USING THE PAST AS THE KEY TO THE PRESENT: INFORMING COASTAL RESOURCE MANAGEMENT WITH GEOLOGIC RECORDS

A Dissertation Proposal Presented

by

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INTRODUCTION

Understanding the complex, interactive processes and rates of change related to sea level rise is mandatory for managing coastal resources well. Commonly, the strategies for remediating or adapting to the effects of sea level rise are informed only by short-term (decadal) data collected from sources such as tide gauges (Barbosa and Silva, 2009), high-resolution GPS (Sella et al., 2007), and surface elevation tables (instruments designed to measure subsidence in marshes; Cahoon et al., 2002). These metrics are routinely employed to assess regional rates of water elevation change, land surface elevation change, and shallow subsidence in marshes, respectively, and are necessary for addressing the style and magnitude of change. But they fail to address *why* or *how* the changes are proceeding and they fail to place the present situation into a longer context of rates and processes. In the in the Mid-Atlantic Coastal Plain (MACP) region of the Eastern U.S., it has become clear that longer-term geologic records are needed to address these questions.

Over the past couple decades, our understanding of sea level processes in the MACP has become increasingly shaped by geologic investigation. In the 1980's, radiocarbon dates on peat beds that were deposited along the Eastern seaboard were used to reconstruct the history of the Holocene sea level transgression that persists today (Peltier, 1985). Spatial trends in this record indicated that vertical motion of the land surface, or land subsidence, had variably impacted the timing of coastal inundation (Peltier et al., 1996). By wedding this record with nearby tide gauge data, present-day subsidence values were calculated over the this area ranging from ~0.8 – 1.7 mm/yr, with the highest measured rate centered on the Delmarva (DELaware, MARyland, and VirginiA) Peninsula, the landmass adjacent to and enclosing the Chesapeake Bay (Fig 1; Engelhart et al., 2009). So while rates of global sea level rise have been estimated at ~1.5-2.0 mm/yr over the last century (Miller and Douglas, 2004), the added effect of land subsidence effectively doubles this rate for the Chesapeake Bay region of the MACP. This area is home to the largest protected expanse of tidal marshland in the Northeast U.S. including the Blackwater National Wildlife Refuge (BNWR; Fig 2); 5,000 acres of tidal wetlands were converted to open water in the BNWR between 1938 and 2006 (Scott et al 2009).

Today is not the first time sea level has risen in the Chesapeake Bay region; the Chesapeake Bay and the Delmarva Peninsula were ironically formed by cycles of rising and falling sea levels (Hobbs, 2004). The Delmarva Peninsula grew as a southward-propagating spit through both coastal marine and fluvial processes in response to major cycles of sea level rise and fall beginning in the Pliocene (~5.0-2.5 My) and continuing through the Pleistocene (~2.5 My to present; review in Hobbs, 2004). When sea levels were lower during glacial lowstands, the ancient Susquehanna and Hudson-Delaware River systems and their tributaries responded by incising as deeply as 50 m into their valleys (Colman et al., 1990). These deep river valleys were later filled with complex assemblages of river, estuary, and open-bay sediment as sea level rose into subsequent interglacial periods (Flemming et al., 2010). With each cycle of cutting and filling, the Susquehanna River system migrated slightly SW, leaving behind a well-preserved record of at least 3 ancestral Chesapeake Bays (Colman et al., 1990). This southwesterly migration has been attributed to the southward expansion of Delmarva as a major barrier spit (Colman et al., 1990), but preliminary interpretations from drilling at BNWR indicate that structural offsets (faults) in the ~12 Ma rocks below may have controlled the locations of ancient river channels.

The surficial deposits and landforms of the BNWR also contain rich details about past sea level rise and coastal inundation. The most recent geologic map of this region defines most of the landforms as having origins at the bottom of a shallow estuary (Owens and Denny, 1986). In drilling through many of these landforms, I found evidence to support this interpretation, but preliminary ages produced for them in this study suggest they were deposited at a time when sea level was far too low for estuarine deposition according to global sea level curves (Lambeck and Chappell, 2001). These subtle features have garnered increased attention because they represent the locations where marsh is expected to migrate in response to sea level rise in the coming decades (USFWS unpublished Blackwater Climate Adaptation Project strategic assessment document). Additionally, if the landforms are relict from the last time the BNWR was inundated and submerged, they preserve details on how this specific landscape responded to the most recent instance of sea level rise. By providing these details for landforms across the BNWR landscape, I can provide an analog for the sea-level rise that this sensitive, low-relief landscape will experience in the coming decades and centuries.

As a collaborative effort with multiple scientists from the Eastern Geology and Paleoclimate Science Center of the U.S. Geological Survey, this study aims to provide long-term records from ancient environments under the BNWR. This includes geologic framework studies incorporating the entire Pleistocene stratigraphy as well as the Miocene units on which the formation and evolution of the Delmarva Peninsula took place. The data collected from this long, complete record provide a comprehensive view of processes unfolding in time and space over many fluctuations of sea level.

My dissertation research fills an essential role for land managers by bridging the data gap between large temporal-scale geologic framework studies and measured trends on historic timescales. The well-known axiom put forth by uniformitarian geologists of the 18th century and popularized during the 19th century that "the present is the key to the past" provided a powerful new perspective for interpreting the antiquity and processes inferred from the rock record. In the context of understanding high rates of relative sea level rise in estuaries and marshes, the reverse is equally powerful: the past behavior of these coast-proximal features best informs their future behavior. With over 40% of the world's population residing in coastal settings (UNEP 2006), the value of the ecosystem services provided by healthy salt marshes cannot be overstated, particularly with the ongoing threat of high rates of sea level rise (Silliman et al., 2008). My study of the BNWR serves as a useful reference for estuaries and their fringing salt marshes worldwide, as all of these geologically young features have their origins in the sea level rise that characterized the last glacial retreat.

HYPOTHESES

1) *The BNWR marsh is overprinted on a relict, estuarine landscape surface that was deposited at a time when regional sea levels were relatively high but global sea levels were relatively low.* By providing a 3-dimensional geomorphologic and surficial geologic framework of the present-day marsh and the landscape on which it developed, I will be able to show how quickly-rising sea levels have

impacted this landscape in the past to better inform mangers planning for the coming decades.

2) *Accelerated rates of land subsidence and marsh loss around the BNWR partially reflect processes related to the growth and collapse of a proglacial forebulge that have been operating through several glacial-interglacial cycles*. By determining the spatial and temporal evolution of the entire Pleistocene geologic framework, I can compare the timing of high and low sea level indicators in the BNWR record with those from global sea level curves.

3) *There are faults in the rocks under the BNWR that are zones of weakness where ancient Susquehanna River channels and their tributaries preferentially incised*. The locations of Quaternary paleochannels, and thus fringing marshes, are therefore at least partially controlled by geologic structures.

OBJECTIVES

The primary objective of my research is to use the geologic record of the Blackwater NWR to help inform adaptation plans that are being drafted by a consortium of resource managers headed by the U.S. Fish and Wildlife Service who are working to maintain marsh habitat in light of ongoing sea level rise. Because this overarching objective and my hypotheses are germane to a range of timescales and methods, there are several derivative objectives in this research:

1) I will provide a surface and near-surface geomorphic inventory of the BNWR including
    a. sedimentologic architectures of surface landforms based on borehole data. Ground penetrating radar (GPR) geophysics will be used on select sites to assess the lateral variability of the deposits in the subsurface;
    b. a chronology for the surficial unit of the BNWR region using the optically stimulated luminescence (OSL) dating method as well as for the

establishment and growth of the active marsh using the radiocarbon dating method;

   c. pollen analyses that provide proxies for the climate when the surficial unit at Blackwater was deposited that can be referenced both to records in other localities regionally and to the Holocene-to-present climates that persisted during establishment and growth of the present-day marsh.

2) I will reconstruct the Pleistocene geologic history and framework under the BNWR including:
   a. a fully mapped distribution of Pleistocene deposits in the subsurface compiled from borehole data across the region;
   b. a chronology for major depositional units that will help determine if regional sea levels were in sync or out of sync with established global sea level curves; this includes
      i. cosmogenic radionuclide (^{26}Al - ^{10}Be) ages for gravel lag deposits in older paleochannels (~200 ka to 4 Ma).
      ii. optically stimulated luminescence (OSL) ages for river and estuarine sands (~10-200 ka);
   c. climate records based on floral assemblages represented in pollen analyses.

3) I will determine the Miocene geologic framework under the western Delmarva Peninsula including
   a. a contour map for the Pleistocene-Miocene contact under Western Delmarva using well logs available from county seats in addition to borehole data;
   b. a high resolution structure contour map of the Miocene units under the BNWR region using a combined lithostratigraphic and biostratigraphic approach based on samples from boreholes.

BACKGROUND:

The Blackwater NWR and Rising Sea Level

The BNWR is located in Dorchester County, MD and includes ~110 km^2 of predominantly tidal wetlands and brackish open water (Fig 2). Along with neighboring protected lands, it represents one of the largest protected complexes of tidal marshland in the Eastern U.S and was designated a wetland of international importance under the Ramsar Convention in 1987. The Refuge was established in 1933 to provide a safe stop-over for ducks and geese along the Atlantic Flyway, a major migratory corridor for birds on the eastern seaboard. The marshes serve many additional functions such as conserving biodiversity, providing nursing grounds for commercially viable fish and shellfish, buffering against storms, and offering destinations for tourism and recreation. Because most of the water flowing through the Blackwater River and to the Chesapeake Bay runs off of the vast farmland in the Blackwater River watershed, the marsh also performs the important ecosystem service of filtering nutrient pollution (Stevenson et al., 2002).

In recent decades, tidal inundation at BNWR has progressively diminished the wetland area and limited the future viability of the marsh for which this refuge was established. In sustainable marshes, high rates of biomass accretion along with mineral sediment trapping generally keep pace with rising sea levels (Allen, 2000). However sediment inputs to the BNWR are low, and RSL rise is outpacing accretionary processes (Cahoon et al., 2010; Kirwan and Guntenspergen, 2012; Stevenson et al., 2002; Stevenson et al., 1985). Evidence from a topographic map produced by the US Geological Survey in 1898 suggests a well-delineated Blackwater River channel flowing through intact marsh within the footprint of BNWR (Fig 3a). The same area was photographed from the air in 1938; this imagery still shows channel morphologies along the Blackwater River, but significant marsh loss had occurred by this time near the confluence of the Blackwater and Little Blackwater Rivers (Fig 3b). From 1938 to the present, these ponds grew in size and coalesced to form larger bodies of water (Fig 3c). The progressive erosion of adjacent wetlands has increased the area of open water such that the confluence of these rivers is now informally called Lake Blackwater. Portions of the main Blackwater River levees still exist and support high marsh, but they are not accreting rapidly enough to keep pace with water level rise (Cahoon et al., 2010). High winds enhance coastal erosion by pushing large volumes of water along the newly elongated fetch of Lake Blackwater, eroding down-wind shorelines, particularly during heavy storms and storm surges.

The ~500 km^2 region surrounding the footprint of the BNWR (full field area as shown in Figure 2) is the ideal location for this study because 1) the Refuge is currently drafting an adaptation plan that includes no subsurface information to respond to current and future rising sea levels; 2) the response of this landscape to previous Pleistocene sea level fluctuations is well preserved in the substrate; 3) access is greatly facilitated by a partnership between the U.S. Geological Survey and the BNWR managers in the U.S. Fish and Wildlife Service. Understanding well the response of this landscape to several previous cycles of sea level fluctuation will provide the proper backdrop for assessing adaptation strategies for sea level rise in the coming decades.

Geologic Framework of the Blackwater NWR

An understanding of the stratigraphy underlying the BNWR places the present-day of RSL rise in the context of a long history of glacial-interglacial sea level fluctuations. The modern Chesapeake Bay occupies a drowned valley carved by the Susquehanna River prior to the beginning of the last ice age (Colman et al., 2002; Reusser et al., 2004). Drilling into the Chesapeake Bay sediments today yields a sequence of material from basal Susquehanna River gravels overlain by deltaic river sands, and covered with Holocene estuarine muds that accumulated as sea levels rose to present levels (Baucom et al., 2000; unpublished data from this report). This sequence of erosion and deposition was repeated through the Pleistocene in cyclic fashion, and the Chesapeake Bay is the outcome of the most recent iteration. With each erosion-deposition cycle, the system migrated in an overall southwesterly fashion, providing a well-preserved record of this long history (Fig 1; Colman et al., 1990; Oertel and Foyle, 1995). At least one, and possibly two paleochannels of the Susquehanna River were predicted to track north to south under the western portion of the study area (Fig. 1; Colman et al., 1990; Genau et al., 1994). These old paleochannels were indeed observed both in geophysical imaging just north of the study area (Fig 4) and in boreholes. But a much greater distribution of deep channels was also penetrated in geographic association with the present-day Blackwater and Little Blackwater Rivers, making for a far more complex Pleistocene stratigraphy under the BNWR than anticipated (Flemming et al., 2011).

Similarly, the Miocene substrate directly underlying Pleistocene-aged deposits shows an unexpectedly high degree of variability. The Miocene units under the BNWR are comprised of marine deposits of the Choptank and Calvert Formations within the Chesapeake Group (Flemming et al., 2011). These units consist of the eroded sediments of the uplifting Piedmont, Blue Ridge, and Appalachian mountains during early middle Miocene time (~13-12 My) that partially filled a major depositional basin called the Salisbury Embayment that was centered on the Delmarva Peninsula (Fig. 1; Poag and Sevon, 1989). The sediments in these deposits range from shelly sand to very fine-grained clay, the grain size variation suggesting variable depths of overlying water, or a different environment of deposition. Borehole data from closely spaced (<1.5 km) holes in the BNWR region indicates sediments derived from very different depositional environments located at similar altitudes. Though individual beds within these formations are not regionally extensive (de Verteuil and Norris, 1996), the variability observed at such a local scale is suggestive of structurally controlled, vertically oriented faults in these sediments. This interpretation corroborates suggestions of possible faulting of the Chesapeake Group in outcrops on the Calvert Cliffs due west of the field area on the Western Shore of the Chesapeake (Fig 1; Powars, 2013). If this is the case, faults that penetrate and offset the Miocene sediments may provide a first-order control on the location of Pleistocene-to-recent rivers, as suggested for Virginia on the western shore of the Chesapeake (Newell, 1985). These channels in turn reflect the locations of present-day marsh as well as the locations projected to host migrated marsh in the coming decades.

Land Subsidence and Glacial Forebulge Collapse

When considering how glacial-interglacial sea level fluctuations affected sea levels in the Chesapeake Bay region, independent vertical change of the land surface must be considered. Current rates of land subsidence in this region are estimated at 1.7 mm/yr, which is commonly attributed to the collapse of the land surface as it seeks glacial isostatic equilibrium (Peltier, 1986; Engelhart et al., 2010). Under this scenario, viscous mantle material flowed away from regions depressed by the weight of continental ice toward peripheral non-glaciated areas. This glacio-isostatic adjustment (GIA) causes a bulging of the land surface in the non-glaciated terrain called a proglacial "forebulge" in which the surface materials are uplifted due to the influx of mantle material below (Peltier, 1986). The scale of uplift remains unknown, but deposits in Virginia have been interpreted to suggest uplift of 40 m during glacial maxima (Pavich and Markewich, 2006; Scott et al., 2010). Deglaciation and the loss of ice sheets reversed this trend, and the unbalanced gravitational forces induce a return-flow of this material back under the previously ice-covered terrain. The result of this out-flow of material in the non-glaciated area is the collapse of the proglacial forebulge.

The idea of GIA-induced land surface change in the MACP has gained significant traction in recent years because it is consistent with the geologic record. A growing number of ages produced for deposits in the Mid-Atlantic region suggest that estuaries existed during time periods when global sea level was severely depressed based on data from coral terraces and the marine isotopic record (Mallinson et al., 2008; Pavich and Markewich, 2006; Scott et al., 2010). Unknown lag-times associated with the rise and fall of peripheral fore-bulges appear to have caused discrepancies between the timing of global sea level change and regional submersion and emergence of the land surface (eg. Fig 5; Scott et al., 2010). This interpretation helps explain age-elevation offsets for estuarine deposits that have long perplexed geologists (Wehmiller et al., 2004). The modeled effects of ongoing GIA (Peltier, 2004) for the Mid-Atlantic region agree well with measured rates of subsidence (Engelhardt et al. 2009) and corroborate results from high-resolution GPS observations (Snay et al., 2007), long-term tide gauge records (Barbosa and Silva, 2009), and wedded GPS and long-term tide gauge records (Sella et al., 2007) from the 20th century.

Blackwater NWR Geomorphology and Marsh Migration

In light of regionally high rates of relative sea level rise, BNWR managers are turning their attention to the details of the geomorphology in this landscape as they plan for marsh migration in the coming decades. In this process, managers are identifying and mapping potential corridors for the eventual migration of marshes through time and across the landscape to a new intertidal zone reflecting a 1 meter rise in sea level, which is projected to occur by the year 2100 (MCCC 2008).

The details of the BNWR surface were only dimly recognized prior to the acquisition of Light Detection and Ranging (LiDAR)-derived elevation data obtained for the region in 2002-2003. While these high-resolution elevation data were collected for the purpose of predicting the impacts of sea level rise and assessing flood hazards (eg. Larsen et al., 2004), they also facilitate a more comprehensive recognition of the geomorphology and processes active on the landscape (DeJong and Newell, in review). These interpretations provide new details on how this region responds to sea level rise.

The broad bench that the BNWR occupies was previously mapped as a generally featureless barrier-back barrier system deposited under shallow water sometime in the Late Pleistocene (Owens and Denny, 1986). But the topographic base maps used were too coarse (20 ft contours) to identify major geomorphic features in the region, so the interpretation was oversimplified. For example a major scarp separates the uplands to the north and the lower topography (and all marsh) to the south. The scarp has been interpreted as a wave-cut regressive shoreline feature (DeJong and Newell, in review). This scarp will act as a major topographic boundary as marsh in the Blackwater River valley migrates to the higher terrain in the north in the coming decades. Likewise, there is a suite of previously unrecognized landforms that will impact the locations of marsh just south of the Blackwater River Valley, and these features show cross-cutting relationships that help to understand the sequence of events that last shaped the BNWR surface (Fig. 6). These landforms are important because 1) present-day marsh likely accreted onto the same landforms, so we can learn how marshes will migrate onto these surfaces by exploring how the marshes migrated onto them in the recent past, and 2) the landforms themselves are interpreted to derive from the last time sea levels rose and submerged this landscape; they are an extension of the stratigraphy below, which details how sea-level rise and inundation proceeds in this landscape. The adaptation plan being drafted for the BNWR specifies additional research needs related to marsh submergence processes, hydrology at the surface and shallow subsurface, and soil moisture and nutrient loads; none of these can be properly addressed without first determining the sedimentology of the landforms themselves.

Applied Geochronology and Palynology

Cosmogenic Radionuclide Burial Dating: Cosmogenic radionuclide (CRN) burial dating uses the measurement of the rare isotopes ^{26}Al and ^{10}Be that are produced on Earth's surface by nuclear reactions between cosmic rays and quartz-bearing rocks. As high-energy cosmic rays enter Earth's atmosphere, they collide with atmospheric gases to produce a variety of secondary particles including neutrons and muons (Lal and Peters, 1967). It is the high-energy collision of neutrons and muons with quartz-bearing material in the upper meters of rock and soil that produces ^{26}Al and ^{10}Be at a fixed and well-known ratio (6.75:1; Balco and Rovey, 2008). The half lives of ^{26}Al and ^{10}Be, 0.705 Myr and 1.36 Myr respectively, allow burial dating of deposits ranging from 0.2 to 4 Ma [these figures are based on the ^{26}Al decay constant of $9.83 \pm 0.25 \times 10^{-7}$ yr^{-1} (from the reference standards of Nishiizumi, 2004) and the ^{10}Be decay constant of $5.10 \pm 0.26 \times 10^{-7}$ yr^{-1} (from the reference standards of Nishiizumi et al., 2007)], a time interval including many major fluctuations of sea level rise and fall in the MACP.

The classic ^{26}Al - ^{10}Be burial dating method requires 1) quartz material that contains no cosmogenic radionuclides prior to exposure, and is then exposed long enough for ^{26}Al and ^{10}Be to accumulate with a ratio that conforms fully to the production ratio, and 2) the quartz material is then buried deeply enough to shield it from further cosmic ray flux (Granger and Muzikar, 2001). Upon burial, the ratio between these two radionuclides diverges from the production ratio because of differential decay at a predictable rate that can be used as a burial clock. This method is ideal for dating river sediments deposited in caves (Granger et al., 1997) or in deep lakes (Balco et al., in press). But many geologic settings, including those represented within the BNWR stratigraphy, do not conform to this simple, two-stage history (single period of exposure followed by instantaneous, deep burial).

An alternative burial dating method has recently been developed to deal with more complex exposure and burial histories. The isochron method enables dating of quartz-bearing material with unknown inherited ^{26}Al and ^{10}Be concentrations and unknown burial histories (Balco and Rovey, 2008). Originally developed to date till-paleosol sequences with samples collected from different depths, a variant of this method involves sampling several (≥3) clasts and/or grain size separates from sand fractions that are derived from different settings within the watershed, and thus subject to different exposure histories, but have identical post-burial nuclide production (e.g. they were buried together simultaneously). The ^{26}Al and ^{10}Be concentrations from all clasts and grain size separates form a linear relationship, or an isochron, in ^{26}Al - ^{10}Be space (Fig 7). The slope of this isochron depends on the ^{26}Al /^{10}Be production ratio, the ^{26}Al and ^{10}Be decay constants, and on the burial time, but it is independent of the production of nuclides during burial. So if clasts are derived from a wide range of sites with diverse erosion rates, and erosion rates in the watershed are high enough (greater than a few meters per million years) that radioactive decay during transport can be disregarded, the slope of the isochron drawn through ^{26}Al and ^{10}Be concentrations can indicate a burial age for the deposit (see Appendix B for governing equations).

The isochron method is appropriate for dating Pleistocene gravels in the BNWR setting. The coarse-grained fluvial deposits that were deposited in discreet stratigraphic horizons during glacial maxima derive from a variety of settings within the Susquehanna basin and were buried by sequences of interglacial bay-fill material of variable thickness at unknown rates. Erosion rates quantified for sub-basins in the Susquehanna watershed at a variety of spatial scales indicate rates that are high enough that radioactive decay does not alter the initial ^{26}Al - ^{10}Be ratios of gravels (Reuter, 2005). Additionally, unpublished amino acid racemization dating on several mollusks recovered in bay fill material overlying gravels in BNWR confirm previous findings (Genau et al., 1994) that the age of the channel gravels on the western Delmarva are within the age range datable by the isochron burial dating method (John Wehmiller, personal communication March, 2012). This method has proven successful for dating terrace gravels with relatively shallow burial (Erlanger et al., 2012) as well as for gravels buried deeply and recovered in a borehole like the current study (Balco et al., in press).

Optically Stimulated Luminescence: Optically stimulated luminescence geochronology measures ionizing radiation accumulated in quartz sand to indicate the time elapsed since buried sediment grains were last exposed to sunlight. Once buried, sediments are exposed to ambient radiation produced by the decay of naturally occurring radionuclides (U, Th, and K) within surrounding sediments, and also to cosmic rays in the case of shallow burial (Aitken, 1998). This low-level radiation produces free electrons that become trapped in crystal lattice defects near the surface of (in my case) quartz grains, and they continue to accumulate so long as the sediments remain shielded from light. The accumulated radiation, or the "equivalent dose" can be measured by exposing the sediments to light in a controlled laboratory environment. This excites the electrons, and they are emitted to produce a measurable luminescence signal, the brightness of which reflects the accumulated ionized radiation. The rate at which the sediments are irradiated during burial, or "dose rate", can be calculated from the concentration of radionuclides in the surrounding material. Age calculations are then made possible by a straightforward calculation:

Age (ky) = Equivalent dose (Gy) / Dose rate (Gy/ky)

The analytical procedures used in optical dating vary extensively, and choosing the appropriate procedure depends upon the nature of the sediment. The method that will be utilized for the BNWR samples is the single-aliquot regenerative-dose (SAR) protocol described by Murray and Wintle (2000). This protocol has been shown to be the best available method for luminescence dating of fluvial deposits and has been successfully and extensively used (review in Rittenour, 2008).

Difficulties may arise when applying OSL dating to river and estuarine deposits (Aitken, 1998; Wallinga, 2002). The main goal in OSL geochronology is to sample material that was fully exposed to sunlight during transport prior to burial so that any luminescence signal remaining from previous episodes of burial was erased (or "bleached"). In full sunlight, this signal is removed by a factor of 10 in a timespan of seconds-to-minutes (Godfrey-Smith et al., 1988). The samples that yield the best luminescence signal are those that experienced multiple episodes of transport over long distances and are composed of well-sorted, medium-grained quartz sand (Aitken, 1998). Eolian sediments, thus, prove to be the ideal material for OSL dating. But the transport mechanisms associated with fluvio-estuarine processes active in the Chesapeake Bay clearly do not ensure such ideal bleaching conditions. Sediment transport may proceed under several meters of water, and in some instances the water may be turbid. These conditions have the potential to greatly reduce light intensity and/or restrict the spectrum of the light reaching the sediment, which may only permit partial bleaching of sand grains (Aitken, 1998; Wallinga, 2002). This situation has the potential to cause age overestimates by incorporating sand grains with high residual, or inherited, luminescence signals at deposition.

Additionally, calculating an accurate radiation dose rate for BNWR sands poses challenges. For the most accurate dose rate calculation, samples should be surrounded by a radius of at least 30 cm of homogeneous sediment and should not have undergone significant water-content variations during burial (Aitken, 1998; Forman et al., 2000); alluvial sands in BNWR do not guarantee either. OSL samples from BNWR were collected from 2.5 ft (0.76 m) length sections of core and I did not always have the option of ensuring a 30 cm buffer of sediment from nearby contacts. Additionally, depending on the antiquity of sample material and the depths from which samples are collected, they potentially have significant variability in the degree of water saturation during burial. This variability reduces the accuracy of dose-rates measured in the lab, thereby increasing the error reported with ages. Despite these obstacles, optical dating has been successfully employed to develop chronologies for fluvial-to-estuarine deposits (review in Rittenour, 2008). I carefully selected my OSL samples by first flight-augering sample locations to target material that minimizeed complications, and any uncertainties related to complications will be included in the errors reported with ages. Two pilot samples from fluvio-estuarine sands typical of the BNWR stratigraphy were run prior to the major sampling campaign, and they produced ages that are consistent within their respective uncertainties as well as with other OSL ages produced regionally (USU-265 and USU-266, Table 1; Mallinson et al., 2008; Pavich and Markewich, 2006; Scott et al., 2010).

Palynology:

Dinoflagellates: Dinoflagellates are unicellular algae best known for their algal blooms that result in a visible coloration of the water known as "red tides". During their life cycle, dinoflagellates go through a zygotic phase in which they produce cysts, or dinocysts, with coatings of dinosporin. This substance makes the dinocysts highly resistant and allows preservation of dinocysts within the fossil record. Many extinct species have proved useful in characterizing the Mesozoic and Cenozoic biostratigraphy, and while no worldwide zonations exist for dinocysts, a zonation scheme was erected for the Miocene stratigraphy in the Salisbury Embayment that includes 10 named and numbered zones (DN1-DN10 in Fig 8; de Verteuil and Norris, 1996). Since its establishment, this dinoflagellate zonation scheme has been widely accepted and employed in stratigraphic studies in the Chesapeake Bay region (ie. Alemán González et al., 2012; Edwards et al., 2005) and is even being used to verify lingering and tentative correlations between regional units that have been studied since the early 1900's (Kidwell et al., 2012).

Preliminary dinoflagellate data from the Miocene stratigraphy under the BNWR indicate presence of dinocyst zones (DZ) 5-7 of de Verteuil and Norris (1996), which correlate with the Middle Miocene Calvert and Choptank Formations (Figure 7). The recognition of these formations would otherwise prove difficult in isolated cores under BNWR, as formational divisions were based on local mollusk assemblages along the Calvert Cliffs (~10 km west of the field area) that do not extend to the BNWR (Shattuck, 1904). Lacking these fossil beds and long lithologic sections for context, dinoflagellates provide a regionally consistent means of providing relative ages and correlations.

Pollen: Pollen assemblages preserved in sediments indicate local to regional vegetation types and thus, by inference, climatic and environmental conditions for the time of deposition (Willard et al., 2003, 2005). In the Chesapeake region, changes in pollen type and abundance over geologically short (centennial) timescales have been shown to statistically reflect changes in forest composition due to precipitation and/or temperature regimes resulting from changing climate (Willard et al., 2003). These data are important to the BNWR record for two reasons. First, since pollen is derived from local to regional terrestrial flora, changes in flora are recorded in sediments regardless of their environment of deposition. Pollen data can thus help match contemporaneous river, estuarine, and marginal marine sediments in the BNWR stratigraphy for 3-dimensional paleographic reconstructions similar to those produced on similar-aged deposits in coastal North Carolina (Culver et al., 2011). Second, pollen data can help determine the relationship of deposits in the BNWR stratigraphy that are separated by subtle contacts. It is sometimes difficult to assess whether a contact represents an unconformity (a major time-gap between bounding units) or just a short-term change in energy gradient (like a storm event or the passing of a laterally migrating stream). By showing relative proportions of species abundance, pollen spectra analyses can determine any differences in forest assemblages between these units.

Pollen analysis has proven to be a powerful tool in interpreting Holocene to late Pleistocene environments of the mid-Atlantic region. The first major investigation of Pleistocene pollen on Delmarva took place in the late 1970’s and was focused on Late Wisconsin-aged deposits (Sirkin et al., 1977). At that time, several landforms on the uplands were first confirmed as being derived from cold, dry conditions similar to tundra or taiga based on pollen indices (Denny and Owens, 1979; Denny et al., 1979; Sirkin et al., 1977). More recent studies on similar units west of the Chesapeake Bay (Markewich et al., 2009) and on Delmarva (Newell and DeJong, 2011) corroborate these findings, but remain focused on the Wisconsinan-aged deposits. The units penetrated beneath the BNWR present a unique opportunity to extend this record likely by at least 100 ky for the Delmarva Peninsula. Recently, the first continuous climate record spanning the time period from 115-15 ka was produced for the Mid-Atlantic region based on paleovegetation shifts shown in pollen records from cores drilled just 75 km W-NW of the BNWR (Litwin et al., 2013). This record spans the timeframe relevant to research objectives 1) and 2) and thus provides an excellent frame of reference for contextualizing results from the BNWR.

<u>Subsurface Data Acquisition in the BNWR</u>

The altitude within the study area rarely exceeds 2 m asl, and exposures of surficial deposits and underlying substrate are uncommon, ephemeral, and usually related to land-use practices. Therefore any exploration into the subsurface in this landscape requires access via drilling and geophysical logging and profiling. Three drilling platforms and one ground penetrating radar instrument were made available from the USGS for subsurface studies at the BNWR.

Drilling platforms:

Hollow-stem Augering: The cores from the BNWR were collected using a hollow-stem auger continuous sampling system (CME-75). Sediment cores are collected in 7.6 cm (3 in) diameter plastic liners in an inner core barrel that is straight-pushed inside ~21 cm (8.25 in) diameter augers (Fig 9a). Lacking any rotational motion, the resulting sediment cores provide exquisite sedimentary details. These cores were used to collect pollen samples and OSL samples and to provide detailed sedimentologic information about the surface units in and around the BNWR.

Flight Augering: Flight augering with the Central Mine Equipment (CME)-45 drill was used for a majority of locations on land. With this set-up, we drilled an 11.4 cm (4.5 in) diameter solid-stem auger into the ground and then straight-pulled them to analyze the sediments on the auger flights (Fig 9b). This provided accurate depths to contacts as well as samples for sedimentology, geochronology (cosmogenic nuclide) and palynology. If drilled carefully with a one-to-one ratio of rotation to depth, the sediments are minimally disturbed such that sedimentary structures remain intact. This is by far the most cost-effective means of accessing the subsurface, and we used this method to locate optimal locations for coring with hollow-stem augers.

Vibracoring: Accessing subsurface information in water-locked areas like BNWR proves difficult due to the challenges associated with access with large machinery. There are no roads within the footprint of Lake Blackwater. It is too large to exclude in a regional dataset; too shallow for barges or boats large enough for mounted drill rigs. The USGS responded to this need by developing a drill-mounted hovercraft in hopes that by merely skimming the water, researchers could gain access to these remote locations and provide information that was not previously attainable. The result was the Hoverprobe 2000 (HP2000), a hovercraft-mounted, hydraulically powered sonic core (vibracore) drill (Fig 9c; Newell and Queen, 2000). The HP2000 is capable of capturing up to 15 m of 6.35 cm (2.5 in) diameter core in ~1.5 m (5 ft) sections in BNWR sediments.

Ground Penetrating Radar: Geophysical methods will be used to better constrain the lateral extent of units seen in boreholes and to assess the subsurface architecture of landforms that will one day host migrated marsh. Ground penetrating radar (GPR) will be employed in this study using an unshielded, 25 MHz MALÅ Rough Terrain Antenna (RTA) system. Because the BNWR area is so close to sea level, high groundwater levels and saturated sediments present a major challenge to geophysical exploration. But the low frequencies associated with the RTA setup help combat shallow radar attenuation and should allow sub-surface visualization up to ~10 m. GPR has been successfully employed to image the shallow subsurface in similar field areas on the Virginia coastal plain (Mallinson et al., 2008, Swift et al., 2003).

RESEARCH DESIGN

Each of the three major hypotheses outlined above requires its own strategy for evaluation; I needed a unique dataset to test each hypothesis derived from sediments at varying depths in the subsurface. I prioritized drill site locations so as to address more than one hypothesis and serve multiple objectives wherever possible. Hypothesis 1 includes features readily identified in the BNWR geomorphology, and so it is the only hypothesis that could be addressed with sites that were not not guided by previously gained information. I thus made this my first priority and chose my first sites so as to penetrate these landforms, and I continued drilling through to the deeper stratigraphy to address the older Pleistocene (hypothesis 2) and also the Miocene (hypothesis 3) units where possible. I chose a wide spatial distribution to cover the full suite of landforms over the BNWR area in this way, and then as patterns became apparent in the deeper stratigraphy, I used them to further guide my approach as well as future drilling campaigns to address any additional questions or complexities that arose. The end result is a full coverage of borehole locations over the field area with local clusters of data points where necessary, such as near the margins of paleochannels. To help differentiate specific methods for each major hypothesis, they are presented here individually:

Hypothesis 1 Methods:

Establishing whether the prominent landforms around the BNWR were derived from an estuary when global sea levels were relatively low required analysis of the entire suite of landforms represented in the BNWR area. To this end, I drilled 12 hollow-stem auger cores in a wide spatial distribution of these landforms (magenta circles; Figure 2) in order to collect samples for sedimentology, geochronology, and pollen analyses to determine the environments, timing and climate of deposition, respectively. I then flight augered 45 boreholes (orange circles; Figure 2) to map the distributions of units seen in sediment cores. Additionally, I drilled 10 vibracores along two transects near the confluence of the Blackwater and Little Blackwater Rivers (yellow circles; Figure 2) to gain a greater understanding of the relationship between the active marsh and the landscape on which it grew. I collected 8 radiocarbon samples from these cores to constrain the onset and growth of the active salt marsh at the BNWR. Finally, I ran GPR transects across several representative landforms to analyze the lateral extent of sedimentary packages in the subsurface.

I am bracketing the ages of landforms using OSL methods wherever appropriate sands were available. Lacking natural exposures of deposits in the BNWR, OSL samples were extracted from sediment cores. First, datable sands needed to be located. To identify sands for OSL dating, I flight augered landforms of interest and determined the depths to appropriate sands for the method. I then painted core liners with several coats of black paint to ensure they would not transmit light and cored the sands using the hollow-stem coring system. When we pulled the steel inner core barrel out of the augers, we placed it directly on pipe vices under a thick tarp. I then carefully extracted the core liner from the core barrel under the tarp, placed liner caps on each end, wrapped it in black trash bags, and placed it in a box ensuring that the sand was never exposed to light.

I also collected pollen from the Pleistocene-to- Holocene stratigraphy in both sediment cores and auger flights from select cores to track environmental changes through time within individual deposits and to compare relative populations of species between multiple units to ascertain whether climate proxies are consistent landform-to-landform (and thus the landscape represents one phase of deposition). This analysis is of particular interest in comparing units above and below the scarp that separates the uplands in the north and the marshland to the south (orange line, Fig 2). Pollen data may allow me to ascertain whether this scarp is erosional, and thus units may have been deposited coevally on either side of the scarp, or depositional, such that units deposited below the scarp were deposited in a later sea level high stand than the upland landforms. Pollen samples collected from cores were extracted by separating a 1 cm half-round (half core) section with a sharp knife and then trimming it with a razor to ~2 cm^3 of material for analysis. Pollen samples collected from auger flights required care to avoid contamination from other horizons. Only competent sediments that adhered tightly to auger flights were sampled. I collected sediments off a single auger flight and then scraped all sides so that only the inner sediments were sampled and any material from other horizons that may have stuck to the outside were not avoided.

Hypothesis 2 Methods:

Discerning whether the growth and collapse of a proglacial forebulge has caused lag times in the relative highs and lows of regional sea levels through the Pleistocene requires establishing a well constrained geologic framework with robust age control. To this end, I have been mapping out the distribution of deposits in the subsurface based on detailed sedimentologic and stratigraphic analysis largely from flight auger locations (for example see Appendix A.) I am producing age control for the entire framework using two geochronologic methods. The oldest channel deposits underlying BNWR will be dated using the cosmogenic isochron burial method. Upon completion of the drilling campaign, I took inventory of all gravels that I had encountered and sampled from both sediment cores and auger flights under BNWR. I then reviewed where these gravels fit within the stratigraphic architecture of BNWR as established from sedimentologic analyses and preferentially subsampled gravels based on relative age and source area to establish a chronology for the entire framework of both Susquehanna River-derived (Western BNWR) and Choptank River-derived (Eastern BNWR) paleochannels. In all, 8 isochron ages will be produced for a total of 32 clasts (^{26}Al–^{10}Be pairs). Because the youngest ages obtainable by the isochron method are similar to the oldest ages obtainable with OSL methods, I am using OSL to extend the chronology to the surficial units addressed in hypothesis 1. I collected additional OSL samples below the uppermost deposit addressed in hypothesis 1 for this purpose. These methods produce ages for sea level low-stands (basal gravels and sands at the bottom of paleochannels) and sea level high-stands (fluvial and estuarine sands near the top of sedimentary sequences) that can be compared with established global sea level curves.

Additionally, where multiple cut-and-fill deposits are encountered in stacked relationships, pollen samples will be collected from each unit to help track the behavior of climate through time. The younger portion of this record will be referenced against a long (~115 ky) paleoclimate record produced from pollen analyses from a core on Virginia's Western Shore (Litwin et al., 2013).

Hypothesis 3 Methods:

To test whether Pleistocene paleochannels incised into and occupied locations where the Miocene stratigraphy is faulted requires both regional (lower resolution) and local (higher resolution) distributions of data. The regional distribution was created by choosing drill sites for hypotheses 1 and 2 that extend from the western-most shores of the Delmarva landscape to the eastern-most portion of the field area. I established transects of Miocene sediments in this process in such a way that they align with the most thoroughly studied exposures of the units at the Calvert Cliffs (Fig. 1). Detailed analysis of the sedimentology is being used to first provide a lithologic framework of units. I am complementing this framework with interpreted well logs available from Dorchester County, from which I am interpreting depths to the Miocene surface. I am using these combined data to create a contour map of the Miocene surface. I sub-sampled sediment cores and auger cuttings for analysis of dinoflagellate populations in the Miocene sediments. This dataset is well-constrained in the Tertiary stratigraphy of the Chesapeake region and the Calvert Cliffs specifically and has been shown to finely resolve the ages of Miocene deposits independent of environment in which the host sediments were deposited (ie. Kidwell et al., 2012). Dinoflagellate samples were sampled in the same way that pollen samples were collected as mentioned above. I collected dinoflagellate samples at least 1m from major contacts, as bioturbation near contacts can cause contamination. Higher densities of data were collected where possible near paleochannels to gain a better sense of the Miocene units in these locations. A combined lithologic and biostratigraphic analysis will allow me to finely resolve any vertical offsets in the rocks and produce a structure contour map for them.

Laboratory Methods

Cosmogenic Dating: Sample processing for cosmogenic radionuclide dating was completed at the Cosmogenic Radionuclide Laboratory at the University of Vermont. Gravels that were sub-sampled from core and auger samples were crushed and ground into the 90-500 μm fraction to purify quartz for analysis. Because many gravels yielded less material than typically desired, and they generally consisted of pure quartzite, I modified the usual quartz purification procedure used in the laboratory (Kohl and Nishiizumi, 1992) primarily by using slightly weaker concentrations of acids and shorter etching intervals. Samples experienced a 24 hour 6N HCl bath followed by three 24 hour baths in 0.5% HF, 0.5% HNO_3 solution. The remaining opaque and heavy minerals were removed from the grain size separates (non-clasts) using LST heavy liquid, as these samples tended to be less pure than pulverized quartzite clasts. The samples were then dried and tested for purity on an inductively coupled plasma (ICP) optical emission spectrometer. If a sample failed this test, it was treated with one more HF-HNO_3 bath.

Once pure, the samples were transferred to the cosmogenic laboratory where they were spiked with ^{9}Be, dissolved completely in concentrated HF, and run through cation and anion columns for isolation of Be and Al. The Be and Al fractions were then precipitated as hydroxides, dried off to form small pellets, and packed into targets with Nb or Ag for measurement at either the Lawrence Livermore National Labs (Be) or the Scottish Universities Environmental Research Center (SUERC) accelerator mass spectrometers.

Optically Stimulated Luminescence Dating: The cores collected for OSL geochronology were split at the USGS in Reston, VA in a windowless laboratory under limited, red-filtered light. Once split, sands from target OSL intervals were collected exclusively from the very inner portion of the core for added confidence that the sampled sands were never exposed to light. The samples were then placed in a light-tight box and brought to the Utah State University Luminescence Laboratory (USULL), where I processed them to pure quartz. A narrow grain size fraction (either 90-120 μm or 180-120 μm based on availability in each sample) was isolated by means of wet sieving, heavy minerals were extracted via density separation using sodium polytungstate (SPT), and carbonates and feldspars were removed through a series of hydrochloric and hydrofluoric acid baths. The remaining quartz fraction was mounted as 2-mm diameter aliquots on aluminum disks for OSL analysis on a RISO TL/OSL-DA-15B/C reader with blue-green light stimulation (470nm), which provided the equivalent dose used for final age calculations. Dose-rate samples were collected from sands surrounding the OSL samples to determine paleo-dose rates.   Finally, water-content samples were collected and analyzed immediately after core liners were opened and OSL samples extracted.

Palynology and radiocarbon dating: Samples for both pollen and dinoflagellate analyses are being processed by collaborators at the US Geological Survey in Reston, VA. Dr. Christopher Bernhardt and Dr. Lucy Edwards and are taking the lead on all sample processing related to pollen and dinoflagellate analyses, respectively, in their laboratories at the USGS. Samples for radiocarbon dating were submitted to Dr. Jack McGeehin, who processed the samples in his laboratory at the USGS and submitted them for AMS at the NSF-Arizona Accelerator Mass Spectrometry facility in Tucson, Arizona.

Ground penetrating radar imagery: I collected these data with field assistance from an undergraduate UVM Geology student who I am mentoring through the Rubenstein Mentoring Program. Stefan Christie will use these data to complete his undergraduate research and his BS degree. We will reduce this data together this spring using RADAN software available from the Geology Department at the University of Vermont.

PROCESSED DATA and PRELIMINARY INTERPRETATIONS

Sedimentology

I have analyzed core samples and auger samples to describe the sedimentologic details of the BNWR stratigraphy. This included hundreds of descriptions including color (from fresh cores or from fresh auger cuttings in the field using the Munsell Color Chart;), grain size, mineralogy, organic material, and fossils (Appendix A). These descriptions are currently being used to compile 2-dimensional cross-sections across the field area (Fig. 10) and ultimately a 3-dimensional geologic framework for the Pleistocene-Holocene stratigraphy with age control and environmental proxies based on pollen spectra analyses.

Geochronology and Palynology:

Optically Stimulated Luminescence: 26 OSL samples were processed at the USULL, and 12 are currently being analyzed there (Table 1). The remaining 14 samples were shipped to the USGS Luminescence Dating Laboratory in Denver, CO, and up to 12 of these will be analyzed based on final results at Utah State. I am interpreting preliminary analytical results from the USULL to suggest that estuarine deposition in the BNWR region proceeded from ~80-45 ka, possibly with short hiatuses between these timeframes. Deposition during this entire time period conflicts with global sea level curves and supports records from coastal margins of Virginia to the south (Mallinson et al., 2008, Scott et al., 2010) and from the Potomac River valley (Pavich and Markewich, 2006) due west of the BNWR indicating submergence of the mid-Atlantic coastal land surface at that time.

Cosmogenic Radionuclide Dating: Eleven clasts have been measured for ^{10}Be at the LLNL; one clast from each isochron and 3 clasts from a single isochron. The ^{10}Be concentrations from multiple isochrons and within the cluster of 3 samples from one isochron show a spread over an order of magnitude, which reflects the variability of inherited ^{10}Be concentrations in source rocks included in the fluvial gravels. Though no ^{26}Al has been measured yet for isochron calculations, the dynamic range in ^{10}Be concentrations is encouraging and it suggests enough variability in source rock erosion rate to produce an isochron based on results by Balco and Rovey (2008).

Miocene Lithostratigraphy and Dinoflagellates: The Miocene substrate under the BNWR region has been penetrated in 35 locations at elevations of ranging from 5 m to 53 m below sea level, depending on the degree (depth) of Pleistocene incision. Fossil dinoflagellates have been identified and counted 10 of these locations. While the spatial resolution of completed samples is still too low to address my original hypothesis that the Miocene stratigraphy is faulted near the locations of paleochannels, the completed analyses have allowed me to confidently identify Miocene units at the formational level, and in some cases at individual members within formations. This challenges previous assertions that this stratigraphy is impossible to map in the subsurface (de Vertuille and Norris, 1996), though the spatial resolution of borehole data required to do so is typically cost prohibitive.

Pollen and Paleoenvironments: Pollen has been analyzed from six cores, two of which span several distinct and major fill units under the BNWR. These records have greatly assisted in making preliminary interpretations on the timing of deposition and the environmental changes within and between these units (Fig. 11 a, b). They have also assisted in making correlations between units in multiple boreholes. Attempts to correlate these records to the long pollen-based paleoclimate record on the Western Shore of Virginia (Litwin et al., 2013) are awaiting geochronologic control from OSL samples in cue at the USGSLL.

EXPECTED FINDINGS and PRODUCTS

This study will be the first high-resolution subsurface analysis in a region that is suffering the greatest effects of relative sea level rise on the North American eastern seaboard. By determining the distribution, timing, and depositional environments of units from the deepest and oldest channel-fill deposits to the modern surface of the BNWR, we gain a much greater perspective into how this landscape responds to dramatic (>100 m) sea level fluctuations. In testing the three major hypotheses of this study, I will provide:

1) A comprehensive, 3-dimensional reconstruction of the Pleistocene geologic framework under the Blackwater NWR.
2) A full chronology for the evolution of the BNWR region through several glacial-interglacial sea level fluctuations.
3) A full characterization of the geomorphic features surrounding the BNWR marshland that will significantly affect future marsh migration.

4) Determination of relative shifts in climate in the MACP determined from proportions of flora represented in the pollen record between multiple depositional units
5) Tight biostratigraphic constraints on the distribution of the Miocene stratigraphy in a region where the nature of these units is poorly understood
6) Determine if deep-seated faults penetrate the Miocene stratigraphy and control Pleistocene-to-recent locations of distributions of marsh

Upon publication of papers related to the three major hypotheses, and upon re-entry to full-time status with the U.S. Geological Survey, I will also update and publish the geologic mapping in the Blackwater, Golden Hill, and Taylor's Island 7.5' USGS quadrangles, Dorchester County, Maryland with cross-sections that include data from this study. To make my findings more accessible to the general public, I will produce a U.S. Geological Survey (USGS) Factsheet that includes a summary of my findings for distribution at the BNWR Visitor Center.

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TIMELINE

Fall 2010 (TA Support)

- TA: Geol 001—Introductory Geology with Dr. Char Mehrtrens; Geol 007—Earth Hazards with Dr. Paul Bierman
- Courses: Geol 217: Vermont Field Geology; Geol 295: Teaching in the Geosciences; Geol 371: Critical Writing in Earth and Environmental Sciences; NR 243: GIS Practicum
- Plan locations and logistics for first drilling campaign

Spring 2011 (TA Support)

- TA: Geol 008—The Dynamic Earth with Dr. John Hughes
- Courses: CE 369: Applied Geostatistics; Geol 233: Environmental Isotope Geochemistry; NR 346: Digital Image Processing

Summer 2011

- First drilling campaign: Augered 15 locations; sediment cores collected from 10
- Compiled data from previous drilling accomplished at the US Geological Survey
- Sub-sampled cores for OSL and pollen samples

Fall 2011 (TA Support)

- TA: Geol 151—Geomorphology with Dr. Paul Bierman
- Courses: Geol 295: X-Ray Diffractometry; NR 385: Envisioning a Sustainable Future [for fulfillment of cross-cultural experience]
- Sedimentologic work on auger samples

Spring 2012 (TA Support)

- TA: Geol 007—Earth Hazards with Dr. Paul Bierman
- March, 2012 drilling campaign: Augered 8 locations
- Begin processing samples for non-dissertation collaborative varve project
- Measure varve samples at Scottish Universities Environmental Research Center

Summer 2012

- Processed 26 OSL samples at the Utah State University Luminescence Laboratory
- August drilling campaign: Augered 12 locations
- TA: Geol 172: Regional Geology of Colorado with Dr. Stephen Wright
- Sedimentologic work on auger samples

Fall 2012 (USGS Support)

- Begin Graduate Teaching Program with the Center for Teaching and Learning for partial fulfillment of teaching requirements
- Co-teach Geol 151: Geomorphology with Dr. Paul Bierman to fulfill classroom component of Doctorate teaching requirements
- Processed quartz from gravels for isochron dating samples in the Mineral Separation Laboratory at the University of Vermont
- Present preliminary findings on varve project at AGU; San Francisco, CA

Spring 2013 (USGS Support)

- Process isochron samples in the Cosmogenic Laboratory at the University of Vermont
- Present preliminary data at NE GSA in Bretton Woods, NH: Further Evidence For Late Pleistocene Land Surface Adjustment In Response To A Glacio-Isostatic Adjustment In The Mid-Atlantic
- Make plans for final drilling campaign including making contacts with private landowners
- Begin dissertation proposal based on analytical funding outlook from USGS
- Present preliminary data on varve project at EGU in Vienna, Austria

Summer 2013

- [Have Baby]
- GPR work in field area: 13 transects (with student mentee Stefan Christie)
- Final drilling campaign to field area: augered 13 holes in new locations
- Write dissertation proposal
- Continue research and preliminary data analysis

Fall 2013 (USGS Support)

- Present and defend dissertation proposal
- Written and oral comprehensive exams
- Continue data analysis
- Measure BNWR isochron samples at LLNL and SUERC
- Finish lab work on varve project

Spring 2014 (USGS Support)

- GPR data reduction and analysis (with student mentee Stefan Christie)
- Final data analysis and synthesis
- Write papers as chapters for dissertation
- Defend dissertation

Summer-Fall 2014 (USGS Support)

- Final formatting and submittal of journal articles in dissertation

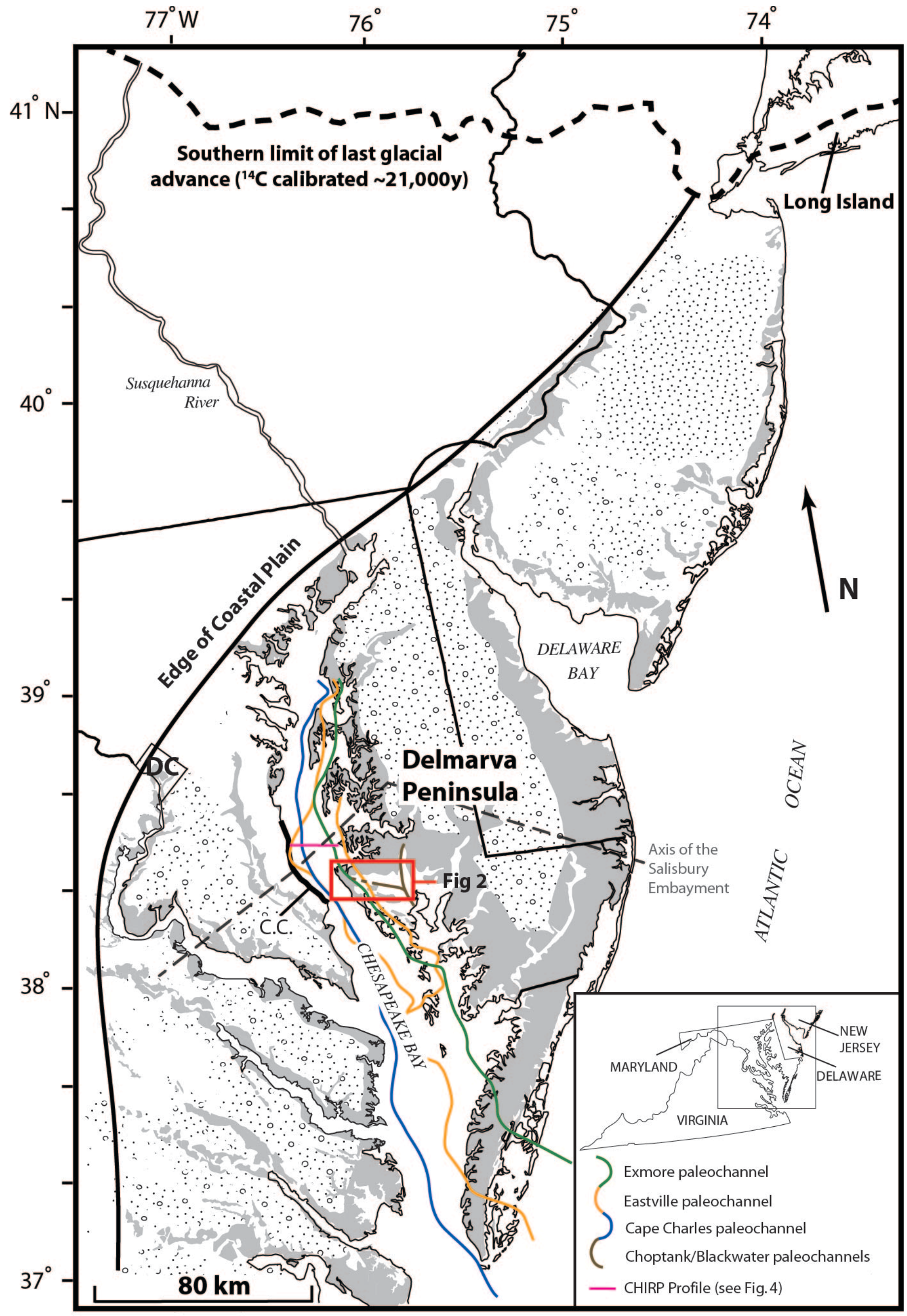


Figure 1. The Chesapeake Bay region of the Mid-Atlantic Coastal Plain. Circle-and-dot hatching indicates late Miocene-Pliocene sand and gravel deposits; shaded regions show low-land terraces from Late Pleistocene transgressions (white fringe where buried under Holocene sediments); C.C. shows location of the Calvert Cliffs (bold black line). Exmore, Eastville, and Cape Charles paleochannel locations from Colman et al., 1990 and un-named Choptank/Blackwater paleochannel from Fleming et al., 2011 and preliminary drilling for this study. Axis of the Salisbury Embayment from Powars et al., 2013. Modified from Newell and DeJong, 2011.

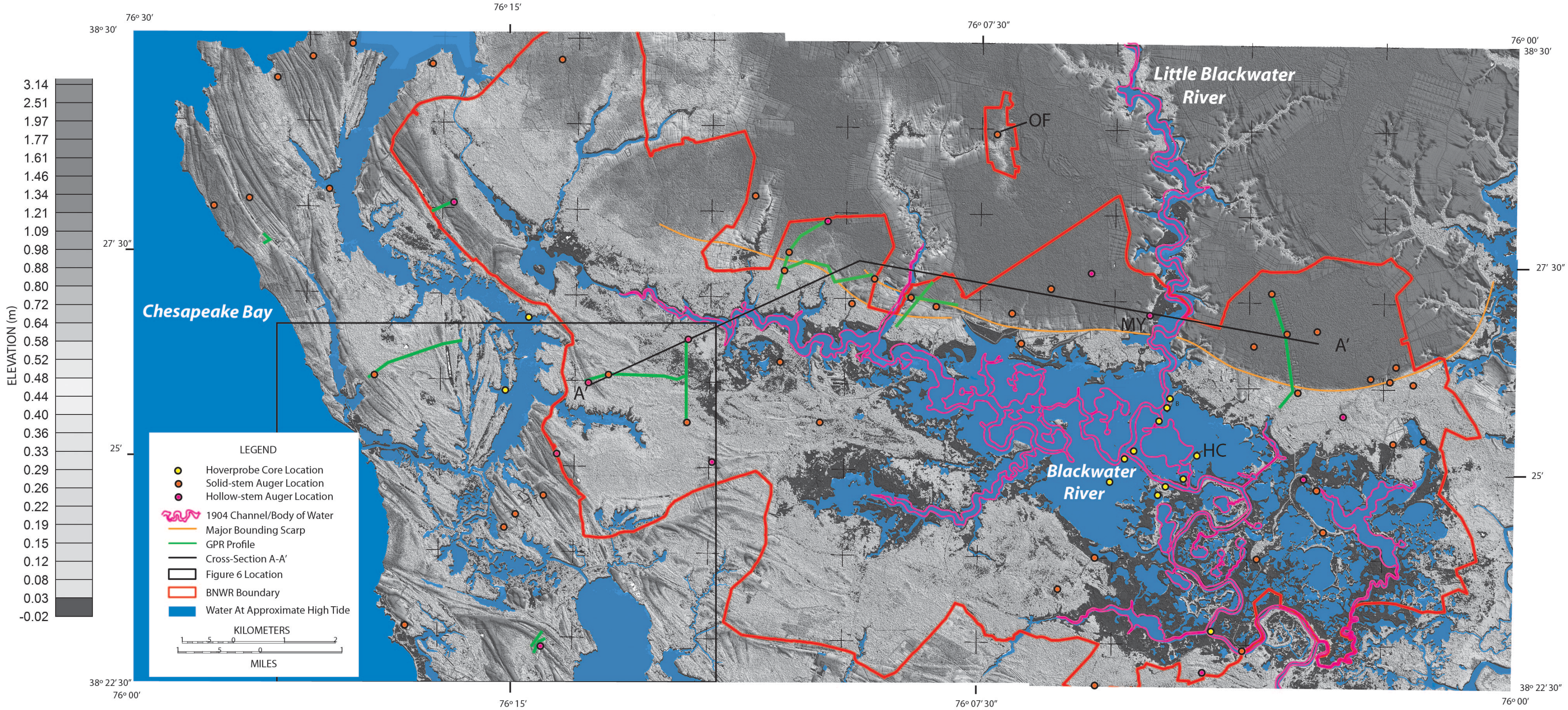


Figure 2. LiDAR DEM of the study area showing locations of boreholes and GPR lines as well as key features indicated in the text; areas in grays-cale reflect land, areas in blue reflect waterways at high tide.

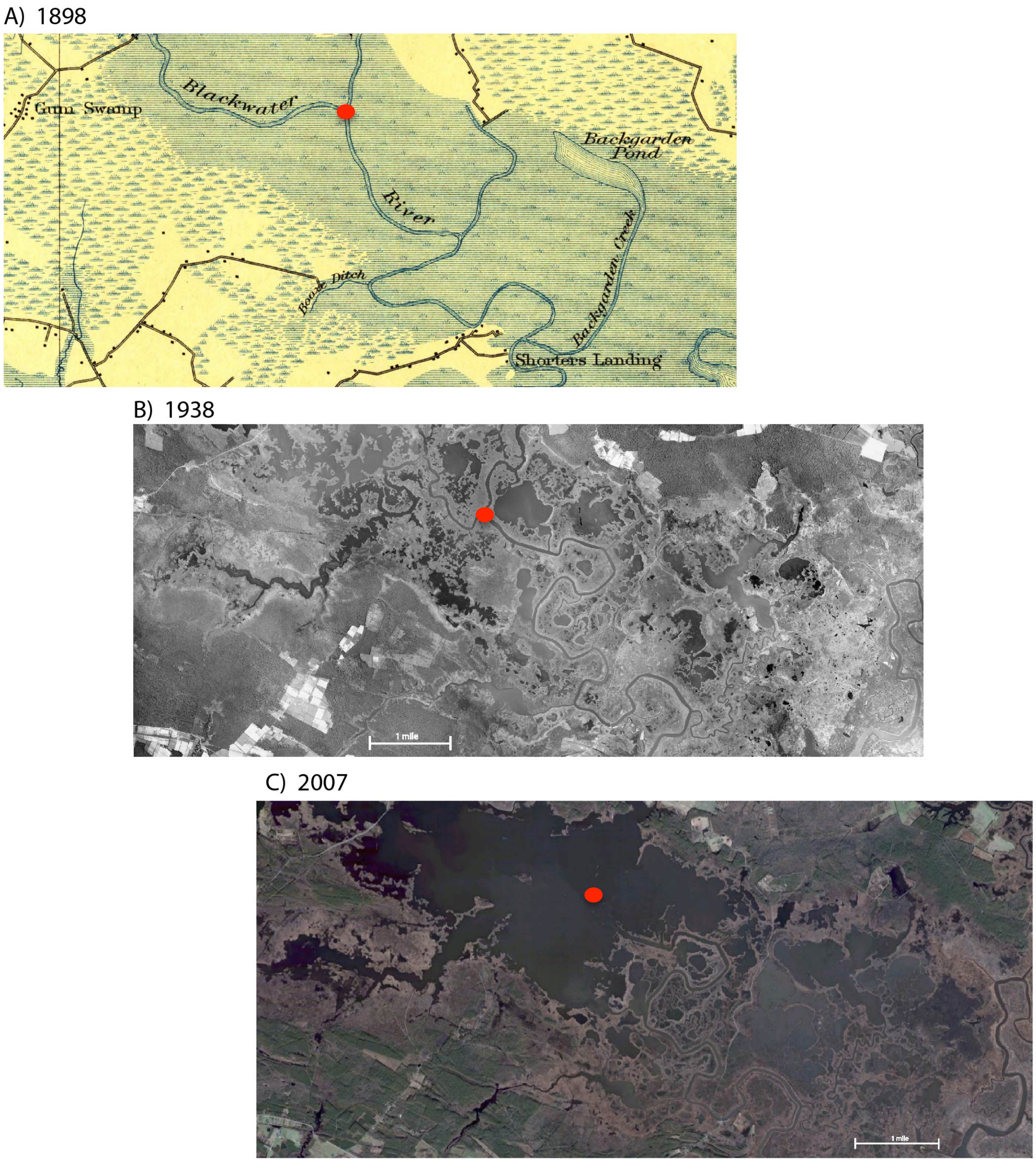


Figure 3. Over 100 years of landscape change at BNWR visible from A) original surveys (1898; from USGS Topographic Map series); B) 1938 (orthorectified aerial photograph); and C) 2007 (from Bing Maps). Note well-delineated channels in 1898, the formation of open-water ponds in 1938, and the coalesced ponds to "Lake Blackwater" in 2007. The location of the red dot is the same for each image (the confluence of the Little Blackwater and Blackwater Rivers) and is added for reference.

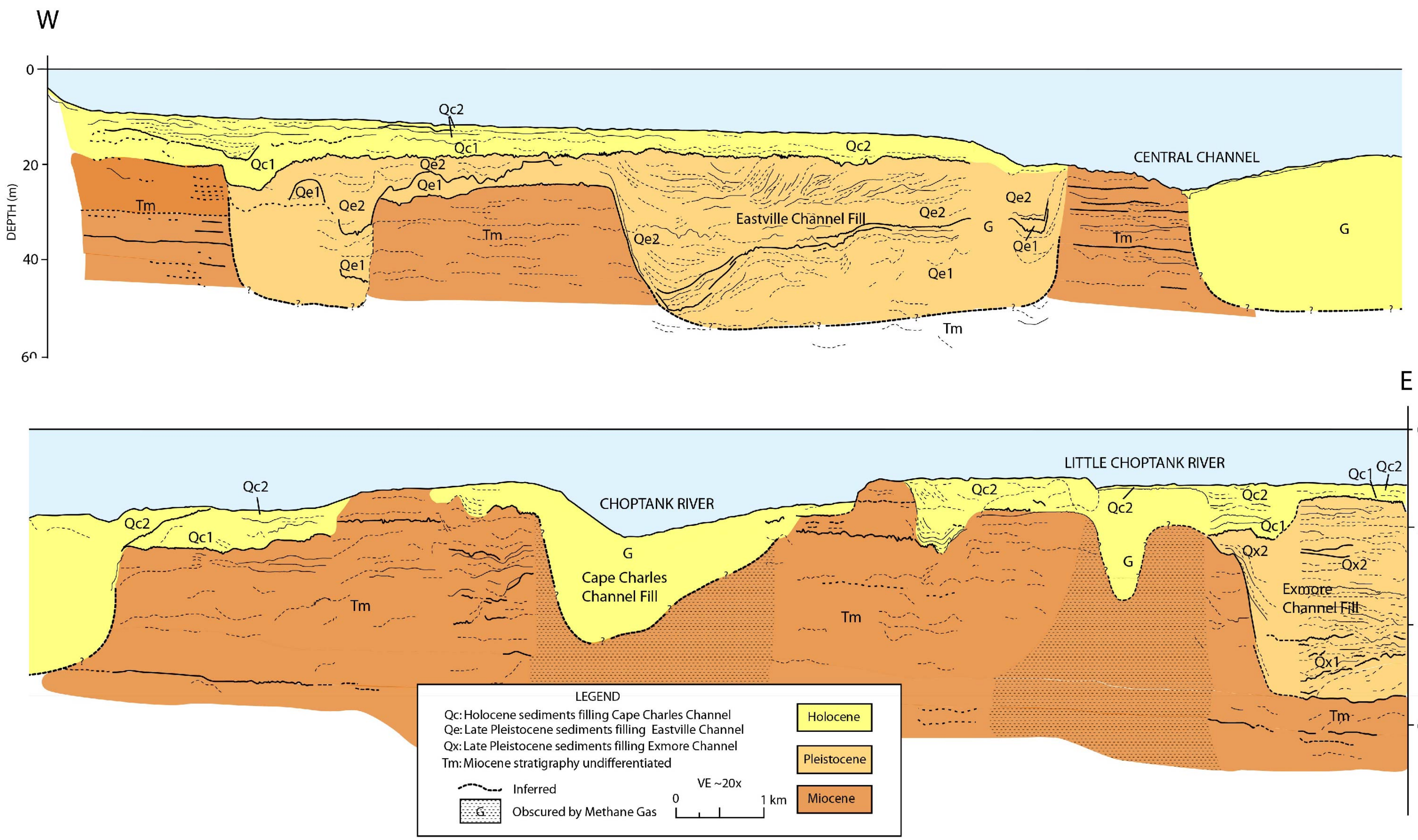


Figure 4. Geologic interpretation of a CHIRP Geophysics Profile of the mainstem Chesapeake Bay approximately 9 km north of the study area (38° 35' N, 76° 30.645'W to 38° 35' N, 76° 20'W; see Figure 1). A cross-section of the Exmore Paleochannel of the Susquehanna is located due north of the deep channel deposits observed in the field area. Collected by the Naval Research Laboratory from an X-star system off the MD Geological Survey research vessel the Discovery, later renamed the Kerhin.

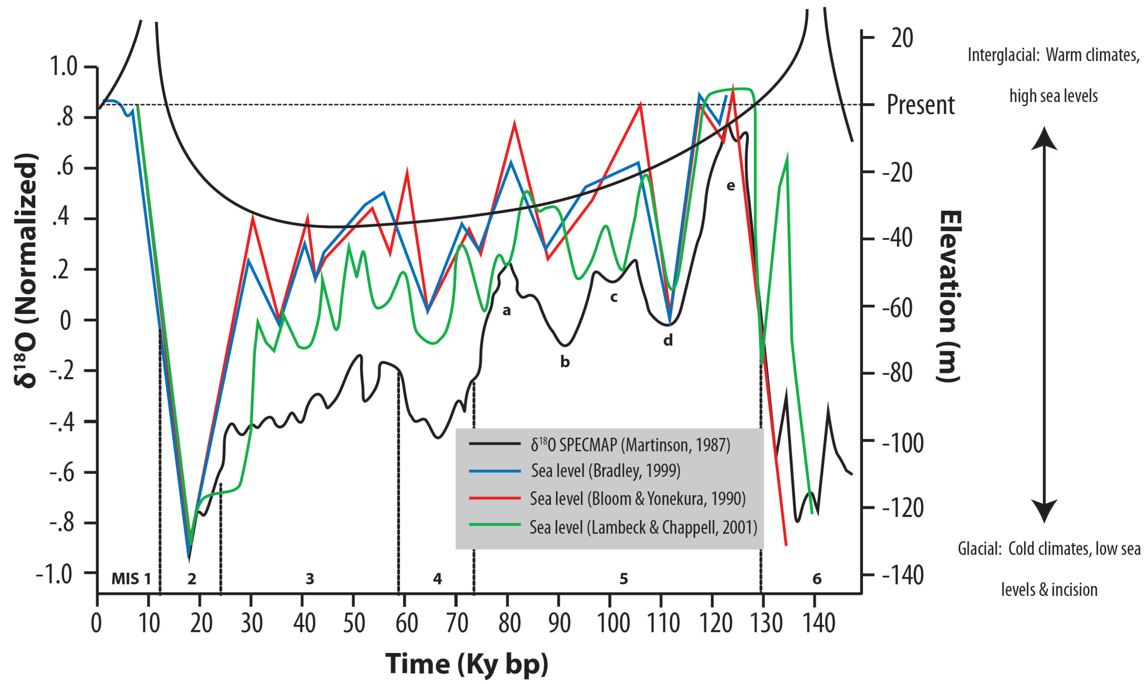


Figure 5. A theoretical glacioisostatic curve of the land surface (upper curved black line) draped over several independent global sea level curves showing the potential for submergence of the MACP landscape during periods of globally depressed sea levels. The glacioisostatic curve is based on ages produced for regional geologic deposits indicating fluvial to estuarine sedimentation, and therefore submergence of the MACP landscape. Land surface would have steadily remained at present sea level (dotted line) in the absence of vertical motion through time. Modified from Scott and others (2010).

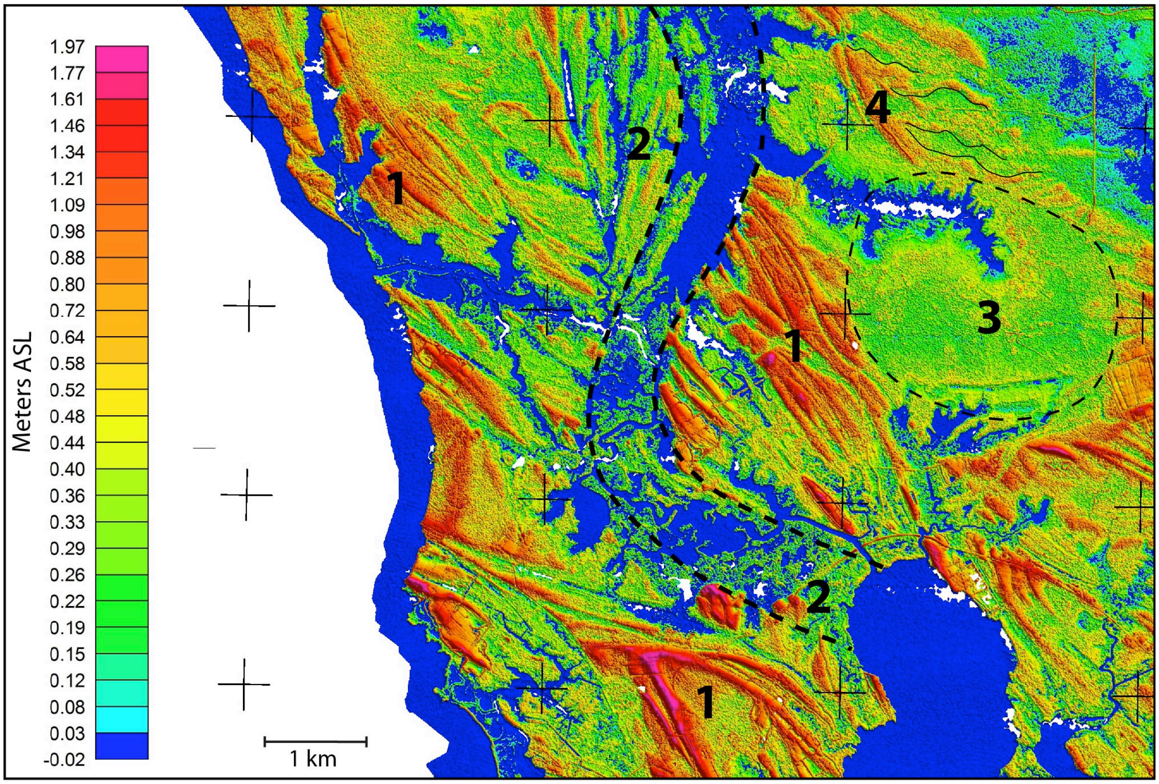


Figure 6. Map of the southwestern portion of the field area with variable elevation intervals that show subtle features at lower elevation as well as the higher-elevation features. This location shows cross-cutting geomorphic relationships near Blackwater NWR: 1) Large NW-SE trending estuarine dunes; 2) Large meanders of a river channel truncate these dunes and cut the view in half from north to south. This is seen in association with large point bar deposits seen on the NW and SE edges of meanders. 3) The edge of a raised-rim elliptical basin (interpreted as an ephemeral pond active during the LGM) also truncates the dune field; 4) Smaller dunes form thin sinuous WNW-ESE linears across the landscape north of the basin. Features 2, 3, and 4 have been interpreted as cold climate (periglacial) landforms derived from processes active during the Last Glacial Maximum. See inset box on Fig. 2 for location; modified from DeJong and Newell (in review).

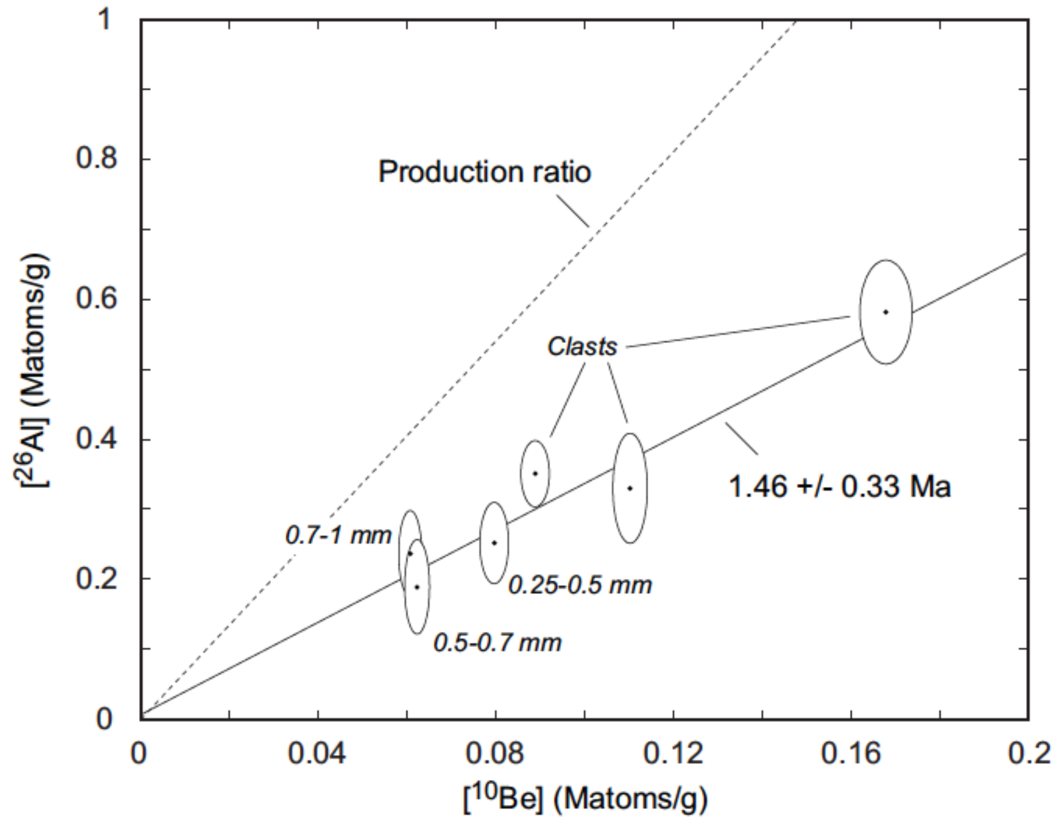


Figure 7. Example ^{26}Al-^{10}Be burial isochron from Balco et al. (in press). Clasts and sand fractions are sourced from different regions in the watershed, and so were subject to varying exposure histories and erosion rates. But because they were buried together, they experienced identical postburial nuclide production, so the ^{26}Al and ^{10}Be concentrations from all clasts and grain size fractions will form a linear array, or isochron, in ^{26}Al-^{10}Be space. These concentrations are plotted as ellipses representing 68% confidence intervals, and the slope of a regression line through these points depends only on the duration of burial. An age for the deposit can thus be determined from the slope (see Appendix B for governing equations). This method is useful for dating Susquehanna River-derived fluvial deposits sourced from the Piedmont, Valley and Ridge, and the Appalachian Plateau that have a range of exposure histories prior to burial.

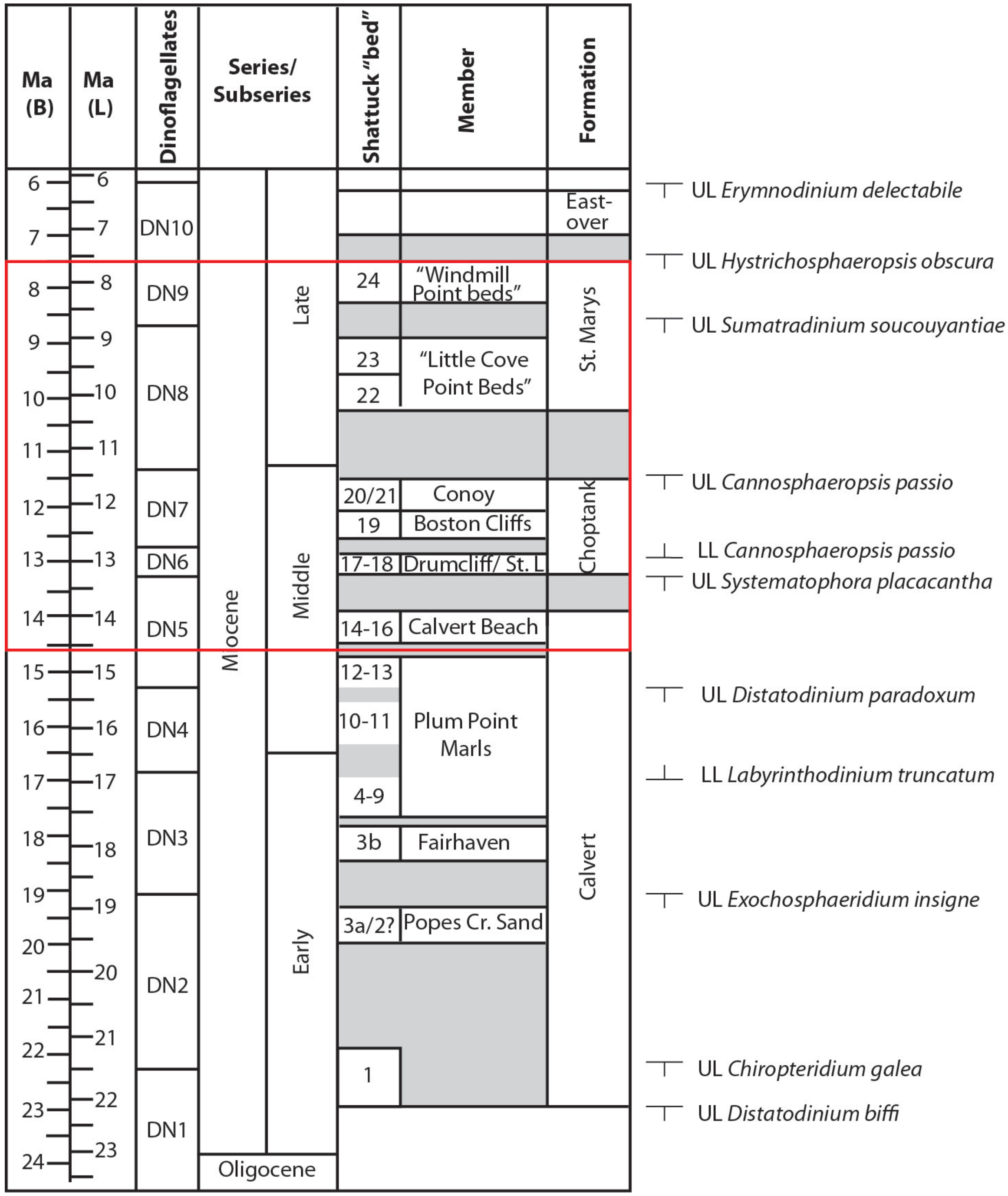


Figure 8. Chronostratigraphic and biostratigraphic context of the Miocene units of the Salisbury Embayment; red box indicates units penetrated under the BNWR. Species list to the right indicates upper- (UL) and lower- (LL) limits in the stratigraphic record. Modified from de Verteuil and Norris (1996); Shattuck "beds" defined in Shattuck (1904); B is the timescale of Berggren et al. (1995), L is the timescale of Lourens et al. (2004).

Figure 9. The three platforms used for drilling the BNWR substrate and examples of sediments typically retrieved from these methods: A) Truck-mounted CME-75 hollow-stem auger system; B) truck-mounted CME-45 solid-stem auger system; C) Hovercraft-mounted vibracore system (HP2000).

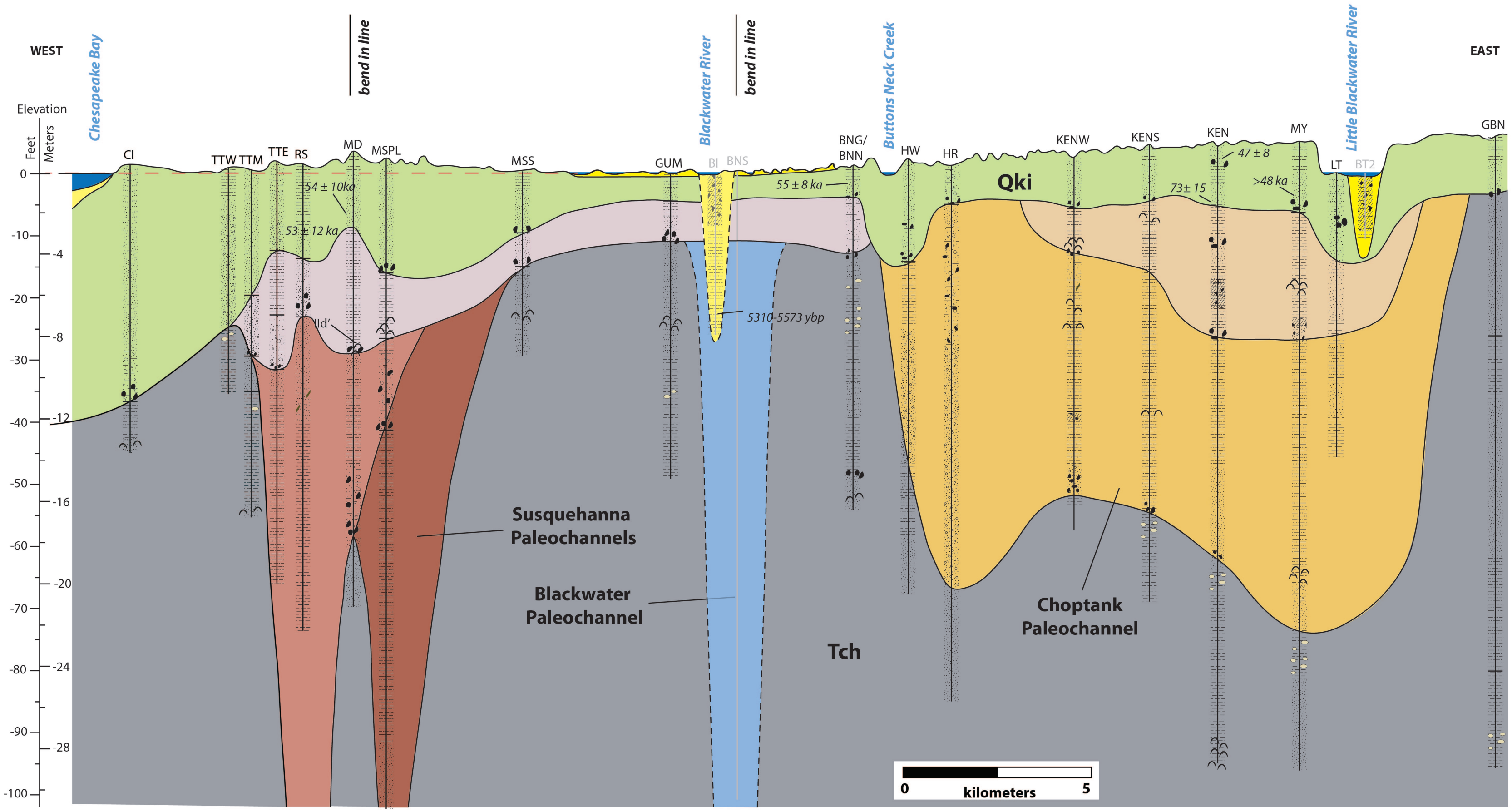


Figure 10. Preliminary west-east cross-section from 21 boreholes showing the Holocene (yellow), Pleistocene (green, shades of orange, shades of red, blue), and Miocene units under the BNWR. Ages indicated in "ka" are preliminary OSL ages; age indicated as "ybp" is a calibrated radiocarbon age. Note two coreholes near the Blackwater River and one near the Little Blackwater River (colored gray) are projected into the line of section.

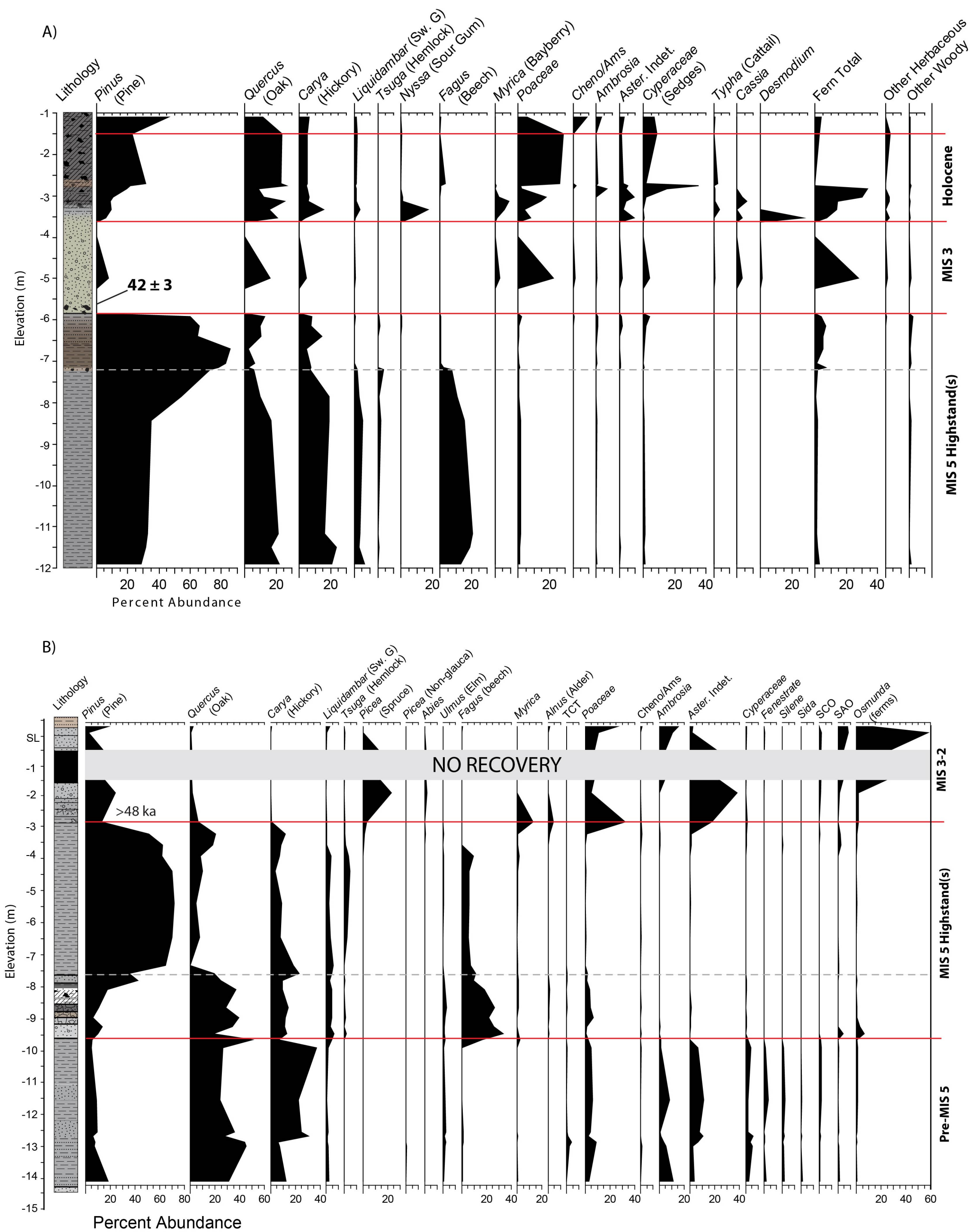
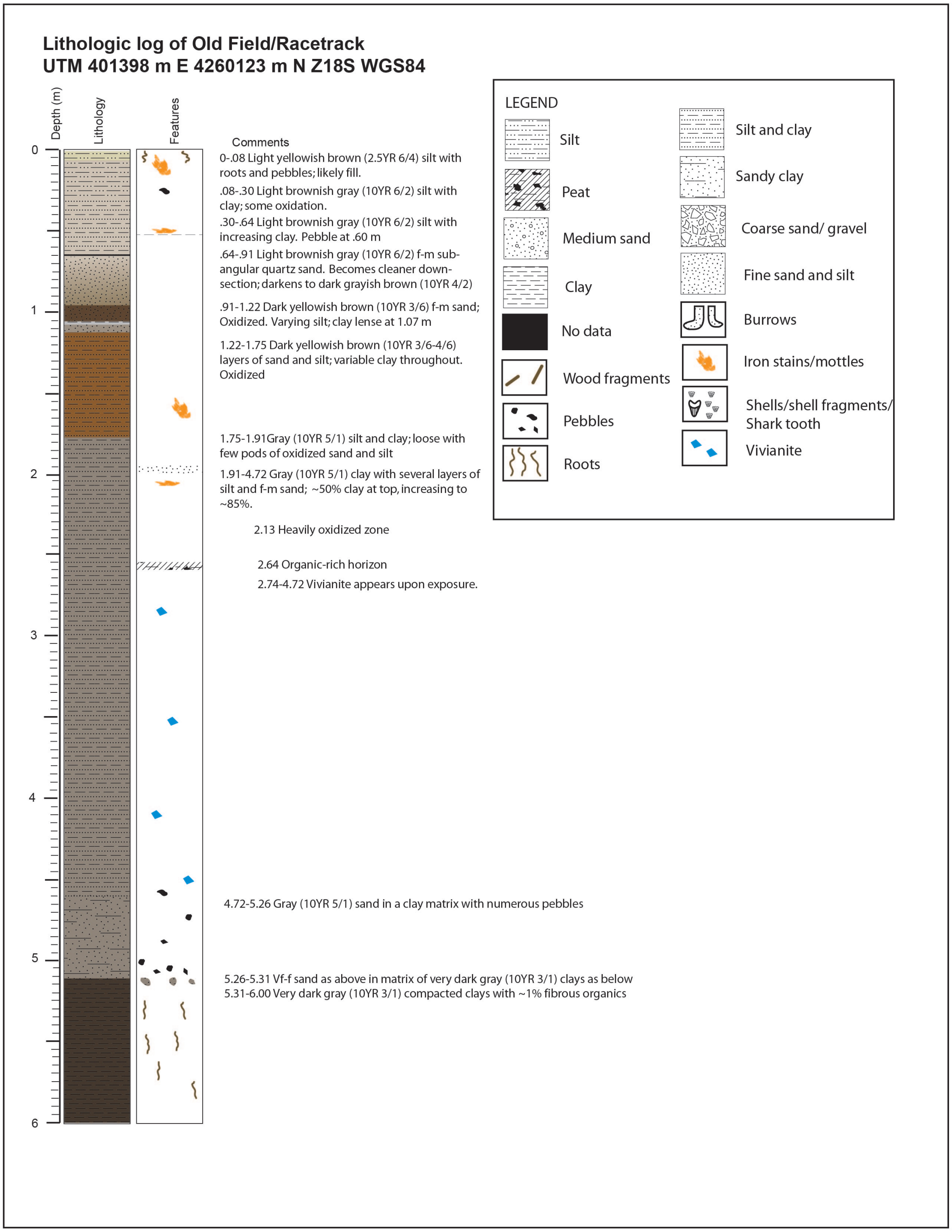


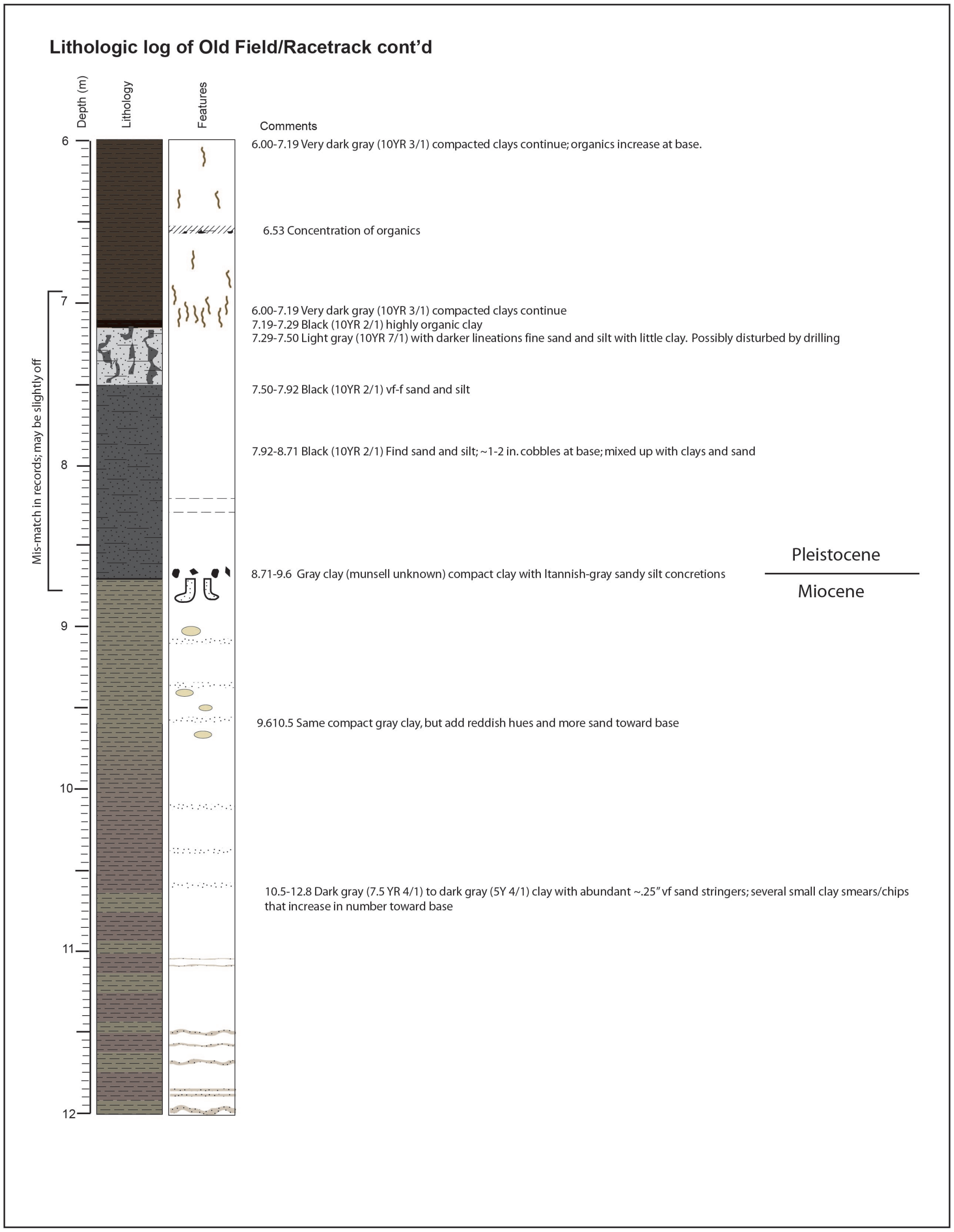
Figure 11. Examples of pilot pollen analyses run for cores in the BNWR from A) lower in the topography (Harpers C core; HC on Fig 2) and B) from the uplands (Maintenance Yard core; MY on Fig 2). Note changes in environment and/or climate correlate with and help interpret the lithologic record (shown in vertical column to the left). The age of 42±3 indicates the age of a pilot OSL sample run on the same core.

TABLE 1. OSL and radiocarbon samples for this study. Numbers in parentheses behind OSL ages indicate number of aliquots run out of the 20 that are needed to be considered publishable.

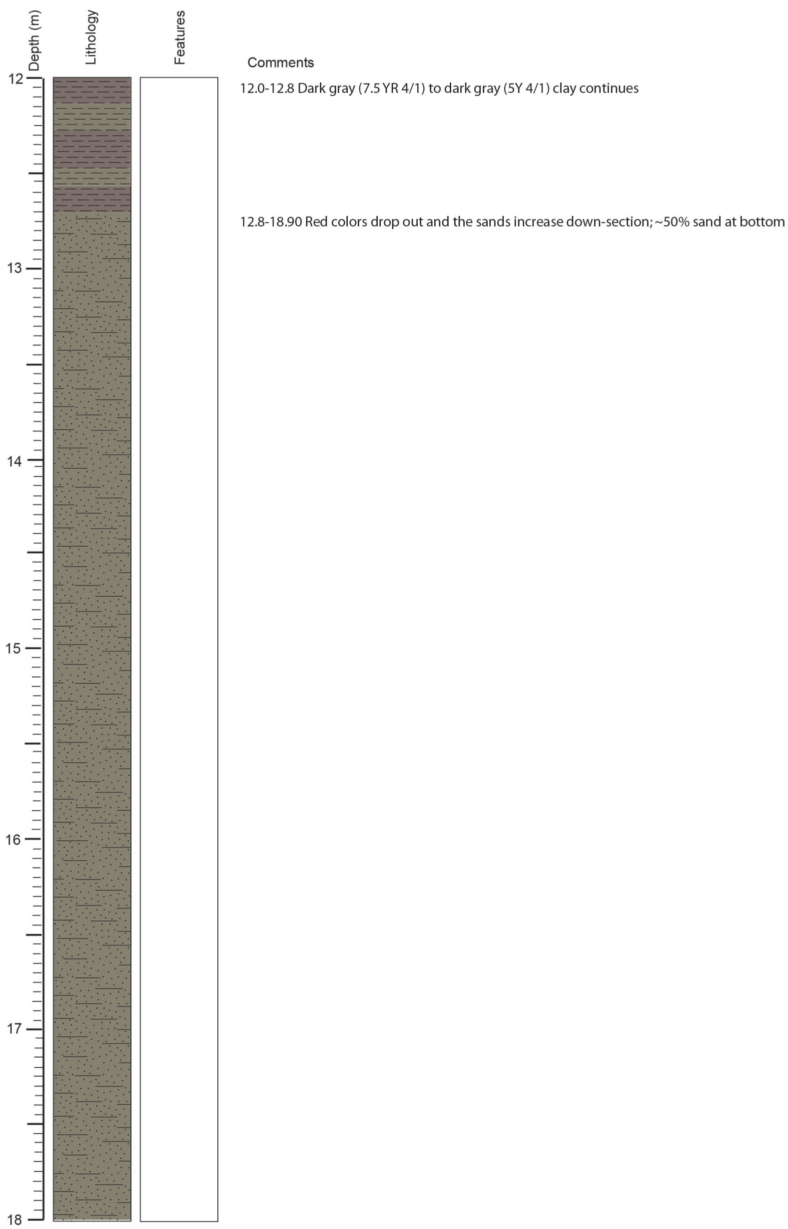
LABORATORY ID	CORE	UTM E	UTM N	DEPTH (m)	METHOD	AGE (10^3 yr BP)
COMPLETED AGES						
WW6532	Barbadoes Isl.	405012	4252175	3.73	Radiocarbon	Modern
WW6533	Barbadoes Isl.	405012	4252175	3.75	Radiocarbon	690-907
WW6535	Barbadoes Isl.	405012	4252175	7.83	Radiocarbon	1395-1543
WW6536	Barbadoes Isl.	405012	4252175	8.03	Radiocarbon	1950-2149
WW6537	Barbadoes Isl.	405012	4252175	8.31	Radiocarbon	1739-1966
WW6539	BW Transect 5	404223	4253005	3.9	Radiocarbon	Modern
WW6540	BW Transect 6	404223	4253005	8.35	Radiocarbon	8-278
WW6541	BW Transect 7	404223	4253005	8.55	Radiocarbon	5310-5573
USU-265	Harpers C	405773	4253089	4.6	OSL	42 ± 3
USU-266	Harpers C	405773	4253089	4.3	OSL	43 ± 3
AGES IN PROGRESS						
USU-1203	Tubmans Road	395369	4252883	3.37	OSL	72 ± 18 (8)
USU-1204	Russel Swamp	391983	4253086	4.4	OSL	59 ± 19 (10)
USU-1208	Moneystump	394768	4255314	2.79	OSL	59 ± 13 (11)
USU-1209	Parsons	389816	4258523	2.7	OSL	39 ± 6 (8)
USU-1211	Reber Dune	391606	4248973	1.48	OSL	59 ± 21 (4)
USU-1213	Reber Dune	391606	4248973	8.66	OSL	61 ± 13 (9)
USU-1216	Maple Dam	407991	4252580	2.06	OSL	52 ± 10 (11)
USU-1219	Kuehnle Dune	409068	4253704	2	OSL	50 ± 9 (5)
USU-1221	Robins P.L.	405966	4248454	2.82	OSL	79 ± 24 (5)
USU-1226	Buttons Neck	397724	4258012	1.23	OSL	62 ± 10 (10)
USU-1222	Kentuck	403510	4256878	1.94	OSL	43 ± 10 (4)
USU-1225	Kentuck	403510	4256878	5.72	OSL	67 ± 14 (6)
SAMPLES AWAITING ANALYSIS						
USU-1201	*Tubmans Road*	*395369*	*4252883*	*2.61*	--	--
USU-1202	*Tubmans Road*	*395369*	*4252883*	*2.85*	--	--
USU-1205	*Russel Swamp*	*391983*	*4253086*	*8.58*	--	--
USU-1206	*Russel Swamp*	*391983*	*4253086*	*8.92*	--	--
USU-1207	*Moneystump*	*394768*	*4255314*	*2.5*	--	--
USU-1210	*Parsons*	*389816*	*4258523*	*4.43*	--	--
USU-1212	*Reber Dune*	*391606*	*4248973*	*2.48*	--	--
USU-1215	*Maple Dam Rd*	*407991*	*4252580*	*1.66*	--	--
USU-1218	*Kuehnle Dune*	*409068*	*4253704*	*1.14*	--	--
USU-1220	*Kuehnle Dune*	*409068*	*4253704*	*2.33*	--	--
USU-1223	*Kentuck*	*403510*	*4256878*	*3.31*	--	--
USU-1224	*Kentuck*	*403510*	*4256878*	*5.44*	--	--
USU-1227	*Buttons Neck N*	*397724*	*4258012*	*2.36*	--	--
USU-1228	*Kentuck*	*403510*	*4256878*	*3.22*	--	--

Appendix A: Example stratigraphic column including detailed lithologic descriptions from Old Field (OF on Fig. 2)

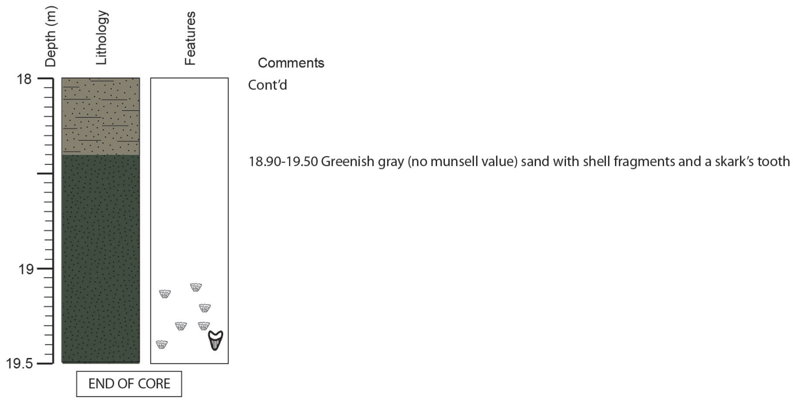



Lithologic log of Old Field/Racetrack cont'd
Depth (m)
Lithology
Features
Comments
6
7
8
9
10
11
12
Mis-match in records; may be slightly off
6.00-7.19 Very dark gray (10YR 3/1) compacted clays continue; organics increase at base.
6.53 Concentration of organics
6.00-7.19 Very dark gray (10YR 3/1) compacted clays continue
7.19-7.29 Black (10YR 2/1) highly organic clay
7.29-7.50 Light gray (10YR 7/1) with darker lineations fine sand and silt with little clay. Possibly disturbed by drilling
7.50-7.92 Black (10YR 2/1) vf-f sand and silt
7.92-8.71 Black (10YR 2/1) Find sand and silt; ~1-2 in. cobbles at base; mixed up with clays and sand
8.71-9.6 Gray clay (munsell unknown) compact clay with Itannish-gray sandy silt concretions
Pleistocene
Miocene
9.610.5 Same compact gray clay, but add reddish hues and more sand toward base
10.5-12.8 Dark gray (7.5 YR 4/1) to dark gray (5Y 4/1) clay with abundant ~.25" vf sand stringers; several small clay smears/chips that increase in number toward base

Lithologic log of Old Field/Racetrack cont'd



Lithologic log of Old Field/Racetrack cont'd



Appendix B: Equations governing the isochron burial age calculations.

The measured ^{26}Al and ^{10}Be concentrations ($N_{10,m}$ and $N_{m,}$; atoms g^{-1}) in each individual clast or sand fraction are:

$$N_{10,m} = \frac{P_{10}(0)\Lambda}{\varepsilon} e^{-t_b\lambda_{10}} + N_{10,pb} \tag{1}$$

$$N_{26,m} = \frac{P_{26}(0)\Lambda}{\varepsilon} e^{-t_b\lambda_{26}} + N_{26,pb} \tag{2}$$

where $P_i(0)$ is the surface production rate of the nuclide i (atoms g^{-1} yr^{-1}), Λ is the attenuation length for spallogenic production (generally assumed to be 160 $g*cm^{-2}$), ε is the erosion rate ($g*cm^{-2}yr^{-1}$) where the clast originated, λ_i is the decay constant for nuclide i, t_b is the duration of burial (yr), and $N_{26,pb}$ and $N_{10,pb}$ are the post-burial ^{26}Al and ^{10}Be concentrations (atoms g^{-1}) in that clast. Because the upstream erosion rate for any particular clast is unknown, we can eliminate ε by solving (1) for Λ/ε and substituting into equation (2). The result is a relationship between the measured ^{26}Al and ^{10}Be concentrations for a set of clasts:

$$N_{26,m} = \frac{P_{26}(0)}{P_{10}(0)} e^{-(\lambda_{26}-\lambda_{10})t_b} N_{10,m} - \frac{P_{26}(0)}{P_{10}(0)} e^{-(\lambda_{26}-\lambda_{10})t_b} N_{10,pb} + N_{26,pb} \tag{3}$$

Equation (3) is the key to the isochron burial dating method because it yields a linear relationship between measured ^{26}Al and ^{10}Be concentrations regardless of the erosion rate where the clasts originated, and the slope of the regression line can determine an age of burial independent of assumptions related to subsurface nuclide production rates or the burial history of the clasts.