oriented northwest-southeast. The primary and lie lines are spaced at approximately 1.5 km and 3.6 km intervals, respectively.

The primary and tie-lines across the southern Research Lease No. 1 aliquots (line number series 300 and 400, respectively) are oriented parallel to the longer 100 and 200 series lines (Figure 2). The 300 and 400 series lines are spaced to provide coverage at 150-meter-spacing in the primary direction and 600-meter spacing in the tie-line direction. The closer line spacing of the 300 and 400 series lines were collected with the intent of illustrating how tighter line spacing could provide subsurface information needed to complete a site characterization study such as the identification of geohazards now required prior to BOEM's approval to begin activities related to offshore renewable energy resource development (BOEM, 2015a; Figure 2).

1.1.1.1 High-Resolution Chirp Sub-Bottom Profiler

High-resolution Chirp profiles were collected throughout the 2013 Fugro survey using an EdgeTech 3200-XS Sub-Bottom Profiling (SBP) system towed approximately 25 meters behind *Tiki XVI* in a SB-216S tow vehicle approximately 2 to 3 meters below the sea surface (Figure 12). For the 2013 survey, the transmitted frequency modulated pulse had a length of 20 milliseconds and swept over the 2 to 15 kilohertz range at a pulse rate of 8 hertz. The Chirp system provides excellent resolution in the near-seafloor beds, especially if the material is fine-grained and the correct acquisition parameters are used. For the 2013 Fugro survey, the Chirp's positioning and the selection of equipment parameters listed above provided a vertical resolution of roughly 10 centimeters and a horizontal resolution typically less than 1 meter. Reflections recorded in coarse-grained deposits typically penetrate 5 meters or less while penetration of over 20 meters is observable in fine-grained clays and silts. All navigation information and sub-bottom data were time tagged and logged to a hard drive.

1.1.1.2 Multi-Channel Boomer Seismic Reflection Data

An Applied Acoustics Engineering's CSP seismic energy source was used to power the Subsea Systems d-plate "boomer" system. The boomer plate(s) is an electro-mechanical transducer made of an insulated aluminum plate and a rubber diaphragm adjacent to a flat wound electrical coil. A short duration high-energy pulse is discharged from the energy source into the coil and the resulting magnetic field repels the plate in the transducer. The plate motion is transferred to the water by the rubber diaphragm, generating a broadband acoustic pulse that does not have strong cavitation or ringing. The source was fired at 0.75 second intervals to provide an average shot point interval of 1.5 meters. The speed of the vessel was maintained at nominally 4 knots to provide equidistant intervals between each shot point. In unusual circumstances, when winds, waves and/or currents altered the ability to maintain a constant speed of 4 knots, firing rates were adjusted in order to provide constant shot point distances.

The transmitted acoustic signal was received using a Subsea Systems' ethernet-based GeoEel digital hydrophone array. The hydrophone streamer consisted of 32-channels with two separate sections (Figure 12). The front section was comprised of 16 channels with each channel separated by a distance of 1.56 meters (i.e., 1.56 mgi), while the aft section consisted of 16 channels with a 3.125 mgi. The streamer geometry allows the data to be processed using the near 16 channels at a 1.56 mgi, utilizing 24 channels with a 3.125 mgi or processing all 32 channels utilizing the near 16 channels with a 1.56 mgi and the aft section of the streamer with a 3.125 mgi.

The streamer and boomer source were towed approximately 0.5 meters below the water surface. Data were recorded at a 0.25-millisecond sampling rate and the processed record length is 250 milliseconds for the 1.56-mgi data and 500 milliseconds for the processed 3.125-mgi data. Data were stored on hard disk in SEG-Y format for later processing. The boomer MCS data provided insight into deposits located over 100 meters below the seafloor and vertical resolution of approximately one meter (e.g., Figures 14 and 15).

3.1.2 Data Processing

1.1.1.3 Sub-bottom (Chirp) Profiler

Chirp sub-bottom data processing included checking and de-spiking all navigation points using Starfix.Proc, an application for automated (batch) processing of navigation data. After the data were cleaned, verification was made that the corrected navigation files were referenced from the towed position (where the sub-bottom was towed from the vessel). The corrected navigation data were then inserted into a raw JSF file (Edgetech's Proprietary format) using Starfix.Gplot (Addxyz). The JSF files were replayed through EdgeTech's Discover sub-bottom acquisition and processing software. Unlike typical Chirp processing methods that utilize a matched filter to produce a correlation from the raw signal (e.g., Quinn et al., 1998), the EdgeTech 3200-XS Sub-Bottom Profiling system makes use of proprietary amplitude and phase weighted functions for the transmitted pulse and a pulse compression filter that maximizes the signal to noise ratio (SNR) over a wide band of frequencies (EdgeTech, 2015). Following the data filtering, the JSF files were then converted to SEG-Y format and loaded into IHS Kingdom Suite version 8.8 for interpretation.

After loading the data into the workstation, the data were further enhanced to improve the ability to interpret the data by applying filters, gain settings, and correcting for apparent sea state artifacts.

To improve the ability to map the deeper portion of the Chirp record, an Automatic Gain Control (AGC) was applied to every Chirp line using a window of 15 milliseconds (Figure 16). While a Time-Varying Gain (TVG) may provide some improvement over the application of AGC, for Chirp data a TVG is often applied after auto-picking the seafloor which was not performed due to presence of sea state artifacts.

Fugro has developed a method that not only preserves the original data as collected at sea, but also removes the influence of the sea state without removing true geologic features. To do this, the seafloor of each Chirp line was picked by the seismic interpreter. Next, a gridded multibeam bathymetry dataset that was collected during acquisition of the Chirp data in 2013 was imported into the seismic project and converted to a horizon. The bathymetry grid was converted to a horizon and the Chirp lines were repositioned so that the picked seafloor horizon was correctly positioned at the multibeam-derived seafloor and thus eliminating the influence of the sea state (Figure 16). While this method showed significant improvement in the capability to interpret the subsurface for the 2013 Fugro dataset, caution should be used in applying this method to other dataset if: 1) the bathymetric dataset was collected either prior to or after Chirp data acquisition and significant changes (e.g., sand wave migration, current erosion) in the seafloor occurred between the collection of the two datasets, 2) the bathymetric dataset is of poor quality and/or low resolution (i.e., the grid's cell size is too large to properly image bedforms such as megaripples and sandwaves with wavelengths as small as 5 meters) when compared to Chirp data and 3) the seafloor of the Chirp data was not interpreted with care and precision.

1.1.1.4 Multi-channel (Boomer) Seismic Reflection Data

Several basic processing steps are typically applied to raw multi-channel seismic data prior to interpreting the data. The three main processing steps involve a) deconvolution which improves the temporal resolution by providing a sharper and more consistent seismic wavelet, b) common mid-point (CMP) stacking which increases the SNR through attenuation of random noise and multiples, and c) migration which attempts to reposition diffraction-producing point scatterers and dipping beds and faults to their true subsurface locations. For this report, the boomer MCS data were processed using three different receiver geometries in order to determine the benefits and disadvantages of acquiring data with different acquisition parameters. The acquisition parameters specifically analyzed include the ability to properly resolve near-surface features using variable intervals (i.e., distances) between each hydrophone group array, the impact of imaging as a function of uniform or hybrid receiver array designs and how the length between the boomer seismic source and farthest hydrophone group (i.e., far offset) influences depth of investigation and noise suppression. Additionally, an unprocessed single-channel example of Line 206 was used to show the benefits of acquiring and processing multi-channel seismic data.

To provide the best image resolution for these acquisition parameters, a final binning interval of 0.39 meters, equal to one-half the nominal binning interval for the streamer group interval was used. To increase fold and signal-to-noise ratio for this short CMP spacing, a three-element source mix was used with weights of 1-2-1 to form an acoustic beam focused downward with minimal side-lobes in the radiation pattern. Further random noise attenuation was accomplished after stacking, but before migration, by applying an F-X predictive filter with a high-cut frequency set to 900 Hertz. The remainder of the processing steps and the specific parameters used are typical for multichannel high-resolution seismic data listed below.

- Trace Editing, Scaling and Filtering,
- Spiking Deconvolution,
- Spatial Filter Design and Velocity Analysis,

- Normal Move-out Correction and Stack,
- Post-Stack Migration,
- Surface-Related Multiple Suppression, and
- Post-Migration Predictive Deconvolution.

At the onset of the data processing phase of this study, we evaluated several processing methods in order to select the method that provided the highest quality data. We also assessed whether to proceed with processing the 16 channels at 1.56 mgi dataset or 32 channels at 3.125 mgi. During the evaluation we compared processed data from the 1.56 mgi and 3.125 mgi streamers from selected lines. Based on our assessment, the 1.56 mgi streamer data provided slightly higher resolution and more detail particularly within 20 to 30 ms (approximately 15 to 25 meters) of the seafloor. However, the 3.125 mgi streamer provided more coherent signal in the interval between about 30 to 100 ms (approximately 25 to 75 meters) below the seafloor. Thus, for the purpose of providing a geologic framework of the study, we deemed that the 3.125 mgi would be the preferred dataset for interpretation during the Phase 1 study.

3.2 PALEO-LANDSCAPE RECONSTRUCTION

The Quaternary Period is characterized by changes in environmental conditions largely resulting from multiple episodes of ice sheet growth and glacial retreat. Glaciation in the Northern Hemisphere affected a large portion of the U.S. Atlantic Margin, not only by the submergence/emergence of regions near the coastlines due to eustatic sea level rise and fall but also by uplift and subsidence of regions due to glacioisostatic adjustment. The advance of glaciers into a previously unglaciated region results in the depression of land beneath the glacier and uplift of the proximal unglaciated region (e.g., Hobbs et al., 2008).

Much of the U.S. Mid-Atlantic coast is characterized by landforms associated with barrier-island systems (e.g., North Carolina's Outer Banks) and estuaries (e.g., Chesapeake Bay) that are indicative of a rising sea level. During the most recent sea level rise beginning in the Late Pleistocene, estuarine and barrier island systems migrated from former shoreline positions that are now submerged along the Atlantic OCS to their present position. In order to determine how these landforms evolved in space and time it is necessary to reconstruct a relative sea-level curve.

The reconstruction of past relative sea level requires accurate dating of geologic materials that can be correlated directly to former water levels. Along the U.S. Atlantic Margin, radiocarbon dating of plant material originating in coastal marshes (e.g., peat deposits) has provided insight into local variations in sea level rise throughout the Holocene (e.g., Engelhart and Horton, 2009). While dating these deposits has provided significant insight into regional relative sea level trends over the past 12,000 years BP, sea level positions from the time interval spanning the Last Glacial Maximum (approximately 20,000 years BP) until the Holocene in the Virginia WEA are unavailable. For this study, we have estimate approximate sea levels for the past 20,000 years BP using information contained in the Holocene sea level database for the Atlantic coast (Engelhart and Horton, 2009), the sea level information derived from Barbados corals (Fairbanks, 1992) and the dates for archaeological periods, significant climate events and sea level episodes defined and described in the BOEM-funded TRC Environmental Corporation (2012) report (Figure 17).

At the beginning and end of each archaeological, climatic and geological event of significance, the inferred position of former shorelines during the Late Pleistocene/Holocene transgression was plotted in plan-view using current bathymetric elevations surrounding the Virginia WEA (Figures 18a to 18c). The position of these inferred shorelines are approximations intended only to give a generalized overview of the submergence of the continental shelf in the area of interest for this study. These former shoreline positions, based on present-day elevations, do not account for erosion, deposition or glacio-isostatic adjustment occurring between the data represented in each image in Figures 18a to 18c and the present. This study provides an approximate correlation between the sea level rise curve (Figure 17) and interpreted paleo-landform features identified in Phases 1 and 2 of this study.

3.3 ASSESSING INFLUENCE OF LINE SPACING AND ORIENTATION ON PALEO-LANDFORM IDENTIFICATION

The portion of the New Jersey coastline used to model the influence of line spacing and orientation encompasses the outer Coastal Plain approximately 16 km north of Atlantic City, New Jersey where the Mullica River empties into Great Bay and Little Egg Inlet provides a link to the Atlantic Ocean. Tidal inlets separate the barrier islands of Brigantine Beach, Pullen Island and Long Beach Island (Figure 19). According to Oertel and Kraft (1994), the transition from northern wave-dominated barrier islands such as Long Beach Island to more tidally-influenced barrier islands to the south occurs approximately at Little Egg Inlet (Figure 19). The presence of features formed under the influence of both wave and tidal processes was one reason this area of New Jersey was selected to analyze line spacing and orientation for the present study. The second reason the site was selected is due to similarities in the subsurface structure in the Virginia WEA and the Great Bay, New Jersey region.

Carignan et al. (2009) created a single, digital elevation model (DEM) covering the Great Bay, New Jersey area with an approximately cell size of 10 by 10 meters by compiling bathymetric and topographic data from multiple sources (Figure 19). The availability of this dataset provides an excellent opportunity to compare present-day landforms with continuous spatial coverage to analogous paleo-landforms imaged in the seismic data collected during Fugro's 2013 Virginia Ocean Geophysical Survey and interpreted in this report. Fugro used the Carignan et al. (2009) DEM to analyze the influence of line spacing and orientation on the ability to interpret paleo-landforms. The three line spacings modeled were:

1. A reconnaissance-scale survey composed of a grid with primary lines spaced every 1500 meters and perpendicular tie-lines spaced every 3600 meters. The area analyzed is roughly the same size as the Virginia WEA (approximately 23.9 by 19.2 km) and the line spacing is the same spacing used in the 2013 Fugro survey (Figures 2 and Figures 20a to 20d).
2. A site characterization scale survey composed of a grid with primary lines spaced every 150 meters and perpendicular tie-lines spaced every 500 meters. The area analyzed is approximately 6 by 6 km which is slightly larger than a typical 4.8 by 4.8 km OCS block. The line spacing was selected to agree with BOEM's recommended guidelines for a site characterization survey (Figures 21a to 21d; BOEM, 2015a).
3. An archaeological scale survey composed of a grid with primary lines spaced every 30 meters and perpendicular tie-lines spaced every 500 meters. The area analyzed

is approximately 1.5 by 1.5 km which is slightly larger than a typical 1.2 by 1.2 km OCS block aliquot. The line spacing was selected to agree with BOEM's recommended guidelines for an archaeological/historic property survey (Figures 22a to 22d; BOEM, 2015b).

Modeling the influence of line orientation on the ability to interpret paleo-landforms was completed by using the line spacings described above and rotating them by 45 degrees producing a series of images that present a summary of each line orientation per figure:

1. Figures 20a, 21a, and 22a utilize primary lines oriented north-south and tie-lines oriented east-west. This grid geometry is used to mimic the collection of a seismic survey that does not consider the geometry (e.g., dominant strike and dip) of the features that are intended to be properly interpreted with the seismic dataset.
2. Figures 20b, 21b, and 22b utilize primary lines oriented northwest-southeast and tie-lines oriented northeast-southwest. This survey design represents the most common line orientation used in seismic exploration where the primary lines are collected along the regional dip. It should be noted that the primary lines of the reconnaissance survey shown in Figure 20b represent true dip-lines; meandering tidal inlets, highly sinuous creeks and variable orientations present on Pullen and Egg Island make it difficult to collect primary lines that run parallel to the varying dip direction seen on Figures 22a and 22b.
3. Figures 20c, 21c, and 22c utilize primary and tie-lines located 90 degrees from the lines shown in parts (a) and represent the design of a survey without considering the morphology of the landforms.
4. Figures 20d, 21d, and 22d utilized primary and tie-lines located 90 degrees from the lines shown in parts (b). The primary line orientation is perpendicular to the predominant dip of the landforms (e.g., Great Bay seen in Figure 20d, Little Egg Inlet in Figure 21d and the tidal channels of Egg Island in Figure 22d) and oblique to the present shoreline. Therefore, this particular grid orientation would likely best resolve the bays and channelized geomorphologic features.

The specific method used to analyze line orientation and spacing in Figures 20 through 22 involved the extraction of elevation data from the original DEM along every cell that intersected the survey lines. Next, the elevation at these cells were used to interpolate a grid across the area. Finally, the interpolated grid is shown in the bottom right corner of each part of Figures 20 through 22 with the present shoreline displayed on top of the grid in Figure 20 and transparent overlays of edge detection maps produced from the original DEM for Figures 21 and 22. The shoreline and edge detection overlays helped to identify where true features are and are not resolved as a result of the line spacing and orientation used to create the grid. Unresolved features are delineated using red lines or polygons.

4.0 DISCUSSION AND RESULTS

4.1 SEISMIC ACQUISITION PARAMETERS AND PROCESSING TECHNIQUES

The seismic systems and processing steps described in this section focus primarily on data collected by Fugro in 2013 and later reprocessed for this study to aid in the identification of paleo-landforms. Other high-resolution seismic systems and advanced processing techniques mentioned in this section are in no way meant to be comprehensive. These alternative systems and processing methods are mentioned here only to provide comparison with the boomer and Chirp data processed and interpreted for this study.

4.1.1 Seismic Acquisition System and Geometry Determination

The design of a seismic survey requires balancing of cost, time and effort in order to properly meet the objectives of each individual survey program. After determining that the logistics needed to conduct a survey are met (e.g., staff availability, proper weather conditions, site access, time constraints), the next step is determining the proper equipment to use for the survey. Offshore site investigations and marine archaeological studies require the use of high-resolution seismic systems to provide adequate imaging of the shallow subsurface (BOEM, 2015a and 2015b). While it would be ideal if a single acquisition system could be used to meet the needs of the engineering geologist and the archaeologist, unfortunately the tradeoff between resolution and depth of penetration is something that cannot be overlooked by either party. Therefore, it is necessary to collect seismic data using a medium penetrating system (such as a boomer) and also a high-resolution system (e.g., Chirp or echosounder) similar to the data collected as part of Fugro's 2013 VA WEA geophysical survey and described in BOEM's guidelines for seismic data collection as part of the site characterization requirements for offshore renewable energy development (BOEM, 2015a).

The main types of high-resolution seismic systems used to image the subsurface are listed in Table 3-1. Each system is characterized by a range of seismic energy frequency content used to image the subsurface. The determination of what seismic system is best suited to meet the objective of an individual project must take into account the trade-off between the depth of penetration and the vertical resolution of each system (Figures 13 and 23a). The marine archeologist is typically interested in obtaining the most detailed image of the subsurface near the seafloor where potential artifacts are most likely located and therefore a Chirp or echosounder (single or dual frequency) system is commonly utilized. Medium penetration systems (e.g. boomer or sparker) are typically used to correlate subsurface layers between geotechnical cores, borings and cone penetrometer test soundings (CPTs) and evaluate geohazards to support the planning and design of offshore structures. Typically, high-resolution Chirp and/or echosounder data are collected in conjunction with boomer and sparker data during the same survey to provide co-located data collected at the same time.

Table 4.1-1. Typical Characteristics of Different High-Resolution Seismic Systems

Seismic Source	Frequency Range	Vertical Resolution	Depth of Penetration
Pingers (Echosounders)[1]	3 to 12 kHz	5 to 20 cm	< 30 m in fine-grained sediment < 10 m in coarse-grained sediment
Chirp[2]	400 Hz to 24 kHz	2 cm to 1 m	< 150 m in fine-grained sediment < 20 m in coarse-grained sediment
Boomer	300 Hz to 6 kHz	10 cm to 1 m	< 300 m

Seismic Source	Frequency Range	Vertical Resolution	Depth of Penetration
Sparker[3]	40 Hz to 1.5 kHz	30 cm to 10 m	100 m to 1 km
Airgun (High-resolution)[4]	20 Hz to 2 kHz	20 cm to 20 m	20 m to 1 km

[1]Unlike conventional echosounders that emit a constant waveform with a single frequency, parametric echosounders transmit two high-frequency signals that produce a lower frequency signal through interference of the two transmitted frequencies.

[2]Chirp systems transmit a frequency modulated (FM) pulse that provides a high-resolution, low noise image by correlating the reflected data with the transmitted pulse.

[3]Frequency of a sparker system is tip and depth dependent

[4]High-resolution, small airgun sources differ from conventional O&G surveys that require a large energy source from airgun arrays to penetrate deep into the subsurface. High-resolution airgun surveys make use of a single or very few airguns with small air chamber volumes and shorter streamers, group intervals and offsets than a typical O&G survey. For example to image the shallow stratigraphy in Lake Simcoe, southern Ontario, Canada, Pugin et al. (1999) made use of a single airgun (1 cubic inch, ~1500 psi) fired every 5 meters and a 24-channel, 5 mgi streamer.

The ability to resolve paleo-landforms using seismic data is limited by subsurface conditions (e.g., wipe-out zones below gas-rich sediments), the field parameters used during data acquisition and the processing techniques applied to improve subsurface imaging. The transmitted and recorded frequencies, the seismic survey's geometry (i.e., source and streamer configuration) and the distance and orientation between adjacent lines are important parameters to consider when designing a survey and should be largely determined by the anticipated size and depth of buried subsurface features. The transmitted signal used by each seismic system shown in Table 4.1-1 is characterized by the frequency content and bandwidth which are related to the depth of penetration and the ability to resolve beds of varying vertical thicknesses. Seismic energy with higher frequency content provides higher resolution data but does not penetrate as deep as lower frequency data.

The above statement relating frequency content to vertical resolution and depth of penetration is a generalization that does not consider limitations imposed by the seismic survey's geometry (e.g., source and receiver offset), power levels used to generate the source signal, and the ability to process the data post acquisition. For seismic data consisting of a single source and receiver, the typical image that is produced represents a normal incidence reflection profile.

The selection of a medium-penetrating multi-channel seismic (MCS) system requires consideration not only of the frequencies transmitted as needed to penetrate and resolve the feature(s) of interest for a specific investigation, but also selection of the geometry of the survey and line orientation (e.g., Evans, 1997; Sheriff and Geldart, 1999). Determining the seismic survey's geometry is essential for the collection of MCS data because those parameters influence a number of critical factors such as the ability to achieve the maximum signal-to-noise ratio, determine the shallowest and deepest feature properly imaged and avoid aliasing so that the feature(s) of interest for the survey are resolvable.

The acquisition geometry used for the collection of the boomer MCS data for the 2013 Fugro WEA geophysical survey is shown in Figure 12. The selection of those parameters were based on the objective of the survey, mainly to compliment the data collected using the Chirp system (Figures 23a, 23b, 24a and 24b) and properly image the subsurface to a depth needed to map the base of unconsolidated Holocene/Late Pleistocene sequence (Horizon 30 shown in the seismic sections in Figures 14 and 15; Gridded horizon shown in Figure 10) and determine subsurface sediment variability down to a depth slightly in excess of potential future construction of wind turbines (e.g., Horizon 30 shown in the seismic sections in Figures 14 and 15; Gridded horizon shown in Figure 25).

A final consideration when designing a geophysical survey, as described in BOEM (2015a and 2015b) is minimal interference between the different geophysical systems. Coastal Planning & Engineering, Inc. (a CB&I Company), contracted by the Maryland Energy Administration, conducted a high-resolution geophysical survey in 2013 using a multichannel sparker seismic system for medium-penetration subsurface imaging. The electrical arc produced when triggering the sparker system caused short and distinct interference patterns visible in the magnetometer data as anomalous peaks, in the side scan sonar images as horizontal acoustic streaks and in the Chirp sub-bottom profiles as vertical acoustic streaks (Coastal Planning & Engineering, Inc., 2014). While these interference patterns were present in the data, their evenly spaced, distinct character allowed the artifacts to be discerned in the data and not mis-interpreted according to the Coastal Planning & Engineering, Inc. (2014) report.

4.1.2 Seismic Data Processing: Chirp Profiles

In general, processing of Chirp data requires minimal user interaction as the system's software automatically 1) deconvolves, correlates or match filters the transmitted signal with the received signal, 2) produces an analytic signal and 3) produces the envelope from the complex modulus of the analytic signal. These processing steps greatly improve the ability to interpret Chirp profiles resulting in an increased signal-to-noise ratio and smoothing an otherwise ringy signal (Quinn et al., 1998; Henkart, 2006). The Chirp's envelope is most-commonly used by geophysicists to interpret the data and map horizons. Amplitude gain is often applied to account for signal attenuation with depth so that deeper reflectors are more pronounced (Figure 16). If the seafloor has been autotracked, a time varying gain (TVG) is used, otherwise a windowed automatic gain control (AGC) may be applied. Chirp data should not be recorded as true amplitudes and not have TVG and AGC applied when recorded. TVG and AGC can be applied when interpreting the data to help enhance deeper sections of the data. True amplitude data allow the interpreter to compare relative amplitudes of reflectors to each other which is important part of the interpretation process. In the marine environment, waves can produce false undulations in the profile and swell filtering can remove this issue (Figure 16).

If the above processing steps are not applied correctly, the ability to make full use of the Chirp data will be severely limited (e.g., compare the unprocessed and processed profiles in Figure 16). Care must be taken when choosing the time-window and amplitude threshold for computer autotracking of the seafloor. If a mute is applied of the autotracked surface, it is possible that portions of the seafloor will be absent from the final image. Swell filters must also be applied with care or true seafloor features such as sandwaves can be smoothed over and essentially removed from the data.

Further signal processing of Chirp data is possible, although applied far less often. Trace mixing sums and averages multiple adjacent traces to produce a profile that can result in a more coherent profile and also a smaller file size. If the data is noisy and coherent reflectors are more or less flat, trace mixing can provide an improved subsurface image. Where large, sharp vertical changes occur along the profile (e.g., incised terrace, faults), migration may be applied in order to try to collapse diffractions and move dipping events to their supposedly true subsurface location. Migration requires the use of the correlated signal since the envelope signal contains no phase information and only positive values.

Recently, Baradello (2014) presented a Chirp processing sequence similar to the processing applied to land-based Vibroseis data by using the uncorrelated Chirp signal. In brief, this method creates a minimum-phase pulse through the application of a Wiener filter, followed by predictive deconvolution, FX-deconvolution and finally, Stolt migration. The final product is a seismic section that contains phase information and both higher vertical and lateral resolution than a typical Chirp profile produced using the envelope signal (Baradello, 2014). The benefit of using a more in-depth processing sequence is apparent in the images shown in Baradello (2014). The time and expertise required to perform this processing operation is often not available to a developer and may only be warranted if a known or highly probable archaeological feature is present in the survey.

4.1.3 Seismic Data Processing: Multi-Channel Boomer Data

The MCS data acquired by Fugro in 2013 in the Virginia WEA utilized a 32-channel streamer with the nearest 16-channels comprised receiver groups spaced every 1.56 meters apart while the 16-channels farthest from the boomer seismic source were comprised of groups of hydrophones each spaced 3.125 meters apart. Processing of MCS data greatly improves the ability to resolve subsurface features. Figures 26a to 26e show multiple examples of the same portion of seismic Line 206 processed using different group interval spacings (and incorporating different numbers of channels) with accompanying text boxes for each image explaining the main enhancements and drawbacks of the various processing techniques applied. Each part (i.e., a through e) of Figure 26 contains a 200 millisecond section approximately 2.75 km long that provides an image deep subsurface and how non-primary reflections (e.g., seabed multiple) influence interpreting the deep strata. As recommended by BOEM (2015a and 2015b), the seismic image should provide adequate imaging of the stratigraphic and structural variability extending 10 meters beyond the maximum depth of disturbance potentially impacted by offshore renewable energy development. This includes not only the depth impacted by construction of meteorological towers and wind turbines, but also the depth disturbed by geotechnical data collection such as the drilling of boreholes.

Also shown in Figures 26a through 26e, is an inset of Line 206 that contains an incised-valley filled by multiple stacked, channelized features. This inset covers an interval approximately 15 meters below the seafloor and is meant to show how well boomer data fulfills BOEM's (2015a and 2015b) recommendation to provide vertical resolution of 0.3 meters over a 10-meter interval below the seafloor. Vertical resolution or the limit of separability (the ability to define the top and bottom of a bed) of seismic data is typically defined by the Rayleigh limit of resolution which requires that a bed has a thickness of 1/4 of the dominant wavelength to be properly resolved. The dominant wavelength is equal to the velocity divided by the dominant frequency. To vertically resolve the top and bottom of a bed 0.3 meters thick, the dominant frequency of the received seismic signal (assuming a velocity of 1,500 meters per second) would need to be 750 Hertz or higher. The limit of visibility (ability to detect a bed) is generally considered to be 1/10 to 1/40 of the dominant wavelength of the seismic data.

As with any seismic survey, the primary objective of data collection and processing is to provide the highest quality data over the feature(s) of interest defined in the project's scope. For the present study, Fugro attempted to process a single multi-channel seismic dataset collected over the Virginia WEA using three different streamer configurations. Additionally, a single-channel section (taken from channel #4 of the MCS data) is shown in Figure 26a to allow comparison with the processed MCS data shown in Figures 26b to 26e. Processing of single-channel seismic data is limited, due to the inability to increase the SNR as a result of CMP-binning, Normal Moveout correction and stacking. The primary processing techniques applied to single-channel seismic sections are deconvolution, frequency filtering and migration.

At the onset of the data processing for Phase I of the Virginia Ocean Geophysical Survey, Fugro evaluated several processing methods in order to select the method that provided the highest quality data that would satisfy the objective of the survey. One effort that was performed during this trial phase resulted in processing Line 500 near the Chesapeake Light Tower with 16 channels at 1.56 mgi dataset and also with 24 channels at 3.125 mgi (Fugro, 2013b). Based on the original assessment, the 1.56 mgi streamer data provided slightly higher resolution and more detail particularly within 20 to 30 ms (approximately 15 to 25 meters) of the seafloor. However, the 3.125 mgi streamer provided more coherent signal in the interval between about 30 to 100 ms (approximately 25 to 75 meters) below the seafloor.

For Line 206, processing results utilizing hydrophone groups spaced evenly every 3.125 meters are shown in Figure 26b. In order to map seismic reflectors below the occurrence of the seafloor multiple, a surface-related multiple suppression process was applied to the 3.125 mgi, data (Figure 26c). The focus of the present study was to determine whether data processed with shorter group intervals could provide higher-resolution data to help identify paleo-landforms and characterize the shallow subsurface for site investigation studies. The three main improvements seen by processing data with shorter group intervals (i.e., 16 channels at 1.56 mgi compared to 24 channels at 3.125 mgi) is the ability to define small features close to the seafloor that dip at angles greater than approximately 10 degrees (e.g., channel margins), the ability to resolve features of limited lateral continuity and the ability to resolve features at a higher vertical resolution (Figures 26b and 26d).

After the 1.56 mgi data was loaded into the SMT seismic project, it became clear that the 1.56 mgi boomer data (when compared with the 3.125 mgi data) facilitated better correlation with seismic events imaged using the high-resolution Chirp system and improved our ability to interpret the shallow section (Figure 27). Additionally, the 1.56 mgi data provided greater horizontal resolution so that portions of surfaces that were difficult to map using the 3.125 mgi data due to reflector discontinuities (produced due to inadequate spatial sampling) were properly resolved (Figures 26b and 26d). The only observed benefit of using the 3.125 mgi dataset to interpret the shallow section came from the fact that the higher fold used when processing the data improved the ability to interpret data where noisy traces had severely degraded the image (compare the inset in Figures 26b and 26d).

After comparing the processed seismic data using the 1.56 mgi and 3.125 mgi, a third processing method using all 32 channels collected with variable group intervals (1.56 mgi and 3.125 mgi for the nearest and farthest sections from the boomer source, respectively) was performed and allowed the shallow surface to be imaged in sufficient detail along with an increase in the SNR in the deeper section due to the utilization of more channels (Figure 26e). Therefore, for the purpose of providing a geologic framework of the study for Phase 1, the remaining data were processed using a hybrid method that incorporated the 32 channels of data as a 3.125 mgi data set. A summary of the main parameters that were influenced by the processing techniques used in this summary are shown in Table 3-2.

While the processing of the data using the difference group intervals were performed by an experienced seismic data processor, there are also opportunities to improve the ability to image features through the use of various filters after the data has been loaded into a seismic workstation for interpretation. In Figure 28, the loaded boomer MCS data contains frequencies covering a large bandwidth and correlation of reflectors with the Chirp sub-bottom profile appears to be poor. Through the application of a high-pass Butterworth filter, reflectors in the MCS section that dip towards the center of the image (up to approximately 275 meters offset) are well aligned with the dipping reflectors seen in the Chirp data.

Table 4.1-2. Influence of Boomer Acquisition Parameters on Subsurface Imaging

Acquisition Parameter	Single Channel	16-Channel MCS	24-Channel MCS	32-Channel Hybrid MCS	Influence on Subsurface Imaging
Number of Channels	1	16	24	32	More channels provide improved SNR by increasing CMP fold More channels can be used to shorten the group interval More channels can provide greater far offsets
Group Interval (meters)	-	1.56	3.125	1.56 (nearest 16 channels) 3.125 (farthest 16 channels)	Shorter group intervals reduces spatial aliasing so dipping beds are properly imaged improving horizontal resolution
Hydrophones per group (spaced every 0.78125 m)	2	2	4	2 (nearest 16 channels) 4 (farthest 16 channels)	More hydrophones in each group increases SNR
CMP Interval (meters)	-	0.78125	~1	~1	Smaller CMP intervals provides improved SNR
CMP Fold	-	8	24	24	Higher fold provides improved SNR
Bandwidth (hertz)*	140 to 260	100 to 650	100 to 650	100 to 650	Higher frequencies provide greater vertical resolution
Dominant Frequency (hertz)*	~120	~120	~120	~120	Higher frequencies provide greater vertical resolution
Far Offset (meters)	6.25	30.25	80.25	80.25	**Increasing far offset** Positive effects: • Allows for improved velocity analysis • Helps suppress multiples • Provides greater depth of investigation • Are required to map deep, dipping reflectors Negative effects: • NMO stretch reduces SNR from stacking

*Frequency content measured between seafloor and first seafloor multiple for Line 206

4.2 PALEO-LANDSCAPE IDENTIFICATION AND SHORELINE RECONSTRUCTION

The creation of the "Paleo-Landform Catalog", described in this section of the report and shown in Figures 29a through 29e, was completed in hopes of providing both the general public and members of the research community with a visual aid to help understand how the various landforms were interpreted through the use of seismic reflection data. Additionally, submission of an archaeological assessment report to BOEM requires a paleolandscape reconstruction analysis including interpreted seismic sections for each landform of archaeological interest identified (BOEM, 2015b). The “Paleo-Landform Catalog” can be used to help inform future offshore renewable energy developers with a template to perform this task. While the images presented in this section were taken from the 2013 Fugro Survey on Virginia’s Outer Continental Shelf, the paleo-landforms identified are not unique to offshore Virginia and represent common landforms that can be found both in modern settings as well as preserved in the geologic units buried below the Earth’s surface.

The ability to resolve paleo-landforms using seismic data is limited by the subsurface conditions and the original design of the seismic survey, specifically the frequency content of the system, the geometry of the source and streamer and the distance and orientation between adjacent lines. The identification of paleo-landforms were accomplished using multichannel (boomer) seismic data and Chirp sub-bottom profiles acquired by Fugro in 2013 and reprocessed for this study. Various paleo-landforms were identified within the study area and linked to key geologic events of local, regional and global significance. Glacioeustatic processes have dominated the geologic landscape during the Quaternary Period leading to multiple episodes of glacial advance and retreat, land subsidence and isostatic rebound and falling and rising seas.

Interpretation of paleo-landforms on the OCS with 2-D seismic data is a difficult task that is aided by knowledge of past coastline positions (Figures 18a to 18c), the utilization and correlation of different data types (e.g., Figures 23a, 23b, 24a and 24b), and when available, the incorporation of ground-truthed data such as that determined from grab samples, cores and petrophysical information. While most of the images shown in the “Paleo-Landform Catalog” are taken from the Chirp dataset, we stress the importance of the multichannel “boomer” dataset in allowing us to put these Chirp lines in their proper context. For example, the meandering channel sequences outlined in Figure 29f were aided by interpretation of the boomer MCS data (Figure 24b). Without the ability to correlate horizons laterally across the dataset, features such as those found within the broad incised valley could have been attributed to localized features of limited lateral extent (e.g., Figures 14 and 15).

Through the use of correlating horizons using the boomer MCS data, structural variations (i.e., strike and dip) and the deposition of depocenters could be identified (Figures 10 and 25). The paleochannels interpreted in Figure 9 are a result of correlating the base of the Holocene/Late Pleistocene sequence using the boomer data. Without the MCS data, correlation of this horizon would not have been possible. Additionally, the boomer data collected in the WEA allowed correlation with Uniboom data collected by Woods Hole Oceanographic Institute aboard *Atlantis II* in 1975 during Leg 2 of Cruise 89. The base of the Holocene/Late Pleistocene sequence mapped in the 2013 Fugro VA WEA correlated with the base of a large infilled-valley imaged in the 1975 Uniboom data that likely represents the ancestral Susquehanna River that delivered sediment from the east to the present-day shelf break near the Norfolk Canyon.

Through the use of 1) the Relative Sea Level (RSL) curve from Figure 17, 2) the inferred former shoreline positions based on this RSL curve and the modern bathymetry (Figures 18a to 18c), 3) previous geologic studies of the Virginia Continental Shelf (e.g., Swift et al., 1973; Swift, 1975; and Coleman et al., 1988) and 4) the generalized geologic models of Figure 5 for a barrier island system (Reinson, 1992) and a tide-dominated estuary (Dalrymple et al., 1992) the reconstruction of a complex geologic history of the Virginia Continental Shelf can be determined through rigorous analysis.

4.2.1 Paleo-Landform Identification: Impact of Line Spacing/Orientation

Landforms are three-dimensional bodies with distinct morphologies that can often provide clues about environmental processes (of geological, chemical and biological origin) that contributed to their creation and modification. The best way to identify the geometry of a paleo-landform using remote sensing, would require the acquisition and interpretation of a 3-D dataset with the proper resolution so that the entire three-dimensional body could be recognized. The collection of 3-D datasets are not uncommon in geotechnical engineering studies but they are far less common than 2-D data primarily due to the cost needed to acquire, process and interpret the data. Given that the U.S. offshore renewable energy industry is still in the early stages of development, the likelihood of collecting a 3-D seismic survey along the Atlantic OCS in support of renewable energy development seems unlikely unless the identification of a preserved pre-contact archaeological site is discovered and a small-scale 3-D Chirp survey is collected over the site.

In order to understand the optimal orientation and spacing between adjacent seismic lines collected as part of a 2-D HRG survey for offshore renewable energy development, Fugro utilized the DEM described in Section 3.3 near Great Bay, New Jersey to help understand the limitations imposed by the geometry of the area illuminated by subsurface imaging. The analysis presented in this section of the report represents a "best-case scenario" where there is total illumination of the subsurface horizon of interest along each line. In reality, this will very rarely be the case given variable environmental/geologic conditions such as the presence of noise produced during data acquisition, the transmission of limited seismic energy into the subsurface due to large vertical changes in the velocity and/or density present in the subsurface, or poor imaging due to the masking of primary reflections by multiples. While the data acquired and processed in the identification of paleo-landforms will limit the seismic interpreter's ability to map the subsurface, one point we hope has been made apparent in the present study is that the use of multiple yet complementary data sets (with different resolving capabilities and penetrating capabilities) will lead to the most comprehensive understanding of subsurface conditions (e.g., Figures 23a, 23b, 24a and 24b).

1.1.1.5 Line Spacing Discussion

As described in previous sections, designing a survey is limited not only by the objective of the survey but also by the budget and time required to conduct, process and interpret the data collected. While BOEM (2015a and 2015b) has provided recommendations on the proper line spacing needed for site characterization and archaeological surveys for both project siting and along the transmission cable corridor, line spacing for a regional or reconnaissance-scale survey is largely left up to the lessee with a few caveats suggested by BOEM (2015a). BOEM (2015a) recommends that if the lessee intends to use the reconnaissance data as part of a phased approach for completing a site characterization study, they will need to use seismic acquisition system(s) that will satisfy the resolution and depth of penetration standards as recommended by BOEM and that the amount of time between the reconnaissance survey and a more site specific geophysical survey be minimized given the dynamic nature of the seabed.

These regional surveys, such as the 2013 Fugro VA WEA Geophysical Survey used in the present study, can be used to help formulate the regional structural and stratigraphic framework of the area of potential offshore renewable development, and by making use of larger spacing between adjacent lines, the financial costs needed to focus initial development in a new field can be minimized. Even though the 2013 Fugro VA WEA survey was collected with the intent of providing a regional perspective on the subsurface, the high-resolution seismic datasets still provided detailed information about the various sub-environments within the large paleovalley mapped in the east-northeast section of the Virginia WEA.

After defining the size of smallest target needed to be resolved in a seismic survey, Evans (1997) suggests that at least three lines crossing the feature are required: one line defining the center and two defining the edges. If the target is roughly circular, the spacing between the lines should be equal to the radius and the tie-lines should be collected with spacing less than or equal to the circular features diameter (Evans, 1997). On the other hand, if the target is an elongated body, such as a channel, an inlet or a barrier island, the primary lines should be collected perpendicular to the maximum length and also need to be spaced at most half the length of the elongated feature (Evans, 1997). One way to ascertain whether or not the survey's design properly sampled the feature(s) of interest will become obvious once in the hands of a seismic interpreter. If the interpreter is unable to correlate the feature from line-to-line, the survey's line spacing is inadequate. Unfortunately, the interpretation of the data often comes post acquisition, but with new technology that allow data transmission between the vessel and seismic processors and interpreters in near real-time, it may be possible to collect infill lines before the survey comes to conclusion.

1.1.1.6 Line Orientation Discussion

The orientation of lines collected as part of a standard 2-D seismic survey grid are designed such that primary lines run parallel to the maximum dip direction while tie-lines are oriented perpendicular to the primary lines along strike. Designing a seismic survey therefore requires knowledge about the size, shape and orientation of the intended target(s) that can best be determined through the use of pre-existing seismic data within the survey area. If seismic data does not exist, the use of available geological and/or geophysical data (e.g., borings, geologic maps, bathymetric trends, regional gravity and/or magnetic surveys) within or near the survey area can help define geologic trends and guide the selection of line orientation. If knowledge of the subsurface is extremely limited, Evans (1997) suggests collecting perpendicular sets of lines that form a uniform grid over the entire survey area. While not based on underlying geologic conditions, the position of pre-existing offshore structures, primary navigation routes, and prevailing oceanographic conditions may also dictate the orientation of data collection. If oceanographic currents are strong, feathering of the streamer used for the collection of MCS data may cause problems in CMP binning if the positioning of the hydrophone groups are not accurately recorded and a rough sea-state can also contribute significant noise for HRG surveys since the source and streamer are towed very close to the sea-surface.

Line orientation must be carefully considered so that important subsurface features are imaged adequately and in areas containing multiple targets, each target should be crossed at least once, preferably along the direction of maximum dip (Evans, 1997). There are numerous reasons why primary lines are collected along dip, most importantly is that dip lines provide the clearest image of subsurface bedding and structural changes. Strike-lines are needed in areas that have no preexisting seismic data so that correlation between dip lines is possible and a coherent picture of the subsurface is produced. The orientation of the lines collected as part of the 2013 Fugro VA WEA survey was selected so that the primary lines were perpendicular to the regional trend of the buried offshore paleo-channel system that underlies the Mid-Atlantic OCS (Fugro, 2013b). The collection of the lines in this direction was to ensure that the primary lines were collected perpendicular to direction of maximum dip at the edges of the paleo-drainage system.

Choosing the dip direction as the primary line orientation also minimizes the influence of 3-D effects on the imaging of the subsurface. If a line is collected oblique to the dominant dip direction (i.e., cross-dip line), the underlying geologic structure is obscured since the first reflections to return from the subsurface will be from the updip plane of the dipping layer and therefore the reflector from a dipping bed will appear shallower than it is in reality. Another important consideration related to line orientation is the effect of migration on the proper positioning of dipping events. In 3-D surveys, diffractions produced from point scatterers are considered part of the seismic signal because 3-D migration will properly position these events in their true subsurface adding to an improved image of the subsurface. In 2-D datasets, the origin of a point that leads to diffraction events can be located out of the plane of the line surveyed and therefore 2-D migration will lead to misties because dipping beds imaged on dip lines will be repositioned in the correct location while the same dipping beds will appear flat on strike lines and will not be repositioned in migration (Evans, 1997).

While line spacing and orientation have been discussed above, there are several other considerations that must be taken into account. For example, when collecting a MCS seismic line, the line must begin and end a certain distance in excess of the survey area so that there is full fold coverage within the area of interest. Additionally, if diffractions are only partially imaged within the survey, collection of lines outside of the original area of focus will allow proper migration of these events. As a final note, the more ground-truth data available for correlation of subsurface reflectors, the better the outcome of the interpretation of the subsurface. For example, Figure 30 shows the view of the Great Bay, New Jersey region as that shown in Figure 19 with the exception that areas corresponding to sand ridges mapped in the VA WEA have been overlain on top of the New Jersey DEM to simulate the inability to penetrate greater than 10 meters below the subsurface with Chirp data. If only Chirp data were collected in an offshore environment with similar buried geomorphologic features, a significant amount of information could not be resolved no matter the line spacing or orientation chosen. In situations like this (or where shallow gas limits the ability to use MCS data to map the subsurface), the true nature of the subsurface can only be determined through the analysis of cores, borings and CPTs.

1.1.1.7 Results of the Line Spacing and Orientation Analysis

As described in Section 3.3, three different line spacings and four different line orientations were analyzed for the present report which greatly influence the ability to properly image and interpret subsurface stratigraphy of different geometries. The results from our analysis of line spacing and orientation are shown in Figures 20a to 20d for a reconnaissance-scale survey, Figures 21a to 21d for a site characterization survey and Figures 22a to 22d for an archaeological survey. The results of these features resolved and unresolved as part of this analysis are described in Table 4.2-1.

Of the three survey-sizes analyzed, the reconnaissance-scale survey showed the greatest impact resulting from the limitations of identifying paleo-landforms due to line spacing and orientation. One explanation for this is the overall orientation of features aligned parallel with the shoreline, with the exception of the Mullica River that drains the mainland and the various inlets that allow the exchange of water between the bays and the Atlantic Ocean. For the smaller-scale "site-characterization" and "archaeological" surveys, the paleo-landforms are less aligned with the shoreline and the channels and creeks are more sinuous. For a regional or reconnaissance-scale survey it is highly recommended to take into consideration the underlying geometry of the feature(s) of interest. Almost all features, with the exception of the inlets, are best imaged in Figure 20b where the primary lines are aligned in the dominant dip direction.

The line spacing for each survey serves the need of each survey's general objective. With the aid a seismic interpreter observing not only the surface of the mapped paleo-landforms, but also the seismic character in cross-sections, the overall transition from a fluvial environment to an offshore shoreface would likely be discernable given the optimal line orientation for the regional survey. It is apparent that the tie-line spacing is much tighter with respect to the area surveyed for the site characterization survey and while this may seem disproportionate, the line spacing allows the collection of an archaeological scale survey through the acquisition of three lines between every two lines of the site characterization survey. The line spacing of the site characterization survey would very likely show enough detail into the shallow subsurface to allow any sediment variability or geohazards to be properly identified.

The archaeological-scale survey images the subsurface in significant detail that at the outset of collection of this data it may be necessary to determine the cost/benefit analysis of collecting a 3-D Chirp survey if the feature(s) are likely of very high archaeological importance. The specific objectives of an archaeological survey need to be defined up front so that if, for example, a levee of a highly sinuous channel is the archaeological site of interest, the survey is oriented to best image the area surrounding the site.

Table 4.2-1. Line Spacing and Orientation Analysis

Survey Scale		**Primary Line Orientation**			
		N-S	NW-SE	E-W	NE-SW
Reconnaissance (Figure 20) 1500 X 3600 m	Resolved	-Antecedent topography (Leeds Point/Parkers Landing) -Great Bay	-Orientation of Antecedent topography -Great Bay -Barrier Island (Long Beach Island) -Offshore ridges	-Antecedent topography (Leeds Point/Parkers Landing) -Great Bay	-Orientation of Antecedent topography -Great Bay -Little Egg Harbor and Reeds Bay -Offshore ridges

Survey Scale		Primary Line Orientation			
		N-S	NW-SE	E-W	NE-SW
	Unresolved	-Highly sinuous portions of Mullica River -Inlets (Brigantine Channel; Inlets connecting Little Egg Harbor with Little Egg Inlet) -Barrier Island (Long Beach Island) -Offshore ridges	-Highly sinuous portions of Mullica River -Inlets (Brigantine Channel; Inlets between Great Bay Blvd. and Barrel Island) -Seven Islands	-Highly sinuous portions of Mullica River -Inlets (Brigantine Channel; Inlets between Great Bay Blvd. and Barrel Island) -Little Egg Inlet channel is not true shape -Offshore ridges	-Highly sinuous portions of Mullica River -Inlets (Brigantine Channel; Inlets connecting Little Egg Harbor with Little Egg Inlet) -Barrier Island (Long Beach Island)
Site Characterization (Figure 21) 150 X 500 m	Resolved	-Little Egg Inlet main tidal channel -Overall morphology of edge of Long Beach and Pullen Island	-Little Egg Inlet main tidal channel -Overall morphology of edge of Long Beach and Pullen Island	-Little Egg Inlet main tidal channel -Overall morphology of edge of Long Beach and Pullen Island -Details of Seven Islands	-Little Egg Inlet main tidal channel -Overall morphology of edge of Long Beach and Pullen Island -Details of Seven Islands
	Unresolved	-Beach ridges of Long Beach Island -Small, sinuous creeks of Pullen Island and Great Bay Blvd. -Details of Seven Islands	-Sharp edge of Little Egg Inlet main tidal channel -Beach ridges of Long Beach Island -Small, sinuous creeks of Pullen Island and Great Bay Blvd. -Details of Seven Islands	-Beach ridges of Long Beach Island -Small, sinuous creeks of Pullen Island and Great Bay Blvd.	-Sharp edge of Little Egg Inlet main tidal channel -Beach ridges of Long Beach Island -Small, sinuous creeks of Pullen Island and Great Bay Blvd.
Archaeological (Figure 22) 30 X 500 m	Resolved	Most features (See individual images)			
	Unresolved	Connections between drainages (see individual images)			

5.0 CONCLUSIONS

For Phase II of the Virginia Ocean Geophysical Survey, Fugro reprocessed and reinterpreted boomer and Chirp data collected by Fugro in 2013 over the Virginia WEA. The reprocessing of the previously collected data allowed Fugro to interpret diagnostic paleo-landforms in the dataset associated with incised-valleys, barrier island systems and estuarine environments. The reconstruction of past shorelines in the region surrounding the Virginia WEA supported our interpretation of the various identified paleo-landforms. Our ability to interpret details of the subsurface were enhanced through interpreting regional horizons using medium-penetrating boomer MCS data in conjunction with detailed mapping of high-resolution Chirp data. Using BOEM's (2015a and 2015b) recommendations for the collection of seismic data prior to the geotechnical information in support of site characterization and archaeological studies for offshore renewable energy development, Fugro analyzed the various seismic systems, acquisition parameters and line spacings/orientations to meet the recommendations of BOEM.

5.1 IMPLICATIONS IN SUPPORTING SITE CHARACTERIZATION FOR OFFSHORE WIND ENERGY DEVELOPMENT

BOEM (2015a) includes no specific guidelines related to the acquisition of a reconnaissance-scale seismic survey, such as the survey collected by Fugro in 2013 over the Virginia WEA and utilized in this study. BOEM's (2015a) only recommendations are that 1) if the lines surveyed at a regional-scale are to be included as part of a phased approach, that they are collected with the proper resolution and penetration depth required for a site characterization study, 2) the lines are spaced at such a distance that infill lines can be collected to provide adequate coverage and 3) the span of time between collection of the reconnaissance survey and a site characterization survey is minimized given the dynamic seafloor environment. In Phase I (Fugro, 2013b) and Phase II (the present study) of the Virginia Ocean Geophysical Survey, our goal was to prove the usefulness of a regional-scale survey needed to conceptualize subsurface details needed to properly design a smaller-scale survey required to pass BOEM's approval before offshore industrial activities commence. These two phases also hope to provide inexperienced lessees with information to help their understanding of operating in a new marine environment.

Specifically, the regional Fugro 2013 survey provided many of the requirements needed for a site investigation survey. For example, a structure and thickness map to the base of the Late Pleistocene/Holocene unconformity was mapped and deeper horizons were also mapped that potentially could lie at depths impacted by future offshore renewable energy development, such as turbine construction and borehole drilling. The collection, processing and interpretation of both the Chirp and boomer MCS data were used together with the Chirp data helping characterize the shallow subsurface and internal geometries of paleo-channels while the boomer MCS data provided a fuller picture of the subsurface with deeper penetration and horizons that were mappable across the survey area. The boomer MCS data also provides amplitude information that can be used to infer rock properties based on acoustic impedance contrasts.

Identification of many geological hazards would also be possible using a reconnaissance-scale survey if the hazards have a large areal extent, such as a regional fault or shallow biogenic gas formed in a back barrier system. In areas with poor signal penetration due to shallow gas or large increases in acoustic impedance contrasts, a reconnaissance survey can help define these areas and guide how to best image the subsurface using other acquisition systems and field parameters for site characterization studies. The reconnaissance survey collected by Fugro in 2013 also provided correlation between the nearest boring at the Chesapeake Light Tower and to onshore outcrops near the mouth of Chesapeake Bay.

The needs of the geotechnical engineer and/or engineering geologist, are best met through the use of both Chirp and boomer seismic data. The acquisition of Chirp or echosounder data should always be collected if MCS data is being acquired because the added benefit far outweighs the minimal efforts to process the data even if the data are never used in the final analysis. Other added benefits in acquiring and processing MCS data come from the suppression of coherent and random noise such as reverberations and multiple reflections. Other processes such as deconvolution and migration also improve the temporal and spatial resolution of the data. Our own efforts to improve the resolution of the shallow section by using closer-spaced group intervals illustrates the added benefit of MCS data processing.

BOEM's (2015a) suggested line spacing for site characterization surveys appear to provide adequate coverage in the area of New Jersey analyzed as needed to characterize subsurface variability. Line orientation seems less important in site characterization studies unless geologic features have distinct orientations. For example, if the collection and interpretation of Chirp data is of prime interest and sand ridges are aligned in a specific direction, it would be optimal to collect data in troughs parallel to the ridges. Using this method, the areas with the thinnest sand accumulation in the ridge troughs are adequately sampled and if the sand ridges do not run the entire length of the survey, the intervening lows between the ridges should be sampled by tie-lines.

5.2 IMPLICATIONS FOR SUPPORTING MARINE ARCHEOLOGICAL RESEARCH

In a sense, the archaeological community interested in prehistoric human occupation of the continental shelf face the same challenge that is confronted by the O&G industry and largely absent in the development of renewable energy: How do I locate resources, be they cultural or mineral, in an area that cannot be observed directly? The O&G tackled this problem through the use of remote sensing, applying knowledge derived from analogous geological settings found in other parts of the world and by making use of nearby data (e.g., outcrops, wells, seismic data) to understand a frontier area. These same techniques will be required to advance the study of archaeological resources located on the OCS.

The location of future offshore renewable energy development is in an area that has not been subject to extensive archaeological investigation in the past. Archaeologists will have to make use of the extensive amounts of information that exist at analogous archaeological sites located and onshore and apply both proven and new techniques to study these frontier areas. Through funding studies such as the present study, BOEM is attempting to ensure that developers conduct better designed surveys in order to gather information required to reconstruct former landscapes, consider the level of preservation of these landscapes, and make use the existing knowledge of onshore archaeological site distribution as an analogy for modelling the potential for the presence and location of sites offshore.

The guidelines of BOEM (2015b), recommend that lessees, applicants or developers seek the advice of a member of the historic preservation professional or a contractor (e.g., archaeologist, geomorphologist, architectural historian) prior to a pre-survey coordination meeting with BOEM in order to identify potential historic sites within the region affected by proposed activities related to alternative energy planning and development. This report describes in detail that there are numerous pre-survey decisions that need to be made prior to the onset of the geophysical survey. Equipment selection, survey line orientation and data processing will all require the involvement of a team of professionals. The inclusion of an archaeologist in this survey design team is vital to the success of the geophysical survey and guarantees that the data is sufficient to meet all of the needs required by BOEM (2015a and 2015b). This is the reason BOEM requests that the developer engage with a consulting archaeologist along with BOEM early in the planning process.

The present study highlights how the acquisition and analysis of reconnaissance-scale survey can greatly aid the planning of smaller-scale archaeological surveys. While the primary line spacing of the 2013 Fugro survey is 50 times larger than an archaeological survey, the survey fulfilled many of the recommended products produced for an archaeological-scale survey, at a coarser scale. The acquisition of both high-resolution Chirp data and the application of varying processing methods used to improve the resolution of the boomer MCS data show that many of the paleo-landforms buried in the Virginia WEA could be properly identified (including the delineation of multiple generations of channel fill) and these paleo-landforms could accurately by tied to the regional Late Pleistocene/Holocene unconformity that could only be properly mapped with the boomer data.

In order to properly identify potential pre-contact archaeological sites inundated by Late Quaternary sea level rise and within the depth interval possibly impacted by offshore renewable activities, it is necessary to collect boomer data. Chirp data will also need to be acquired to provide the proper resolution in the upper 10 to 15 meters below the seafloor. An archaeological survey needs to be defined with specific objectives and input from a professional marine archaeologist, because at such tight line spacing, the surveys orientation needs to be based on where a potential preserved site is positioned and the likely orientation of the site such as along the levee of a migrating channel. For this reason, we agree with BOEM (2015b), that their recommendations are not meant to provide a one-size-fits-all surveying method but rather a template for discussion. Developers should be encouraged to put more thought into survey design and interact with BOEM to ensure that developers with little experience in the offshore environment do not underestimate the level of effort needed to conduct a proper geophysical survey.

The recreation of a Relative Sea Level curve near the Virginia WEA and the modeling of past shorelines have shown the distinct correlation between the creation and modification of paleo-landforms in the area. Specifically, the present bathymetry in the study area shows relict, preserved paleo-landforms that likely avoided erosion during transgression due to the inundation of the Virginia WEA during Meltwater Pulse 1b (MWP1b) when rapid sea-level rise led to the barrier-bypassing.

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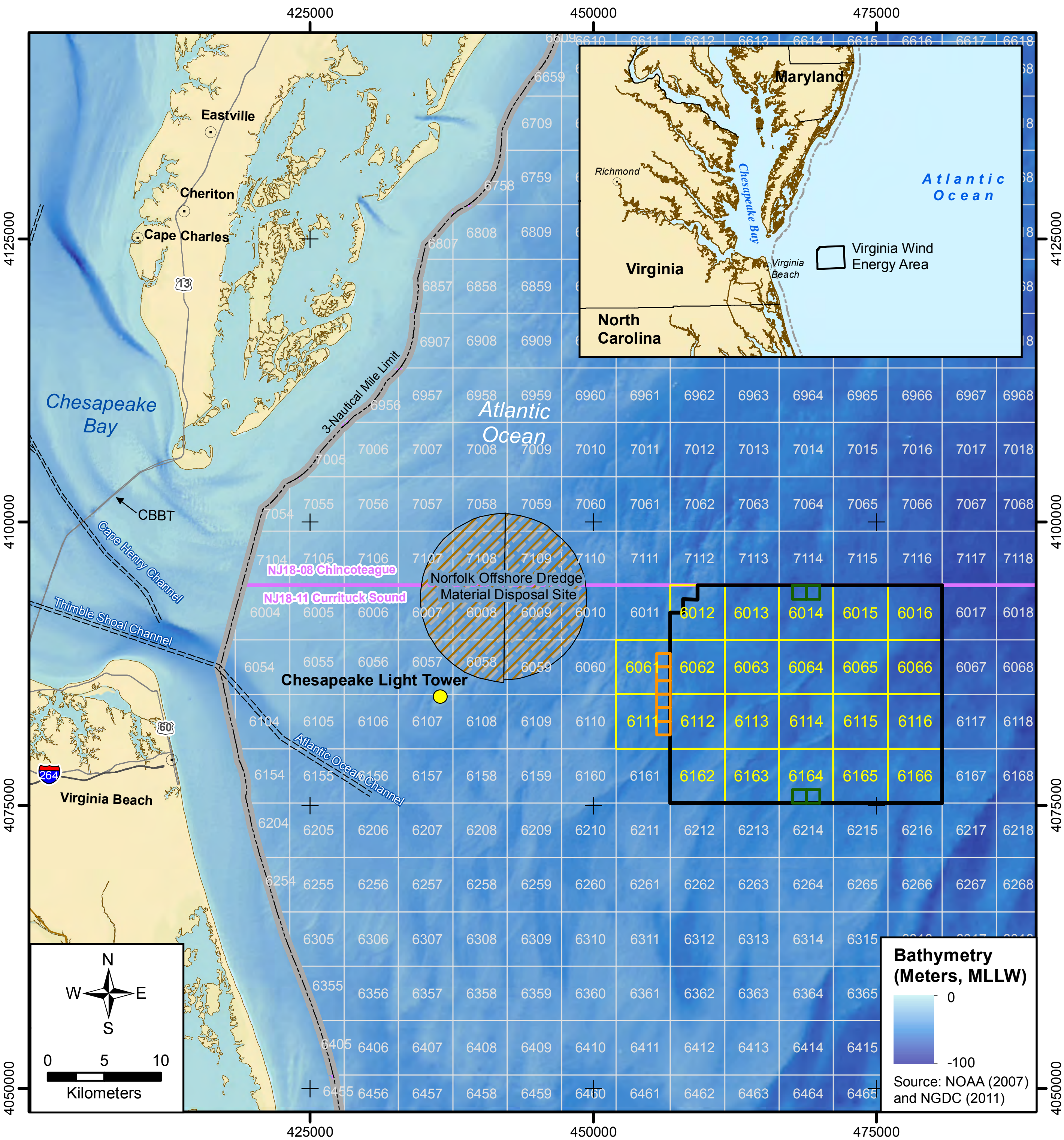
FIGURES



CBBT = Chesapeake Bay Bridge-Tunnel

LEGEND

- Virginia Wind Energy Area
- 6015 Wind Energy Area OCS Lease Block
- Meteorological Tower Aliquot
- Demonstration Project Lease Aliquot
- + Coordinate Grid is UTM Zone 18N, NAD 1983, Meters

PROJECT LOCATION MAP
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 1

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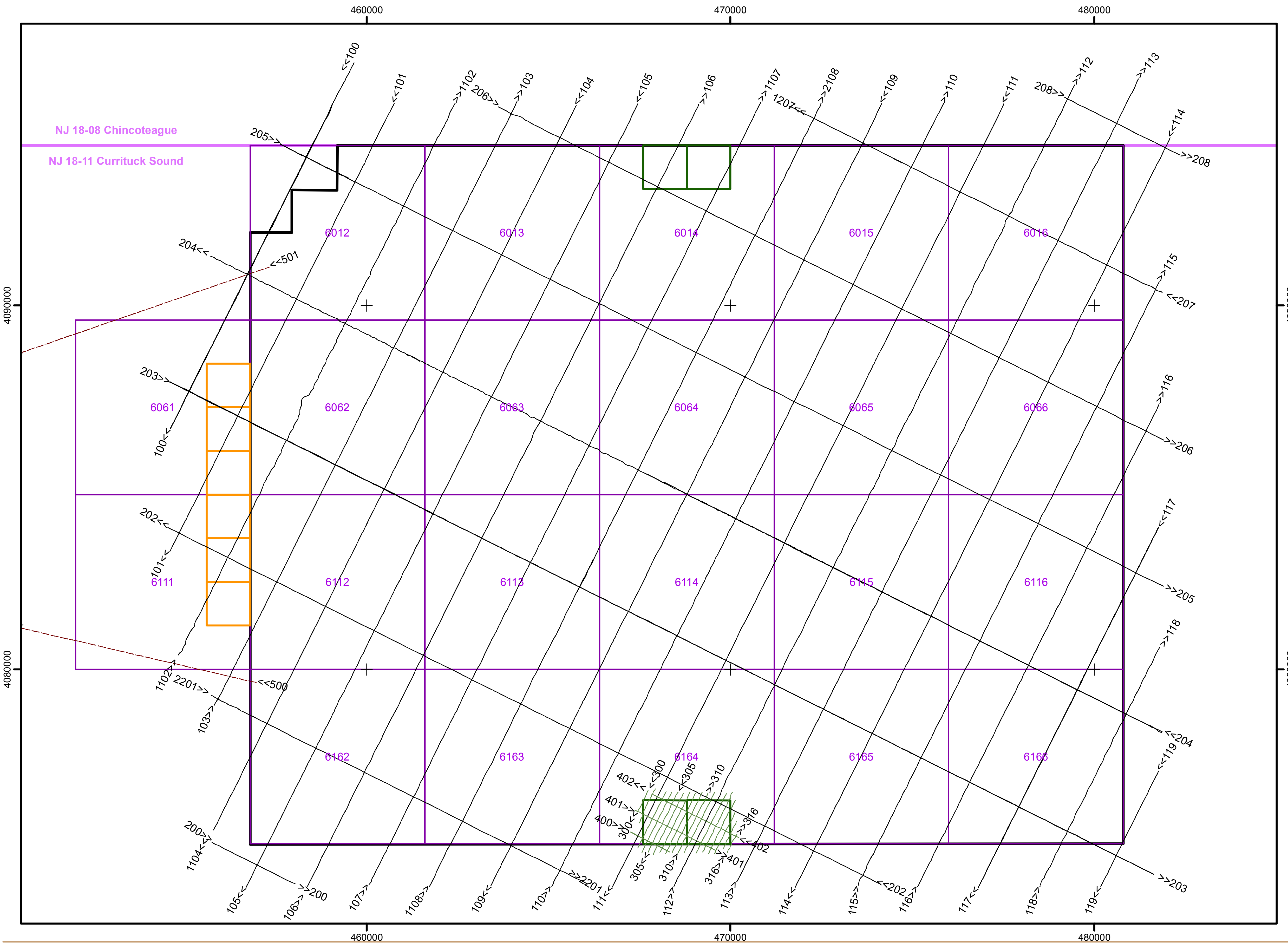

- Virginia Wind Energy Area
- 6016 Wind Energy Area OCS Lease Block
- Demonstration Project Lease Aliquot
- Meteorological Tower Aliquot
- + Coordinate Grid is UTM Zone 18N, NAD 1983, Meters

Fugro 2013 Survey Tracklines

- WEA Survey Line (100 and 200 series)
- Met Tower Survey Line (300 and 400 series)
- Regional Survey Line (500 series)
  Only the most easterly portions of the 500 series lines are shown here. These lines were collected as tie-lines to Chesapeake Light Tower and the mouth of Chesapeake Bay. These lines were not used for the present report. For details, refer to Fugro (2013).

Notes:

1. Marine survey data were collected from May 28 through July 3, 2013 onboard the *Tiki XIV*.
2. Differential Global Positioning System (DGPS) corrections were obtained from Fugro's Starfix II wide area differential network, downloaded from a communications satellite.
3. Survey equipment utilized for data collection included the following systems:
   - -R2 Sonic 2024 Multibeam Echosounder
   - -Applanix POS MV Vessel Motion and Attitude Recording System
   - -Edgetech Model 4125 Side Scan Sonar System
   - -SonarWhiz Map Side Scan Sonar Data Aquisition System
   - -Marine Magnetic Corporation SeaSpy Magnetometer
   - -Edgetech 3200 Spread Spectrum Sub-bottom Profiler (Chirp) System
   - -Edgetech Discovery Sub-bottom Profiler Data Acquisition System
   - -Applied Acoustic Engineers CSP Seismic Energy Source and Subsea System's Double-plate "Boomer" System
   - -GeoEel 32-channel Hydrophone Array Streamer (Channels 1-16 at 1.562mgi and Channels 17-32 at 3.125mgi)
   - -Blue Ocean Moving Sound Velocity Profiler
   - -Coastal Oceanographics "Hypack" Navigation System
   - -Starfix Seis Navigation

N
W E
S

0 2
Nautical Miles

0 3 6
Kilometers

2013 SURVEY VESSEL TRACKLINES
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 2

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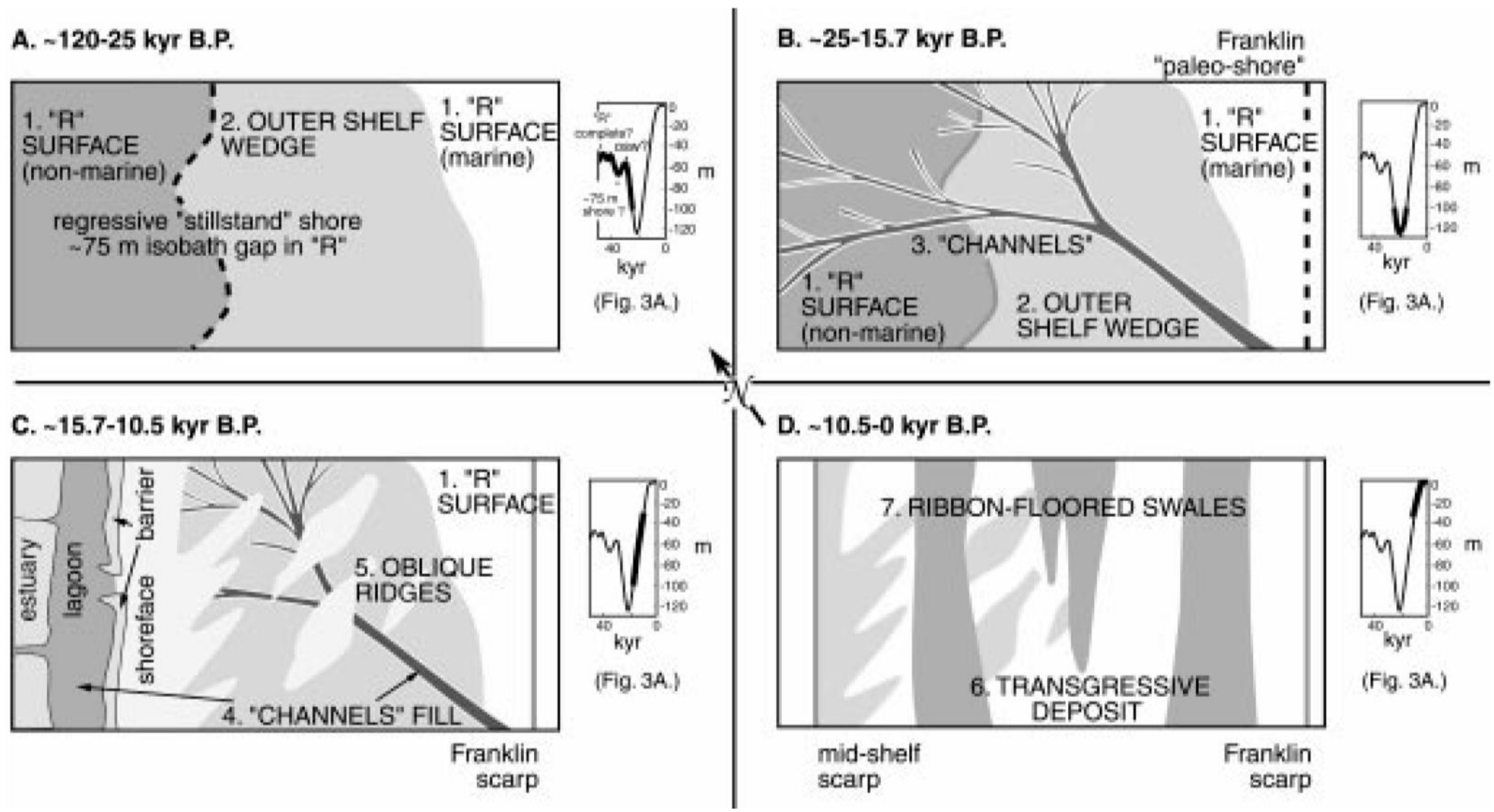


Schematic geologic evolution of the mid-shelf corridor since ~120 kyr B.P. The portion of the global eustatic curve (inset Fig. 3A above) displayed in each cartoon is marked with a heavy black line. (A) Depicts period when the shoreline moved seaward across the mid-shelf corridor during the last regression (~120-25 kya); (B) shows the Wisconsin glacial maximum, when the mid-shelf corridor was subaerially exposed, and “channels” were carved (~25-15.7 kya); (C) illustrates the portion of the Holocene transgression when the shoreline moved from the Franklin “paleo-shore” to the mid-shelf scarp, and “channels” were infilled with an upward-deepening succession of lagoonal and estuarine muds; estuaries, lagoons, shoreface barriers, and nearshore shores/oblique ridges comprised the various depositional environments in this cartoon (~15.7-10.5 kya); (D) shows the modern seafloor of the mid-shelf corridor (10.5 kyr to Present). Shelf currents have reworked and winnowed the oblique ridges, creating the surficial unit. *“Channels” and other subsurface features (e.g. deltas, unconformities, etc.) have no seafloor bathymetric expression*, and the ribbon-floored swales represent erosion of the surficial unit.

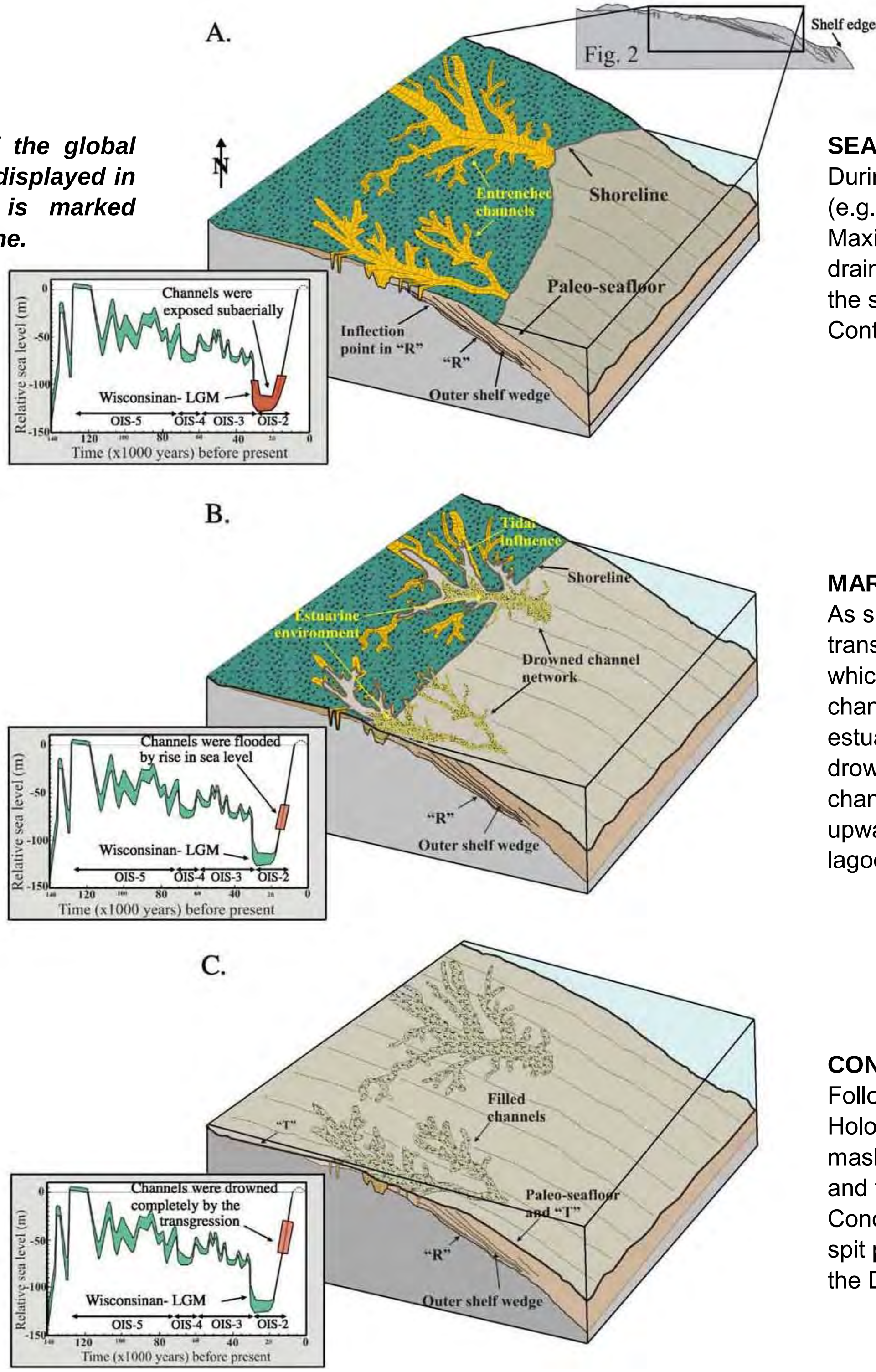
Source: Duncan et al. (2000)

GEOLOGIC EVOLUTION OF MID-SHELF CORRIDOR

Virginia WEA Geophysical Survey Phase II

Virginia Outer Continental Shelf

The portion of the global eustatic curve displayed in each cartoon is marked with a red outline.



SEA LEVEL LOWSTANDS
During Sea Level Lowstands (e.g. Wisconsin – Last Glacial Maximum ~25-15.7 kya), drainage systems developed on the subaerially exposed Continental Shelf.

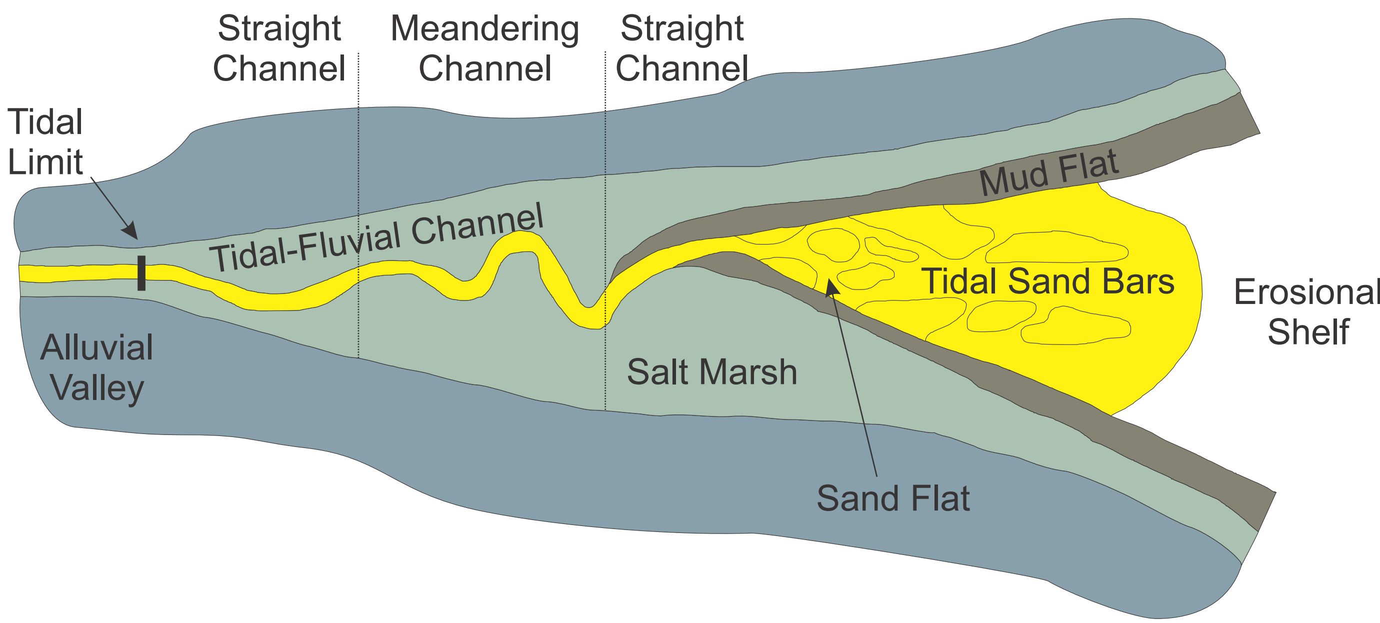
MARINE TRANSGRESSION
As sea level rose, the shoreline transgressed across the shelf which resulted in: 1) fluvial channels transitioning to estuarine environments, and 2) drowning, infilling, and burial of channels; channels infilled with upward deepening succession of lagoonal and estuarine muds.

CONDITIONS TODAY
Following transgression, Holocene-age marine sediments mask the location of channels and the materials that infill them. Conditions also underlie barrier spit prograding deposits along the Delmarva Peninsula.

Source: Nordfjord et al. (2005)

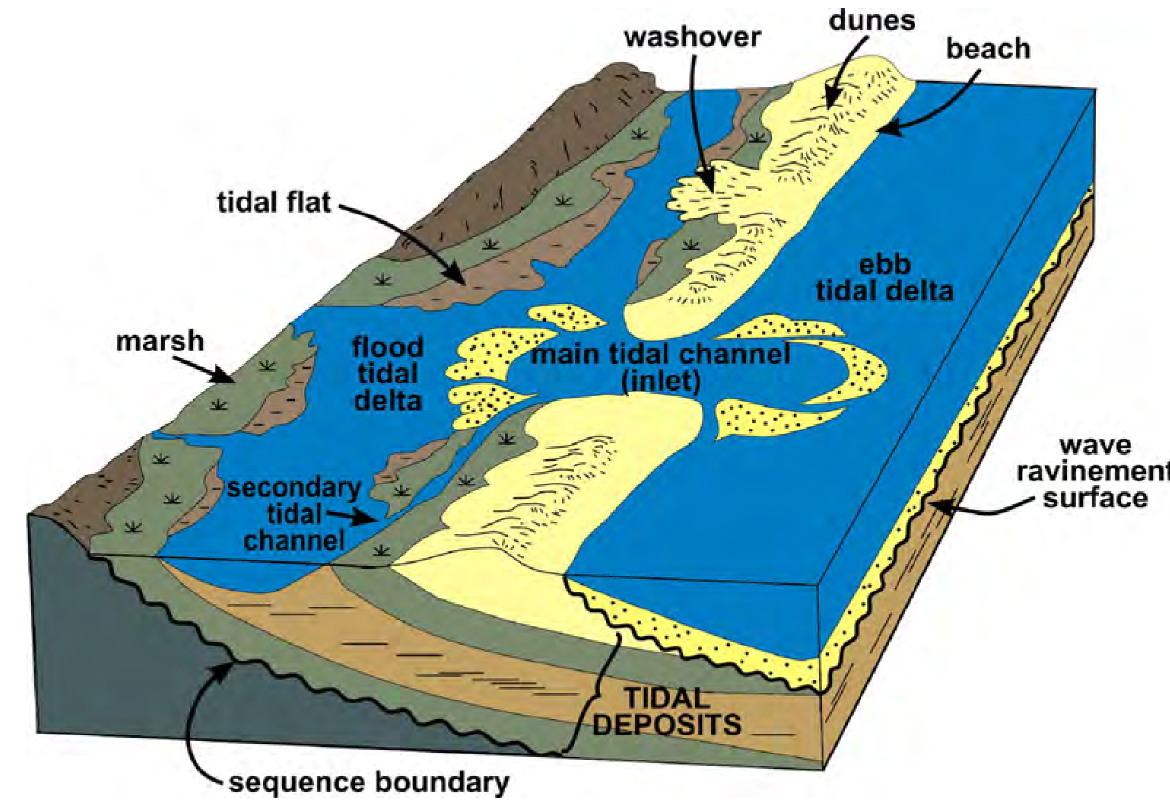
EXAMPLE OF CHANNEL INCISION AND BURIAL
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

TIDAL-DOMINATED ESTUARY



Modified from Dalrymple et al., 1992

BARRIER ISLAND SYSTEM



Source: Dalrymple and Choi, 2007 (modified from Reinson, 1992)

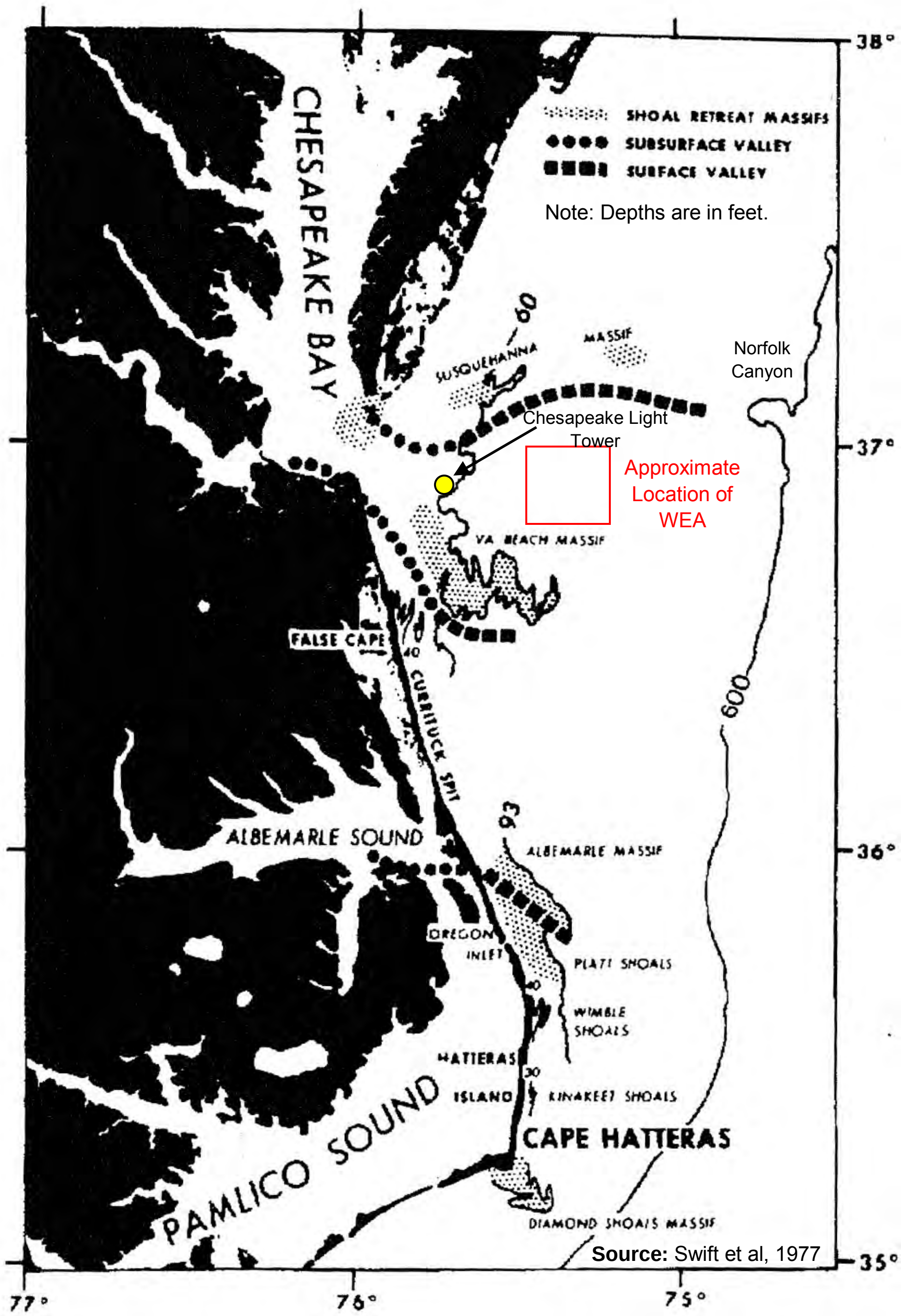
The two models shown above are used in the “Paleo-Landform Catalog” presented in Figures 25a to 25g.

The paleo-landforms identified within the project area are not unique to offshore Virginia and represent common landforms that can be found both in modern settings as well as preserved in the geologic units buried below the Earth's surface.

The present configuration of the Middle Atlantic Coast of the United States can be divided into distinct sections (Massachusetts-Rhode Island; Long Island; New Jersey; the Delmarva Peninsula; and Virginia-North Carolina) that correspond to a repeating pattern of barrier-fronted coastal compartments separated by estuaries (Fisher, 1967; Oertel and Kraft, 1994).

GEOLOGIC MODELS USED IN PALEO-LANDFORM CATALOG
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

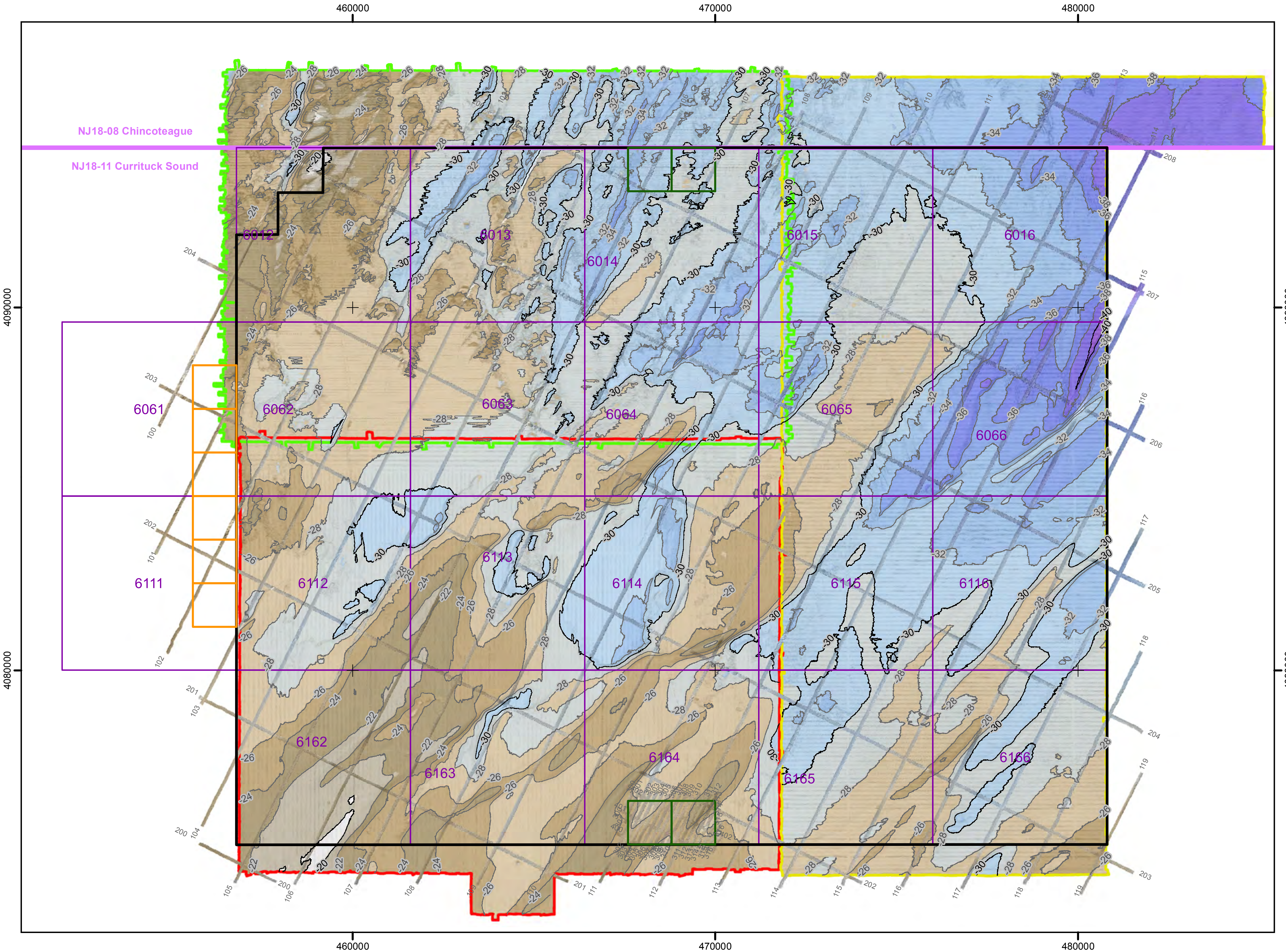
FIGURE 5



The graphic above depicts major physiographic features of the inner continental shelf offshore southeastern Virginia. This area has similar features as with other locations in the Middle Atlantic Bight, which include a shelf valley, shoal retreat massif (compound bathymetric high consisting of smaller-scale highs), and sand ridges/shoals (shoreface-connected, nearshore, and offshore). In general, nearshore sand ridges trend north-south with relief up to approximately 10 meters. These features extend 15 kilometers offshore toward well-defined southwest-trending scarp whose toe lies at roughly 43 meters. The Virginia Beach Massif is an east-west trending bathymetric high segmented into north-south trending sand ridges and swales. This feature has a “comblike pattern” with “teeth” extending from the spine of the massif towards the north. Modified from Swift et al. (1977).

PHYSIOGRAPHY

Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf



LEGEND

100 Survey Vessel Navigation Trackline

Virginia Wind Energy Area

6016 Wind Energy Area OCS Lease Block

Demonstration Project Lease Aliquot

Meteorological Tower Aliquot

Coordinate Grid is UTM Zone 18N, NAD 1983, Meters

Bathymetry (Meters, MLLW)
Source: NOAA (2011-2012) and Fugro (2013)
Darker bathymetry swaths, oriented NW-SE and NE-SW, indicate the extent of the Fugro 2013 survey.

-18 to -20
-20 to -22
-22 to -24
-24 to -26
-26 to -28
-28 to -30
-30 to -32
-32 to -34
-34 to -36
-36 to -38
-38 to -40
-40 to -42

Major contour interval is 10 meters.

Minor contour interval is 2 meters.

NOAA Hydrographic Survey Extents

H12309 (2011)
H12503 (2012)
H12502 (2012)

Notes:
1. Fugro (2013)- Bathymetric data are from a multibeam survey conducted for DMME/BOEM in the WEA from May 28 through July 3, 2013.
2. NOAA (2011 & 2012)- Bathymetric data are from hydrographic surveys conducted in 2011 and 2012.
3. Water depth values within the WEA are based on both the Fugro and NOAA data sources. Values given are in meters and reference MLLW.

N
W
E
S

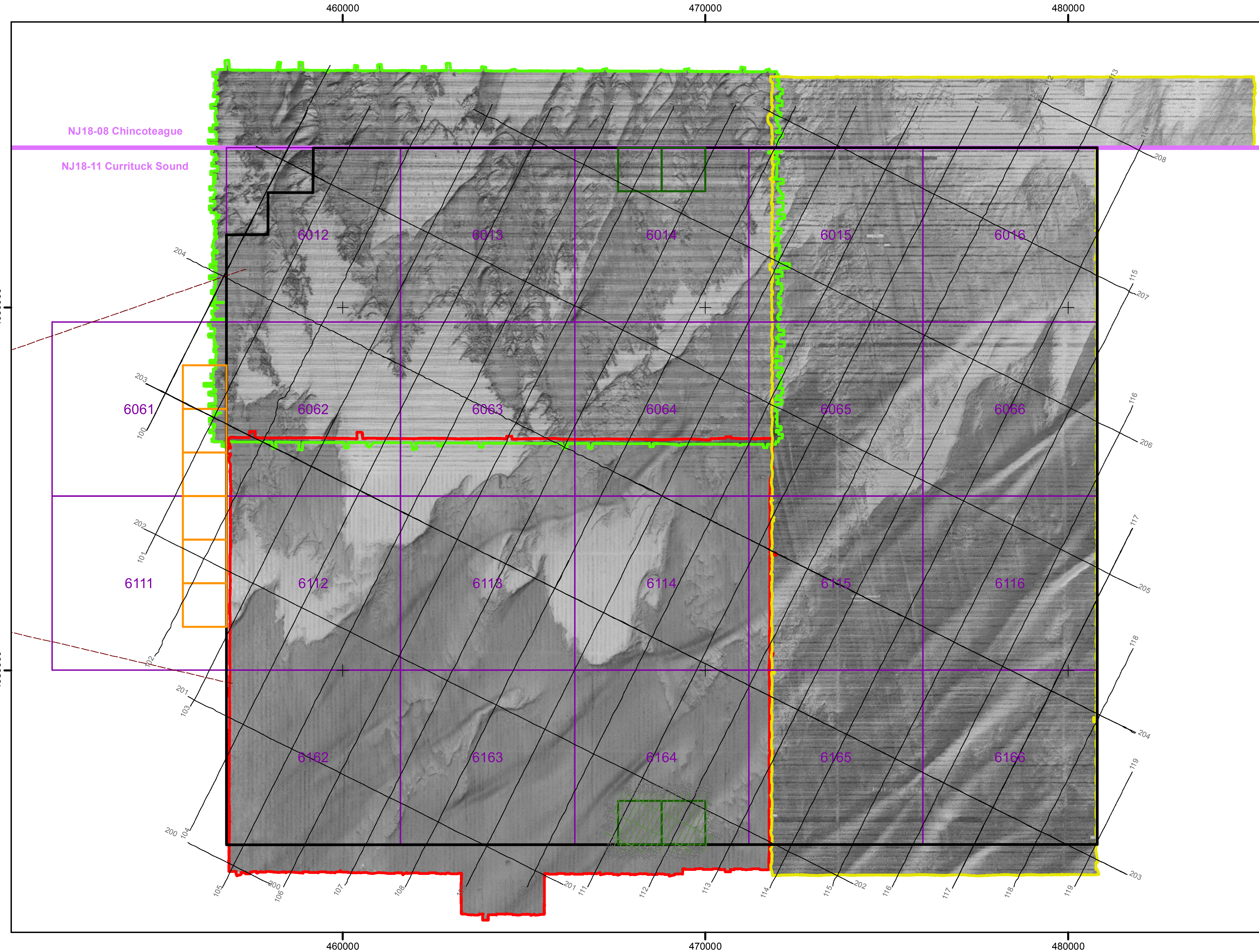
0 2
Nautical Miles

0 3 6
Kilometers

WEA BATHYMETRY
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 7

N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig-7_WEA_Bathy.mxd, 2/4/2016, sullivans



LEGEND

- 100 Survey Vessel Navigation Trackline
- Virginia Wind Energy Area
- 6016 Wind Energy Area OCS Lease Block
- Demonstration Project Lease Aliquot
- Meteorological Tower Aliquot
- + Coordinate Grid is UTM Zone 18N, NAD 1983, Meters

Side Scan Sonar Reflectivity/ MBES Backscatter Intensity

High

Low reflectivity/intensity is inferred to indicate fine-grained sediments while granular soils (sands and gravels) typically have high reflectivity/intensity.

Low

NOAA Hydrographic Survey Extents

- H12309 (2011)
- H12503 (2012)
- H12502 (2012)

Source: This figure is a modified version of Chart 4, Fugro (2013).

N W E S

0 2 Nautical Miles

0 3 6 Kilometers

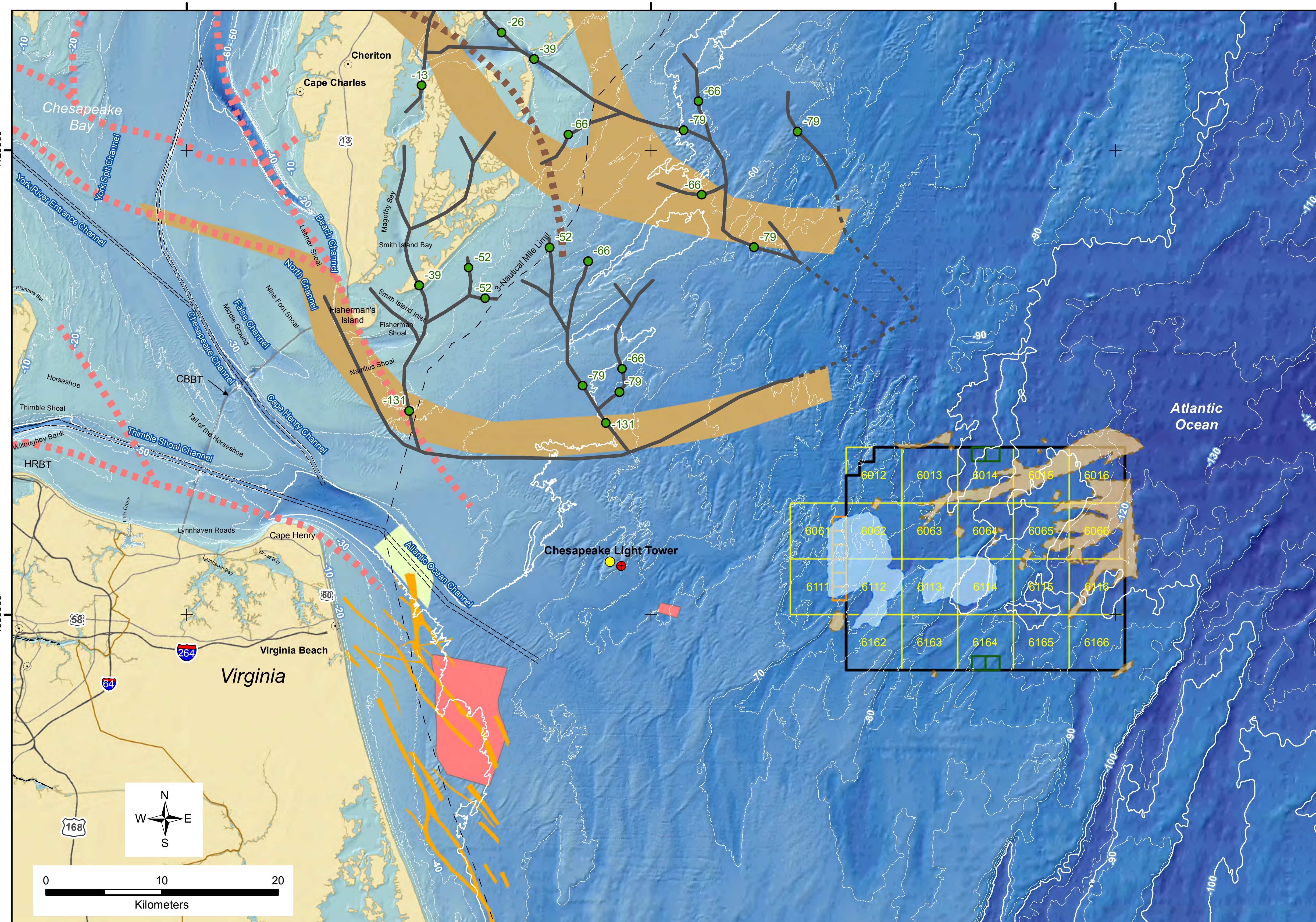
SIDE SCAN SONAR AND BACKSCATTER MOSAIC OVERLAIN ON SLOPE IMAGERY

Virginia WEA Geophysical Survey Phase II

Virginia Outer Continental Shelf

FIGURE 8

N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig-8_WEA_SSS.mxd, 2/5/2016, sullivans



LEGEND

- Chesapeake Light Tower
- Fugro Borehole (1963)
- Virginia Wind Energy Area
- 6061 Wind Energy Area OCS Lease Blocks

Virginia OCS Aliquots

- Meteorological Tower Aliquot
- Demonstration Project Lease Aliquot

INTERPRETED PALEOCHANNELS

Interpreted from 2013 Fugro WEA Survey

- Deeper Channels Interpreted from Boomer Seismic Data

Ancestral Cape Charles River System (Oertel and Foyle, 1995)

- Interpreted Paleochannel
- Inferred Paleochannel Tract
- -131 Interpreted Paleochannel Thalweg with Elevation of Channel Bottom (Feet, MSL)

Offshore Southeastern Virginia Interpreted Paleochannel/Channel Complex

- Kimball et al. (1991); Hobbs (1997)
- Chen et al. (1995)
- AOC Seismic Survey (S&ME, 2009)

Ancestral Susquehanna River System (Coleman et al., 1988)

- Eastville Channel
- Cape Charles Channel
- Ancestral Susquehanna River System (Oertel and Foyle, 1995)

Bathymetry (Feet, MLLW)

0
-300
Contour Interval is 10 Feet

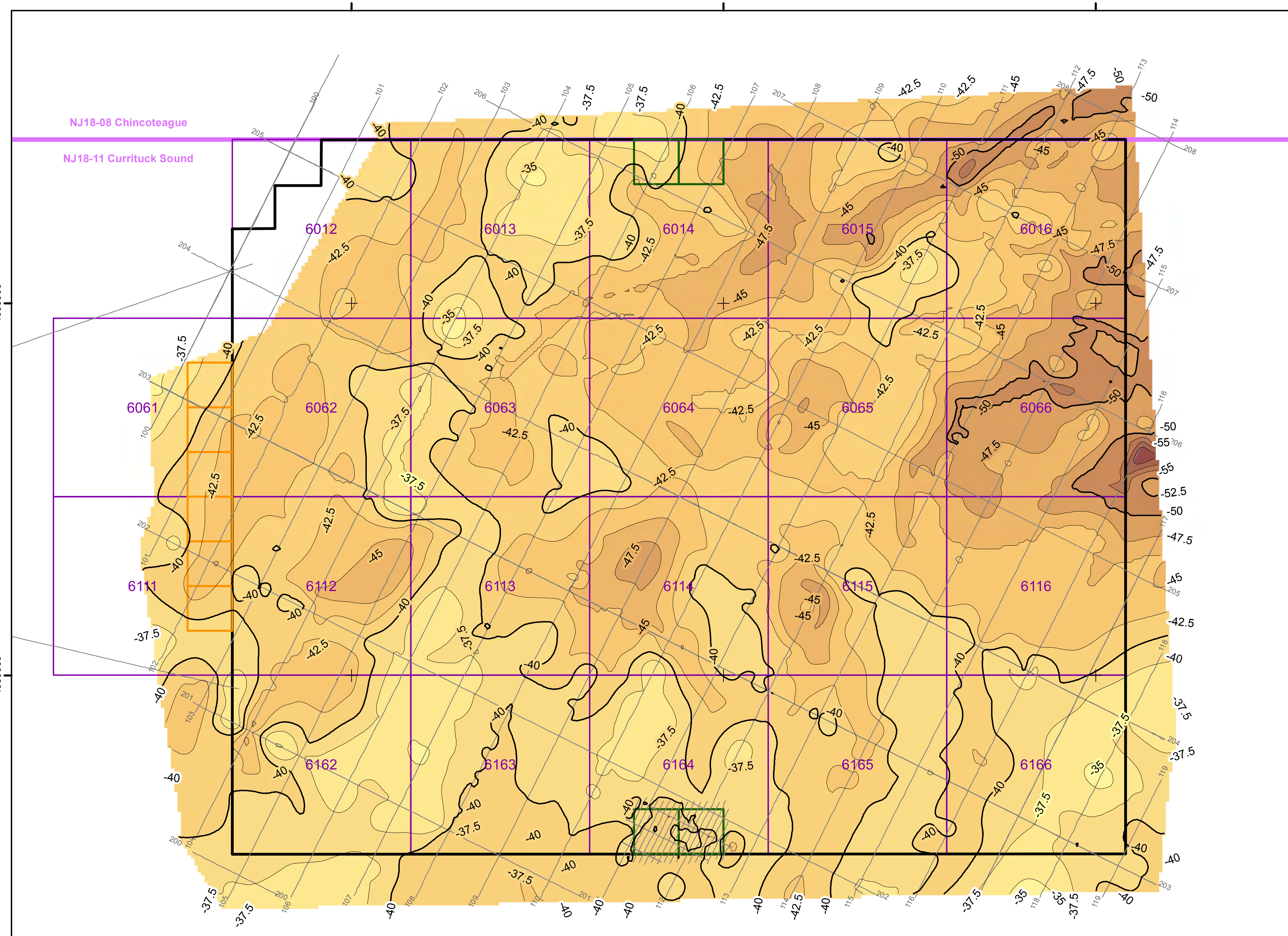
Source: NOAA (2007) and NGDC (2011)

Coordinate Grid is UTM Zone 18N, NAD 1983, Meters

INTERPRETED PALEO-CHANNEL LOCATIONS

Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 9



LEGEND

Survey Vessel Navigation Trackline

Virginia Wind Energy Area

6016 Wind Energy Area OCS Lease Block

Demonstration Project Lease Aliquot

Meteorological Tower Aliquot

Coordinate Grid is UTM Zone 18N, NAD 1983, Meters

Approximate Elevation of Horizon 30, Meters (Re. MLLW)

Horizon 30 is inferred to be related to the Tertiary-Quaternary boundary. Time-to-depth conversions based on V_p = 1,500 m/s; thus elevation should be considered approximate.

Major contour interval is 10 meters.

Minor contour interval is 2.5 meters

- -32.4 - -30
- -34.9 - -32.5
- -37.4 - -35
- -39.9 - -37.5
- -42.4 - -40
- -44.9 - -42.5
- -47.4 - -45
- -49.9 - -47.5
- -52.4 - -50
- -54.9 - -52.5
- -57.4 - -55
- -59.4 - -57.5

N S W E

0 2 Nautical Miles

0 3 6 Kilometers

ELEVATION CONTOURS OF HORIZON 30

Virginia WEA Geophysical Survey Phase II

Virginia Outer Continental Shelf

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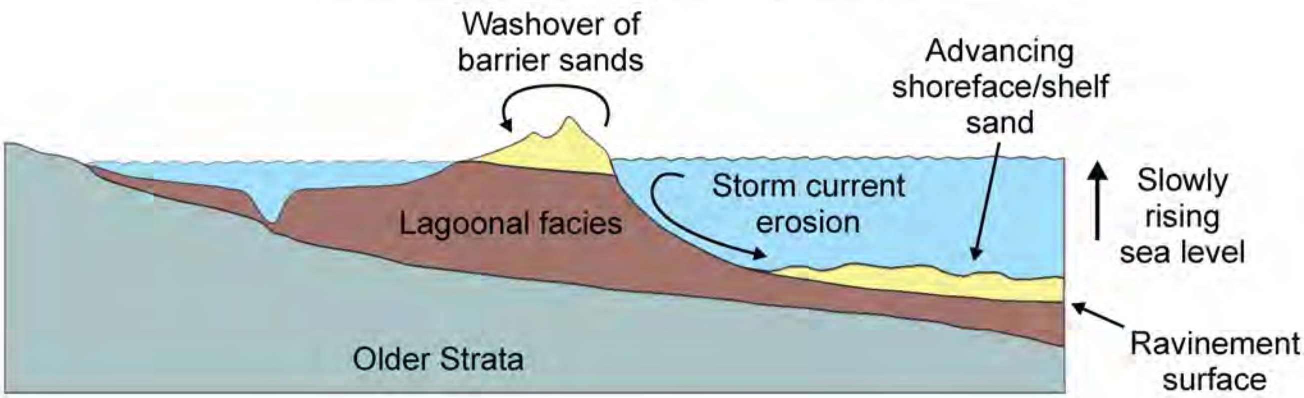
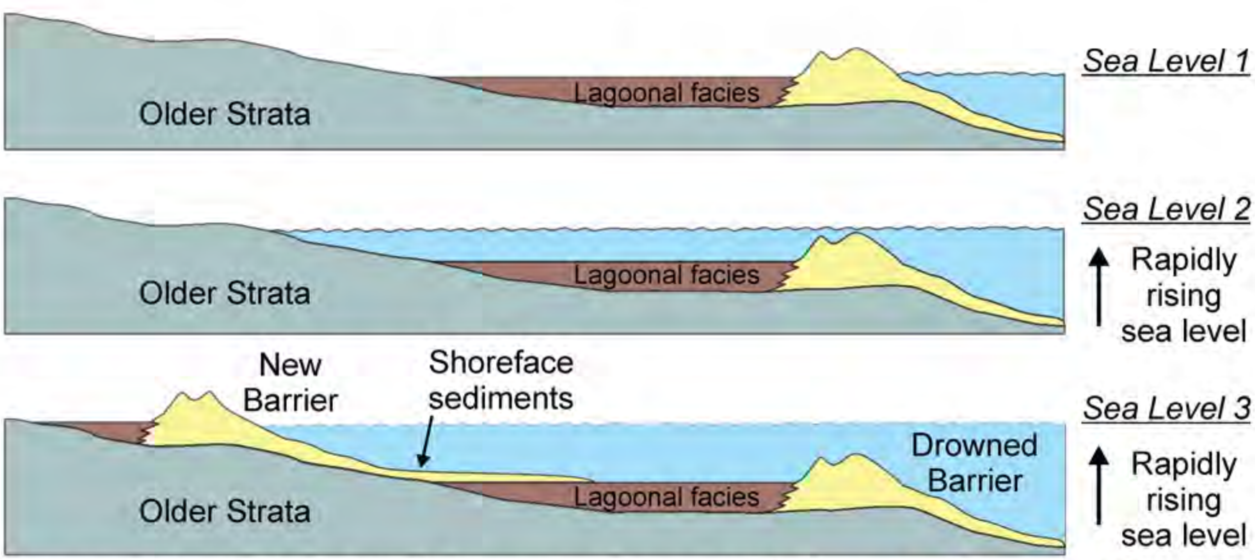
FIGURE 10

Shoreface Retreat (Site Erosion)



In-Place Drowning (Site Preservation)

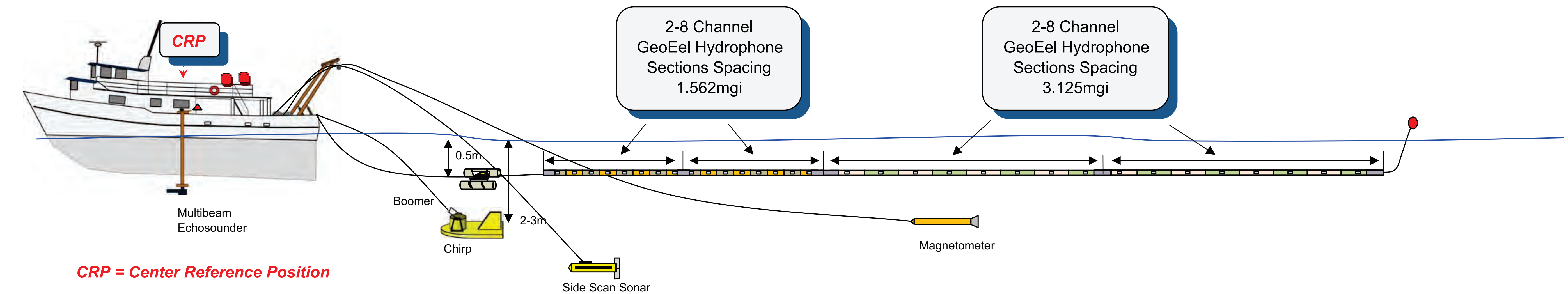


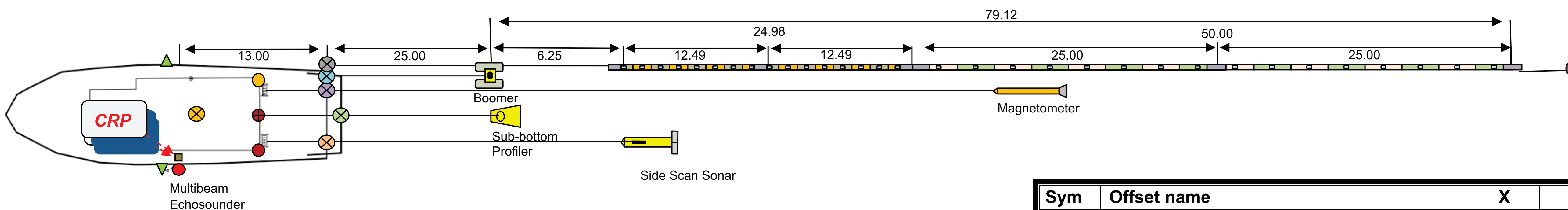
Sources: Fischer, 1961; Swift, 1975; Rampino and Sanders, 1980; Reading and Collinson, 1996

Note: Based on sea-level reconstruction from the Mid-Atlantic region, portions of the WEA were possibly inundated during Melt Water Pulse 1b which is associated with an increase in the rate of relative sea level rise. The drumstick-shaped bathymetric high occurring in the VA WEA (oriented SW-NE roughly between OCS blocks 6114 to 6016) appears to represent the in-place drowning of a tidally-influenced barrier island. This feature lies within the region affected by a stillstand of sea-level during the Holocene (Swift et al., 1977, 1978).

LANDWARD BARRIER MIGRATION DURING TRANSGRESSION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

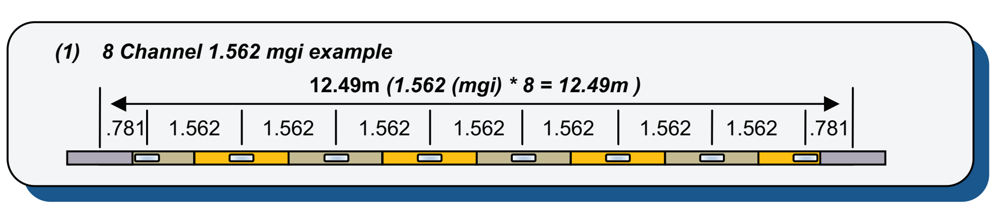
FIGURE 11

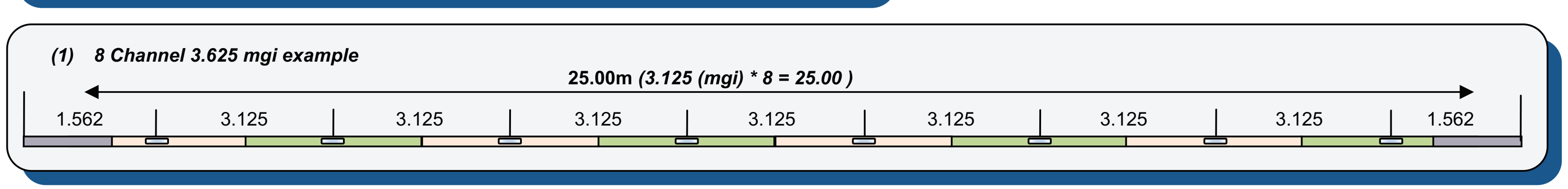




Multibeam, Seismic, Sub Bottom Profiler, Side Scan Sonar and Magnetometer Systems

Dimensions in Meters
Not to Scale

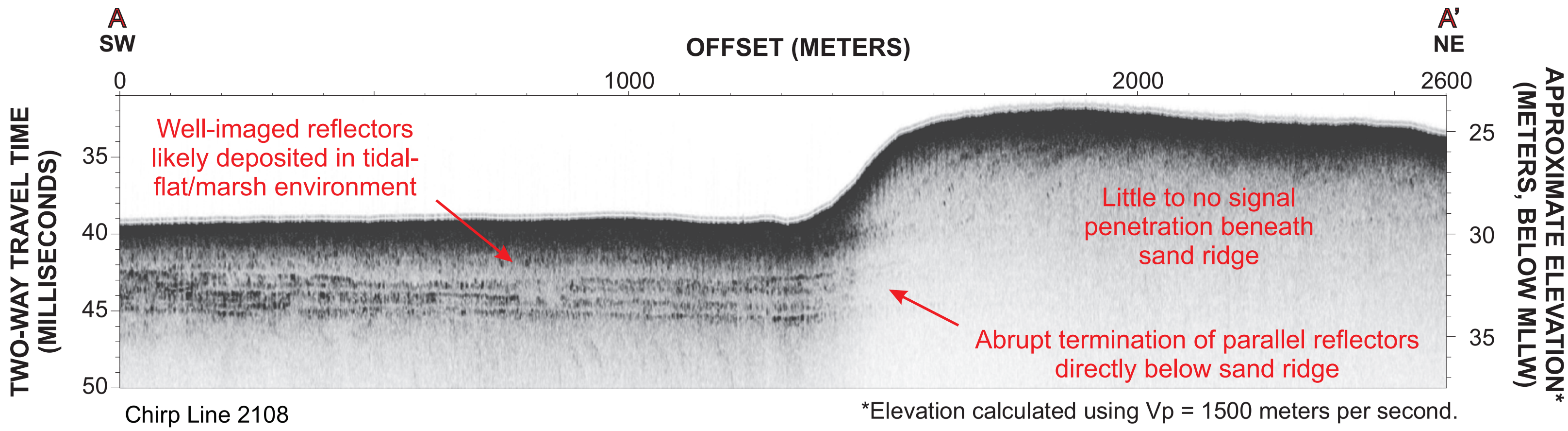




Sym	Offset name	X	Y	Z
■ (olive square)	IMU (Center Reference Position CRP)	0.000	0.000	0.000
● (red, large)	MBE Acoustic Center	-.752	.186	-5.454
● (red)	Port POSMV (Primary Antenna)	.614	-6.521	2.202
⊕ (red)	Starboard POMV Antenna (Vector Antenna)	2.574	-6.521	2.221
● (yellow)	Trimble 461 Antenna (Secondary Nav)	5.284	-6.330	2.267
⊗ (yellow)	Trimble 461 Antenna (Vector Antenna)	3.446	-1.282	3.410
⊗ (orange)	Side Scan Sonar Tow point / Cable Counter	1.658	-11.515	2.000
⊗ (green)	Sub Bottom Profiler Tow Point	2.862	-11.483	-.148
⊗ (purple)	Magnetometer Tow Point /Cable Counter	4.365	-11.509	2.00
⊗ (blue)	Boomer Tow Point	5.601	-11.517	0.00
⊗ (grey)	Streamer Tow Point	5.799	-11.510	0.00
▽ (green)	Port Ultrasonic Sensor (Static Draft)	-.752	.531	-.246
△ (green)	Starboard Ultrasonic Sensor (Static Draft)	6.553	.291	-.251
	All Units are in Meters			

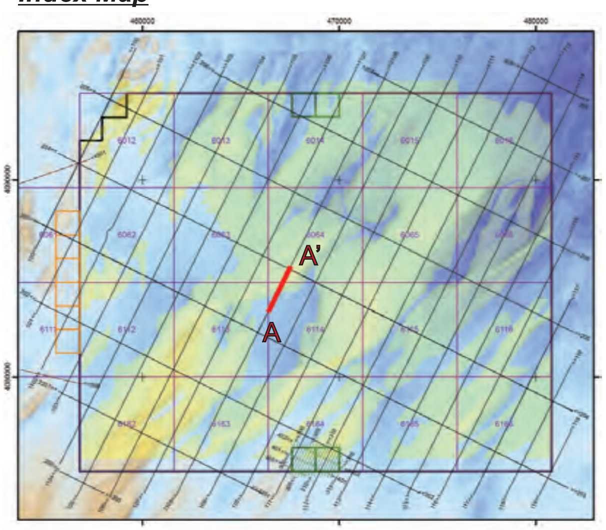
***TIKI XVI* GEOPHYSICAL SYSTEM**
TOW CONFIGURATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 12



*Elevation calculated using Vp = 1500 meters per second.

Index Map



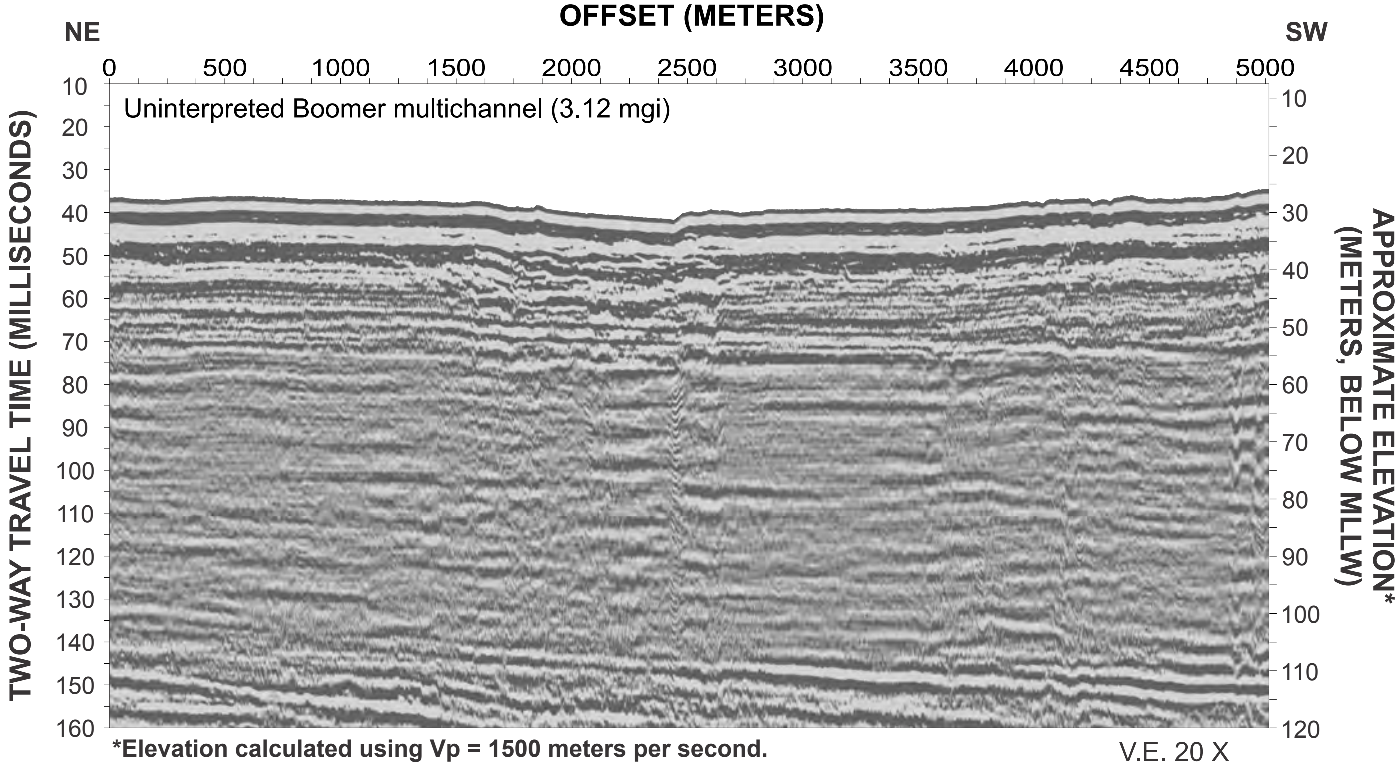
Light yellow/green transparency in the above index map marks areas of limited Chirp signal penetration due to the presence of surficial sand ridges. Areas shaded blue to brown are exposed fine-grained tidal flat/marsh deposits with greater Chirp signal penetration.

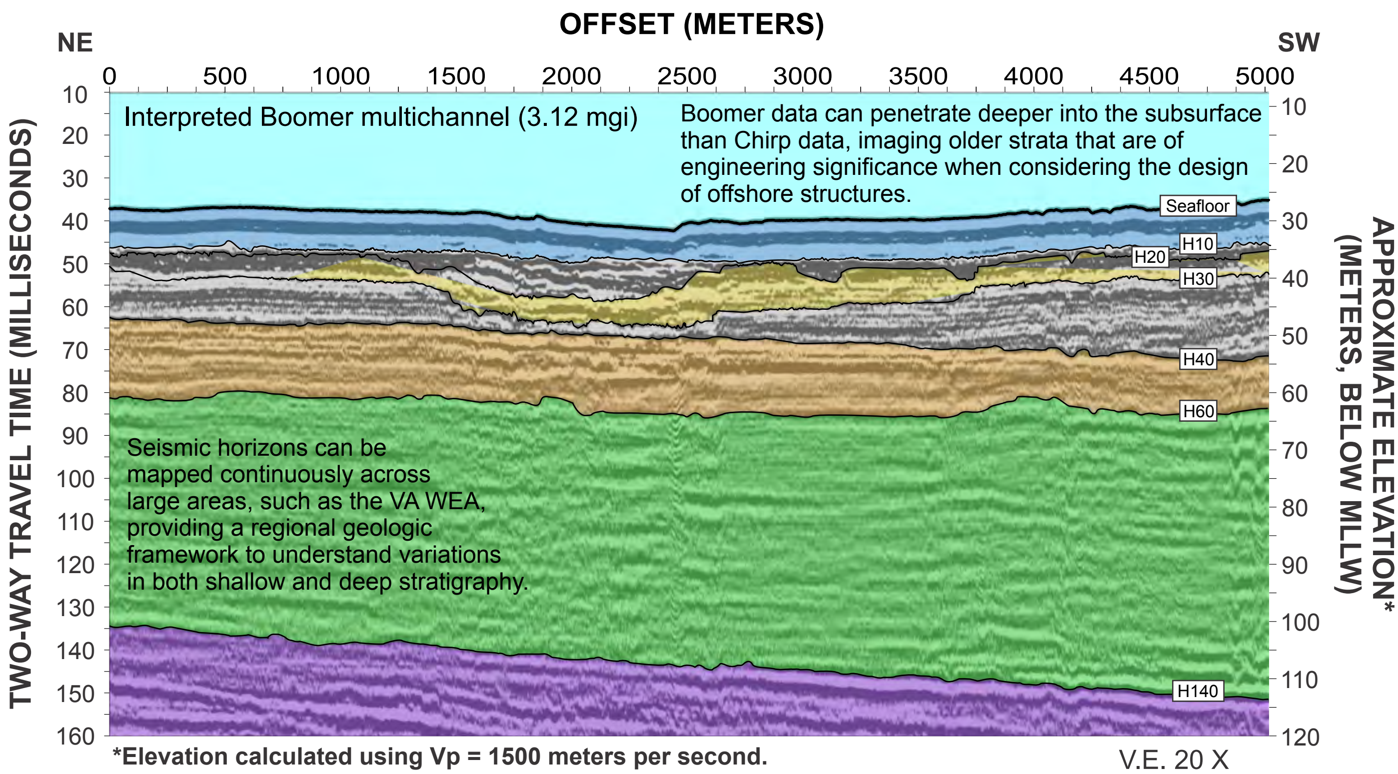
Full Spectrum Chirp 3200-XS System/SB-216S Tow Vehicle

Pulse Bandwith Selected:	2 to 15 kHz
Pulse Length:	20 milliseconds
Penetration in Coarse Sand[#]:	6 meters (typical)
Penetration in Soft Clay[#]:	80 meters
Vertical Resolution:	6 cm (2 to 15 kHz)
Beam Width:	17 degrees (2 to 15 kHz)

[#] *Penetration represents optimal acquisition parameters and subsurface conditions such as a tow depth within 5 meters of the seabed and no gas present in the sediment. For this survey, the system was not towed near the seabed, which is common in regional-scale surveys.*

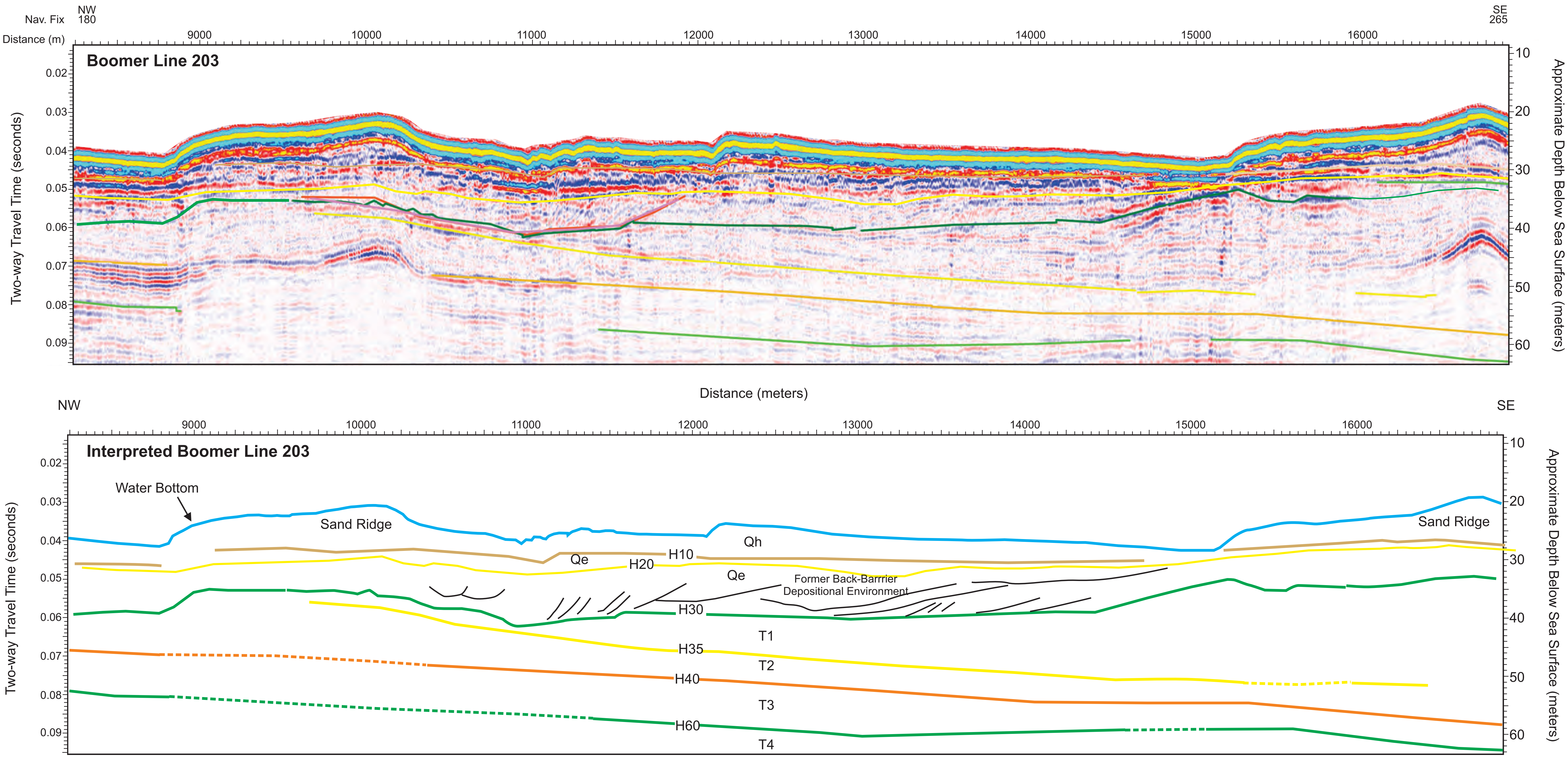
DEPTH OF PENETRATION LIMITATIONS IN CHIRP DATA
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

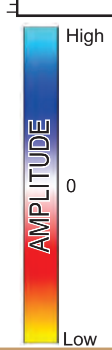




IMAGING OF DEEP SUBSURFACE WITH MCS DATA
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 14





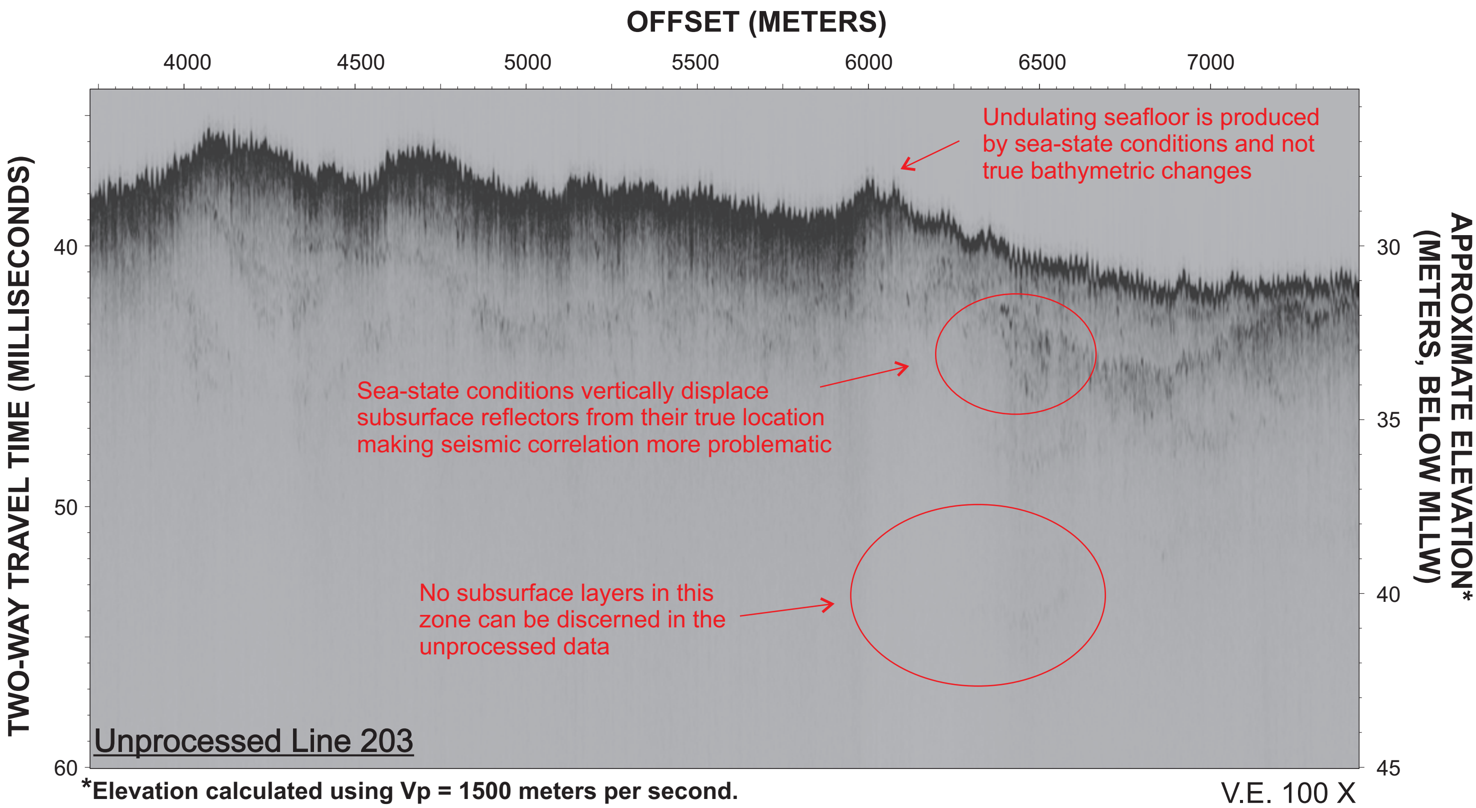
Notes:
1) Time-to-depth conversions are approximate and calculated using Vp = 1,500 meters per second.

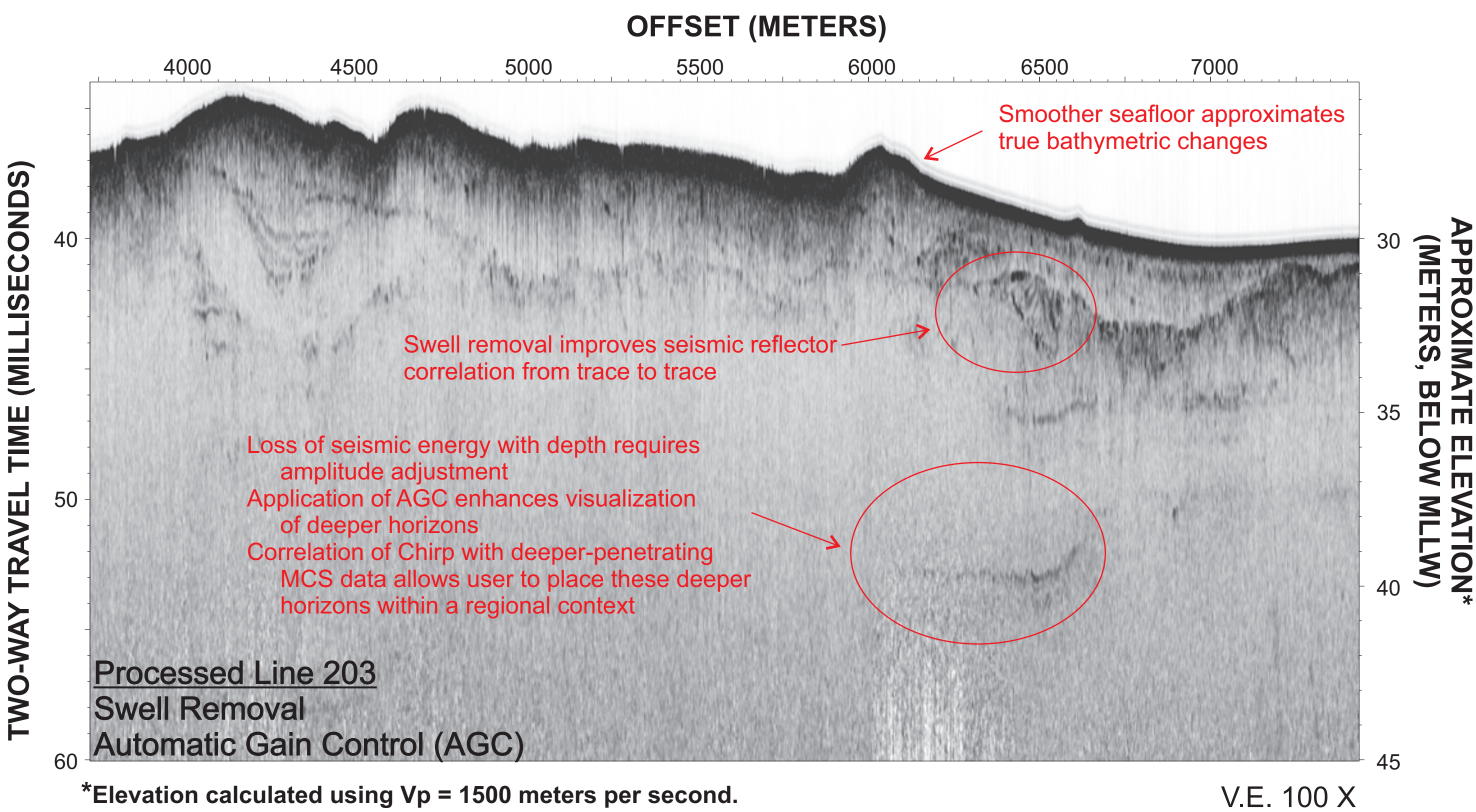
2) Seismic data were collected using a 32-channel hydrographic array and a double-plate boomer energy source powered at approximately 300 joules per plate.

Qh = Quaternary Marine Deposits: Comprised of sand ridges and modern surficial shelf deposits
Qe = Quaternary Transgressive Deposits: Typically fluvial, estuarine, lagoonal, and back-barrier deposits
T1 through T5 = Tertiary Deposits: Typically alternating sand and clay/silt strata deposited in marine environment

REGIONAL SEISMIC RECORD
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 15



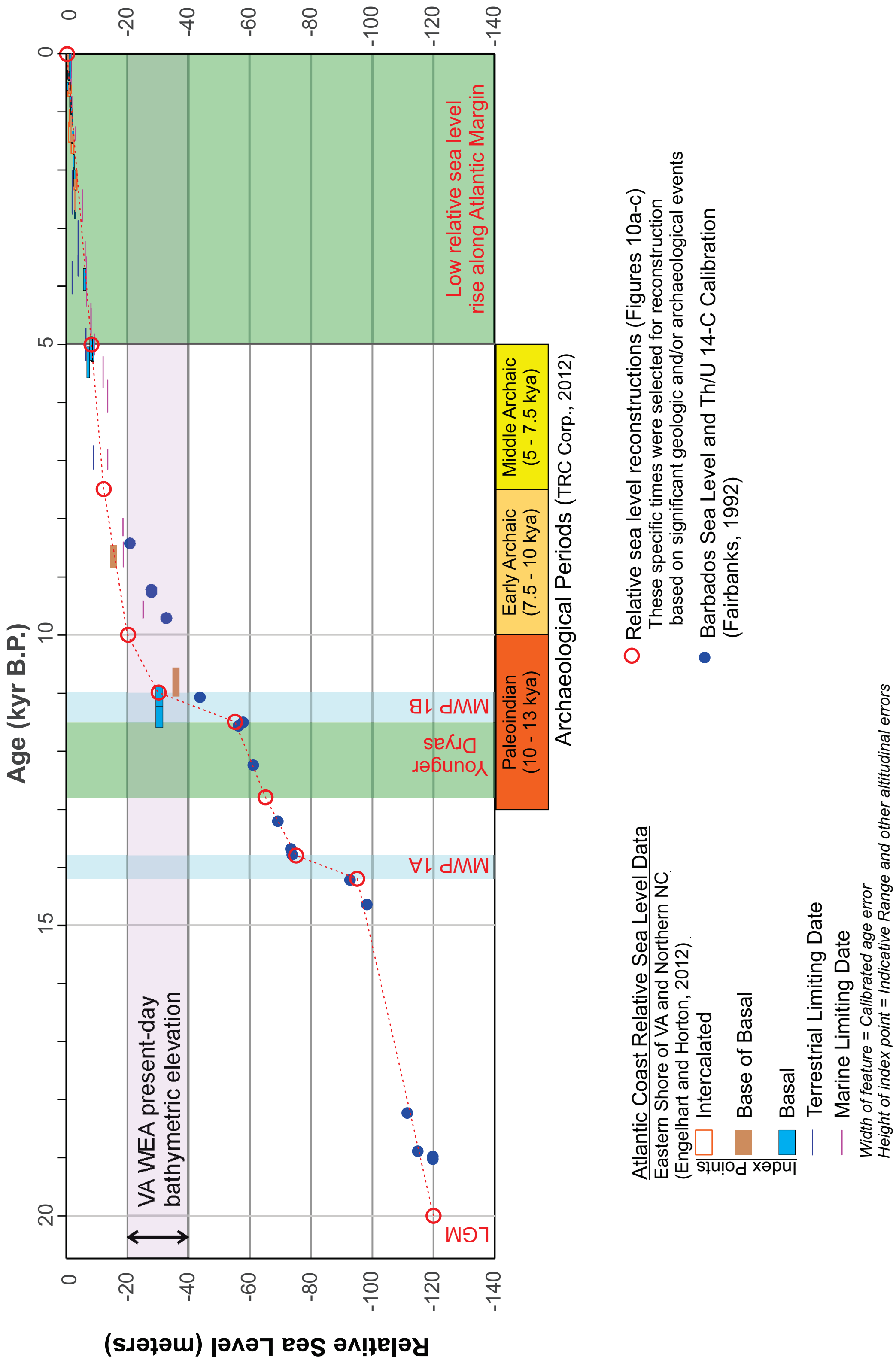


PROCESSING OF CHIRP DATA

Virginia WEA Geophysical Survey Phase II

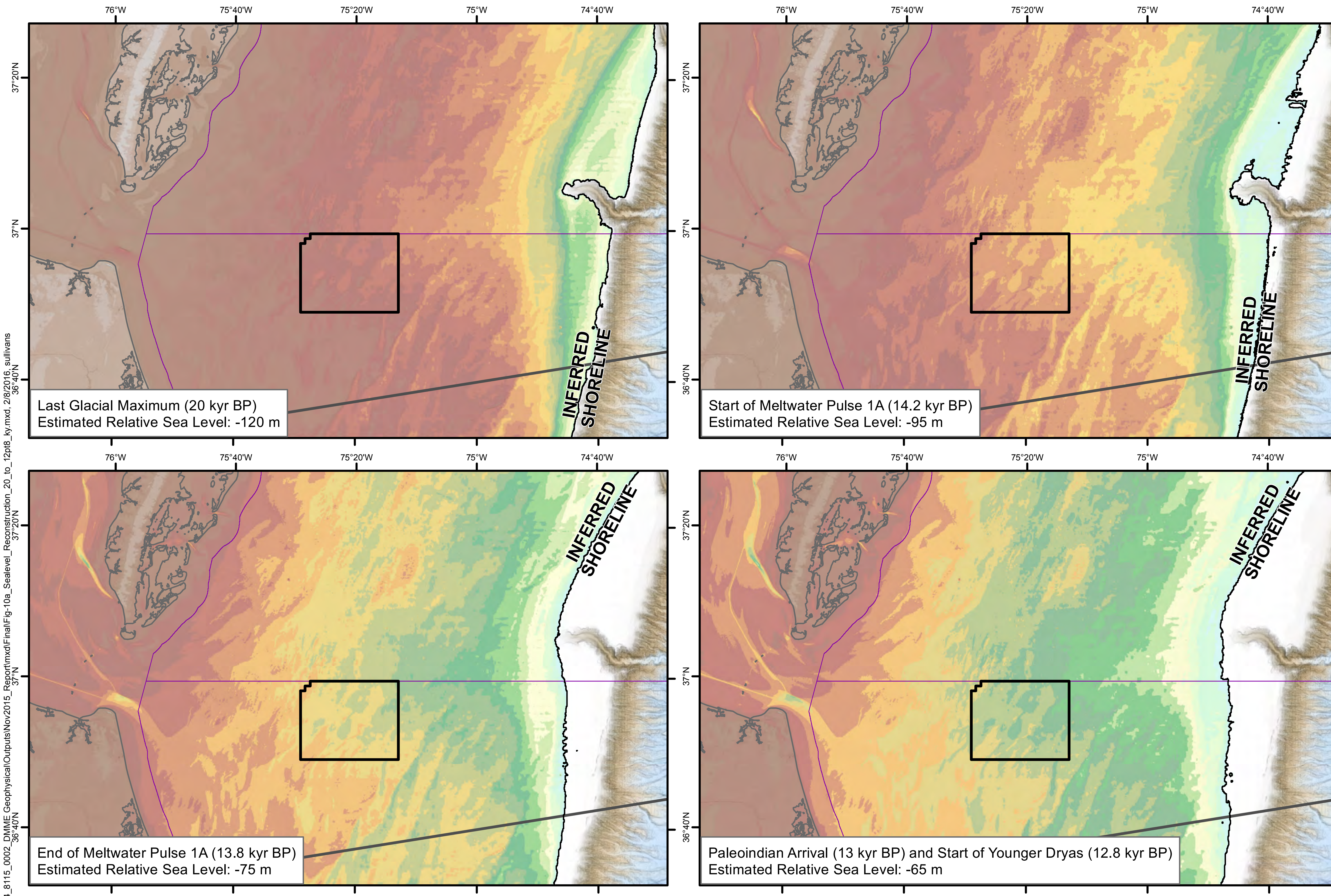
Virginia Outer Continental Shelf

FIGURE 16



RELATIVE SEA LEVEL CURVE
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 17



Legend

- Virginia Wind Energy Area
- Atlantic OCS Protractions
- State Boundary OCS Extension

Paleo-elevations as determined by reconstruction of Relative Sea Level (RSL)

See Figure 9 for details of RSL reconstruction

Elevations are based on present-day topography and bathymetry (GEBCO) and do not account for erosion, deposition or glacioisostatic adjustment.

150 meters
0 meters
0 meters
-3000 meters

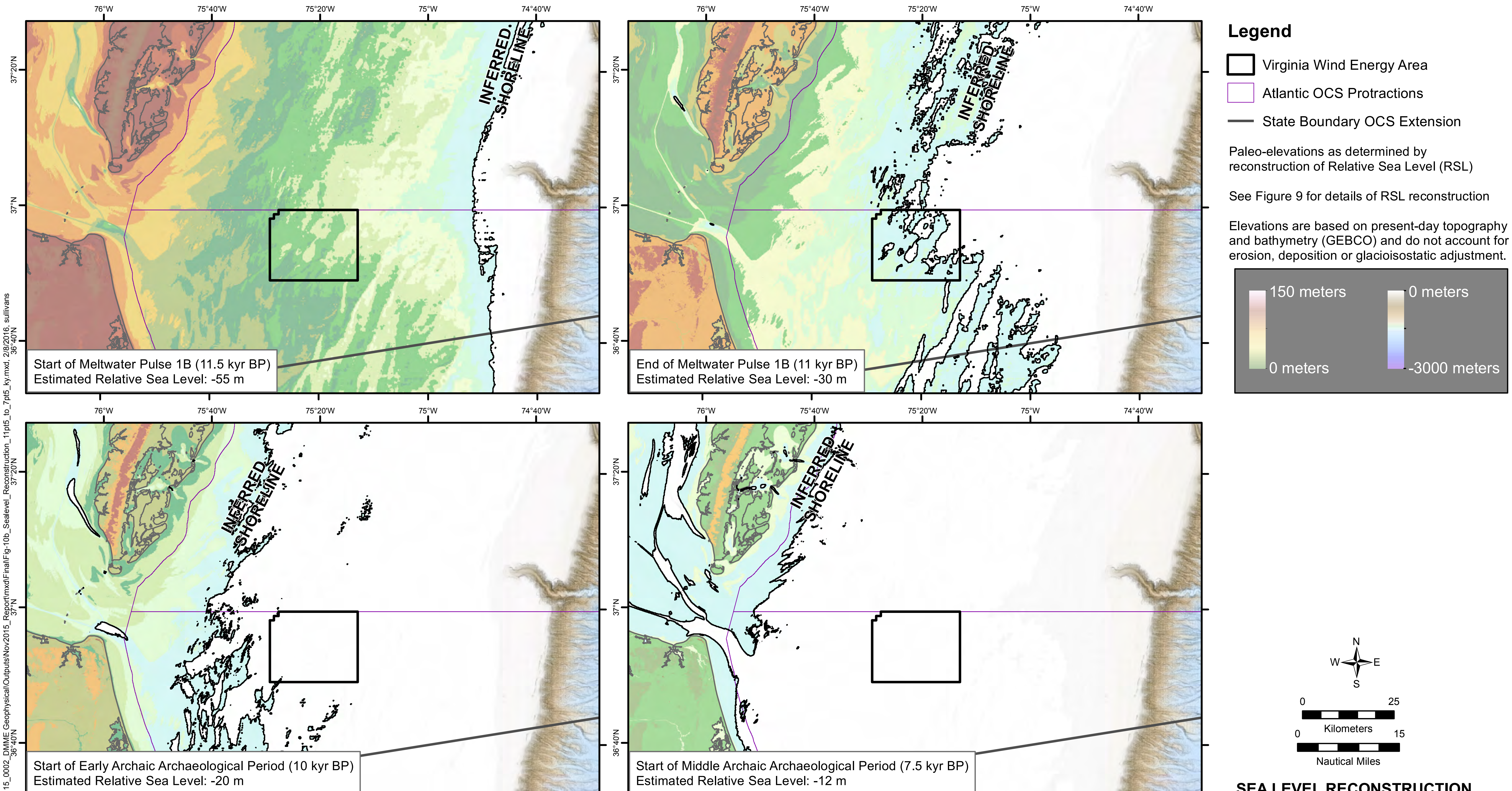
N
W E
S

0 25
Kilometers
0 15
Nautical Miles

SEA LEVEL RECONSTRUCTION
20,000 TO 12,800 YEARS BP
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

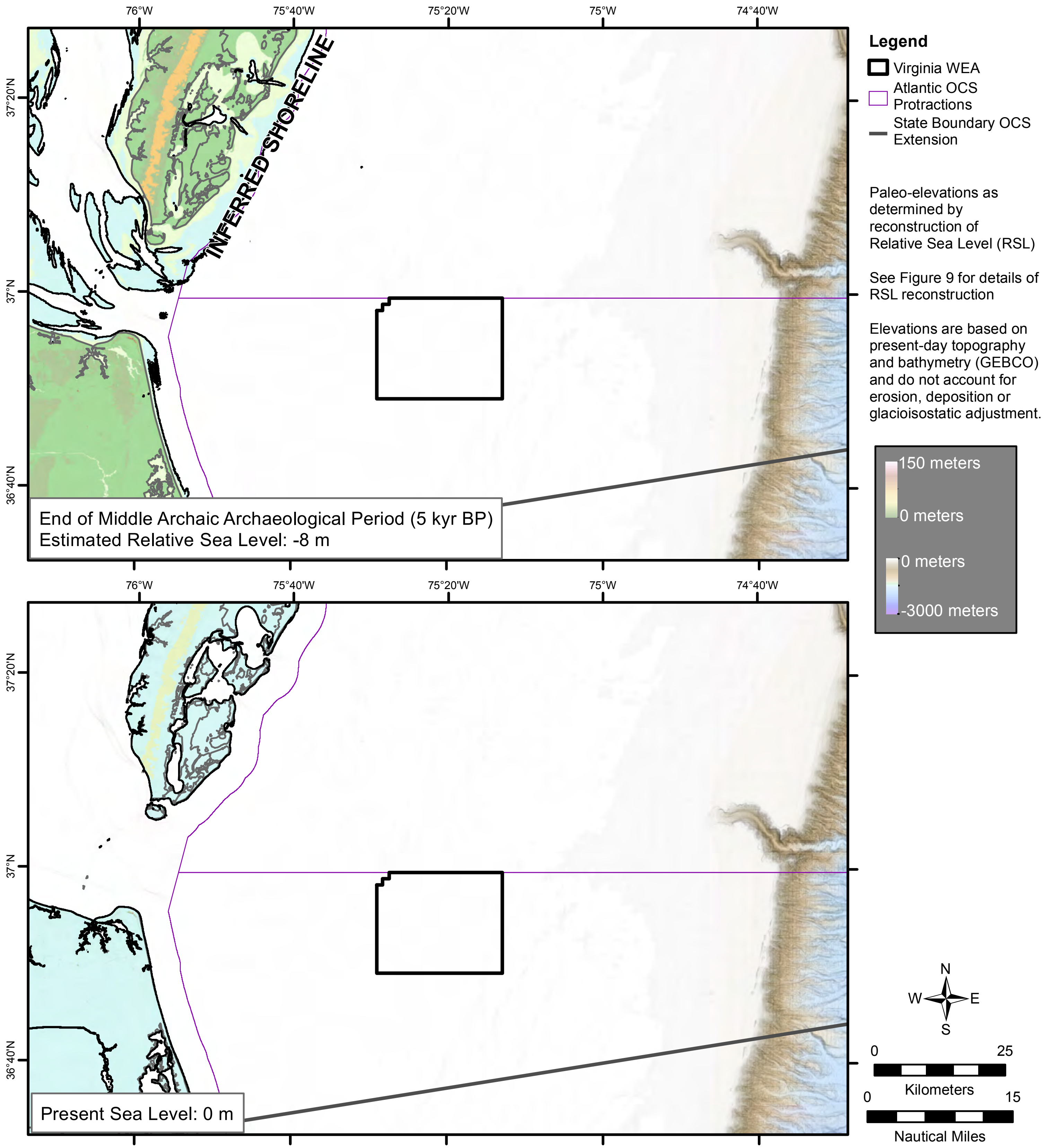
FIGURE 18a

N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig-10a_Sealevel_Reconstruction_20_to_12pt8_kyr.mxd, 2/8/2016, sullivans



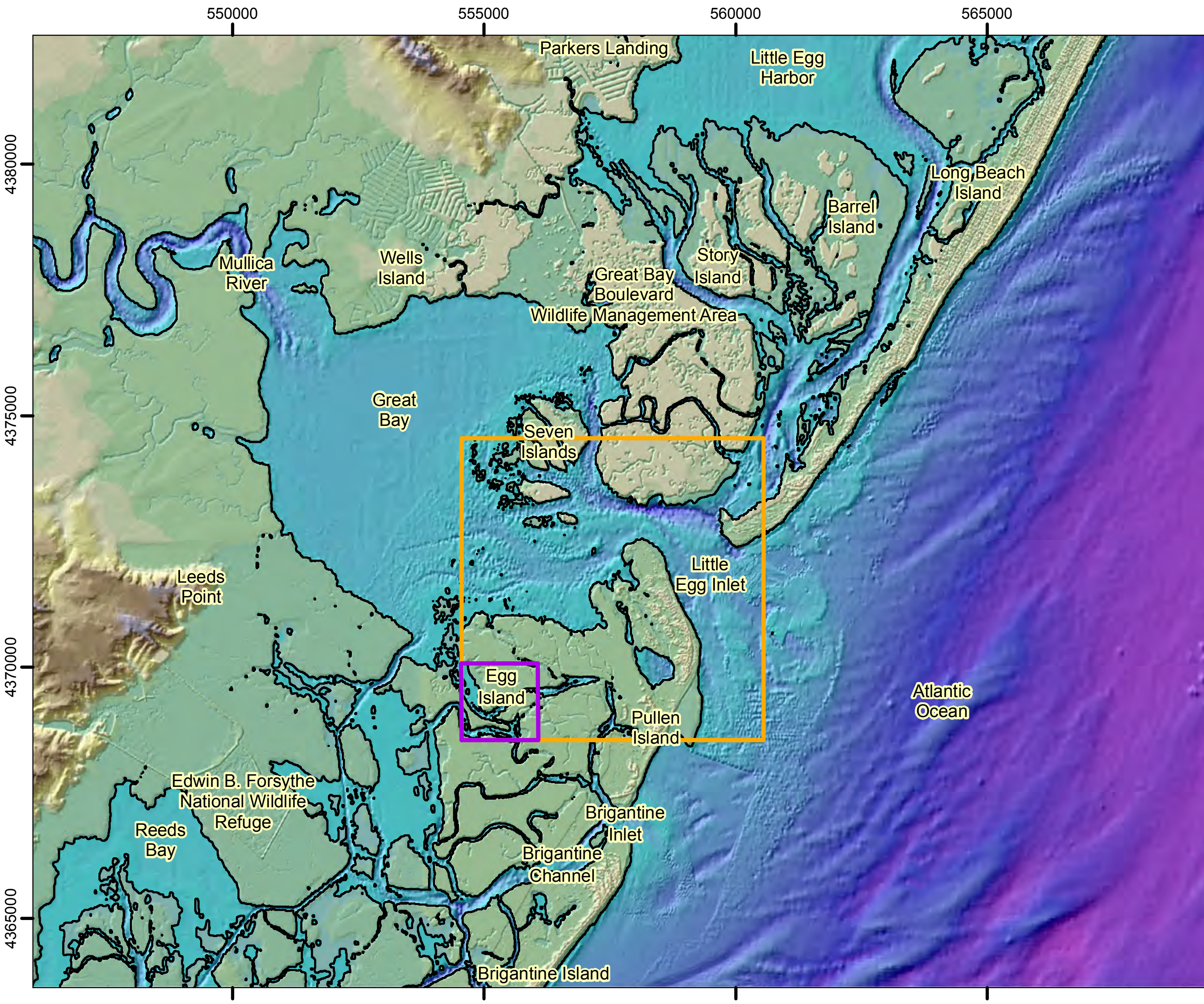
SEA LEVEL RECONSTRUCTION
11,500 TO 7,500 YEARS BP
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 18b



SEA LEVEL RECONSTRUCTION
5,000 YEARS BP AND PRESENT
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 18c



Legend

Analyzed for 30 by 500 m line spacing

Analyzed for 150 by 900 m line spacing

Coastline (Mean Low Water)

N W E S

0 5 Kilometers

Topography

MHW (meters)

High : 25

Low : -1.25

Bathymetry

MHW (meters)

High : -1.25

Low : -25

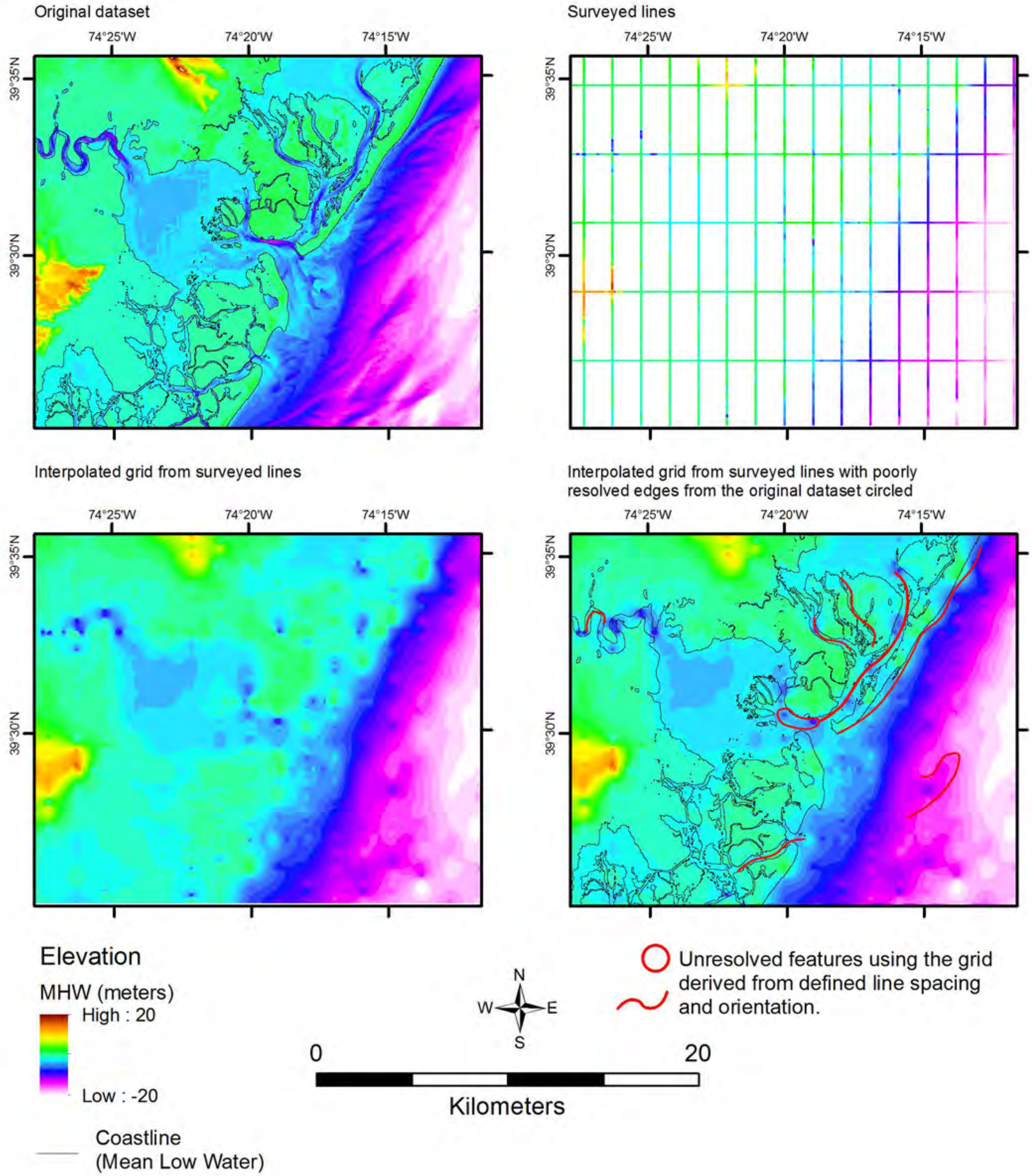
DEM Notes:
Topography and bathymetry used in analysis of survey line spacing and orientation from a portion of the "Digital Elevation Model of Atlantic City, New Jersey" compiled for the Pacific Marine Environmental Laboratory NOAA Center for Tsunami Research (Carignan et al., 2009).

DEM details:
Cell Size: 1/3 arc–second
Date Completed: October 10 2007
Horizontal Datum: WGS 84
Projection: Geographic (degrees)
Vertical Datum: MHW (meters)

ANALYSIS OF SURVEY LINE SPACING AND ORIENTATION
DIGITAL ELEVATION MODEL OF GREAT BAY, NEW JERSEY

Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

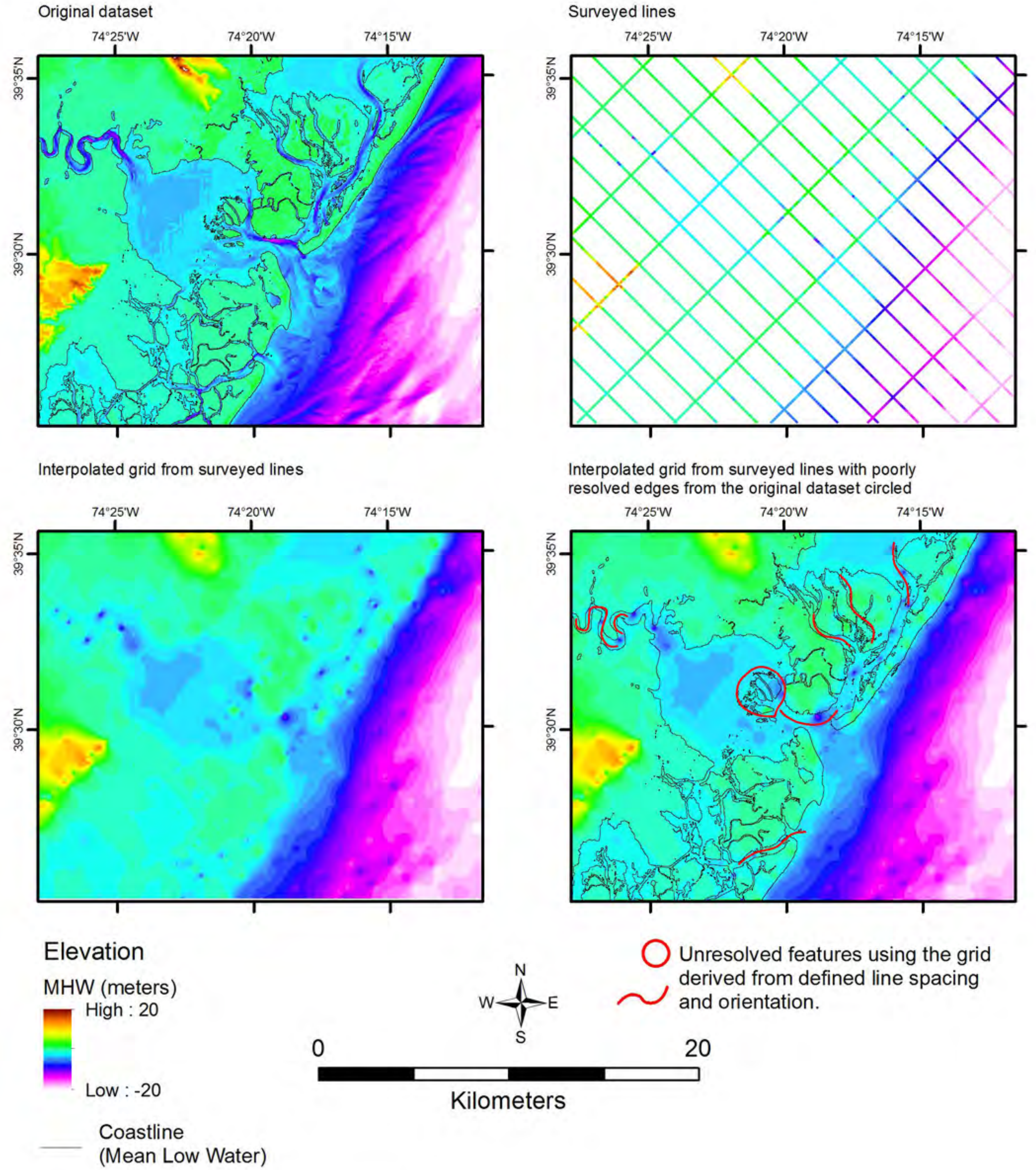
FIGURE 19



SURVEY LINE SPACING - 1500 X 3600 METERS
NORTH-SOUTH PRIMARY LINE ORIENTATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

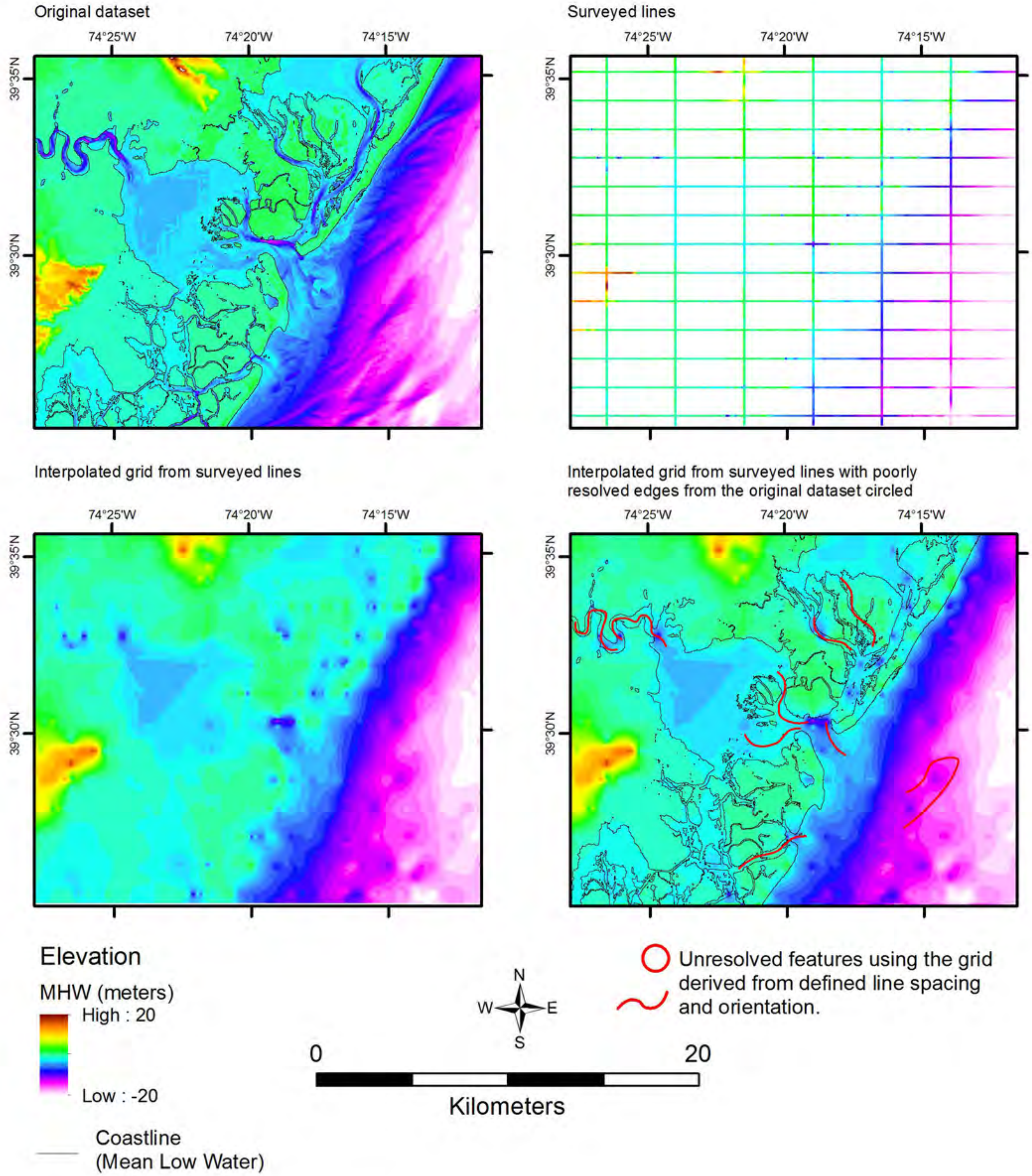
FIGURE 20a

N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig20a-Line_Spacing_Regional_Scale_1500by3600m_0deg.mxd, 6/2/2016, SULLIVANS



SURVEY LINE SPACING - 1500 X 3600 METERS
NORTHWEST-SOUTHEAST PRIMARY LINE ORIENTATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

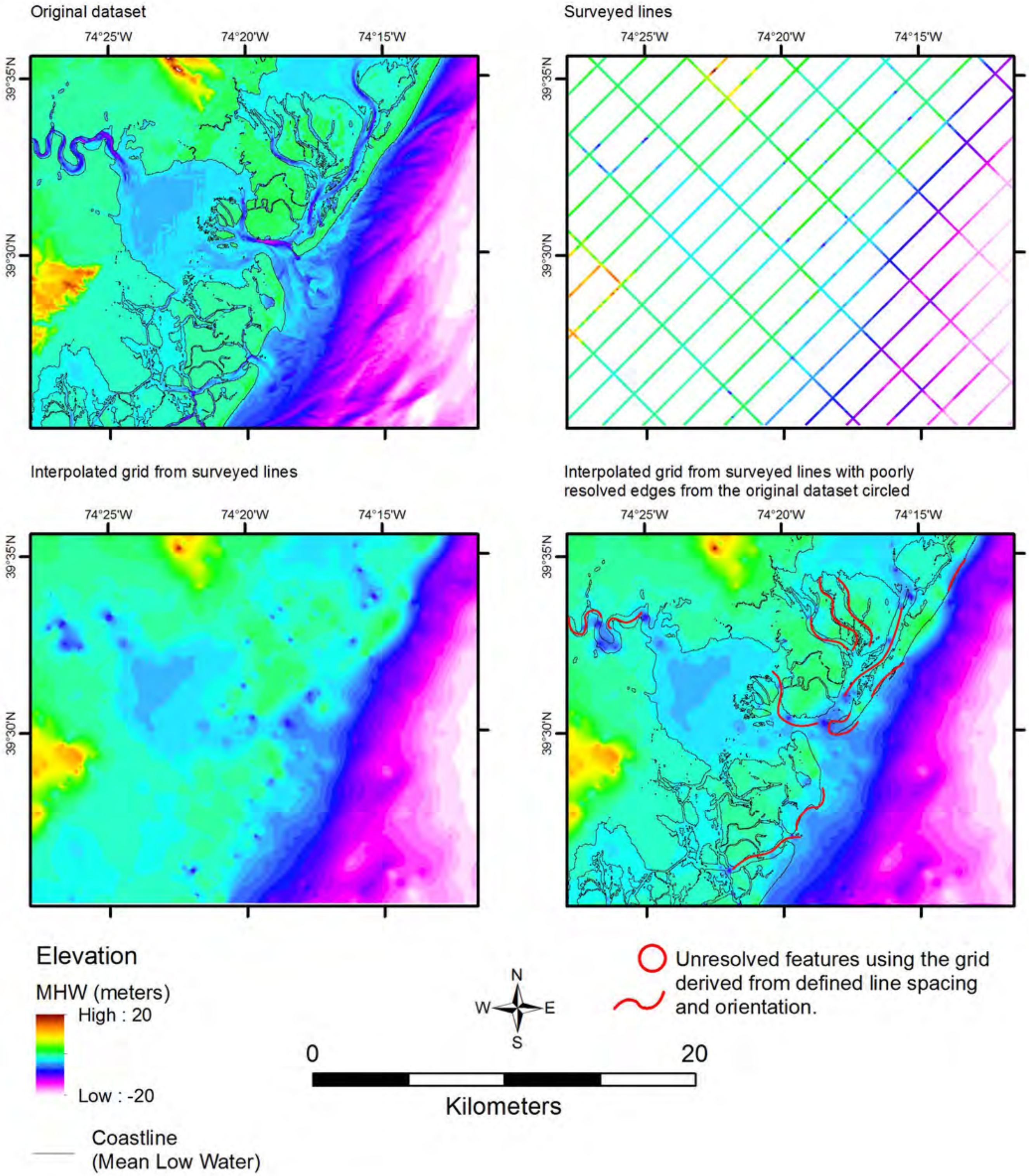
FIGURE 20b



SURVEY LINE SPACING - 1500 X 3600 METERS
EAST-WEST PRIMARY LINE ORIENTATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 20c

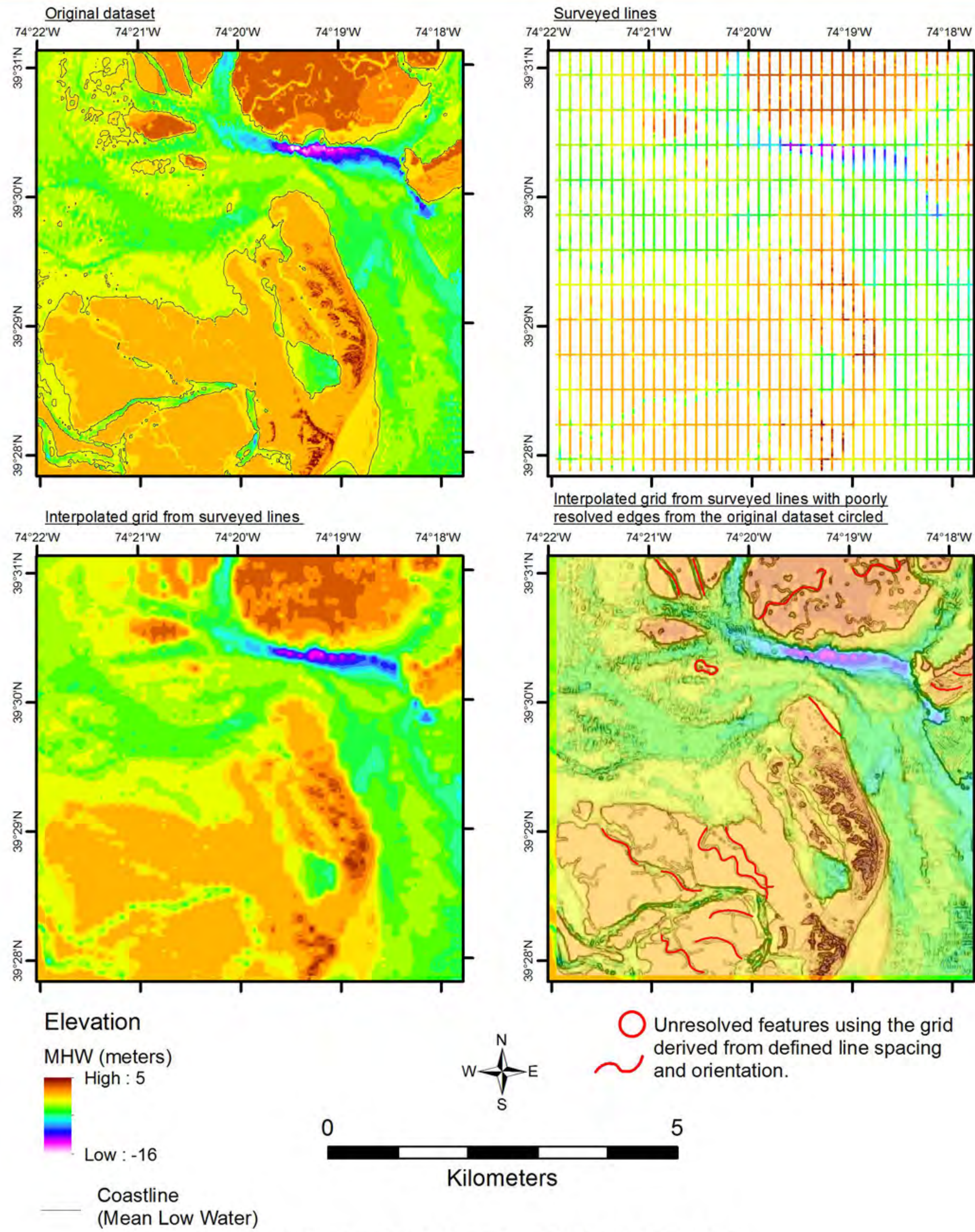
N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig20c-Line_Spacing_Regional_Scale_1500by3600m_90deg.mxd, 6/2/2016, SULLIVANS



SURVEY LINE SPACING - 1500 X 3600 METERS
NORTHEAST-SOUTHWEST PRIMARY LINE ORIENTATION

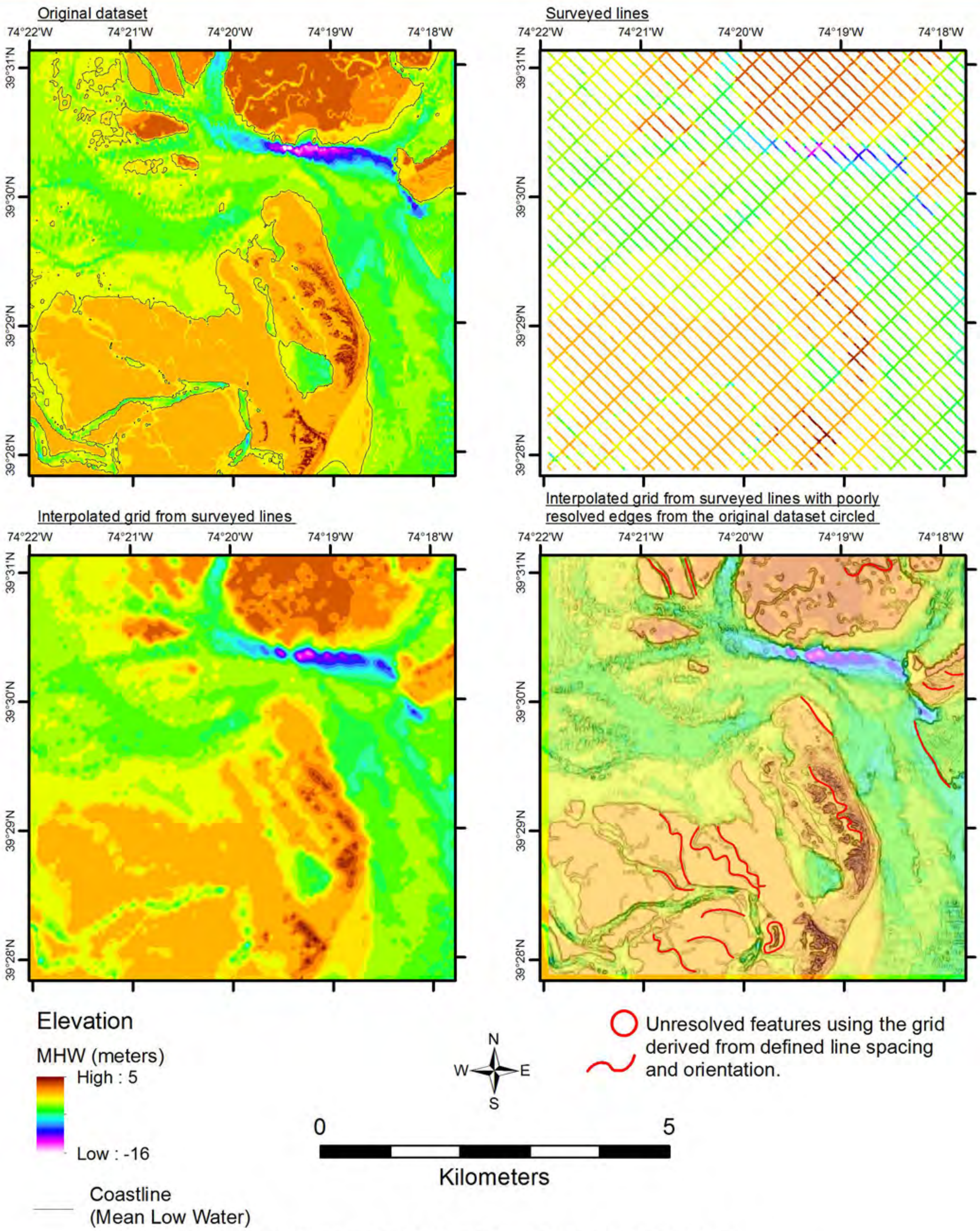
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 20d



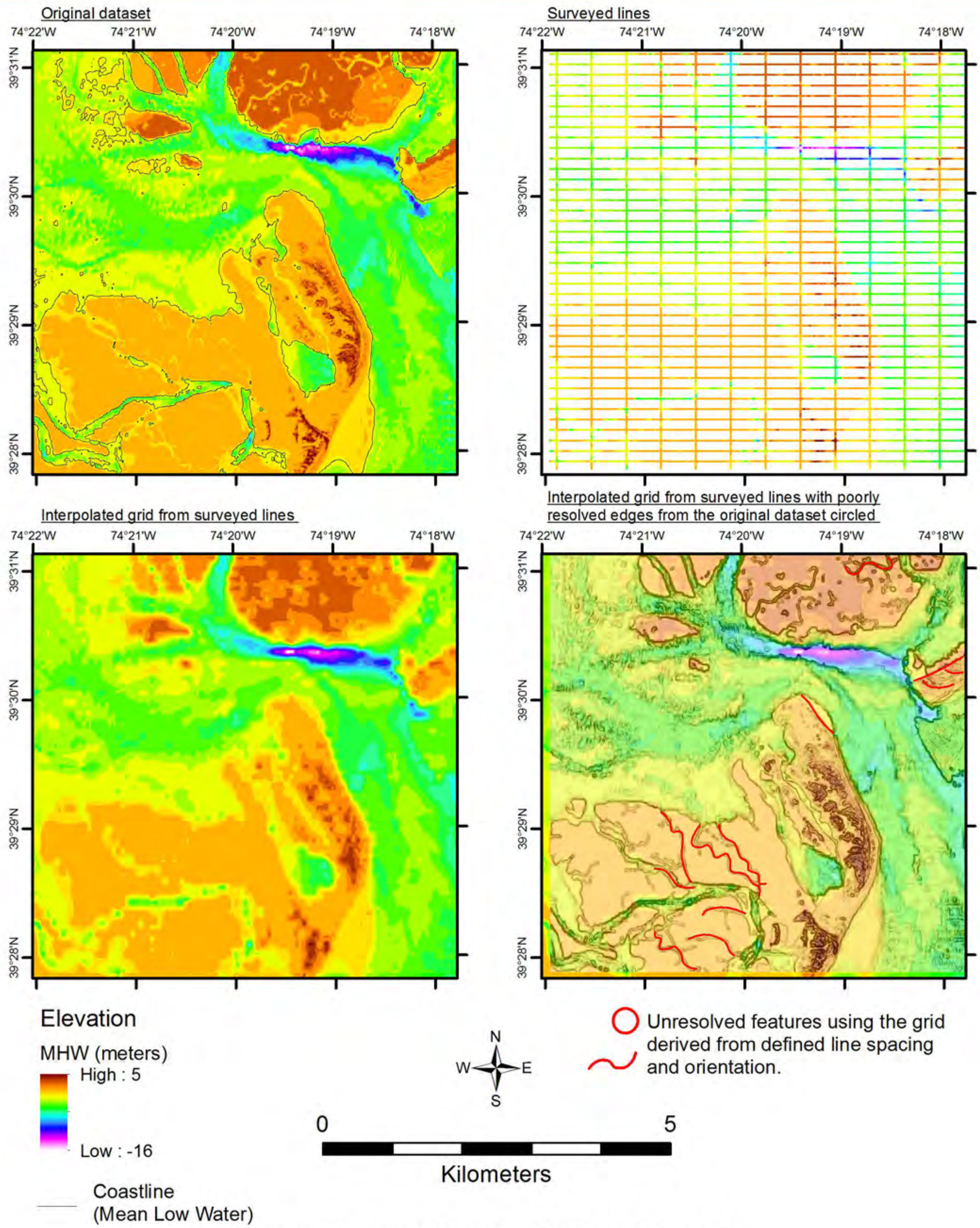
SURVEY LINE SPACING - 150 X 500 METERS
NORTH-SOUTH PRIMARY LINE ORIENTATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 21a



SURVEY LINE SPACING - 150 X 500 METERS
NORTHWEST-SOUTHEAST PRIMARY LINE ORIENTATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 21b



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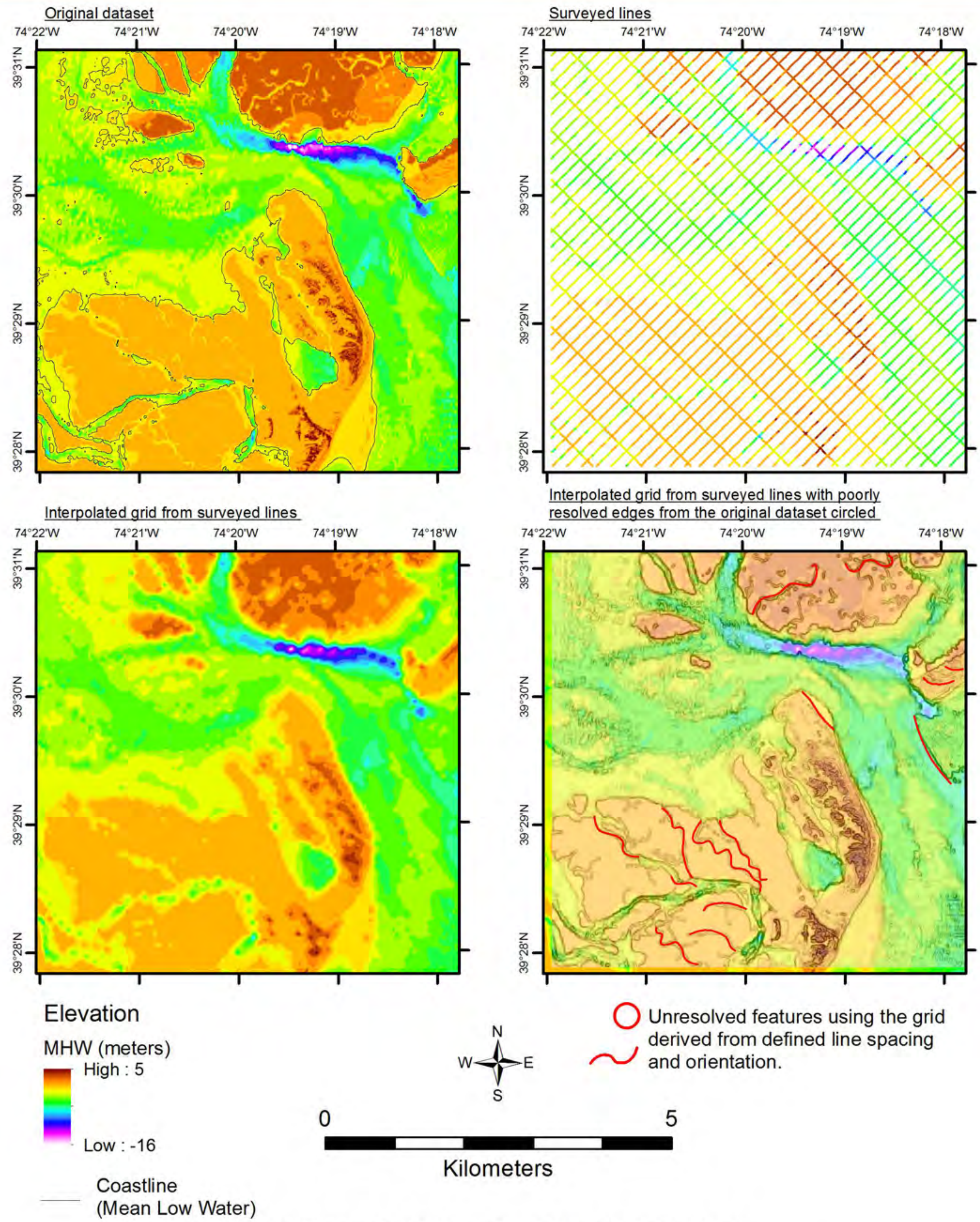
SURVEY LINE SPACING - 150 X 500 METERS
EAST-WEST PRIMARY LINE ORIENTATION

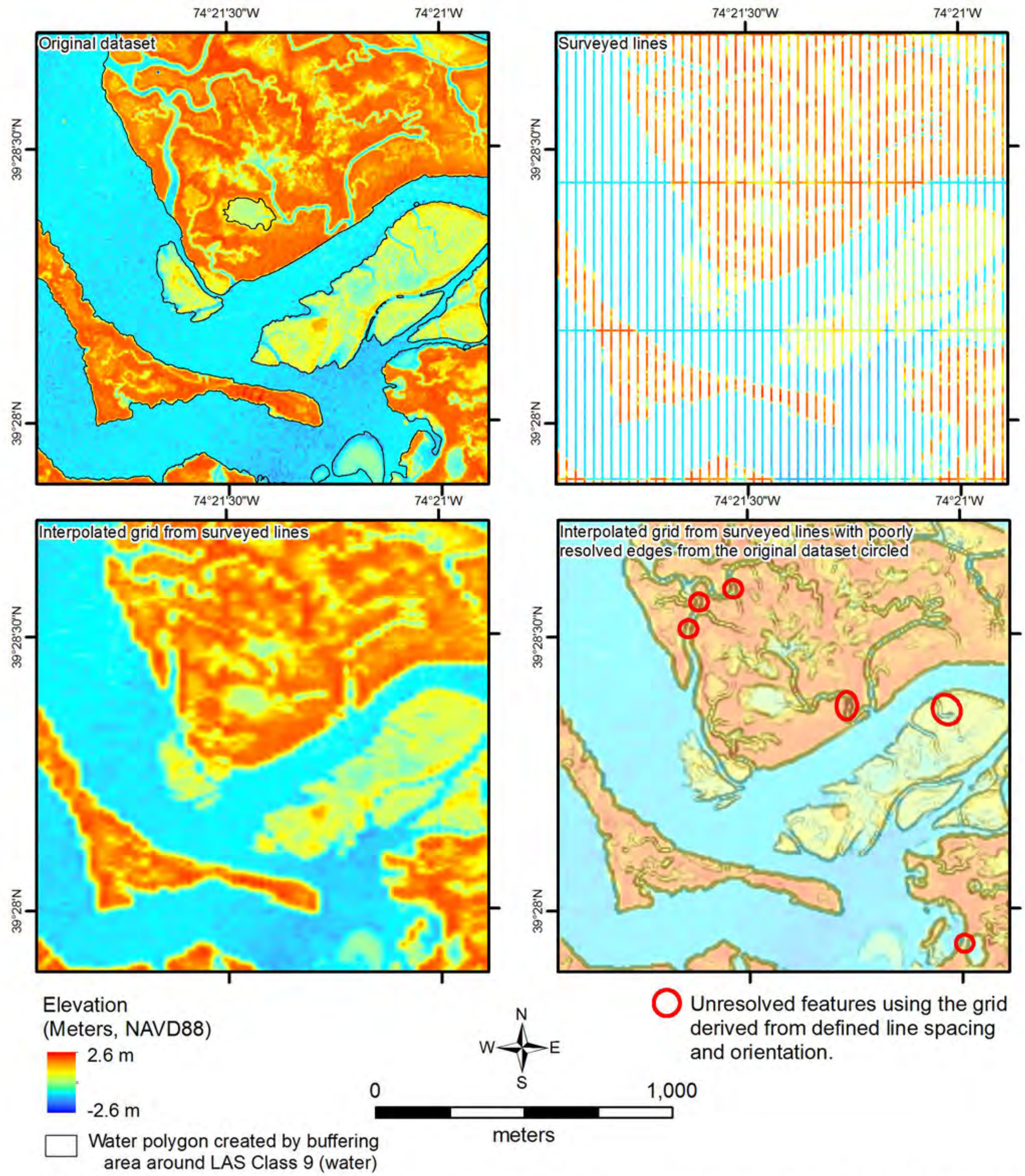
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 21c



SURVEY LINE SPACING - 150 X 500 METERS
NORTHEAST-SOUTHWEST PRIMARY LINE ORIENTATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 21d

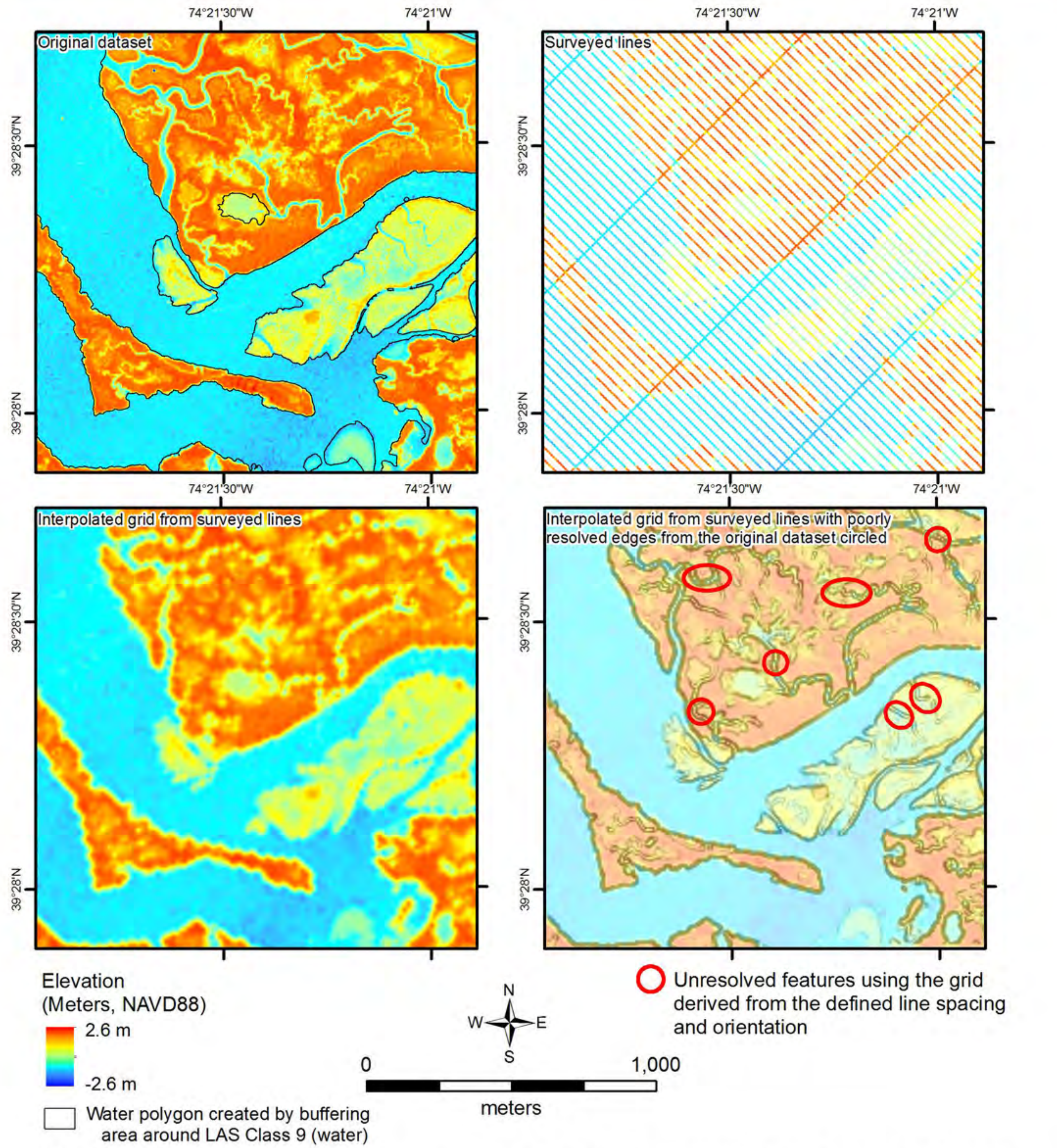


Note: The elevation data used for the 30 by 500 meter line spacing analysis came from a LiDAR DEM (RAMPP, 2011). LiDAR acquisition and processing to bare-earth was conducted by Fugro EarthData, Inc. The cell size of the above gridded DEM is approximately 6 by 6 meters. The tighter cell size allows smaller features to be resolved which is necessary for analyzing the 30 meter line spacing, although the areas at or below water level are not accurate topographic elevations.

SURVEY LINE SPACING - 30 X 500 METERS
NORTH-SOUTH PRIMARY LINE ORIENTATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 22a

N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig22a-Line_Spacing_Arch_Scale_30by500m_bnw_0deg.mxd, 6/2/2016, SULLIVANS



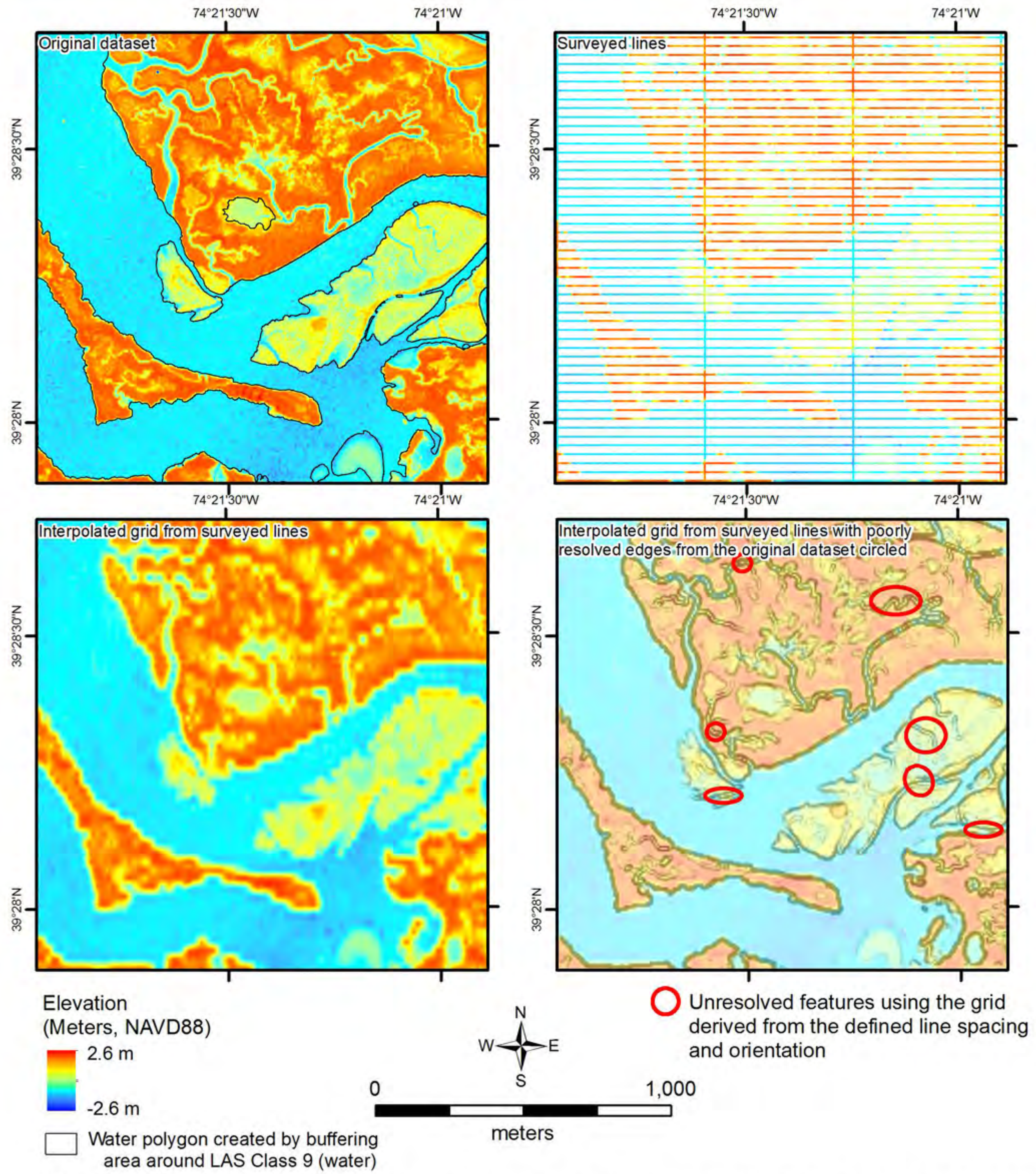
Note: The elevation data used for the 30 by 500 meter line spacing analysis came from a LiDAR DEM (RAMPP, 2011). LiDAR acquisition and processing to bare-earth was conducted by Fugro EarthData, Inc. The cell size of the above gridded DEM is approximately 6 by 6 meters. The tighter cell size allows smaller features to be resolved which is necessary for analyzing the 30 meter line spacing, although the areas at or below water level are not accurate topographic elevations.

SURVEY LINE SPACING - 30 X 500 METERS
NORTHWEST-SOUTHEAST PRIMARY LINE ORIENTATION

Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 22b

N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig22b-Line_Spacing_Arch_Scale_30by500m_bnw_45deg.mxd, 6/2/2016, SULLIVANS

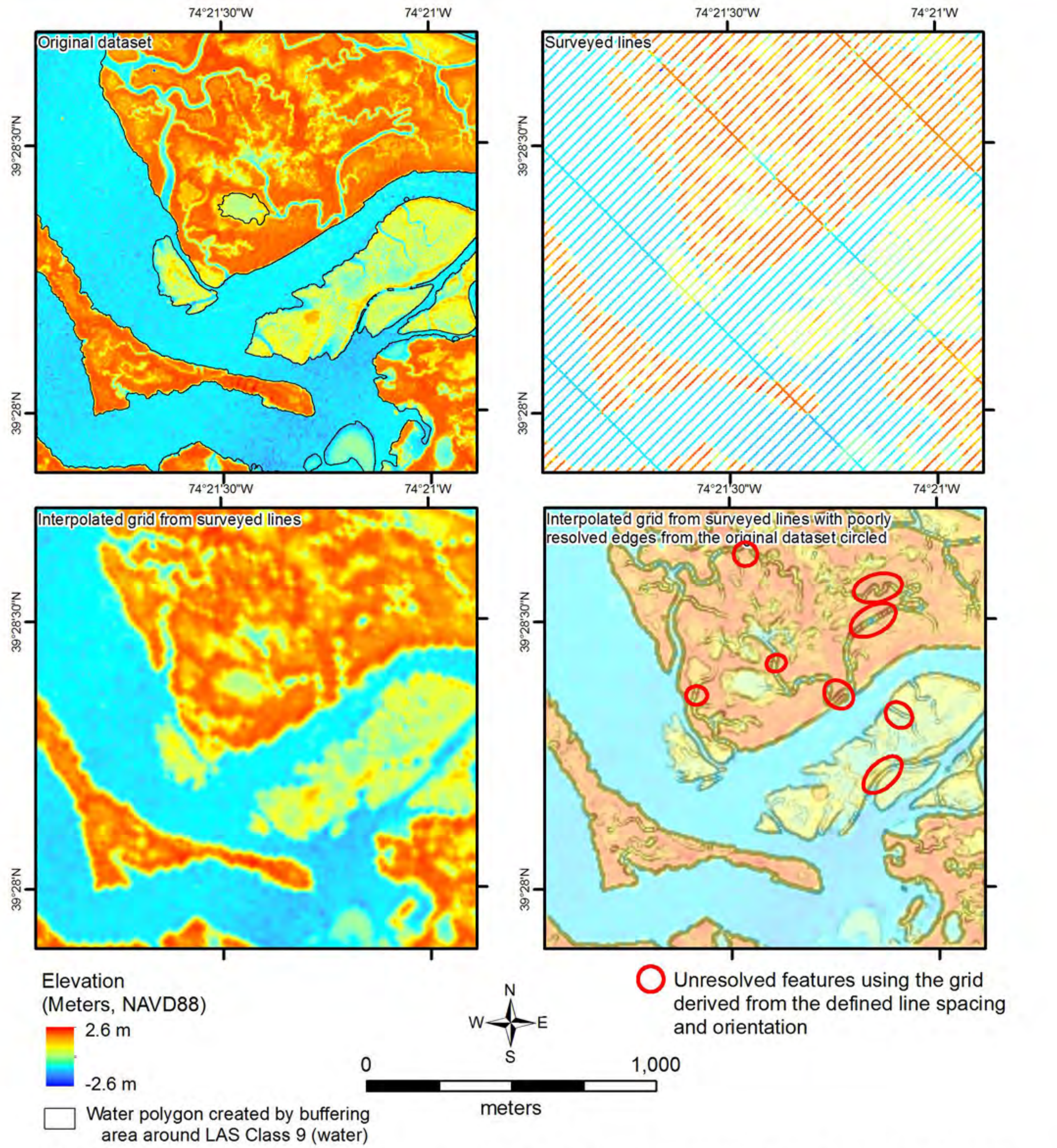


Note: The elevation data used for the 30 by 500 meter line spacing analysis came from a LiDAR DEM (RAMPP, 2011). LiDAR acquisition and processing to bare-earth was conducted by Fugro EarthData, Inc. The cell size of the above gridded DEM is approximately 6 by 6 meters. The tighter cell size allows smaller features to be resolved which is necessary for analyzing the 30 meter line spacing, although the areas at or below water level are not accurate topographic elevations.

SURVEY LINE SPACING - 30 X 500 METERS
EAST-WEST PRIMARY LINE ORIENTATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 22c

N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig22c-Line_Spacing_Arch_Scale_30by500m_bnw_90deg.mxd, 6/2/2016, SULLIVANS



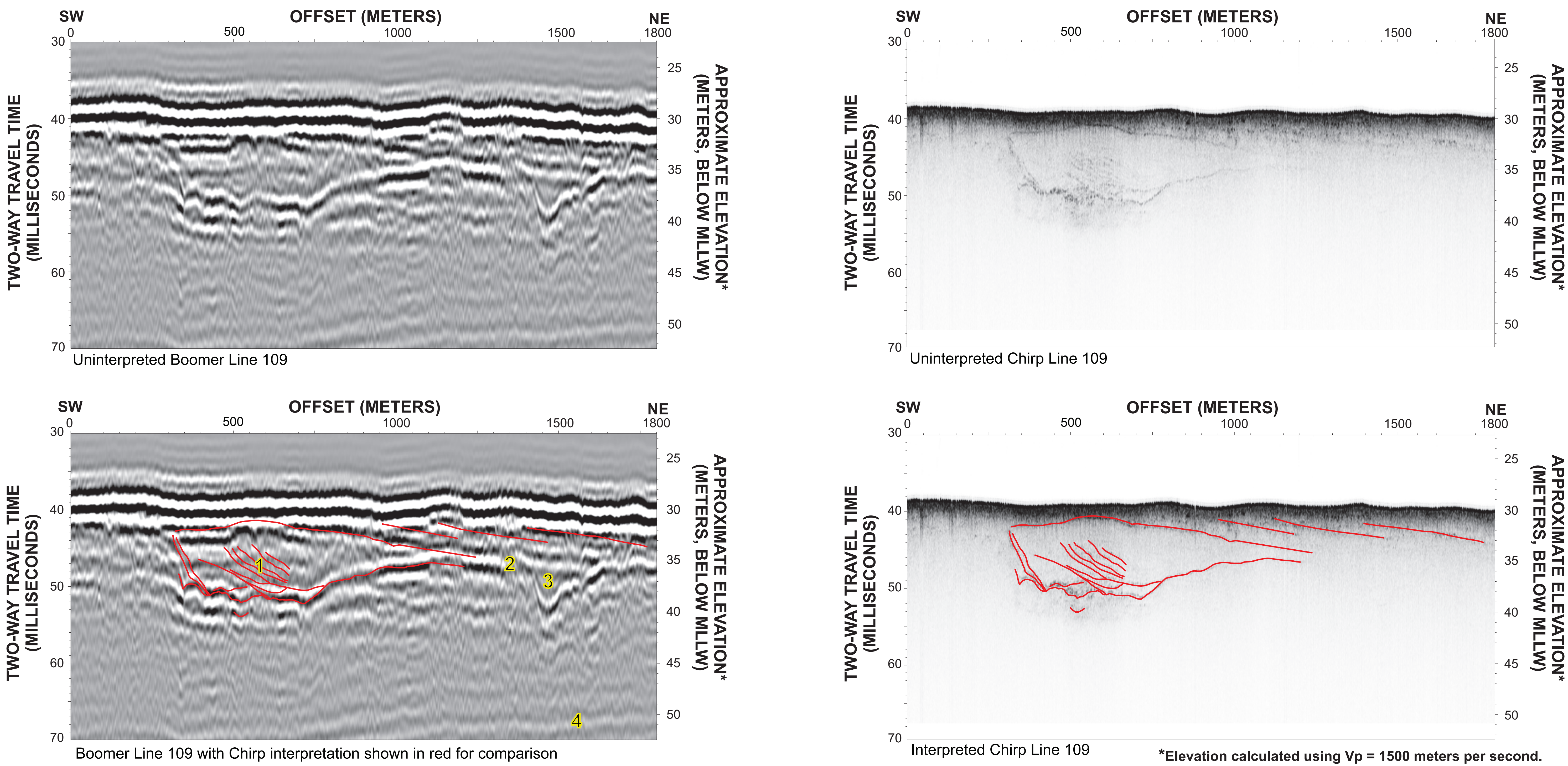
Note: The elevation data used for the 30 by 500 meter line spacing analysis came from a LiDAR DEM (RAMPP, 2011). LiDAR acquisition and processing to bare-earth was conducted by Fugro EarthData, Inc. The cell size of the above gridded DEM is approximately 6 by 6 meters. The tighter cell size allows smaller features to be resolved which is necessary for analyzing the 30 meter line spacing, although the areas at or below water level are not accurate topographic elevations.

SURVEY LINE SPACING - 30 X 500 METERS
NORTHEAST-SOUTHWEST PRIMARY LINE ORIENTATION

Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 22d

N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig22d-Line_Spacing_Arch_Scale_30by500m_bnw_135deg.mxd, 6/2/2016, SULLIVANS



Notes:

1 Subtle dipping internal reflectors within incised valley are unresolvable with boomer data

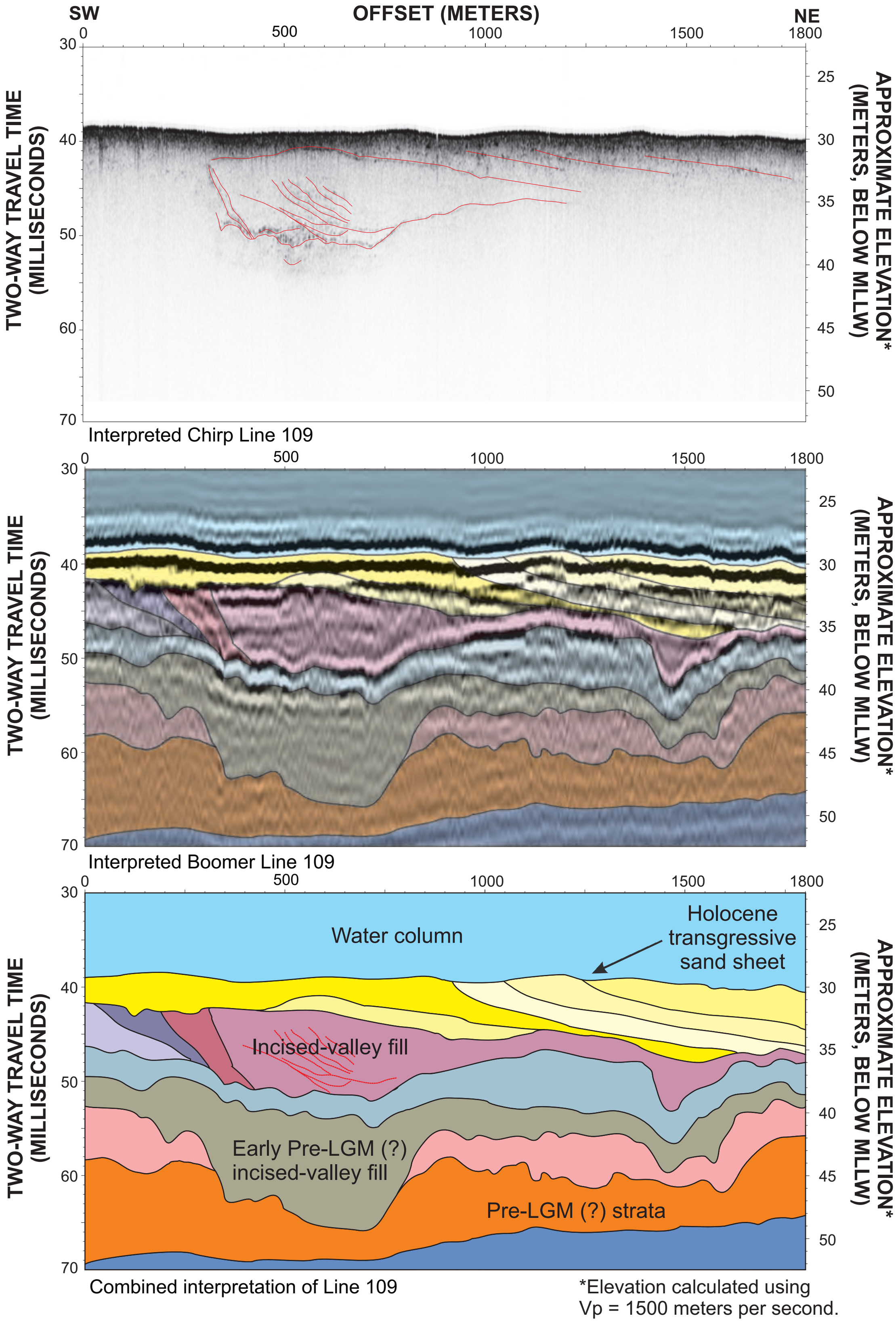
2 Correlation of erosional base excellent between boomer and Chirp data

3 No indication of deeper channel in Chirp profile, probably due to thickened Holocene sediment package

4 Mapping of subsurface reflectors at depths greater than 10 meters below the seafloor are generally only possible with boomer data

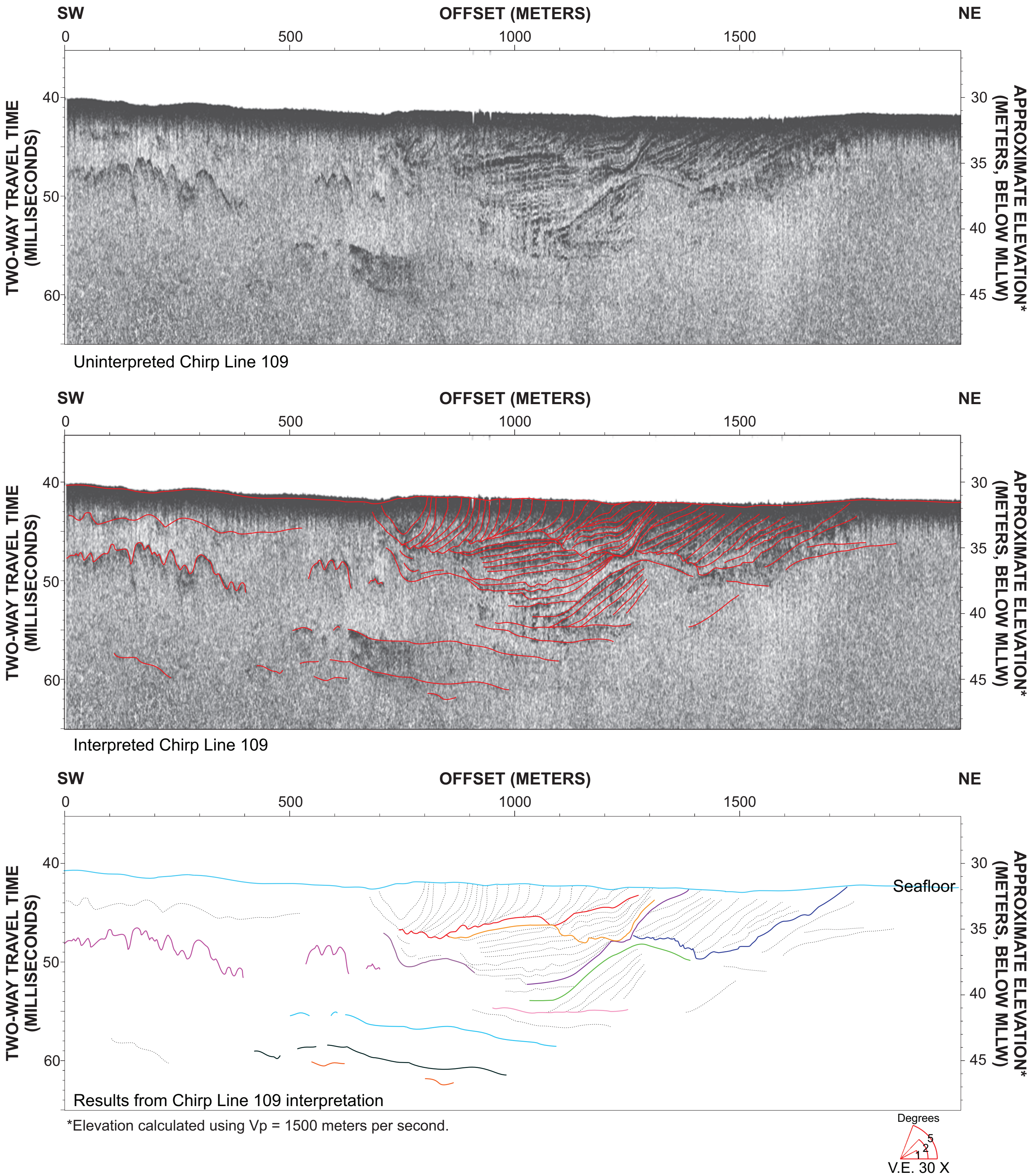
DATA COMPARISON
BOOMER AND CHIRP LINE 109
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 23a



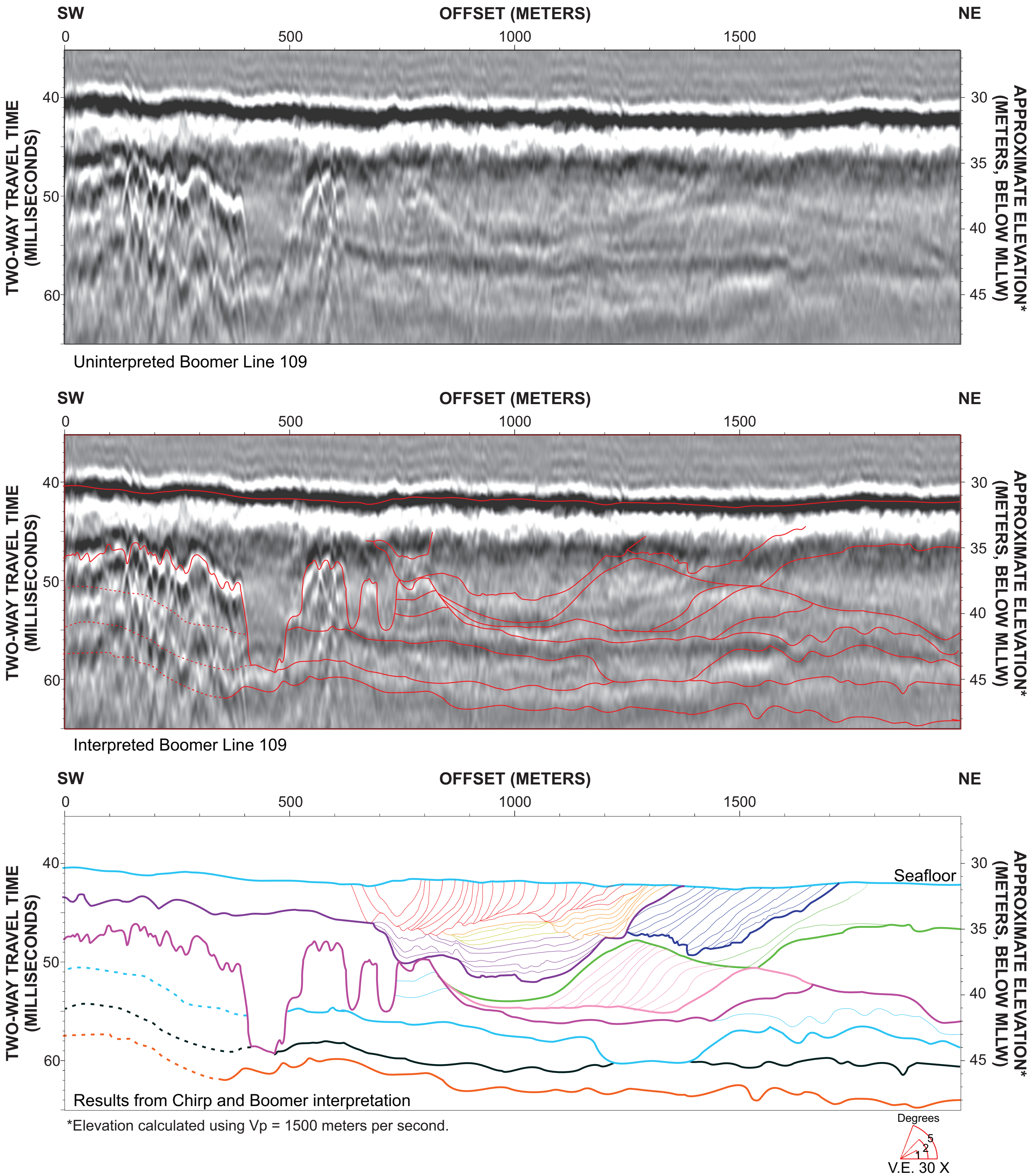
UTILIZING MULTIPLE SEISMIC DATA TYPES TO AID INTERPRETATION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 23b



GEOLOGIC INTERPRETATION BASED ON CHIRP DATA
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

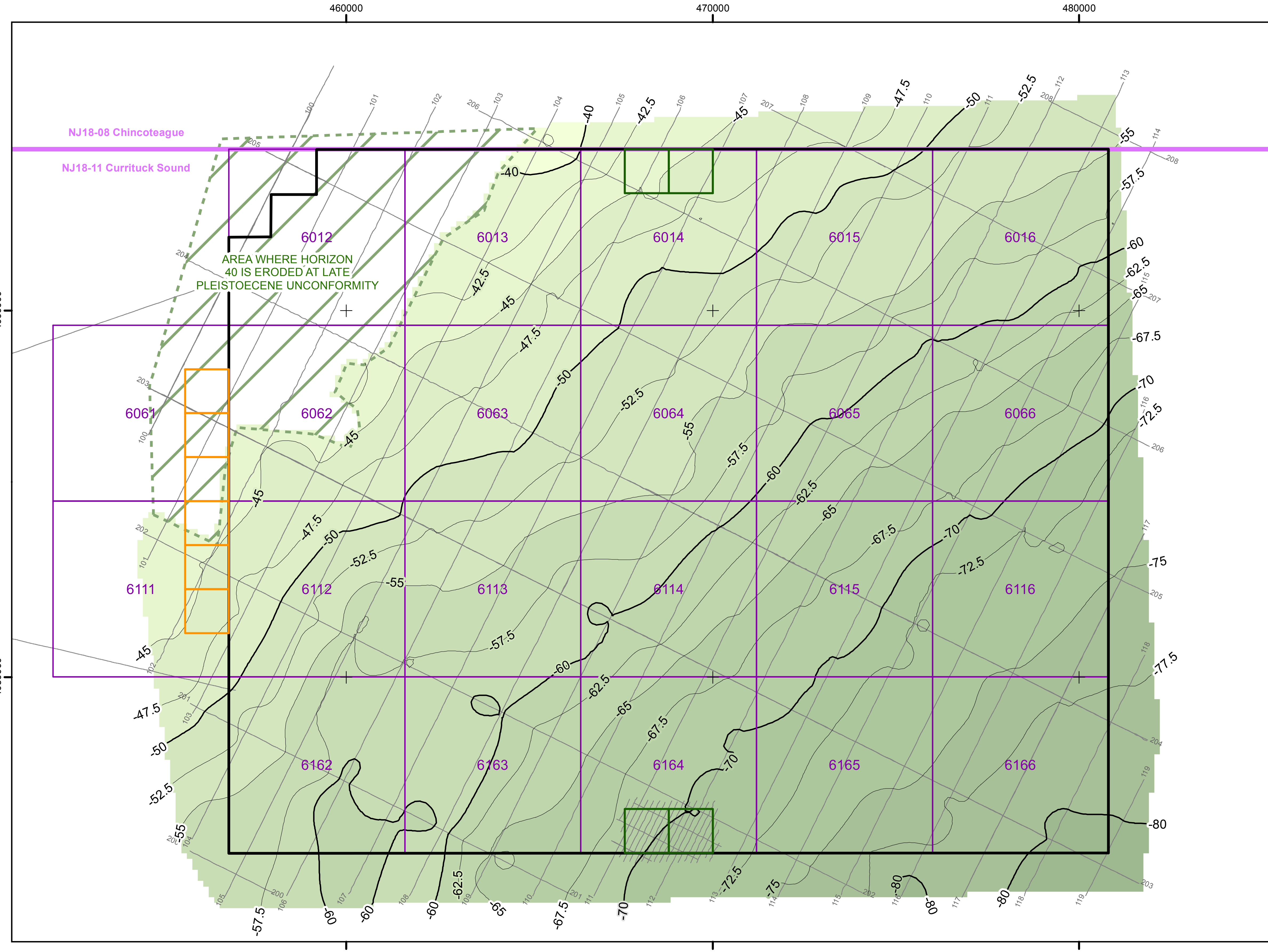
FIGURE 24a



*Elevation calculated using Vp = 1500 meters per second.

GEOLOGIC INTERPRETATION BASED ON BOOMER AND CHIRP DATA
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 24b



LEGEND

- Survey Vessel Navigation Trackline
- Virginia Wind Energy Area
- 6016 Wind Energy Area OCS Lease Block
- Demonstration Project Lease Aliquot
- Meteorological Tower Aliquot
- Coordinate Grid is UTM Zone 18N, NAD 1983, Meters

Approximate Elevation of Horizon 40, Meters (Re. MLLW)

Horizon 40 is inferred to be related to a Tertiary strata. Time-to-depth conversions based on V_p = 1,500 m/s; thus elevation should be considered approximate.

- Major contour interval is 10 meters.
- Minor contour interval is 2.5 meters

-39.9 - -35
-44.9 - -40
-49.9 - -45
-54.9 - -50
-59.9 - -55
-64.9 - -60
-69.9 - -65
-74.9 - -70
-79.9 - -75
-82.5 - -80

N W E S

0 2 Nautical Miles

0 3 6 Kilometers

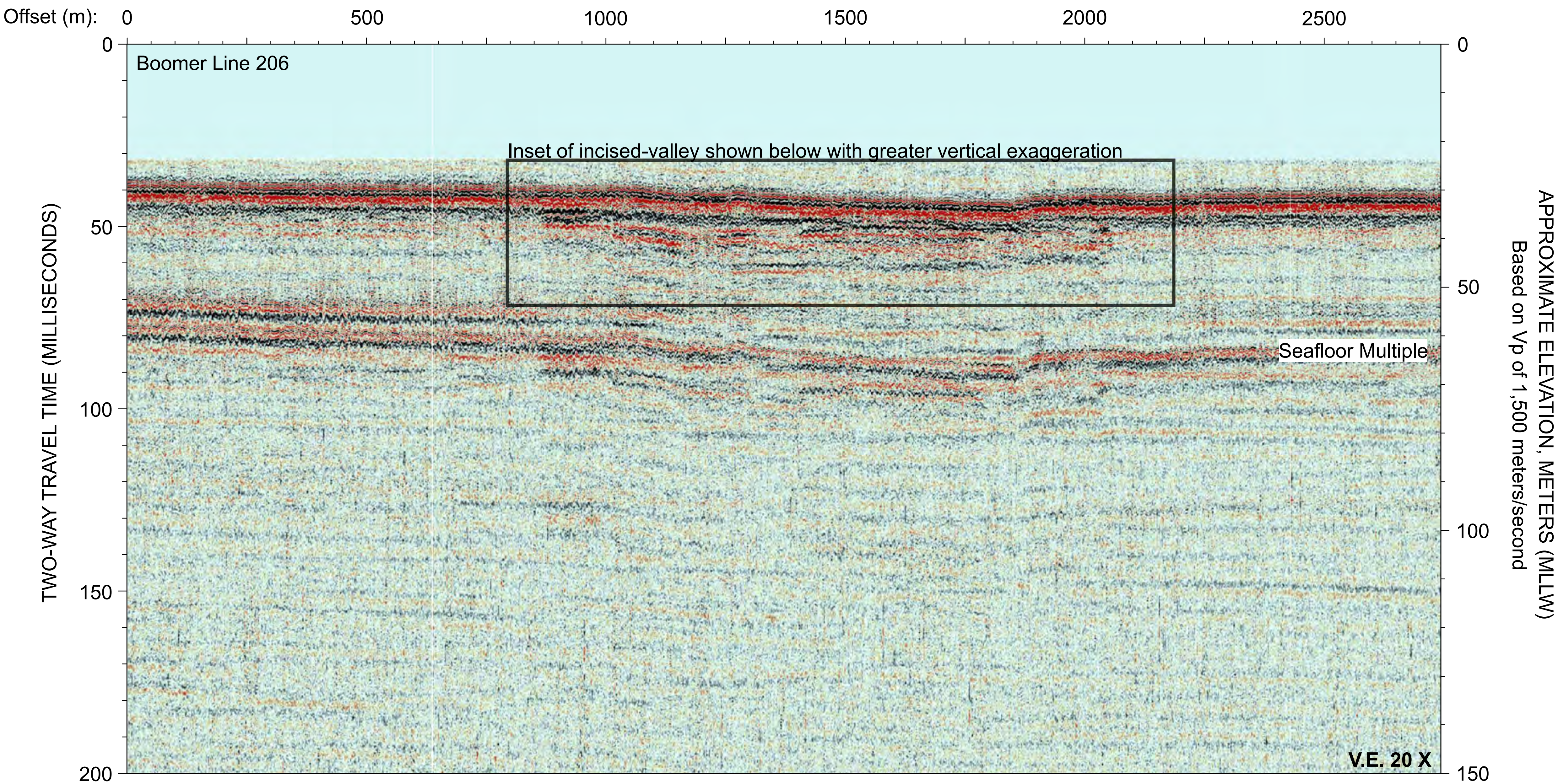
ELEVATION CONTOURS OF HORIZON 40

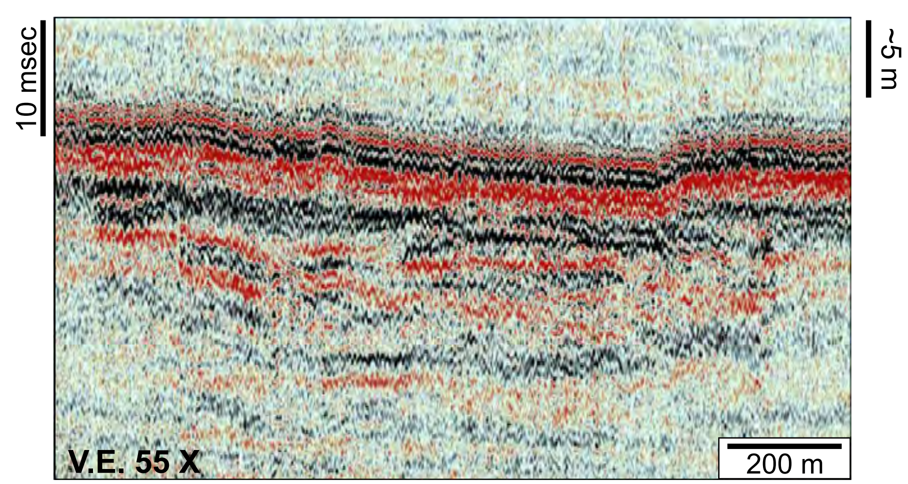
Virginia WEA Geophysical Survey Phase II

Virginia Outer Continental Shelf

FIGURE 25

N:\Projects\04_2015\04_8115_0002_DMME Geophysical\Outputs\Nov2015_Report\mxd\Final\Fig-23_Elev_H40.mxd, 2/5/2016, sullivans





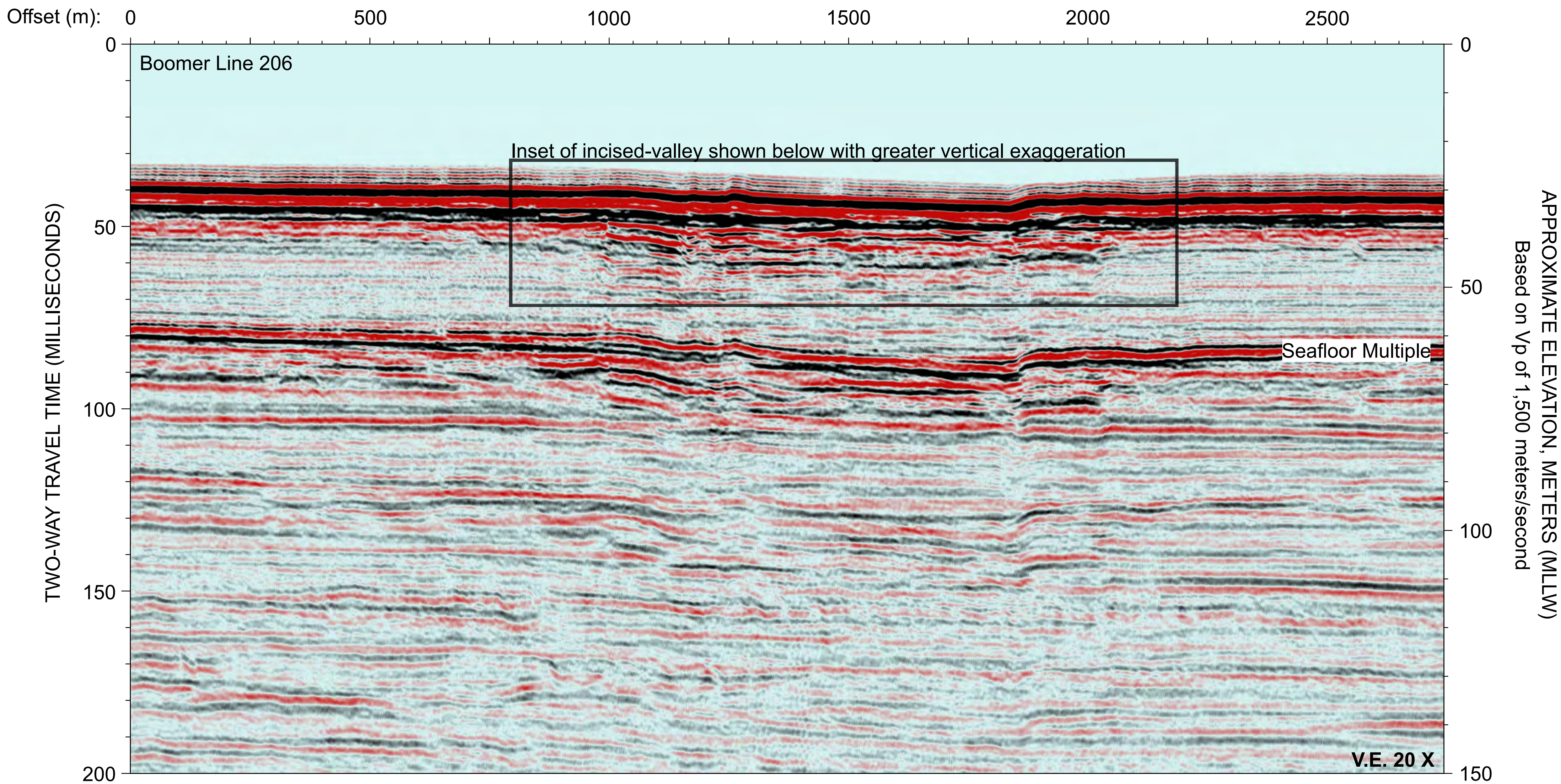
Single Channel (channel #4)

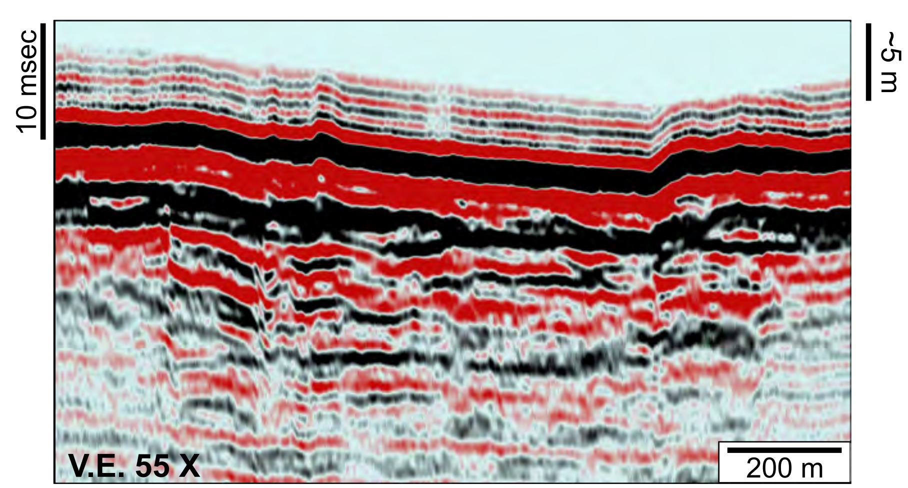
A single-channel seismic (SCS) section from the multi-channel seismic (MCS) dataset was exported to display the benefits of various processing techniques that cannot be applied to SCS profiles.

The data example shown above highlights many problems associated with SCS data, such as:
1) Low fold results in noisy data. Stacking common-midpoint (CMP) data considerably increases the signal-to-noise ratio in MCS data.
2) The contamination of primary seismic reflections from the subsurface is severely degraded below the seafloor multiple. Normal-move out (NMO) can significantly reduce the presence of the multiple in MCS data. A variety of other signal processing techniques can be used to try to suppress the multiple.
3) While deconvolution can be applied to SCS data, it has not been completed for this example. This leads to poor vertical resolution as can be seen in the inset of the incised-valley.
4) As is obvious in the Figures 26b to 26e, there are individual channels within the incised-valley in the inset. Since the data example above has not been migrated, dipping edges of these channels have not been repositioned to their proper location, and therefore they cannot be resolved.

BOOMER MCS DATA PROCESSING
SINGLE CHANNEL
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 26a





3.12-mgi (24 channels) MCS

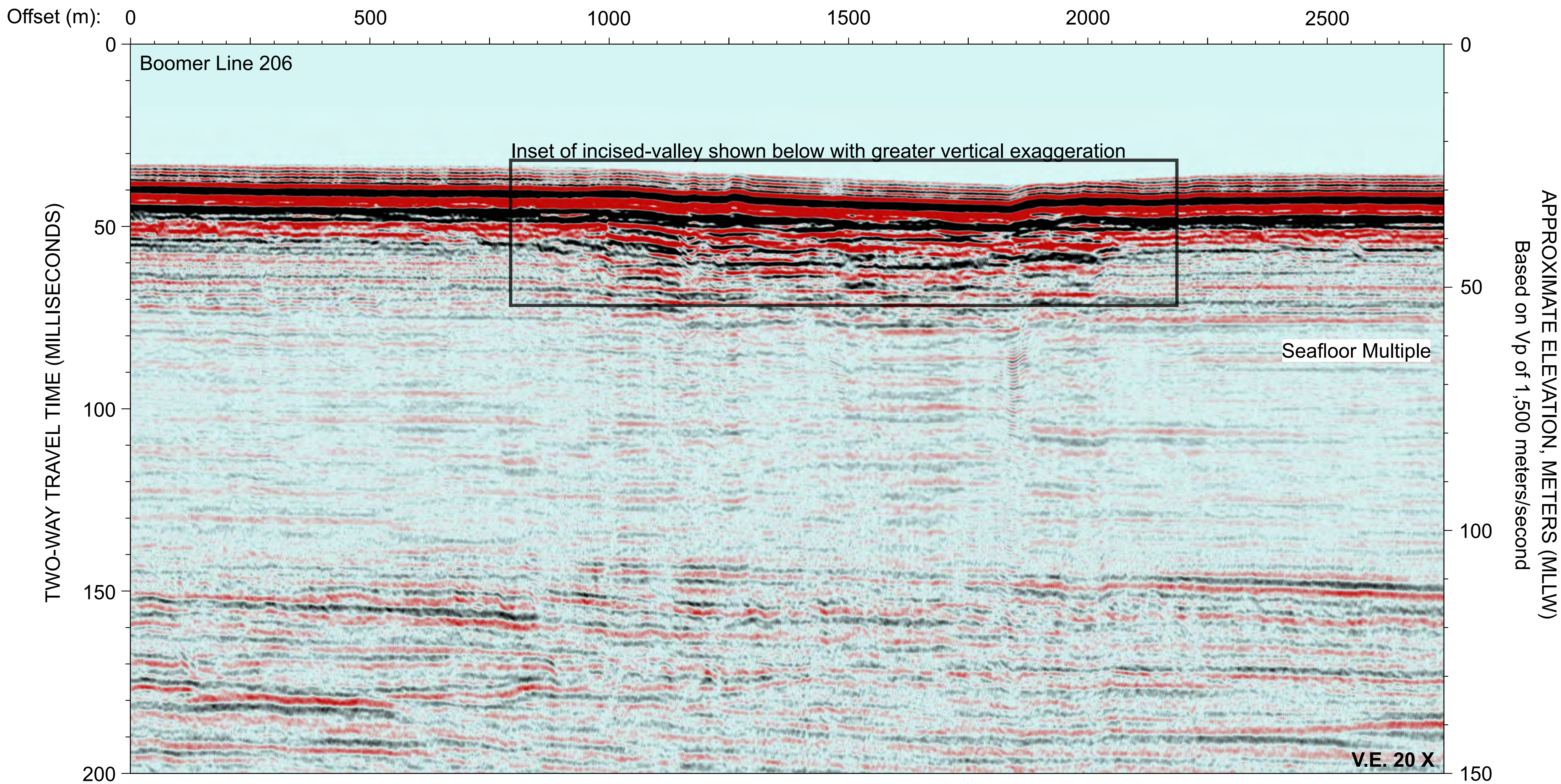
A 24-channel, 3.12-mgi multi-channel seismic (MCS) profile shown above went through a standard processing routine as described in Section 3.1.2.

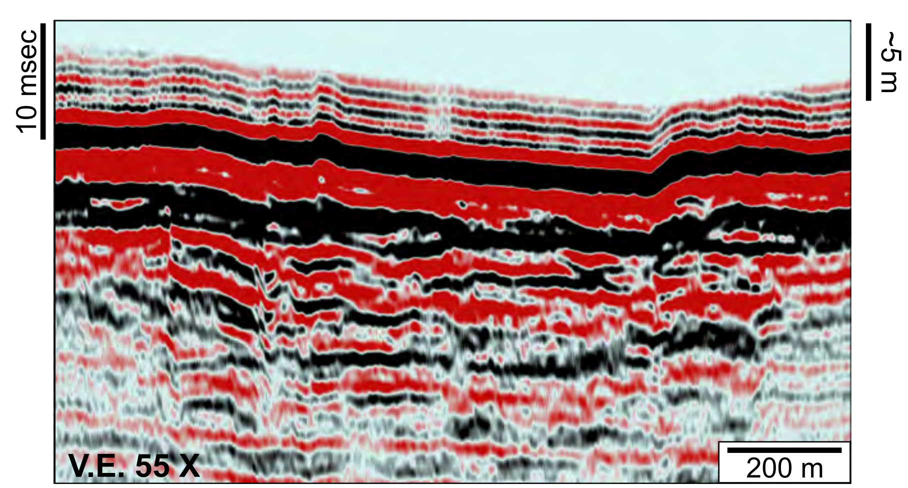
The data example shown above highlights many of the benefits of MCS data over SCS (Figure 26a). Examples include:

1) The data was processed using 24-channels so there is a significant increase in the signal-to-noise ratio (SNR) compared to Figure 26a.
2) Primary reflections can be viewed beneath the multiple allowing deeper horizons to be mapped in the dataset, although multiples still substantially obscure the deeper section.
3) Deconvolution was applied both pre- and post-stack and the result is a significant increase in temporal resolution. Individual channels within the incised-valley can be seen within the inset image to left.
4) The vertical resolution is limited due to the spacing of the hydrophones along the Geo-Eel streamer.

BOOMER MCS DATA PROCESSING
24 CHANNEL, 3.12 mgi
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 26b



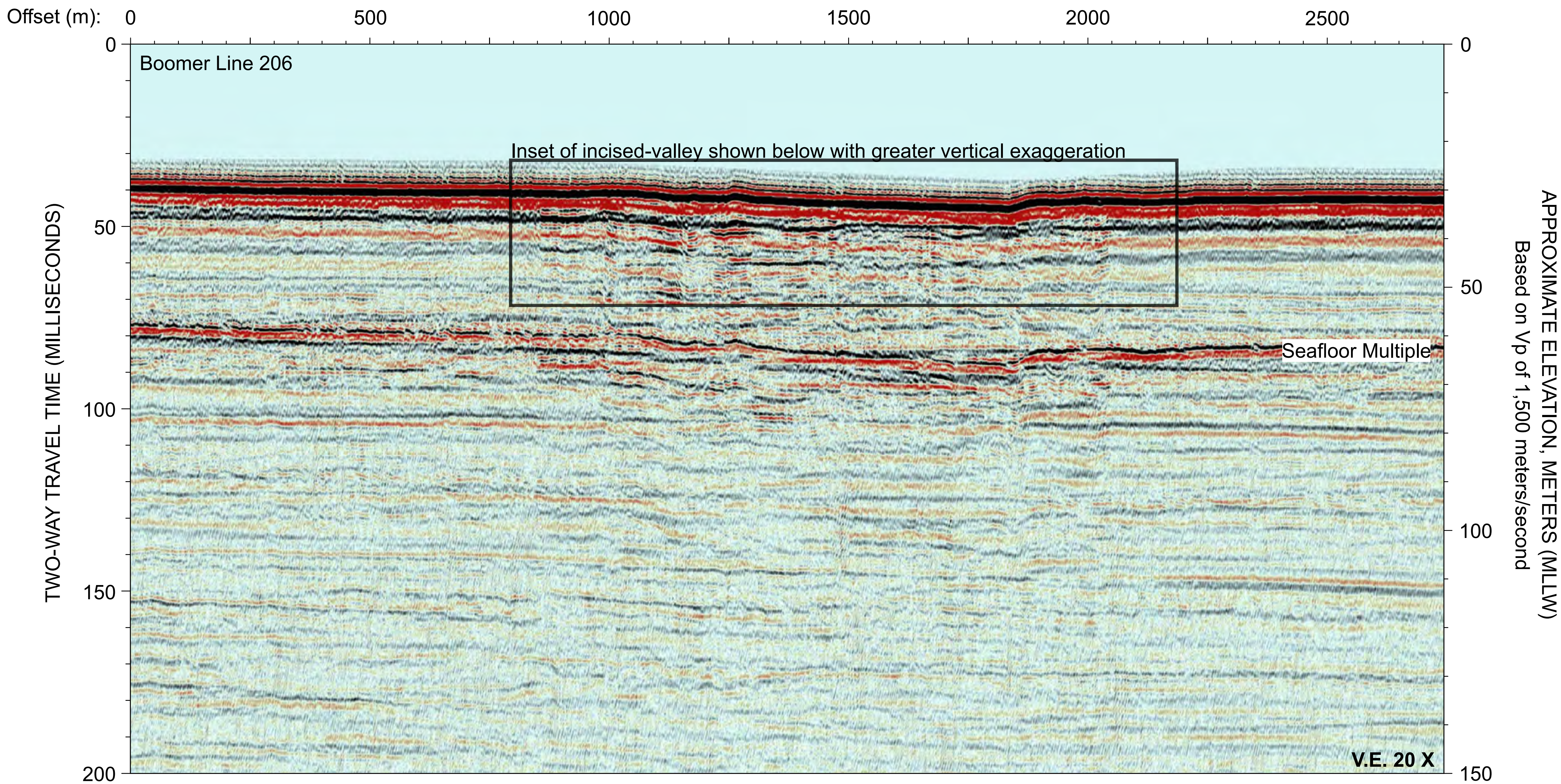


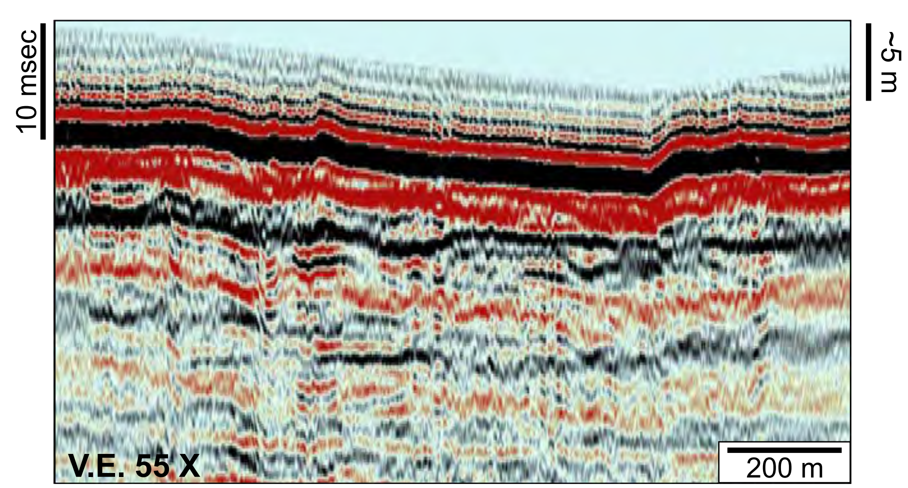
3.12-mgi (24 channels) MCS with multiple suppression

The profile shown above is a 24-channel, 3.12-mgi multi-channel seismic (MCS) profile like the profile shown and described in Figure 26b with the exception that the above image underwent Surface-related multiple suppression. When compared with Figure 26b, the area below the seafloor multiple at approximately 80 millliseconds now contains almost entirely primary reflections. The ability to interpret the deep subsurface is significantly improved.

BOOMER MCS DATA PROCESSING
24 CHANNEL WITH MULTIPLE SUPPRESSION
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 26c



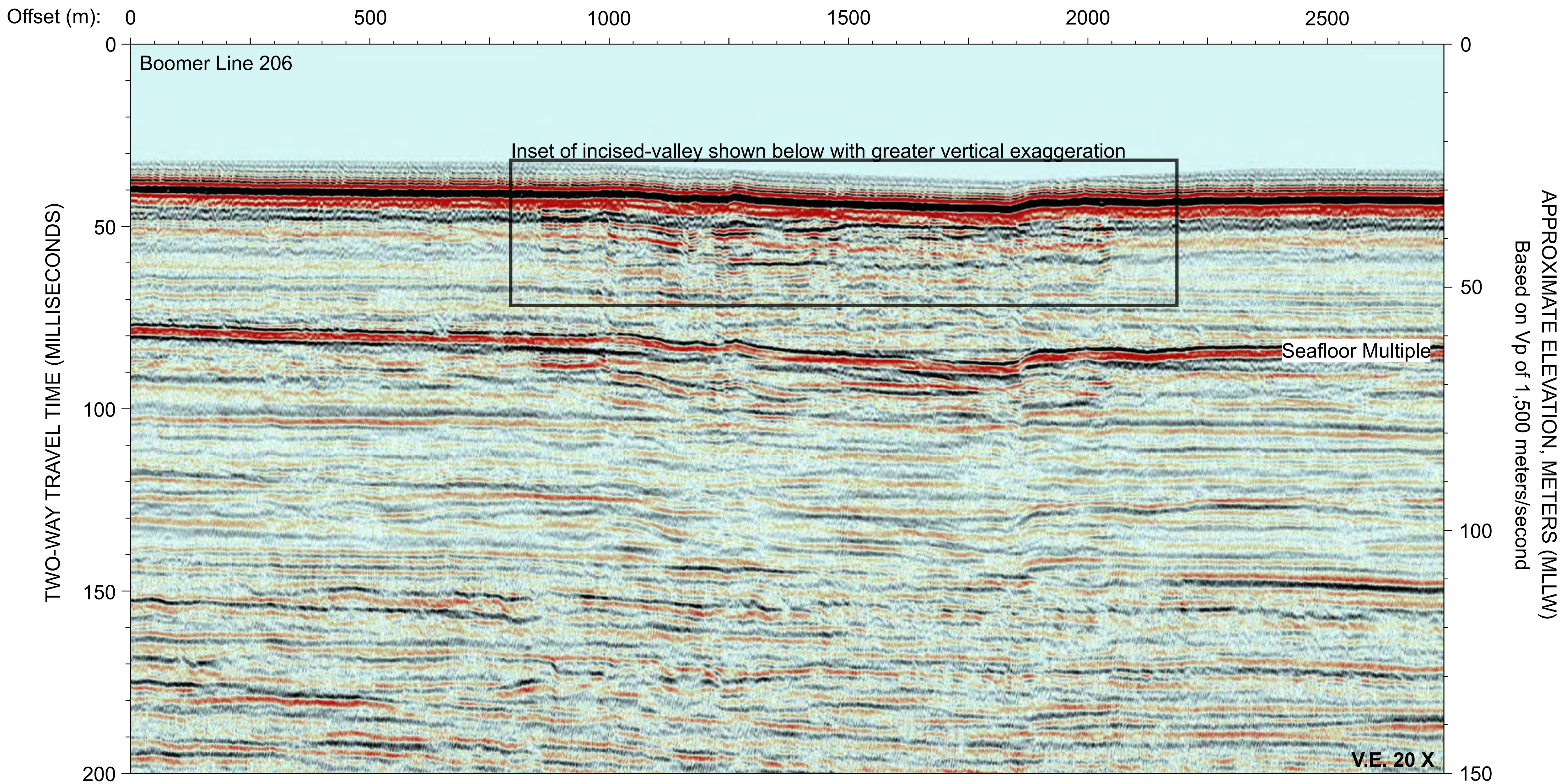


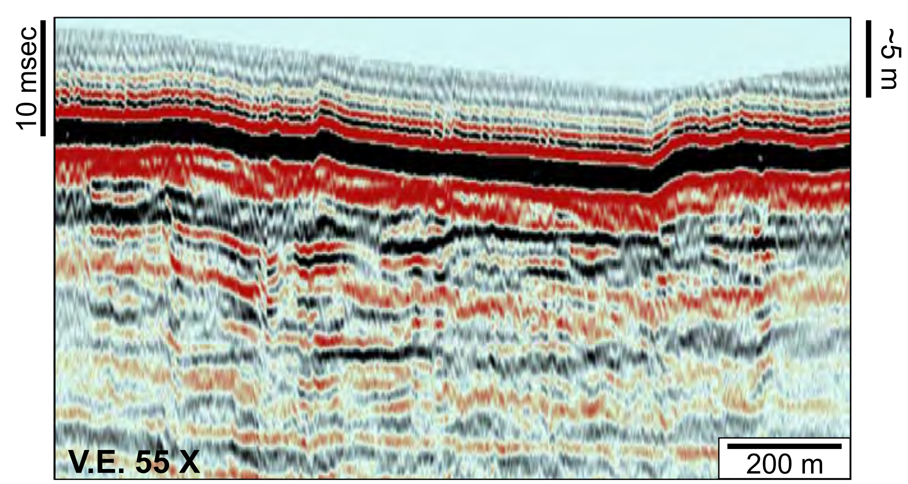
1.56-mgi (16 channels) MCS

The profile shown above is a 16-channel, 1.56-mgi multi-channel seismic (MCS) section that was processed specifically for this report. The intent of processing the data acquired with a shorter group interval was to improve the capability to resolve smaller-scale subsurface features. The benefit of using a shorter group interval is beneficial for two reasons. Smaller group intervals result in a narrower Fresnel zone radius, which is the main criteria governing horizontal resolution. If the group spacing is too large, small lateral variations cannot be properly resolved. The second reason shorter group intervals are beneficial is to ensure there is no spatial aliasing that can occur in highly dipping beds. Comparison of the above image with the sections shown in Figures 26b and 26c shows the two benefits of a shorter group interval. Within the inset image to the left, channel margins are better resolved and there appears to be more lateral variability along the line. The downside of using the 16-channel configuration is that the fold is decreased and so there is a lower signal-to-noise ratio. Another setback to using the 1.56-mgi is that the far offset is half the value of the 3.12-mgi data. Therefore, deeper horizons are not as well imaged since the far offset governs the ability to resolve the deeper section.

BOOMER MCS DATA PROCESSING
16 CHANNEL, 1.56 mgi
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 26d



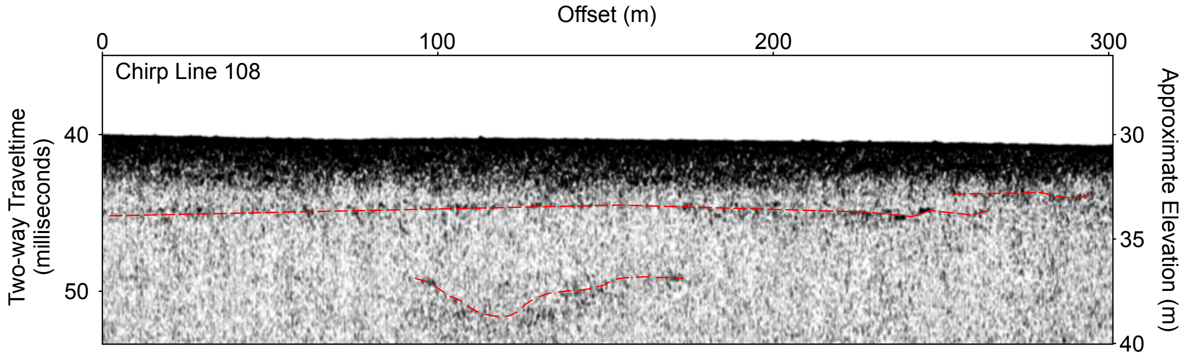


Hybrid streamer (32 channels) MCS

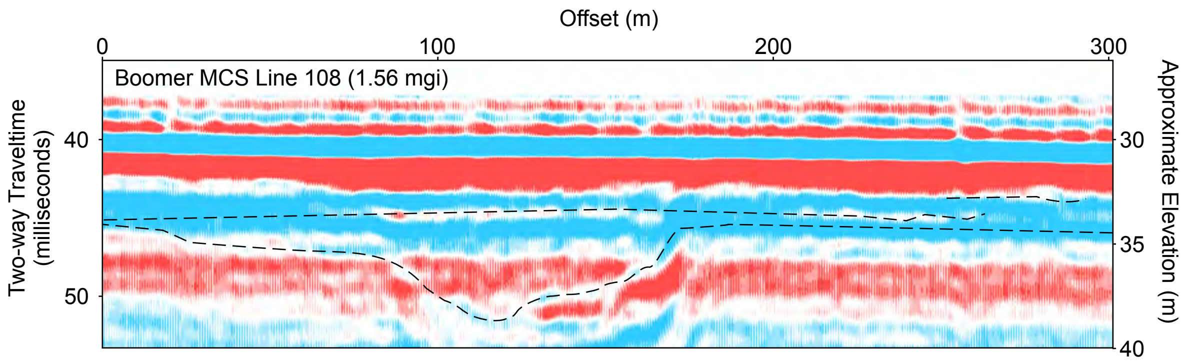
After comparing the processed seismic data using a 1.56-mgi with the originally processed 3.12-mgi, we determined that there is a significant tradeoff between the higher resolution gained when processing the data using the 1.56-mgi and the higher signal-to-noise ratio (due to utilizing more channels) seen in the 3.12-mgi data. To try to improve the SNR while maintaining high resolution, the section shown above was processed using all 32 channels with a hybrid group interval (i.e., both 1.56 meters and 3.12 meters). The result is an image that has an improved SNR and good depth of penetration. In the inset image to the left, the imaging of small channels with steep dips are resolved and there appears to be limited loss in the horizontal resolution as compared to the 16 channel data (Figure 26d).

BOOMER MCS DATA PROCESSING
32 CHANNEL HYBRID STREAMER
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

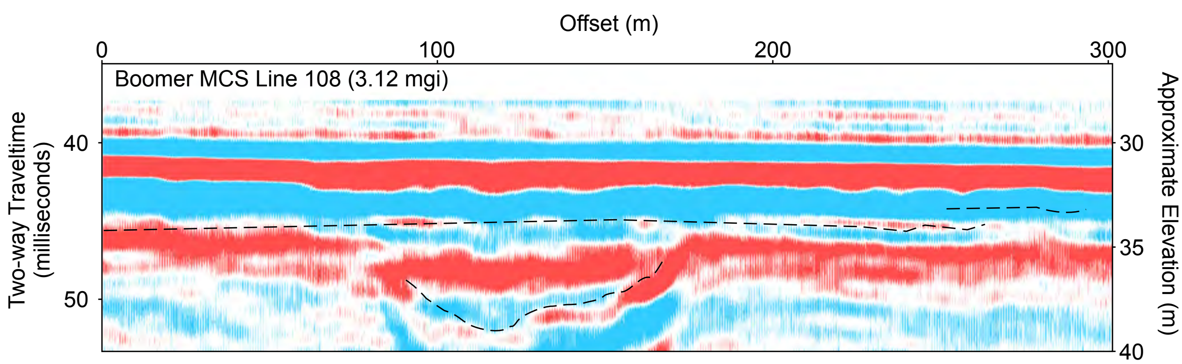
FIGURE 26e



This is a typical example of a Chirp profile.
There are two relatively flat reflectors likely representing a surficial sand sheet and a deeper channelized feature that is not observed outside of a small area less than 100 m wide.



Boomer data is typically not useful in mapping reflectors less than 5 meters below the seafloor due to limited vertical resolution.
The two uppermost reflectors from the Chirp data are observable in the 1.56-mgi boomer data. Without a Chirp profile and/or ground-truth data (e.g., borings), these reflectors would likely be overlooked by a seismic interpreter. The above image illustrates with proper seismic acquisition and processing, Boomer data can be used to map the shallowest subsurface.
The shape of the channel's thalweg is consistent with the shape seen on the Chirp profile.
The channel's margins are well-defined with the 1.56-mgi data and the erosional base can be mapped across the entire profile.

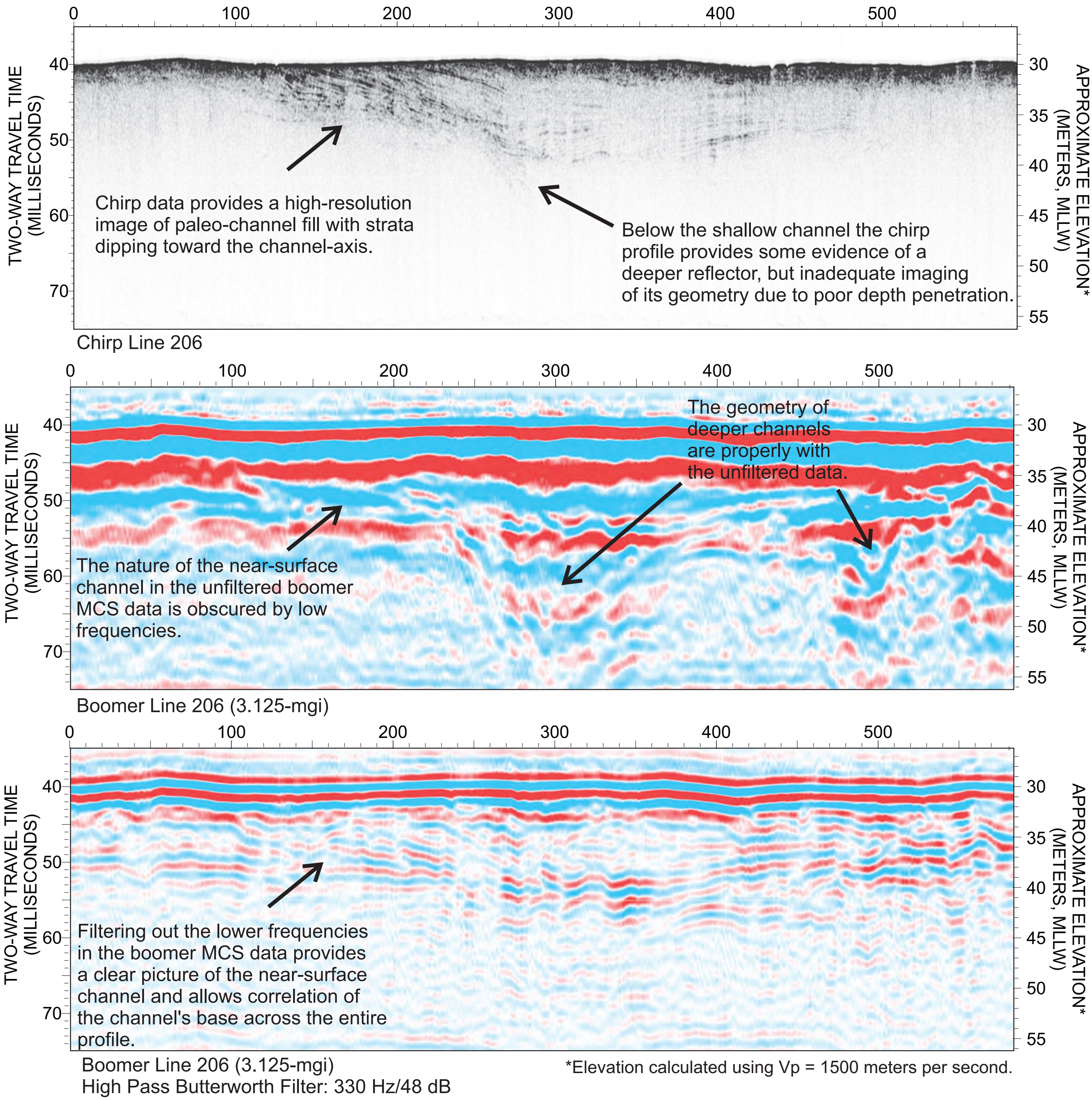


The two uppermost reflectors from the Chirp data are not as well-defined in the 3.12-mgi data.
The shape of the deeper channel's thalweg is not as well-delineated using the 3.12-mgi data.
Compared to the 1.56-mgi data, the channel's margins are not as well-defined and the erosional base cannot be mapped across the profile.

*Elevation calculated using Vp = 1500 meters per second.

COMPARING 3.12- AND 1.56-MGI BOOMER DATA WITH CHIRP PROFILE
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

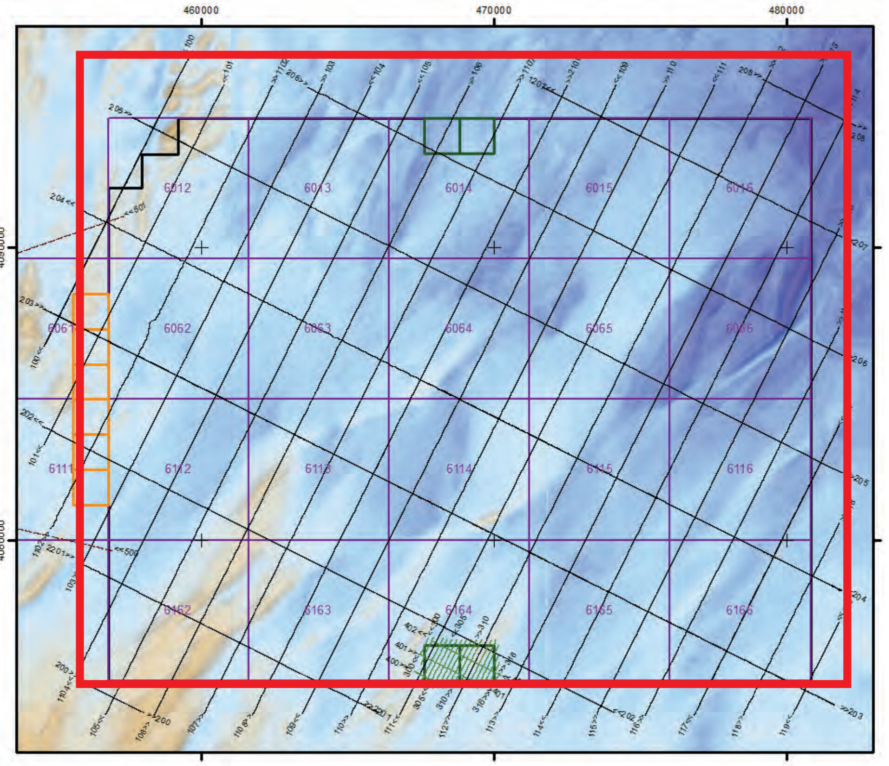
FIGURE 27



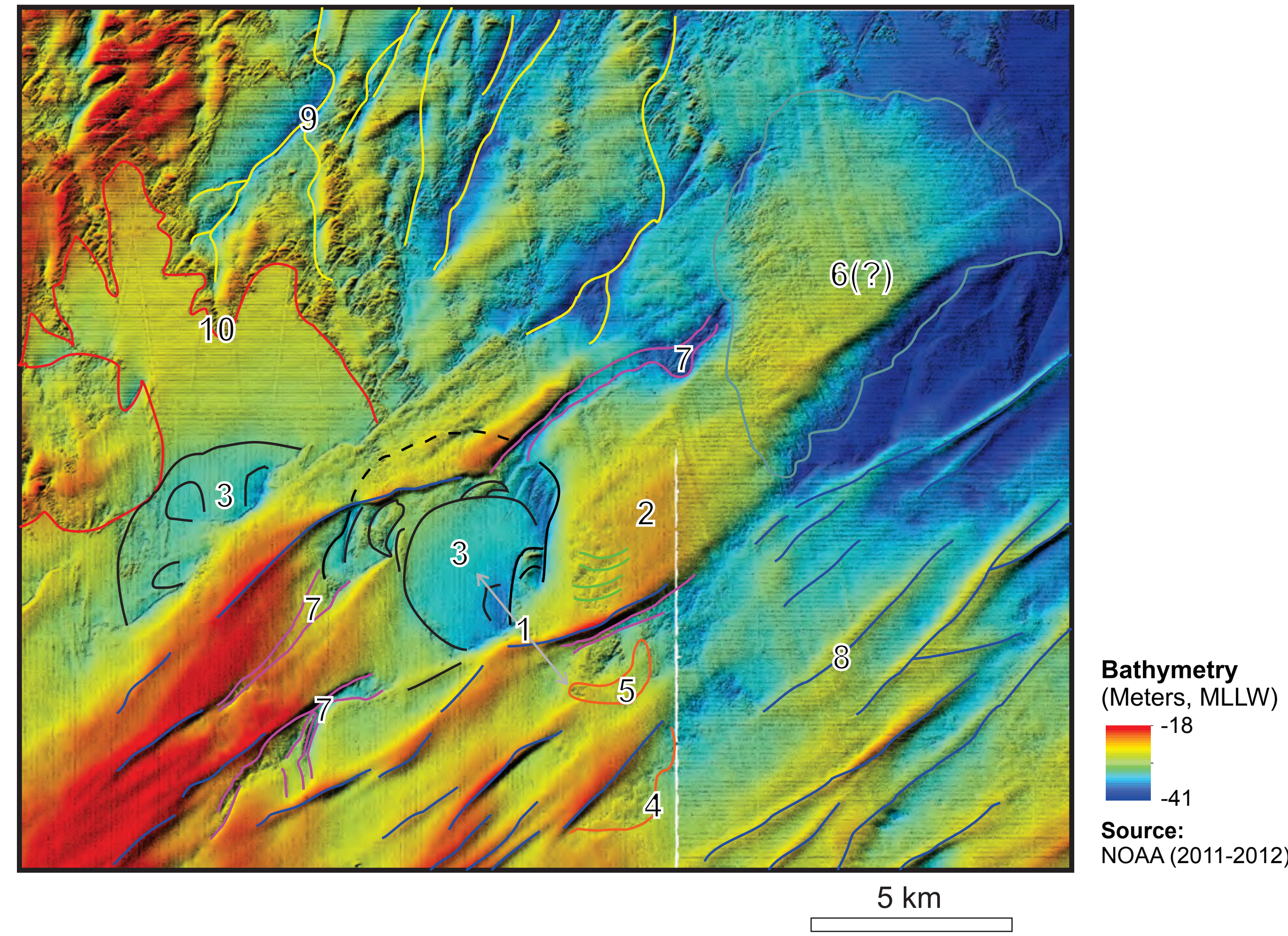
POST-STACK FILTERING TO IMPROVE SEISMIC IMAGING
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 28

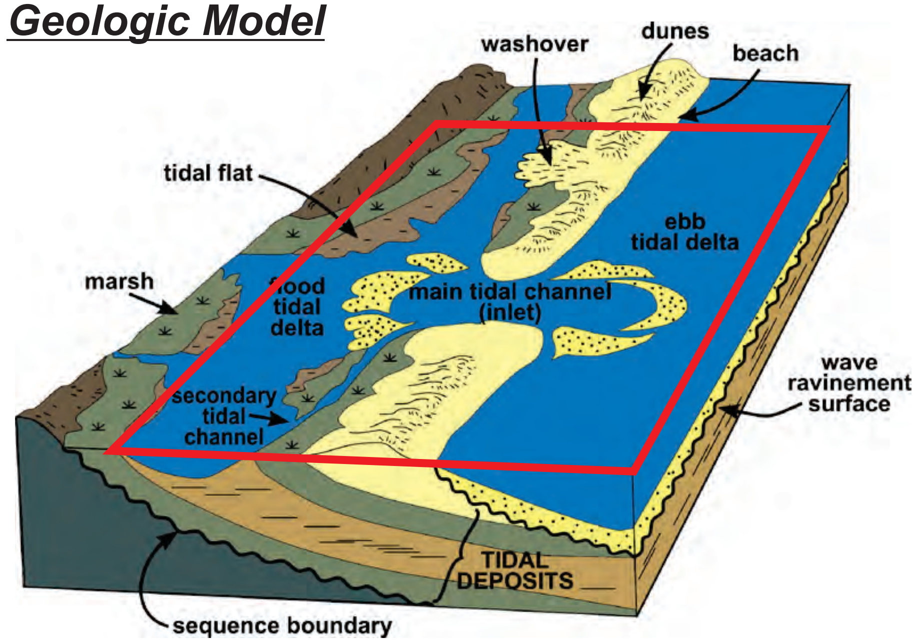
Index Map



Location of interpreted bathymetry image is indicated by red rectangle



Geologic Model



Source: Dalrymple and Choi, 2007 (modified from Reinson, 1992)

Approximate location of interpreted bathymetry image within the context of the barrier-island system geologic model is indicated by red rectangle

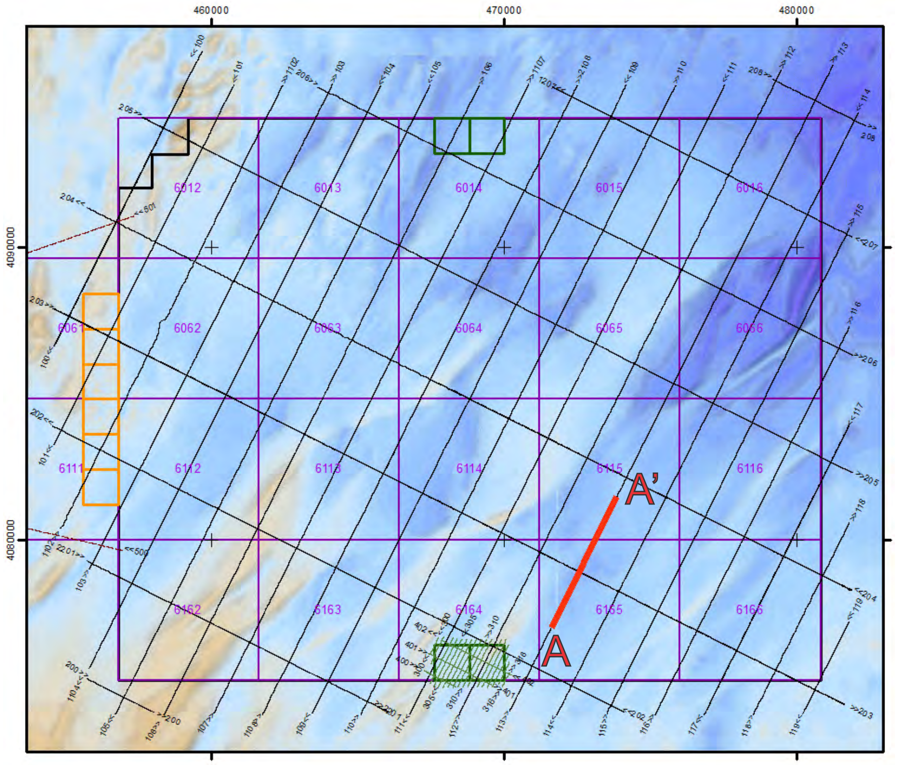
Interpretation of a Drowned Barrier-Island System Based on Bathymetric Characteristics

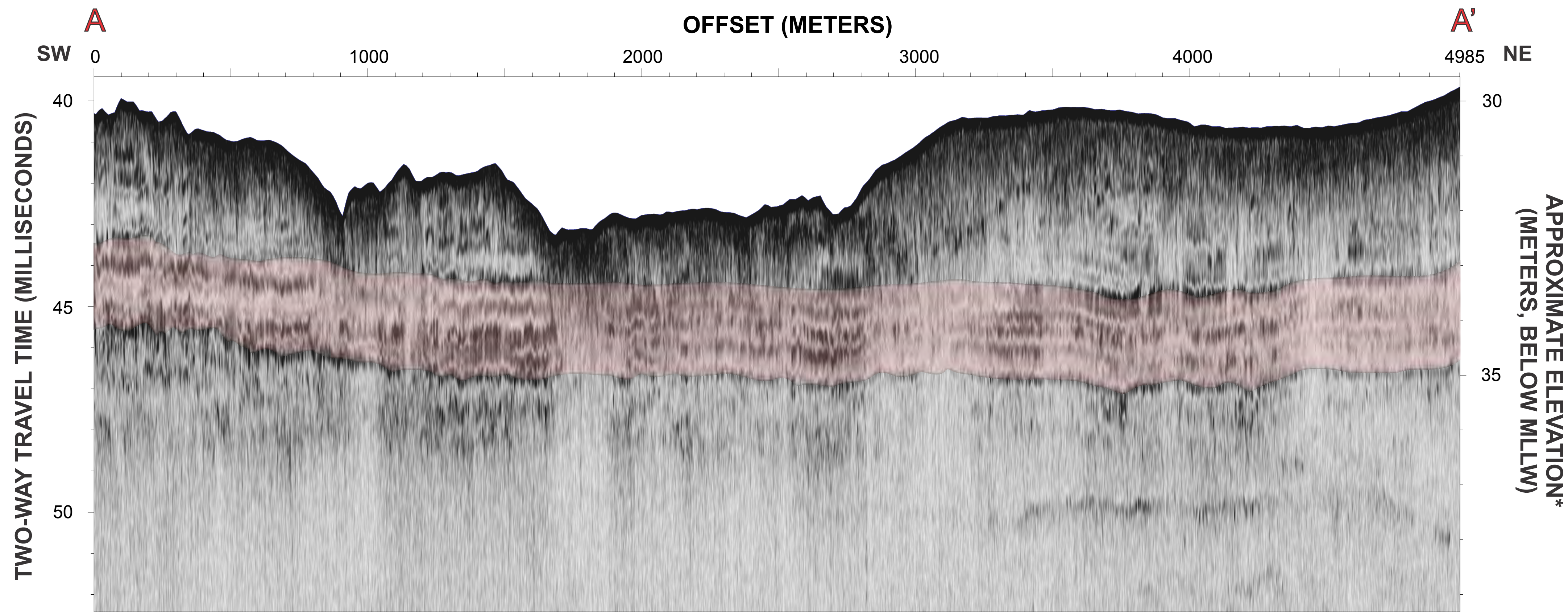
1. Closed-off tidal-channel inlet. Bathymetric low on the northwest side
2. Drumstick morphology typical of a tidally-influenced barrier-island system with multiple beach dune ridges. The accretion of beach ridges contribute to the barrier's wide-end morphology
3. Flat associated with flood tidal delta, surrounded by arcuate lobes of sand
4. Possible remnants of seaward limit of ebb tidal delta
5. Possible swash bar associated with ebb tidal delta and marginal flood channel hugging the seaward side of barrier
6. Washover fan showing large amounts of scour occurring in steeper seaward slope which is possibly the former foreshore area and the source of the sand for the washover fan
7. Tidal inlets oriented parallel to the former shoreline
8. Transgressive sand ridges which obscure former morphology as they were deposited above the wave ravinement surface. They are oriented oblique to larger features
9. Linear to slightly sinuous bathymentric lows that appear to be are draining into regional low associated with the Norfolk canyon
10. Interfluve that perhaps limited the estuary's basin-size

INTERPRETED PALEO-LANDFORMS
BARRIER-ISLAND SYSTEM
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 29a

Index Map

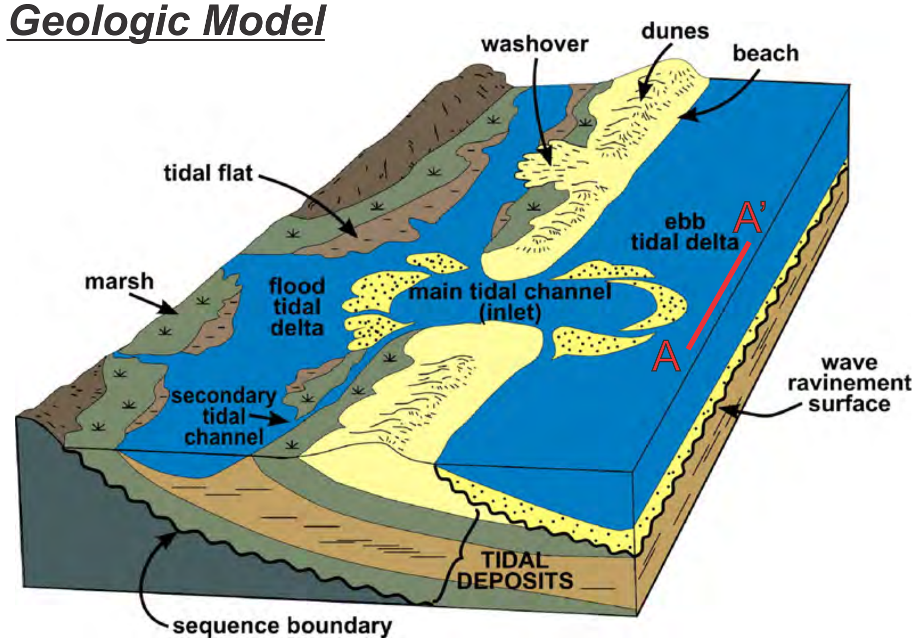




*Elevation calculated using Vp = 1500 meters per second.

CHIRP LINE 1113 (SP 7347-18482) V.E. 200 X

Geologic Model



Source: Dalrymple and Choi, 2007 (modified from Reinson, 1992)

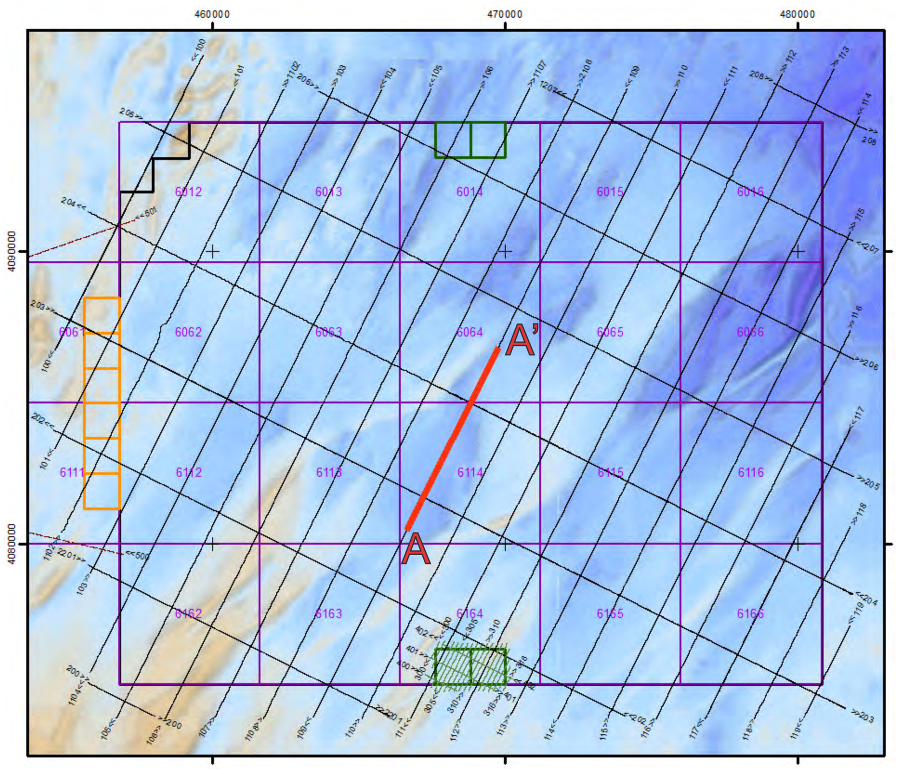
Interpretation of a Tidal Flat/Marsh Based on Seismic Characteristics

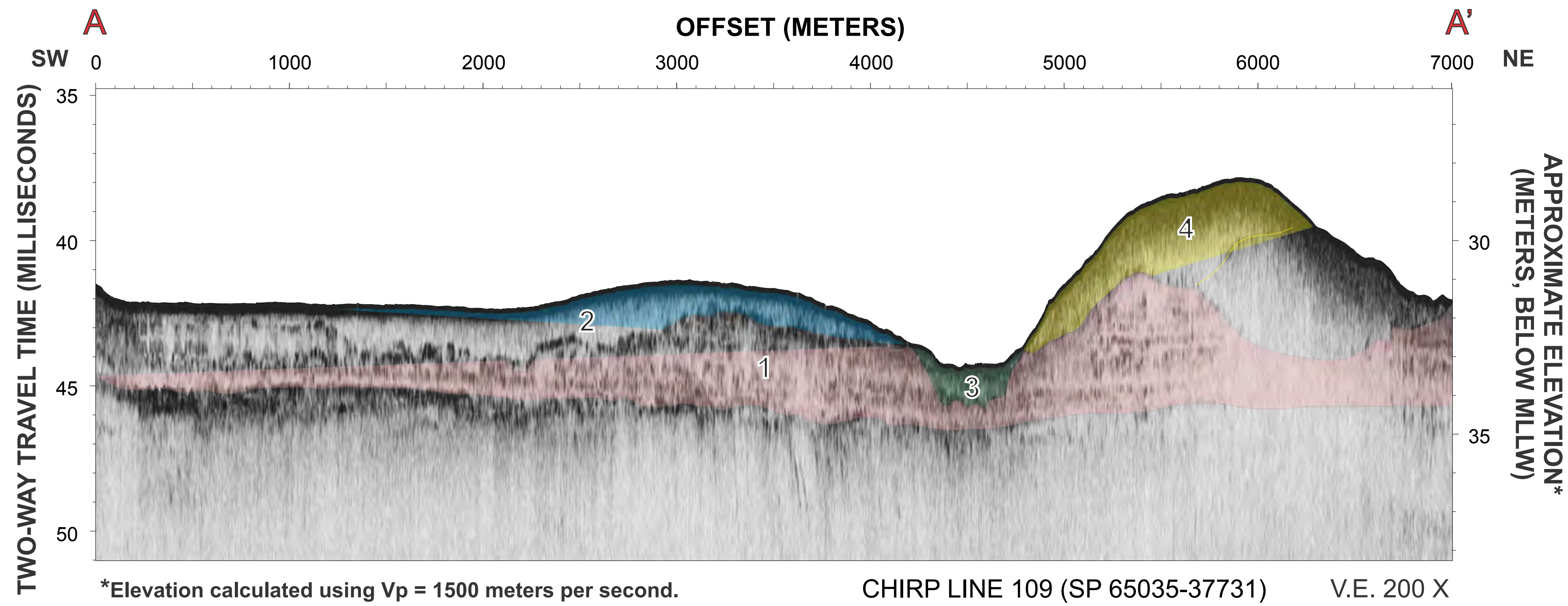
Interpretation	Seismic Character
Alternating layers of fine-grained material deposited in a tidal flat and marsh environment preserved below the transgressive ravinement surface which is overlain by offshore transgressive sand ridges and possible remnants of a former barrier island and/or its associated ebb-tidal delta	Continuous, flat lying, parallel reflectors below seismically-transparent, mounded deposits

INTERPRETED PALEO-LANDFORMS
TIDAL FLAT/MARSH
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

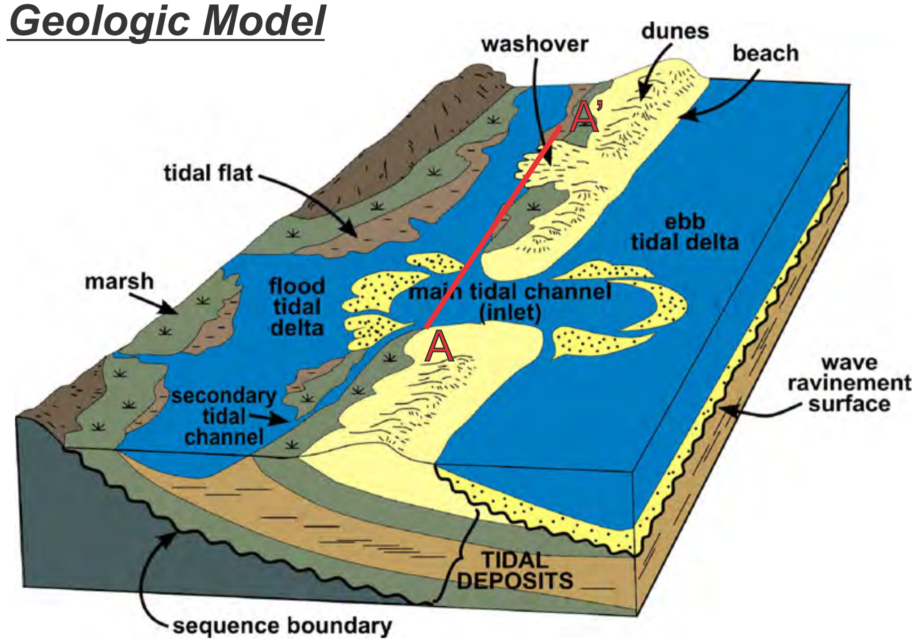
FIGURE 29b

Index Map





Geologic Model



Source: Dalrymple and Choi, 2007 (modified from Reinson, 1992)

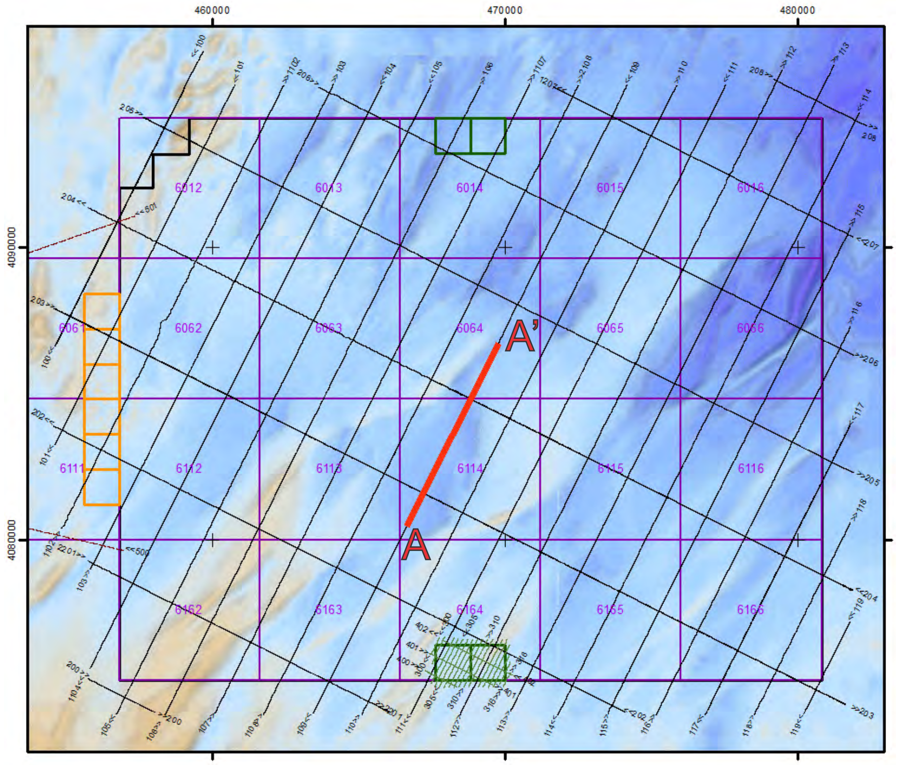
Interpretation of Barrier Island-Lagoonal System Based on Seismic Characteristics

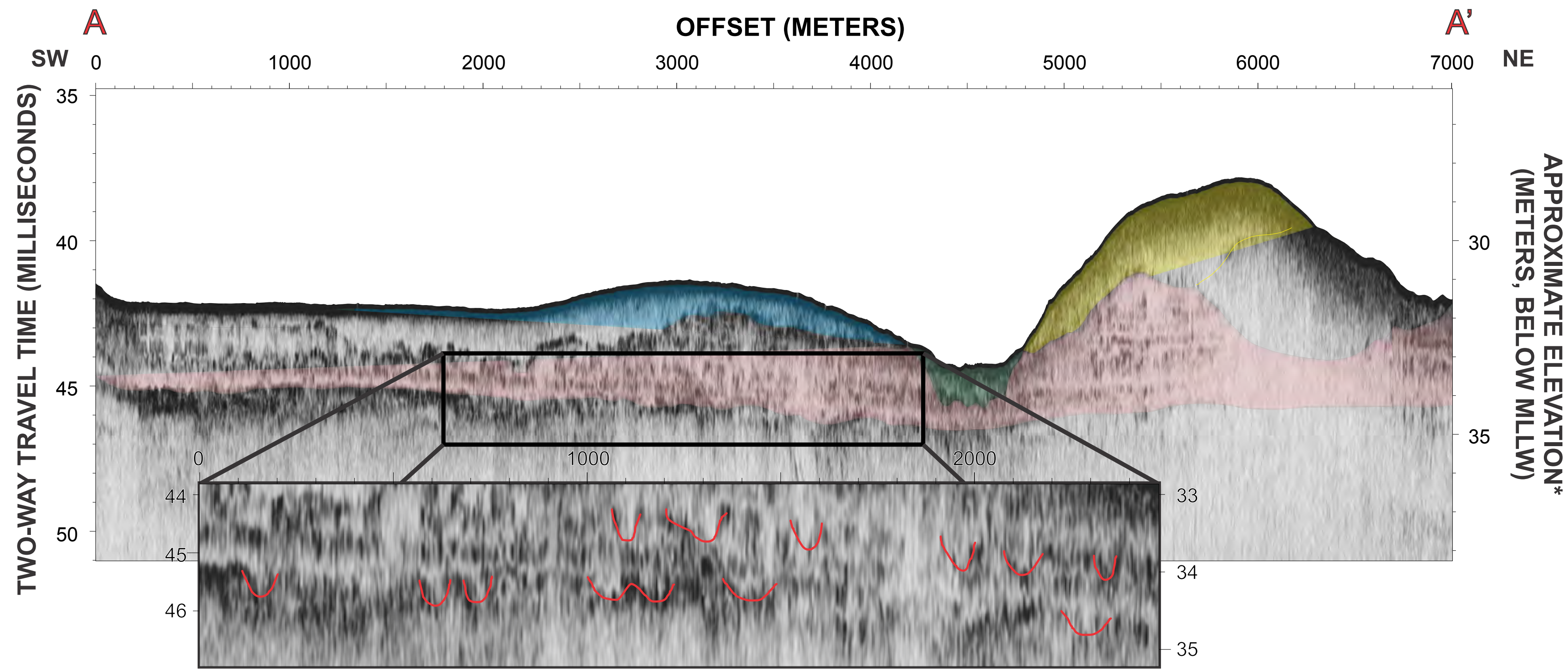
Interpretation	Seismic Character
1) Marsh and tidal flat deposits	1) Generally flat, continuous parallel reflectors
2) Remnants of flood-tidal delta	2) Transparent package scouring into underlying unit 1 and displaying a mounded bathymetric high adjacent to unit 3
3) Tidal channel	3) Isolated, narrow package with steep sides in bathymetric low
4) Possible washover fan or apron	4) Transparent, bathymetric high displaying channel-like erosion into underlying unit 1

INTERPRETED PALEO-LANDFORMS
BARRIER ISLAND-LAGOONAL SYSTEM
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 29c

Index Map

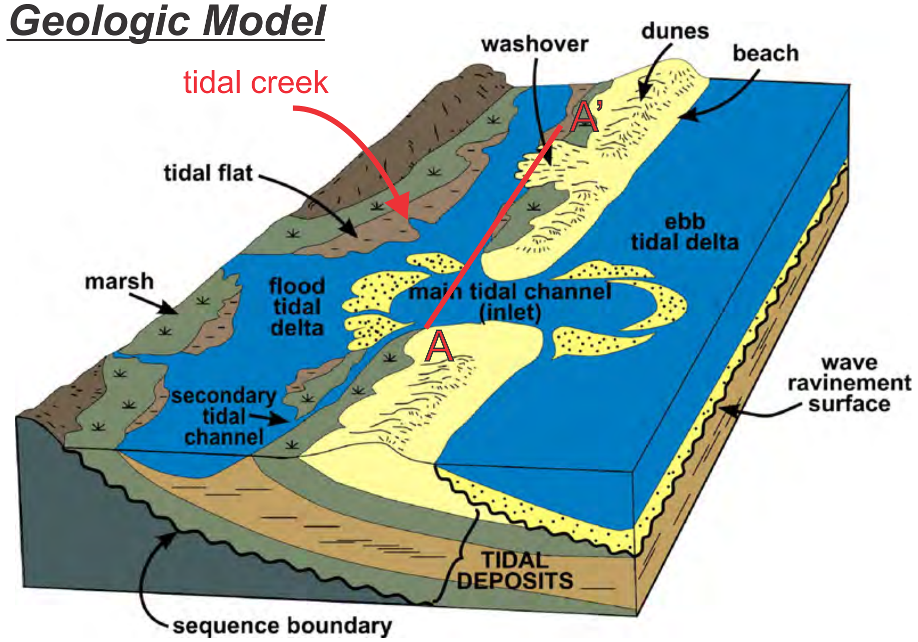




*Elevation calculated using
Vp = 1500 meters per second.

CHIRP LINE 109 (SP 65035-37731) V.E. 200 X

Geologic Model



Source: Dalrymple and Choi, 2007 (modified from Reinson, 1992)

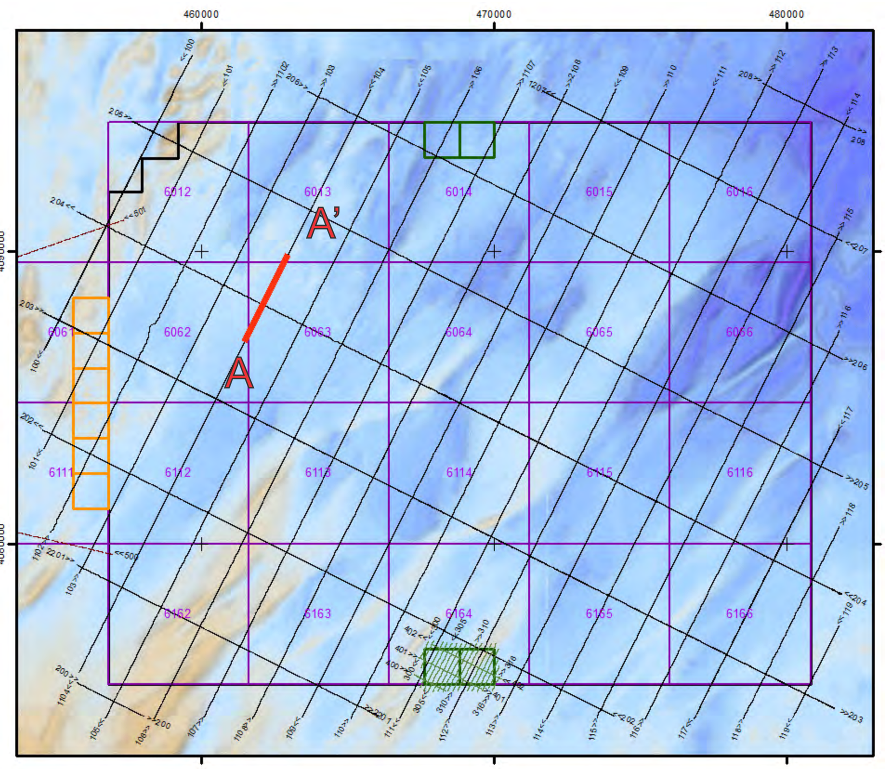
Interpretation of Tidal Creeks Based on Seismic Characteristics

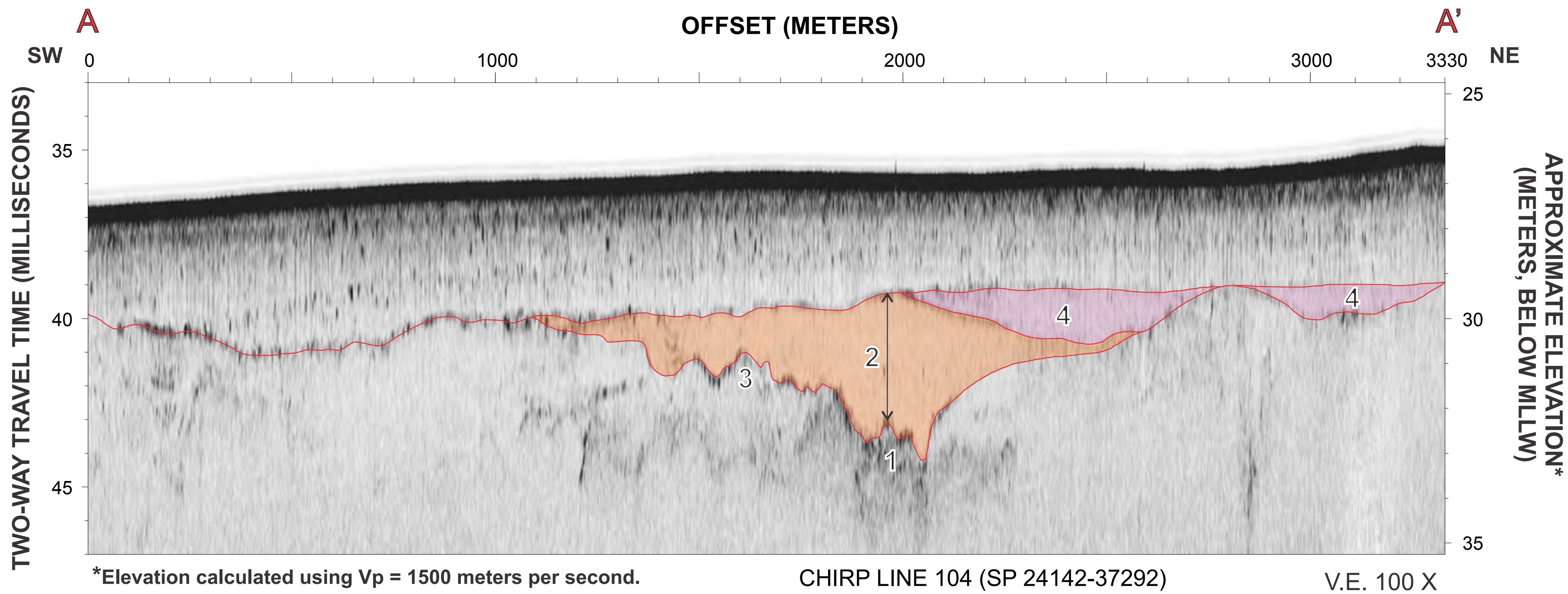
Interpretation	Seismic Character
Tidal creeks within larger tidal flat/marsh deposit	Numerous, narrow, concave up transparent bodies located within a package of flat lying continuous reflectors

INTERPRETED PALEO-LANDFORMS
TIDAL CREEKS
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 29d

Index Map

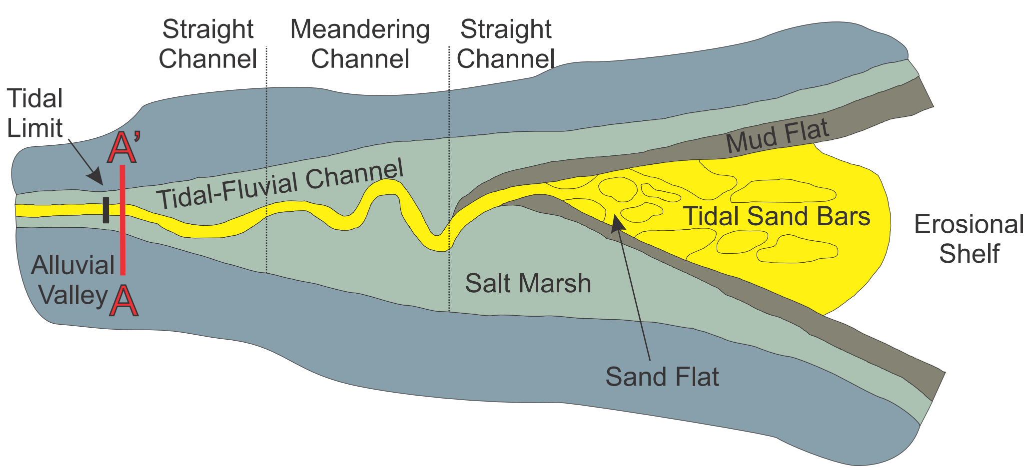




Interpretation of Fluvial Channels Based on Seismic Characteristics

Interpretation	Seismic Character
1) Gravel lag at base of fluvial channel	1) High amplitude reflectors at the channel's base
2) Erosion of a floodplain by fluvial incision	2) Localized deep incision into generally flat lying transparent strata
3) Multiple stages of incision by high-gradient rivers or amalgamation of many fluvial channel deposits	3) Jagged erosional base
4) Tidally-influenced fluvial channel fill during transgression	4) Seismically-transparent channel fill by shallow, wide channels with asymmetric cross-channel geometry

Geologic Model

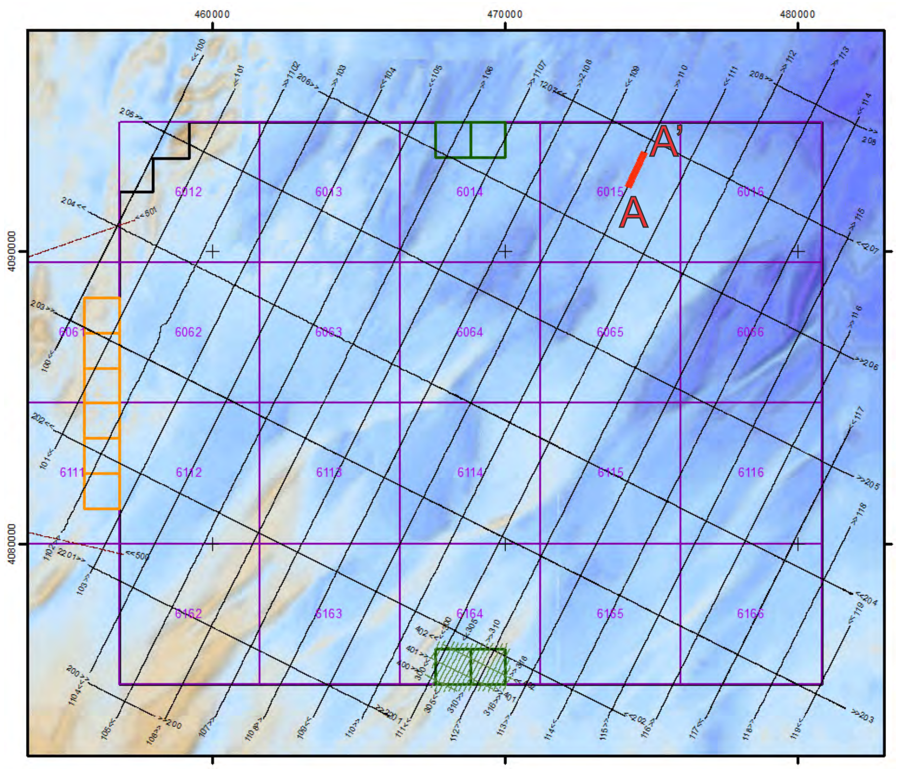


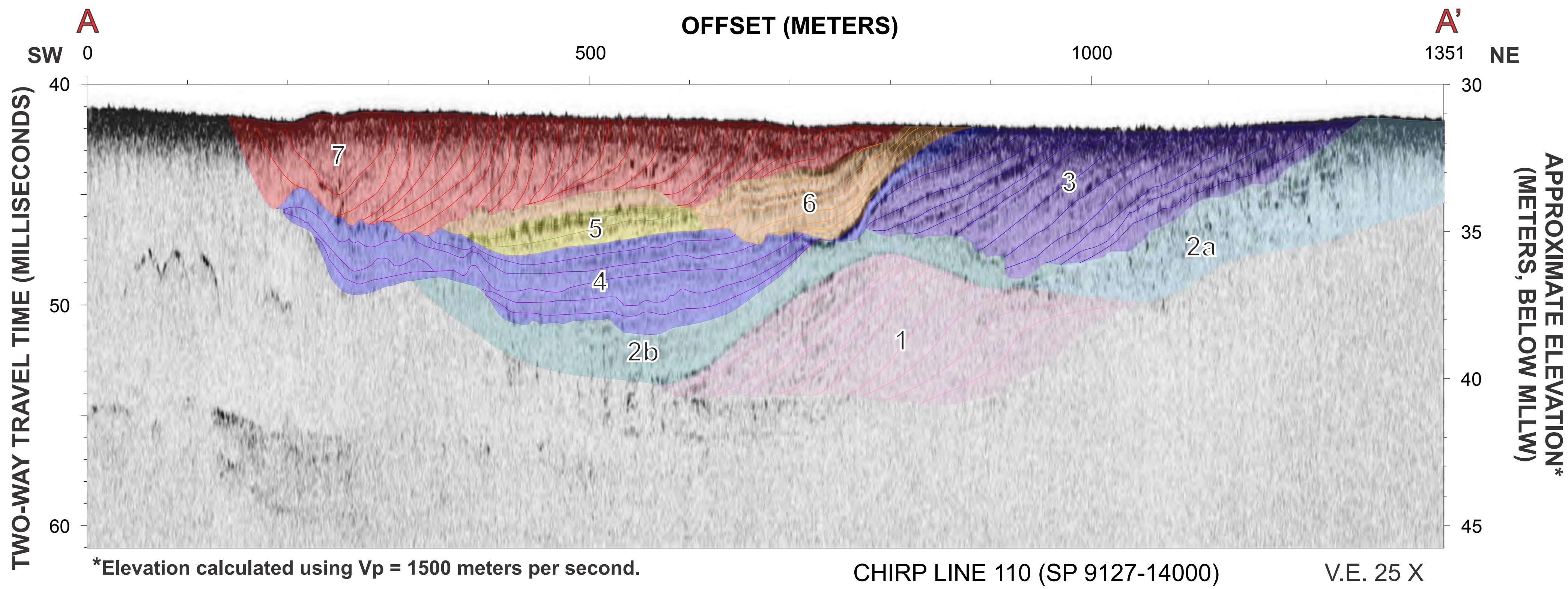
Modified from Dalrymple et al., 1992

INTERPRETED PALEO-LANDFORMS
FLUVIAL CHANNELS
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 29e

Index Map

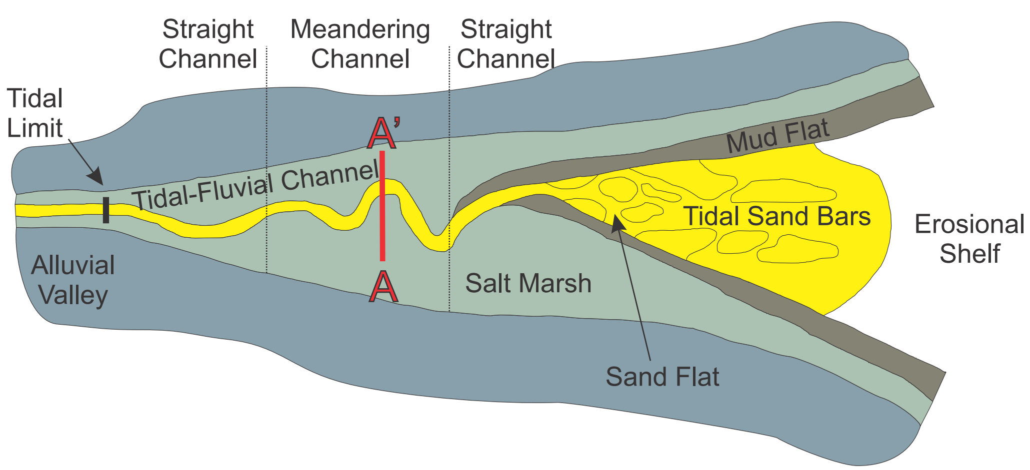




Interpretation of Multi-phase Fill by Meandering Channels Based on Seismic Characteristics

Interpretation	Seismic Character
1) Laterally migrating tidal-fluvial channel	1) Isolated stratigraphic unit with sigmoidal geometry and internal reflectors downlapping onto a relatively flat horizon
2) Tidal flat/marsh cover	2)Units with relatively uniform thickness overlain on top of pre-existing topography showing some evidence of concordant internal reflectors with the top and base of units
3) Laterally migrating tidal-fluvial channel eroded by transgression	3) Isolated stratigraphic unit with internal reflectors downlapping onto an erosional surface. Top portion of unit is truncated at the seafloor
4) Possible channel-fill along broad channel axis or oblique view of accretionary package	4) Broad, generally concordant reflectors onlapping onto pre-existing strata
5) Tidal flat/marsh cover	5) Small, concordant reflectors onlapping onto pre-existing topographic highs of unit 4
6) Laterally migrating tidal-fluvial channel eroded by transgression	6) Isolated stratigraphic unit with internal reflectors downlapping onto an erosional surface. Top portion of unit is truncated at the seafloor
7) Laterally migrating tidal-fluvial channel eroded by transgression. Former channel axis at southwestern end.	7) Same as units 3 and 6 with concave-up geometry near southwestern end

Geologic Model

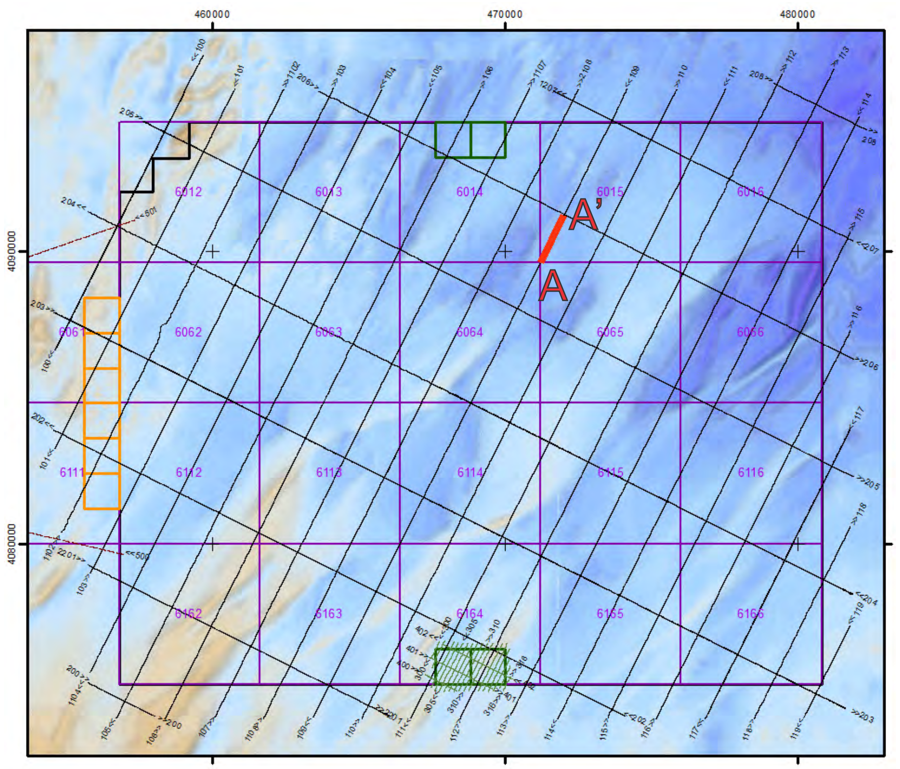


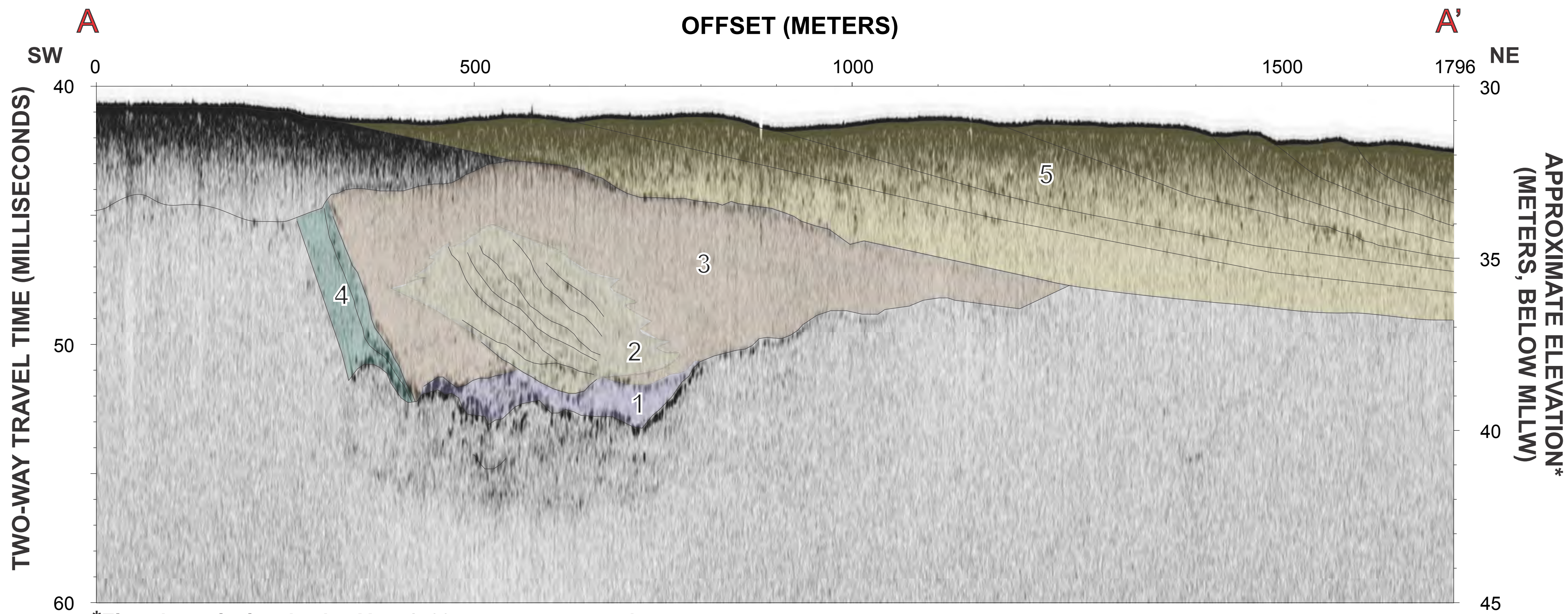
Modified from Dalrymple et al., 1992

INTERPRETED PALEO-LANDFORMS
MEANDERING CHANNEL
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 29f

Index Map

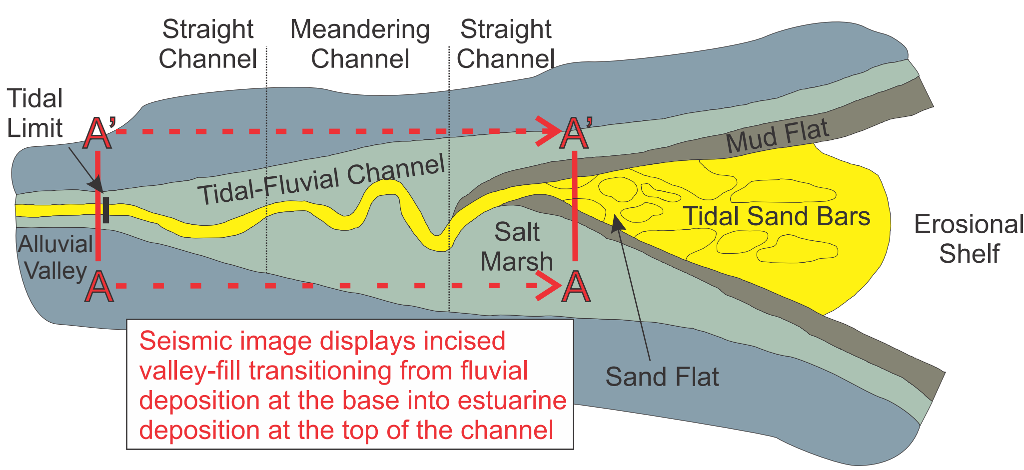




*Elevation calculated using Vp = 1500 meters per second.

CHIRP LINE 109 (SP 18323-25276) V.E. 40 X

Geologic Model

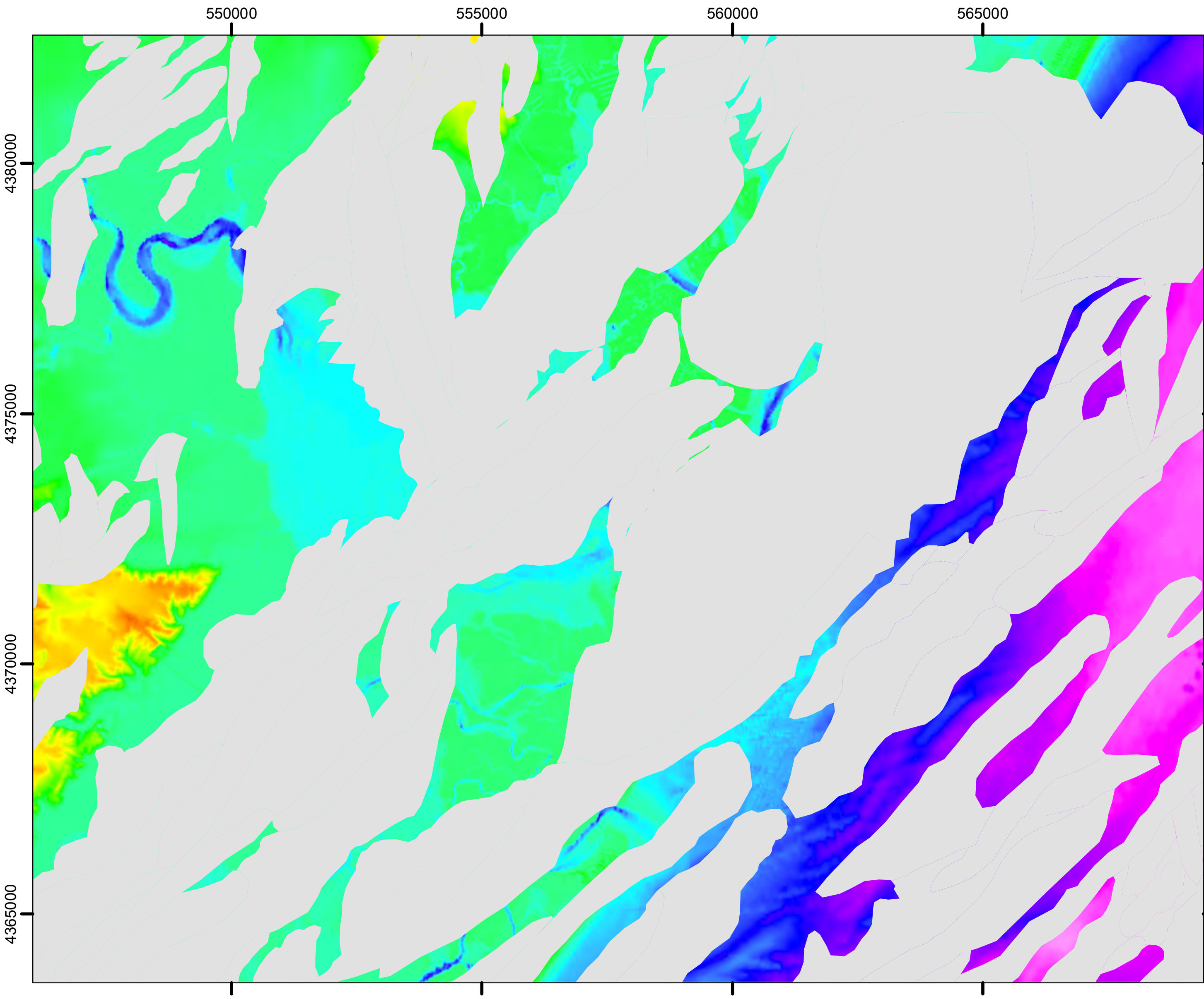


Modified from Dalrymple et al., 1992

Interpretation of Incised-Valley Fill Based on Seismic Characteristics

Interpretation	Seismic Character
1) Fluvial gravel lag deposited during low stand	1) High amplitude reflectors at base of incised valley
2) Tidal-fluvial channel of estuary filling valley during transgression	2) Dipping, parallel reflectors isolated within valley
3) Mud flat	3) Transparent region positioned between valley wall and isolated unit 2
4) Possible salt marsh	4) Dipping, parallel reflectors along valley margin
5) Offshore transgressive sand ridges	5) Package of roughly parallel, dipping reflectors that thicken and become more inclined near the seafloor where the reflectors intersect the troughs

INTERPRETED PALEO-LANDFORMS
INCISED VALLEY-FILL
Virginia WEA Geophysical Survey Phase II
Virginia Outer Continental Shelf



Outlines of sand ridges mapped using multibeam bathymetry in the VA WEA reprojected onto the DEM in the Great Bay, NJ region

N
W E
S

0 5
Kilometers

Elevation

MHW (meters)

High : 25

Low : -25

DEM Source: Digital Elevation Model of Atlantic City, New Jersey (Carignan et al., 2009)

Notes:

The above image is shown to convey the possible limitations of imaging the subsurface using Chirp systems in coarse-grained material. The outlines of sand ridges were mapped throughout the VA WEA and then reprojected (i.e., shifted) over the NJ DEM that was used to analyze the influence of line spacing and orientation on the ability to image the subsurface in Figures 27 to 29. The above DEM is continuous and could represent the collection of a 3-D dataset over an area of similar size to the VA WEA. Even with perfect coverage, the presence of sandy sediments would severely limit the ability to interpret paleo-landforms in the subsurface.

ANALYSIS OF SURVEY EQUIPMENT: CHIRP LIIMITATIONS
POOR SIGNAL PENETRATION IN COARSE SEDIMENT

Virginia Wind Energy Area Geophysical Survey Phase II
Virginia Outer Continental Shelf

FIGURE 30

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under US administration.

The Bureau of Ocean Energy Management

As a bureau of the Department of the Interior, the Bureau of Ocean Energy (BOEM) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS) in an environmentally sound and safe manner.