

**PALEOCHANNELS IN LOWER DELAWARE BAY  
AND THE DELAWARE INNER CONTINENTAL SHELF**

by

Daniel P. Childers

A dissertation submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Geology

Summer 2014

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AND THE DELAWARE INNER CONTINENTAL SHELF**

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## **DEDICATION**

To my greatest teachers my Mom and Dad:

Joyce and Hugh Childers

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## TABLE OF CONTENTS

|                       |      |
|-----------------------|------|
| LIST OF TABLES .....  | viii |
| LIST OF FIGURES ..... | ix   |
| ABSTRACT .....        | xiv  |

### Chapter

|  |    |
|--|----|
| 1 INTRODUCTION .....   | 1  |
| Study Area and Background .....  | 5  |
| Seismic Data used for this Project .....   | 7  |
| Previous Regional Seismic Studies of Paleochannel Evolution .....  | 12 |
| Research Questions to be addressed .....   | 14 |
| Significance of Proposed Work .....  | 16 |
| 2 ANALOG SEISMIC PROFILES TO THREE-DIMENSIONAL GIS MODEL:<br>CONSTRAINING THE GEOMETRY OF SUBSURFACE<br>PALEOCHANNELS BENEATH DELAWARE BAY ..... | 18 |
| Methodology .....  | 21 |
| From Analog to GIS-compatible data .....   | 21 |
| From GIS-database to 3-D surfaces .....  | 29 |
| Paleochannels .....  | 39 |
| Results .....  | 41 |
| Central Channel .....  | 41 |
| Southern Channel .....   | 41 |
| Northern Channel .....   | 43 |
| ArcScene™ 3-D .....  | 43 |
| Conclusion .....   | 45 |
| 3 CONSTRAINING THE GEOMETRY OF SUBSURFACE<br>PALEOCHANNELS BENEATH DELAWARE BAY AND THE MID-<br>ATLANTIC INNER CONTINENTAL SHELF .....           | 48 |
| Study Area and Background .....  | 50 |

|  |     |
|--|-----|
| Previous Work .....  | 50  |
| Bathymetry .....   | 56  |
| Methods .....  | 56  |
| Kriging Model .....  | 59  |
| Discussion.....  | 62  |
| Delaware Bay .....   | 62  |
| Central Channel .....  | 68  |
| Inner Shelf – Orange Paleochannel .....  | 72  |
| Inner Shelf – Blue Paleochannel .....  | 74  |
| Rehoboth and Indian River Bays.....  | 76  |
| Another Channel – Yellow Channel.....  | 77  |
| Conclusions .....  | 78  |
| 4 UPPER PLIOCENE-LOWER PLEISTOCENE UNCONFORMITY<br>UNDERLYING THE DELAWARE INNER CONTINENTAL SHELF ..... | 81  |
| Introduction .....   | 81  |
| Methods .....  | 88  |
| Results .....  | 90  |
| Discussion.....  | 98  |
| Conclusion.....  | 102 |
| 5 CONCLUSION .....   | 103 |
| Methods of Analysis.....   | 104 |
| Models of Paleochannels.....   | 105 |
| Value of Research.....   | 107 |
| Remaining Questions.....   | 108 |
| REFERENCES .....   | 110 |
| Appendix<br>DGS CORE DESCRIPTIONS .....  | 115 |



## LIST OF TABLES

|           |  |    |
|-----------|--|----|
| Table 2.1 | Example of Excel™ Spreadsheet as formatted for ArcMap™ .....   | 25 |
| Table 2.2 | Modeling methods, parameters and the Cross Validation results<br>for the Seafloor. See text for detail of the results .....                | 25 |
| Table 3.1 | Timeline with MIS ages and approximant ages of the<br>paleochannels in this study compared to the ages of<br>Knebel and Circé (1988) ..... | 57 |

## LIST OF FIGURES

|            |   |    |
|------------|---|----|
| Figure 1.1 | General location figure showing positions of four major paleochannels of the Delaware River. The paleochannels have been termed the Blue, Orange, Green, and Red by Krantz and co-workers (McGeary et al., 1991; Krantz et al., 1993; Murphy, 1996).....  | 2  |
| Figure 1.2 | Paleochannels along Delaware's inner continental shelf. Shaded channels were mapped by Williams (1999). Orange and Blue paleochannels initially mapped by Krantz and co-workers (McGeary et al., 1991; Krantz et al., 1993; Murphy, 1996).....  | 4  |
| Figure 1.3 | Bathymetry of inner continental shelf. Study area locations with major bathymetric features of lower Delaware Bay and the Delaware inner shelf.....   | 6  |
| Figure 1.4 | Tracklines for existing seismic profiles. 1974 tracklines shown in red; 1990 tracklines shown in green; 1992 tracklines shown in blue; Williams 1999 tracklines shown in orange. ....   | 9  |
| Figure 1.5 | Example seismic profile from Krantz et al. (1993) and interpretation from Murphy (1996).....  | 10 |
| Figure 1.6 | Example profile of Williams (1999) 3.5 kHz seismic data. Darker black lines within the profile denote reflections identified by Williams (1999). The horizontal distance across the profile is approximately 280 m. Thin horizontal lines denote depths of 7.5, 15, and 22.5 m below the towfish, respectively. Core P151-01 is a vibracore collected by Ocean Surveys, Inc. in support of the Williams (1999) study..... | 11 |
| Figure 2.1 | Seismic profiles and ArcGIS calculated profile. Analog profiles scanned into digital form. a. Analog seismic profile of the Southern paleochannel. b. Profile showing the various reflectors. c. Profile from ArcGIS™ model.....  | 22 |

|            |  |    |
|------------|--|----|
| Figure 2.2 | Study area showing ships track and the ancestral Delaware River after Fletcher et al., 1990. Line X-X' is the location of the seismic profile referenced in Figure 2.1.....  | 24 |
| Figure 2.3 | Comparison of three kriging models lower Delaware Bay seafloor. A. NOAA DEM was used to ground truth the kriging model, B. Simple kriging model, normal score transform, stable type, C. Ordinary kriging model, log transform, stable type, D. Ordinary kriging model, log transform, K-Bessel type. .... | 36 |
| Figure 2.4 | Model of the paleochannels of the Lower Delaware Bay. Paleochannel results; blue is the Central, orange is the Southern and green the Northern paleochannels. ....   | 42 |
| Figure 2.5 | Details of the Southern paleochannel, the breaks are due to no seismic data in those areas. ....   | 44 |
| Figure 2.6 | ArcScene™3-D views of the Southern and Central paleochannels, upper image from 20° angle, and lower, 10° view angle. The kriging process extended the channel banks by containing the trend surface beyond the seismic data. ....  | 46 |
| Figure 3.1 | Three buried drainage systems for the Delaware River after Knebel and Circé (1988) and Gill (1962). The three channels of Knebel and Circé (1988) will be studied in the work, the Northern, Central, and the Southern. ....   | 52 |
| Figure 3.2 | Early map of paleochannels to be modeled. The general positions of four major paleochannels of the Delaware River. The paleochannels have been termed the Red, Green, Blue, and Orange, by Krantz and co-workers (McGeary et al., 1991; Krantz et al., 1993; Murphy, 1996). ....                           | 53 |
| Figure 3.3 | Bathymetry of inner continental shelf. Study area locations with major bathymetric features of lower Delaware Bay and the Delaware inner shelf. ....   | 58 |
| Figure 3.4 | Paleochannels of the Delaware Bay. The primary channel of this study are the Blue (called the Central channel by Knebel and Circé (1988)) and the Orange or Southern by Knebel and Circé (1988). We show that the Blue paleochannel connects with the Blue on the inner shelf. ....                        | 63 |

|             |  |    |
|-------------|--|----|
| Figure 3.5  | Orange paleochannel enlarged with the main channel of the Blue paleochannel indicated. The Orange paleochannel appears to possibly merge with the Blue paleochannel as they exit the bay. Could indicate theis are concurrent as suggested by Knebel and Circé (1988) or as we argue two separate that overlap. .... | 64 |
| Figure 3.6  | ArcScene™ 3D view of Delaware Bay paleochannels. Northern (green), Blue (blue) and Orange (orange) paleochannels, view from 30° angle looking up the bay. Darker colors indicate deeper sections. ....   | 65 |
| Figure 3.7  | Map of modeled paleochannel surfaces. Northern (green), Blue (blue) and Orange (orange) paleochannels. Depths measure from sea level. Darker colors indicate deeper sections. Orange emerges from beneath the Blue in on the shelf .....   | 66 |
| Figure 3.8a | Paleochannels of the Delaware River. The Blue/Central follows the path of the Orange/Southern out of the bay. A narrow paleochannel (The Yellow) was observed in the seismic data. The paleochannels from the coast of Delaware flow toward the Blue and Orange. ....  | 69 |
| Figure 3.8b | Inset of Cape May area. Our interpretation of the Northern paleochannel crossing Cape May south of the Cape May Canal connecting with the Green paleochannel differs from Krantz et al. (1993). ....   | 70 |
| Figure 3.9  | The buried Omar/Beaverdam contact depth based on seismic interpretation. Note a slightly deeper section (35-40 m) just southeast of the bay Mouth, this follow the path of the paleochannel of the Delaware River. ....  | 79 |
| Figure 4.1  | Map of the study area. Wells (green), cores (blue) offshore and seismic lines (red), line Y-Y' shows seismic profile above. ....   | 84 |
| Figure 4.2  | Seismic profile of the high-amplitude reflection studied in this work. Annotation shows the reflection in green and one of the paleochannels of the Delaware River highlighted in orange. Other reflections present but not highlighted are later events. ....   | 85 |

|             |  |    |
|-------------|--|----|
| Figure 4.3  | Model of the lower seismic reflection. The reflection depth based on seismic interpretation using a constant seismic velocity in saturated sediments of 1500 m/s. The interpolation was done using ArcGIS™ Geostatistical Analysis. Note a slightly deeper section (35-40 m) just southeast of the bay mouth; this follow the path of the paleochannel of the Delaware River. .... | 86 |
| Figure 4.4  | Composite schematic summary of the Delaware geology of the Omar and Bethany Formations from Groot et al. (1990). ....  | 87 |
| Figure 4.5  | Rehoboth Beach area with the cores and seismic lines. Cores collected by the Delaware Geological Survey, Oj54-01, Oj54-02, Pj15-01 and Pj25-06, and seismic profiles were used, a north-south line (13R33L6WC) and a crossing east-west line (13R58L25WC) from State of Delaware's Department of Natural Resources and Environmental Control. ....                                 | 91 |
| Figure 4.6  | Seismic profile showing that the top of the Beaverdam Formation (blue line) is just below the surface about 5 m below surface with dips to 15 m in depression or paleochannel. X indicates the position where the profile crosses line 13R33L6WC, 250 m from start of line. Colors represent the sedimentary units, for detailed sediment descriptions see Appendix. ....          | 92 |
| Figure 4.7  | Core Pi 15-01 and seismic profile showing the top of the Beaverdam Formation. Core position is 190 m east of the profile track line; the reflection and core depth difference is due to the seaward slop to the contact. Pi 15-01 .....  | 93 |
| Figure 4.8  | Core Oj 54-01 core description is less clear in correlating with the reflection. Core Oj 54-02 W142m is located 142 m west of line 13R33L6WC and shows the depth to the Beaverdam to be 15 m deep. Oj 54-01 .....  | 94 |
| Figure 4.9  | Cross-section from Ramsey (2011). Beaverdam Formation (Tbd) with two paleochannels and younger Ql Holocene lagoon deposits, and the Qlh Lynch Heights Formation. ....  | 96 |
| Figure 4.10 | ArcScene Image of the model as the Omar/Beaverdam contact. High angle view of the upper surface of the Beaverdam Formation produced in ArcScene™, facing north. Gray is the contact between the Beaverdam Formation and the Omar and other overlying strata. Blue is the model of one of the paleochannels of the Delaware River. ....   | 99 |

|             |  |     |
|-------------|--|-----|
| Figure 4.11 | ArcScene image of the model as Beaverdam and Bethany Formation contact. Contact between the Beaverdam Formation and the lower Bethany Formation (gray) showing that uplift would need to have occurred. High- angle view produced in ArcScene™, facing north. Blue is the model of one of the paleochannels of the Delaware River..... | 100 |
|-------------|--|-----|

## **ABSTRACT**

A method is developed for taking older analog seismic profiles and building a database of depths to significant reflection events that can be entered into GIS software to create models of subsurface features. Subsequent maps and three-dimensional (3-D) images of the subsurface can then be visualized allowing for more accurate analysis and interpretation. This methodology is applied to paleochannel networks present in the subsurface beneath the lower portion of Delaware Bay and the bordering Mid-Atlantic inner continental shelf. The project uses older analog seismic profiles to model these paleochannels in ArcGIS™ and as a 3-D model in ArcScene™. To constrain optimal parameters to be used in the subsurface modeling, seafloor depths were determined from the seismic profiles, input into the Geostatistical Analyst routines, and then correlated to existing NOAA DEM bathymetry. Simple kriging for extended areas and Universal Kriging using anisotropy, for paleochannels channels gave the best statistical and visual results. The models of the paleochannels were then entered into ArcScene™ to create 3-D views allowing the subsurface geology to be analyzed and interpreted. The modeling results provide better constraints on the geometry of the paleochannels and can be used to better understand the recent geologic evolution of the region in response to sea-level fluctuations.

Located under the lower Delaware Bay are three buried drainage systems of the Delaware River the Northern, Central and Southern as suggested by Knebel and Circé (1988). On the inner continental shelf four major subsurface paleochannels of the Delaware River were identified in several seismic profiles collected by Belknap and Kraft (1985), and McGeary et al., 1991; Krantz et al., 1993; 1994). This study improves the understanding of the stratigraphy underlying Delaware Bay and the inner shelf and examines the correlation to the paleochannels within bay and determines the relative ages. The Central paleochannel is the youngest and continues on the shelf as the Blue paleochannel, heading southeast 50 km, where it turns to the east and extends toward Baltimore Canyon. The Southern paleochannel extends as the Orange and appears also to extends toward Baltimore Canyon, is the next oldest. The oldest paleochannel is the Northern which is suggested to connect to the Green on the inner shelf.

During the analysis of the seismic profiles along the inner continental shelf, a deeper reflection (40 m to 60 m below sea level) was observed in many of the profiles. This reflection was modeled in the same manner with ArcGIS™ Geostatistical Analysis and correlated with onshore strata. Two models were produced: the first used the seismic data above to model a surface, and the second used onshore well data to model surfaces of two likely candidates. Then each of the onshore surface models is projected to connect with the offshore surface model. The best match was the Beaverdam Formation with the overlying Omar Formation. This was then confirmed by using near shore seismic profiles and associated core data. The Beaverdam Formation underlies much of the state of Delaware and Atlantic inner continental shelf.



## Chapter 1

### INTRODUCTION

A relatively large dataset of seismic and core information collected in the middle to lower portions of Delaware Bay and off the coast of Delaware over the past few decades has yet to be fully studied. These data have mostly been used to delineate potential sand resources for beach replenishment, to characterize sites for possible storage of dredge spoil from deepening of the Delaware Bay navigation channel, or to describe the general geology of the middle to lower portion of the bay and the inner continental shelf (Krantz et al., 1993; Murphy, 1996; Williams, 1999).

A few investigations have interpreted the existing seismic data in an attempt to delineate paleochannels and to use them to help decipher the Neogene to present evolution of this portion of the Mid-Atlantic continental margin. Most recently, Krantz and co-workers, using data that they collected in 1990 and 1992 as well as 1974 data from Belknap and Kraft (1985), identified four major subsurface paleochannels of the Delaware River (McGeary et al., 1991; Krantz et al., 1993). These were initially identified from north to south as the Red, Green, Blue, and Orange paleochannels (Figure 1.1). Based on their spatial relationships, the Blue paleochannel was identified as the youngest (Krantz et al., 1993; Murphy, 1996). The internal stratigraphy and geographic distribution of the Blue paleochannel was studied in further detail by Murphy in her 1996 Master's Thesis (Murphy, 1996).

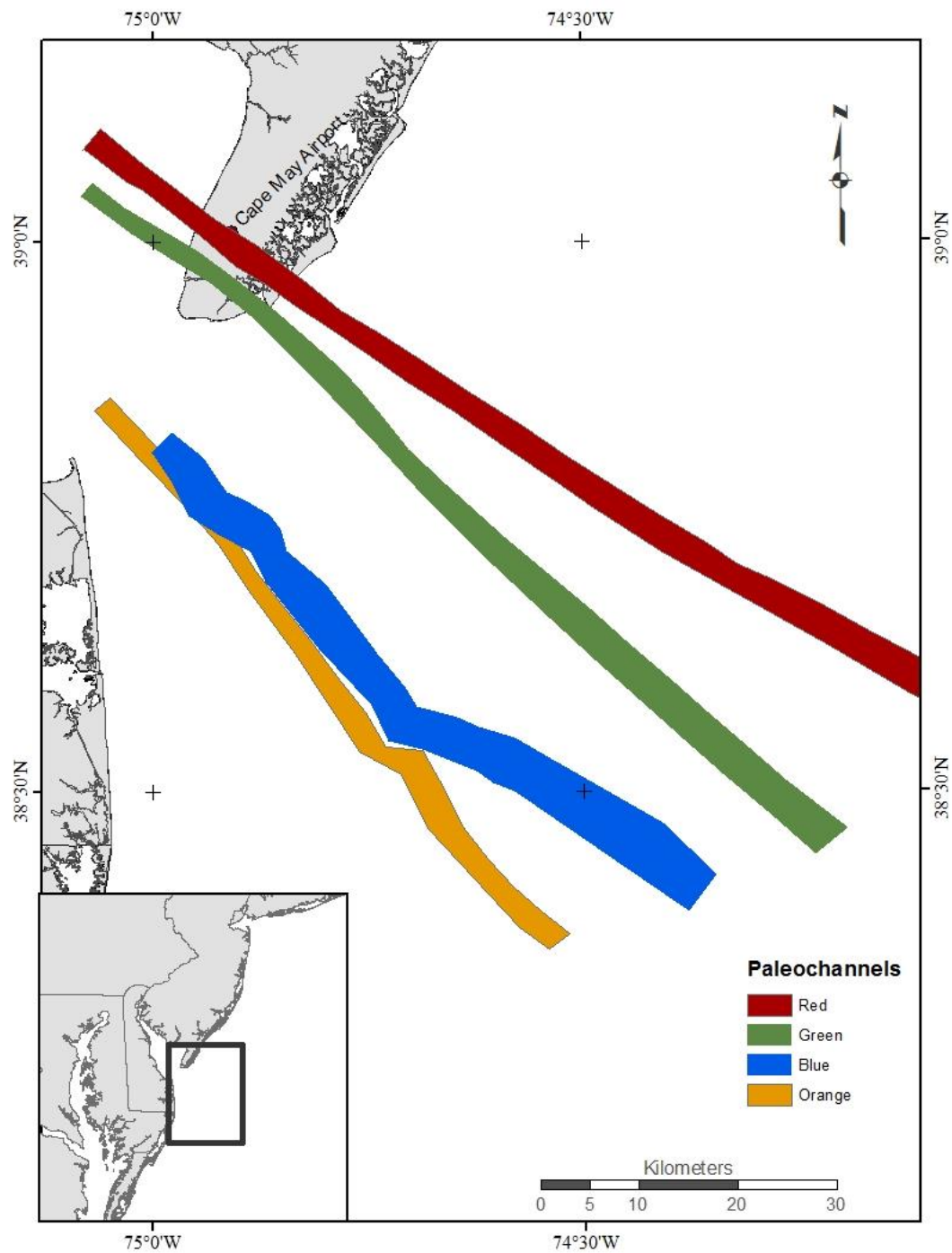


Figure 1.1 General location figure showing positions of four major paleochannels of the Delaware River. The paleochannels have been termed the Blue, Orange, Green, and Red by Krantz and co-workers (McGeary et al., 1991; Krantz et al., 1993; Murphy, 1996).

In a 1999 Master's Thesis, Williams used seismic profiles and data from cores to investigate the sand resources off the coast of Delaware (Williams, 1999). In his work, Williams (1999) included descriptions of paleochannels associated with the Indian River, Rehoboth Bay and Assawoman Bay. The paleochannel system that Williams identified is shown in Figure 1.2 with the Blue and Orange paleochannels as a reference.

The research in this dissertation integrates the work of Murphy (1996), Williams (1999), and Krantz and co-workers (McGeary et al., 1991; Krantz et al., 1993) by comparing the drainage networks along the Delaware inner continental shelf with the major paleochannel systems of the Delaware River. Over the past several interglacial cycles, the course of the lower Delaware River and Bay has changed (Kraft and Belknap, 1986). During glacial advance and lower sea stands, the river valleys reached as far as the edge of the continental shelf (Twitchell et al., 1977). Subsequent transgressions caused the river valleys to flood creating an estuarine system and filling the river channel (Twitchell et al., 1977).

This project analyzes the paleochannels in the lower Delaware Bay and in the Delaware inner continental shelf in order provide more detail to better constrain the geologic evolution of this area. The method employed in this analysis includes scanning selected analog paper seismic profiles into a digital form that can then be used within a GIS framework.

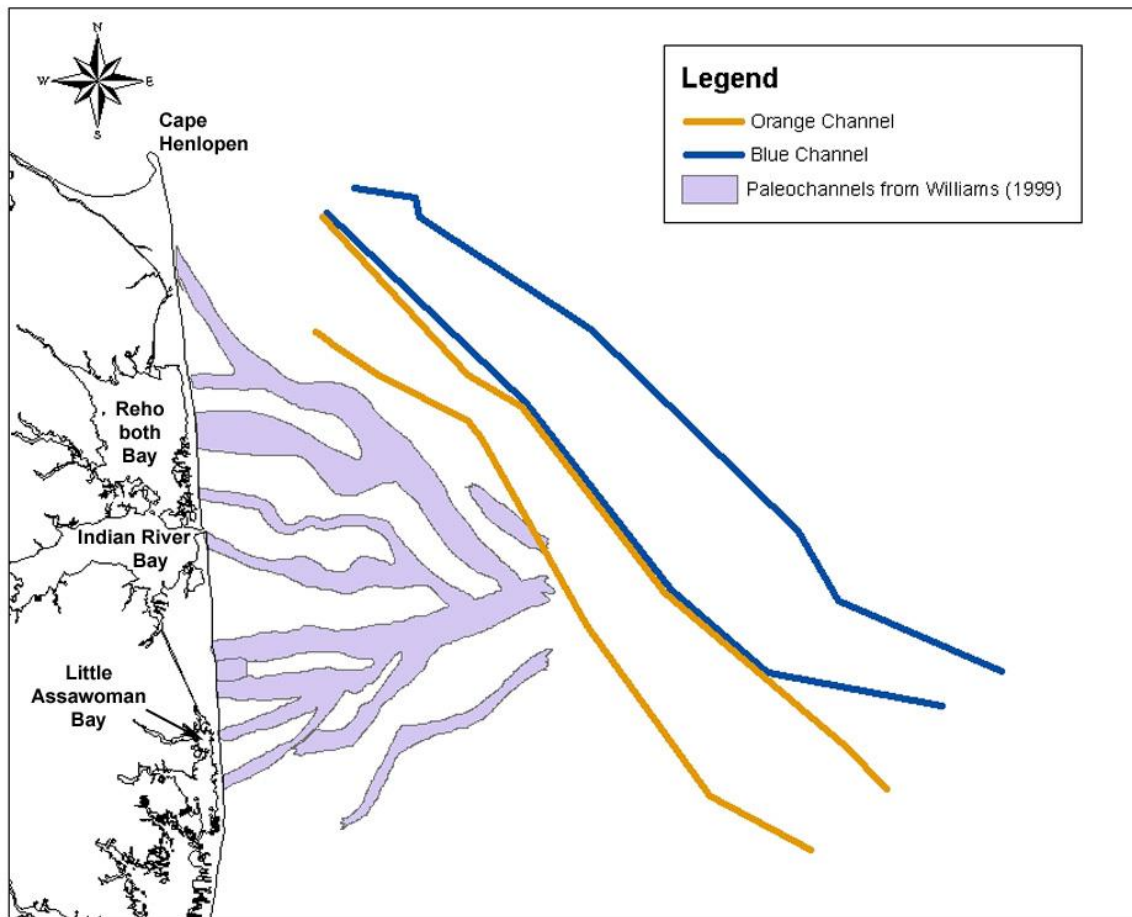


Figure 1.2 Paleochannels along Delaware's inner continental shelf. Shaded channels were mapped by Williams (1999). Orange and Blue paleochannels initially mapped by Krantz and co-workers (McGeary et al., 1991; Krantz et al., 1993; Murphy, 1996).

## **Study Area and Background**

The study area consists of the middle to lower portions of Delaware Bay and extends out onto the Mid-Atlantic inner continental shelf off the coast of Delaware (Figure 1.3). Many geologic processes including marine, estuarine, coastal, and fluvial processes have shaped the stratigraphy and morphology of the area. It contains evidence of deposition in the form of shoals, deltas, infilling of river and stream beds, and erosion in the form of downcutting (Krantz et al., 1993; Murphy, 1996). Underlying the Delaware Bay and Atlantic coastal plain is a geosyncline with the axis running through the Baltimore Canyon. The basement is of igneous and metamorphic Paleozoic age rocks, that are faulted, downwarped, and filled with Mesozoic and Cenozoic sediment (Belknap and Kraft, 1977).

Throughout the Quaternary, the area has been incised by the Delaware River and smaller streams during low sea-level stands and eroded during subsequent transgressions (e.g., Gill, 1962; Sheridan et al., 1974; Twichell et al., 1977; Belknap and Kraft, 1985; Knebel and Circé, 1988). The inner continental shelf sediments are of shallow marine and coastal deposits that show rapid transgression and regression during the Quaternary Period (Belknap and Kraft, 1977). Sediments of the coastal plain and inner continental shelf vary from coarse to fine fluvial, littoral, and marine sands, likely of Sangamon interglacial time (Belknap and Kraft, 1977). The present shelf geomorphology is due to fluvial, estuarine, and marine processes during the Holocene (Murphy, 1996).

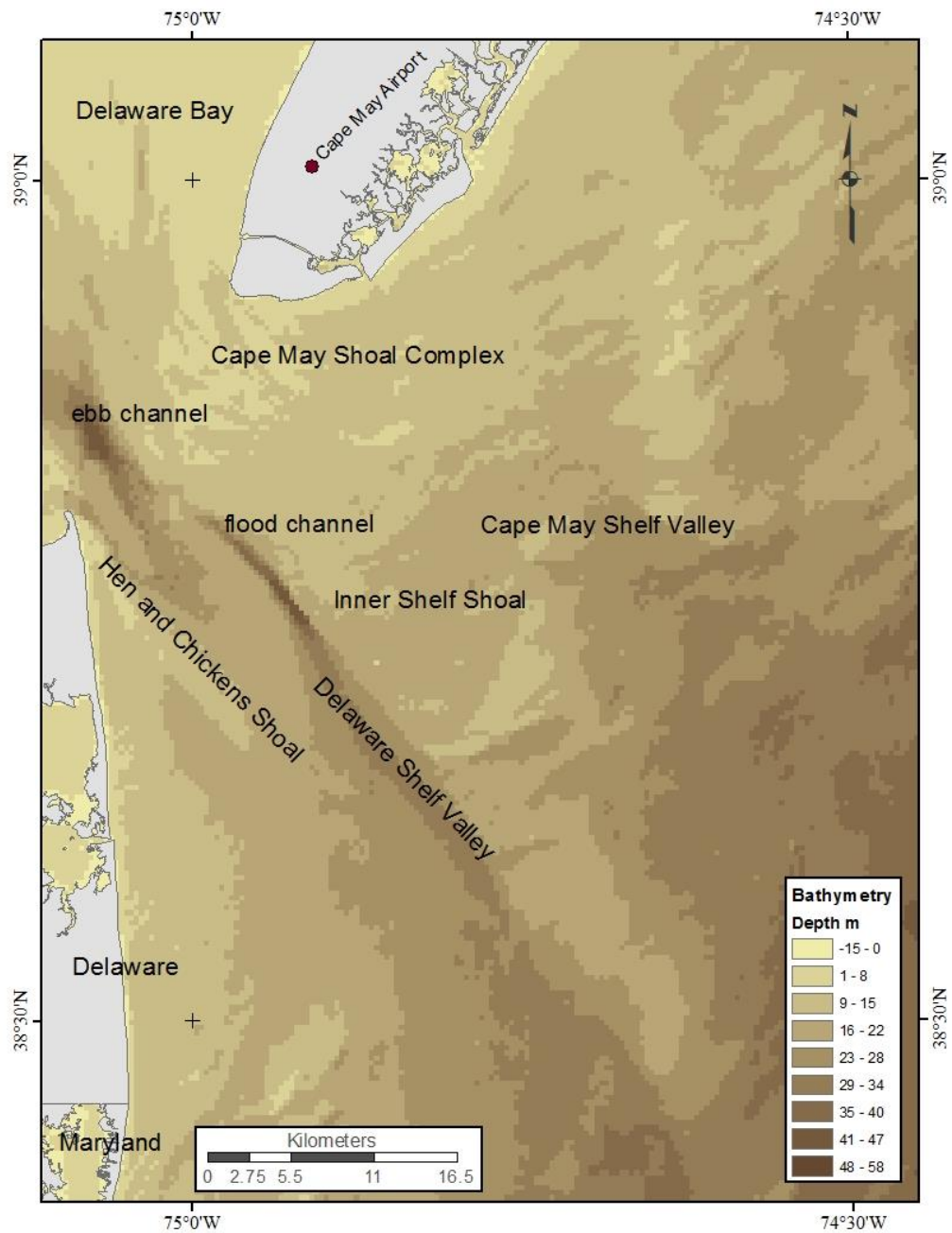


Figure 1.3 Bathymetry of inner continental shelf. Study area locations with major bathymetric features of lower Delaware Bay and the Delaware inner shelf.

Major bathymetric features in this area include the incised channels and bordering shoals within Delaware Bay, the deeply scoured flood and ebb tidal channels near the mouth of the Bay, and on the inner continental shelf the Delaware and Cape May Shelf Valleys and major shoals such as Hen and Chicken Shoal, the Inner Shelf Shoal, and the Cape May Shoal Complex (Figure 1.3). Modern transgression and regression processes on older topography produced these bathymetric features (Belknap and Kraft, 1985).

The Delaware Shelf Valley is an ancient equivalent of the Delaware Bay when sea level was at a lower stand. Currently longshore drift and tidal sediment transport are both eroding and infilling the paleochannels (Murphy, 1996). The bay mouth is characterized by two channels, an ebb channel just inside the bay and a flood channel seaward of the mouth (Figure 1.3). As the tides ebb and flood scouring channels transporting and depositing sediments farther in the bay and out on the continental shelf (Murphy, 1996).

### **Seismic Data used for this Project**

There are three major sets of existing seismic data available to be use in this project. The first is the dataset used by Krantz and co-workers (1993), the second set was collected by the Maryland Department of Natural Resources in August 1992 and August. 1993 on the *RV Discovery* (Williams, 1999), and the third set was collected as part of the ongoing Delaware Bay Benthic Mapping Project.

Krantz and co-workers, including Murphy (1996), used three single-channel seismic reflection datasets in their analyses: Uniboom (250-1000 Hz) data collected in 1974 by Daniel Belknap and Chris Kraft (1985); Datasonics (3.5 kHz) data collected in 1990; and Geopulse Uniboom (300-4000 Hz) data collected in 1992 (McGeary et al., 1991; Krantz et al., 1993). The survey area for this dataset lies mostly on the inner continental shelf ranging from north of Cape May, New Jersey to the Maryland/Delaware state boundary (Figure 1.4).

These reflection profiles were analog recorded on thermal paper and were not digitally processed. The 3.5 KHz data show depths of ~20 meter sediment penetration while the 1974 and 1992 Uniboom data penetrate to ~70 m beneath the sea-bottom (Murphy, 1996). An example profile of the data is shown in Figure 1.5.

Williams (1999) in his analysis used 3.5 kHz analog single-channel seismic reflection data that were collected in 1992 and 1993 by the Maryland Department of Natural Resources. His study area extended along the Delaware coast to distances of 20 km offshore (Figure 1.4). The data show maximum penetration depths of ~20 m into the sub-bottom. An example profile of the data is shown in Figure 1.6.

Williams (1999) integrated his seismic data with sediment descriptions from vibracores that were collected in the area by Ocean Surveys, Inc. in November 1992. The vibracores penetrated to depths of ~6 m into sea-floor sediments. Vibracores samples were described, sediment grain-sizes were determined, and clay samples were analyzed for mineralogy and pollen content. Radiocarbon dating, pollen analysis, and amino acid racemization were used to estimate age of the sediments (Williams, 1999).



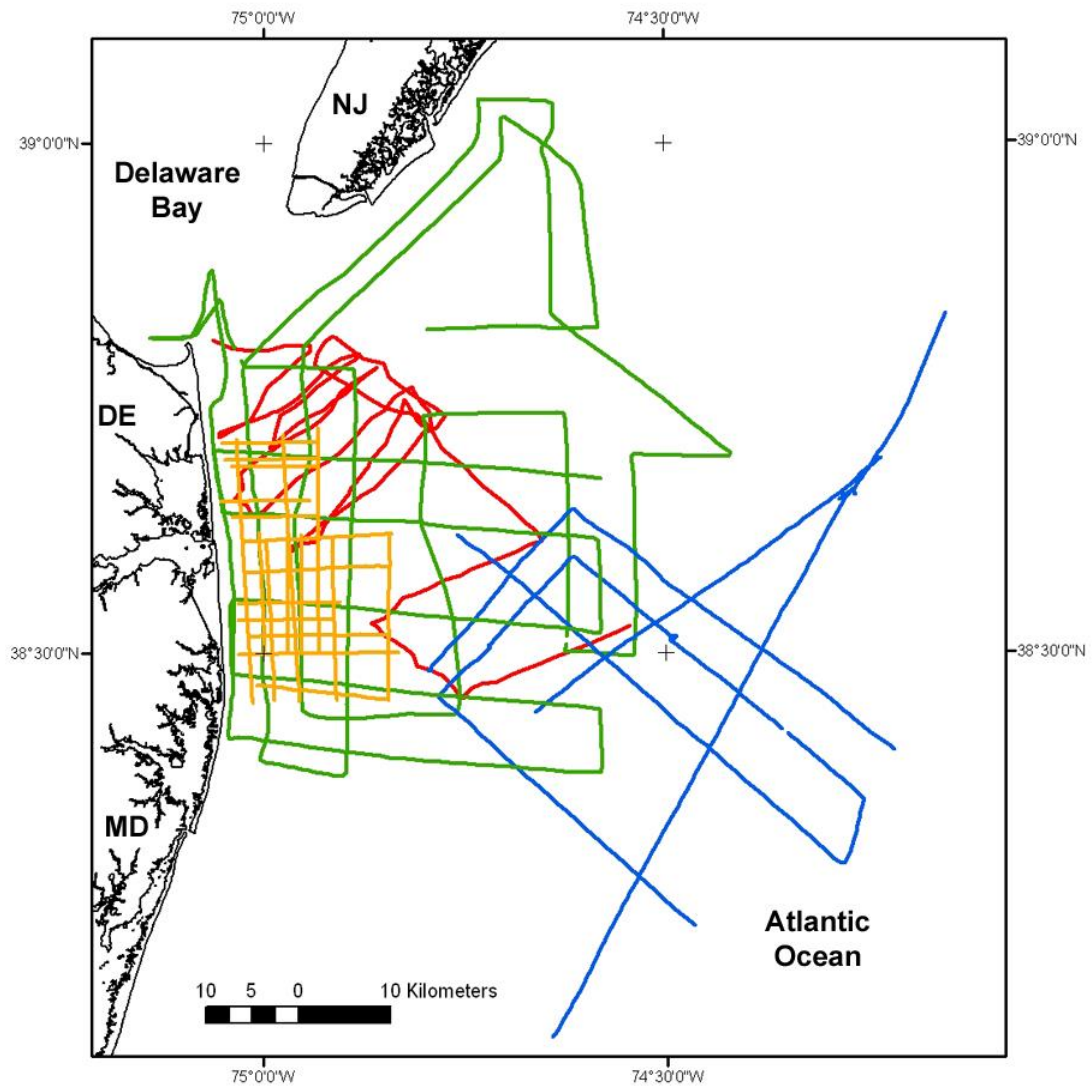


Figure 1.4 Tracklines for existing seismic profiles. 1974 tracklines shown in red; 1990 tracklines shown in green; 1992 tracklines shown in blue; Williams 1999 tracklines shown in orange.

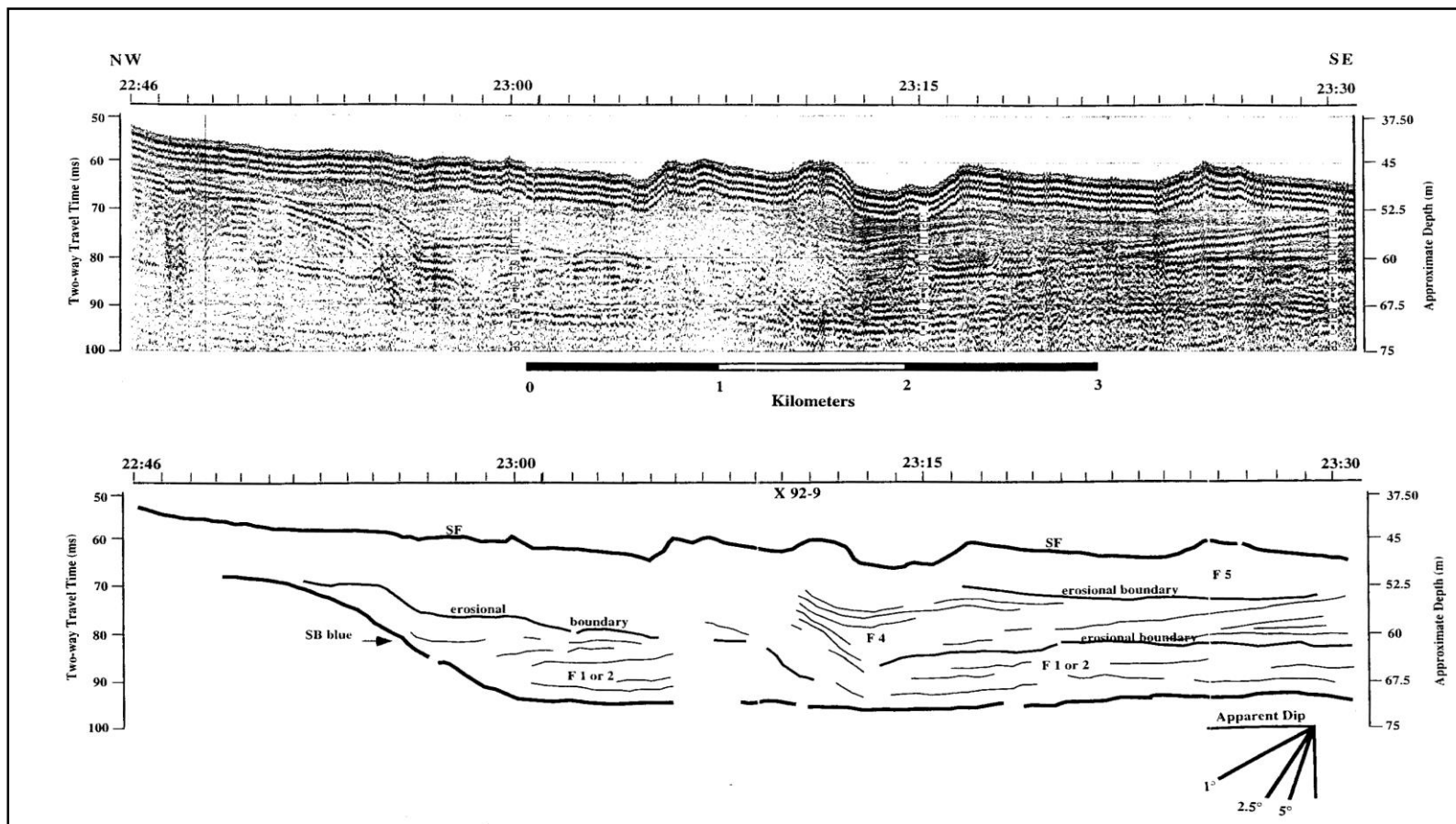


Figure 1.5 Example seismic profile from Krantz et al. (1993) and interpretation from Murphy (1996).

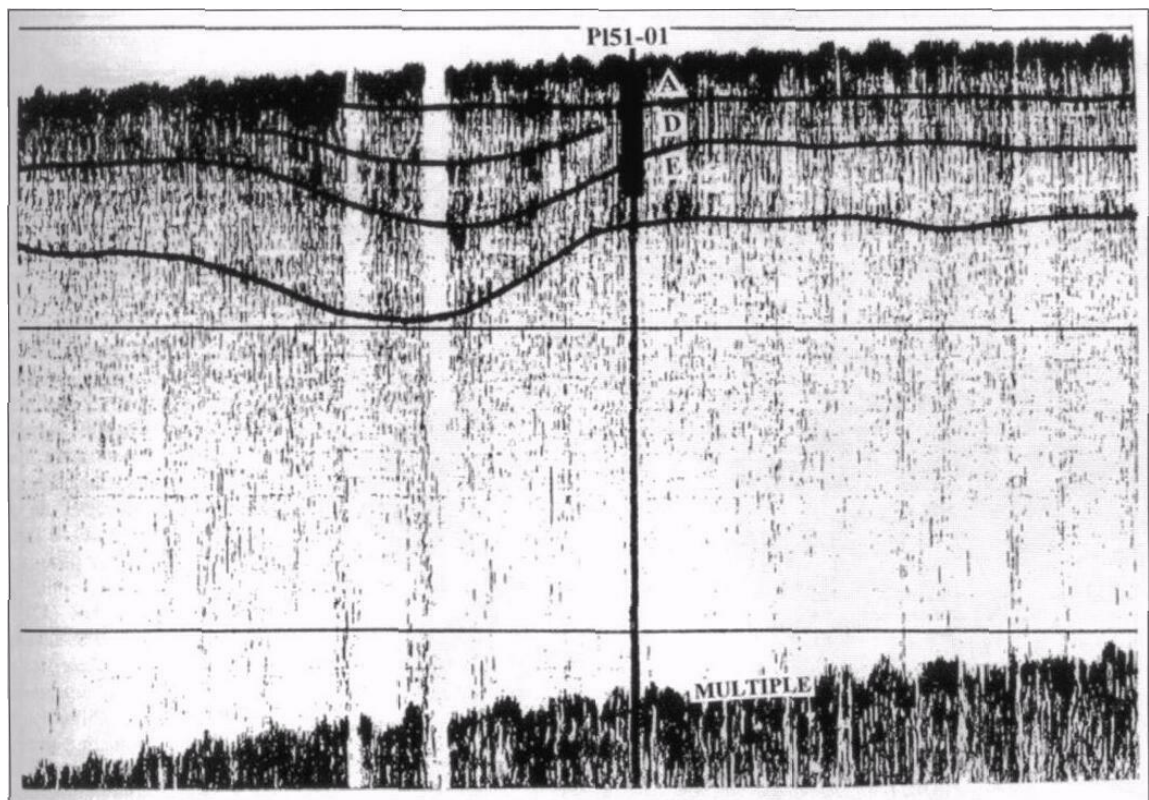


Figure 1.6 Example profile of Williams (1999) 3.5 kHz seismic data. Darker black lines within the profile denote reflections identified by Williams (1999). The horizontal distance across the profile is approximately 280 m. Thin horizontal lines denote depths of 7.5, 15, and 22.5 m below the towfish, respectively. Core P151-01 is a vibracore collected by Ocean Surveys, Inc. in support of the Williams (1999) study.

The Delaware Benthic Mapping Project was conducted by the Delaware Department of Natural Resources and Environmental Control (DNREC) with a mission to identify and map the benthic habitat and sub-bottom sediments of these areas. “The Delaware Benthic Mapping Project integrates data collected using a RoxAnn seabed characterization system, a chirp sonar sub-bottom profiler, a multibeam bathymetric mapping system, surface grab samples, vibracore samples and video images to identify and map the benthic (bottom) habitat and sub-benthic (sub-bottom) sediment layers in Delaware Bay and Delaware’s coastal Atlantic Ocean (Madsen, 2014). Data collected with the chirp sonar profiler of the sub-bottom sediment layers in Delaware’s coastal Atlantic Ocean are used in this project

#### **Previous Regional Seismic Studies of Paleochannel Evolution**

Colman and Mixon (1988) used high-resolution seismic reflection profiles collected in the main section of the Chesapeake Bay, coupled with on- and offshore bore holes, to develop a model for the geologic evolution of the lower Delmarva Peninsula including the ancestral Susquehanna drainage system. They identified a series of paleochannels, the Exmore, Eastville and Cape Charles channels of Pleistocene age. Colman and Mixon (1988) concluded that these paleochannels were associated with subsequent episodes of channel filling with estuarine/lagoonal muds covered by prograding spits.

Toscano et al., (1989) identified five stratigraphic units of the inner shelf off Maryland. They used high-resolution seismic profiles along with vibracoring and amino

acid racemization to determine ages. Tuscano and York (1992) suggest the paleochannels are pre-Holocene in age and were formed during various transgression/regression cycles. During the low sea stand, the channels are formed followed by infilling as sea level rises.

Oertel and Foyle (1995) studied a similar system of paleochannels on the ocean side of the lower Delmarva Peninsula. Using 750 and 2000 Hz Geopulse boomer systems integrated with additional seismic data, they imaged four major paleochannels (Oertel and Foyle, 1995). Three of these could be traced back to the Colman and Mixon (1988) paleochannels with the fourth interpreted to be a tributary of the Eastville channel (Oertel and Foyle, 1995). The infill material of these paleochannels contained several seismic facies indicating fluvial, transgressive estuarine, estuary entrance spit, and estuary entrance shoal environments (spit is sediments extending from a point of land, shoal sediment deposited to shallow depths).

Information from an extensive vibracore dataset (Chrzastowski, 1986), coupled with additional bore holes (Ramsey, 1999) beneath the Indian River and Rehoboth Bays and along the barrier coastline of Delaware' indicates the presence of two major Pre-Holocene age paleochannels cutting into Pleistocene to late Miocene age sediments. These paleochannels, one beneath Rehoboth Bay and the other beneath Indian River Bay, trend predominantly from west to east from the Inland Bays out onto the inner continental shelf. These paleochannels are also identified in the Williams (1999) dataset.

In the middle to lower portion of Delaware Bay and onshore in southern New Jersey, several workers have used seismic, ground-penetrating radar, and core data to characterize Delaware River paleochannel systems (Gill, 1962; Knebel and Circé, 1988; Newell et al., 1995; O'Neal, 1997). The paleochannels identified beneath the Cape May Peninsula of New Jersey were determined to be of Illinoian age with Sangamonian infill by Gill (1962). Newell et al. (1995) determined that these paleochannels cut into Miocene-age sediments and had infill consisting of the late Pliocene age Beaverdam Formation. In a more recent study, Lacovara (1997) suggests that the age of the infill of the Delaware River paleochannel under Cape May is Pliocene, around 2.3 Ma. This paleochannel depth is approximately 180 feet and is infilled by the Cape May Formation and the Fishing Creek Formations (Lacovara, 1997). The Fishing Creek Formation was described and proposed by Lacovara (1997).

Knebel and Circé (1988) identified three large paleovalleys using seismic data the Northern, Central and Southern Valleys beneath lower Delaware Bay. These paleovalleys are thought to be pre-Wisconsinan in age (Knebel and Circé, 1988). From the lower bay to offshore, the Central and Southern Valleys merged, forming a paleovalley that corresponds to the ancestral Delaware River valley mapped by Sheridan et al., (1974) and Twichell et al., (1977).

### **Research Questions to be addressed**

Over the past several interglacial cycles, the course of the lower Delaware River and Bay has changed (Kraft and Belknap, 1986). During glacial advance and lower sea

stands, the river valleys reached as far as the edge of the continental shelf (Twitchell et al., 1977). Subsequent transgressions caused the river valleys to flood creating an estuarine system and filling the river channel (Twitchell et al., 1977). The major hypothesis of this work is that the Delaware River paleochannel system and the Indian River and Rehoboth Bay paleochannel system are linked and that relative age relationships can be determined and correlated to known ages of other paleochannel systems. With the ages of other paleochannels that have been published and with the use of GIS, to provide a framework that allows comparison of the data, a relationship of each paleochannel to a specific transgression can be accomplished. A second hypothesis is that relative ages can be determined to a reasonable degree of accuracy once the determination to specific transgressions has been completed.

This dissertation project looks at the relationship of Krantz and co-workers' and Williams' paleochannels and how the channels have evolved through the various regression-transgression cycles. This analysis also involves incorporating the results from earlier analyses of ancestral Delaware River drainage (Sheridan et al., 1974; Twitchell et al., 1977; Chrzastowski, 1986; Knebel and Circé, 1988) to develop better constraints on the evolution of the region.

The project determines the linkage between the Rehoboth, Indian River, and Little Assawoman Bay paleochannels of the Delaware coast with the Delaware River paleochannels (Figure 1.2). It addresses age relationships of these identified paleochannels, specifically the Orange and Blue channels of the Delaware River (McGeary et al., 1991; Krantz et al., 1993; Murphy, 1996) with those running off the

coast of Delaware (Williams, 1999). The seismic reflection observed on the profiles are correlated with the geologic units of the Omar and Beaverdam Formations found onshore and with the general geologic cross section of Ramsey (1999). Using the available chirp sub-bottom data with older analog data, these inner continental shelf drainage patterns are projected northward into the Bay.

### **Significance of Proposed Work**

To better monitor the changes in the coastal and estuarine environments, accurate spatial data and a way to analyze and display the information is necessary. The advent of computers and computer mapping has led to the development of Geographic Information Systems (GIS) which is a sophisticated modeling and mapping program that stores and analyzes spatial information. For this research ESRI's desktop ArcGIS™ is used. As GIS has become more and more useful, it has also become more complex. One of the new efforts has been the creation of a defined marine data model developed by the users of ArcGIS™ in the fields of marine sciences such as marine geologists, oceanographers, and marine archaeologists along with many others involved with marine and coastal studies. The data model provides a structure to analyze data, produce maps and create 3-dimensional views to give a clearer understanding of the coastal regions (Wright et al., 2007). This model works well with large datasets with many different components, such as seismic, cores, bathymetry, bottom grabs, sediment samples, etc.



An additional aspect of the research examines the results from the mapping of the paleochannels to further investigate initial settlements along the North American continental land mass in the area of Delaware. The initial settlement along the eastern coast most likely occurred approximately 10,000 or more years ago with the cessation of the last glacial time period during the Pleistocene Ice Age and the start of the current interglacial period (Kraft, 1976). Since global sea level was much lower (up to 100 m) during the glacial interval, coastal settlements would have been located on what is now the inundated continental shelf. The youngest of the paleochannels (e.g., the Blue paleochannel of the Delaware River system), would have marked the position of fresh water rivers draining to the estuary. It is along these paleochannels that the likelihood of settlement would have been highest. Thus the positions of the paleochannels may provide key data in constraining potential locations of settlement. Research by Hoyt (1990) and Kraft and Belknap (1983) suggest that sediments preserved on the continental shelf could preserve archaeological sites.

The following chapters are manuscripts to be submitted to a scientific journal. Chapter 2 explains the GIS methodology used to model the paleochannel surfaces, Chapter 3 describes the geology of the paleochannels, and Chapter 4 looks at the offshore reflection observed in many of the seismic profiles that is projected onshore to correlate with known strata.

## Chapter 2

### **ANALOG SEISMIC PROFILES TO THREE-DIMENSIONAL GIS MODEL: CONSTRAINING THE GEOMETRY OF SUBSURFACE PALEOCHANNELS BENEATH DELAWARE BAY**

Countless paper rolls of analog marine seismic data collected from thousands of kilometers of ship's tracklines are stored in filing cabinets, map cases and boxes. In most cases, only limited interpretation of these original data has occurred and thus there is a potential loss of valuable subsurface information as the paper degrades with time. Analog seismic data were commonly collected from the 1950's to the 1990's after which digital recording and storage were utilized.

One method of preserving analog seismic profiles for future analysis, interpretation and visualization is to electronically scan the profiles and digitally store the scanned images. There are commercially available seismic software packages with this capability which also provide subsequent data processing and analysis. This digital storage option as an output from scanning is the best way to preserve these data. However, faced with equipment and/or financial limitations, digital scanning may not always be an option. For example, rolls of analog seismic data may be on the order of 0.6 m (2 ft.) wide and several meters long requiring larger than page size scanners capable of handling rolls of input. If there are a large number of profiles, the scanning

process can be time consuming and, depending on the type of access to a large format scanner, costly.

The paper presents an alternative methodology of identifying reflections on analog marine seismic profiles, building a database of two-way travel times (or depths) to significant reflection events utilizing a Geographical Information Systems (GIS), and generating two- and three-dimensional (3-D) images of the subsurface. This methodology allows, with available digital storage space and archiving, a utilitarian way of preserving the significant aspects of these valuable marine data.

Analog marine seismic profiles are typically collected using an onboard or towed seismic source emitting a seismic pulse at a predetermined frequency (or frequencies), and seismic receiver recording the amplitude of incoming seismic pressure waves as a function of time. The recorded seismic waves include reflections off the water/bottom interface and sub-bottom seismic boundaries. Reflections of seismic energy occur at boundaries where a change in acoustic impedance occurs. Acoustic impedance is the product of the density of the layer through which the seismic wave is traveling and the seismic velocity through that layer. The greater the difference in acoustic impedance, the greater the amount of energy reflected at the boundary.

Incoming pressure waves, including seismic reflections, to the seismic receiver are converted to electrical pulses with the size of the pulse proportional to the amplitude of the waves. Profiles of analog marine seismic data were commonly generated using thermal printers in which the electrical pulses were sent to heating elements on a rotating ribbon activating thermosensitive paper. The resulting print-out,

characteristically on a roll of paper, consists of a series of darker lines with intervening lighter areas. The darker lines correspond to greater amplitude electrical pulses which in turn were created by higher amplitude seismic pressure waves recorded by the receiver. Most of the higher amplitude waves are associated with seismic reflections occurring at boundaries where changes in acoustic impedance have occurred. Figure 2.1a displays an example of an analog seismic profile, 2.1b highlighted the reflections? Features, and 2.1c illustrates the interpreted ArcGIS™ model profile.

Interpretation of analog seismic profiles has typically consisted of examining the long rolls of thermal paper, identifying the water/bottom boundary and key sub-bottom reflections, and tracing them along the profile. This type of interpretation has usually involved colored pencils (and erasers) with particular reflections identified by a particular color and subsequently labeled with a number or letter identifier. Locations of key reflections are then be plotted on maps with the ship's tracklines or illustrated in cross-sections.

With the ability of computers and advances in spatial analysis, more recent seismic data are collected and analyzed digitally, so the need for paper and colored pencil are less essential, and perhaps archaic. A number of specialty software programs are able to process seismic data and produce maps, cross-sections and 3-D images. One of the main objectives of this paper is to demonstrate the feasibility of using a non-specialized program to accomplish the same tasks. The two-way travel time (depth) to individual reflections was measured on the analog seismic profiles, input into a database, and utilized in GIS to produce, 2-D and 3-D maps. GIS software programs

provide sophisticated geostatistical analysis techniques and mapping capabilities that are readily available.

As an example of the methodology, analog marine seismic data are reprocessed and used in the interpretation of a network of ancient river valleys (or paleochannels) present in the subsurface beneath the lower portion of Delaware Bay (Figure 2.2). These data were initially collected and interpreted by Knebel and Circé (1988). Three paleochannels, identified as the Northern, Central and Southern Channels, are present in the study area (Knebel and Circé, 1988). The paleochannels were infilled and overlain by sediments as global sea level rose during time periods of subsequent warmer climate. The 3-D images of the paleochannels generated in this paper were compared with the interpretations of Knebel and Circé (1988) as a check on the suitability of the GIS-based methodology as a utilitarian way of processing analog marine seismic data.

## **Methodology**

### **From Analog to GIS-compatible data**

The Knebel and Circé (1988) analog marine seismic profiles comprise 23 thermal paper rolls each about 0.6 m (2 ft.) wide and 2.7 m (9 ft.) long. The profiles are shown with elapsed time (two-way travel times (TWTT), in milliseconds (ms)) between the emitting of a seismic pulse and subsequent returns to the receiver as a function of geographic position (Figure 2.1).

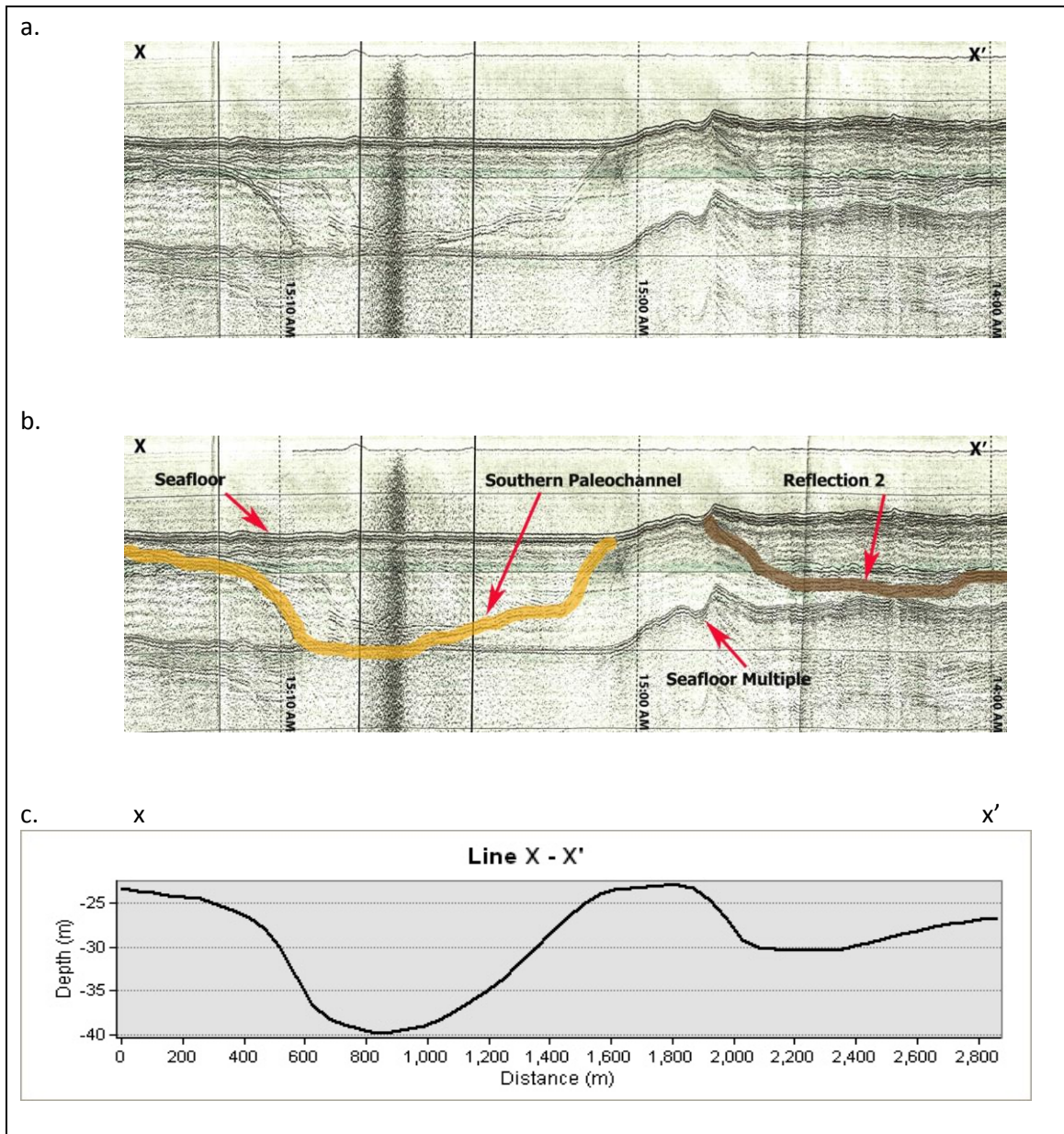


Figure 2.1 Seismic profiles and ArcGIS calculated profile. Analog profiles scanned into digital form. a. Analog seismic profile of the Southern paleochannel. b. Profile showing the various reflectors. c. Profile from ArcGIS™ model.

The sequence of steps that were followed for processing the analog seismic profiles and to generate the 3-D images of the subsurface geology is described below. Initially, navigation data (i.e., latitude and longitude of ship's position as a function of time) from the Knebel and Circé (1988) tracklines (Figure 2.2) were input into Microsoft Excel™ spreadsheets consisting of four columns: FeatureID, latitude, longitude and a reference number unique to each particular ship's track (Table 2.1). The FeatureID was an abbreviated eight digit character corresponding to date and time (e.g., 92061200).

Next, the Knebel and Circé (1988) seismic data were analyzed and several major reflections were visually identified (e.g., Figure 2.1). The reflections are not always clear and often segmented on the printout. The criteria used to define a major reflection included being clearly resolvable and extending for at least 200 m along the profile. For each significant reflection, the TWTT was manually measured from the seismic profile and this time was entered into a separate Excel™ spreadsheet. The TWTT's were converted to depths in meters in a separate column within the spreadsheet assuming a constant sound wave velocity of 1500 meters per second (m/s). The format of this Excel™ spreadsheet identified each given point on a reflection as a separate row with the corresponding columns providing, in addition to TWTT and calculated depth, descriptive information including the corresponding FeatureID from the navigation data (latitude and longitude) and the reference number unique to that ship's track (Table 2.1).

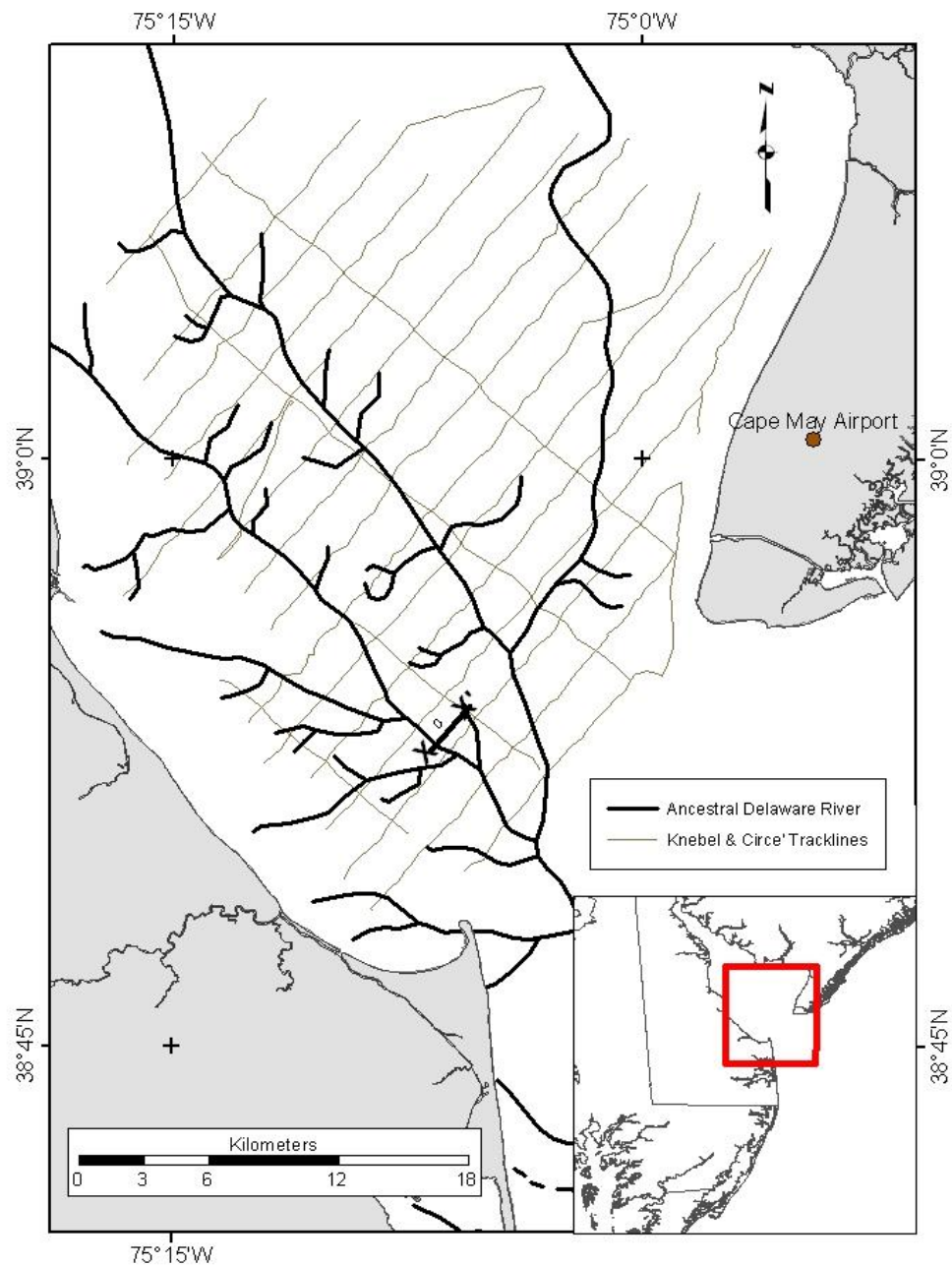


Figure 2.2 Study area showing ships track and the ancestral Delaware River after Fletcher et al., 1990. Line X-X' is the location of the seismic profile referenced in Figure 2.1.



**Table 2.1** Example of Excel™ Spread sheet as formatted for ArcGIS™.

| FeatureID | Latitude | Longitude | Label | TWTT | ReflectorID | Bathmetry | Depth | Line |
|-----------|----------|-----------|-------|------|-------------|-----------|-------|------|
| 902425    | 38.7810  | -74.9855  | 25    | -23  | 0           | -17       | 17    | 90-O |
| 902430    | 38.7807  | -74.9758  | 30    | -23  | 0           | -17       | 17    | 90-O |
| 902431    | 38.7807  | -74.9739  | 31    | -25  | 0           | -19       | 19    | 90-O |
| 902432    | 38.7807  | -74.9720  | 32    | -27  | 0           | -20       | 20    | 90-O |

**Table 2.2** Modeling methods, parameters and the cross validation results for the seafloor. See text for detail of the results.

| Methods and Statistical Results                 |          |              |        |           |           |            |          |            |  |      |            |           |      |
|---|----------|--------------|--------|-----------|-----------|------------|----------|------------|--|------|------------|-----------|------|
| Run   | Method   | Transform    | Trend  | Type      | Optimized | Anisotropy | Lag Size | Lag Number |  | RMS  | Mean Stand | RMS Stand | Ave  |
| 1   | Ordinary | None         | None   | Stable    | No        | No         | 758      | 12         |  | 2.2  | 0.011      | 0.81      | 2.9  |
| 2   | Ordinary | Log          | Second | Stable    | No        | Yes        | 772      | 12         |  | 1.8  | 0.03       | 0.77      | 2.4  |
| 3   | Ordinary | Log          | Second | Spherical | No        | Yes        | 772      | 12         |  | 1.98 | 0.043      | 0.78      | 2.17 |
| 4   | Ordinary | Log          | Second | K-Bessel  | No        | Yes        | 772      | 12         |  | 1.8  | 0.036      | 0.78      | 2.02 |
| 5   | Ordinary | Log          | Second | Stable    | Yes       | Yes        | 257      | 12         |  | 1.73 | 0.052      | 0.77      | 2.18 |
|   |          |              |        |           |           |            |          |            |  |      |            |           |      |
| 1   | Simple   | None         | None   | Stable    | No        | No         | 733      | 12         |  | 2.27 | 0.05       | 0.82      | 2.89 |
| 2   | Simple   | Normal Score | Second | Stable    | No        | Yes        | 488      | 12         |  | 1.54 | 0.18       | 0.63      | 2.77 |
| 3   | Simple   | Log          | Second | Stable    | No        | Yes        | 479      | 12         |  | 1.9  | 0.084      | 0.79      | 2.11 |
| 4   | Simple   | Log          | Second | Sphere    | No        | Yes        | 488      | 12         |  | 1.49 | 0.16       | 0.63      | 2.67 |
| *5  | Simple   | Normal Score | Second | Stable    | Yes       | Yes        | 488      | 12         |  | 1.54 | 0.18       | 0.63      | 2.77 |
| * The Optimize function did not work for Simple |          |              |        |           |           |            |          |            |  |      |            |           |      |

The data were originally organized into two separate databases, one of navigation and another of calculated depths (TWTT's multiplied by 1500 m/s, the assumed velocity of saturated sediment). This was done because each navigation point has several different reflections, each with an associated depth value. Having data in two or more databases, there is a need to assimilate the specific pieces of data and there are various applications for accessing and using the information. This can be done early in the process of building a dedicated database or in a spreadsheet such as Access™ or Excel™, also most GIS applications can accomplish the processing. If the data are intended for a specific project, the data can be set up in the collection stage. For large projects multiple databases may be accessed by many users with different objectives. The process described below is a method of selecting and combining data from several databases for this project.

After generating all of the navigation and reflection Microsoft Excel™ spreadsheets, the data were exported to a Microsoft Access™ database to take advantage of the ability for Access™' to specify an appropriate data type (e.g., text, integer, or float) for each field. For example, the FeatureID (i.e., abbreviated eight digit number corresponding to date and time) was defined as a long integer, the navigation latitude and longitude data were floating values, and the ship's track reference number was set as text value characters.

In the next step, a GIS-shapefile corresponding to the ship's navigation was created from the Excel™ table containing the latitude and longitude data using the "Create Feature class from XY Table" tool in ArcGIS™. This navigation layer provides

the foundation for creating 3-D surfaces for each paleochannel. All other data or attributes associated with the navigation file are in the Access™ created database directly readable within ArcMap™. A particular attribute can be selected for a criteria of interest, such as depth. To build a surface models, for this project, the depth to each reflection identified on the seismic profiles was needed to be in ArcGIS™. The attribute query function in ArcMap™ was used to select a depth of reflection combined with the navigation layer to create a shapefile for each depth reflection surface. The steps for querying the database for the identified reflections and building a new shapefile are outlined below. Note, as the ArcGIS™ program evolves, these step may change.

#### In ArcMap™

To create a table for each depth reflection:

Open the Depth table in the database (i.e. Reflection #1)

“Select by Attribute” tool

Double click on “Reflections” field

Click ‘=’

Click ‘Get Unique Values’

Double click the desired Reflector

Apply

Under Table options tab

Export

Selected records

Export as a new table

Repeat above for each Reflection

To build a shapefile from the Access™ database:

New tables that were created above need to be joined with the navigation data one at a time:

Right click Navigation shapefile  
Under Join and Relates  
Select “Join”

Choose field (Feature ID)  
Choose Table to be joined  
Select “Keep only matching records”  
Save as a new shapefile

A new shape file containing the navigation, depths and other is information created. At this point this new shapefile needs to be saved as a new and different file and the depth data be removed from that original or master Navigation shapefile. This is need to be done in order to retain the original data or it will be lost.

Right click on the Navigation shapefile  
Under Join and Relates  
Select “Remove joins”  
Select either choice

This will return the original navigation shapefile.

At this point the original navigation layer is back as it should be and a new map layer has been created. This process is to be repeated for each reflector.

If the data in an Excel™ table contain the navigational fields and only have one reflector, there is no need to join the data tables. The only step needed to produce a shapefile.

In ArcCatalog  
Table of Contents – in the Excel™  
Right click the Excel™ sheet  
Create Feature Class – from X-Y table

Drag and drop the new shapefile you just created into ArcMap™

Now that the data are set up in shapefiles and the mapping and modeling can begin.

### **From GIS-database to 3-D surfaces**

It is not practical to collect marine seismic data at a high spatial resolution to capture meters to sub-meter detail over a three-dimensional region (several hundreds of kilometers) of study. Instead, marine seismic data are normally collected in an organized pattern of profiles that are separated by distances of meters to tens to hundreds of meters, depending on the scope of investigation. Given that the along profile seismic data is collected at discrete points typically separated by distances of meters, there is generally a large discrepancy in the spacing between along-profile data and the separation between profiles. For example the Knebel and Circé data used in this study consisted of approximately 2000 seismic traces (data points) from ship's tracklines that were spaced approximately 2 km's apart (Figure 2.2). Data are collected continuously along the ship's trackline seismic. The seismic depth values were not corrected for tide heights. Although seismic measurements are continuous, reflections are not always visible. Within the paleochannel where the reflections change depth in a short distance, measurement was made at 140-150 m apart to better calculate the surface in the model. Elsewhere in areas of smooth topography and no more than 1000 m were used. This was based on one-half the trackline spacing of 2 km. These along-track closely-spaced (100-200 m) and between track greater distance (2 km) data were used in the generation of surfaces using spatial interpolation. The result represents the Delaware Bay seafloor and buried paleosurfaces to a reasonable degree of accuracy.

ArcMap™ and ArcScene™ were used to analyze and model the data to produce maps and 3-D images representative of the seismic profiles data collected. These data are created using statistical methods to provide estimates of the depths between trackline data. Kriging is a common method used in geological applications to generate a grid of cells from datasets that contain extensive data along a trackline or profile. For example, Chung and Rogers (2010) used kriging to interpolate depth to bedrock. They divided their study area into geomorphic regions to provide better results. After trying several models, they determined that ordinary kriging with spherical models and different lag sizes, gave the best statistical results with a root mean square standardized error of 1.0 and prediction errors near zero. Erdroğan (2009) compared several methods of interpolation to produce a digital elevation model of a hill at Afyon Kocatepe University campus with ordinary kriging and radial basis spline functions being the best methods. The greatest RMS errors were found at steep surfaces within the area analyzed.

In another example, Facas et al. (2010) examined the effects of anisotropy, which is the directional dependency of the data. They used kriging to investigate anisotropy on soil compaction by a construction roller on a road surface. By first measuring soil compaction of the roller in the x-direction and then in the y-direction, semivariograms maps in both (x and y) directions were produced. The semivariogram analyses indicated that anisotropy is present in the data, and kriging provided a valid means to model a surface (Facas et al. 2010).

ArcGIS™ 3D Analyst suggests that when there is no directional component in the data and there is good spatial coverage of the features of interest, then ordinary or simple kriging are good interpolation methods. Kriging interpolation is commonly used in geologic applications (Wilson, 2006 and Chung and Rogers, 2010). Isaaks and Srivastava (1989) and Kennedy (2009) recommend universal kriging when dealing with directional and/or distance bias in the data. Based on the previous studies results, kriging was a starting point for this project to take original point observations and create paleochannel surfaces. For modeling the seafloor, ordinary kriging was used since there is no directional component.

Exploration tools exist in many GIS software packages to examine data and determine the validity of using kriging to model a surface based on these data. The tools include examining data distribution, trends, directional components and outliers (ESRI? tutorial, Performing Spatial Interpolation Using ArcGIS™ 10, 2011). One of the ArcGIS tools available is the Geostatistical Analyst Explore Data tool that can be used to evaluate methods of surface creation that will give satisfactory results. This tool includes the generation of histograms, QQ plots, trend analyses and semivariograms.

Kriging, similar to other interpolation methods, assumes that the input data are spatially continuous and assumes no spatial autocorrelation, stationary, and normally distributed (ESRI tutorial, Performing Spatial Interpolation Using ArcGIS™ 10, 2011). The data in this project are spatially continuous, with data points occurring along discrete tracklines and, as shown by a semivariogram, are spatially autocorrelated. The data analysis shows no local variation indicating that the data are also stationary. A

histogram of seafloor depths measured from the seismic profiles shows a non-Gaussian, skewed distribution, however. To have the depth data approximate a normal distribution, a log transformation was applied. The data show a general southeast trend of increasing depth though out of the bay and the Atlantic Ocean. To remove this trend before the application of kriging, a second order trend removal was applied using the geostatistical wizard in ArcGIS™. Lastly, the data are assumed to be evenly distributed over the study area. If all the assumptions are not met, kriging may still provide reasonable results, given an understanding of the project's goals and the limitations (Young, personal communication, 2011).

Several kriging methods with various transformations and trend removal parameters were used to determine the most appropriate interpolation model for the data. By statistically comparing the methods, to quantify the model's accuracy. The output statistics provides a numerical measure of the accuracy, and is an aid to the final geologic interpretation.

A semivariogram analysis is a key function in the kriging interpolation process that graphs the semi-variance or difference between the values of two points (Y-axis) versus the distance between the two points (X-axis). Following the ESRI Virtual Campus Course, "Performing spatial interpolation using ArcGIS™ 10", binning is a process of sorting data pairs, in a semivariogram, based on their relative distance and direction. This assumes that the data points separated by similar distances will have close to the same value. If the data are stationary, then the semivariogram represents the spatial autocorrelated structure of the data. Two nearby points are more closely related



and should have very small differences in value; as the distance between the points increases, the spatial relation becomes less significant.

Graphically, the semivariogram is a plot displaying the values of the square of the difference between the two points on the Y-axis and the distance between the two points on the x-axis (ESRI ArcGIS™ Desktop 10 Help, 2011). The value or height on the y-axis is known as the sill, in our model the sill is 1.1, and the sill defines the limits of the neighborhood search radius (ESRI ArcGIS™ desktop 10 help, 2011). At some distance, defined as the range, the value no longer continues to increase with distance and those distant points should have no effect on the interpretation (Isaaks and Srivastava, 1989). The range plotted on the semivariogram's x-axis is at a distance of 2.7 km. The model is easily compared to the average to see how the model fits to the empirical points. Different types or functions of semivariogram models can be run depending on the shape of the semivariogram curve. Steep curves indicate nearer points will have a greater influence on the model's prediction (ESRI ArcGIS™ desktop 10 help, 2011).

As stated previously, the semivariogram models assume data are isotropic (values are the same in all directions). However, topography is quite variable, with hills and valleys that are not symmetrical resulting in elevation data this are not isotropic but anisotropic. Semivariogram models are capable of calculating anisotropy by accounting for values with directional dependences. Facas et al. (2010) ran kriging models with and without anisotropy. Their model comparisons found that the directional component has a high influence on the on the results. With data that has an orientation in a particular

direction the setting for anisotropy should be included. For the data in this study, points running along the river channel bottom have values closer in depth in comparison to points running perpendicular to the channel, which have greater depth differences.

The primary objective of the geologic study was to investigate the buried paleochannels using seismic data. To validate how well the kriging method creates a geologic surface model from our dataset, we choose to first model the seafloor. This model is compared to an existing, high spatial resolution seafloor bathymetry from NOAA Bathymetry map for Delaware Bay (map; DE/NJ (M090) Bathymetric Digital Elevation Model). Several runs of the models for the bay seafloor using ordinary and simple kriging and different parameters were compared to determine the best interpolation based on the statistical results.

Both simple and ordinary kriging were run on the seafloor data beginning with the default setting in ArcGIS™ Geostatistical Analyst wizard to establish a baseline. The Trend Analysis indicates the data trends in two directions and suggested that a second order trend removal. First, ordinary kriging using log transform (to approximate a normal distribution) and second order trend removal (to account for overall trend in the data) was completed with the stable, spherical, K-Bessel semivariogram models. Next a final ordinary kriging run using the optimize function that allows the Geostatistical Analyst to calculate a best fit. The second set of kriging runs included, five runs using simple kriging with different transforms (to approximate a normal distribution) including a normal score transform and log transform. With stable and spherical model types performed. The attempts to use the optimized function, a process

that lets ArcGIS™ Wizard set the parameters, gave no results, so the parameters were set manually.

In order to determine how well the models predicted the unknown values, a statistical comparison such as cross validation is used to test the reliability of the model results, and to determine the model and method parameters to create the most reliable surface. Cross validation is a process to determine the accuracy of the predicted surface. The process involves removing a sample point for the dataset, calculating the value of the removed point, and repeating this process for all points, then plotting the actual value versus the predicted value. An example of the cross validation compares the results of the seafloor model. The model comparisons are shown on Table 2. The measurement output errors from the cross validation listed in Table 2 include root mean square value (RMS), mean standardized, root mean square standardized, and average standard error. The best models are those with low RMS and average standard error, root mean square standardized close to 1. Moreover, the mean standardized value near zero, and having small differences between RMS and average standard error indicates a better model.

The three best fitting models were also compared visually to the NOAA Bathymetry (NOAA National Geophysical Data Center, U.S. Coastal Relief Model, NGDC Coastal Relief Model Vol. 02 1 degree by 1 degree block, <http://www.ngdc.noaa.gov/mgg/coastal/crm.html>). The NOAA Bathymetry is established as the ground truth (Figure 2.3A). All ten models show the broad features evident in the NOAA bathymetry seafloor. However, the top three models (simple,

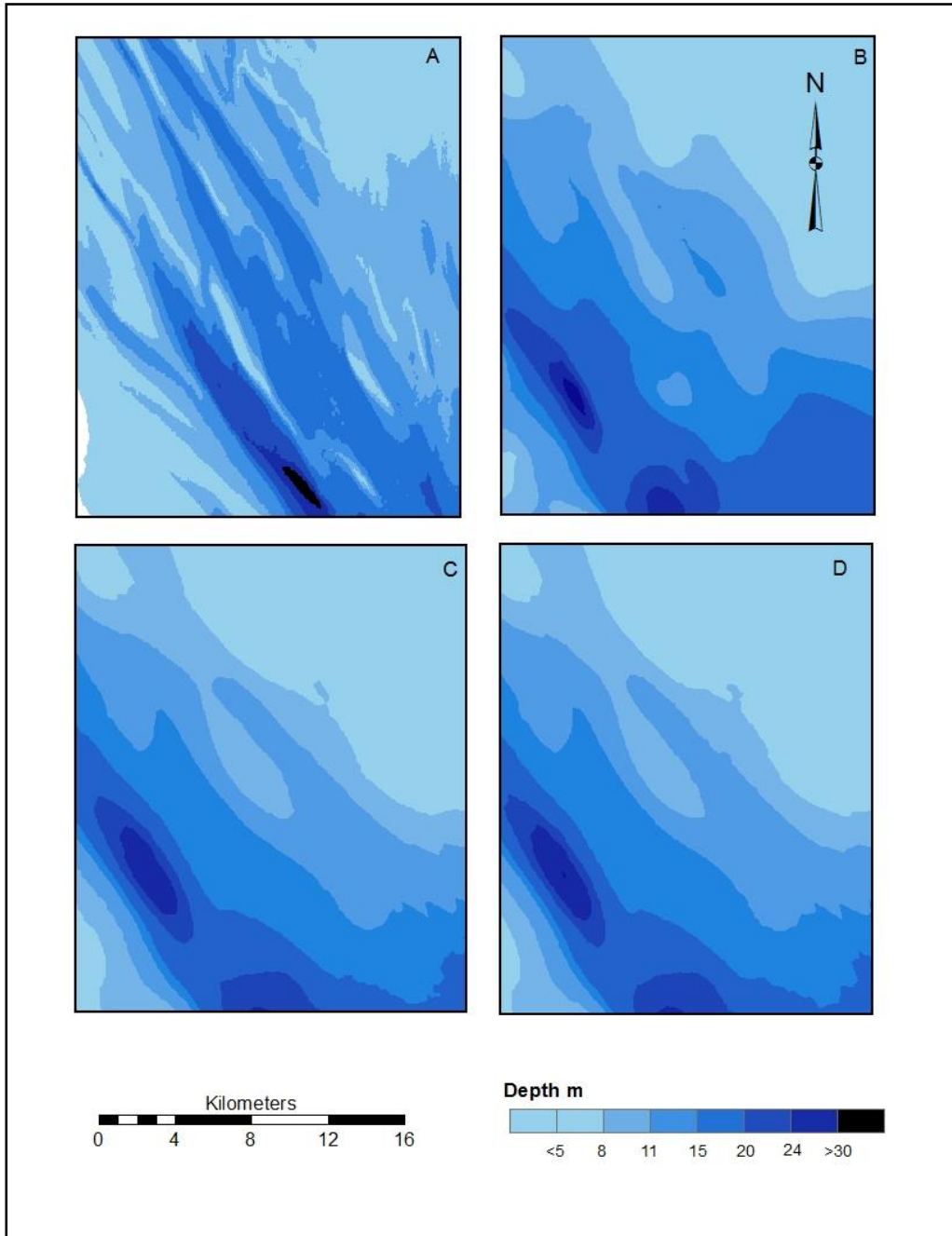


Figure 2.3 Comparison of three kriging models lower Delaware Bay seafloor. A. NOAA DEM was used to ground truth the kriging model, B. Simple kriging model, normal score transform, stable type, C. Ordinary kriging model, log transform, stable type, D. Ordinary kriging model, log transform, K-Bessel type.

stable; ordinary, stable, and ordinary, K-Bessel) display a better visual fit along with the statistics with Model A in Figure 2.3A appearing the best match. The NOAA Bathymetry as a higher spatial resolution of 90 square meters (grid cell size) of the where the resolution of the data in this study was calculated in ArcGIS™ to be approximately 230 square meters. Knebel and Circé (1988) seismic track lines used in this study were several kilometers apart so the resolution of the bathymetry is lower, but should still show a strong resemblance. As shown in Figure 2.3 the deeper areas match well and the shallow sections match the same pattern in the model and the NOAA DEM. The shallow areas have less seismic coverage but still show a close match to the control. Using ArcGIS™ the model depth values subtracted from that of the NOAA DEM show the differences range from less than a meter to several meters in actual value. The differences are most likely due to the fact that measurements were not corrected to sea level and any minor changes that occurred throughout the bottom sediment over the time span of the surveys. Comparing the models resulting interpolated seafloor depths with actual NOAA bathymetry measurements aid in the choice of model types and parameters and give a higher confidence in the appropriate model to create a reliable surface from the reflectors.

Using the NOAA sea floor bathymetry as a comparison, the statistical results of the simple kriging model gave the highest confidence. Slight statistical differences in the best models (simple and ordinary) indicate that any of these models could be used with confidence of creating a reasonably accurate surface. In order to model long

narrow swaths of data as indicative of paleochannels, running in a specific direction, incorporation of anisotropy is necessary. With the reduced number of points per unit area provided less data is available in the calculation of the direction of anisotropy. Initially, the semivariogram used only data points in one seismic line to calculate for anisotropy. To correct for this, the search radius of sample points used in interpolation is increased to include more points, accomplished with the nearest neighbor settings in the semivariogram. By setting the nearest neighbor to a larger spatial extent will let ArcGIS™ include points from parallel seismic lines. The channel direction will be needed to compensate for anisotropy. However, creating a surface with second order trend gave very extreme values at the edges, creating a model that extended above sea level. After further investigation, it was recommended to use first order trend in the kriging model (ESRI blog, support help, 2012). Using first order trend showed equally good error statistics as that of the second order trend model. Both first and second order trend models show only minor differences in the main section of the channel and only differ at the extent of the seismic data points, with the first order not showing extremes in the outer sections of the interpolation.

It must be noted that the geologic surface produced by the kriging interpolation scheme in Geostatistical Analyst Extension are not permanent layers but temporary dynamic layers. To enable additional processing, the dynamic layer must be output to a permanent grid by which the calculated points are reinterpreted in the raster conversion and new predicted values produced. This may create an image that has a much larger range of spatial values than that of the measurements. For example, in the Southern

channel, the ordinary kriging models resulted in depths of the buried paleochannel at the perimeters extending well above sea level. During the transformation for trend removal, the extrapolation in some cases continues beyond the spatial extent of the observations by assuming the trend continues in the same manner, which leads to extreme values at greater distances (personal communication ESRI Technical Support, 2012). Not using a trend as one of the model parameters alleviated this problem and produced reliable results. For the longer Central paleochannel, the universal kriging with a constant trend removal did not produce the erroneous the effect of extending the surface beyond the spatial extent of the geographic area.

### **Paleochannels**

Several models were run for each of the subbottom reflectors to compare the statistics using the set parameters and determine the best solution for creating the surface models for each subbottom reflector data. Based on the cross validation of these models and the visual comparison to the seafloor of the NOAA Bathymetry, the simple kriging model produced the best results as shown in Figure 2.3B and 2.3C. Since no comparison data exist, it must be emphasized that this is only a starting point. By performing several kriging methods and analyzing the minimum error statistics along with one's geologic expertise with the region, an optimal interpolation scheme may be determined. The same model and parameters were attempted for the buried features as used for the seafloor. These model parameters did not work as well as expected. This is due potentially to measurement points of the seafloor distributed over a more regularly

spaced and larger area, whereas the data for the paleochannels are in long narrow strips. It was found that universal kriging works better than simple kriging for creating buried paleochannels surfaces that are long narrow features. The buried paleochannel data contain anisotropy, whereas the seafloor data covered a larger more uniform area and are more isotropic (with no preferred direction). The following settings were used to model the paleochannels in ArcGIS™ Geostatistical Analyst Wizard:

### **Input datasets**

#### **Dataset - Central Paleochannel**

##### **Method Kriging**

|                          |     |
|--------------------------|-----|
| Type - Universal         | SI* |
| Output type - Prediction | SI  |

##### **Dataset #1**

|                       |    |
|-----------------------|----|
| Trend type - Constant | SI |
|-----------------------|----|

##### **Trend removal**

|                                |    |
|--------------------------------|----|
| Local Polynomial Interpolation | SI |
|--------------------------------|----|

##### **Searching neighborhood**

|   |     |
|---|-----|
| Smooth                                    | SI  |
| Type - Smooth                             | SI  |
| Smoothing factor - 0.2                    | Cal |
| Angle -151° (Paleochannel flow direction) | SI  |

##### **Variogram**

|                     |     |
|---------------------|-----|
| Semivariogram       | SI  |
| Number of lags - 12 | Cal |
| Lag size - 580      | Cal |
| Nugget - 7          | Cal |

##### **Model type**

|                    |     |
|--------------------|-----|
| Stable             | SI  |
| Anisotropy - Yes   | SI  |
| Minor range - 2327 | Cal |



Direction - 151°  
Partial sill - 34

**SI**  
**Cal**

\*SI- Selected by interpreter  
Cal- Calculated by ArcGIS™ Geostatistical Analysis

## **Results**

### **Central Channel**

The Central channel is a long paleochannel that trends from northeast to southwest in the lower portion of Delaware Bay. Model results of the Central Channel, using universal kriging, visually show the expected characteristics of a river. Another paleochannel parallels the Central channel following along the present southern portion of the Delaware Bay (referred to as the Southern Channel). The two appear to merge at the Bay mouth at the edge of the survey area as shown in Figure 2.4.

### **Southern Channel**

The Knebel and Circé (1988) seismic survey contained fewer seismic lines that imaged the Southern channel, and thus fewer points available to be used to define the position and shape of the channel. Their interpretation suggest this merges with the Central channel, this study suggest the two channel are different channels and not active at the same time. As shown in Figure 2.4, the surface models show the geometry of the paleochannels well. The Southern paleochannel underlies the present tidal scour channel that may have influenced the path of the current channel. Viewing both

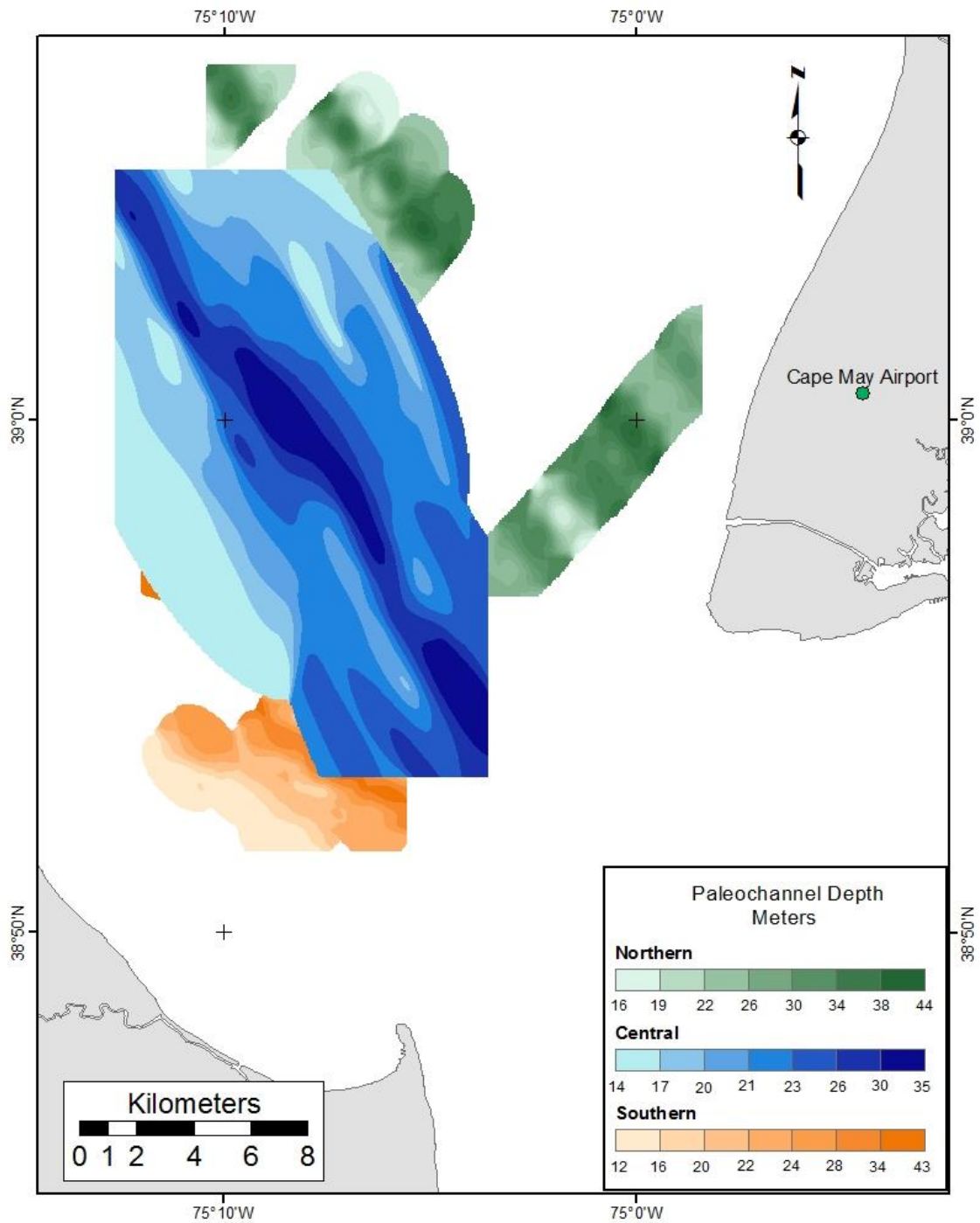


Figure 2.4 Model of the paleochannels of the Lower Delaware Bay. Paleochannel results; blue is the Central, orange is the Southern and green the Northern paleochannels.

channels together, it is evident that the Central channel parallels the Southern and may merges near the bay mouth Figure 2.4.

The Southern paleochannel is stratigraphically deeper and overlapped by the Central paleochannel withh a detailed image of the Southern paleochannel is shown in Figure 2.5. The 3D section of the Southern paleochannel matches the seismic profile shown in Figure 2.1, as well as several parallel seismic profiles.

### **Northern Channel**

To the north of the Central Channel lies a paleochannel that parallels the Central and Southern Channels (Figure 2.4). Knebel and Circé (1988) suggest that this is the oldest paleochannel in Delaware Bay, and have named it the Northern Channel. The Northern Channel trends southeast cutting under the current Cape May peninsula just south of the Cape May Canel. At the time the Northern paleochannel was active, the southern end of Cape May would not have prograded this far south. The presence of the Northern, Central and Southern paleochannels show global sea level fluctuated at least three times, flooding the river valleys as sea-level rose then eroded a new channel as sea-level lowered

### **ArcScene™ 3-D**

The surface models for the paleochannels were exported as separate raster layers and read directly into ArcScene™ to produce 3-D images of the subsurface.

ArcScene™ is an application of Desktop ArcGIS™ that displays and manipulates 3-D images, allowing them to be viewed from varying perspectives. To visualize the

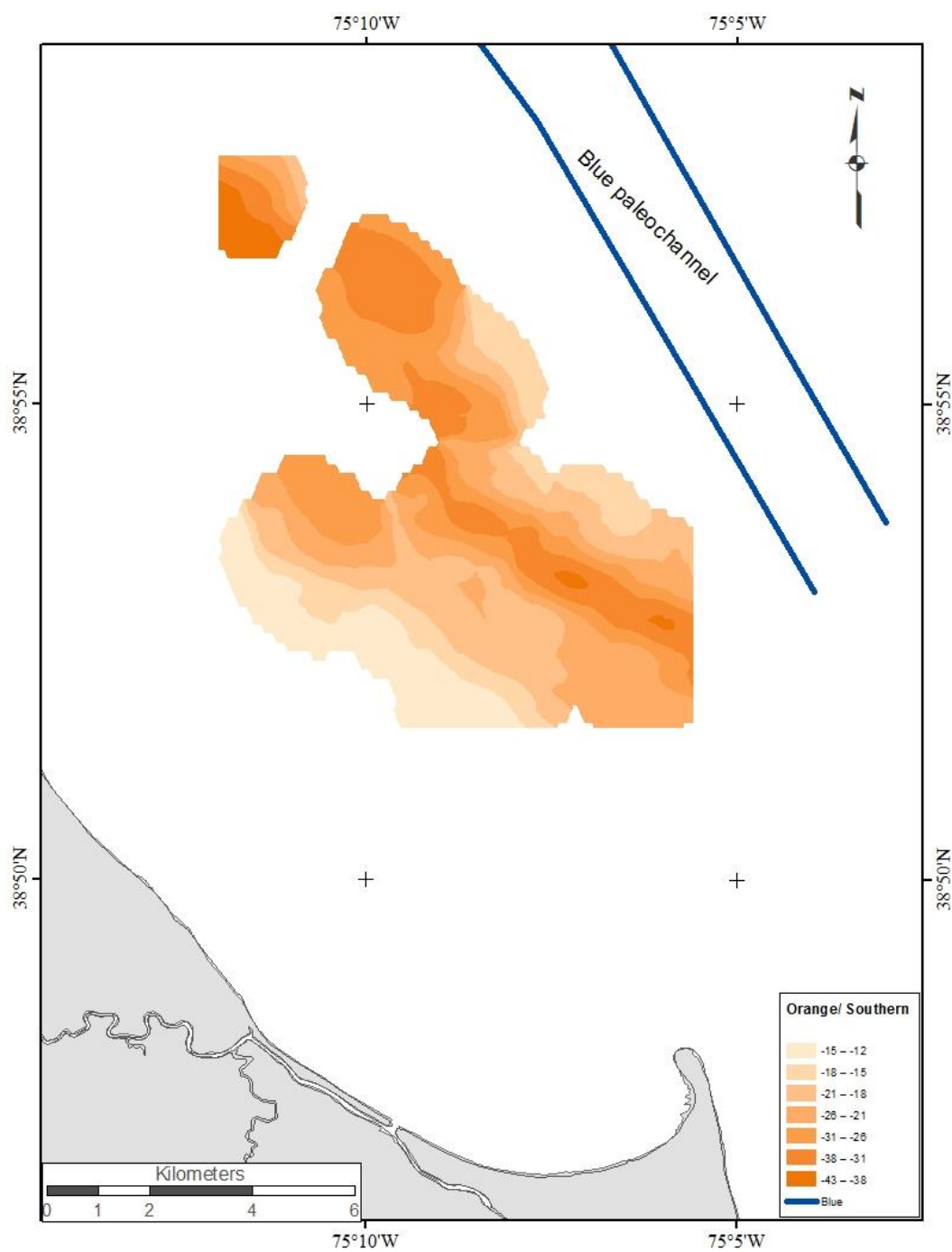


Figure 2.5 Details of the Southern paleochannel, the breaks are due to no seismic data in those areas.

paleochannel network in ArcScene™, the x, y coordinates and the depth, measurements in a uniform vertical and horizontal units. To enhance the view of the overall shape of the paleochannels given that the horizontal distance values (x, y coordinates) were much larger (ten's to hundreds of meters) then the vertical depths (meters to tens of meters), and a base height to 50 in the layer properties. ArcScene™ uses a factor to convert the layer elevation value into scene units; some experimenting was needed to achieve the value.

A representative ArcScene™ 3-D visualization of the Central and Southern paleochannel is shown in Figure 2.6. In this scene, the base of the paleochannel is shown, without its subsequent infill, as it would have appeared as an active river system during a time period of globally lower sea level (Figure 2.6). The 3-D views from different observing angles show the channel as well as the banks and how water has flowed through the channels. From a small viewing angle (Figure 2.6 lower panel), the stratigraphic levels of the paleochannels are more easily determined. One problem is that the kriging model surfaces project the outer edges farther beyond the range of data, extent with the lower surface above the upper.

## **Conclusion**

This methodology demonstrates the utility of using GIS to construct a database from older analog marine seismic profiles, allow manipulation, to generate two- and three-dimensional images of the subsurface. In the absence of being able to utilize

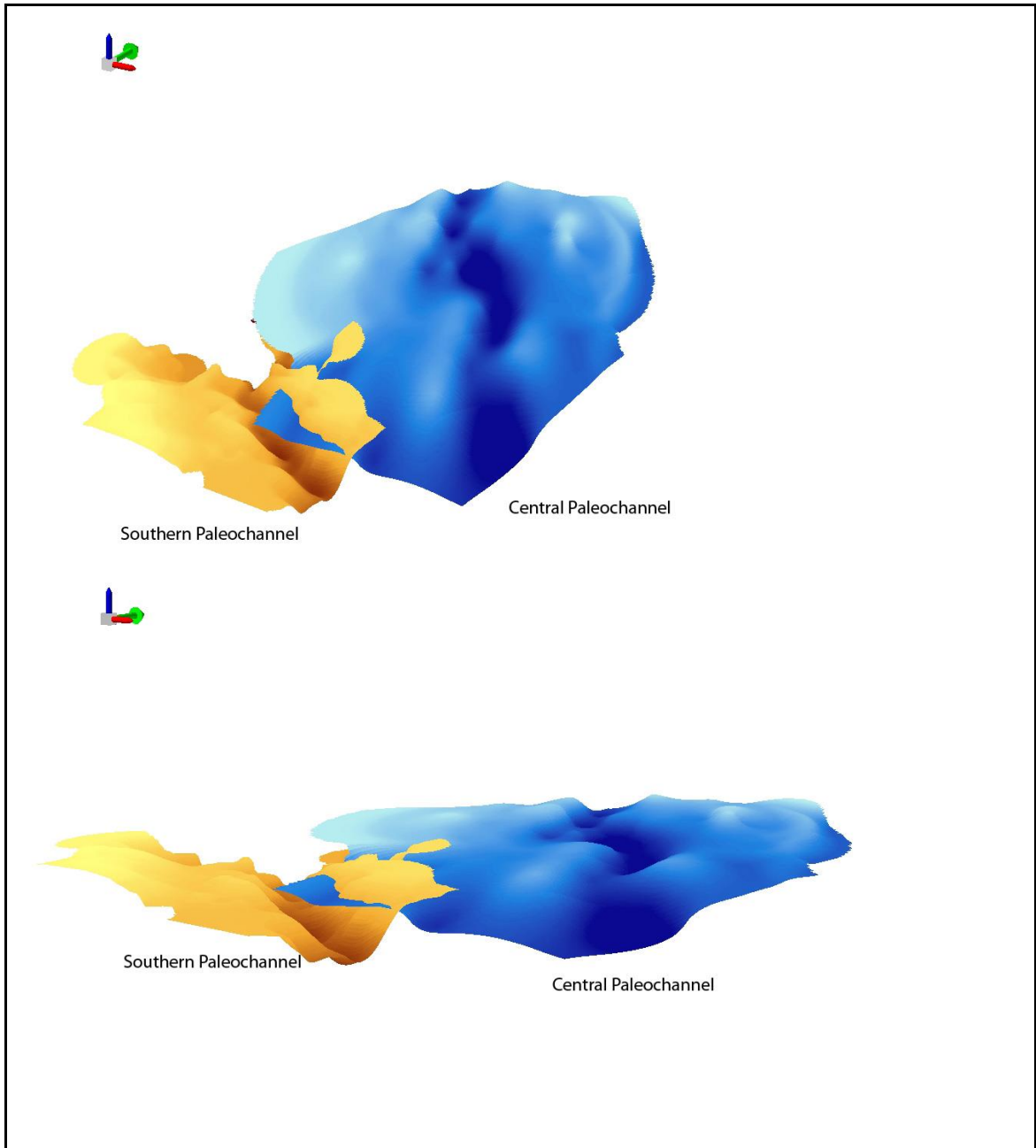


Figure 2.6 ArcScene™3-D views of the Southern and Central paleochannels, upper image from 20° angle, and lower, 10° view angle. The kriging process extended the channel banks by containing the trend surface beyond the seismic data.

commercially available seismic processing software to automatically convert paper profile, this methodology is a utilitarian way to preserve valuable historical data.

Although the process is time consuming, the methodology demonstrates that GIS is a valuable tool aids the geological sciences with the ability to store large amounts of data, and to enable processing to generate maps, tables and 3-D images.

This process can be used to model any geological application that has depth or elevation measurements along with locational reference, from producing 3D views of large features such as mountains and valleys down to individual outcrops. Plotting earthquakes by depth to visualize plate tectonic processes. Any discipline that deals with subsurface data such as seismology, hydrogeology, coastal sand resources, and the correlation of drill cores will benefit from using 3D modeling and mapping. Identifying potential archaeology sites is a fantastic tool for the interpretation of the earlier people and their lives.

The ability GIS has to analyze and model spatial data provides an advantage when it comes to accessing specific data from large databases and relating that data to is of great need in many science fields. When older data are formatted into usable digital forms, it is preserved and can then be more easily accessed, allowing for additional research that includes these older, yet valuable, data resource.

## Chapter 3

### **CONSTRAINING THE GEOMETRY OF SUBSURFACE PALEOCHANNELS BENEATH DELAWARE BAY AND THE MID-ATLANTIC INNER CONTINENTAL SHELF**

Over the past few decades, a significant amount of seismic and core data has been collected in the middle to lower portions of Delaware Bay and adjacent inner continental shelf of Delaware and southern New Jersey that has yet to be fully studied. The data have been used primarily to delineate potential sand resources for beach replenishment, to characterize sites for possible storage of dredging spoils from the Delaware Bay navigation channel, and to describe the general geology of the middle to lower portions of the bay and the inner continental shelf (Krantz et al., 1993, 1994; Murphy, 1996; Williams, 1999).

Only a few investigations have interpreted existing seismic data to delineate paleochannels and to use them to decipher the evolution of the Delaware Bay portions of the Mid-Atlantic continental margin. Knebel and Circé (1988) suggested three buried drainage systems for the Delaware River within Delaware Bay: the Northern, Central, and Southern paleochannels (Figure 3.1). Large infilled paleochannels have been detected in coreholes on land near where the Northern paleochannel projects under Cape May (Gill, 1962; Lacovara, 1997). The Central and Southern paleochannels flow toward the current bay mouth (Knebel and Circé, 1988). Additionally, Krantz and co-



workers, using data they collected in 1990 and 1992, as well as 1974 data of Belknap and Kraft (1985), identified four major subsurface paleochannels of the Delaware River (McGeary et al., 1991; Krantz et al., 1993, 1994). These were identified initially from north to south as the Red, Green, Blue, and Orange paleochannels (Figure 3.2), with the Blue being the youngest based on superposition and cross-cutting relationships (Krantz et al., 1993, 1994; Murphy, 1996). The internal stratigraphy and geographic distribution of the Blue paleochannel was studied in further detail by Murphy in her 1996 Master's Thesis (Murphy, 1996). This paper examines the paleochannels of Knebel and Circé (1988) and identifies any relationship to the paleochannels of the inner shelf of McGeary et al. (1991) and Krantz et al. (1993, 1994).

Following glacial sea-level lowstands, as sea level rises river valleys in coastal areas are progressively submerged, filling the channels and low areas with sediments. Such buried river channels are referred to as paleochannels and/or paleovalleys. (In this paper the term *paleochannel* will represent the main channel and thalweg, and *paleovalley* will represent the broader floodplain and subsequent estuary.) An improved understanding of the stratigraphy underlying Delaware Bay and the inner shelf will allow geologists to assess potential locations for siting offshore wind turbines and identify potential sand resources to be used for beach replenishment in coastal communities.

## **Study Area and Background**

The study area consists of the middle to lower portions of Delaware Bay and extends onto the inner shelf off the coast of Delaware and southern New Jersey. Many geologic processes, including open marine, estuarine, coastal, and fluvial processes, have shaped both the stratigraphy and the geomorphology of the area. River sediment transport and tidal action have formed shoals and cut scour channels near the mouth of the Delaware Bay (Belknap and Kraft, 1985; Krantz et al., 1993, 1994; Murphy, 1996). Previous work indicated that throughout the Quaternary, the area has been incised by the Delaware River and smaller streams during sea-level lowstands and eroded during subsequent transgressions (e.g., Gill, 1962; Sheridan et al., 1974; Twichell et al., 1977; Belknap and Kraft, 1985; Knebel and Circé, 1988; Knebel et al., 1988).

Major bathymetric features in this area include incised channels and bordering shoals within the Delaware Bay, deeply scoured flood- and ebb-tidal channels near the mouth of the Bay, and the Delaware and Cape May Shelf Valleys and major shoals such as Hen and Chickens Shoal, the Inner Shelf Shoal, and the Cape May Shoal Complex on the inner shelf (Swift, 1972).

## **Previous Work**

Three major sets of existing seismic data are available for this project. The first set is data used by Krantz and co-workers (1993, 1994); the second set collected by the Maryland Department of Natural Resources (MDNR) in August 1992 and August 1993

on the RV *Discovery* (Williams, 1999), and the third set collected by Daniel Belknap and Chris Kraft in 1974.

Krantz and co-workers (1993, 1994), including Murphy (1996), used three single-channel seismic reflection datasets in their analyses: Uniboom (250-1000 Hz) data collected in 1974 by Daniel Belknap and Chris Kraft (1986); Datasonics (3.5 kHz) data collected in 1990 (McGeary et al., 1991); and Geopulse Uniboom (300-4000 Hz) data collected in 1992 (Krantz et al., 1993, 1994). The survey area for this datasets lies mostly on the inner continental shelf ranging from north of Cape May, New Jersey, to the Maryland/Delaware state border.

These reflection profiles were analog records on thermal paper and were not digitally processed. The depth of penetration below the sea floor is typically ~20 m for the MDNR seismic data and ~70 m for the 1974 and 1992 Uniboom data (Murphy, 1996).

A similar seismic-stratigraphic studies have been conducted in Chesapeake Bay and on the inner shelf off the Virginia coast. Colman and Mixon (1988) collected high-resolution seismic reflection profiles with a boomer and a 3.5-5 kHz seismic reflection system over a grid of 2600 km in the main section of Chesapeake Bay. The profiles were coupled with onshore and offshore boreholes to develop a model for the geologic evolution of the lower Delmarva Peninsula including several generations of the

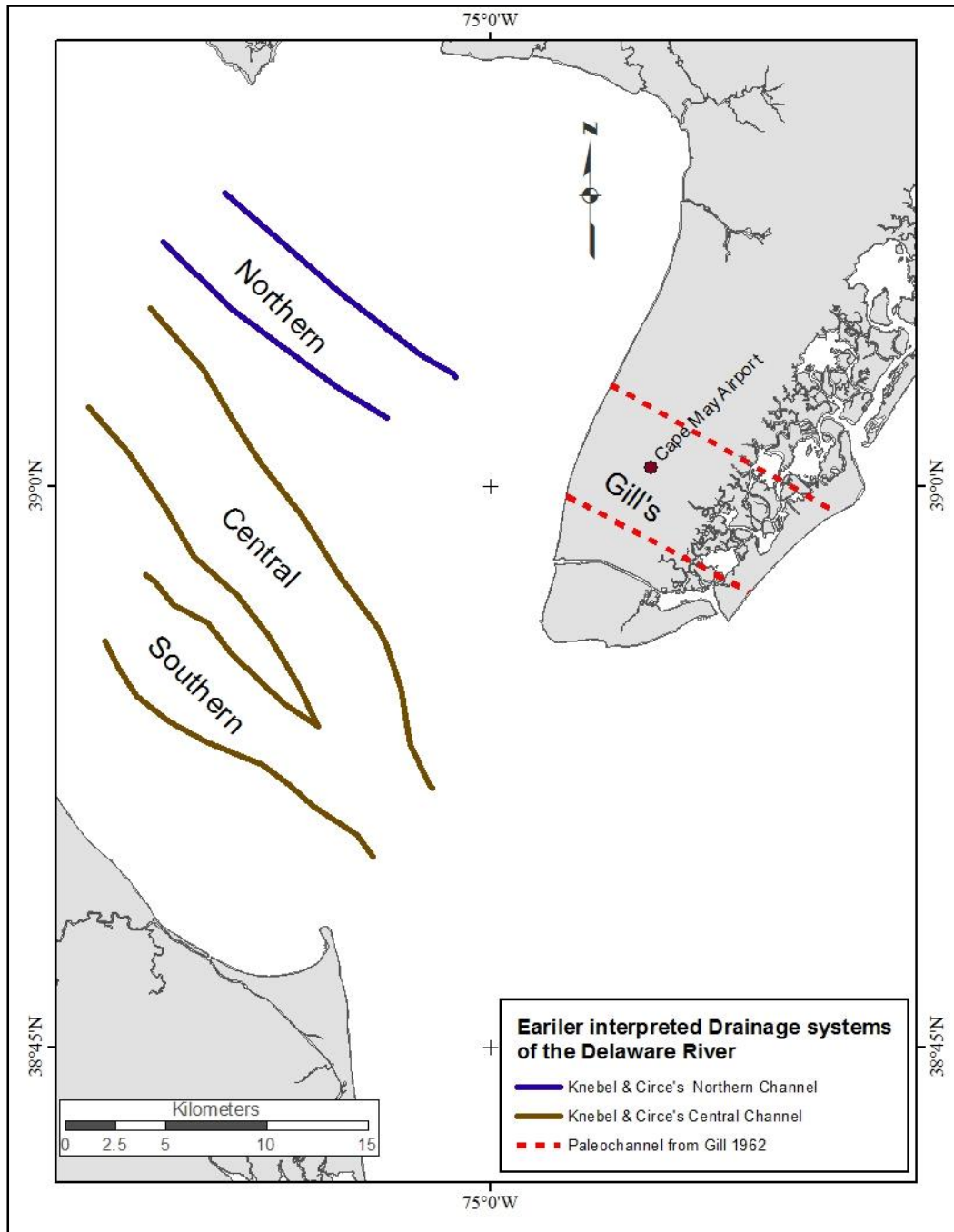


Figure 3.1 Three buried drainage systems for the Delaware River after Knebel and Circé (1988) and Gill (1962). The three channels of Knebel and Circé (1988) will be studied in the work, the Northern, Central, and the Southern.

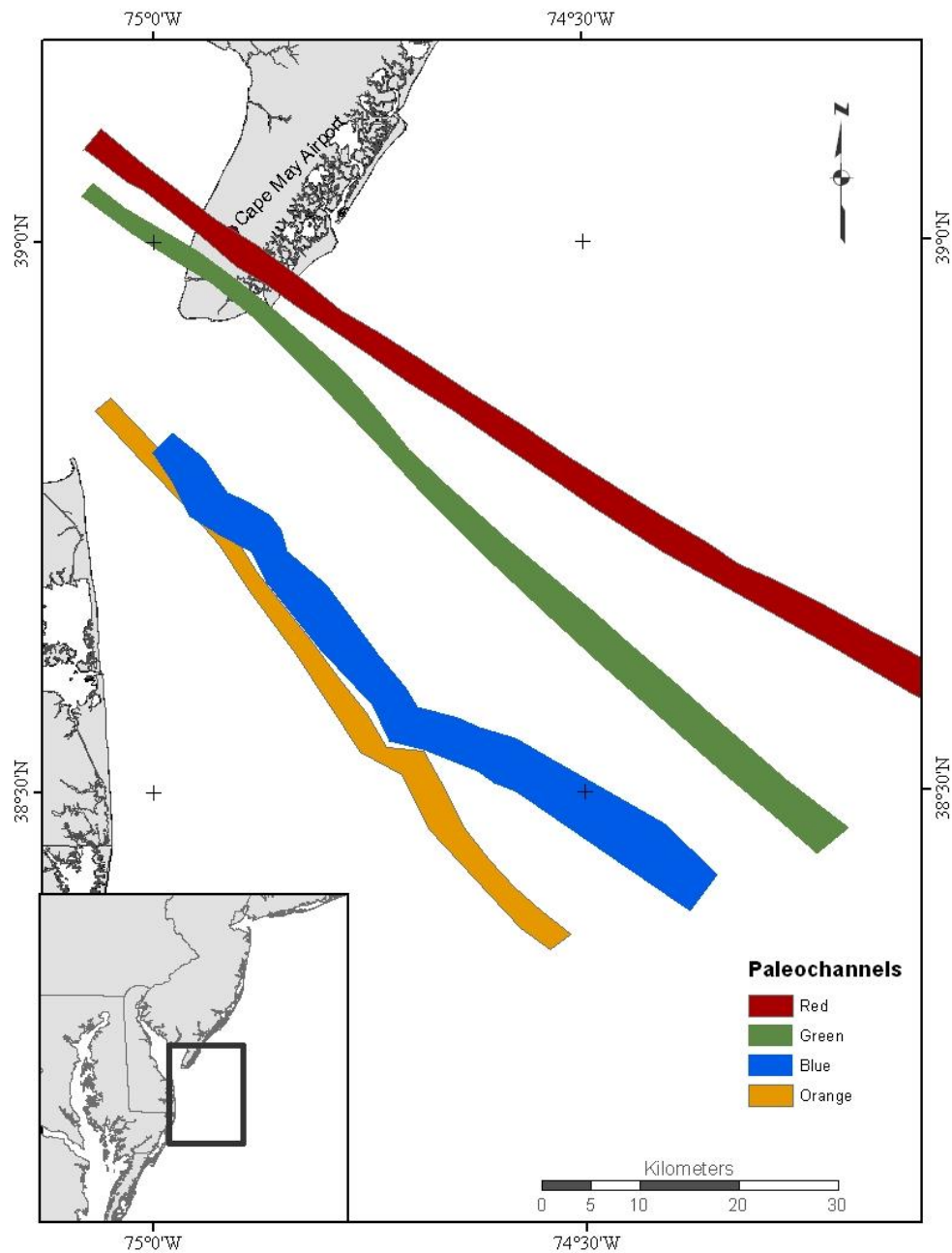


Figure 3.2 Early map of paleochannels to be modeled. The general positions of four major paleochannels of the Delaware River. The paleochannels have been termed the Red, Green, Blue, and Orange, by Krantz and co-workers (McGeary et al., 1991; Krantz et al., 1993; Murphy, 1996).

ancestral Susquehanna drainage system. Colman and Mixon (1988) identified a series of paleochannels, the Exmore, Eastville, and Cape Charles channels of middle to late Pleistocene age. They interpreted the age progression of these paleochannels to be associated with repeated episodes of channels filling with estuarine/lagoonal muds and subsequently being overlain by large-scale prograding spits.

Oertel and Foyle (1995) studied a similar system of paleochannels on the Atlantic side of the lower Delmarva Peninsula. They imaged four major paleochannels using 750 and 2000 Hz Geopulse boomer systems and covering approximately 1000 km of seismic tracks (Oertel and Foyle, 1995). Three of these could be traced back to the Colman and Mixon (1988) paleochannels. The fourth, the Belle Haven, was interpreted to be formed when the main Exmore paleochannel shifted south, cut across the interfluvium, and merged with the Eastville paleochannel as the Nassawadox spit developed along the early Delmarva Peninsula (Oertel and Foyle, 1995; Foyle and Oertel, 1997). Infill material of these paleochannels is characterized by several seismic facies indicating fluvial, transgressive estuarine, estuary entrance spit, and estuary entrance shoal environments (Oertel and Foyle, 1995; Foyle and Oertel, 1997).

Interpretations of an extensive vibracore data set (Chrastowski, 1986), additional boreholes (Ramsey, 1999; 2011; Ramsey and Tomlinson, 2012), and chirp sub-bottom profiles (Brown, 2006) within and near Delaware's Indian River and Rehoboth Bays and along the barrier coastline indicate the presence of two major pre-Holocene paleochannels cutting into Pleistocene to upper Miocene sediments (Chrastowski, 1986; Ramsey, 1999). These incised channels, one beneath Rehoboth

Bay and the other beneath Indian River Bay, trend, from source to mouth, predominantly west to east onto the inner shelf. These same paleochannels were also imaged in the Williams (1999) dataset.

In the middle to lower portions of Delaware Bay and on land in southern New Jersey, several workers used seismic, ground-penetrating radar, and core data to characterize several paleochannels of the Delaware River (e.g., Gill, 1962; Knebel and Circé, 1988; Newell et al., 1995; O'Neal, 1997). The paleochannel identified beneath the Cape May Peninsula was originally proposed by Gill (1962) to be of Marine oxygen Isotope Stage (MIS) 7 interglacial time with MIS 5e infill (glacial ages listed in Table 3.1). Newell et al. (1995) suggested that these paleochannels are cut into Miocene sediments with the infill consisting of the Beaverdam Formation deposited during the late Pliocene. Lacovara (1997) reported a maximum paleochannel depth of 55 m and Pliocene age for the infill, but in contrast to Newell et al., (1995) proposed that the sediments are of the Cape May and Fishing Creek Formations.

Knebel and Circé (1988), using a 300-3000 Hz Uniboom seismic system along 500 km of tracklines in southern Delaware Bay, identified three large paleochannels, which they named the Northern, Central, and Southern paleochannels. The Southern and Central paleochannels were interpreted as having been incised in the MIS 2, and the Northern paleochannel as MIS 6 (Knebel and Circé, 1988). In Knebel and Circé's interpretation, the Central and Southern paleochannels merge in the lower Bay and correlate with the ancestral Delaware River valley mapped by Sheridan et al. (1974) and Twichell et al. (1977). Knebel and Circé (1988) suggested that the Southern

paleochannel was a tributary system that drained the central Delaware upland and joined the Central paleochannel near the current bay mouth.

### **Bathymetry**

The modern Delaware Bay is a drowned river valley inundated as a result of the Holocene sea-level rise (Knebel et al., 1988; Fletcher et al., 1990). The bathymetry of lower Delaware Bay is characterized by three large tidally scoured channels and intervening shoals that trend northwest to southeast (Knebel et al., 1988). In the southeastern portion of the Bay, and extending from the Cape May Peninsula, is a shoal complex consisting of arcuate to linear ridges. These shoals are created and maintained by currents and wave action that rework surficial sediments (Weil, 1976; Knebel and Circé, 1988). Figure 3.3 shows the Delaware Bay bathymetry from the NOAA DEM (DE/NJ (M090) Bathymetric Digital Elevation Model).

The inner shelf offshore from the bay mouth consists of flood-dominant and ebb-dominant tidal channels. The channels exit the bay mouth and create several sets of shoals and shelf valleys. A major scour channel exists heading southeast along the trend of the Delaware River and Bay system. The inner shelf has generally low relief with a gentle seaward slope.

### **Methods**

For this study, seismic data were compiled from previous surveys, including that of Kraft and Belknap (1985), Knebel and Circé (1988), Knebel et al. (1988), McGeary



**Table 3.1** Timeline of glacial ages with Marine oxygen Isotope Stage (MIS) and approximate ages of the paleochannels in this study compared to the ages of Knebel and Circé (1988).

|                          | Years ago |                           | MIS | Formations       | Our ages     | Knebel and Circe        |
|--------------------------|-----------|---------------------------|-----|------------------|--------------|-------------------------|
| <b>Holocene</b>          |           |                           | 1   |                  |              |                         |
| <b>Late Pleistocene</b>  | 10000     | <b>Late Wisconsinan</b>   | 2   |                  |              |                         |
|                          | 15000     |                           |     |                  |              |                         |
|                          | 20000     | LGM                       |     |                  | Blue<br>???  | Central and<br>Southern |
|                          | 25000     |                           |     |                  |              |                         |
|                          | 30000     | <b>Middle Wisconsinan</b> | ??? | <b>Omar</b>      |              |                         |
|                          | 35000     |                           |     |                  |              |                         |
|                          | 40000     |                           |     |                  |              |                         |
|                          | 45000     | Interstadial              | 3   |                  |              |                         |
|                          | 50000     |                           |     |                  |              |                         |
|                          | 55000     |                           |     |                  |              |                         |
|                          | 60000     |                           |     |                  |              |                         |
|                          | 65000     |                           |     |                  |              |                         |
|                          | 70000     | stadial                   | 4   |                  | Orange<br>?? |                         |
|                          | 75000     |                           |     |                  |              |                         |
|                          | 80000     | interstadial              | 5a  |                  |              |                         |
|                          | 85000     | <b>Early Wisconsinan</b>  |     |                  |              |                         |
|                          | 90000     | stadial                   | 5b  |                  | Orange<br>?? |                         |
|                          | 93000     |                           |     |                  |              |                         |
|                          | 100000    | interstadial              | 5c  |                  |              |                         |
|                          | 105000    |                           |     |                  |              |                         |
|                          | 110000    | stadial                   | 5d  |                  | Orange<br>?? |                         |
|                          | 115000    |                           |     |                  |              |                         |
|                          | 120000    | interglacial              | 5e  |                  |              |                         |
|                          | 125000    | <b>Sangamon</b>           |     |                  |              | Gill's channel 1962     |
|                          | 130000    |                           |     |                  |              |                         |
| <b>Mid Pleistocene</b>   | 135000    |                           | 6   |                  | Green<br>??  | Northern                |
|                          | 140000    | <b>Illinoian Glacial</b>  |     |                  |              |                         |
|                          | 145000    | interglacial              | 7   |                  |              |                         |
|                          | 150000    |                           |     |                  |              |                         |
|                          | 750000    |                           |     |                  |              |                         |
| <b>Early Pleistocene</b> |           |                           |     |                  |              |                         |
|                          | 1800000   |                           |     |                  |              |                         |
| <b>Late Pliocene</b>     |           |                           |     | <b>Beaverdam</b> |              |                         |
|                          | 2500000   |                           |     |                  |              |                         |

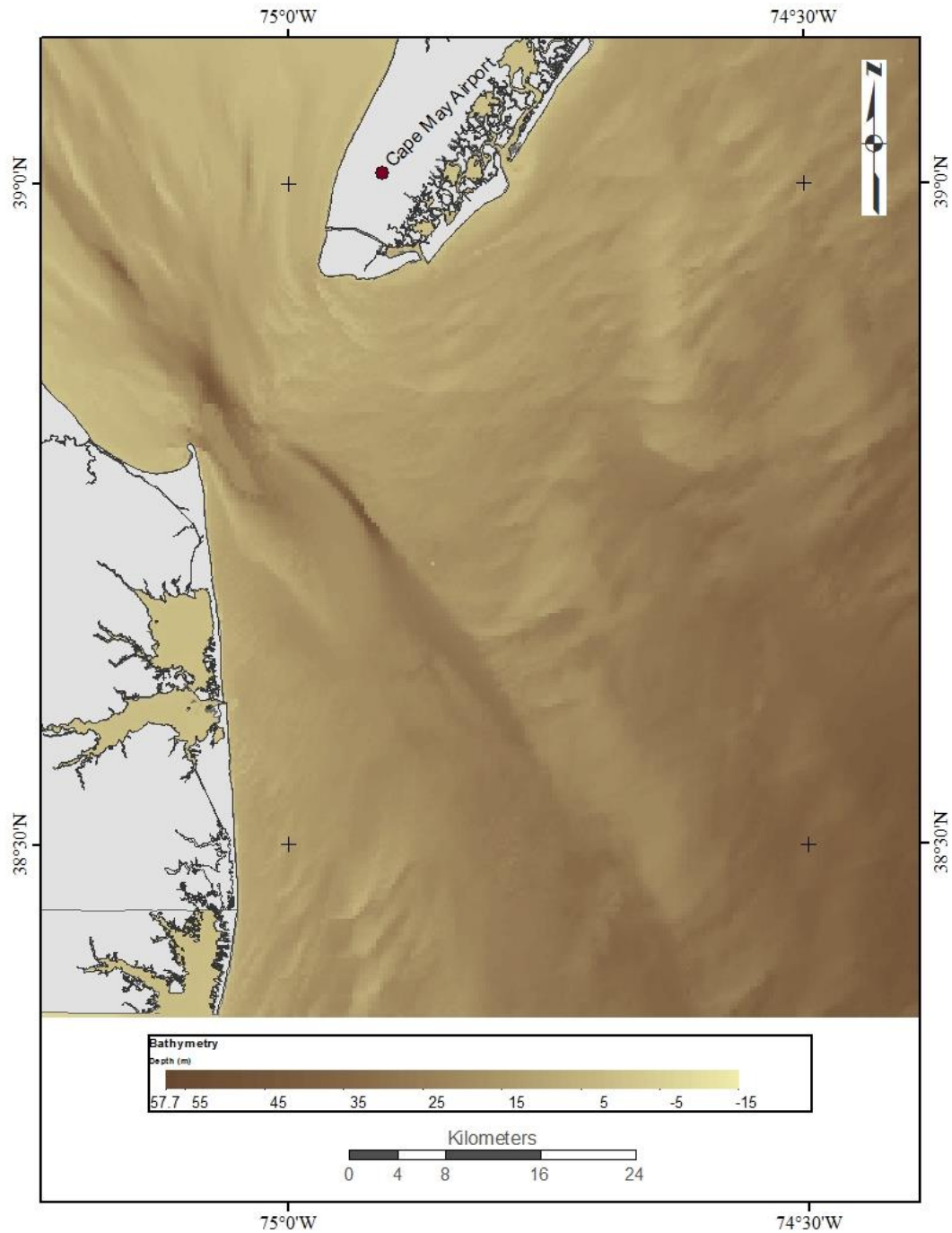


Figure 3.3 Bathymetry of inner continental shelf. Study area locations with major bathymetric features of lower Delaware Bay and the Delaware inner shelf.

et al. (1991), and Krantz et al. (1993, 1994). Seismic data obtained by Knebel et al. (1988) were imported into ArcGIS™ to be mapped, analyzed, and modeled in three dimensions. Depths to major reflections were measured in two-way travel time (TWTT) and converted to meters assuming a seismic velocity in sea water of 1500 meters per second (m/s). Geographic positions associated with reflections were converted to decimal degrees for input to ArcGIS™. Major reflecting surfaces were identified and correlated with reflections in adjacent seismic profiles to produce interpreted paleosurfaces.

### **Kriging Model**

For the analog seismic profiles from the inner shelf, two-way travel time (TWTT) to each major reflection was measured manually at one-minute intervals along the profile. For each measurement, ship position and TWTT were entered into an Excel™ spreadsheet. TWTT was converted into depth (m) using an assumed velocity of 1500 m/s in water saturated sediment. Positions and depths with a trackline identifier were imported into an Access™ database to be imported into ArcGIS™ to produce shape files.

ArcGIS™ was used to model the subsurface features and to produce the maps for this project. Kriging is a method for interpolating surfaces by using the depth features class to model a surface for each buried channel. Kriging interpolates the values of unknown points by comparing known points and the distance between them

(ESRI tutorial, Performing Spatial Interpolation Using ArcGIS™10, 2010). Several kriging interpolation methods were used to produce 3-D surface models of the base of each paleochannel system based on the works of Isaaks and Srivastava (1989), Wilson (2006), Erdroğan (2009), Kennedy (2009), and Chung and Rogers (2010).

- Simple kriging - good spatial coverage and no directional component in the data
- Ordinary kriging - good spatial coverage and no directional component in the data
- Universal kriging - directional and/or distance bias in the data, i.e. river channels

ArcCatalog™ was used to convert positions from the database into a feature class for ArcMap™. In ArcMap™, Geostatistical Analysis was used to build a kriging model to create a surface from the seismic depths. The setup wizard for ArcMap™ presents the user with the following options, including our setting:

Step one

Analysis type → Universal  
Transform → none  
Trend removal → Constant order

Step two

Variable → semivariogram  
Anisotropy → True  
Direction → 150 (the declination of the river course)

Final Step

Search neighborhood → smooth

The final screen shows the cross-validation results. The surface was statistically analyzed to test the validity of the model. This process was repeated for each reflection to create each paleochannel surface. Like any modeling process, kriging has limitations

and should not be the final product, but rather an integral part of the geologic interpretation process.

A statistical comparison of these three kriging methods found that for data in a long narrow path such as a river channel, Universal kriging produces a realistic model. For data that are distributed more uniformly over the study area, Simple and Ordinary kriging worked equally well, giving good statistical results. Modeling with anisotropy uses data in a specific direction to model a surface. An example of anisotropy is that elevation measurements along the longitudinal profile of a river channel are closer in value than points measured across the channel. Distance separating the seismic lines and a sudden course change in the channel would affect the way the model calculates the anisotropy, and the surface created may have a few anomalous connections that may lead to misinterpretation.

The resulting surface maps were exported to ArcScene™ for visual interpretation with 3-D perspective. In ArcGIS™, a kriging model does not create a true layer but a temporary dynamic layer used within ArcMap™ (Using ArcGIS™ 3D Analyst, ESRI, 2002). The kriging model must be exported from ArcMap™ as a raster to ArcScene™ or a similar program (ArcGIS™ 3D Analyst, ESRI, 2002.) Because the rasterization process recalculates the cell size and elevation values, these images should be used for visualization only.

The paleochannels beneath Delaware Bay based on the seismic data of Knebel and Circé (1988) are presented in Figure 3.4 as a map produced by kriging. Figure 3.5 shows a more detailed look at the Orange paleochannel. ArcScene™ 3-D views of the

paleochannels are presented in Figure 3.6. The surface model of the inner shelf (Figure 3.7) was produced by kriging the combined seismic data from Kraft and Belknap (1986), McGeary et al. (1991), and Krantz et al. (1993; 1994). These maps and 3-D views were the basis of the geologic interpretation in this study.

## **Discussion**

### **Delaware Bay**

The position and depths of major seismic reflections in the Knebel and Circé (1988) dataset were measured at two-minute intervals along the tracklines. The reflections show clearly the edges of the Northern, Central and Southern paleochannels of Knebel and Circé (1988), but the base of the paleochannels are more difficult to interpret. The seismic profiles across the Northern paleochannel show reflection events that may indicate a deeper base to the incised valley, which contains several infill sequences. These deeper reflections suggest that the true bottoms to these channels may be obscured and are deeper in the section, and that there may have been multiple occupations of the broader valley feature. Further research, including drilling to determine the depths and ages of the channels, is required to determine if they are part of the same drainage system or reoccupation by a succession of separate paleochannels. The downstream portion of the Northern paleochannel trends under the Cape May Peninsula near the Cape May Canal with the base of the thalweg at approximately 40-44 meters deep. In the same region, Gill (1962) interpreted coarse sediments from several wells as paleochannel fill.

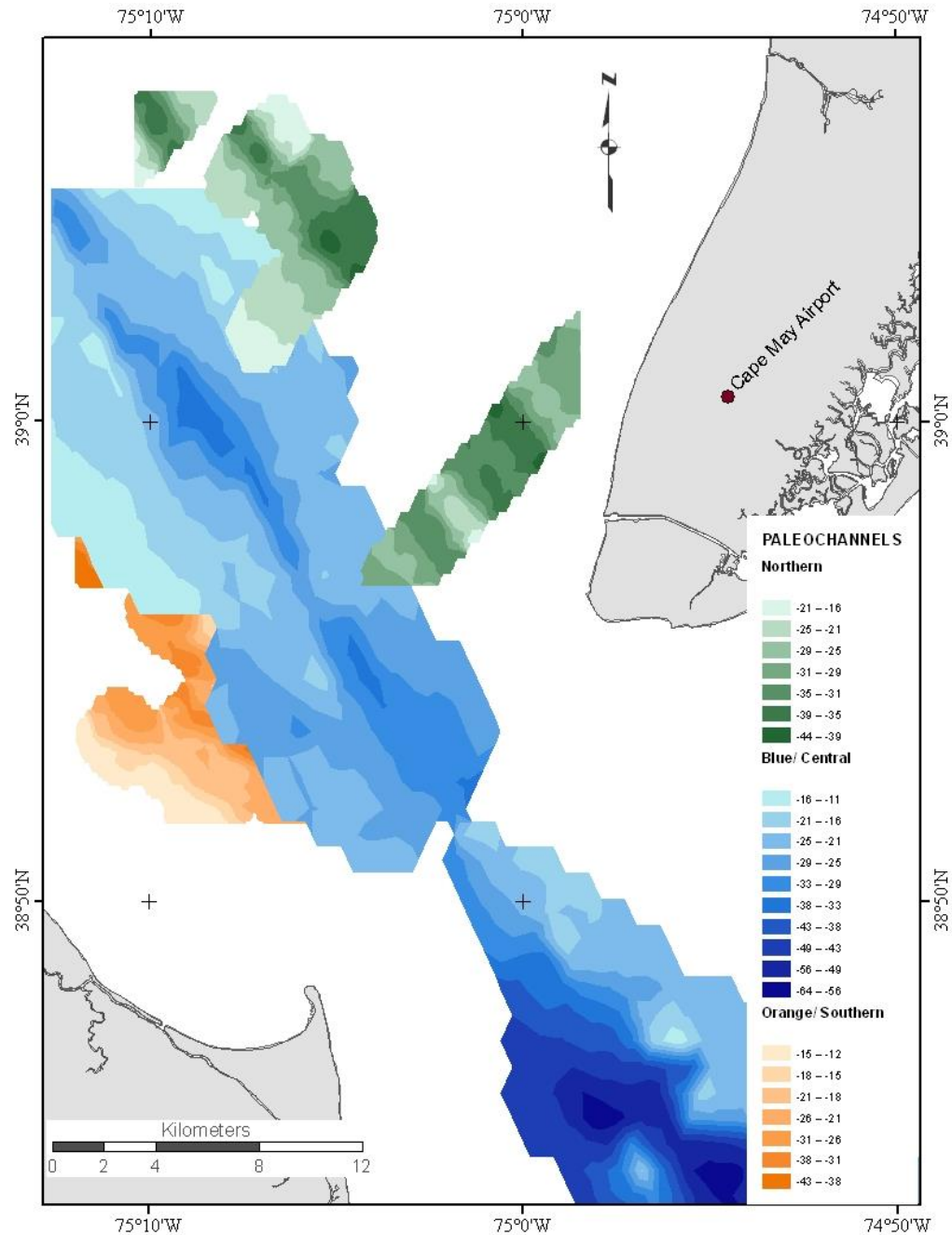


Figure 3.4 Paleochannels of the Delaware Bay. The primary channel of this study are the Blue (called the Central channel by Knebel and Circé (1988)) and the Orange or Southern by Knebel and Circé (1988). We show that the Blue paleochannel connects with the Blue on the inner shelf.

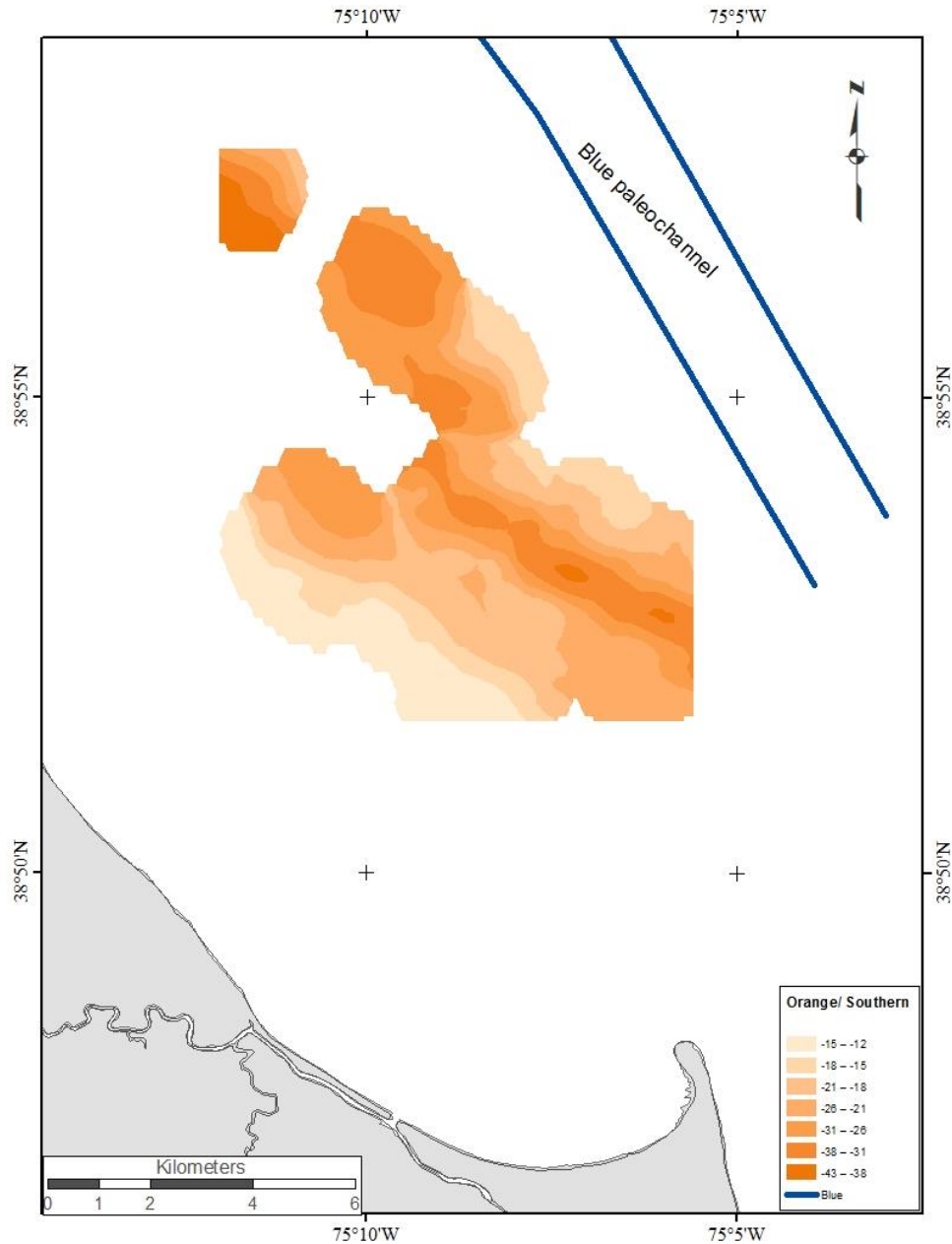


Figure 3.5 Orange paleochannel enlarged with the main channel of the Blue paleochannel indicated. The Orange paleochannel appears to possibly merge with the Blue paleochannel as they exit the bay. Could indicate this are concurrent as suggested by Knebel and Circé (1988) or as we argue two separate that overlap.



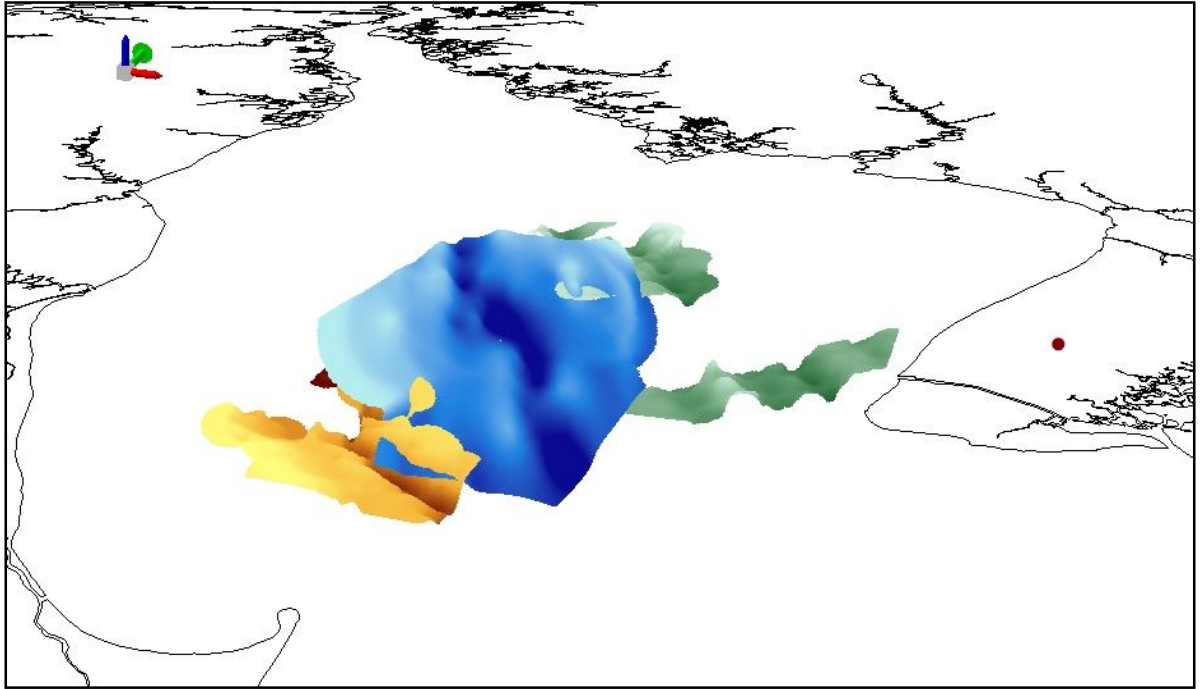


Figure 3.6 ArcScene™ 3D view of Delaware Bay paleochannels. Northern (green), Blue (blue) and Orange (orange) paleochannels, view from 30° angle looking up the bay. Darker colors indicate deeper sections.

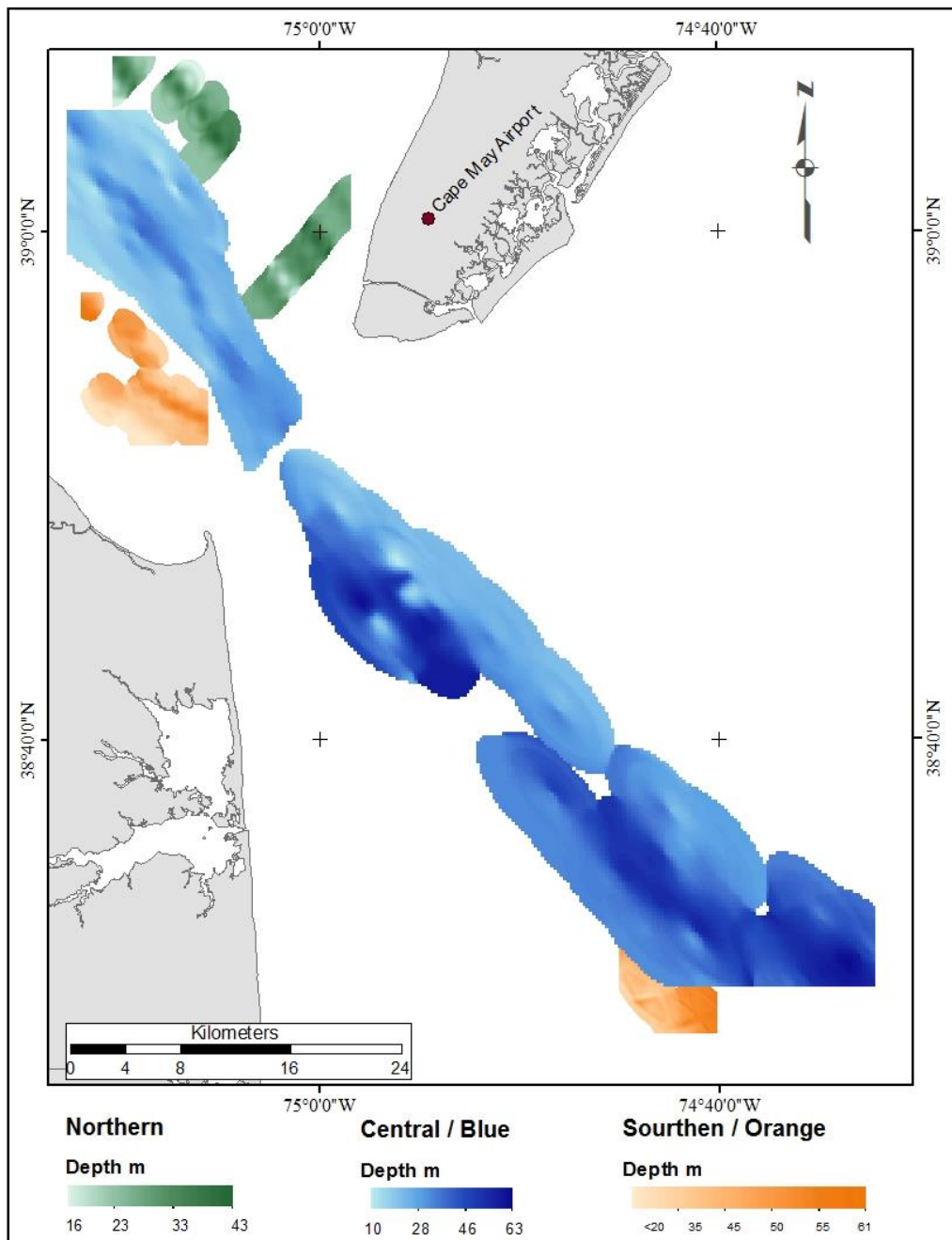


Figure 3.7 Map of modeled paleochannel surfaces. Northern (green), Blue (blue) and Orange (orange) paleochannels. Depths measure from sea level. Darker colors indicate deeper sections. Orange emerges from beneath the Blue in on the shelf

The southern bank of Gill's (1962) paleochannel lies north of the Cape May Canal, and we project the Northern paleochannel (shown in green) to just south of the canal (Figure 3.8 and 3.8b). A sharp northeast turn and a steep drop in elevation of at least 10 m would be required for the two paleochannels to be connected. The Fishing Creek Formation described by Lacovara (1997) is formed from infill of the paleochannel mapped by Gill (1962). Lacovara (1997) determined the depth to the base of the Fishing Creek Formation to be at 55 m below sea level in the Cape May County Airport core hole. The average gradient of the Northern paleochannel beneath Delaware Bay is 0.4 m/km. In the short distance from the bay shoreline to the Cape May County Airport, the gradient would need to be a substantially steeper 1.1 m/km. This implies that the paleochannel described by Gill (1962) is not an extension of the Northern paleochannel in the Delaware Bay, but rather a separate and distinct paleochannel.

The Northern paleochannel appears to be heading toward the Green paleochannel on the inner shelf identified by McGeary et al. (1991) and Krantz et al. (1993; 1994) (Figure 3.8). No evidence of other paleochannels deeper or to the north of the Northern paleochannel was found in the bay. McGeary et al. (1991) and Krantz et al. (1993; 1994) observed another paleochannel, the Red paleochannel, on the inner shelf north of the Green paleochannel. The Red paleochannel is the oldest of those identified on the inner shelf and may correlate with the paleochannel described by Gill (1962) and Lacovara (1997) that crosses beneath the north-central section of the Cape May Peninsula.

The Northern paleochannel is the older paleochannel beneath Delaware Bay identified by (Knebel and Circé, 1988); they interpreted that incision occurred during the MIS 7 lowstand at approximately 135 ka. With a subsequent cycle of transgression and regression, the Central paleochannel was formed as sea level fell, shifting the Delaware River system to the south with the progression of the ancestral Cape May Peninsula. According to Knebel and Circé (1988), the Central paleochannel merged with the Southern paleochannel near the mouth of Delaware Bay. The southward shifts of the ancient Delaware River appear to be concurrent with the development of Cape May Peninsula. A paleogeographic description of Cape May Peninsula around 120 ka in the interglacial period (MIS 5e) shows sea level rising and the development of barrier islands, forming what is now Cape May (Lacovara, 1997). As sea level rose, the Northern paleochannel would have been infilled and buried as Cape May prograded to the south. During the next glacial period as sea level fell, the Delaware River would have flowed more easily south of the developing Cape May.

### **Central Channel**

The Central paleochannel of Knebel and Circé (1988) extends out of Delaware Bay and can be correlated with the Blue Paleochannel of Krantz et al. (1993; 1994) on the inner shelf. Krantz et al. (1993; 1994) and Murphy (1996) suggested that the Blue paleochannel continues to Baltimore Canyon. If the Blue paleochannel of Krantz et al. (1993; 1994) is the same as the Central paleochannel of Knebel and Circé (1988), then

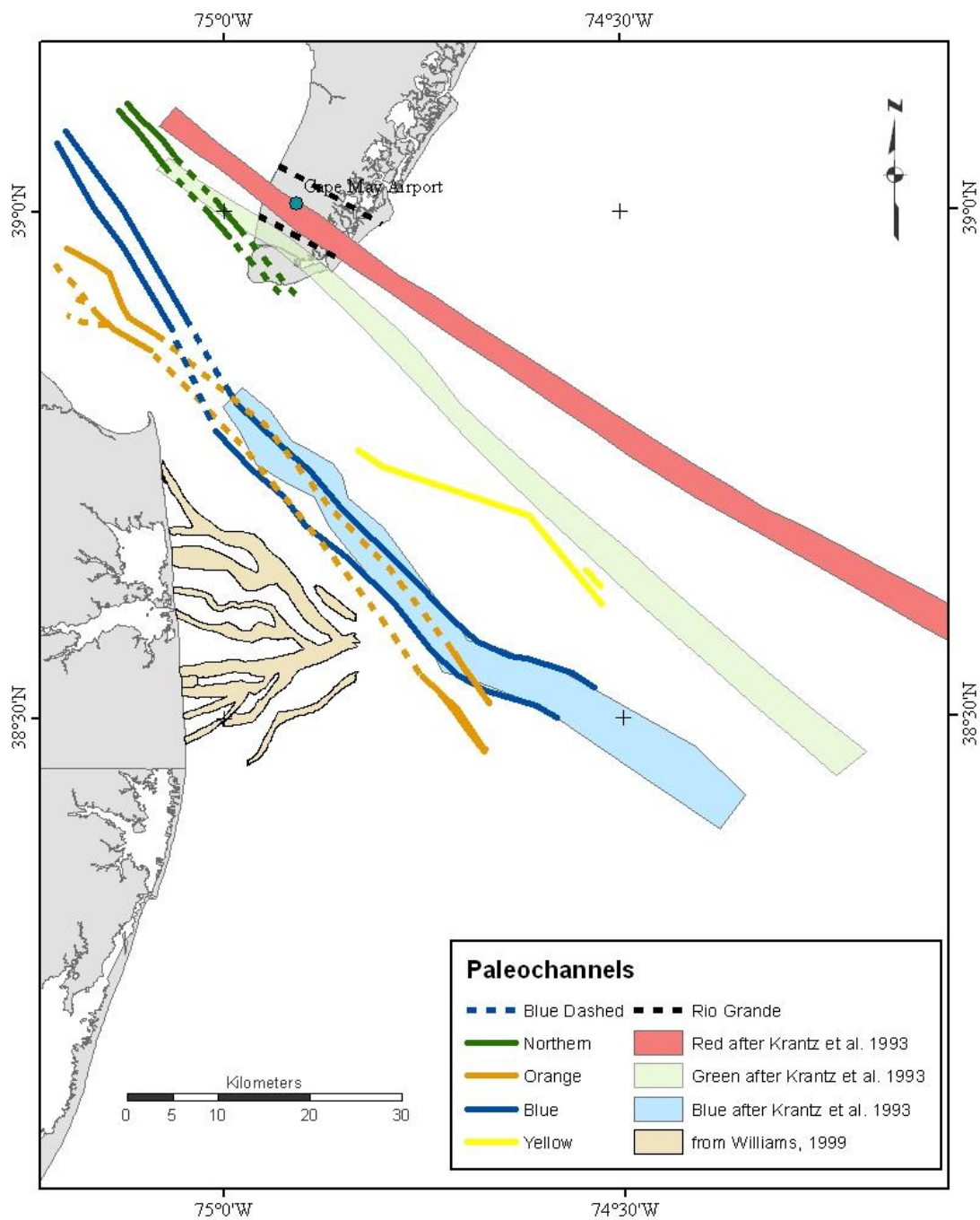


Figure 3.8a Paleochannels of the Delaware River. The Blue/Central follows the path of the Orange/Southern out of the bay. A narrow paleochannel (The Yellow) was observed in the seismic data. The paleochannels from the coast of Delaware flow toward the Blue and Orange.

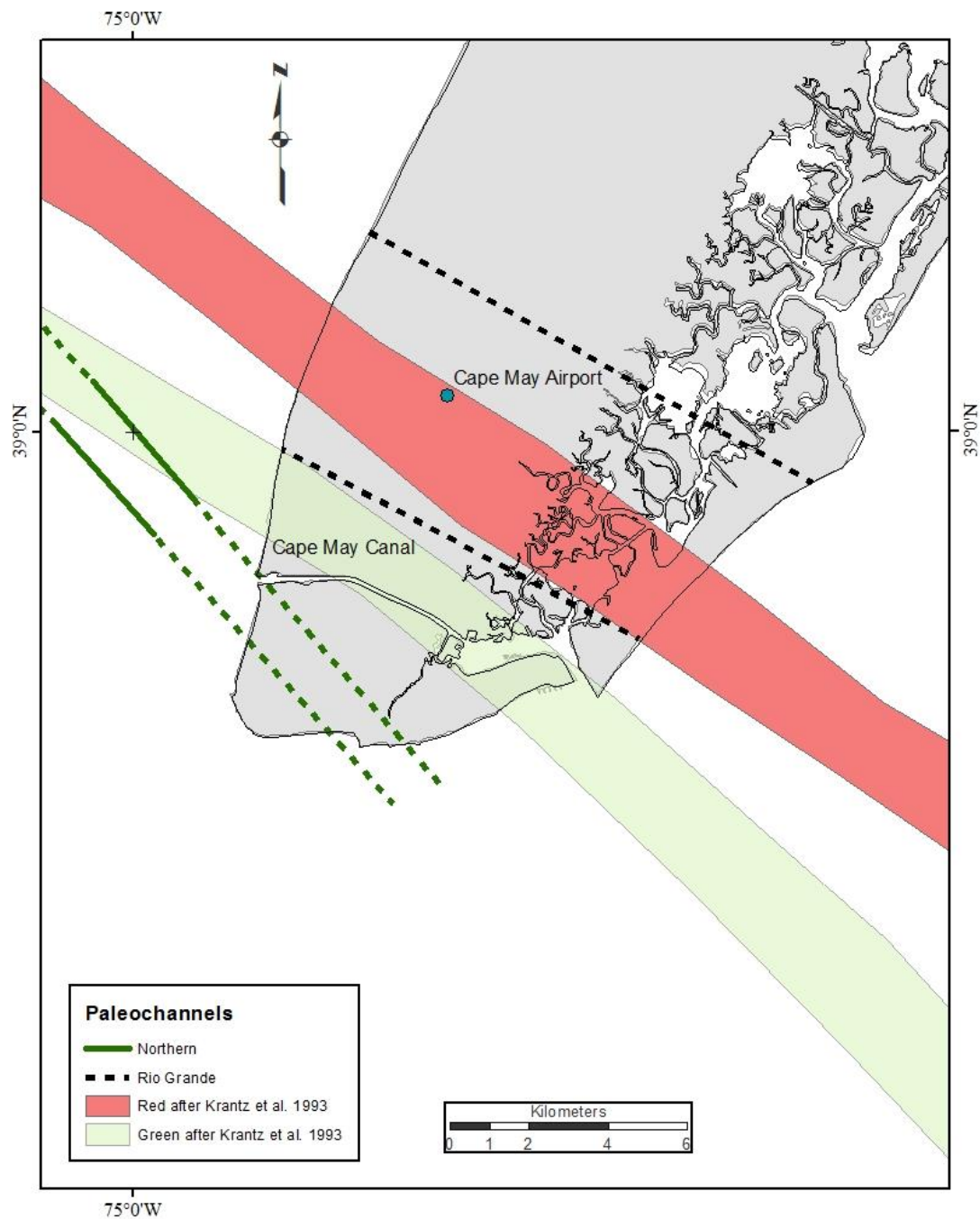


Figure 3.8b Inset of Cape May area. Our interpretation of the Northern paleochannel crossing Cape May south of the Cape May Canal connecting with the Green paleochannel differs from Krantz et al. (1993).

the Central is the youngest of the Delaware River paleochannels. In general, the base of the Blue paleochannel lies below modern tidally scoured channels. Knebel and Circé (1988) suggested that the Central paleochannel and the Southern channel were contemporary, with the Southern paleochannel being a tributary of the Central (Figure 3.4). In their interpretation, Knebel and Circé (1988) indicated that the Central paleochannel turned sharply to the south near the bay mouth and merged with the Southern paleochannel. Sediment movement around Cape May with littoral drift and strong tidal currents scoured and reworked the seafloor of the bay-mouth area.

Most of the available seismic data end just before the bay mouth, and what data there are in this area do not penetrate deeply enough to show the bases of the paleochannels, due to the hard surficial sediments produced by the compaction and scour of wave and tide action. The existing data do not preclude the Southern paleochannel being older than and separate from the Central as it continues onto the shelf. This would have possibly formed during the Illinoian glaciation (MIS 6) that ended about 135 ka.

In the southwestern portion of the Delaware Bay study area of Knebel and Circé (1988), two of the seismic lines show a shallow paleochannel that merges with the Southern paleochannel and is in line with the Mispillion River. We have also observed that a number of larger modern axial tidal scour channels in the middle of Delaware Bay tend to align with the paleochannels. The underlying geological fill material of the paleochannel may allow for scouring to take place.

The formation and evolution of the southward shift of younger paleochannels and the development of the Cape May Peninsula is comparable to the evolution of the lower Chesapeake Bay. The Chesapeake Bay formed from fluvial erosion by the Susquehanna River and major tributaries during low sea levels. With the rise in sea level, the fluvial system flooded, creating an estuarine/bay feature (Colman and Mixon, 1988). Colman and Mixon (1988) inferred that Chesapeake Bay developed through at least three generations of barrier-spit and channel fill indicating three highstands and three lowstands. Chesapeake Bay consist of a series of paleochannels of Pleistocene age, progressively younger to the south with the development of the lower Delmarva Peninsula (Colman and Mixon, 1988; Oertel and Foyle, 1995; Foyle and Oertel, 1997; Hobbs, 2004) as a succession of barrier spits prograding southward (Colman and Mixon, 1988). A similar southward progression of the paleochannels at the mouth of Delaware Bay is believed to be in response to the development of the Cape May Peninsula, as noted by Lacovara (1997).

### **Inner Shelf – Orange Paleochannel**

Sea level fell during the late Wisconsinan glaciation (MIS 2), exposing the previous seafloor as a coastal plain and allowing the carving of new channels as the rivers flowed farther out to the lowstand ocean shoreline. The river tends to follow along the path of earlier systems. As the Holocene transgression began, the flooding process filled the Blue channel. Approximately 40 km southeast of the bay mouth, the Orange paleochannel appears in seismic profiles as distinctly separate from the Blue



paleochannel. The surface associated with the Orange paleochannel shows similar characteristics to that of the Blue paleochannel (Figure 3.7). The main Orange channel lies just south of and parallel with the Blue, with a distinct interfluvium between the two. The Blue cuts the northeastern margin of the Orange, then midway onto the inner shelf the Orange continues heading southeast as the Blue turns more eastward. This study infers that the courses of both the Orange and Blue paleochannels continue to Baltimore Canyon. The Orange paleochannel is deeper and is cut into by the Blue, making the stratigraphic position of the Orange lower and therefore older.

It is possible that the Blue may represent a reoccupation of the Orange channel, but no clear evidence of this was observed. Sections of what appear to be the boundary of the Orange paleovalley are visible in the seismic profiles. This suggests that during the subsequent transgression the broader incised valley of the Orange system would have been flooded and spread laterally to create a wider estuary similar to the present bay geomorphology described by Kraft and Belknap (1986) and Murphy (1996). This is equivalent to the modern Delaware River and Bay system, where rising seas flooded the river channel and filled in with sediments. Williams (1999) mapped a section of what he suggested is the Orange paleochannel; this study suggests that this is a section of the south bank of the Orange paleovalley as it was being flooded or a tributary of the Orange and not the main paleochannel. It is not as deep as the main paleochannel and too far west.

### **Inner Shelf – Blue Paleochannel**

The course of the Blue paleochannel as it crosses the inner shelf is depicted by the ArcGIS™ model derived from the seismic data (Figure 3.7). Several of the seismic profiles show subtle meandering of the fluvial channel and lateral transport of infilling sediments into the channel once it was submerged. Profiles also show a wider estuary that developed as the transgression proceeded. The overall shape of the valley is broadly U-shaped with a relatively flat bottom. Midway out on the inner shelf the valley appears more V-shaped in profiles 92-7 and 92-4, with a return to the U-shape farther offshore. Trending southeast from the upper Delaware Bay in a fairly straight line, the Blue paleochannel follows a course of approximately 141 degrees with a turn to the east about 50 km from the bay mouth. The turn coincides with the more V-shaped cross section. From there, the Blue paleochannel trends toward Baltimore Canyon. This is consistent with the conclusions of Krantz et al. (1993, 1994) and Murphy (1996), but differs from earlier studies that suggest the paleochannel flowed to Wilmington Canyon farther north (Twichell et al., 1977). The inconsistency may be due to data limitations of the Twichell et al. (1977) study. With subsequent seismic surveys identifying several paleochannels, rather than a single channel, it is conceivable that the earlier interpretation with the limited data led to connecting segments of several independent paleochannels as one. This single paleochannel would have appeared to head northeast toward Wilmington Canyon.

Results for our study show that the Central paleochannel of Knebel and Circé (1988) continues as the Blue paleochannel onto the continental shelf (Figure 3.7). The

Central/Blue system is the most recently formed paleochannel, most likely incised during the last glacial maximum (MIS 2) and infilled during the Holocene sea-level rise. A lack of core data precludes obtaining a more precise age for any of these paleochannels.

On several profiles, the Blue channel clearly cuts the Orange channel, indicating that the Orange was filled in prior to the incision of the Blue. During the Holocene, flooding of the lowlands of the Blue valley and coastal erosion occurred, moving the shoreline farther inland. As this process continued, sediment accumulation in the deeper sections slowly filled the Blue channel. Currently tidal scour within the bay occurs above the antecedent channels, possibly due to position and ease of cutting the infill. This may direct the course of the next river channel during future sea-level falls.

There are two possible explanations for the development of the Blue and Orange paths. Our first hypothesis is that the Blue paleochannel reoccupied the older Orange paleochannel from the mouth of the Delaware Bay out on the inner shelf to the point of the eastward turn where the Orange appears as a separate deeper channel (Figure 3.7). An alternate hypothesis is that Knebel and Circé's (1988) Southern Channel is not concurrent with the Central/Blue but is actually older and is the farther landward section of the Orange paleochannel. The Southern paleochannel, if concurrent with the Central, would have formed during the last glacial maximum. If on the other hand it is not concurrent with the Central, it would likely be older. Having no direct ages for the Orange paleochannel on the shelf, it may be as young as MIS 4 or 3, 70-30 ka to as old

as (MIS 5d, 115 ka). During the subsequent sea-level cycle, the Blue channel eroded and obscured much of the Orange. Core samples of the infill are needed to better constrain the age of and the relation between these two channels.

### **Rehoboth and Indian River Bays**

Williams (1999) examined the shallow stratigraphy of the innermost shelf just off the Delaware coast from Cape Henlopen to the Delaware/Maryland border. He found a network of paleochannels originating from west of the Delaware coast that merged into one major channel. This channel heads east-northeast and appears to flow into the Orange and/or Blue channels. The spacing of the seismic tracklines missed the actual confluence of the channels. Several of the profiles from the Williams (1999) dataset show shallower channels that match the position and depths and can be inferred to be the main incised valley of the Indian River. The profiles indicate that the main channel was reoccupied (Williams, 1999). These paleochannels are shown in Figure 3.8 along with all the interpreted paleochannels. In the seismic profiles, segments of small paleochannels within the Orange paleovalley can be observed. These segments appear to be from the Lewes River paleo-drainage system mapped by Williams (1999). Several small, younger paleochannels are present in the Orange paleovalley, indicating the high number of streams and rivers flowing from the shore of ancient Delaware as the Indian River and Bethany Beach paleo-drainage systems. Several channels flow east, turn northeast and converge with the other channels from the Delaware coast, then head toward the Orange and Blue paleochannels of the Delaware River. Williams (1999)

observed several reoccupations of some of these channels. The older channels observed onshore incise the Pliocene Beaverdam Formation as interpreted by Ramsey (1999, 2011; Ramsey and Tomlinson 2012). The infilling material is from the Omar Formation of middle to late Pleistocene age (Ramsey, 1999; Groot et al., 1990).

### **Another Channel – Yellow Channel**

Parallel to and north of the Blue paleochannel is a shallower paleochannel designated the Yellow paleochannel (Figure 3.8). Several seismic profiles show the southwest bank of this channel with two lines showing the northeast bank. The width ranges from 0.7-1 km in the seismic profiles showing the north bank. Depth to the base ranges 17-21 m; the Blue paleochannel is 9 to 12 m deeper in the same region. The direction is trending to the southeast, generally paralleling the Blue toward Baltimore Canyon. Several seismic profiles show a deeper reflection at the bottom of the Yellow, and in one profile a third deeper bottom reflection. This indicates that several reoccupations or infilling events have occurred in the Yellow paleochannel. No evidence of the channel in the bay can be found, nor is there evidence as to where it begins. This is consistent with an interpretation as a bay-mouth tidal channel associated with a former position of the Cape May ocean shoreline and shoal system. Little more can be derived from the existing data on this paleochannel.

## **Conclusions**

Delaware Bay and the adjacent inner shelf are underlain by numerous lowstand paleochannels of the Delaware River. Using seismic data and ArcGIS™, these paleochannels were modeled to locate their paths, depths and areal extent, and to better determine their relative ages. Within ArcGIS™, the kriging interpolation method was used to produce surface maps from the depths of the paleochannels bases as measured from the seismic profiles. The 3D images, produced with ArcScene™, along with the maps aided the geologic interpretation.

Using existing analog seismic profiles from several studies covering the inner shelf off the coast of Delaware and within Delaware Bay, depth measurements made manually were put into a database. The database was used in ArcGIS™ to model the antecedent Delaware River system over several sea-level cycles.

Three major paleochannels that underlie Delaware Bay were modeled: the Northern, Central and Southern valleys of Knebel and Circé (1988). The oldest is the Northern Channel, which was traced to the southern Cape May Peninsula just south of the Cape May Canal. This channel was not traced beyond the mouth of the bay, although the direction indicates that it may connect to the Green Channel that lies north of this study area on the shelf.

The Central Channel is the youngest and continues on the shelf as the Blue Channel, heading southeast 50 km, where it turns to the east and extends toward Baltimore Canyon. As sea level rose at the end of the Last Glacial Maximum, the river

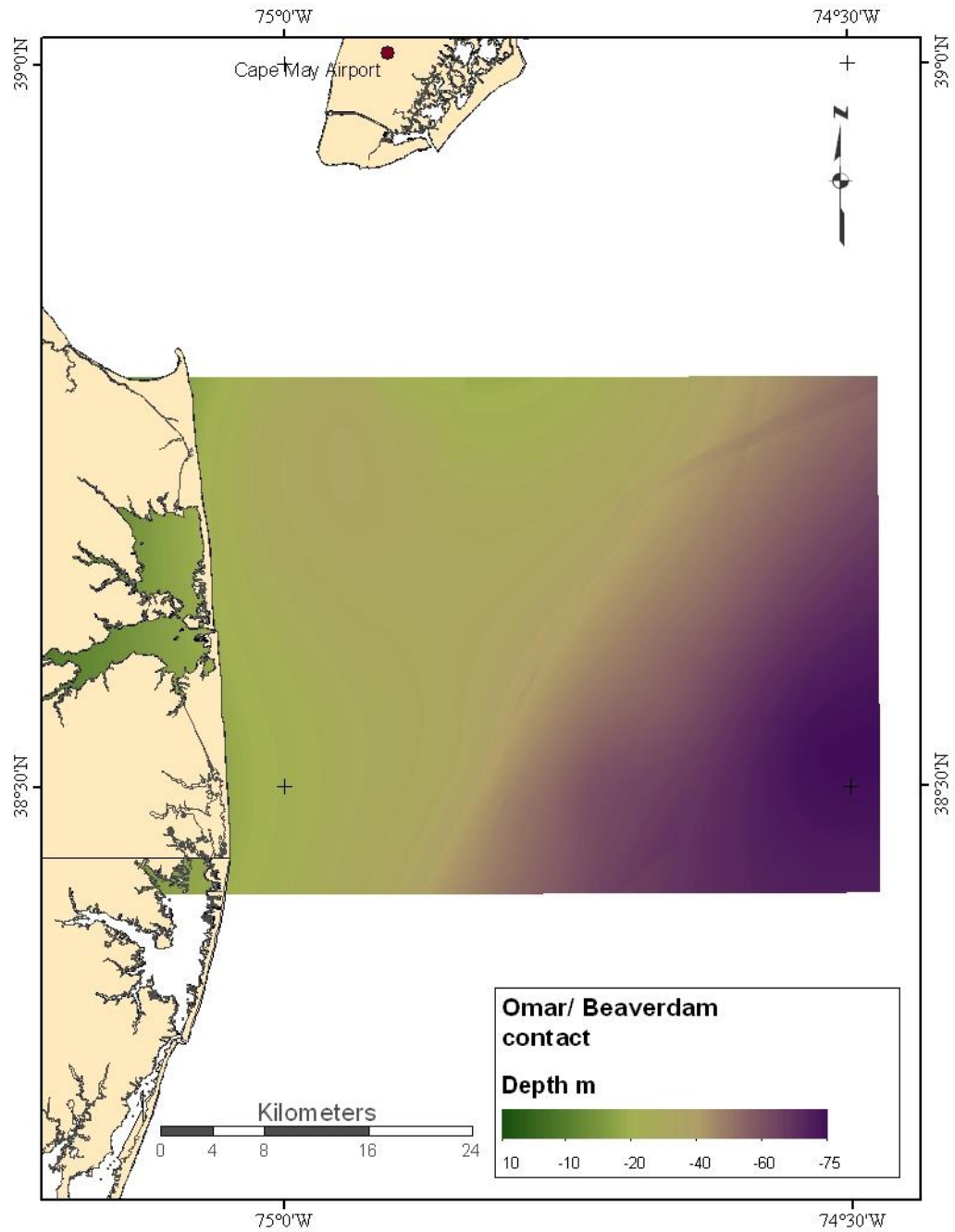


Figure 3.9 The buried Omar/Beaverdam contact depth based on seismic interpretation. Note a slightly deeper section (35-40 m) just southeast of the bay Mouth, this follow the path of the paleochannel of the Delaware River.

valley flooded progressively to create the estuary that is the present Delaware Bay. An earlier regression-transgression cycle, likely the MIS 6 low sea stand to the MIS 5 high sea stand, formed and filled the Orange paleochannel. The remnant emerges from the south side of the Blue paleochannel 41 km southeast of the bay mouth and also heads toward Baltimore Canyon. No unequivocal evidence was found to show an Orange paleochannel farther inshore. The Orange may extend into Delaware Bay as the Southern paleochannel, and as the Blue was being carved in the same path it possibly obscured any evidence of the Orange channel.

Just to the north of the Blue paleochannel on the inner shelf is a narrow shallow paleochannel referred to as the Yellow paleochannel. Only a short segment of the Yellow is observed parallel to the Blue. The Yellow did not intersect with any other paleochannel to allow any determination of the relative age. A more extensive study is needed to define the dimensions, path and age of the Yellow paleochannel.



## Chapter 4

### **UPPER PLIOCENE-LOWER PLEISTOCENE UNCONFORMITY UNDERLYING THE DELAWARE INNER CONTINENTAL SHELF**

#### **Introduction**

During the analysis of the seismic profiles along the inner continental shelf, a deeper reflection was observed in many of the profiles. Depths below sea level to this reflection range from approximately 40 m to 60 m, with a gentle slope (deepening) offshore. In the geologic interpretation of this reflection, two questions arose: Would it be possible to use ArcGIS™ Geostatistical Analysis to model this reflection as a surface that extends inland to determine possible correlations with onshore subsurface lithologic data? If projected onshore, could this reflection be associated with a known formation boundary?

Using ArcGIS™ with good coverage of seismic data, one can model a surface quite readily. The available seismic profiles along the inner continental shelf extend over an area of approximately 960 km<sup>2</sup>. Using data from a small number of wells, spaced over a moderate-sized area (~500 km<sup>2</sup>), a surface representing a boundary between two lithologic layers can also be modeled showing its general trend based on its common occurrence in the wells. Can these two surfaces, one represented by a seismic reflection and the other by a contact between two differing lithologies, spaced at

~40 km apart, be modeled as one? This would create a study area of approximately 3000 km<sup>2</sup>. If the model allows a correlation between the two separated surfaces, then a determination can be made as to which lithologic contact is represented by the offshore seismic reflection data. Given this, a more detailed surface could be modeled. This process was carried out along the current coastline and inner continental shelf off Rehoboth Beach, Delaware, using data from an additional four cores and two seismic lines offshore to model the more detailed surface (Figure 4.1).

High-amplitude seismic reflections with depths ranging from approximately 40 m to 60 m was observed in a number of the inner shelf seismic profiles (Figure 4.2). The reflection is relatively horizontal, with a gentle dip oceanward, indicating little relief. Using Kriging interpolation in ArcGIS™ Geostatistical Analysis, a surface was created using the location and depth of the reflection as determined from the seismic data (assuming a seismic velocity in saturated sediments of 1500 m/s). The surface generated in the analysis indicates that the reflection slopes (deepens) gradually toward the east and southeast (Figure 4.3). The modeled surface is shown in general to be smooth with little change in depth, in agreement with the seismic profiles (Figure 4.2).

Geological maps of Sussex County, Delaware (Ramsey, 1992, 2010), show several formation boundaries that could correlate with this deeper offshore reflection. The most likely onshore boundaries that would correlate, based on depths, are the contact of the Beaverdam Formation with the Omar Formation or other overlying formations or the contact between the Beaverdam and the underlying Bethany Formation (Figure 4.4). Several formations overlie the Beaverdam in Delaware,

including the Omar, Sinepuxent, Ironshire Formations and others (Ramsey, 2010). By modeling a surface using the depths to the upper contact of the Beaverdam with one of these formations, and repeating the process for the Beaverdam and underlying Bethany contact, it can be determined if a correlation exists between the upper or lower boundary of the Beaverdam Formation and the reflection in the profiles.

The Beaverdam Formation is described as Pliocene in age although fossil evidence for dating is lacking (Ramsey, 1992, 2010; Groot et al., 1990). The lithology of the Beaverdam consists of white to buff to greenish-gray quartz sand and some potassium feldspar along with some gravelly sand and silty clay (McLaughlin et al., 2008; Groot et al., 1990). The depositional environment is interpreted to be fluvial and estuarine (McLaughlin et al., 2008; Groot et al., 1990). The base of the formation is characterized as fine to medium sand, moderately well-sorted with pebbles and granules. A more detailed description of the Beaverdam Formation can be found in Ramsey (2010). The Bethany Formation of the upper Miocene consists of clayey and silty beds containing discontinuous sand lenses (in McLaughlin et al., 2008 after Anders, 1986, 2004; Ramsey, 2003). The Omar Formation overlies the Beaverdam Formation at an unconformity (Groot, 1990). The Omar Formation is characterized as a heterogeneous unit of fine to coarse sand, silty sand, clayey silt, and silty clay. The sand colors range from white to tan to bluish-gray, with the portions below the water table more brown to bluish-gray (Groot, 1990).

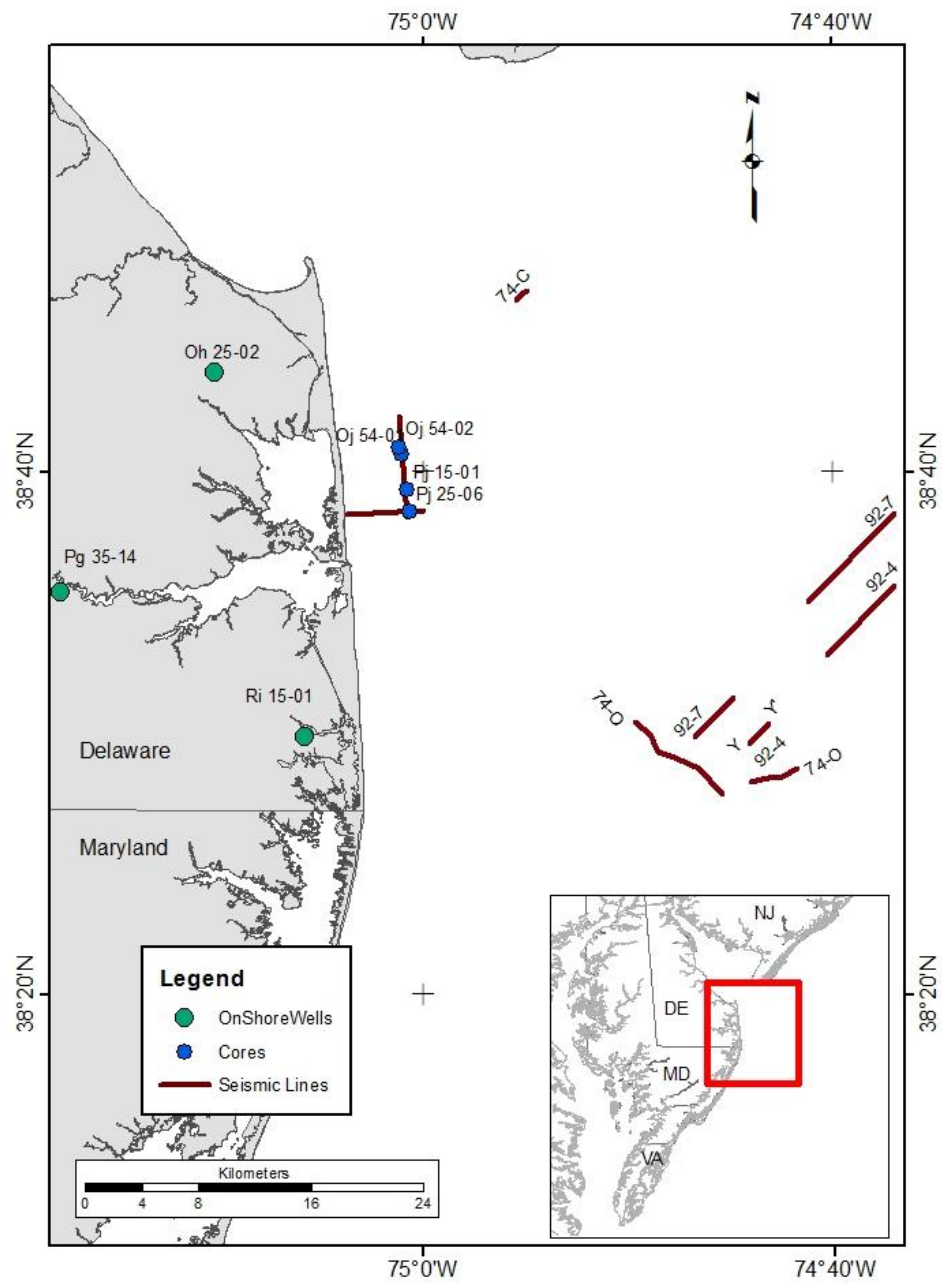
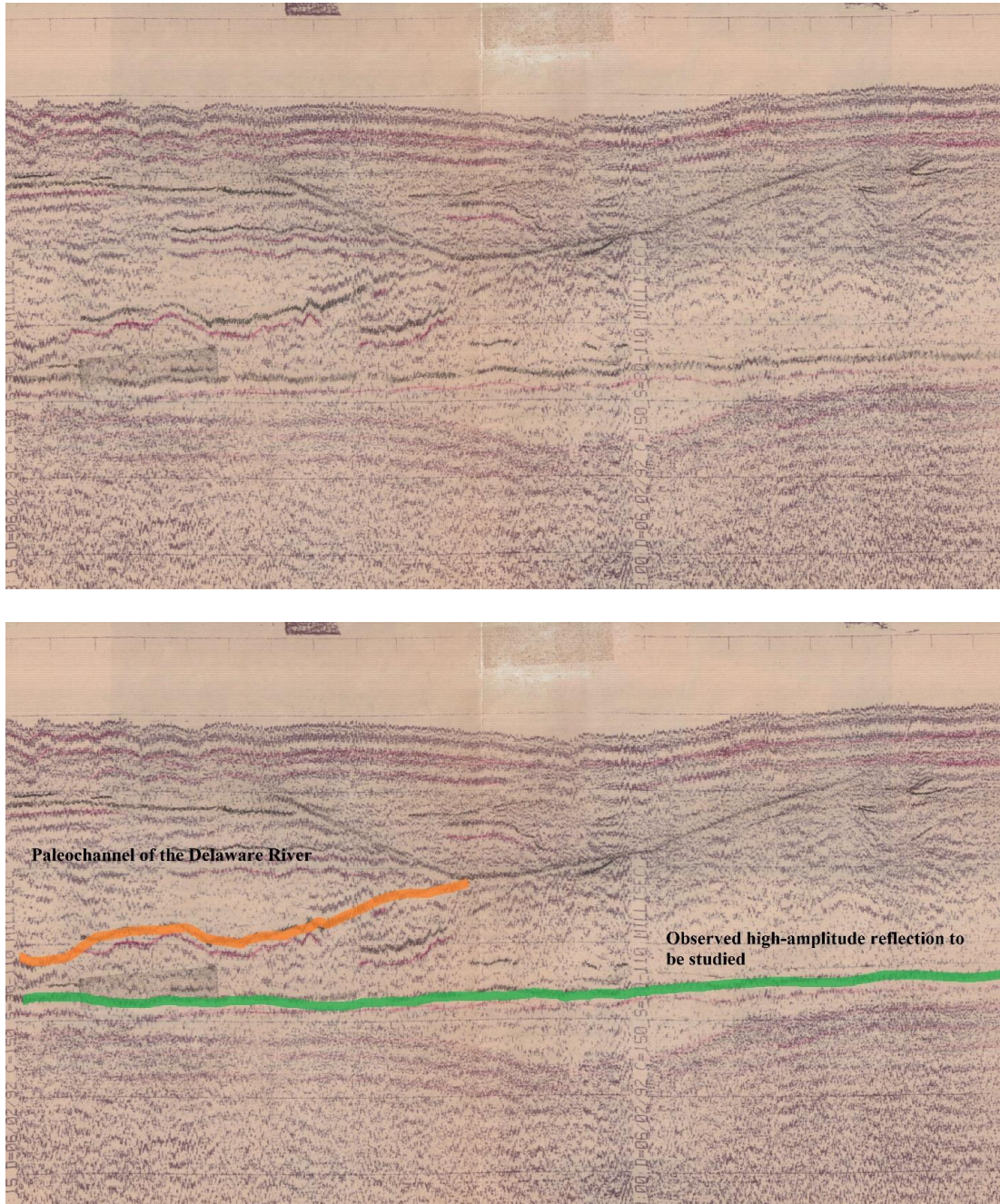
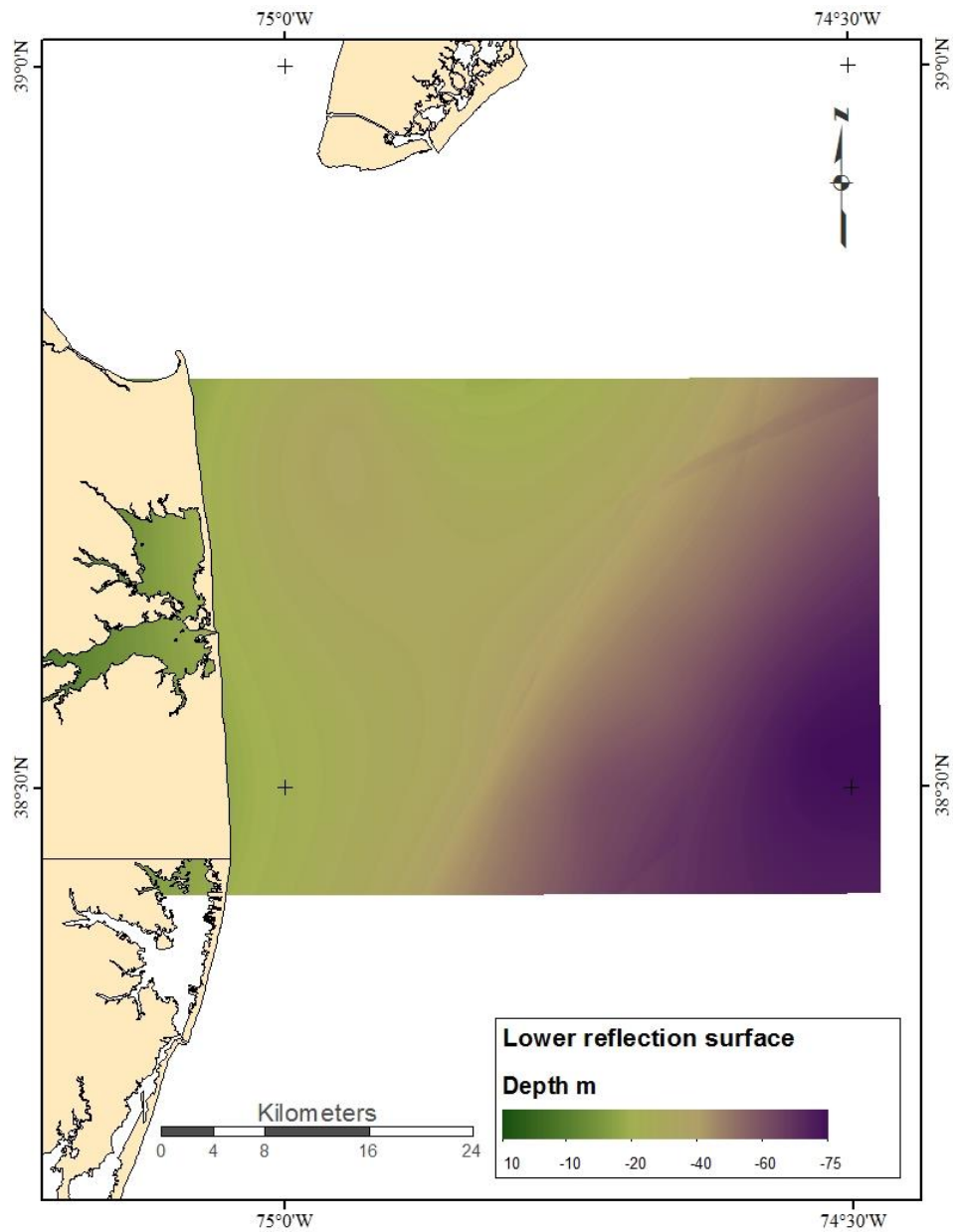


Figure 4.1 Map of the study area. Wells (green), cores (blue) offshore and seismic lines (red), line Y-Y' shows seismic profile above.



**Figure 4.2** Seismic profile of the high-amplitude reflection studied in this work. Annotation shows the reflection in green and one of the paleochannels of the Delaware River highlighted in orange. Other reflections present but not highlighted are later events.



**Figure 4.3** Model of the lower seismic reflection. The reflection depth based on seismic interpretation using a constant seismic velocity in saturated sediments of 1500 m/s. The interpolation was done using ArcGIS™ Geostatistical Analysis. Note a slightly deeper section (35-40 m) just southeast of the bay mouth; this follow the path of the paleochannel of the Delaware River.



| Formation | Gamma Ray Log | Lithology | Palynomorphs   | Environment of deposition                    | Amino zones         | Age                            | Inferred climate            |
|-----------|---------------|-----------|--|--|---------------------|--------------------------------|-----------------------------|
| Omar      |               |           | <u>Pinus</u><br><u>Picea</u><br><u>Quercus</u><br><u>Carya</u>                         | <u>Sphagnum</u> bog<br>lagoonal<br>estuarine | II a<br>b<br>c<br>d | Quaternary                     | Temperate and cold          |
|           |               |           | <u>Quercus</u><br><u>Pinus</u> and scattered exotics                                   | estuarine<br>lagoonal                        |                     | Pliocene                       | Temperate or warm temperate |
| Beaverdam |               |           | <u>Quercus</u><br><u>Carya</u><br><u>Pinus</u><br><u>Pterocarya</u><br>High NAP        | estuarine                                    |                     | Pliocene                       | Temperate                   |
|           |               |           | <u>Quercus</u><br><u>Carya</u><br><u>Pinus</u><br><u>Taxodium</u><br><u>Pterocarya</u> | fluvial - deltaic                            |                     | early Pliocene or late Miocene | Warm temperate              |
| Bethany   |               |           | <u>Scladophytis</u><br><u>Symplocos</u><br><u>T. edmundii</u>                          | deltaic                                      |                     |                                | Warm temperate              |

Figure 4.4 Composite schematic summary of the Delaware geology of the Omar and Bethany Formations from Groot et al. (1990).

## **Methods**

The depths to the upper and lower contacts of the Beaverdam Formation from geologic data from three onshore wells were used to model surfaces for these contacts. ArcGIS™'s Geostatistical Analysis was used to generate the surfaces using an approach that was similar to that employed for the reflections from the seismic profiles. Analysis of the data was done using kriging. Simple kriging, setting the transformation to none, and a constant order trend removal were used to process the data. A semivariogram was used with a setting of no for anisotropy and a smooth nearest neighbor search to produce the new data values. The statistical analysis was done using a cross-validation to test the validity of the results and was found to be within the statistical parameters.

The surfaces were then used to correlate the onshore features to the deeper offshore seismic reflection. As shown in geologic cross-sections generated by Ramsey (2010) along the Atlantic coast of Delaware, the Beaverdam is incised by paleochannels. An effort was made to use wells in the onshore area that occur within the interfluvium and not within any down-cut paleochannels. The three wells chosen met the criteria that the upper contact of the Beaverdam with the Omar Formation was relatively continuous and not incised by river/stream down-cutting. The wells used were: Pg53-14, at 0 m to the contact between the Omar and Beaverdam Formations; Oh25-02, at 8 m depth below sea level to the contact; and Ri15-01, at 18 m depth below sea level to the contact. These wells are described in detail in Groot et al., (1990) and their locations are shown in Figure 4.1. A second ArcGIS™ model was generated for the depth of the contact between the Beaverdam and the underlying Bethany Formation. The depth to



the Beaverdam- Bethany unconformity is about 30 meters below sea level, dropping to 36 m toward the coastline. As discussed in further detail in the Results section, the model that showed the best fit to the data is that of the shallower Omar/Beaverdam contact.

To confirm that the seismic reflection can be correlated with the upper contact of the Beaverdam Formation with the Omar Formation, a study using seismic profiles and core descriptions was conducted in a smaller area off Rehoboth Beach, Delaware. The model indicated that nearshore depths below sea level to the top of the Beaverdam Formation are in the 10-20 m range in this area (Figure 4-3). Seismic data collected by Ocean Surveys Inc. for the Delaware Benthic Mapping Project conducted by the Coastal Program of the State of Delaware's Department of Natural Resources and Environmental Control and core data from the Delaware Geological Survey were used to identify the Beaverdam Formation (Figure 4.5). Two primary seismic profiles were used, a north-south line (13R33L6WC) and a crossing east-west line (13R58L25WC). Four cores located near the seismic lines were chosen; their DGSID identifiers were Oj54-01, Oj54-02, Pj15-01 and Pj25-06, respectively.

Chesapeake Technology, Inc.'s SonarWiz™ software was used for processing the seismic data and displaying the cores on the seismic profiles. Each core's lithological description was entered into SonarWiz™ and the core location and its corresponding subsurface lithology was placed on the profiles (Figures 4.6 - 4.8). Cores located more than 50 meters off the seismic profile are indicated at the end of the identifier as direction and distance from the seismic line (i.e., Oj-55-01 W150m; this

would indicate that the core was 150 meters west of the profile). Color codes represent sediment descriptions, but not necessarily the formation themselves.

## **Results**

The surfaces generated by ArcGIS™ based on the deep seismic reflection event were compared with the contacts between the Omar and Beaverdam Formations and the Beaverdam and Bethany Formations as defined onshore (Ramsey, 1999, 2010, 2011; McLaughlin, 2008). The stratigraphy underlying the Delaware coast (Figure 4.9) consists of Holocene sediments deposited during the past 10,000 years in a transgressive barrier-lagoon system with rising sea level (Kraft et al., 1987; Ramsey, 1999). The Holocene overlies the middle to upper Pleistocene Omar Formation (Groot et al., 1990) and the upper Pleistocene Ironshire and Sinepuxent Formations (Ramsey and Tomlinson, 2012). These Pleistocene formations were deposited in coastal and paludal environments similar to the present, with lagoon, spit, and tidal-channel sub-environments (Ramsey, 1999, 2010). Underlying the Omar Formation is the Pliocene Beaverdam Formation (Groot et al., 1990; Ramsey, 2010). The Beaverdam Formation was deposited in a fluvial to estuarine environment (Benson, 1990).

In the model correlation between the ArcGIS™ generated surfaces, the shoreward projections match fairly closely the unconformity marking the basal contact of the Omar Formation with the underlying Beaverdam Formation (Figure 4.3). Onshore, the depth of the unconformity between the Omar and the underlying Beaverdam Formation was based on lithologic data from three wells:

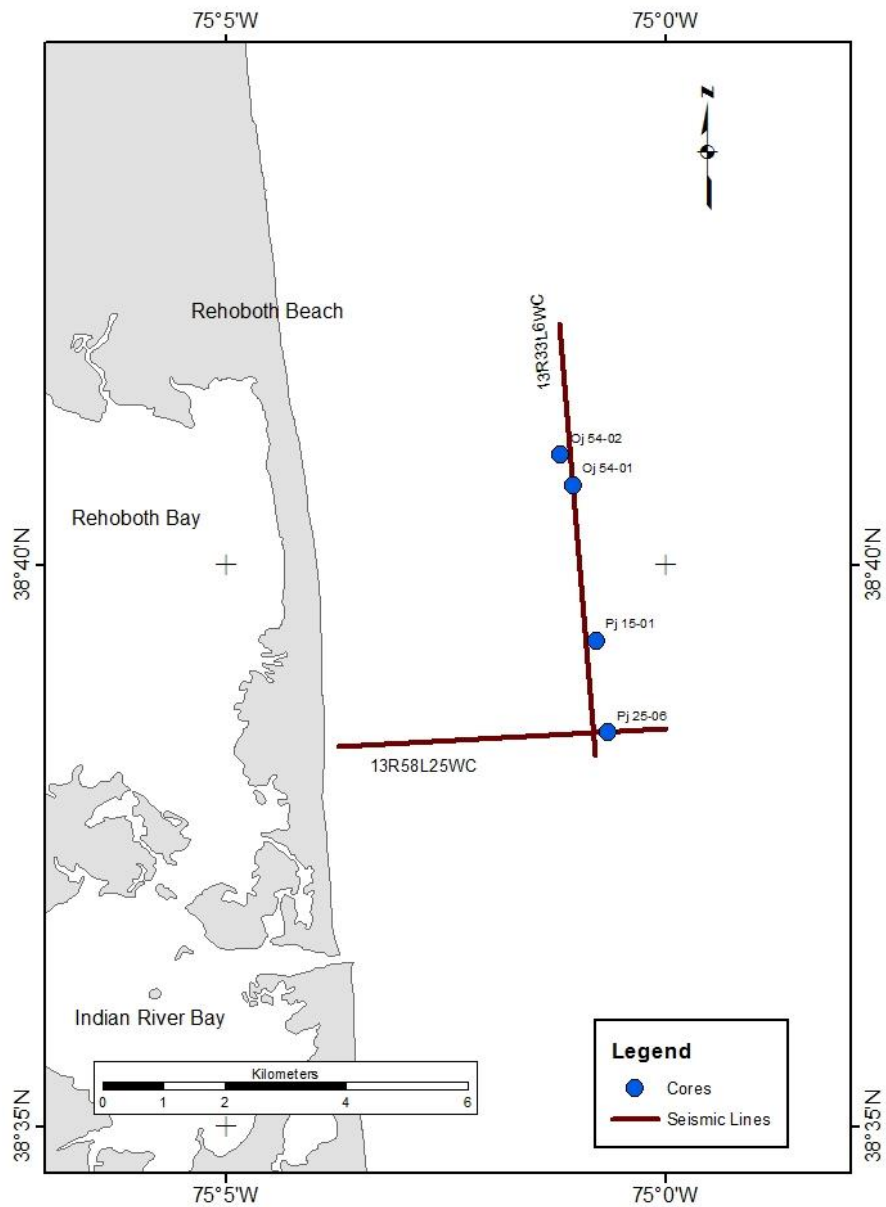


Figure 4.5 Rehoboth Beach area with the cores and seismic lines. Cores collected by the Delaware Geological Survey, Oj54-01, Oj54-02, Pj15-01 and Pj25-06, and seismic profiles were used, a north-south line (13R33L6WC) and a crossing east-west line (13R58L25WC) from State of Delaware's Department of Natural Resources and Environmental Control.

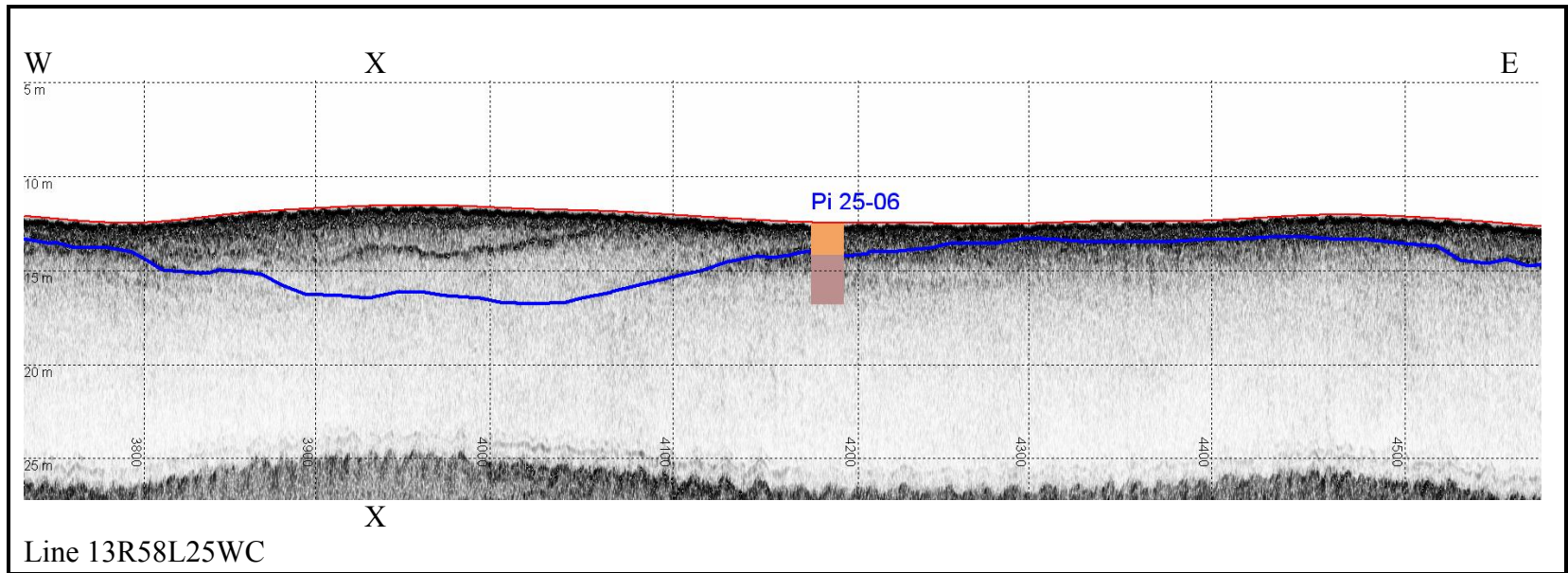


Figure 4.6 Seismic profile showing that the top of the Beaverdam Formation (blue line) is just below the surface about 5 m below surface with dips to 15 m in depression or paleochannel. X indicates the position where the profile crosses line 13R33L6WC, 250 m from start of line. Colors represent the sedimentary units, for detailed sediment descriptions see Appendix.

Sandy brown - Holocene offshore units (sheet-sand deposits)

Rosy brown - Pliocene Beaverdam Formation.

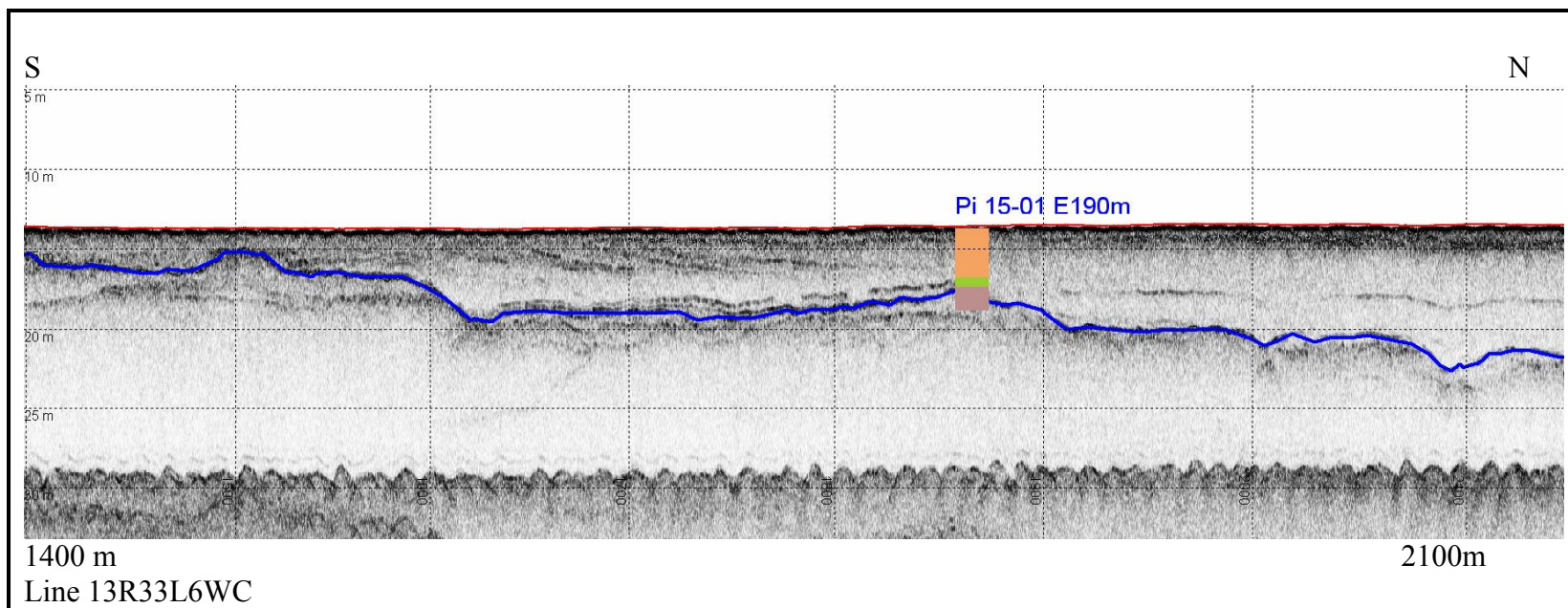


Figure 4.7 Core Pi 15-01 and seismic profile showing the top of the Beaverdam Formation. Core position is 190 m east of the profile track line; the reflection and core depth difference is due to the seaward slop to the contact.

Pi 15-01

- Sandy brown – Holocene offshore units (sheet-sand deposits)
- Yellow green - Holocene offshore units (Marsh deposits)
- Rosy brown - Pliocene Beaverdam Formation.

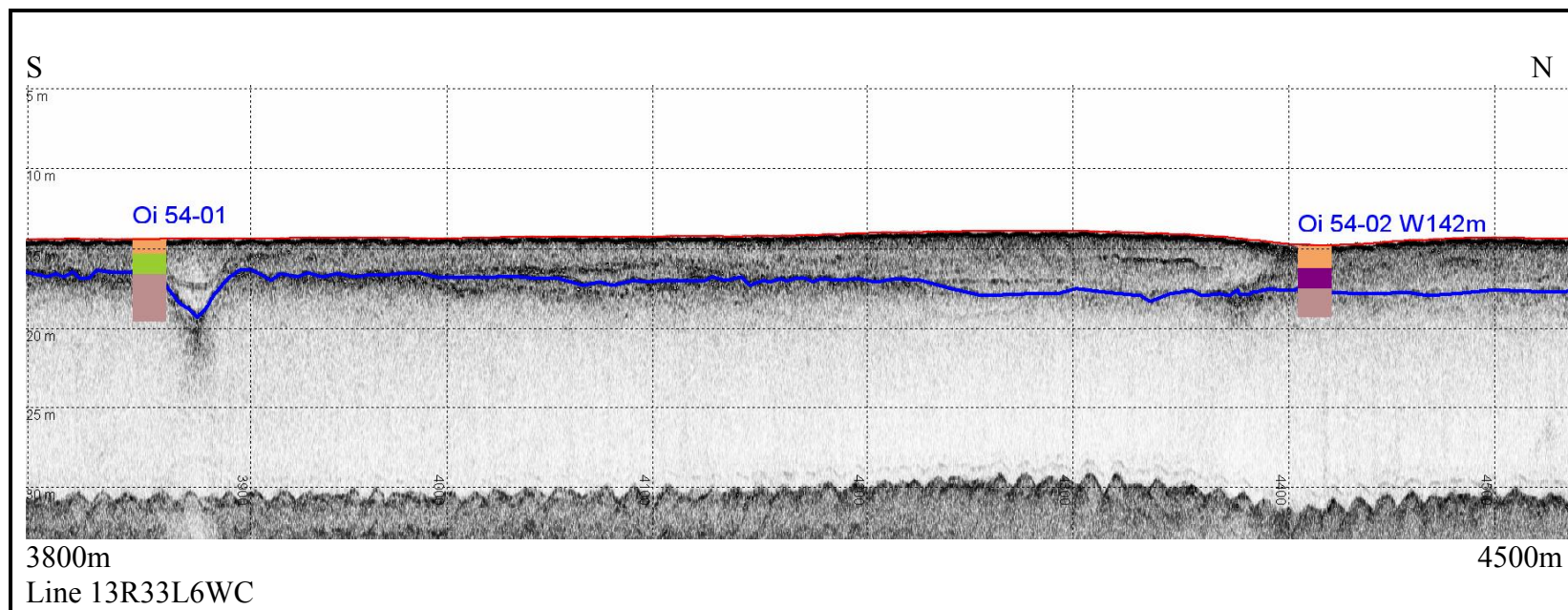


Figure 4.8 Core Oj 54-01 core description is less clear in correlating with the reflection. Core Oj 54-02 W142m is located 142 m west of line 13R33L6WC and shows the depth to the Beaverdam to be 15 m deep.

Oj 54-01

Sandy brown – Holocene offshore units

Yellow brown - Holocene offshore units (Lagoon deposits)

Rosy brown - Pliocene Beaverdam Formation.

Oj 54-02

Sandy brown – Holocene offshore units

Purple – Pleistocene Lynch Heights Formation

Rosy brown - Pliocene Beaverdam Formation.

Pg53-14, at 0 m; Oh25-02, at 8 m; and Ri15-01, at 18 m, (Groot et al. 1990) (depths measured from sea-level). The depth to the Omar/Beaverdam contact ranges from 12-20 m below sea level along the Delaware coast (Ramsey, 1999, 2010, 2011; McLaughlin, 2008; Ramsey and Tomlinson 2012). The upper portion of the Beaverdam is incised by a number of fluvial channels that are filled with Omar and other sediments, resulting in an uneven contact (Ramsey, 1999). This unconformity occurred near the late Pliocene-early Pleistocene boundary (Groot et al., 1990). The model shows a surface that slopes gently southeast and extends beneath most of coastal Delaware and the inner shelf. The model indicates the surface is of generally low relief, with a slight depression beneath the paleochannels of the Delaware River (Figure 4.3).

A surface model of the Beaverdam and its lower contact with the Bethany Formation was produced for comparison. Three-dimensional images produced using ArcScene™ show that connecting these two features produces a rise of several 10's of meters in the surface just offshore (Figures 4.10 and 4.11). This correlation therefore requires that uplift of the seaward portion of the Beaverdam Formation must have occurred. No present evidence from the region suggests that this uplift would have occurred, however. Therefore the most likely scenario is that the seismic reflection is associated with the contact between the Beaverdam



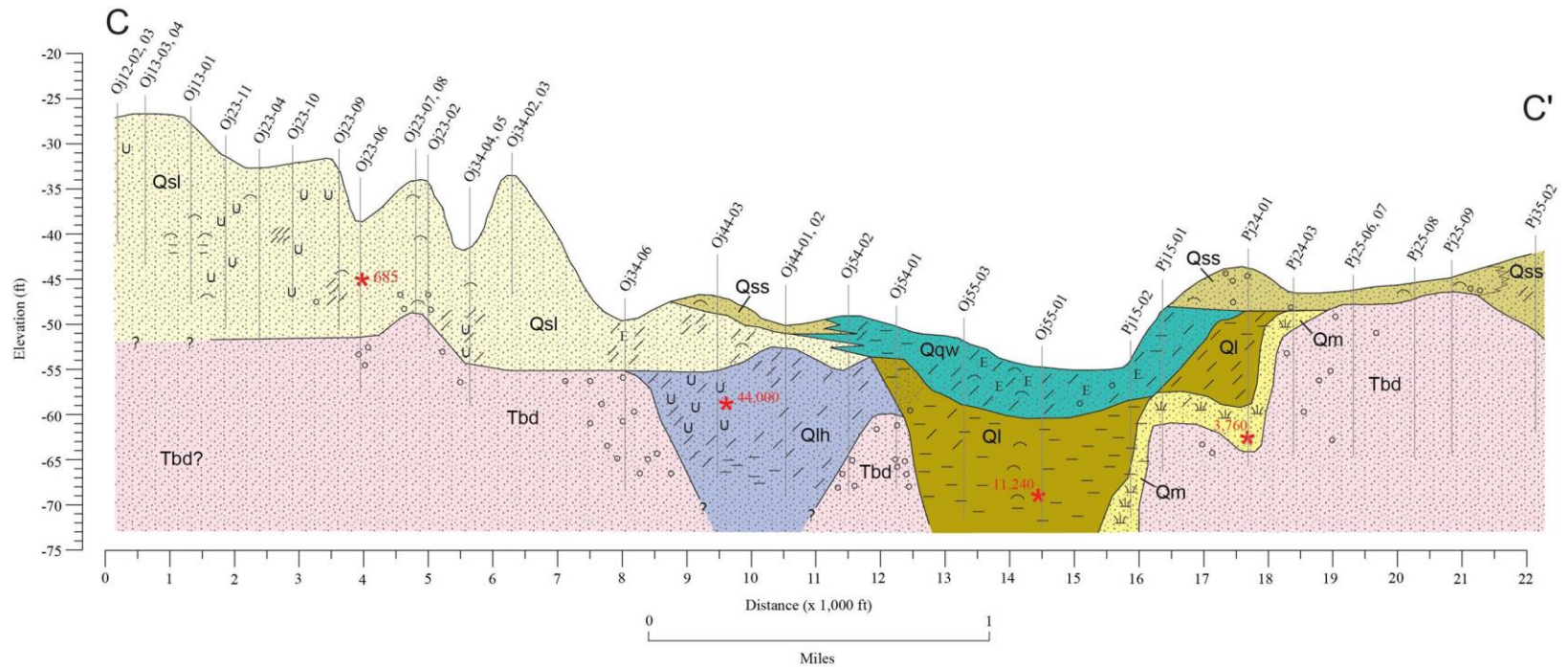


Figure 4.9 Cross-section from Ramsey (2011). Beaverdam Formation (Tbd) with two paleochannels and younger Ql Holocene lagoon deposits, and the Qlh Lynch Heights Formation.



Formation and the overlying Omar Formation, as correlated with the onshore wells. In the nearcoastal, shallow offshore wells, the Beaverdam Formation is in some areas in contact with the Omar Formation and in other areas the contact is with younger strata, such as the Ironshire and Scotts Corners Formations as well as the Holocene of sheet sands, lagoon and marsh deposits (Ramsey, 2010; Ramsey and Tomlinson, 2012).

The interpretation of the seismic profiles in the Rehoboth Beach area suggests that the reflection is associated with the upper contact of the Beaverdam Formation with overlying material as highlighted in blue in Figures 4.6 – 4.8. The Beaverdam Formation is found just below the current seafloor at depths from 5-15 m along with paleochannels incised 20-30 m into the Beaverdam. These depths match the results from the ArcGIS™ model (Figure 4.3). This interpretation was aided by the cross-section (Line C-C') from the Geologic Map of the Fairmount and Rehoboth Beach quadrangles, Delaware (Ramsey, 2011). Core descriptions from the Delaware Geological Survey were added to the profiles; the depths are measured from Mean Low Low Water (MLLW):

- Core Pj 25-06 located on profile 13R58L25WC matches the Beaverdam reflection at approximately 50 m depth below sea level. The material at this depth is described as (USCS: SW), orange medium sand, little coarse sand, little gravel, little fine sand, trace silt/clay (see Appendix) (Figure 4.6).

- Core Pj 15-01 E190m shows the Beaverdam to be present at 27.3 m depth below sea level; the Beaverdam upper section is described as (USCS: SW), gray, coarse sand with some very coarse gravel and some silt (see Appendix), and is located 190 m east or inland of seismic line 13R33L6WC. The difference in the reflection depth and core depth is due to the seaward slope of the contact. (Figure 4.7)
- Oj 54-01 the Beaverdam at 24.6 m depth below sea level is described as a dark gray mud and gravel (see Appendix). The core description is less clear in depicting the Beaverdam (Figure 4.8).
- Oj 54-02 W142m is located 142 m west of line 13R33L6WC and shows the depth to the upper Beaverdam to occur at a depth of 29.8 m below sea level. It is described as medium–very coarse sand, gravel, light olive brown (see Appendix). The difference in depth between the core and reflection is that where the seismic profile reflection is observed it is in a shallow depression (Figure 4.8).

## **Discussion**

As observed in the inner continental shelf seismic profiles and the ArcGIS™ model, a buried surface was found to be gently sloping toward the east-southeast. The associated seismic reflection indicates a relatively smooth surface with little relief. This result was also produced in the surface model generated with the kriging ArcGIS™ application. Another model based on the measurements in the onshore wells also

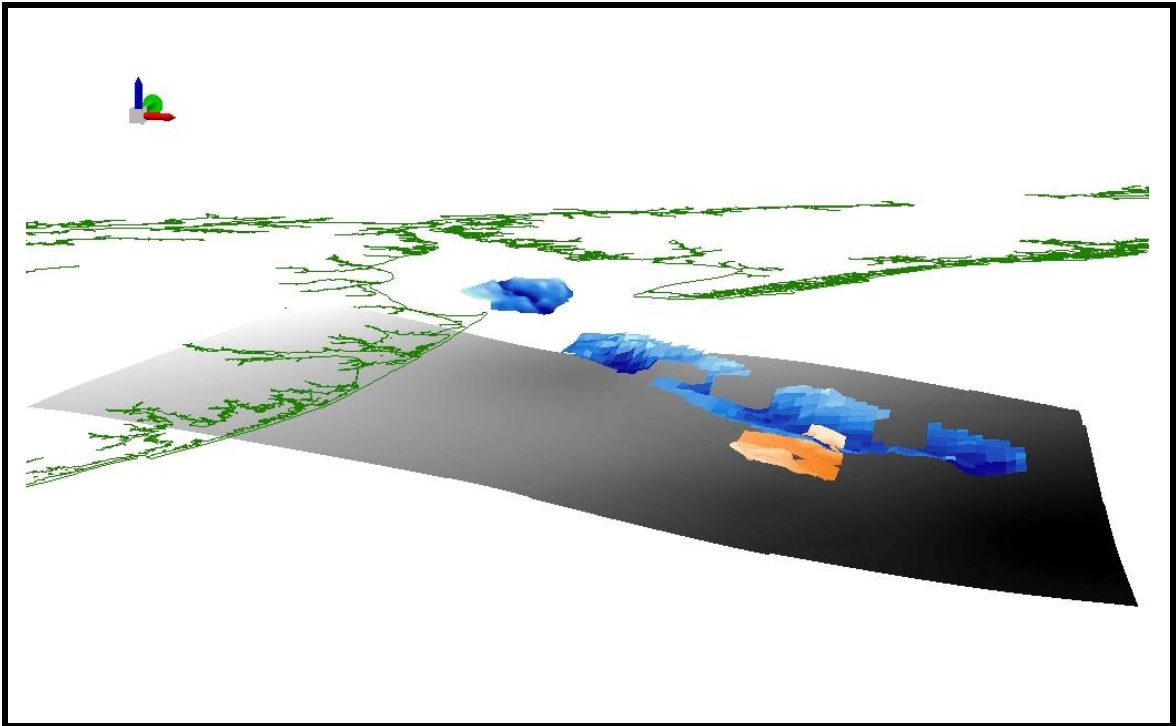


Figure 4.10 ArcScene Image of the model as the Omar/Beaverdam contact. High angle view of the upper surface of the Beaverdam Formation produced in ArcScene™, facing north. Gray is the contact between the Beaverdam Formation and the Omar and other overlying strata. Blue is the model of one of the paleochannels of the Delaware River.

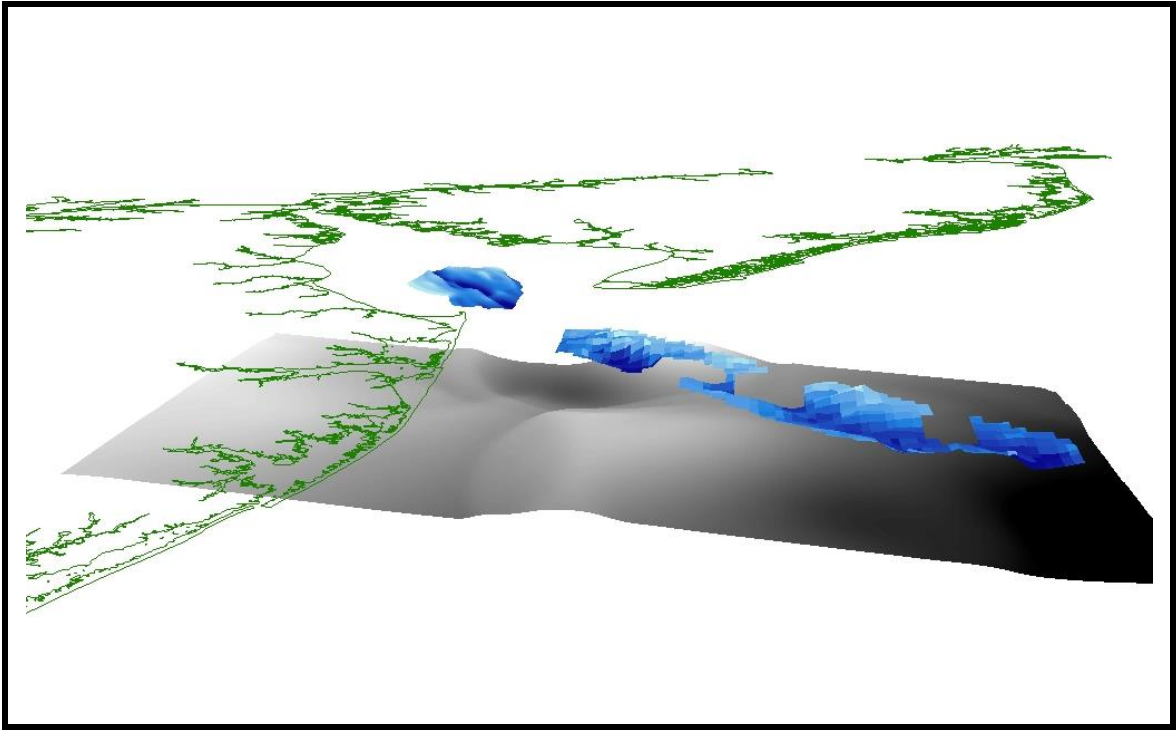


Figure 4.11 ArcScene image of the model as Beaverdam and Bethany Formation contact. Contact between the Beaverdam Formation and the lower Bethany Formation (gray) showing that uplift would need to have occurred. High- angle view produced in ArcScene™, facing north. Blue is the model of one of the paleochannels of the Delaware River.

showed an east-southeast sloping surface at the appropriate depths. Combining these models produced one continuous surface gently dipping east and southeast in an oceanward direction.

Based on the depth in the wells, the surface was identified as the contact between the Beaverdam Formation and the overlying Omar Formation. To confirm this, a study of a smaller area off Rehoboth Beach, Delaware, was conducted. The seismic profiles were combined with core data to correlate the lithology with the seismic reflection. Based on data from these cores, the sediment lithology match that of the sediments of the Beaverdam Formation.

A depression in the Beaverdam surface can be observed under the paleochannels of the Delaware River (Figures 4.3). A question is proposed for future study as to the origin of this depression. Is the depression caused by subaerial erosion by the paleochannels? It is shown in some of the seismic profiles to be deeper than the paleochannels that have been mapped (Murphy, 1996, and in this work), this could be due to an earlier paleochannel that was not observed in the seismic data. Is it an underlying structure that developed a depression or hole that led to the formation of the Delaware Bay and the course of two of the paleochannels? The depression could possibly be an artifact of the seismic reflection method such as a change in the sediment compaction. A higher compacted or denser sediment can cause a change in the seismic velocity that would alter the calculated depths. This would require deep penetrating seismic data and deep wells to be drilled to begin to answer these questions.

## **Conclusion**

In the Rehoboth Beach detailed study area, seismic profiles indicate that the top of the Beaverdam is shallow, 12-18 m below sea level, with incisions cutting down to ~20–30 m below sea level. The depths in cores in the Rehoboth Beach area also match the seismic profiles indicating that this reflection is indeed the upper contact of the Beaverdam Formation with the overlying material. This matches the model of onshore wells and offshore seismic data, which produced the surface for the larger geographic area.

Using a limited amount of data distributed over a large area, it is possible to model a surface. Seismic data provide some constraints on the geology; however it should be supported whenever possible by other geological information, such as core samples, in order to better constrain interpretations of the region. It must be mentioned that models are just that, models. They have limitations and must never be the end of the story but one aspect of the interpretation. By combining the seismic and core data, the confidence in the interpretation can be considered much stronger.

## Chapter 5

### CONCLUSION

Beneath the subsurface of the lower portion of the Delaware Bay and the bordering Mid-Atlantic inner shelf is a network of paleochannels. The seismic profiles showing the major reflections for this area are in the older analog paper form. In order to examine the geology and interpret the relationships of the paleochannels, a methodology for extracting the data and building a digital database to model these paleochannels in ArcGIS™ and as 3-D models using ArcScene™ was developed.

This investigation was divided into two major parts. First, a method was developed to take analog seismic profiles and convert them into an appropriate format for use in digital mapping and analysis in ArcGIS™. The second part was to use the digitized data to model subsurface paleochannel geometry beneath the Delaware Bay and inner shelf and to map and create 3D images. This allows the determination of the stratigraphy of the paleochannels and constrains the geological relationship and relative ages. Krantz et al. (1993) and McGeary et al. (1991) identified four paleochannels on the inner shelf off the coast of Cape May, New Jersey, and Delaware Bay. These seismic profiles were used in this investigation to model two inner shelf paleochannels and to correlate these with the paleochannels within the bay. Murphy (1996) described

the shape, dimension and path of one of the paleochannels on the inner shelf. Knebel and Circé (1988) identified three paleochannels beneath the Delaware Bay

### **Methods of Analysis**

The steps for using existing analog seismic data were as follows:

1. Identify, track and correlate major reflections.
2. Measure Two Way Travel Time (TWTT) to each reflection manually for each minute along the track line. Enter all measurements into Excel™ along with its corresponding feature identifier. Then use the Excel™ formula functions to convert the TWTT into depths, with the assumption of 1500 m/s as the velocity of seismic waves through saturated sediment.
3. Add columns for seismic trackline number or identifier and other pertinent information.
4. Import the Excel™ spreadsheet into an Access™ database.
5. Create an Excel™ spreadsheet with the corresponding navigation data and import it into the Access™ database.
6. Use ArcCatalog to create a shapefile with either the Access™ database or Excel™ spreadsheet.
7. Use ArcMap™ to create surface models from the new shapefiles using the geostatistical analysis extension.

Geostatistical analysis has several methods of interpolation of data; for this project kriging was chosen. Several kriging interpolation methods, Simple, Ordinary,



and Universal, were used in this study to produce surface models of the buried paleochannels. Kriging interpolates a surface by comparing known points and the distance between them to compute the value of unknown points. In ArcGIS™ a kriging model does not create a true layer but a temporary dynamic layer used within the ArcMap™. From ArcMap™ it must be exported as a raster to use in ArcScene™ or other programs. The raster process recalculates the values so the final results will not have the identical values as calculated in the model.

Using ArcGIS™ to model surfaces of subbottom features and stratigraphy such as paleochannels and then producing maps and using them in ArcScene™ to produce 3D images is an immense aid to geologist. Computer programs are not magic boxes where information is fed in and all the answers pop out. It is up to the geologist to use the information as a part of the investigation. The maps and images are where the geological study begins.

### **Models of Paleochannels**

Within the Delaware Bay three major paleochannels were modeled: Northern, Central and Southern. The oldest Northern Channel was traced to the southern Cape May Peninsula at the Cape May Canal. This was not traced beyond the bay although the direction suggests that it may connect to the Green Channel that lies north of this study area on the continental shelf.

The Central Channel is the youngest and continues on the shelf as the Blue paleochannel heading southeast approximately 50 km where it turns to the east and

extends toward the Baltimore Canyon. The Blue on the inner shelf shows a flat U-shaped channel changing to a more V-shape with the eastward turn. As sea level transgressed the river flooded creating the estuarine environmental of the current Delaware Bay.

An earlier regression and transgression cycle formed the Orange paleochannel. The Orange paleochannel emerges from the south side of the Blue paleochannel 40 km southeast of the bay mouth and also turns toward the east heading to the Baltimore Canyon. No viable evidence was found to show an Orange paleochannel farther inshore. The Orange may extend into the bay as the Southern paleochannel and as the Blue was being carved in the same path it obscured any evidence of the Orange channel.

A shallow paleochannel designated the Yellow paleochannel was detected and mapped. This paleochannel lies just north of and paralleling the Blue paleochannel. Evidence in the seismic profiles suggests one or possibly two reoccupations or major flooding events. The Yellow appears to be contemporary with the Blue as possibly a tributary or a tidal scour.

A number of paleochannels draining from the east coast of Delaware merge into a larger trunk valley. This trunk appears to converge with the Orange and or Blue paleochannels. None of the seismic profiles overlapped the convergence of these systems therefore no direct conclusions about the interactions could be made.

A deeper reflection was detected throughout the inner shelf on many of the seismic profiles. The model indicated this to be a generally southeast sloping surface. Seismic-stratigraphic correlation of this reflection on the inner shelf to onshore

formations was made using geophysical data from onshore wells. Ordinary kriging models were run and the results showed the surface is most likely to be the Omar/Beaverdam formation contact.

One aspect of this study was to evaluate the feasibility of using the Arc Marine GIS data model as a method of organizing the data. The Arc Marine GIS data model is designed to provide structure for the storage and analysis of a large amount of marine data to combine components of many databases together. The Arc Marine GIS data model is an evolving effort to create and define a data model for the broadly-defined marine community (Wright et al., 2007). Wright et al. (2007) have published a reference book entitled, "Arc Marine: GIS for a Blue Planet" in which the standards and best practices from a series of case studies that have been used to develop the Arc Marine data model are described. This data model is designed to provide structure for the storage and analysis of marine data, and to help users create various maps and 3-dimensional depictions of the marine environment (Wright et al., 2007). After evaluating the Arc Marine GIS model it was determined that the Arc Marine GIS is better suited for an array of datasets from a number of different instruments and methods and this project needed only seismic data.

### **Value of Research**

To better monitor the changes in the coastal and estuarine environments one needs to have good spatial data and a way to analyze and display the information. The advent of computers and computer mapping has led to the development of Geographic

Information Systems (GIS), which use any data that have spatial components. Using old analog seismic measurements converted into a database allows for the development of a model of the relationships of the paleochannels and constrains the geology of this study. This project shows a method of extracting data from analog seismic profiles to be imported into ArcGIS™ for analysis and modeling. Good quality surface maps of subsurfaces and buried features can be produced from seismic tracks that are some distances apart and are covering a large geographic area.

An additional aspect of the research will be to use the results from the mapping of the paleochannels to further investigate initial settlements along the North American continental land mass in the area of Delaware. High-resolution multibeam and subbottom profilers' could be used to constrain the paleo-environmental settings so that potential areas most capable of preserving archaeological artifacts can be determined. Ancient settlements are likely found near rivers, thus the location of paleochannels would be beneficial to archaeological investigation. This process can be of further use in research in the Delaware Bay and inner shelf including the placement of offshore wind turbines.

### **Remaining Questions**

Some remaining questions have been revealed in the course of this study that would require further inquiry. To provide more precise ages of the paleochannels, deep cores are needed for sediment analysis and samples for age dating. These will aid in

determining whether the Southern paleochannel is concurrent with the Central or is older and a section of the Orange.

Additional detailed seismic coverage in more concentrated areas in the northern section of the Delaware Bay and off the coast of New Jersey would be needed to determine if the Green paleochannel is an extension of the Northern paleochannel. Several specific regions need seismic data to connect the paleochannels east of New Jersey to those within the bay and beneath Cape May peninsula. Seismic data collection in smaller geographic areas would be needed to determine the relationship of the Lewis River, Indian River and Bethany beach paleo-drainage system, and the Orange and Blue paleochannels on the inner shelf.

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## **APPENDIX**

### **DGS CORE DESCRIPTIONS**

0554-01

| Drilling Log                               |  | 1 of 2 Sheets   |             |
|--|--|---|-------------|
| 1. Project                                 |  | KHV   |             |
| 2. Location                                |  | 769929.89E, 247323.02N  |             |
| 3. Drilling Agency                         |  | Alone Ocean Seismic Survey, Inc.  |             |
| 4. Hole No. (As shown on drawing 188)      |  | KHV-39  |             |
| 5. Name of Driller                         |  |   |             |
| 6. Direction of Hole                       |  | <input checked="" type="checkbox"/> Vertical <input type="checkbox"/> Inclined _____ Degree from Vertical |             |
| 7. Thickness of Overburden                 |  |   |             |
| 8. Depth Drilled into Rock                 |  |   |             |
| 9. Total Depth of Hole                     |  | 17.7 ft   |             |
| 10. Size and Type of Bit                   |  |   |             |
| 11. Datum for Elevation Shown (TOM or MSL) |  | MLLW  |             |
| 12. Manufacturer's Designation of Drill    |  |   |             |
| 13. Total No. of Overburden Samples Taken  |  | Disturbed   | Undisturbed |
| 14. Total No. of Core Boxes                |  |   |             |
| 15. Elevation Ground Water                 |  |   |             |
| 16. Date Hole                              |  | Started   | Completed   |
|  |  | 6/9/93  | 6/9/93      |
| 17. Elevation Top of Hole                  |  | -49.7'  |             |
| 18. Total Core Recovery for Logging        |  | %   |             |
| 19. Signature of Inspector                 |  | JV D-JK   |             |

| Elevation | Depth | Legend | Classification of Materials (Description)                                      | % Core Recovery | Box or Sample No. | Remarks (Drilling time, water loss, depth of weathering, if significant) |
|-----------|-------|--------|--|-----------------|-------------------|--|
| a         | b     | c      | d  | e               | f                 | g  |
| 0         | 0     | SC     | Dark gray, wet, clayey sand  | 100             |                   |  |
|           | 1     |        | $\phi_m = -0.019$<br>72% Gravel =<br>82% Silt =<br>5% Clay<br>6% clay 11% Fine |                 |                   | Sample at 2.0'   |
|           | 2     | SP     | Brown silt and fine sand   |                 |                   |  |
|           | 3     | SW     | Gray, medium to fine sand with mud   |                 |                   |  |
|           | 4     |        |  |                 |                   |  |
|           | 5     |        |  |                 |                   |  |
|           | 6     | SW     | Gray, medium to fine sand with mud   | 100             |                   | Sample at 6.6'   |
|           | 7     |        | $\phi_m = 2.73$<br>$\rho_m = 1.8$  |                 |                   |  |
|           | 8     | GP     | Dark gray mud and gravel   | 100             |                   |  |
|           | 9     |        |  |                 |                   |  |
|           | 10    | SM     | Dark gray muddy sand   |                 |                   |  |

NG FORM 1838

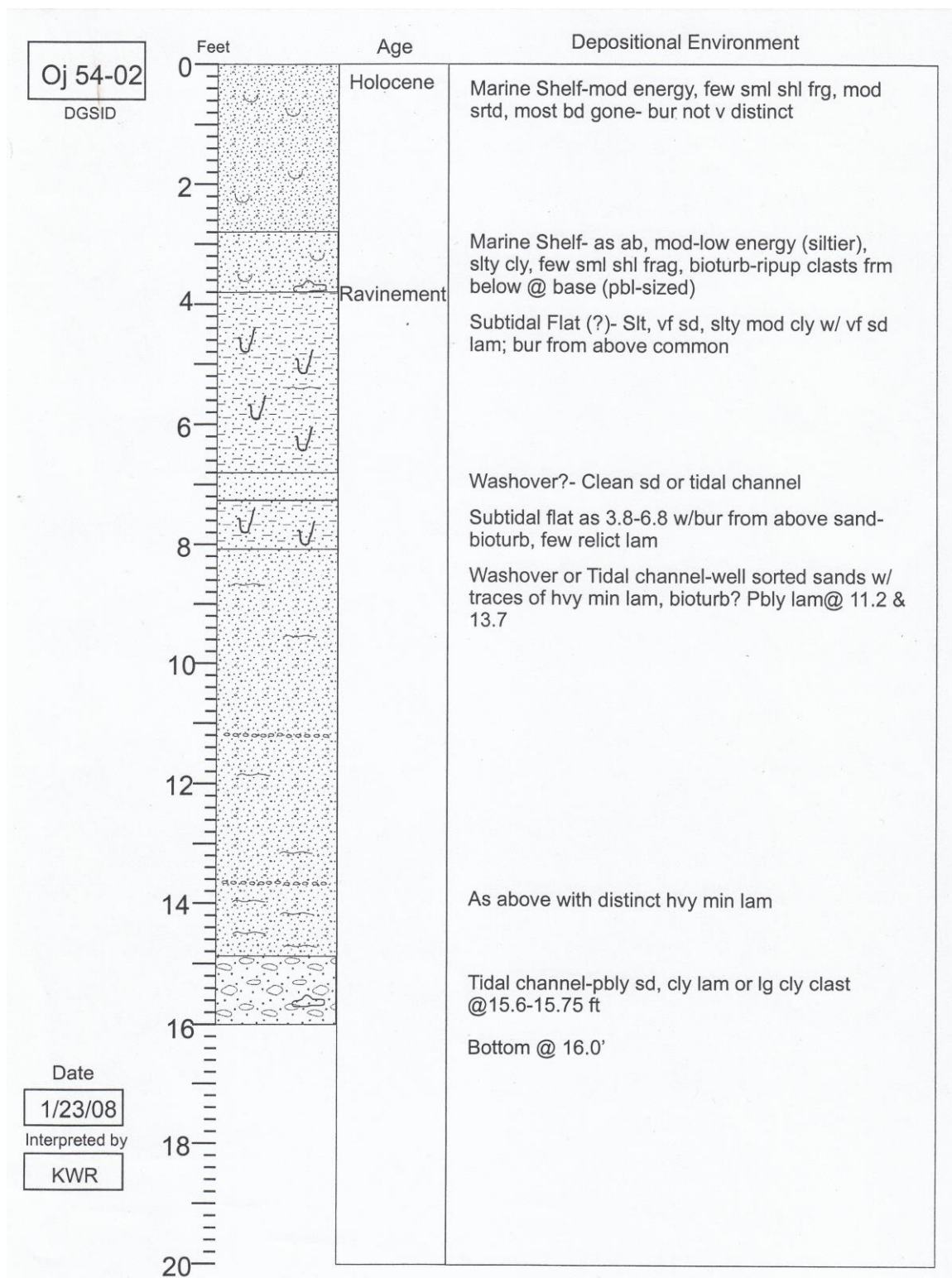
Project

Hole No.

332

054-01

| Drilling Log (Cont Sheet) |       |        | Elevation Top of Hole -49.7'              |                 | Hole No. KHV-39   |  |
|---------------------------|-------|--------|---|-----------------|-------------------|--|
| Project KHV               |       |        | Installation                              |                 | Sheet 2 of 2      |  |
| Elevation                 | Depth | Legend | Classification of Materials (Description) | % Core Recovery | Box or Sample No. | Remarks (Drilling time, water loss, depth of weathering, if significant) |
| a                         | b     | c      | d   | e               | f                 | g  |
|                           | 10    |        |   |                 |                   |  |
|                           | 11    | GP     | Gray, gravelly, medium sand<br>$\phi_m =$ |                 |                   | Sample at 11.0'  |
|                           | 12    | GP     | Light gray, gravelly coarse sand          |                 |                   |  |
|                           | 13    |        |   |                 |                   |  |
|                           | 14    | GP     | Brown, gravelly, sand                     |                 |                   |  |
|                           | 15    |        |   |                 |                   |  |
|                           | 16    | GP     | $\phi_m = -0.95$<br>Brown, gravelly sand  |                 |                   | Sample at 15.0'  |
|                           | 17    |        |   |                 |                   |  |
|                           | 18    | SP     | Light brown, medium sand                  |                 |                   |  |
|                           | 19    |        | 17.7 ft Recovery                          |                 |                   |  |
|                           | 20    |        |   |                 |                   |  |
|                           | 21    |        |   |                 |                   |  |





Pj 15-01

| Drilling Log (Cont Sheet) |       | Elevation Top of Hole -48.6' |   | Hole No. KHV-38   |                   |  |
|---------------------------|-------|------------------------------|---|-------------------|-------------------|--|
| Project KHV               |       | Installation                 |   | Sheet of 2 Sheets |                   |  |
| Elevation                 | Depth | Legend                       | Classification of Materials (Description)             | % Core Recovery   | Box or Sample No. | Remarks (Drilling time, water loss, depth of weathering, if significant) |
| a                         | b     | c                            | d   | e                 | f                 | g  |
|                           | 10    | SP                           | Dark gray, medium sand; trace round gravel; wet       |                   |                   | Sample at 10.5'  |
|                           | 11    |                              |   |                   |                   |  |
|                           | 12    | SP                           | Dark green-gray, medium to fine sand                  |                   |                   |  |
|                           | 13    | SW                           | Gray, coarse sand; some very coarse gravel; some silt |                   |                   |  |
|                           | 14    |                              |   |                   |                   | Sample at 14.0'  |
|                           | 15    |                              |   |                   |                   |  |
|                           | 16    | SW                           |   |                   |                   |  |
|                           | 17    |                              | 17.4 ft Recovery                                      |                   |                   |  |
|                           | 18    |                              |   |                   |                   |  |
|                           | 19    |                              |   |                   |                   |  |
|                           | 20    |                              |   |                   |                   |  |
|                           | 21    |                              |   |                   |                   |  |

G FORM 1836

Project

Hole No.

|   |  |   |  |
|---|--|---|--|
| Project <b>KHV</b>  |  | 1 of 2 Sheets   |  |
| 2. Location <b>771243.60E, 238958.70N</b>   |  | 10. Size and Type of Bit  |  |
| Drilling Agency <b>Alpine Ocean Seismic Survey, Inc.</b>  |  | 11. Datum for Elevation Shown (TOM or MSL) <b>MLLW</b>                  |  |
| 4. Hole No. (As shown on drawing tag) <b>KHV-38</b>   |  | 12. Manufacturer's Designation of Bit                                   |  |
| 5. Name of Driller  |  | 13. Total No. of Overburden Samples Taken                               |  |
| 6. Direction of Hole<br><input checked="" type="checkbox"/> Vertical <input type="checkbox"/> Inclined _____ Degree from Vertical |  | Disturbed <input type="checkbox"/> Undisturbed <input type="checkbox"/> |  |
| 7. Thickness of Overburden  |  | 14. Total No. of Core Boxes   |  |
| 8. Depth Drilled into Rock  |  | 15. Elevation Ground Water  |  |
| 9. Total Depth of Hole <b>17.4 ft</b>   |  | 16. Date Hole Started <b>6/9/93</b> Completed <b>6/9/93</b>             |  |
|   |  | 17. Elevation Top of Hole <b>-46.5'</b>                                 |  |
|   |  | 18. Total Core Recovery for Logging <b>%</b>                            |  |
|   |  | 19. Signature of Inspector <b>JV GZ</b>                                 |  |

| Elevation | Depth | Legend | Classification of Material (Description)      | % Core Recovery | Box or Sample No. | Remarks (Drilling time, water loss, depth of weathering, if significant) |
|-----------|-------|--------|---|-----------------|-------------------|--|
| a         | b     | c      | d   | e               | f                 | g  |
| 0         | 0     | SC     | Dark gray-brown clayey sand; occasional shell | 100             |                   | Sample at 1.3'   |
| 1         | 1     |        |   |                 |                   |  |
| 2         | 2     |        |   |                 |                   |  |
| 3         | 3     | SC     | Dark gray-brown, clayey sand                  |                 |                   |  |
| 4         | 4     |        |   |                 |                   |  |
| 5         | 5     |        |   |                 |                   | Sample at 5.4'   |
| 6         | 6     |        |   |                 |                   |  |
| 7         | 7     | SC     | Dark gray-brown, clayey sand                  |                 |                   |  |
| 8         | 8     |        |   | 100             |                   |  |
| 9         | 9     | SM     | Muddy sand with traces of peat                |                 |                   | Sample at 9.2'   |
| 10        | 10    |        |   |                 |                   |  |

ENG FORM 1836

Project

Hole No.

340



0, 25-06

|   |  |  |  |   |  |  |  |
|---|--|--|--|---|--|--|--|
| <b>DUFFIELD ASSOCIATES</b> 5400 LIMESTONE ROAD<br>WILMINGTON, DELAWARE 19808-1222<br>TEL: (302)229-8434 FAX: (302)229-8485<br>E-MAIL: DUFFIELD@DUFFINET.COM |  |  |  | <b>Vibrocore KHV-99 R1</b>  |  | Uncorrected Depth : 46.5 feet<br>Tide : +0.9 feet<br>Corrected Depth : 45.6 feet (1)<br>Vibration time : 10'49"<br>Core penetration : 10.8 feet<br>Core recovery : 13.2 feet (3)<br>Percent recovery : 122 % (3) (4) |  |
| U.S. Army Corps of Engineers<br>Vibrocore-Delaware Coast<br>Contract Number DACW-61-98-D-0008<br>Task Order 22<br>2000 Vibrocore: Bethany/South Bethany PED |  |  |  | Date : April 28, 2000<br>Weather : Partly Sunny, 1'-2' seas<br>Vibrocore contractor : Alpine Ocean Seismic Sur.<br>Location : Area B<br>Northing Coord. : N 234,034.0 DE-NAD 83<br>Easting Coord. : E 771,984.0 DE-NAD 83 |  |  |  |

| Depth<br>in<br>Feet | Soil Surf.<br>Elev.<br>-45.6 (1) | USCS  | GRAPHIC | DESCRIPTION   | Core interval | Sample No./Interval |
|---------------------|----------------------------------|-------|---------|---|---------------|---------------------|
| 0                   | -46                              |       |         | Tan/orange medium SAND, little gravel, little fine sand, little coarse sand, trace silt/clay (fine sand lense 5.0'-5.3'). | 1             | 1/0.0-5.0           |
| 5                   | -51                              | SP    |         |   |               |                     |
|                     |                                  | SW    |         | Orange medium SAND, little coarse sand, little gravel, little fine sand, trace silt/clay.                                 |               | 2/5.3-6.3           |
|                     |                                  | SP-SM |         | Tan fine SAND, some medium sand, little coarse sand, trace gravel, trace silt/clay.                                       |               | 3/6.3-7.2           |
|                     |                                  | SW    |         | Gray/tan/orange medium SAND, some gravel, little coarse sand, trace fine sand, trace silt/clay.                           | 2             | 4/7.2-10.0          |
| 10                  | -56                              | SW    |         | Gray/tan/orange medium SAND, some coarse sand, little fine sand, trace gravel, trace silt/clay.                           | 3             | 5/10.0-12.8         |
| 15                  | -61                              |       |         |   |               |                     |
| 20                  |                                  |       |         |   |               |                     |

Notes:

- Corrected water depth and soil surface elevation datum is NGVD.
- Sample depths are based on core recovery lengths.
- Core recovery measured in field, may not be reflected in total sample length.

- Percent recovery reflects "over recovery" of sample possibly due to sample heave in liner and/or difficulty of penetration through dense strata.
- Soil descriptions & USCS classifications according to Visual-Manual Procedure (ASTM D 2488) and/or mechanical sieve analysis if analysis performed.

08/07/2000 vibcore logs\vhrc\2000\decoast\khv99r1 bor