ABSTRACT

Title of Thesis:	Mapping and Characterization of the Marlboro Clay formation.
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The Marlboro Clay formation is a geologic formation that outcrops in Prince George's County, Maryland, and is of great significance due to its instability. Water well logs are collected to determine ground water quantity. Marlboro Clay can be easily recognized in the water well log's lithology descriptions due to its pink color. The objectives of this study were to provide data on the morphology and problematic characteristics of soils formed from Marlboro Clay to and use water well log data to create an interpolated Marlboro Clay map. Marlboro Clay samples were smectite and kaolinite dominated and had moderate potential volume change ratings. The particle size varied due to infilling of sediments from the overlying Nanjemoy and underlying Aquia formations. An accurate bottom elevation Marlboro Clay map was created which we strongly anticipate will contribute to improved natural resource and urban planning activities where the Marlboro formation is found.

MAPPING AND CHARACTERIZATION OF THE MARLBORO CLAY FORMATION

By

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Advisory Committee:
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Dedication

I would like to dedicate my thesis to my mother and brother whom have been my strength during tenure at the University of Maryland. They have always provided me with the spiritual guidance, love, wisdom, and encouragement through my every endeavor. Without them, nothing that I have ever accomplished in my life would have been possible.

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Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction and Background

The Marlboro Clay is a geologic unit named after exposures in Upper Marlboro, MD (Darton, 1948) and proposed by Glaser (1971) as a formation. The Marlboro Clay outcrops from Annapolis, MD to the James River in Virginia, yet the majority of the formation out crops in Prince George's County, MD where it averages 5-9 meters in thickness (Statsz and Law, 1991). The Marlboro Clay formation often varies in thickness as a result of varying amounts of erosional truncation at the disconformity (Gibson and Bybell, 1994). Soils formed from Marlboro Clay regolith are mapped in Maryland as the Howell series (USDA/NRCS Soil Survey, 1967). According to the 1967 soil survey for Prince George's County, there are 1,754 (0.56%) acres mapped as Howell.

The Marlboro Clay has colors that range from light gray to pinkish gray and reddish brown clay with laminated silts and very fine micaceous sands. The clay beds often contain pods of fine-grained glauconitic sand (Gibson and Bybell, 1994). The formation is thin and lithologically uniform; it lies stratigraphically between the Nanjemoy and Aquia formations (Statsz et al., 1991). In two core-hole samples that contained Marlboro Clay, the clay fraction was dominated by kaolinite but also consisted of smectite and an illite/smectite mixture (Gibson et al., 2000).

The age of when Marlboro Clay formation was deposited is agreed upon by geologists as being during the late Paleocene/early Eocene (~ 55 million years ago), often referred to as "The Late Paleocene Thermal Maximum" (Berggren et al., 2002). The earth was exposed to momentous changes in temperature causing the ocean waters to change from thermohaline to halothermal driven circulation (Berggren et al., 2002).

Thermohaline driven circulation occurs when vertical circulation of ocean water is induced by surface cooling, causing convective overturning and consequent mixing. Halothermal driven circulation occurs through the formation of warm saline bottom waters at low latitude sites (Berggren et al., 2002). Though most geologists agree on the age at which the Marlboro Clay was deposited, there are contrasting opinions as to the depositional environment of the Marlboro Clay.

Berggren et al. (2002) stated that the Paleocene/Eocene boundary was characterized by widespread $CaCO_3$ dissolution derived from uniformly warm, low oxygen, corrosive bottom waters. These corrosive waters along with global warming (the exact temperature is not explicitly stated) resulted in an abrupt extinction in deep-sea water foraminifera (single-celled protists with shells) and terrestrial mammal fauna (Berggren et al., 2002). During this time calcareous plankton, which includes foraminifera, and tropic benthic foraminifera (nummulitids, discocyclinids, and alveolinids) were the only species that were able to evolve under such extreme temperatures. Such a limited species of calcareous plankton examined in the exposures brought them to the conclusion that the Marlboro Clay may have been laid down in a neritic (a relatively shallow water zone that extends from the high tide market to the edge of the Continental Shelf) depositional environment.

A study was done on the biostratigraphy of a deep core-hole done in Oak Grove, VA by Gibson et al. (1980). In this core-hole the Marlboro Clay was observed. Calcareous microfossils were generally absent, while only agglutinated foraminifera assemblages were found (Gibson et al., 1980). This led them to believe that the Marlboro Clay was laid down in a lagoonal-marine depositional environment. However the relatively uniform lithology and widespread extent of the Marlboro Clay was not consistent with this theory.

Gibson and Bybell (1994) conducted a second investigation examining sedimentary patterns across the Paleocene/Eocene boundary. Nine core-holes were examined in the Central and Northeastern United States Coastal Plain (New Jersey, Maryland, Virginia, and North Carolina), and ten core-holes were examined in the Southeastern United States (South Carolina, Georgia, Alabama and Mississippi). The uppermost Paleocene and the lower most Eocene deposits were widespread in these areas, containing diverse, well-preserved calcareous microfossil assemblages (Gibson and Bybell, 1994). From these observed calcareous microfossil assemblages they were able to make detailed paleo-environmental interpretations of the types of sediment deposited during the Paleocene/Eocene age. From the Central Atlantic region, two core-hole samples, #4 and #9, showed the presence of the Marlboro Clay. Core-hole #4 was located in Waldorf, MD, and core-hole #9 was located in Putney Hill, Virginia. The core-hole samples were taken near the southern and northern ends of the Marlboro Clay depositional area according to USGS geologist John Glaser's mapping (Gibson and Bybell, 1994). There were calcareous foraminiferal assemblages observed in the two core-holes sampled suggesting the Marlboro Clay was deposited in a shallow marine environment (Gibson and By bell, 1994). However, the rarity and unusual composition of preserved calcareous assemblages in the cores implied that abnormal environmental conditions were present in inner to middle neurotic depths during the deposition of the Marlboro Clay (Gibson and By bell, 1994). Though some were deposited at neurotic depths, it was thought that the random occurrences of calcareous assemblages may have been caused by unknown environmental conditions preventing them from existing more consistently.

Overall the Marlboro Clay core-hole samples examined were dominated by benthic (sea bottom) foraminifera assemblages. Plank tonic specimens and calcareous Nan fossils were also observed and documented. This suggests that the Marlboro Clay was deposited in a shallow-marine environment at least partially open to oceanic circulation (Gibson and By bell, 1994). Contrastingly, Baum and Vail (1988) used sequence stratigraphy rather than biological stratigraphy to postulate the depositional environment of the Marlboro Clay formation, through the examination of condensed sections.

Baum and Vail (1988) conducted an investigation using sequence stratigraphy to identify Type 1 and Type 2 sequence boundaries (an erosional surface that separates cycles of deposition) for regional correlation. Seismic/sequence stratigraphy is a technique that integrates log, core, and seismic data to interpret deposition and architecture of sediments in time and space (Prothero and Schwab, 1996). Condensed sections commonly divide type 1 and type 2 sequence boundaries and are identified seismically as downlap surfaces (Baum and Vail, 1988). Condensed sections are thin marine stratigraphic units comprised of pelagic (open ocean sediments derived from phytoplankton) to hemipelagic (sediments derived from both land and open ocean phytoplankton) sediments characterized by low sedimentation rates (Loutit et. al, 1888). They are thin continuous zones of burrowed slightly lithified or marine sedimentary units (Loutit et. al, 1888). Condensed sections form during periods of rapid sea-level rise making them very predictable. The fact that they can be easily predicted and identified in time and space makes them a valuable asset to seismic/sequence stratigraphy.

Condensed sections in the coastal plain are characterized by marine shale's and high concentrations of planktonic organisms, glauconite, sulfides, and phosphates (Baum and Vail, 1988). The glauconite, sulfides, and phosphates are found within the pore spaces of foraminifera as partially glauconitized clays. Commonly, the sediments directly below the condensed section are lithified and glauconitic, containing a diverse assemblage of benthic and planktonic organisms (Baum and Vail, 1988; Loutit et al., 1988.).

Baum and Vail examined a condensed section in Alabama known as the Bashi Marl and Sand formation. The Bashi Marl and Sand formation is a lithologically thin uniform layer of clay with an abrupt layer of glauconitic sand below it. According to Baum and Vail, the Bashi Marl formation was deposited during the late Paleocence/early Eocene event. Though it may go by a different name, the Bashi Marl formation was deposited at the same time as the Marlboro Clay, and has very similar physical characteristics. This investigation provided strong evidence that the Marlboro Clay is a condensed section more widespread than documented.

Problematic Issues:

Some have suggested that the Marlboro Clay has shrink-swell properties. The Marlboro Clay is considered not suitable for building and road infrastructures due to its clayey nature (Statsz et al., 1991). When Marlboro Clays are found on steep slopes there is potential for landslides to occur (Pomeroy, 1989). Landslide susceptibility is the degree of response of the stratigraphic unit and their derivative soils to natural events or artificial slope modifications.

When the Marlboro Clay is found on steep slopes it has the potential to cause landslides. In September of 1975, a landslide occurred in Prince George's County, MD on Chalfont Avenue in the Forest Knolls subdivision (Woodward-Clyde Consultants, 1976). When water infiltrates into the Marlboro Clays on steep slopes, seeps can occur causing weak spots, resulting in a landslide hazard. The nature of the Marlboro Clays can potentially cause cracking in the foundations of homes, buildings and roads. Footers cannot be used to set foundations of homes and buildings. Excavating all of the Marlboro Clay out and back-filling with structural fill is one of the most economically sufficient solutions.

In 1989, United States Geological Survey (USGS) Geologist John Pomeroy published the "Map Showing Landscape Susceptibility in Prince George's County." Marlboro Clays received a rating of 4, which is the highest possible landslide susceptibility rating for this map. John Pomeroy used a numerical rating system to indicate the degree of relative slide proneness: 1 = very low to low susceptibility, 2 = low to moderate susceptibility, 3 = moderate to high susceptibility and 4 = high to severe susceptibility. The formations in Prince George's County with landslide proneness are the Marlboro Clay, Potomac Group, and Calvert Formation.

The Arundel formation, a member of the Potomac Group, is a clayey geologic formation formed during the Cretaceous period (140 to 65 million years ago) that exhibits similar properties (landslide proneness and shrink-swell) to the Marlboro Clay formation and similar in color (dark red instead of pink). Dr. Daniel Wagner (1976) conducted a study on soils with reddish Cretaceous clays in Maryland. He found that the Cretaceous clays characteristic instability led many to believe parent material derived from Cretaceous sediments exhibited shrink-swell characteristics (Wagner, 1976). As a component of this study he performed potential volume change (PVC) analysis on 12 subsoil samples from 4 profiles of the Christiana soil series. Out of 12 samples, 7 of the samples had a critical PVC rating, 1 very critical rating, 3 marginal ratings, and 1 noncritical, which was sampled from overburden material (Wagner, 1976). When the PVC and particle size analyses of these samples were compared, and he concluded that samples with higher clay content generally had the highest swell indices (Appendix A). Clay mineralogy was not performed on the Cretaceous samples utilized in Wagner's thesis, but there have been other experiments conducted that have.

The Pennsylvania State Universities Agricultural Experiment Station (1983) conducted analyses on the mineralogical characterization of selected soils from the northeastern United States. These analyses were performed to contribute to the interpretation and understanding of the relationship between the soils and heavy metals due to increased pollution from effluent and sludge. Analyses were performed on 16 soil series (2 sampled horizons from each soil series) in which clay mineralogy primary was the soil analysis (Johnson and Chu, 1983). Two soil series that were used in this project were the Christiana and Sassafras, both of which are found in Maryland and formed from the Arundel formation. Kaolinite and Illite were the dominant clay minerals found in both soil series with small percentages of smectite.

As part of the critical loads study directed by the Maryland Department of Natural Resources Tidewater Administration, Martin Rabenhorst (1991) performed mineralogical analysis on nearly 100 archived soil samples which represented 35 of the major soil series in Maryland. Three of the soil series sampled, Christiana, Sassafras, and Keyport are all formed from Arundel formation. It was found that Christiana, Sassafras, and Keyport were dominated by kaolinite and illite with very small percentages of smectite (Rabenhorst, 1991).

The Marlboro Clay also presents problems for sewage disposal systems. The slow permeability limits the downward movement of water. On flat terrain, water perches on top of this formation, which raises the water table weakening the material strength of the sediments. The Maryland Department of Environment (MDE) recommends a separation ≥ three feet (.91 m) between the on-site disposal system and Marlboro Clay (Statsz et al., 1991).

Soil and Geologic maps:

A soil survey is an essential component to understanding the natural environment we live in, and managing our lands properly and efficiently. A soil map provides its users with the characteristics of the soils in a given area, classify the soils according to a standard system of classification, plot the boundaries of the soils on a map, and make predictions about the behavior of soils (U.S. Dept. of Agriculture/Soil Conservation Service, 1970). Additionally, soil surveys examine the different uses of the soils and how the response of management affects them.

A soil scientist begins the production of a soil survey by first compiling any and all pertinent information available; orthophotographs, topographic maps, geology maps, transect data, pit data, laboratory analyses, and old soil surveys, if available. Collecting this data prior to beginning a soil survey is paramount because it helps to avoid costly errors, and gives you an idea of what one may see while in the field.

Prior to going out into the field, a soil scientist typically looks at the geology map and the orthophotograph for the given area he/she decides to investigate. The geology map is one of the most important aspects in soil mapping because geology is the one to one link to the soil series parent material. The soil scientist also examines the orthophotograph to attempt to determine if there are any distinctive features (high or low relief landscapes and dark areas that may indicate wetness for example) that can be seen on the landscape.

Once in the field the soil scientist may run a series of transects to observe and determine what types of soils he/she sees on the landscape. A soil scientist may also dig and describe 1-meter deep pits for detailed characterization and analyses of a given soil type. A soil scientist strives to make as many observations as needed to understand the soil/landscape relationships within an area. However, due to time constraints set forth by the county government, a soil scientist must utilize tacit knowledge to construct a soil landscape model to make their best assessment of the different soil types in areas where he/she does not have soils data.

A soil landscape model is a conceptual understanding of which soils appear where in a given landscape (Hudson, 1992). This tacit knowledge is developed through observation of field-collected samples and a conceptual understanding of the factors of soil formation operating in a given landscape. Tacit knowledge is information and techniques rooted in individual experience which involves personal belief, perspective, and values (Hudson, 1992).

Once the soil landscape model has been created, a soil scientist will use this model along with all of their collected field data to delineate the different bodies of soil by hand onto a base map while in the field. Their data are then drafted onto mylar film with the use of a light table. Some soil scientists are now using a geographic information system (GIS) to compile the field data, and perform on screen digitizing. This allows the data to be preserved and easily updated in a continuous format. However, researchers have been developing software that integrates modern GIS technology with proficient human knowledge for digital soil mapping.

The process of geology mapping is very similar to soil mapping. Geology maps are an important resource for understanding the Earth's natural resources (Thomas, 2004). Geology maps are maps that represent the different types of bedrock at or near the earth's surface (Sawin, 1996). A geology map provides the user with a graphic illustration of information including distribution, rock type, age, and horizontal distribution of bedrock near the earth's surface (Sawin, 1996). Geology maps display the geologic structures, which include the fault, strike, and dip patterns that would be exposed if the soils and vegetation were not present. Geology maps can be used as a vital tool to provide predictive information for resource discovery as well as for the design of highways, bridges, buildings, land-use planning, and the evaluation of geologic hazards (Thomas, 2004).

A geologist begins a mapping project by first obtaining all of the existing relevant data on the nature of rocks in the field study area; aerial photographs, soil surveys, borehole records, measured stratigraphic sections, water well logs, and literature (Sawin, 1996). These applicable datasets are used to assist in field-work and interpretation. Once in the field, the geologist will systematically make observations and measurements in areas where rocks are exposed which typically include roads, streams, ridges, and trails (Thomas, 2004). In an urban environment, this would include quarries, highways road cuts, and foundation excavations for new building structures.

When a geologist locates a rock exposure, he/she uses either a topographic map or an aerial photograph to mark the exposures location, and the pertinent information (rock type, strike and dip, formation, and fossils) is recorded. If the rocks have undergone deformation, strike and dip along with any other planar structures are measured and recorded (Thomas, 2004).The measurements are plotted on the map, commonly using bedding and color to indicate the rock type present. If there are no structures present at the rock exposure, a color is simply marked on the map to indicate rock type. In order to maintain consistency from one county to the next, layers of bedrock are identified according to established boundaries and names which usually represent a change from one rock type to another (Sawin, 1996). As more data are plotted onto the base map, the points are connected to symbolize the contact between rock units.

Typically, bedrock is covered by soil and vegetation. Tacit knowledge is used along with existing and field collected data to create a geology map. Some rock outcrops may be miles apart so a geologist must use his/her training and experience to connect the data points by extrapolating and interpreting what happens between rock outcrops (Thomas, 2004).

The geologist uses all of his/her data to assist them in visualizing the different types of bedrock in order to create the map. Collected field data used to be drafted by hand onto mylar film. Now, field collected data is compiled into a geographic information system (GIS), which allows the data to be preserved and easily updated.

Data Compilation/Interpolation Methods:

The Maryland Department of Environment (MDE) houses and maintains a database of all water well permits for the state of Maryland. According to Maryland state law, each permit must provide a detailed lithology description log showing the depth to which the drill operator bored, and the types of sediment observed with increased depth. The depth increments are taken in feet. Commonly, geologists have used the descriptions from water well logs as additional stratigraphic data for their own studies.

Lyons and Jacobsen (1979) conducted a study to determine the available coal resources in Allegany and Garrett County, MD. Several data sources were obtained for this project of which water well logs proved to be one of the main data sources utilized. The water well logs for this project were selected based on two criteria; 1) each well log must contain one or more coal beds present in the lithology description and 2) the location of each well log used must be plotted accurately onto a topographic map (Lyons and Jacobson, 1979). By combining of the available data, they were able to create an updated map stratigraphically displaying the coal resources available for Western MD. Though for this project, the water well logs were used for mapping coal resources (an easily recognizable bed) this concept can be used for mapping other easily recognizable beds as well.

When drilling is taking place, the Marlboro Clay is easily recognized due to its pink and silvery gray color, which is why the Marlboro Clay is considered to be a "marker bed." Additionally, the Aquia, a fine grained (black and green in color), glauconite bearing formation, is clearly identified below the Marlboro Clay. Therefore when filtering through the many water well permits, recognizing those with Marlboro Clay present is not a difficult task. The latitude/longitude coordinates are provided with each water well permit as well, which as of 1988, were required by MDE to be accurate to the nearest 1,000 feet. However, there remains an issue that persists in water well permits, which is that the elevations are rarely provided. If the elevation is given it is typically not very accurate. This problem was resolved by using a high resolution dataset created with Light Detection and Ranging (LiDAR) data.

Light Detection and Ranging data (LiDAR) is generated by using a laser based radar system mounted in an aircraft to measure distances to the bare surface of the earth based on a round trip travel time of the laser pulse (Bowen and Waltermire, 2002). LiDAR radiation does not penetrate into the soil surface like lower frequency radar, and upon return the wavelengths emitted by LiDAR can be easily differentiated from background noise (Rocchio, 2000). These attributes make LiDAR very accurate and attractive for assessing landscape elevations.

Geostatistics has been used as a validation technique in soil mapping projects for quite some time. Geostatistics is the study of samples of data from a complete data set or population to attempt to estimate the behavior of the population.

Objectives:

The objectives of this project were to acquire data on the morphology and problematic characteristics of soils formed from Marlboro Clay regolith and use water well log data to create an interpolated Marlboro Clay map.

Chapter 2: Morphology and Characterization of Soils Formed in Marlboro Clay Regolith

Introduction

The Marlboro Clay is a geologic unit named after exposures in Upper Marlboro, Maryland (Darton, 1948) and proposed by Glaser (1971) as a formation. The Marlboro Clay outcrops from Annapolis, Maryland to the James River in Virginia. The majority of the surficial exposures are found in Prince George's County, MD where it averages 6.0 meters in thickness (Scott and Needelman, in review). The Marlboro Clay formation has slow permeability and exhibits slope instability when found on steep landscapes (Statsz et al., 1991). Due to its problematic characteristics, Prince George's County, Maryland has strict building regulations on areas where this formation is present. On landscapes with low relief it is required that modifications be made (excavating, recompaction, building retaining walls, or subsurface drainage systems) to the landscape prior to any type of building construction (residential homes, commercial buildings, roads, and septic tanks). Statsz et al. (1991) suggested that the problems associated with the Marlboro Clay may be due to slow permeability and shrink-swell caused by expansible clay mineralogy. An additional characteristic associated with the Marlboro Clay formation is acidity. The Marlboro Clay formation lies stratigraphically between two formations, the Nanjemoy and Aquia, both of which are glauconitic and contain sulfidic materials. Materials from these formations mix with the Marlboro Clay through infilled burrows (Gibson and Bybell, 1994). If sulfides are present, the formation will undergo sulfuricization upon exposure to oxygen, releasing acidity and lowering pH (Fanning and Fanning, 1989).

The Marlboro Clay formation varies in thickness as a result of varying amounts of erosional truncation at the disconformity (Gibson and Bybell, 1994). The formation has colors that range from light gray to pinkish gray and reddish brown clay with laminated silts and very fine micaceous sands. This thin formation is valued as a marker bed because of its distinct color, and because it lies stratigraphically between the Nanjemoy and Aquia formations marking the Paleocene/early Eocene boundary (Glaser 1968, 1971). The overlying Nanjemoy formation and underlying Aquia formation were first named by Clark in 1896. The Nanjemoy formation is greenish-black in color and composed of quartz sand, with varying amounts of interstitial silt-clay with as much as 50 percent green glauconite (Glaser, 1971). This formation is generally highly burrowed. The underlying Aquia formation is a sandy, variably glauconitic (<40%), formation with colors that range from dark greenish gray to medium-gray. Under weathered conditions the Aquia formation is a combination of black, white, and grey colors mixed with rusty brown (Glaser, 1971).

The deposition of the Marlboro Clay formation is considered to have occurred during the late Paleocene/early Eocene (~ 55 million years ago), under an environment referred to as "The Late Paleocene Thermal Maximum" (Berggren et al., 2002). The earth was exposed to momentous changes in temperature causing the ocean waters to change from thermohaline to halothermal-driven circulation (Berggren et al., 2002). Thermohaline-driven circulation occurs when vertical circulation of ocean water is induced by surface cooling, causing convective overturning and consequent mixing. Halothermal-driven circulation occurs through the formation of warm saline bottom waters at low latitude sites.

The Paleocene/Eocene boundary was characterized by widespread $CaCO_3$ dissolution derived from uniformly warm, low oxygen, corrosive bottom waters

(Berggren et al., 2002). These corrosive waters along with global warming resulted in an abrupt extinction in deep-sea water foraminifera (single-celled protists with shells) and terrestrial mammal fauna (Berggren et al., 2002). During this time of extreme temperatures, calcareous plankton, which includes foraminifera and tropic benthic foraminifera (nummulitids, discocyclinids, and alveolinids) were the only species that were able to evolve. Based on the observations of such a limited species of calcareous plankton in Marlboro Clay exposures, they believed that the Marlboro Clay may have been laid down in a neritic depositional environment (a relatively shallow water zone that extends from the high tide to the edge of the Continental Shelf) (Gibson et al, 2000). It has also been suggested that the Marlboro Clay was deposited in a shallow-marine environment at least partially open to oceanic circulation (Gibson and Bybell, 1994). Contrastingly, Baum and Vail (1988) suggested that the Marlboro Clay may be a condensed section which is a section of fine-grained sedimentary rock or clay that has accumulated slowly over a long period of time creating a thin layer.

The objective of this study was to acquire data on the morphology and problematic characteristics of soils formed in Marlboro Clay regolith. Potential volume change (PVC), particle-size, and pH analyses were performed on all collected samples. X-ray diffraction, bulk density, and coefficient of linear extensibility (COLE) analyses were performed on selected samples.

Area Descriptions, Methods and Material Studied

Study Area:

Prince George's County, Maryland was the study site selected for this project, which lies within the Atlantic Coastal Plain physiographic province. The Atlantic Coastal Plain is characterized by unconsolidated gravel, sand, silt, and clay ranging in age from Cretaceous to Holocene (Glaser, 1971). The northern part of the county is gently rolling with broad valleys, and the rest of the county is partly dissected with short steep slopes and broad terraces.

Prince George's County is located in south-central Maryland (bordering Washington, DC) (Fig. 2-1). The urbanized county is comprised of 1,291 km^2 of land area with a population of ~840,000 people (United States of the Census, 2003).

Sample Collection:

For this study samples were collected and characterized from 2 pits, 7 deep cores, and 38 1-m surface auger borings, 5 of which were collected at the same site as the deep cores (Fig. 2-1.). Permissions to sample at residential and rural locations were requested by telephone (105 requested) broadly but commonly denied (65 rejected), resulting in limited sample distribution. At pit locations, detailed morphological descriptions were collected according to the standards specified in the USDA/NRCS Field Book for Describing and Sampling Soils (Schoeneberger et al., 2002). Each pit description included: horizonation, horizon depth and boundary, Munsell color, texture, structure, redoximorphic features, slope, natural drainage class, and landscape position. The soil mapping unit in which the pit was excavated was also recorded (Prince George's County Soil Survey, 1967). Each soil horizon was sampled and characterized individually. In addition, within three of the horizons, parafragements of unweathered Marlboro Clay were also collected.

At auger boring locations a bucket auger (7.6 cm in diameter) was used to retrieve samples of Marlboro Clay recording the depth at which we sampled. A detailed soil description of each sample (Munsell color, redoximorphic features, horizonation, texture, drainage class, slope, landscape position, depth to Marlboro Clay, and mapped soil series) was performed (Schoeneberger et al., 2002). At deep cored locations a drill rig was utilized to recover samples of Marlboro Clay >3-m. We recorded the color and depth at which the sample was collected. A global positioning system (GPS) was used to georeference the sites of the soil pits, auger borings, and deep cores.

Laboratory Analysis:

Soil samples were air-dried, crushed, and passed through a 2-mm sieve. The following analyses were performed on the crushed soil material for all samples: PVC, particle-size analysis and pH. On selected samples, x-ray diffraction, bulk density, and COLE analyses were performed.

Potential volume change analysis was performed on samples using a soil volume change meter (Henry and Dragoo, 1965). This device measures the volume change that a soil undergoes when exposed to changing moisture conditions. Each crushed soil sample was added to a compaction ring in three layers. A compaction hammer was used to firmly press and smooth the soil surface to reduce soil dispersion prior to applying the blows.

Each of the three layers was then compressed with a compaction hammer by administering seven blows. The top of the first and second layers were scarified with a knife to ensure proper bonding between layers. The compacted soil was then wetted causing soil expansion, which was gauged by a calibrated proving ring dial. The swell index and hazard potential were estimated using the calibration graphs provided in FHA Publication No. 701 (Lambe, 1960). In order to estimate the variability in potential volume change measurements four replicates were performed on a single sample from one of the pits.

Particle-size analysis was performed by the pipette method (Day and Green, 1986). There was minimal organic matter present, therefore it was not removed. Particle dispersion was achieved by adding .01 grams of sodium hexametaphosphate to a 10 g sample suspended in 200 ml of distilled water agitated 30 min in a mechanical shaker. The sand fraction of each sample was determined gravimetrically following wet sieving. Pipette analyses were used to determine total clay and silt concentrations.

Soil pH was determined using a glass electrode pH meter on air-dried samples mixed with distilled water in a 1:1 ratio. Note that materials that contain some sulfides are likely to partially oxidize during air-drying.

The preparation for x-ray diffraction first involves K and Mg saturation, ethylene glycol salvation (for Mg-saturated samples only), and heat treatments at 300°C and 500°C for K saturated slides and 25°C (room temperature) for K and Mg saturated slides. X-ray diffraction scans were also run at 25°C (room temperature). X-ray scans were run using a Phillips X-ray diffractometer with Cu as its radiation source and a graphite crystal monochrometer to filter all but the Cu Kα. The scans were from 2° 2θ to 30° 2θ. Each scan took approximately 23 minutes. Scans were analyzed using the Phillips X'Pert Organizer software (Koninklijke Philips Electronics, 2000). Bulk density samples were analyzed by the National Soils Laboratory in Lincoln, Nebraska using the clod method (Blake, 1965).

Results and Analysis

Soil Pits:

The full profile description for soil pit A is presented in Table 2-5. In soil pit A, the A horizon was absent indicating that erosion had taken place. There was no interbedding or layering of different formations present in soil pit A indicating that this soil was developed from pure Marlboro Clay regolith.

Potential volume change analyses were run on clayey samples from the following horizons: Bt1, Bt2, Bt3, and Bt4 (Table 2-1). The swell index for Bt horizons in soil pit A ranged from 15,556 kg m^{-2} to 17,300 kg m^{-2} with a mean of 16,283 kg m^{-2}. All four samples analyzed had a PVC rating of marginal. As shown in Table 3.1, the pH of the soil horizons from pit A ranged from 4.1 to 4.5.with a mean of 4.2.

The full profile description for soil pit B is presented in Table 2-6. Within the profile of soil pit B there were three geologic formations present (Table 2-6; Fig 2-2). The A, Ap, and Bt horizons were developed from Marlboro Clay regolith. Within the Bt1, Bt2, and Bt3 horizons, parafragments were present. The 2BC horizon was developed from parent material from the Nanjemoy formation which had a fine sandy loam texture, differing from the clay textures of the Bt horizons developed from Marlboro Clay regolith. The 2BC was a transitional zone back into horizons (3CB1, 3CB2, and 3CB3) developed from parent material from the Marlboro Clay formation. There were three CB horizons which ranged in clay from 41-50% clay. The CBj horizon was developed from a mixture of Marlboro Clay and Aquia formations. The CBj horizon was characterized by an abundance of fine and coarse sand from the Aquia formation with interstitial clay from the Marlboro Clay formation, and jarosite was also present.

Table 2-2 provides the potential volume change data for soil pit B. The following samples were analyzed from soil pit B: Bt1, Bt2, Bt3, 3CB1, 3CB2, 3CB3, and parafragment samples from the Bt1 and Bt2 horizons. The swell index for soil horizons in soil pit B ranged from 14,974 kg m^{-2} to 23,697 kg m^{-2} with a mean of 18,027 kg m^{-2}. According to the potential volume change rating system, 8 of the samples from soil pit B fell within the marginal category, and 2 within the critical category. As shown in Table 2-2, the pH of the soil horizons from pit B ranged from 3.7 to 4.4 with a mean of 4.0.

X-ray diffraction scans were run on the 8 dominantly clayey soil horizons from pit B (Figures 2-4a, 2-4b, and 2-4c) in which kaolinite, clay sized mica, and smectite were the predominant clay minerals. Trace amounts of feldspars and quartz were also detected in each sample, and a trace of goethite was observed in the Bt3 parafragment sample.

Bulk density was run on five soil horizons from pit B (Table 2-3). The bulk density's COLE values for the analyzed samples were low, ranging from .010 cm^{-3} to .035 cm^{-3}. Overall, the COLE values ranged from low to nearly moderate. The 3CB3 sample was the only sample that met the moderate criteria, with a COLE value of .035 g cm^{-3}. The mean COLE value for the collected samples was .024 g cm^{-3}.

Intensive Sampling Site:

The five auger borings (AB 31-AB 35) collected at the same site of the deep cores had matrix colors ranging from 10YR 5/6 (yellowish brown) to 5YR 4/6 (yellowish red) with textures ranging from sandy clay loam (24% clay) to clay (50% clay) (Appendix A). The mean swell index value for the 5 auger borings was 14,160 kg m^{-2}. All of the samples had marginal PVC ratings. The mean pH for the 5 auger borings was 4.1 with a range of 3.5 to 5.0. The seven deep cores were uniform in color with a matrix color of 5YR 5/4 (reddish brown) (Appendix A). The textures of the deep cored samples ranged in texture from silt loam (14% clay) to silty clay loam (38% clay). The clay content of the surficial auger borings was generally higher than the deep cores. The mean swell index value for the 7 deep cored borings was 21,205 kg m^{-2} with 4 of the samples having critical PVC ratings and the remaining having marginal PVC ratings (Refer to Appendix A). The mean pH for the deep cored samples was 4.5 with a range of 2.7 to 6.2.

Auger Borings:

The 33 other surficial auger borings had matrix colors that ranged from 5YR 5/4 (reddish brown) to 10YR 7/2 (light gray) (Appendix A). The textures of the 33 surficial auger borings ranged from loam to silty clay, and varying amounts of glauconite were present in the entire auger borings dataset. Most of the auger borings (55%) contained depletions and iron concentrations. The mean swell index value for the 33 auger borings was 19,045 kg m^{-2}. The mean pH for the 33 auger borings was 3.7 with a minimum and maximum value of 3.1 and 4.1 (Appendix A).

Discussion and Conclusions:

The two profiles described and sampled were located in areas mapped as Howell according to the Prince George's County Soil Survey. Both pits were located in Upper Marlboro, Maryland at a residential development site that had been cleared for construction in 2002. According to the United States Department of Agriculture, Natural Resources Conservation Service's (USDA/NRCS) official soil series description these profiles were accurately identified as Howell. In accordance with the official soil series description, the soils described in these two pits were well drained with increasing amounts of glauconite observed in the lower part of each profile.

According to the textural analyses presented in Table 3.6., samples collected from auger with higher clay contents generally had higher swell indexes. The deep cores however, consisted of much more silt than clay, but still produced high swell index values. The high swell index values within the deep cores may have been due to the presence of silt-sized expansible minerals.

It was initially hypothesized that unweathered samples of Marlboro Clay would have higher clay contents than weathered samples. However, the weathered Marlboro Clay samples analyzed were higher in clay, and the unweathered samples were higher in silt. We believe that because pedogenesis has yet to occur, the clay minerals in the silt fraction have yet to disperse resulting in lower total clay content and higher total silt content.

Prior to performing the particle-size analysis, the dried unweathered and pedogenically affected Marlboro Clay samples were crushed only the dried soil material that passed through a 2-mm sieve was used. While wet sieving the sands, there were chips of Marlboro Clay that did not pass through the .045-mm sieve. Because these chips did not pass through, the total clay content of the samples analyzed may have been underestimated. Had these silt-sized clay minerals passed through, the clay contents of the samples analyzed may have been consistently higher.

The Marlboro Clay formation is burrowed with infilled glauconitic sediments because of the overlying Nanjemoy formation underlying Aquia formation. These glauconitic sand-sized sediments mixing with the Marlboro Clay may be a contributor to the textural variation exhibited.

The pH of the samples collected ranged between 2.7 and 6.2. The majority of the samples collected fell within the range of 3.6 to 4.0. The variation in pH of the Marlboro Clay formation may be due to the degree of infilling from overlying and underlying sediments of the Nanjemoy and Aquia formations. This may indicate that there is an unoxidized zone present contributed by sulfide-bearing glauconitic sediments from the Nanjemoy and Aquia formations causing acidification during sample preparation.

The mineralogy of the samples collected from soil pit B was dominated by kaolinite and smectite (Table 2-4). These data suggest that the smectitic mineralogy of the samples was causing significant shrink-swell deformity. According to Johnson and Chu, 1983 and Rabenhorst (1991), soils derived from the Arundel formation (Christiana, Sassafras, and Keyport) sampled for clay mineralogy showed an abundance of kaolinite, but had very small percentages of smectite concluding that soils formed from Marlboro Clay regolith may exhibit more severe shrink-swell characteristics. However the mineralogical composition of the Marlboro Clay formation may vary because it can be highly burrowed with glauconitic sand-sized sediment, causing variation in the clay percentage.

The COLE values calculated from the bulk density samples were low. Only one of the samples (3CB3) met the moderate criteria, indicating that the Marlboro Clay formation based on these observations may not be as hazardous as once thought.

According to the PVC ratings, the majority of the Marlboro Clay samples analyzed were marginal. In comparison with the Arundel formation samples analyzed by Wagner (1976), Marlboro Clay samples exhibited similar swell index values. In both the Marlboro Clay and Arundel formation, samples with higher clay contents generally had higher swell indexes, but there were some Marlboro Clay samples high in clay content, but had marginal PVC indexes. Therefore Marlboro Clay samples with marginal PVC indexes may not exhibit shrink-swell characteristics preventing building infrastructure, but proper remediation should still be practiced. Due to limited sampling opportunities, we were unable to establish a relationship of the Marlboro Clay formations clay content is relation to location and landscape position. An intensive sampling strategy would have to be conducted on the landscapes where the Marlboro Clay is most commonly found.

Tables:

Table 2-1. Potential volume change (PVC), particle-size, and pH analyses of Marlboro Clay samples from soil pit A.

Horizon	Depth (m)	Swell Index (kg m^{-2})	PVC Rating	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Texture Class	pH
BE	24-32	N/A	N/A	440	330	230	Loam	4.1
Bt1	32-60	15,556	Marginal	160	440	400	Silty Clay	4.2
Bt2	60-88	16,137	Marginal	110	510	380	Silty Clay Loam	4.5
Bt3	88-100	17,300	Marginal	120	540	340	Silty Clay Loam	4.3
Bt4	100	16,137	Marginal	140	510	350	Silty Clay Loam	4.0
Mean		16,283		194	466	340		4.2
Min		15,556		110	330	230		4.0
Max		17,300		440	540	400		4.5

PVC was run on samples with ≥ 15% clay.

Table 2-2. Potential volume change (PVC), particle-size, and pH analyses of Marlboro Clay samples from soil pit B.

Horizon	Depth (cm)	Swell Index ($kg\ m^{-2}$)	PVC Rating	Sand ($g\ kg^{-1}$)	Silt ($g\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	Texture Class	pH
A	0-4	14,974	Marginal	400	350	250	Loam	4.1
Ap	4-15	15,556	Marginal	380	330	290	Clay Loam	4.0
Bt1	15-51	23,115	Critical	140	520	340	Silty Clay Loam	4.3
Bt2	51-76	16,719	Marginal	90	570	340	Silty Clay Loam	4.0
Bt3	76-96.5	16,137	Marginal	200	480	320	Silty Clay Loam	4.4
2BC	96.5-112	N/A	N/A	530	360	110	Very Fine Sandy Loam	3.9
3CB1	112-140	15,556	Marginal	50	540	410	Silty Clay	3.8
3CB2	140-160	18,463	Marginal	40	540	420	Silty Clay	3.7
3CB3	160-180	23,697	Critical	170	330	500	Clay	3.7
3CBj	180	N/A	N/A	310	50	100	Loamy Sand	4.2
Bt1 Parafragments	15	12,067	Marginal	200	200	170	Silt Loam	4.1
Bt2 Parafragments	51	15,556	Marginal	130	130	220	Silt Loam	3.9
Bt3 Parafragments	76			160	160	190	Silt Loam	4.2
Mean		18,027		215	351	282		4.0
Min		14,974		40	50	100		3.7
Max		23,697		530	570	500		4.4

PVC was run on samples with ≥ 15% clay

Table 2-3. Bulk density and coefficient of linear extensibility (COLE) analysis of Marlboro Clay regolith from selected samples from pit B.

Horizon	Bulk Density		COLE[*]
	Moist ($g\ cm^{-3}$)	Oven Dry ($g\ cm^{-3}$)	
Ap	1.24	1.35	0.029
Bt1	1.45	1.53	0.015
Bt2	1.37	1.51	0.024
Bt3	1.41	1.52	0.024
2BC	1.36	1.40	0.010
3CB1	1.27	1.38	0.028
3CB2	1.20	1.33	0.035

[*] COLE is defined as coefficient of linear extensibility.

2.4 X-ray diffraction analysis of Marlboro Clay regolith from selected samples within soil pit B to determine the clay mineralogy.

Horizon	Depth (cm)	Quartz	Mica	Kaolinite	Smectite	Feldspars	Goethite
Bt1	15-51	Tr	XXx	XXX	XXX	Tr	
Bt2	51-76	Tr	XXx	XXX	XXX	Tr	
Bt3	76-96.5	Tr	XXx	XXX	XXX	Tr	
3CB1	96.5-112	Tr	XX	XXX	XXX	Tr	
3CB2	112-140	Tr	XX	XXX	XXX	Tr	
3CB3	140-160	Tr	XXX	XXX	XXx	Tr	
Bt1 Parafragments	15	Tr	XXx	XXX	XXX	Tr	
Bt2 Parafragments	51	Tr	XXX	XXX	XXx	Tr	
Bt3 Parafragments	76	Tr	XXx	XXX	XXX	Tr	Tr

x = < 5% = very low

X = 5-10%; low

XX = 10-30%; moderate

XXX = 30-70%; high

XXXX = >70%; high

Tr = trace

Table 2-5. Soil profile description of Marlboro Clay regolith mapped as the Howell series from soil pit A in Prince George's County, MD.

Side Slope Site, 5%	
Oe	0-7 cm; very dark grayish brown (10YR 3/2) loam; weak medium granular structure; very friable; slightly sticky, very plastic, many very fine and fine roots; abrupt smooth boundary
BE	7-24 cm; yellowish brown (10YR 5/4) loam; weak medium subangular blocky structure; friable; slightly sticky, very plastic, common medium, and many fine roots; clear smooth boundary
Bt1	24-32 cm; brown (7.5YR 5/4) silty clay; strong medium subangular blocky structure; friable; slightly sticky, very plastic; many very fine and fine roots throughout; few dendritic pores; many prominent reddish brown (5YR 5/4) clay films on all ped faces; abrupt smooth boundary
Bt2	32-60 cm; strong brown (7.5YR 5/6) silty clay loam; strong medium angular blocky structure; friable; slightly sticky, very plastic; many fine and very fine roots throughout; few tubular and dentritic pores; many prominent yellowish red (5YR 5/6) clay films on all ped faces; gradual smooth boundary
Bt3	60-88 cm; yellowish red (5YR 5/6) silty clay loam; strong medium angular blocky structure; friable; slightly sticky, very plastic; many prominent yellowish red (5YR 5/6) clay films on all ped faces; medium yellowish red (5YR 5/8) iron concentrations; medium light brownish gray (10YR 6/2) depletions; many very fine and fine tubular pores; gradual smooth boundary
Bt4	100+ cm; yellowish red (5YR 5/6) silty clay loam; strong medium angular blocky structure; friable; slightly sticky, very plastic; many fine roots throughout; few very fine tubular pores

Table 2-6. Soil profile description of Marlboro Clay regolith mapped as the Howell series from soil pit B in Prince George's County, MD.

Back Slope Site, 18%	
A1	0-4 cm; brown (7.5YR 4/3) clay loam; moderate medium granular structure; friable; slightly sticky, very plastic, many very fine and fine roots; clear wavy boundary
Ap	4-15 cm; brown (7.5YR 4/4) silty clay loam; moderate medium subangular blocky parting to weak fine granular structure; friable; slightly sticky, very plastic, few course, common medium, and many fine roots; clear smooth boundary
Bt1	15-51 cm; yellowish red (5YR 4/6) silty clay loam, few medium prominent mottles of light brownish gray (10YR 6/2); moderate medium subangular blocky parting to strong fine angular blocky structure; friable; slightly sticky, very plastic; many very fine and fine roots throughout; very many prominent reddish brown (5YR 5/4) clay films on all ped faces; medium reddish brown (5YR 4/6) iron concentrations; many very fine and fine roots throughout, few dendritic pores; gradual smooth boundary
Bt2	51-76 cm; brown (7.5YR 5/4) silty clay loam; moderate medium subangular blocky parting to strong fine angular blocky structure; friable; slightly sticky, very plastic, very many prominent strong brown (7.5YR 5/6) clay films on all ped faces; medium yellowish red (5YR 5/8) iron concentrations; many fine and very fine roots throughout; few tubular and dentritic pores; gradual smooth boundary
Bt3	76-96.5 cm; brown (7.5YR 5/4) silty clay; moderate medium subangular blocky parting to strong fine angular blocky structure; friable; slightly sticky, very plastic; many distinct strong brown (7.5YR 5/6) clay films on all ped faces; medium reddish brown (5YR 4/6) iron concentrations; many very fine and fine tubular pores and few medium tubular pores; clear wavy boundary
2BC	96.5-112 cm; light olive brown (2.5Y 5/4) very fine sandy loam; weak medium prismatic parting to weak fine subangular blocky structure; very friable; non-sticky, non-plastic; fine yellowish brown (10YR 5/4) and strong brown (7.5YR 5/8) iron concentrations; many fine roots throughout; few very fine tubular pores; clear smooth boundary
3CB1	112-140 cm; brown (7.5YR 5/4) silty clay; weak coarse prismatic structure; very friable; few fine roots; clear smooth boundary
3CB2	140-160 cm; brown (7.5YR 5/4) silty clay; moderate fine angular blocky structure; abrupt smooth boundary
3CB3	160-180 cm; brownish yellow (10YR 6/8) (60%) and light grey (10YR 7/1) (40%) clay; few very fine roots; abrupt smooth boundary
3CBj	180-216 cm; olive (5Y 4/3) sandy clay loam; medium strong brown (7.5YR 5/8) iron concentrations

Figures:

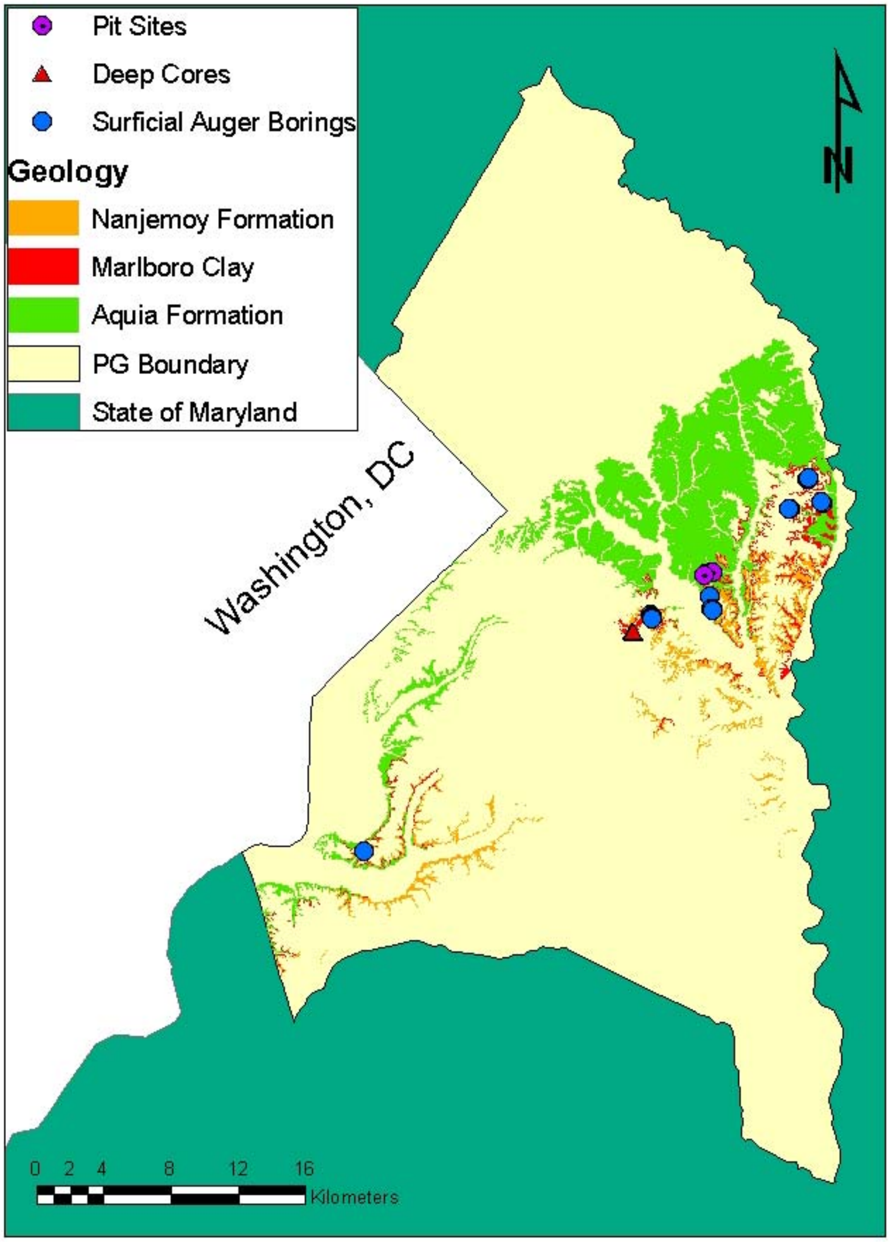


Fig. 2-1. Map of Prince George's County, Maryland showing the location sites of the soil pits, deep cores, and surficial auger borings with suficial deposits of the Nanjemoy, Marlboro Clay, and Aquia formations (Glaser, 1981, 1984) .

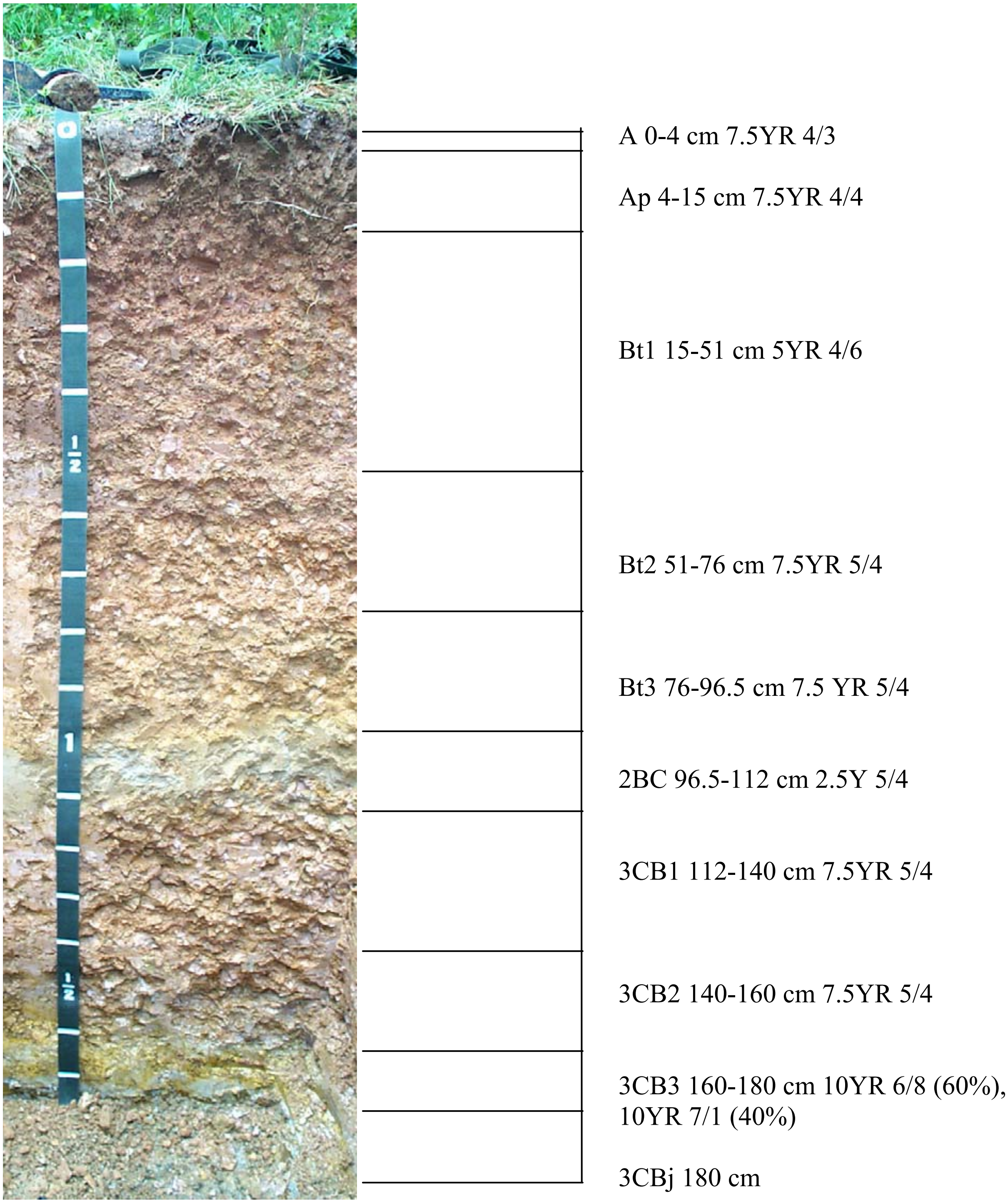


Fig. 2-2. Photograph of soil pit B described as the Howell series with the morphological description included.

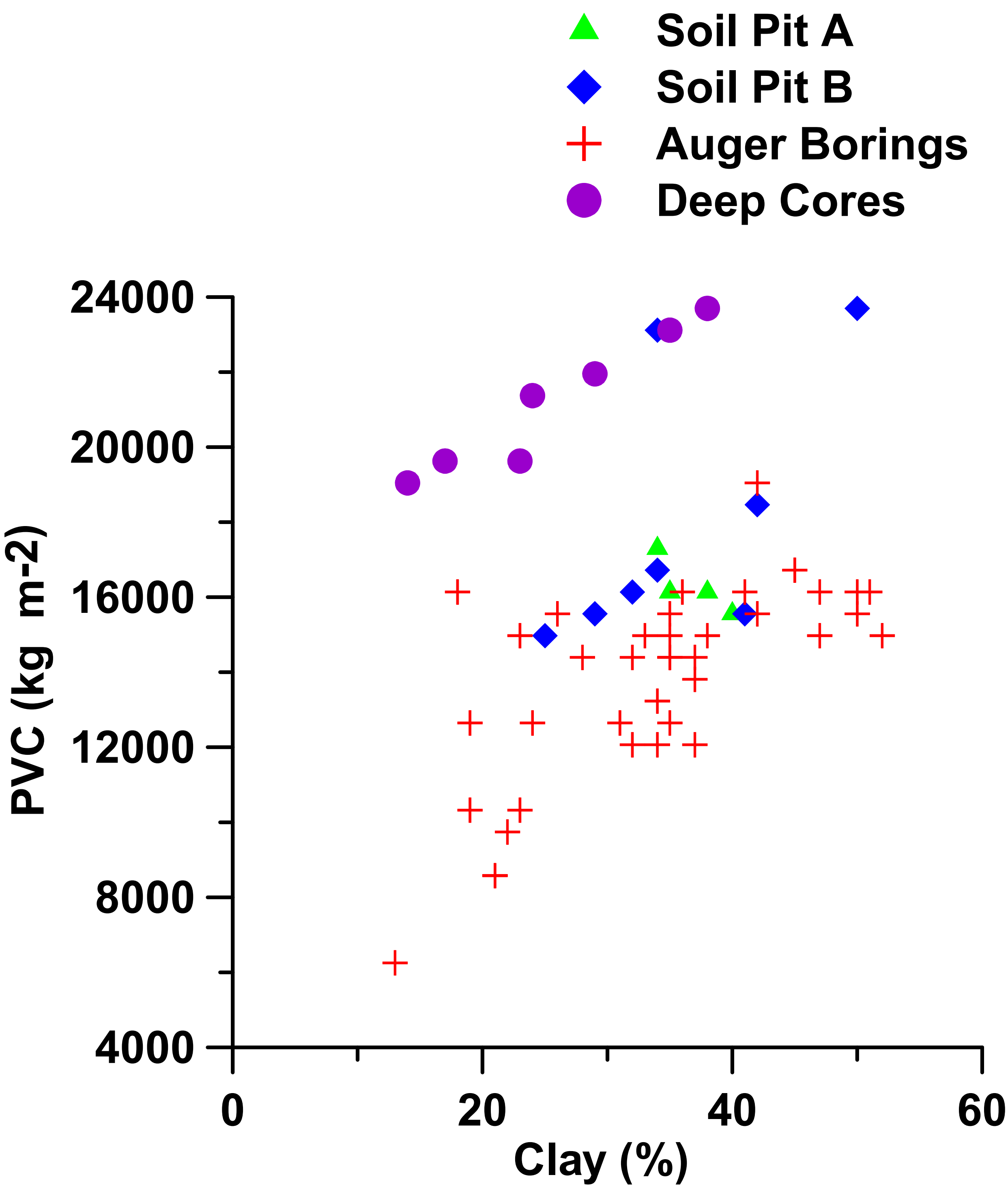


Fig. 2-3. Potential volume change (PVC) versus clay percent curves for Marlboro Clay samples. These samples were collected from soil pits, surficial auger borings, and deep cores.

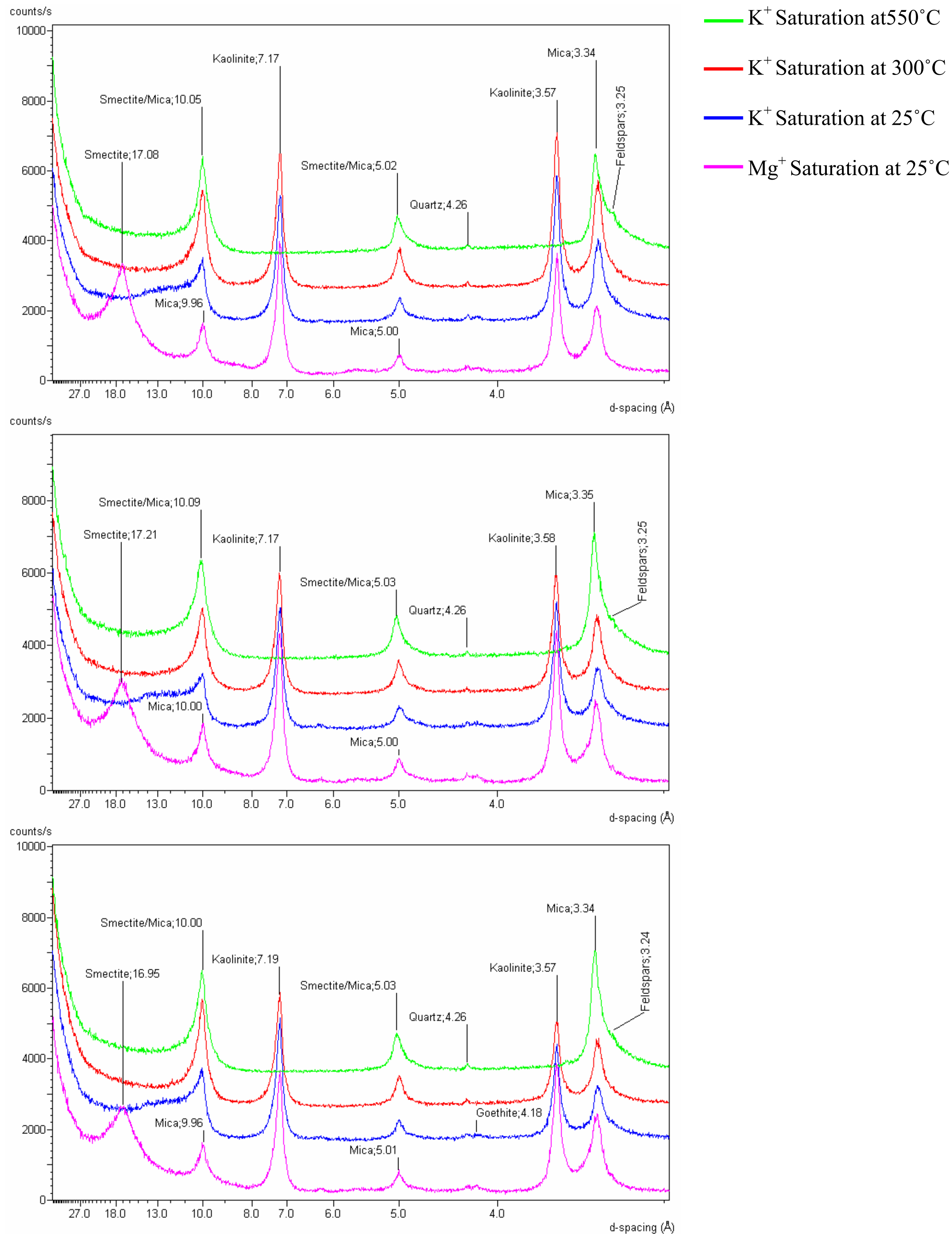


Fig. 2-4a. X-ray diffraction patterns of the Bt1, Bt2, & Bt3 horizons from soil pit B located in Prince George's County, Maryland.

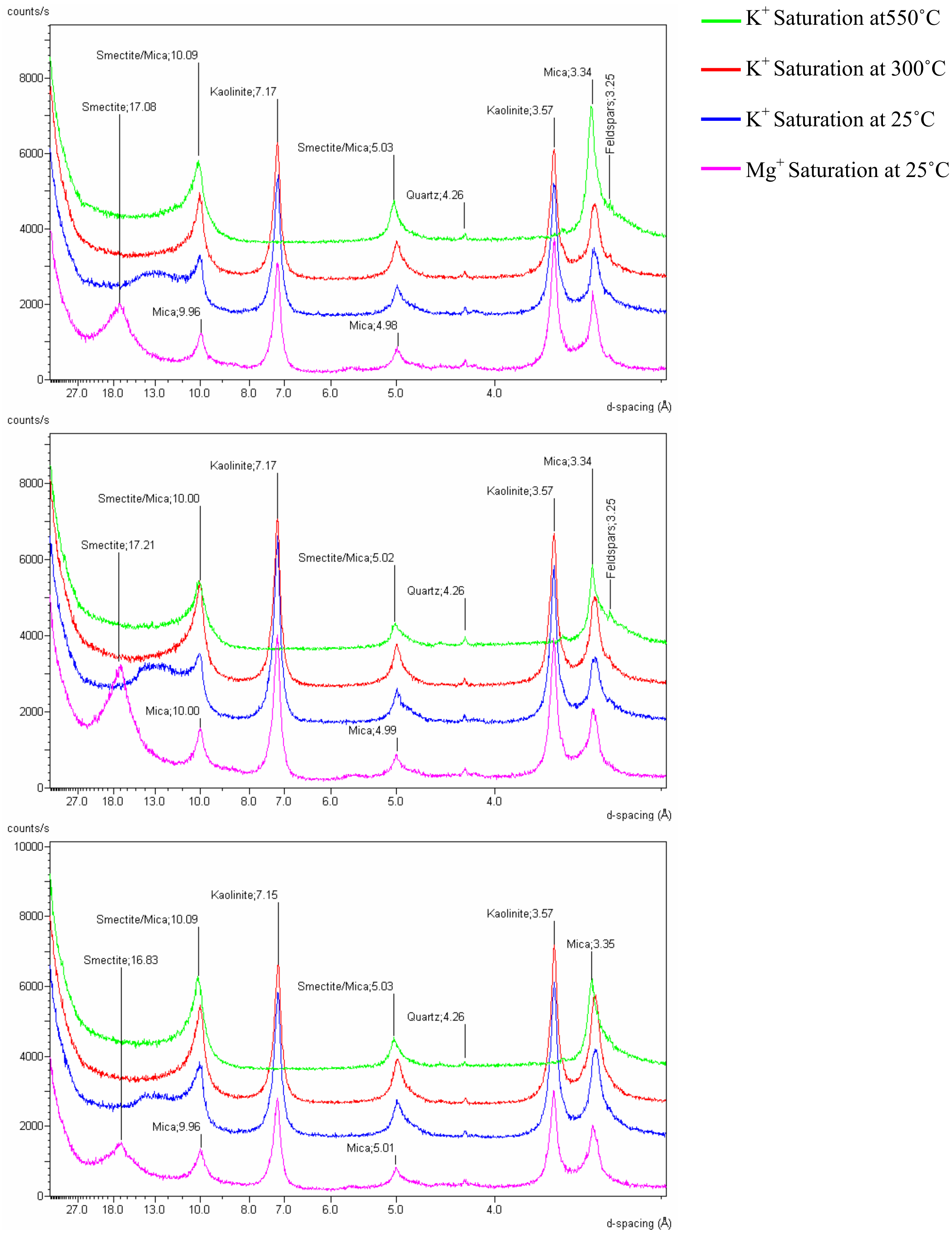


Fig. 2-4b. X-ray diffraction patterns of parafragments from the Bt1, Bt2, & Bt3 horizons from soil pit B located in Prince George's County, Maryland.

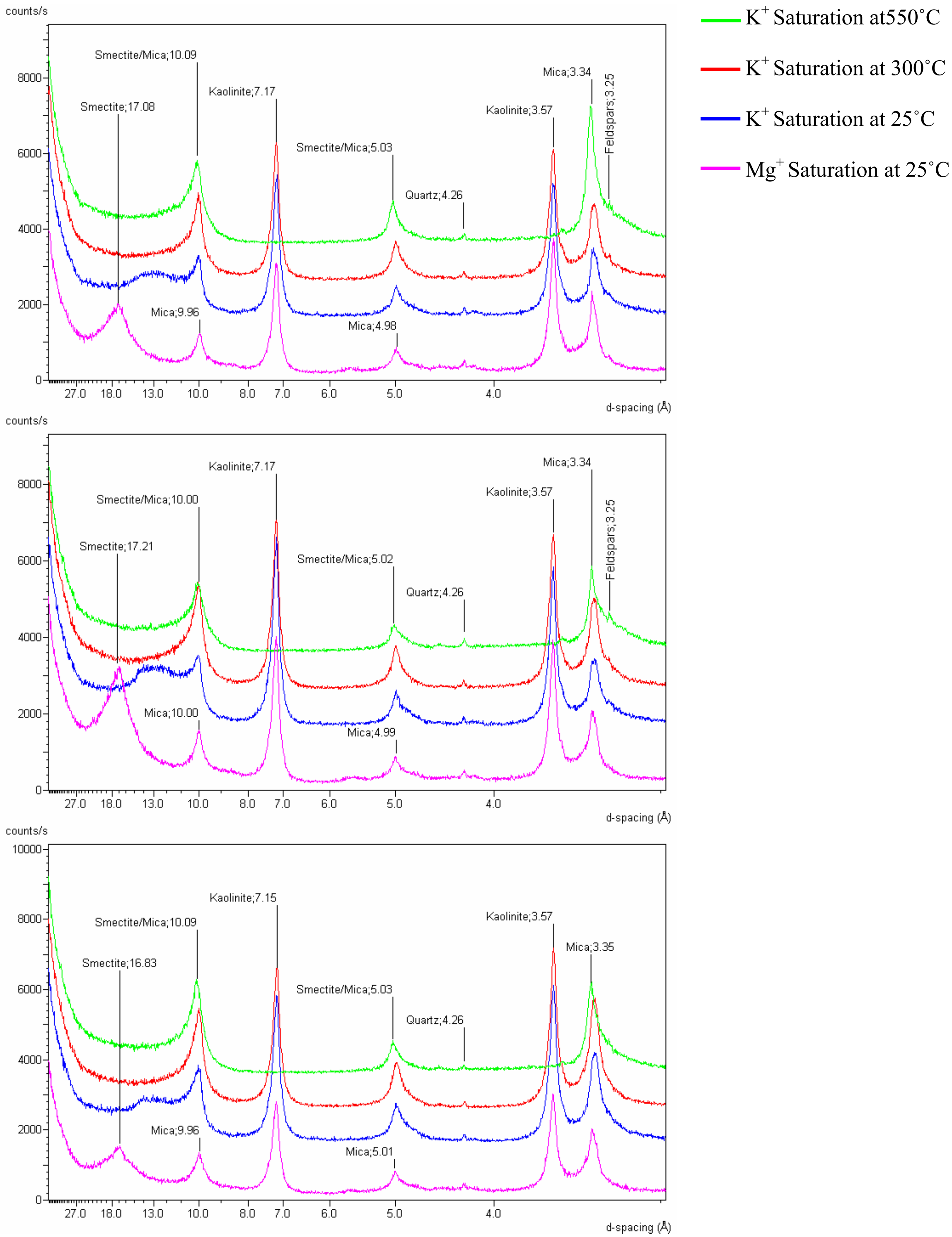


Fig. 2-4c. X-ray diffraction patterns of the 3CB1, 3CB2, and 3CB3 from soil pit B in Prince George's County, Maryland.

Chapter 3: Utilizing Water Well Logs for Soil Parent Material Mapping in the Mid-Atlantic Coastal Plain

Introduction

Soil parent material refers to the types of geologic or anthropogenic materials from which a soil is forming (Fanning and Fanning, 1989). Parent material is used in soil mapping to distinguish between many mapping units. Surficial geology maps are generally not available at the fine scales of regional soil surveys, affirming that utilizing parent material is an intricate part of soil mapping. Soil parent material mapping methods are generally tacit knowledge or quantitatively based. Tacit knowledge is information and techniques acquired from individual experiences, which involves personal beliefs and ideals (Hudson, 1992). Tacit knowledge based mapping involves the development of a mental understanding of soil landscape relationships in a soil-landscape model through experience. Soil and geological surveys in the U.S. are both drawn using tacit knowledge-based methods. Soil scientists develop the tacit knowledge for a soil landscape model by observation of field-collected samples with an intangible understanding of the factors of soil formation. Like soil scientists, geologist develops the tacit knowledge for creating geology maps by using field-collected samples with previously collected data to make interpretations about the geology present.

Quantitative soil mapping utilizes equations to describe the spatial distribution of soil properties in a given landscape (McBratney et al., 2003). Linear modeling uses regression for predicting soil attributes and classification for predicting soil classes. Since the 1960's there has been an emphasis on point-to-raster spatial interpolation modeling such as kriging. Quantitative soil mapping has generally emphasized terrain attributes (Evans, 1998). Soil variation that is dependent on parent material may be related to terrain, but in many cases must be modeled independently. In some cases terrain and quantitative methods can produce adequate parent material maps. However, in cases when a strong correlation cannot be established, other methods must be used.

Parent material maps are often used as input variables in regression-based modeling (Bell et al., 1992, 1994). Tacit knowledge and quantitative soil mapping are also effective methods for mapping parent material when parent material is as a function of terrain. Using terrain to map soils independent of parent material can introduce significant errors, such as when mapping a soil with sharp boundaries. Due to the lack of relationship between terrain and parent material in the Atlantic Coastal Plain in Maryland, these methods are not always effective. The Atlantic Coastal Plain in Maryland is characterized by a wedge of underlain unconsolidated sediments consisting of gravel, sand, silt, and clay (Glaser, 1968, 1971). These sediments overlap the rocks of the eastern Piedmont along the Fall Zone. At the Atlantic coast this wedge of sediments thickens to more than 8,000 feet (Glaser, 1968, 1971). Therefore, geology maps are a necessary component for mapping soil parent material when in areas where a strong relationship between terrain and parent material cannot be established to account for attributes such as low relief or soils with sharp boundaries.

Water well permits are widely collected in the U.S. in urbanized non-sewered areas. Water well logs have many uses including aquifer mapping, pollution potential mapping, and determining ground water levels at residential and commercial building sites. In the state of Maryland, each permit is required to provide a detailed lithology description showing the boring depth and the types of sediment observed, which may have value for parent material mapping. As of 1988, the Maryland Department of Environment (MDE) required that the latitude/longitude coordinates for each water well permit be accurate only to the nearest 1,000 feet. This lack of preciseness of water well logs can potentially introduce high measurement error.

Measurement error inaccuracies arise from microstructures within a given geological material, low sampling intensity, analytical errors, and spatial location errors (Jaksa et al., 1997). There are two measurement error sources with the use of water well logs for parent material mapping: first, vertical errors are introduced when collecting the data due to coring methodology and lack of geology training by the drill operator; second, the location of water well logs are not be precisely known. Kriging methods account for measurement error through the nugget term in the semivariance model. Spatial location measurement errors are generally not modeled under the assumption that this error is negligible.

Potential vertical errors can be minimized if a marker bed is present. A marker bed is a distinctive rock, sand, or clay unit that can be accurately identified by a drill operator (untrained in geology) because it contrasts sharply with the overlying and underlying geologic materials. Most marker beds are deposited rapidly, such as during volcanic or geologically instantaneous depositional events (Thomas, 2004). The Marlboro Clay formation is a marker bed identified by its distinctive pinkish gray color lying stratigraphically below the Nanjemoy formation, which consists of fine to coarse-grained sand with variable amounts of interstitial silt-clay with $\leq$ 50 percent green glauconite, and above the Aquia formation, a fine-to medium grained (black and green in color) glauconite-bearing formation (Glaser, 1971).

The Marlboro Clay can be found outcropping in the U. S. from Annapolis, Maryland to the James River in Virginia. Surficial exposures of this formation are most abundant in Prince George's County, Maryland, where it has been reported to range in thickness from 4.6 to 9.1 m (Fig. 3-1) (Statsz et al., 1991). The thickness of the Marlboro Clay formation varies due to erosional truncation at the disconformity (Gibson and Bybell, 1994). The clay beds often contain pods of fine-grained glauconitic sand (Gibson and Bybell, 1994). The Marlboro Clay formation marks the occurrence of its depositional environment, the Paleocene/early Eocene boundary (Glaser, 1971). The Marlboro Clay has been hypothesized to be deposited in either a shallow, low energy environment or a neritic environment (a relatively shallow water zone that extends from the high tide market to the edge of the continental shelf). The Marlboro clay has colors that range from light gray to pinkish gray and reddish brown clay with laminated silts and very fine micaceous sands.

The objectives of this study were 1) to compare and validate quantitative methods for county-level parent material mapping of the Marlboro Clay formation in Prince George's County using water well log data and 2) to evaluate the effects of location measurement error in non-georeferenced water well log data. The interpolation methods used were global polynomial, inverse-distance weighted (IDW), local polynomial, ordinary kriging, and universal kriging. Results were compared to an existing interpolation-based Marlboro Clay outcropping map using SURFER software (Statsz et al., 1991) and two existing tacit knowledge-based maps – a county-level geological map (Glaser, 1981, 1984) and a soil survey map (USDA-NRCS, 1967).

Area Descriptions and Material Studied

Study Area:

Prince George's County, Maryland was selected as the study site. This area was selected because it has the most abundant known distribution of surficial Marlboro Clay. The Marlboro Clay formation outcrops in two areas with contrasting topographies in Prince George's County. In the southwest part of the county, the Marlboro Clay formation is found on steep slopes ranging from 20-50%, and in the northeast part of the county it outcrops on terraces ranging from 0-5% and steeper slopes ranging from 10-25%.

Prince George's County is part of the Atlantic Coastal Plain physiographic province. The Atlantic Coastal Plain is characterized by unconsolidated gravel, sand, silt, and clay ranging in age from Cretaceous to recent alluvium (Miller, 1911). The soils of the Atlantic Coastal Plain located on low relief are dependent on parent material (geology) because there is a poor relationship between parent material and topography. The northern part of the county is gently rolling with broad valleys with the highest elevation reaching 128 m (Miller, 1911; Cooke, 1952). The remainder of the county is partly dissected with short steep slopes and broad terraces ranging in elevation from 42 to 0 m (Miller, 1911; Cooke, 1952).

Prince George's County is located in the south-central part of Maryland. The county has an area of 1,291 km^2 of land and a population of ~840,000 people (U.S.

Bureau of the Census, 2003). Prince George's County is rapidly urbanizing due to its close proximity to Washington, DC.

Water Well Logs:

For this study, 868 water-well permits located within Prince George's County were recorded from permits issued by the Maryland Department of Environment. These permits were selected based on all available paper copies of water well permits with Marlboro Clay present. The remaining available water well data was stored on microfiche, which was not used due to time constraints. The Maryland Department of the Environment does not require a precise georeferenced location nor elevation of the water-well log.

Two methods were used to estimate the location of the water well logs: The coordinates provided in the water well permits and manual placement. The coordinates provided in the water well permits were calculated using an Alexander Drafting Company (ADC) map for Prince George's County (Alexandria Drafting Company, 2001). Units are given only to the nearest 1,000 feet (305 m). Manual placement was performed by comparing the address and location sketch provided on the log permit to a Color Infrared Digital Orthophoto Quarter Quadrangles (CIR-DOQQs), a Topologically Integrated Geographic Encoding and Referencing system (TIGER) digital roads database, and an ADC map for Prince George's County (Alexandria Drafting Company, 2001). The location sketch on log permits shows the well's location in relation to the nearest town and road(s). The orthophotographs were obtained from the Maryland Department of Natural Resources (MD-DNR). The originals were produced at one-meter resolution to meet the National Map Accuracy Standard (NMAS) at a scale of 1:12,000. The orthophotographs were created in the State Plane Coordinate System 1983. The TIGER roads layer for Prince George's County was acquired from the United States Census Bureau. The Census 2000 TIGER roads layer is an extract of selected geographic and cartographic information from the Census data base. The orthophotographs and the TIGER roads layer were projected to North American Datum (NAD) 1983 UTM Zone 18. The ADC map simplified the effort to locate current streets and roads within Prince George's County. It also provides a legend with mass transit symbols, government and public facilities, outdoor features, and local boundaries (state, county, and zip code). ADC maps are published at a scale of 1:2,000.

To determine the placement accuracy of the water-well log database, a Pathfinder Pro XR global positioning unit and Maryland Property View Pro 2003 were used to locate 50 water well log locations (Fig 3-2). Maryland Property View Pro 2003 is a GIS software program created by Spatial Systems Associates, Inc. in collaboration with the Maryland Department of Planning which provides property information for the state of Maryland (Spatial Systems Associates, Inc., 2003). The units for each parcel in Maryland Property View Pro are provided in Maryland State Plane coordinates. The georeferenced data points were also used as a separate validation data set.

Elevation values of the water well logs were derived from a 2-m digital elevation model (DEM) derived from a Light Detection and Ranging (LiDAR) data set acquired in the form of .61-m contours for Prince George's County from the Maryland Department of Natural Resources (MD-DNR). The LiDAR data was flown by Spatial Systems Associates, Inc., Columbia, Maryland. We used the ArcINFO function Topogrid to convert the .61-m contours to a 2-m DEM (Hutchinson, 1988, 1989; ESRI, 2002). There were 69 logs removed from the dataset based on the following criteria: 1) The sketch map did not provide enough detail to locate the log based on whether or not the nearest town and road was provided, and 2) The overlying Nanjemoy or underlying Aquia formations were not present in the lithology log decreasing confidence that Marlboro Clay was actually present.

Marlboro Clay Interpolation Methods:

The following interpolation methods were performed on the water well log point dataset: global polynomial, inverse distance weighted (IDW), ordinary kriging, local polynomial, and universal kriging (Johnston et al., 2001). All analyses were performed in ArcGIS Desktop 9.0 with Spatial Analyst and Geostatistical Analyst extensions (ESRI, 2004; McCoy et al., 2004). The methods were applied to the bottom elevation and thickness variables. For bottom elevation mapping, water well logs with no Marlboro Clay data were removed; for thickness mapping, logs with outcrops were removed. All interpolations were performed on a 10-m grid. Cells with surface elevation (from LiDAR data) less than predicted Marlboro Clay bottom depth plus predicted thickness $\leq$ 2 m were identified as outcroppings.

Variograms were generated for the bottom elevation and thickness variables for ordinary kriging and universal kriging using Geostatistical Analyst in ArcGIS Desktop 9.0 (ESRI, 2004; Johnston, et al., 2004). For ordinary and universal kriging, powers of 1, 1.5, and 2 were compared and the order with the lowest root mean square error (RMSE) cross validation was used. Each kriging analysis was corrected for anisotropy and the semivariogram model was selected using Geostatistical Analyst. Global polynomial order was determined by using the highest order that provided a marginal statistically significant better fit. For IDW, powers of 1, 1.5, and 2 were compared and the power with the lowest RMSE cross validation was used. Local polynomial analyses were performed using powers of 1 and 2 and the power with the lowest RMSE was retained. For global polynomial, IDW, and local polynomial, the variogram parameters were automatically chosen based on the distance and respective gamma according to the well logs in the dataset.

Validation:

Three data sets were used to validate the interpolation methods. The first was a 50 georeferenced water well log dataset. The second validation data set was collected from a ~102 ha tract of farm land in Upper Marlboro, Maryland that is going to be developed into residential homes. The area has an abundance of outcroppings of Marlboro Clay. As part of the development process, a geotechnology firm collected 61 deep core samples (Fig. 3-2). We were given permission to publish the results of this data set and also augmented their data with an additional 5 surficial auger borings.

A third validation data set was a Marlboro Clay outcroppings data set collected at 38 sites with Marlboro Clay using 1-m deep auger borings (Fig. 3-2). The selection of each site was based on areas undisturbed by suburban development and land owner cooperation. The location of each auger boring was geo-referenced using a Trimble Pathfinder Pro XR GPS unit (GPS Pathfinder Pro XR, Trimble Navigation Ltd., Sunnyvale, California).

Three existing maps were also compared to the interpolation results. The first was a map showing the outcropped deposits of the Marlboro Clay formation mapped at a scale of 1:24,000 and digitally compiled by the United States Geological Survey (USGS) (Glaser, 1981, 1984). The second was a map displaying outcroppings of Marlboro Clay digitized and published at a scale of 1:12,000 by the Maryland National Capital Park and Planning Commission (MNCPPC) (Statsz et al., 1991). The data for this map was compiled from the USGS geology map for Prince George's County. The final map was a soils map for Prince George's County created by the Maryland United States Department of Agriculture, Natural Resources Conservation Service (MD-USDA/NRCS) (USDA/NRCS, 1967), which was mapped and published at a scale of 1:15,840.

Data Analysis:

The inference space for this study was created using ArcMap's "Reshape Feature" to delineate a close-fit polygon around the water well log points (Fig. 3-3a and 3-3b). The inference space had an area of 683.9 km^2, a maximum width of 33.06 km and a maximum height of 47.08 km.

The cross validation residuals for the bottom elevation and thickness maps were given with each associated interpolation method. Cross validation removes each data location, one at a time, and predicts the associated data value (Johnston et al., 2004). Then the predicted and actual values at each location of the omitted points are subtracted to give the residual. Cross validation residuals were categorized into seven classes calculated as a function of the minimum study-wide RMSE (Kaluzny et al. 1989). The breaks between the RMSE classes were created by multiplying the lowest RMSE by -2, -

1, -.5, .5, 1, and 2, with the first and last class being bound by the minimum and maximum residual for the given mapping method.

Results and Analysis

Overview of Water Well Log Dataset:

Due to availability, the distribution of the water well log data set was irregular within the inference space with areas of zero to minimal intensity and areas with high intensity (Fig. 3-3a and 3-3b). There were only two water well logs available within the outcrop areas both in the southwest and central parts of the inference space (Fig. 3-3a and 3-3b). In contrast, there were 169 logs available within the outcrop area in the eastern part of the inference space (Fig. 3-3a and 3-3b).

Of the 868 water well logs, 2 had outcroppings of Marlboro Clay and 11 had no Marlboro Clay (Aquia formation outcropping). After editing, the summary statistics based on the remaining 799 logs are presented in Figures 3-3a and 3-3b. Bottom elevations of the formation ranged from -90.5 to 217.5 m. In the southeast and south most part of the county, bottom elevations were low, ranging from 19.1 to -90.5 m (Fig. 3-3a). There was an upward trend of bottom elevation values going north to south. This trend of elevation values may follow a fault line as proposed by Statsz et al. (1991). Moving west, the bottom elevation values increase, ranging from 126 to 217.5 m. In the western portion of the county, there were a limited number of outlying bottom elevation values, ranging from -91 to -31 m (Fig. 3-3a).

The thickness of the formation ranged from 0.3 to 32.6 m with a mean of 6.0 m. The distribution of the thickness variable was positively skewed with 63 logs greater than

10 m, 14 greater than 14.3 m, and 2 greater than 20 m. The highest thickness values were concentrated in the mid to upper portion of the county (Fig. 3-3b). In the southern part of the county, thickness values ranged from 1.2 to 14.0 m. There were seven logs in the south portion of the county with a thickness value of greater than 11 m. In the lower south west part of the inference space there was limited water well log data available with Marlboro Clay present. This was because Marlboro Clay formation outcroppings are generally found on slopes too steep (> 40%) for residential development.

Location Estimation of Water Well Logs:

The minimum time for manual placement of each water well's location was five to ten minutes. The time it took to locate each water well was attributed to several variables which include: 1) the TIGER roads layer did not accurately identify every road within the county, 2) the orthophograph was flown in 1998, therefore houses built post-1998 could not be seen on the photograph, and 3) the location sketch was not always detailed enough to accurately locate the water well.

Out of 50 logs 27, of the manually placed well logs were closer than the ADC map coordinates (Fig. 3-4). It was therefore determined the manual placement was the more accurate method for location estimation, and was used for the remainder of the analysis. To assess the measurement error of the water well log dataset, 50 water well logs were georeferenced and the parcel locations of these 50 water well logs using Maryland Property View Pro 2003 were used to compare against the manual placement of the same 50 water well logs (Fig. 3-4 and Fig. 3-5). When compared the 50 water well logs had a mean of 720 m with a minimum of 26 m and a maximum of 5,938 m.

However the Maryland Property View Pro 2003 locations had a mean 171 m of with a minimum of 6 m and a maximum of 1,151 m.

Semivariograms:

Both semivariograms provide evidence of spatial autocorrelation of the study variables (Fig. 3-6). The bottom elevation variogram had a low nugget (17.3 m) relative to the overall semivariance and exhibited a range of about 11500 m; for ordinary and universal kriging this variable was modeled using a spherical semivariance function. The thickness variable exhibited steadily decreasing autocorrelation with distance and a high nugget (2.2 m) relative to the overall semivariance; for ordinary and universal kriging this variable was modeled using an exponential semivariance function.

Results of the Mapping Methods:

Results of the bottom elevation modeling and associated cross validation residuals are presented in Figures 3-7a, 3-7b, 3-7c, 3-7d, and 3-7e and Table 3-1. For the global polynomial modeling, the second order polynomial was marginally significant but the third order was not. The global polynomial interpolation generated an irregular trend across the inference space with a trough of high bottom elevations running south to northwest and the lowest values along the eastern boundary of the area (Fig. 3-7a). The cross validation RMSE was 34.5 m. In comparison to the RMSE of the semivariogram, (17.3 m) this interpolation method produced a high RMSE. The residuals were generally clustered with areas of large negative, large positive and small values – an indication that this interpolation method may not have captured finer-scale variations in the formation (Fig. 3-7a).

The IDW interpolation that produced the lowest cross validation RMSE had a power of 2. This interpolation also produced the lowest RMSE overall, which was 22.4 m. In comparison to the RMSE of the semivariogram, (17.3 m) the RMSE is relatively close indicating how well this method modeled the water well log dataset. Results and cross validation residuals are presented in Fig. 3-7b and Table 3-1. Generally, elevations were highest in the middle of inference space and lowest along the eastern edge of the inference space. However, there were small pockets of low elevations in the western area and an area with high elevations in the northeast corner. Residuals were irregularly distributed. There were several residual pairs of under- and over-estimated values, which were a function of applying IDW interpolation to a data set with contrasting adjacent values set apart from other points. In the west of the study area, there were several areas with low and high bottom elevations that are based on a small number of input data.

The local polynomial interpolation that produced the lowest cross validation RMSE had a power of 2, which was 26.0 m. When compared to the nugget of the semivariogram (17.3 m), this interpolation method produced a high RMSE. This method did not model the water well log dataset as well as IDW, but results are presented in Fig. 3-7c and Table 3-1. In the middle of the inference space there was a large trend of high elevations in the center and low to the east; this follows the proposed fault line of Statsz et al. (1991). There were also several areas of local low elevation in the west and one area of high elevations in the north. There were periodic areas of low and high elevation running north-south in the area east of the proposed fault line. In other areas the residuals were irregularly distributed.

The ordinary kriging interpolation that produced the lowest cross validation RMSE (23.8 m) had a power of 2. This method produced the second lowest RMSE next to IDW, but was still high when compared to the nugget of the semivariogram which was 17.3 m (Table 3-1 and Fig. 3-7d). Along the majority of northeast and southeast edge of the there was a trend of low elevations. In the south western region of the inference space, there were pockets of low elevations as well. There was a trend of high elevations present in the middle of the inference space and gradually continued toward the north western edge. In the middle and along the eastern edge of the inference space the residuals were irregularly distributed.

The universal kriging interpolation produced the lowest cross validation RMSE (23.8 m) with a power of 1, but in relation to the nugget of the semivariogram, (17.3 m) this interpolation method's RMSE was high. However, universal kriging's RMSE was nearly identical to ordinary kriging (Fig. 3-7e and Table 3-1). Like ordinary kriging, there was a trend of low elevations along the northeast and southeast edge. In the southwest part of the inference space there were pockets of low elevations present as well. These pockets were indicative of low point distribution in this area. In the middle of the inference space and along the northwest edge, the elevations were high.

Results of the thickness modeling and cross validation residuals are presented in Figures 3-8a, 3-8b, 3-8c, 3-8d, and 3-8e and Table 3-1. For the global polynomial modeling, the second order polynomial produced the lowest cross validation RMSE (3.0 m) with a power of 2 in comparison with powers of 1 and 1.5, indicating that interpolating with a higher power did not over-emphasize nearby points. However, in comparison to the nugget of the semivariogram, (2.2 m) this interpolation method produced a slightly higher RMSE. Results of the cross validation residuals are presented in Fig. 3-8a and Table 3-1. The global polynomial produced a smooth trend across the inference space with troughs of large and small thickness values scattered throughout (Fig. 3-8a). Large thickness values were beyond the prediction range of the linear model, with 42 residuals. These large negative residual values were not present in large areas in the south and west of the study region; but were present through the rest of the study region (Fig. 3-8a). Where present, there were large negative residual values, both solitary and in clusters (Fig. 3-8a) near and apart from medium-sized residuals. The presence of solitary and clustered large residuals may be either due to the varying thickness of the Marlboro Clay formation, or misidentification of the Marlboro Clay formation.

The IDW interpolation that produced the lowest cross validation RMSE had a power of 1 in comparison with powers of 1.5 and 2. This interpolation also produced the lowest RMSE overall, which was 2.8 m which was relatively close to the nugget (2.2 m) of the semivariogram, indicating how well this method modeled the thickness variable (Fig. 3-8b). There were large negative residuals along the southwestern and northwestern edge of the inference space. Scattered throughout the inference space there were small clusters of negative residuals with values ranging from -11.1 to -5.6 m. Overall, there was an even distribution of values ranging from -2.7 to 2.8 m. Local polynomial produced the lowest cross validation RMSE (3.0 m) with a power of 1, which was the third most accurate even though it was close to the nugget of the semivariogram, (2.2 m) (Fig. 3-8c). Along the western edge, in the upper middle, and in the northern areas of the inference space, large negative residuals were present in small clusters. There were few large negative values present in the lower middle and south areas of the inference space. In the most northern area of the inference space there were a limited number of water wells present, indicating that this mapping method did not capture the local variations in the formation. Overall, residuals ranging between -2.7 and 2.8 m were well distributed throughout the inference space.

The ordinary kriging interpolation that produced the lowest cross validation RMSE (2.9 m) had a power of 1, and when compared to the nugget of the semivariogram, (2.2 m) the RMSE is relatively close. The results are presented in Fig. 3-8d and Table 3-1. There were solitary large negative residuals along the western edge of the inference space along with large positive residuals along the northwestern edge of the inference space as well. Solitary large negative residuals were also scattered throughout the middle and upper areas of the inference space. There were no large negative values in the lower southern areas of the inference space. Solitary positive residuals were present in the middle and southwestern areas of the inference space. The majority of the inference space was abundantly filled with solitary and clustered residuals with values ranging from -2.7 to 2.8 m.

Universal kriging produced the lowest cross validation RMSE (3.1 m) with a power of 1 and the results are provided in Fig. 3-8e and Table 3-1. This interpolation method was the least accurate in comparison to the other interpolation methods, but close to the nugget of the semivariogram, (2.2 m). Solitary large positive residuals were present in the northern most part of the inference space. Lone negative residuals were present in the middle and northern areas of the inference space. There were no large negative or positive residuals present in the lower southwestern, middle, or southeastern areas of the inference space. In the middle and lower areas of the inference space pointing west, there were many solitary residuals ranging in value from -2.7 to 2.8 m. In the lower western areas, residuals with the same value were clustered. Moving east going from north to south, residuals ranging from -2.7 to 5.5 m were clustered.

Validation Results:

The results of location measurement error of the bottom elevation and the thickness from the water well log dataset are presented in Fig.'s 3-9a and 3-9b and Table 3-2. For the bottom elevation IDW was the most accurate interpolation method producing an RMSE of 17.4 m. According to Fig. 3-9a, there were 30 water well logs 0 to 20 m off. However, with the exception of the 17 water well logs -20 to 0 m off, IDW produced the smoothest curve. Global polynomial proved to be the least accurate mapping method, producing an RMSE of 30.5 m. According to Fig. 3-9a, there were 20 water well logs 0 to 20 m off, and there were 20 water well logs 20 of 40 m off. Universal kriging was the most accurate interpolation method for the thickness variable, producing an RMSE of 4.7 m. According to Fig. 3-9b, there were 28 water well logs 0 to 10 m off of the actual thickness and 23 water well logs from -10 to 0 m off of the actual thickness. Ordinary kriging and IDW both had RMSE's of 4.9 m. Global polynomial was the least accurate with an RMSE of 5.9. According to Fig. 3-9b, global polynomial had 24 water well logs from 0 to 10 m off of the actual thickness and 23 water well logs from -10 to 0 m off of the actual thickness. Although universal kriging was the most accurate interpolation method, all of the interpolation methods introduced high degrees of error from -10 to 10 m.

Of the 50 georeferenced water well logs, none were at outcropped locations. The local polynomial interpolation and the soil survey correctly identified every georeferenced log as a nonoutcrop location (Table 3-3). The MNCPPC Marlboro Clay map was the least accurate correctly identifying only 35 of the 50 water well locations as non outcrops (Table 3-3). This high degree of error may have been caused by over extrapolation when this map was produced from the USGS geology map for Prince George's, County.

The results of the 38 auger borings, 5 of which are located at the site of the deep cores are presented in Table 3-4. For the 33 auger boring dataset, global polynomial and ordinary kriging produced the best results accurately identifying 15 and 14 auger borings as outcrops, respectively. Local polynomial and universal kriging produced the poorest results, accurately identifying 5 and 6 of the auger borings as outcrops, respectively. For the 5 auger borings dataset, inverse distance weighted and local polynomial produced the best results accurately identifying 3 of the 5 borings as outcrop.

Global polynomial, which proved to be the best method, was only 45% accurate when validated by the 33 auger borings. Global polynomial was 0% accurate when validated by the 5 auger borings. Global polynomial along with the other mapping methods underestimated the 33 auger borings.

The results of the validation residuals for the 61 deep cores are presented in Fig.'s 3-10a and 3-10b, and Table 3-5. For the bottom elevation global polynomial was the most accurate interpolation method producing an RMSE of 27.4 m. There were 18 water well logs -60 to -40 m off and 16 water well logs -20 to 0 m off. There were also 14 water well logs -80 to -60 m off. Inverse distance weighted was the least accurate producing an

RMSE of 47.8 m (Table 3-5). For the thickness, IDW was the most accurate mapping method producing an RMSE of 4.5 m. There were 14 water well logs 4 to 5 m off of the actual thickness. Universal kriging and global polynomial were the least accurate both producing RMSE's of 5.9 m. Although, IDW was produced the lowest RMSE, all of the interpolation methods produced high degrees of error in the 4 to 6 m thickness range.

Discussion and Conclusions

Sources of Error:

There were several errors associated with the use of water well logs to map the bottom elevation and thickness of the Marlboro Clay formation including microtopography of the Marlboro Clay formation, areas of low point density, drill operator error, vertical measurement error, and georeferencing error.

According to the water well log data for the bottom elevation (Fig. 3-3a) the Marlboro Clay does have a 1% dip moving east to west. On the east portion of the inference space the Marlboro Clay has elevations ranging from 126.1 to 217.5 m above sea level and the western edge has a range of 19.1 to -34.0 m below sea level. The elevation values going from north to south in the middle of the inference space range from 73.1 to 165.0 m above sea level. This trend of elevation values in the middle of the inference space may follow the fault line proposed by Statsz et al. (1991).

Vertical measurement errors were introduced when the data was initially collected for each water well log. Through the years, these water well logs have been collected by numerous drill operators and there are no standards available by MDE on coring methodology to account for vertical errors, nor are there requirements on the type, model, or age of the drill operating equipment the driller may use. Secondly, most drill operators have no geology training, and therefore the descriptions presented in the lithology log are limited to color and texture.

Though the manual method was slightly more accurate having 27 of the 50 water well logs closer to the actual location of the georeferenced water well logs, there was still high measurement error introduced. The semivariogram from the bottom elevations raw data had a nugget of 17.3 m. The RMSE for the difference between the manual and actual bottom elevation for 50 water well logs was 47.4 m. Due to such a high RMSE in comparison to the semivariogram, high measurement error is being introduced mostly by the manual placement of the water well logs, but there was also minimal measurement error introduced by the drill operator and the microtopography.

Map Production:

There were a limited number of water well logs with Marlboro Clay present in the southwest portion of Prince George's County because the formation is located on slopes too steep (> 40%) for residential development. There were also a limited number of water well logs in the and northwest portion of Prince George's County. Because of this, there was extrapolation in the bottom elevation and thickness decreasing the accuracy and quality of the maps.

For the five interpolation methods used, based on the cross validation presented in Table 3-1, IDW produced the most accurate bottom elevation and thickness map. The IDW method was the most accurate according to the results of the 50 georeferenced water well log validation dataset for the bottom elevation, but universal kriging was the most accurate method for the thickness (Table 3-2). According to table 3-3, local polynomial correctly identified every georeferenced water well log as not outcrop. However, the other interpolation methods were nearly as accurate with universal kriging only misidentifying 2 water well logs as outcrops, and the remaining interpolation methods misidentifying one as an outcrop. Overall IDW was the most accurate method for both the bottom elevation and thickness maps.

As presented in Table 3-3 the 1967 Soil Survey was the most accurate tacit knowledge based map correctly identifying all 50 georeferened water well logs as outcrop. The USGS geology map was nearly as accurate only misidentifying 2 of the 50 georeferenced water well logs as outcrop. The MNCPPC geology map was the least accurate misidentifying 15 of the 50 georeferenced water well logs. This may have been due to extrapolation errors introduced when interpolating their Marlboro Clay map to a 1:12,000 scale from the USGS geology map which was done at a scale of 1:24,000.

Properly Georeferenced Water Well Logs / MD Property View Pro:

If MDE had required that every water well log in their database be georeferenced, then the measurement error introduced when performing each interpolation analysis for the bottom elevation and thickness maps could have been greatly reduced. Properly georeferencing with the 2 m LiDAR DEM would greatly improve the accuracy of the bottom elevation, and would give a more accurate estimate of the actual thickness of the Marlboro Clay because a drill operator can easily determine where the formation begins and ends. The other forms of measurement error associated with the water well log dataset would persist, but they would be low allowing for a quality map to still be produced if each water well log was properly georeferenced.

The 50 georeferenced water well log dataset using MD Property View Pro was more accurate when compared to the 50 manually georeferenced water well log dataset (Fig. 3-5). Using MD Property View Pro rather than the manual method to georeference the water well log dataset could potentially create more accurate thickness and bottom elevation Marlboro Clay interpolation maps. Using MD Property View Pro could potentially reduce the location measurement error and time would be saved by not having to use a GPS unit to georeference each water well logs location.

For the bottom elevation and thickness, nongeoreferenced maps may be useful on a regional scale, but either MD Property View Pro or proper georeferencing should be done for mapping on a local scale to improve the reliability of the map. Therefore it is strongly recommended that MDE update its regulations on using more modern coring methodology to alleviate elevation errors and accurately georeferencing each water well log to improve maps for natural resource and urban planning.

Tables:

Table 3-1. Cross validation residuals summaries associated with each interpolation method using the bottom elevation and thickness water well log data.

Mapping Method	Minimum (m)	Maximum (m)	#Low	#High	%Low	%High	RMSE (m)
			Bottom Elevation				
Global Polynomial	-98.8	191.6	50	76	6.3	9.5	34.5
Inverse Distance Weighted	-90.3	113.4	13	31	1.6	3.9	22.4
Local Polynomial	-82.7	174.3	15	44	1.9	5.5	26.0
Ordinary Kriging	-81.8	121.4	13	39	1.6	4.9	23.8
Universal Kriging	-94.8	107.7	16	36	2.0	4.5	23.8
			Thickness				
Global Polynomial	-25	9.3	42	2	5.3	0.3	3.0
Inverse Distance Weighted	-26.5	10.9	30	5	3.8	0.6	2.8
Local Polynomial	-26.5	9.2	44	2	5.5	0.3	3.0
Ordinary Kriging	-28.1	9.7	26	4	3.3	0.5	2.9
Universal Kriging	-31.1	19.9	28	16	3.5	2.0	3.1

*

* The # low is defined as the number of residuals < the lowest RMSE; the # high is defined as the number of residuals > the highest RMSE.

Table 3-2. 50 georeferenced water well log dataset used as validation for the five interpolation methods.

Mapping Method	Mean Residual (m)	Minimum (m)	Maximum (m)	#Low	#High	%Low	%High	RMSE (m)
				Bottom Elevation				
Global Polynomial	5.03	-91.63	38.57	6	2	12	4	30.5
Inverse Distance Weighted	1.49	-57.63	30.87	4	0	8	0	17.4
Local Polynomial	1.27	-63.73	42.28	4	2	8	4	23.1
Ordinary Kriging	3.87	-45.68	36.37	2	1	4	2	17.7
Universal Kriging	4.51	-51.63	46.37	2	3	4	6	18.9
				Thickness				
Global Polynomial	2.80	-2.95	17.38	0	8	0	16	5.9
Inverse Distance Weighted	2.08	-3.56	14.38	0	5	0	10	4.9
Local Polynomial	2.78	-2.95	17.38	0	8	0	16	5.9
Ordinary Kriging	1.94	-2.95	15.38	0	4	0	8	4.9
Universal Kriging	1.94	-2.95	15.38	0	4	0	8	4.7

[3]

Table 3-3. 50 georeferenced water-well logs used as validation to determine how many data points each method could correctly identity as a non-outcrop location.

	Not Outcrop n = 50	
	Correct	Wrong
Global Polynomial	49	1
IDW	49	1
Local Polynomial	50	0
Ordinary Kriging	49	1
Universal Kriging	48	2
USGS Geology Map	48	2
MNCPPC Geology Map	35	15
1967 USDA/NRCS Soil Survey	50	0

[3] The # low is defined as the number of residuals < the lowest RMSE; the # high is defined as the number of residuals > the highest RMSE.

Table 3-4. 33 auger borings validation dataset and 5 auger borings from the intensive sampling dataset. The 5 interpolation methods and 2 maps were compared against the validation dataset to determine how many auger borings each method could correctly identify as outcrop. True = outcrop, Over = above outcrop, and Under = below outcrop.

	33 Auger Borings			5 Auger Borings		
	True (m)	Over (m)	Under (m)	True (m)	Over (m)	Under (m)
Global Polynomial	15	4	14	0	5	0
Inverse Distance Weighted	8	6	19	3	0	2
Local Polynomial	5	4	24	3	0	2
Ordinary Kriging	14	6	13	1	3	1
Universal Kriging	6	7	20	0	4	1
USGS Geology Map	13	12	8	2	0	3
MNCPPC Geology Map	16	0	17	2	1	2

Table 3-5. 61 deep cores dataset used as validation for the five interpolation methods.

Mapping Method	Mean Residual (m)	Minimum (m)	Maximum (m)	#Low	#High	%Low	%High	RMSE (m)
				Bottom Elevation				
Global Polynomial	-7.8	-65.0	52.0	1	0	1.6	0	27.4
Inverse Distance Weighted	-41.1	-98.0	10.0	24	0	39.3	0	47.8
Local Polynomial	-30.7	-93.0	14.0	11	0	18.0	0	40.0
Ordinary Kriging	-37.4	-94.0	23.0	19	0	31.0	0	45.7
Universal Kriging	-26.6	87.0	29.0	6	0	9.8	0	36.8
				Thickness				
Global Polynomial	5.3	-1.6	7.0	0	0	0	0	5.9
Inverse Distance Weighted	3.6	-2.6	6.0	0	0	0	0	4.5
Local Polynomial	4.2	-3.5	6.0	0	0	0	0	4.9
Ordinary Kriging	4.7	-2.5	7.0	0	0	0	0	5.2
Universal Kriging	5.2	-1.6	8.0	0	0	0	0	5.9

[4]

[4]The # low is defined as the number of residuals < the lowest RMSE; the # high is defined as the number of residuals > the highest RMSE.

Figures:

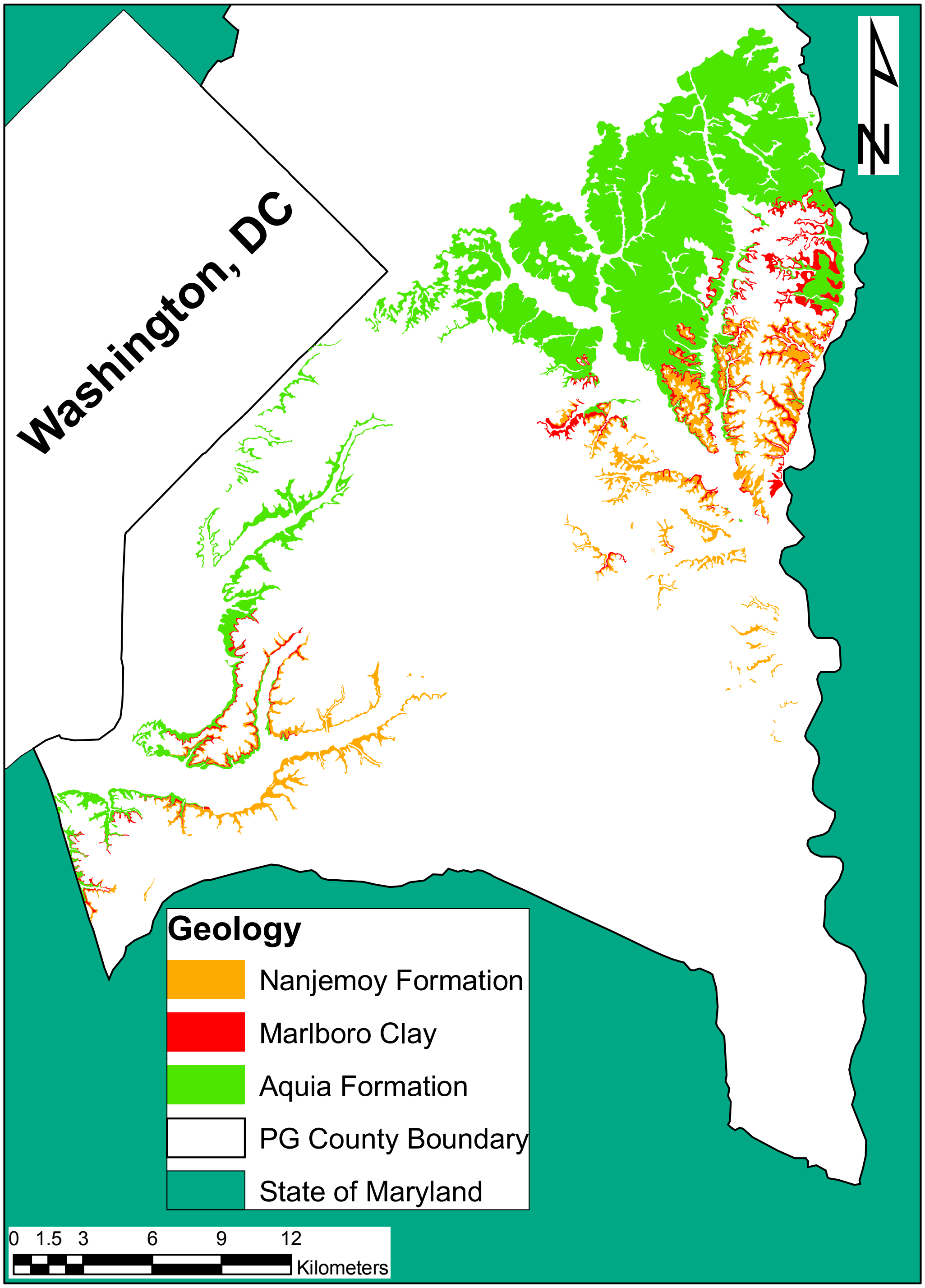


Fig. 3-1. Geology map of Prince George's County, Maryland showing the surficial deposits of the Nanjemoy, Marlboro Clay, and Aquia formations (Glaser, 1981, 1984).

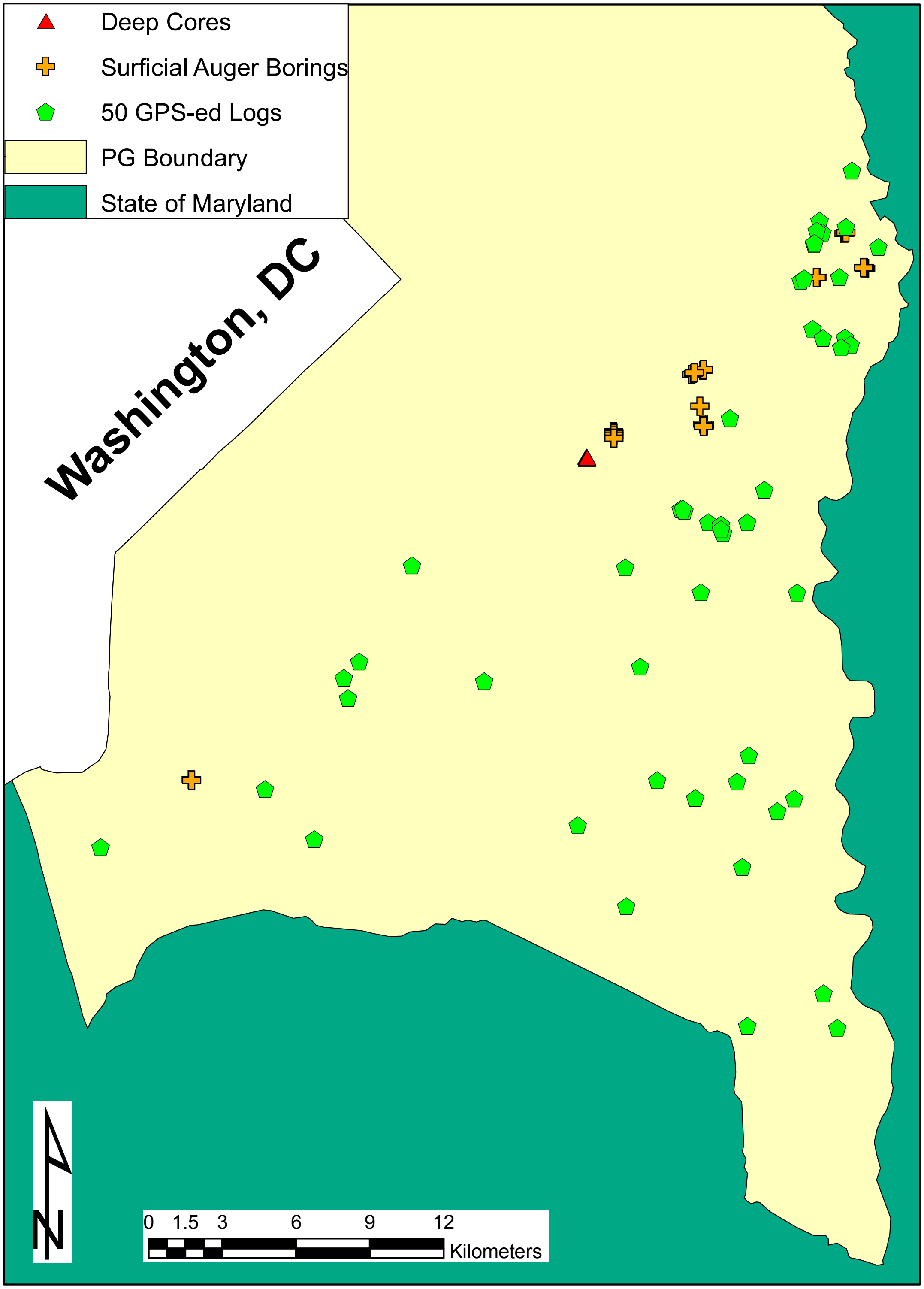


Fig. 3-2. The location of the validation data in Prince George's County, Maryland, which includes collected samples of Marlboro Clay from 61 deep cores , 38 surficial auger boring, along with 50 georeferenced water well logs.

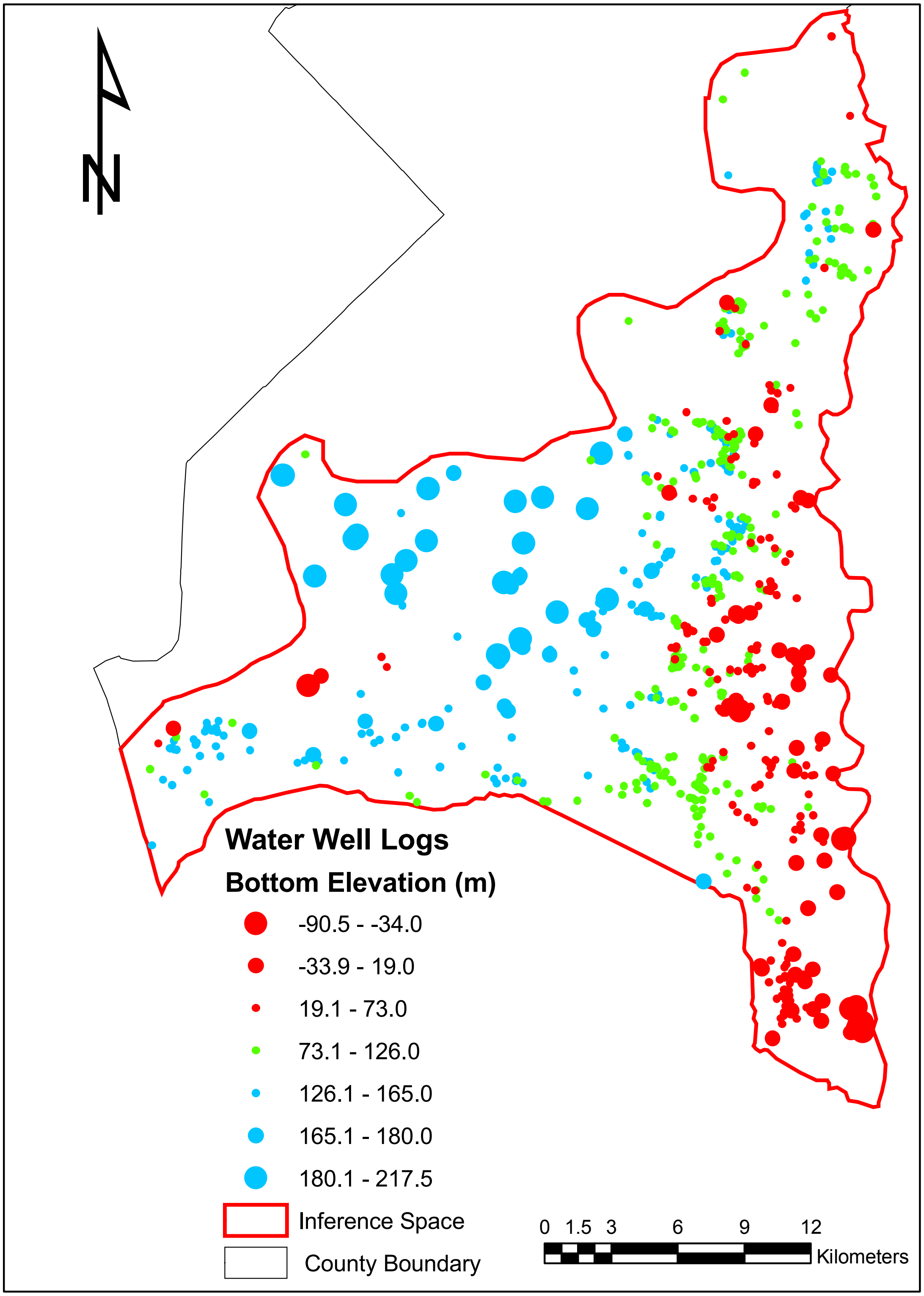


Fig. 3-3a. Site map of Prince George's County, Maryland with the water well log's bottom elevation for the Marlboro Clay formation.

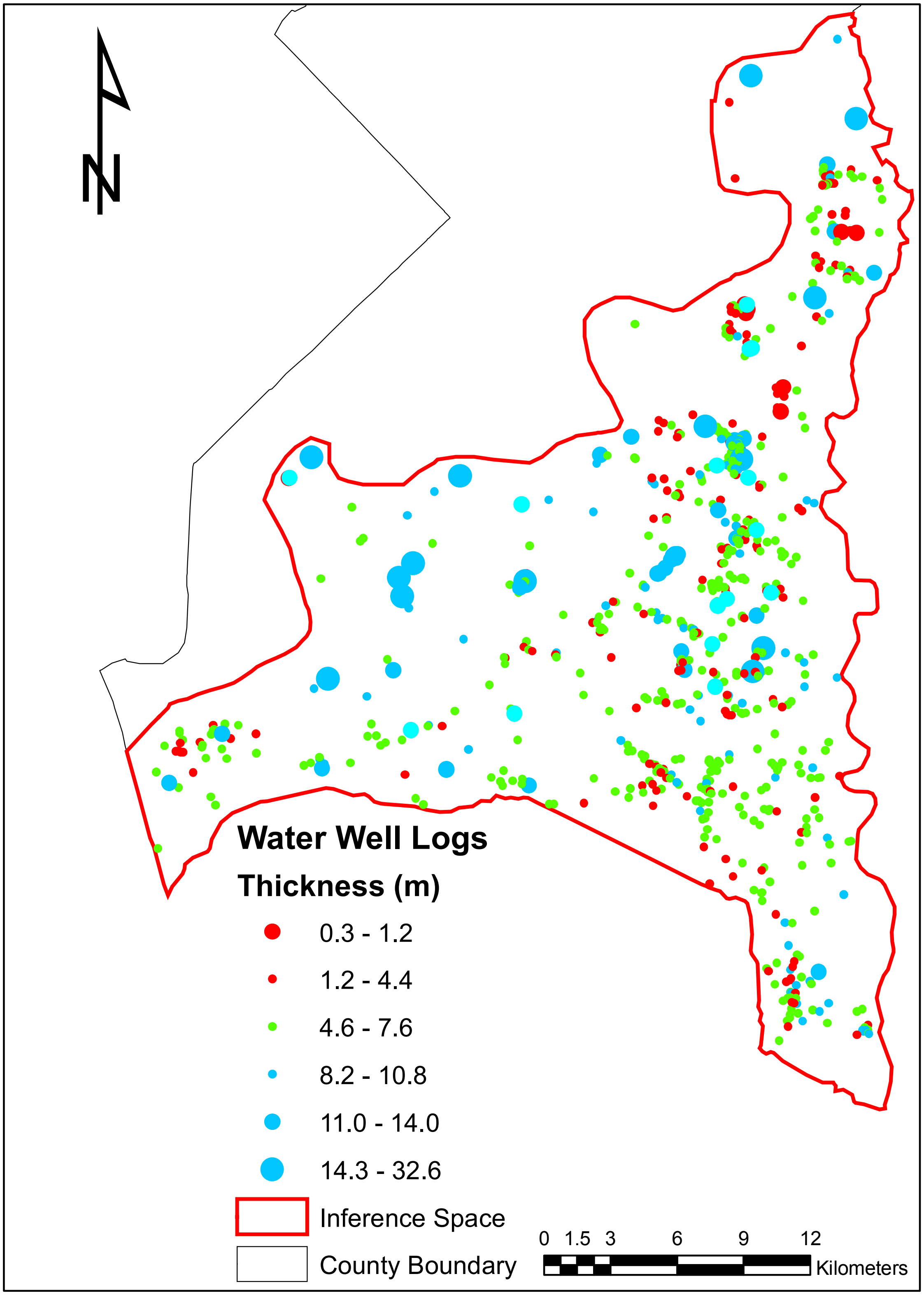


Fig. 3-3b. Site map of Prince George's County, Maryland with the water well log's thickness for the Marlboro Clay formation.

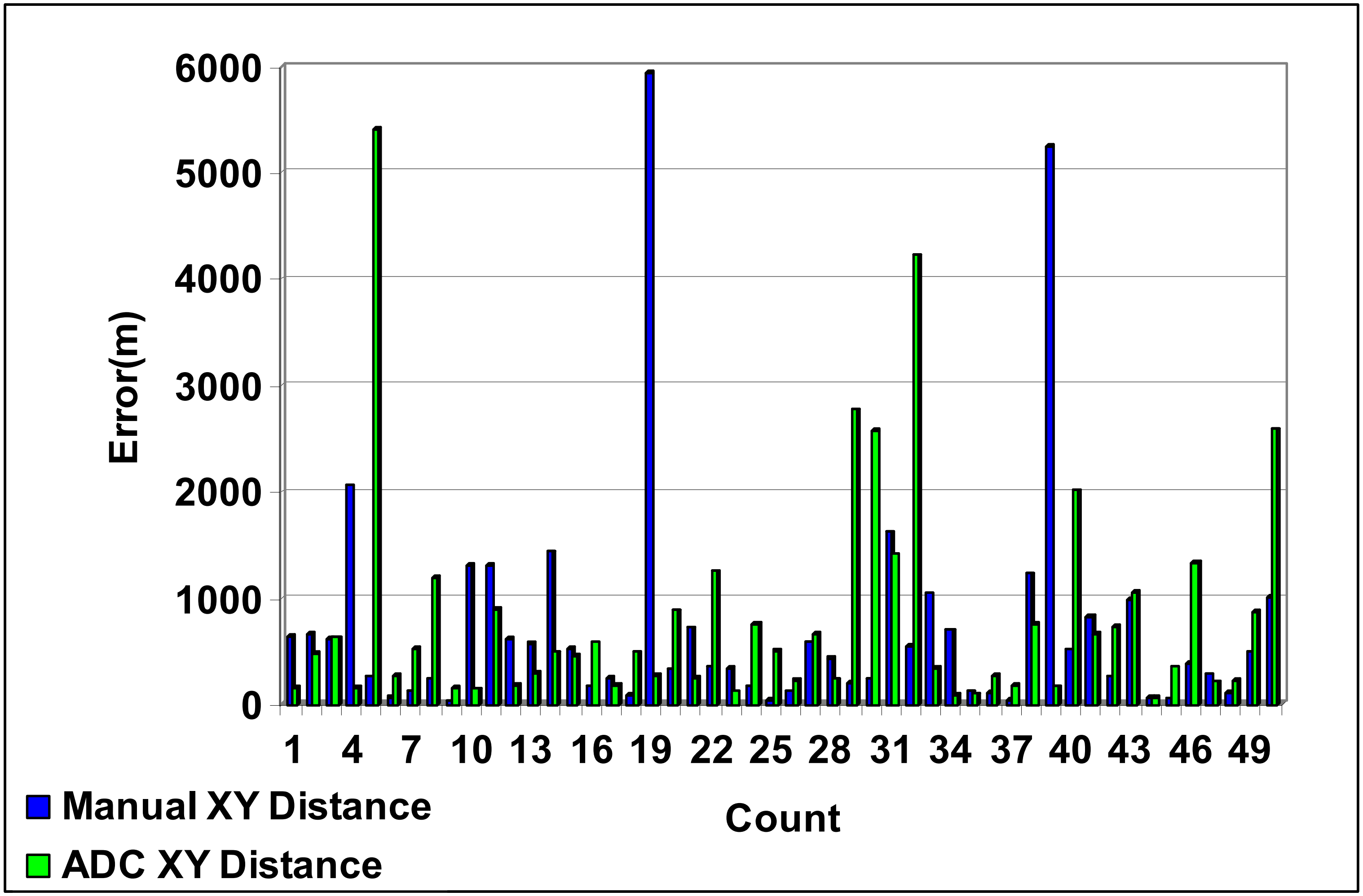


Fig. 3-4. Histogram comparing the location error introduced by using the manual and ADC grid methods for the 50 water well logs dataset.

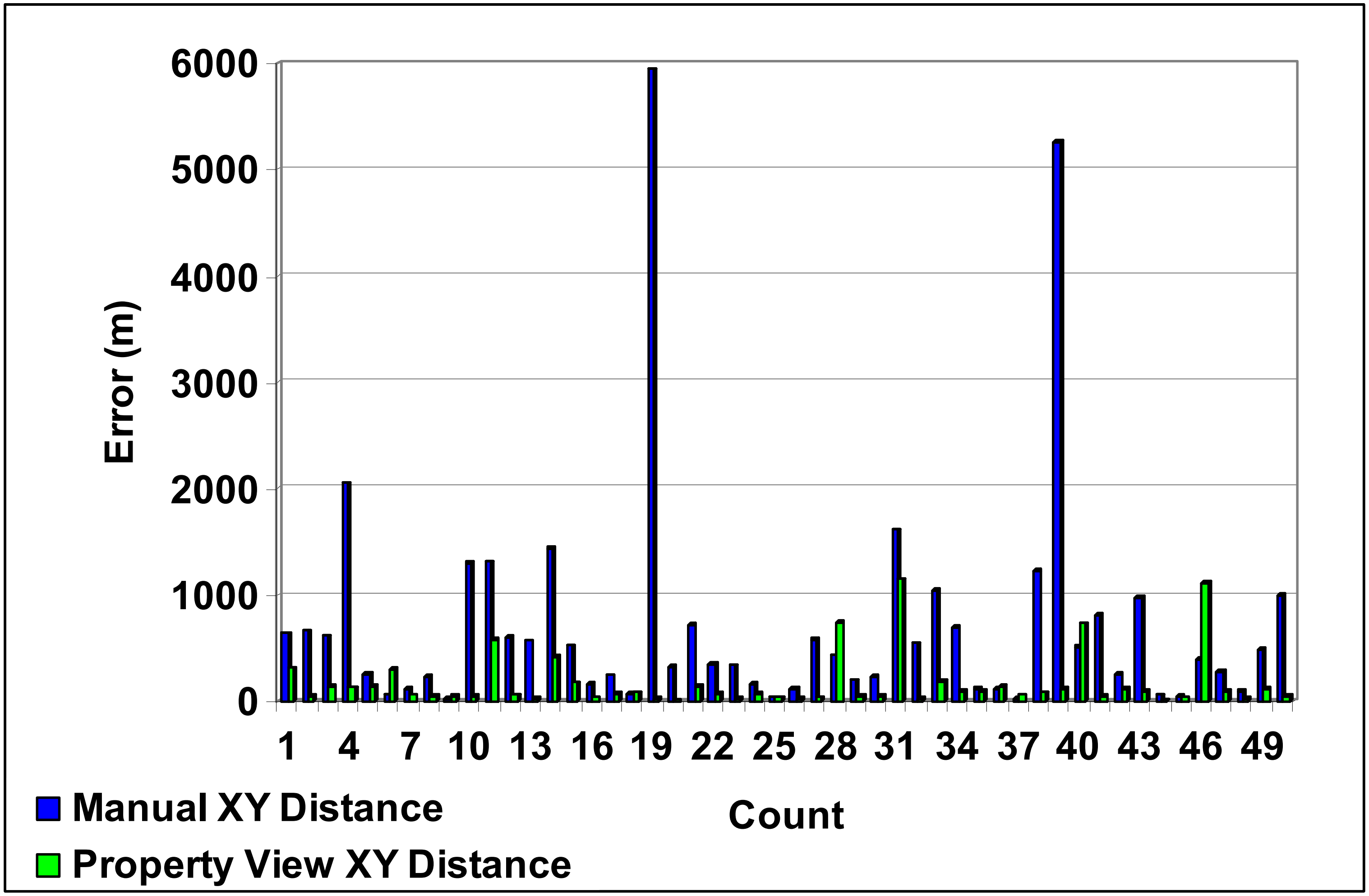
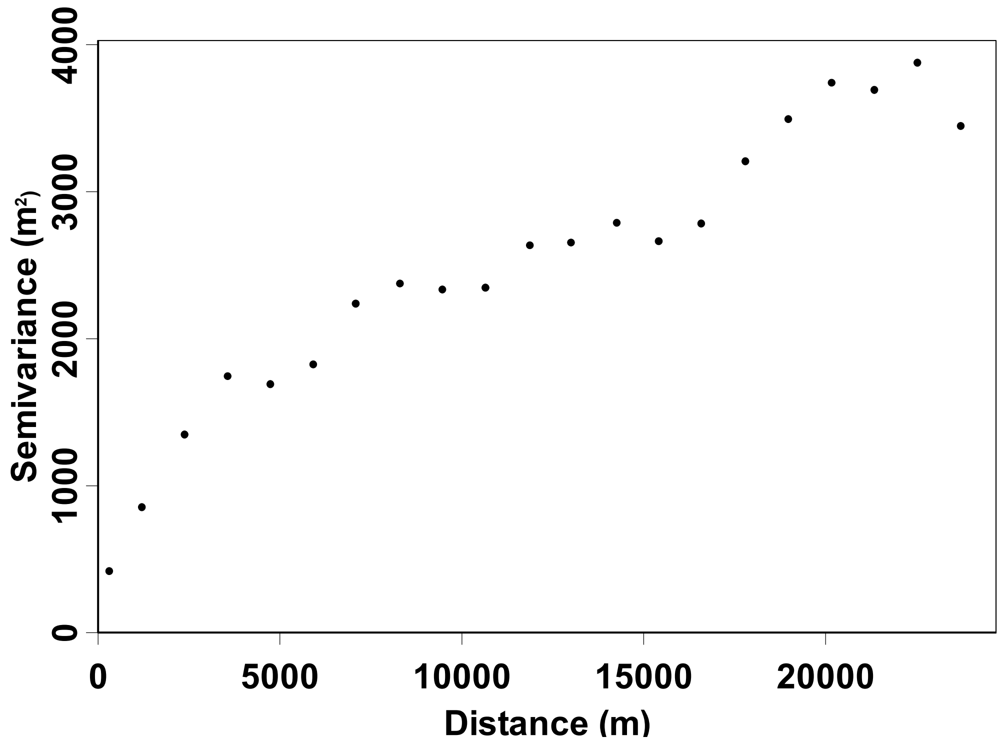


Fig. 3-5. Bar graph comparing the location error introduced by using the manual and MD Property View methods for the 50 water well logs dataset.



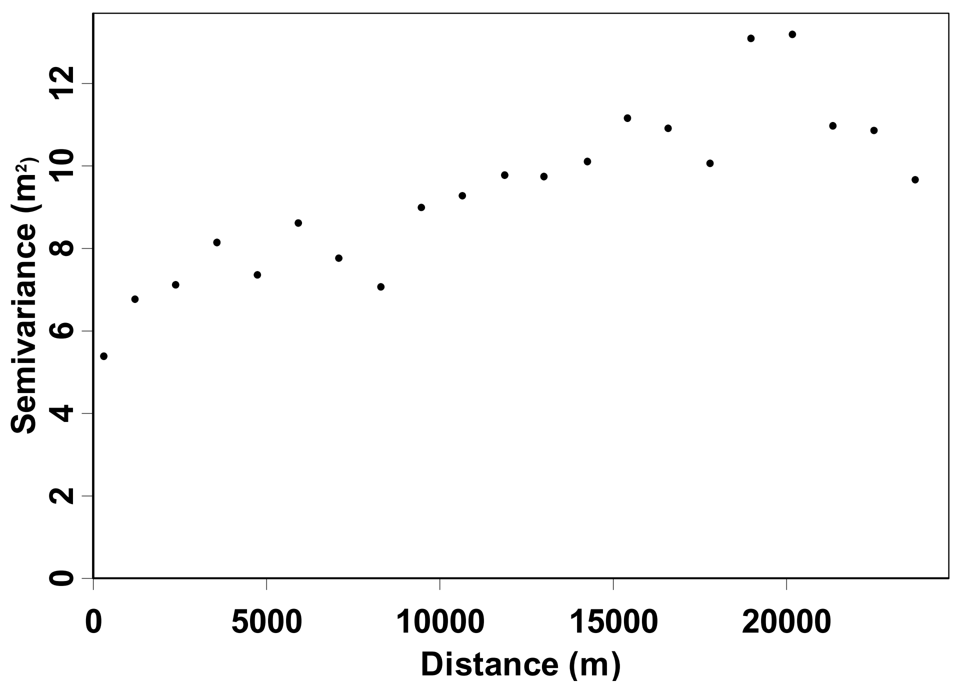


Fig. 3-6. Variograms measuring semivariance versus distance for the bottom elevation and thickness of the Marlboro Clay formation derived from the water-well logs.

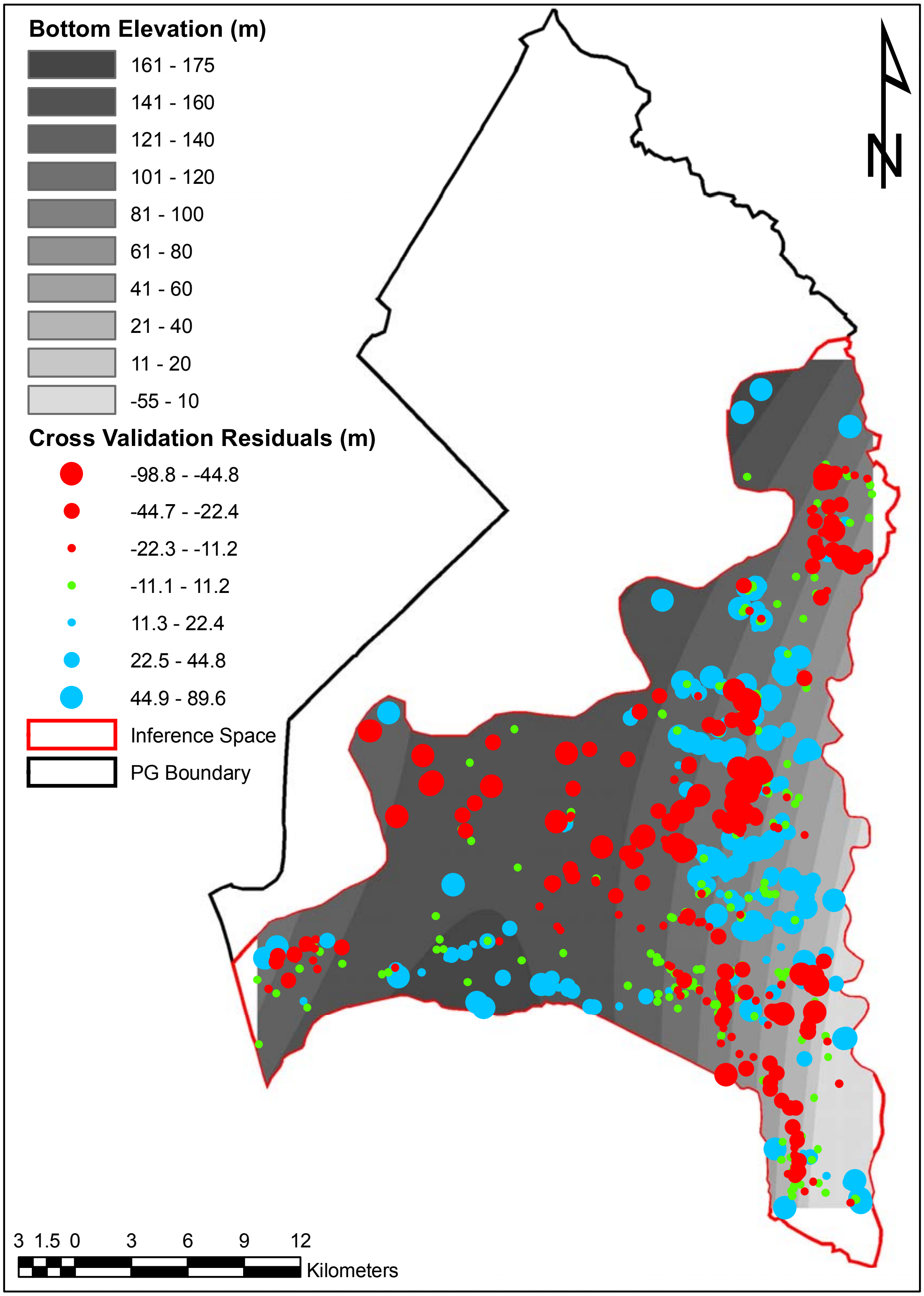


Fig. 3-7a. Bottom elevation map using the global polynomial function with the cross validation residuals included.

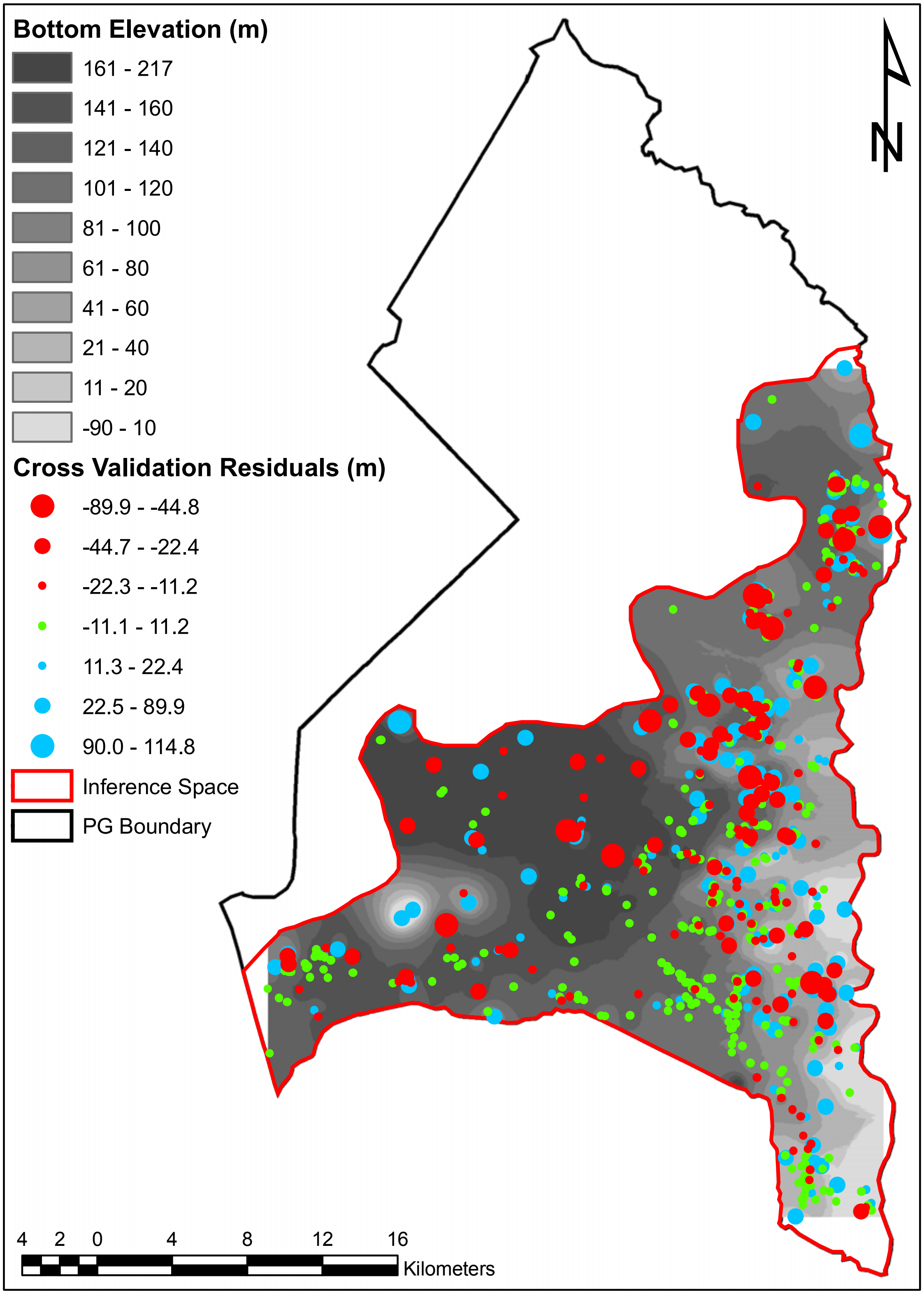


Fig 3-7b. Bottom elevation map using the inverse distance weighted function with the cross validation residuals included.

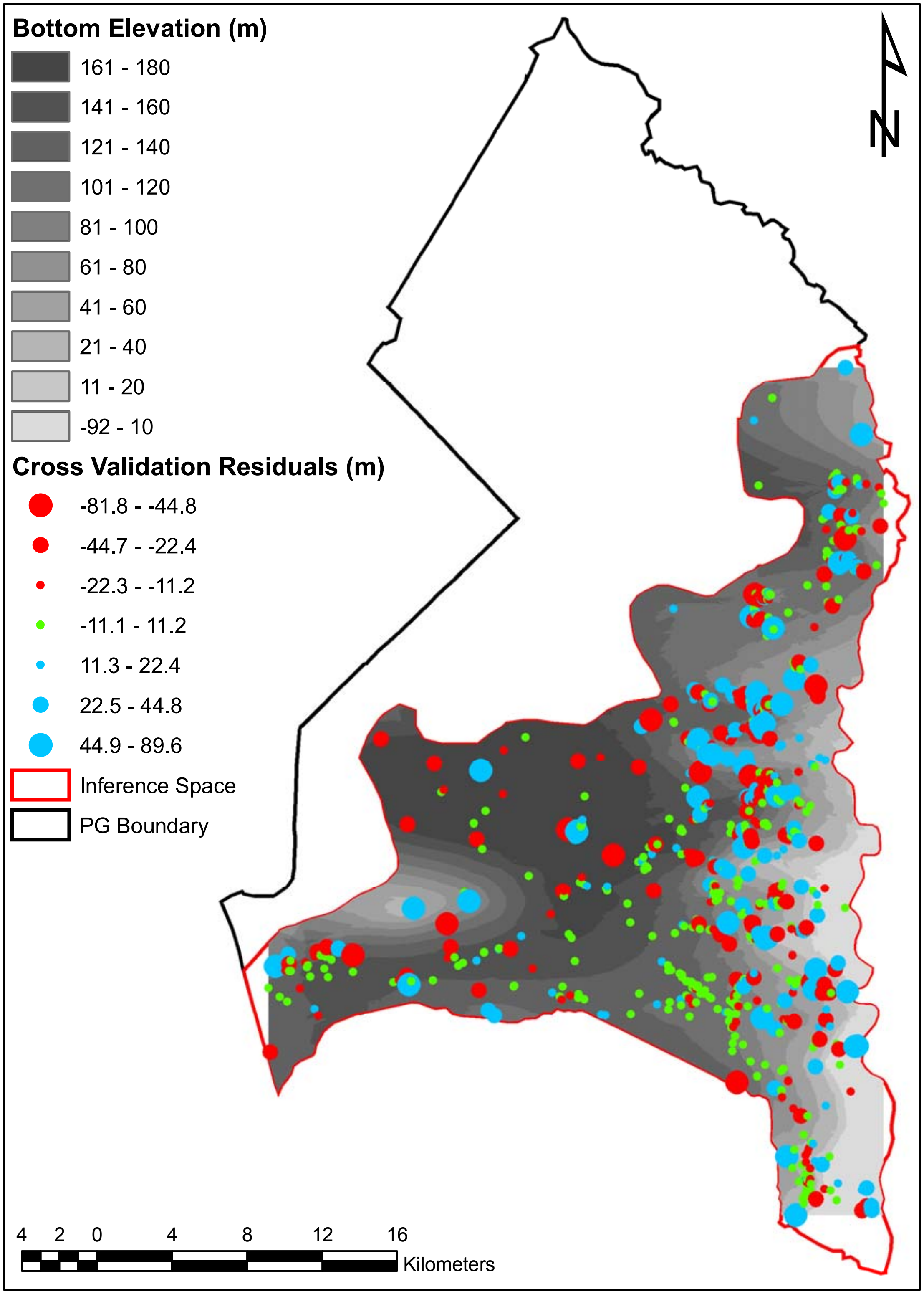


Fig 3-7c. Bottom elevation map using the ordinary kriging function with the cross validation residuals included.

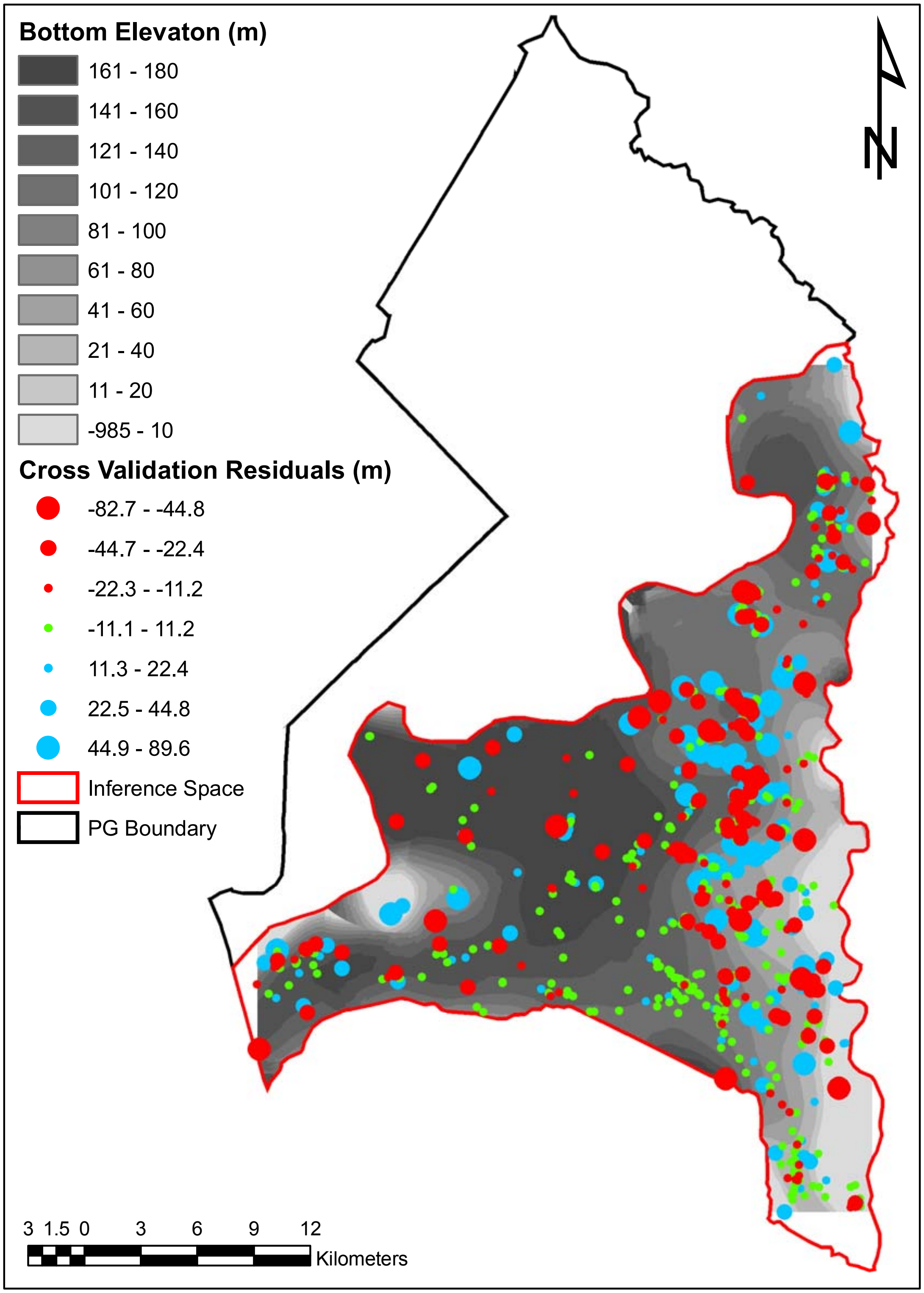


Fig. 3-7d. Bottom elevation map using the local polynomial function with the cross validation residuals included.

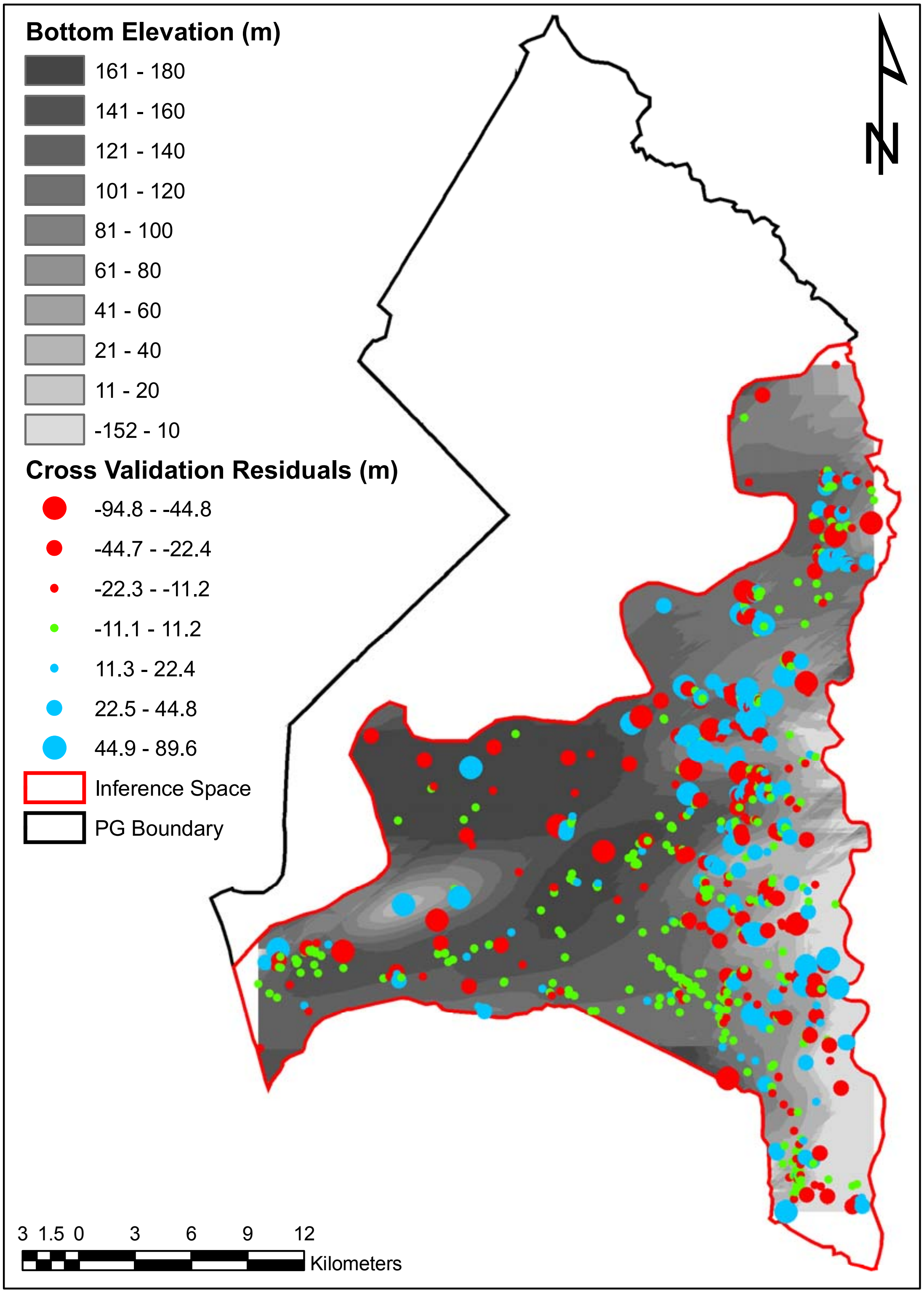


Fig. 3-7e. Bottom elevation map using the universal kriging function with the cross validation residuals included.

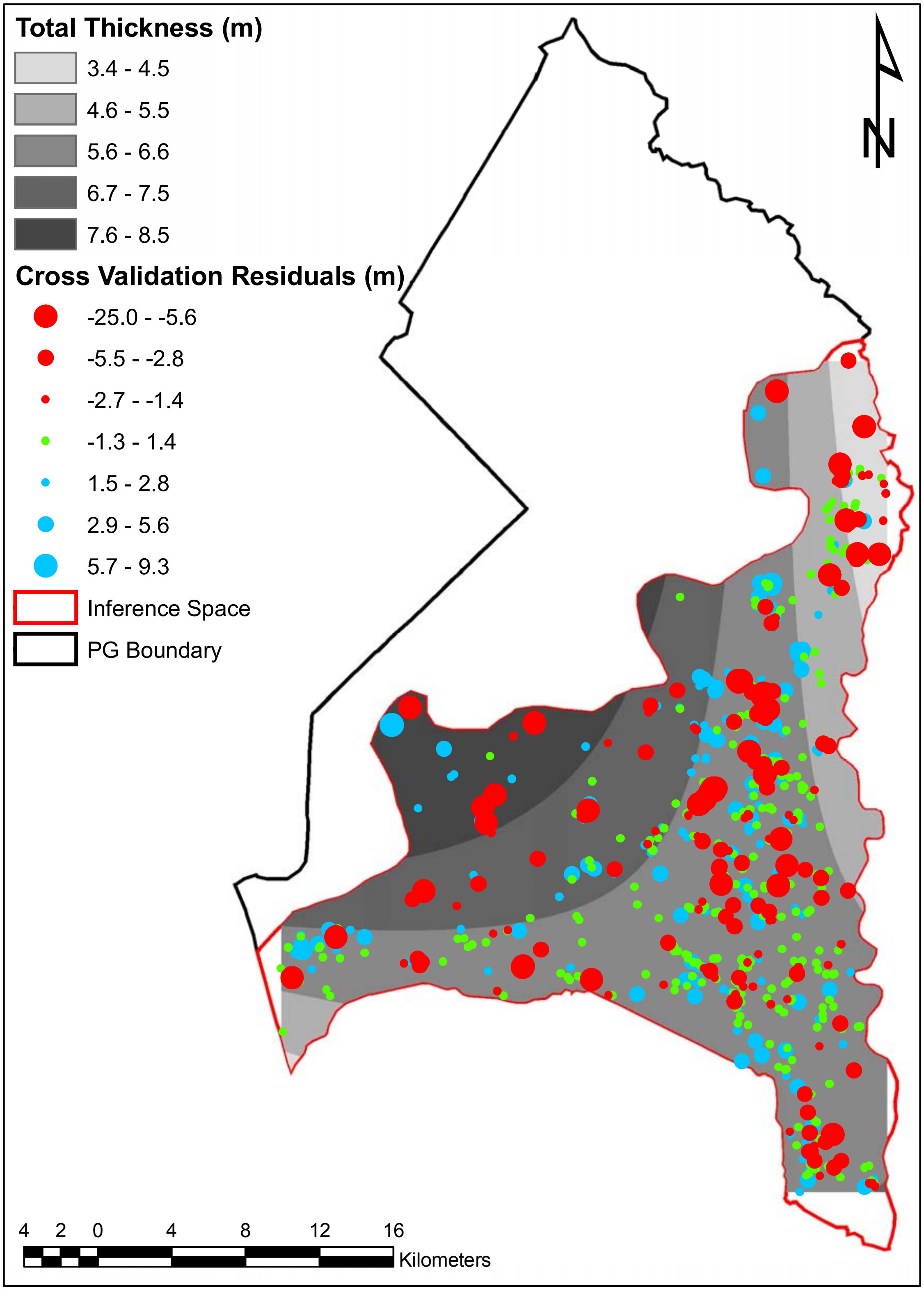


Fig. 3-8a. Thickness map using the global polynomial function with the cross validation residuals included.

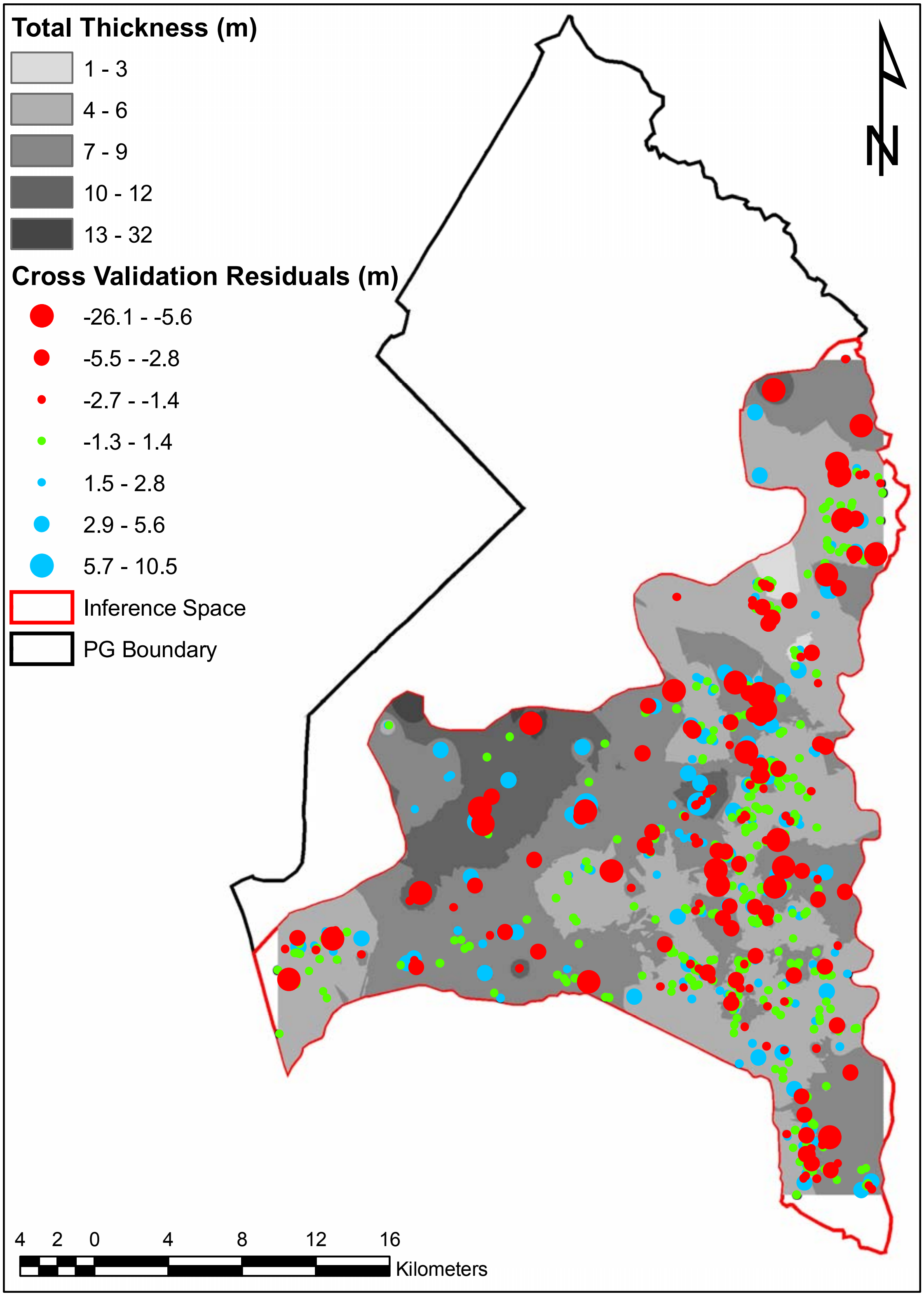


Fig. 3-8b. Thickness map using the inverse distance weighted function with the cross validation residuals included.

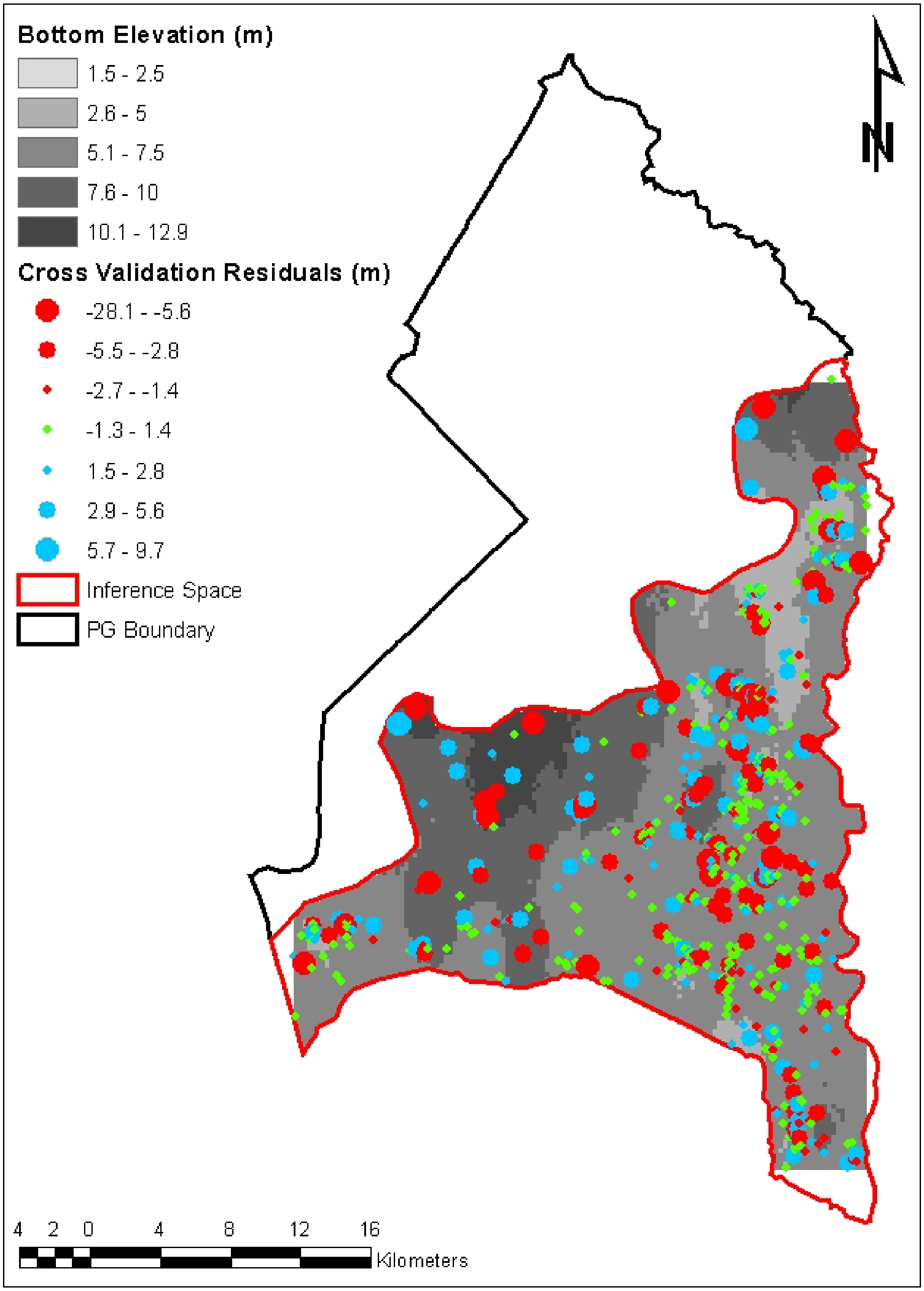


Fig. 3-8c. Thickness map using the ordinary kriging function with the cross validation residuals included.

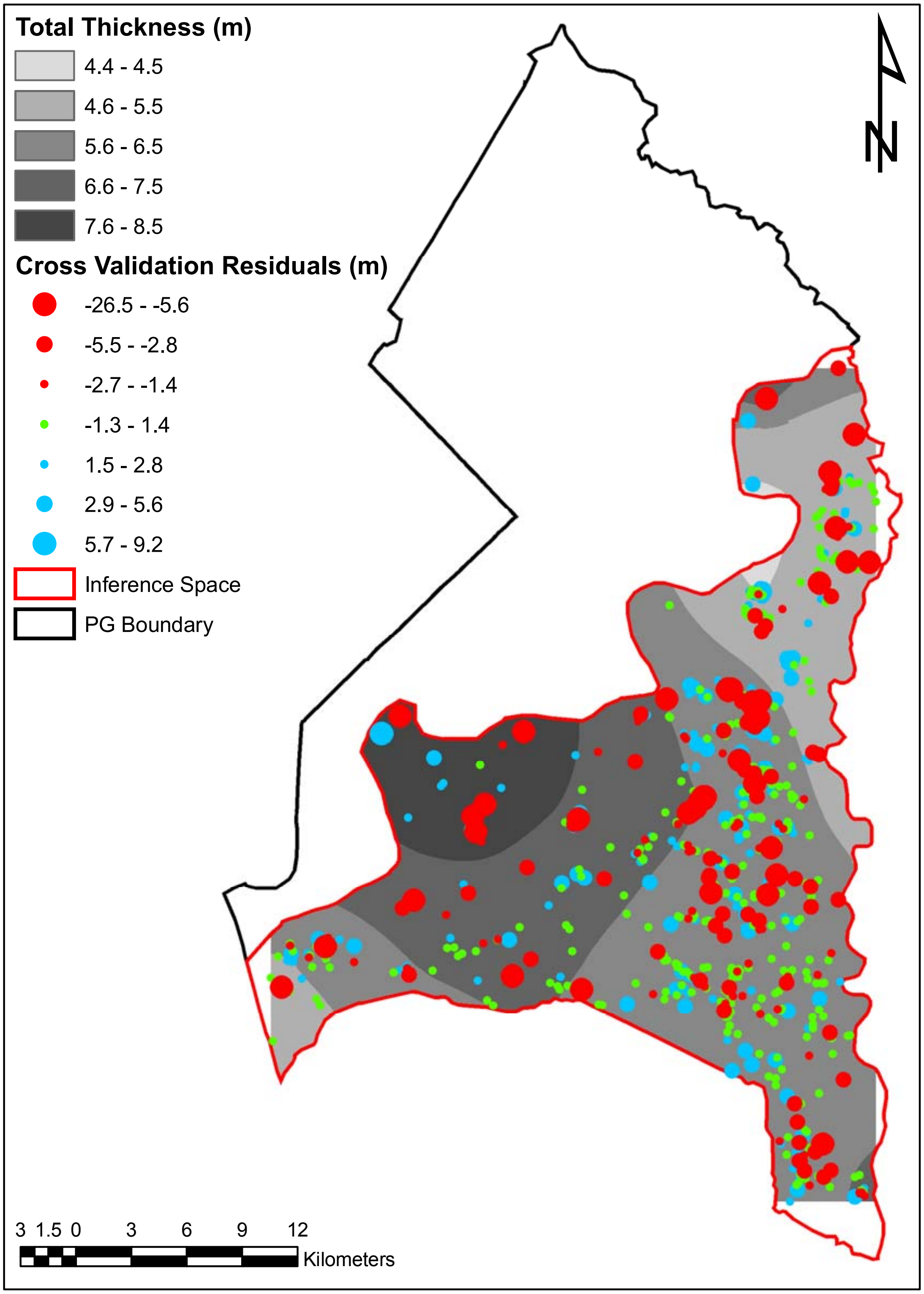


Fig 3-8d. Thickness map using the local polynomial function with the cross validation residuals included.

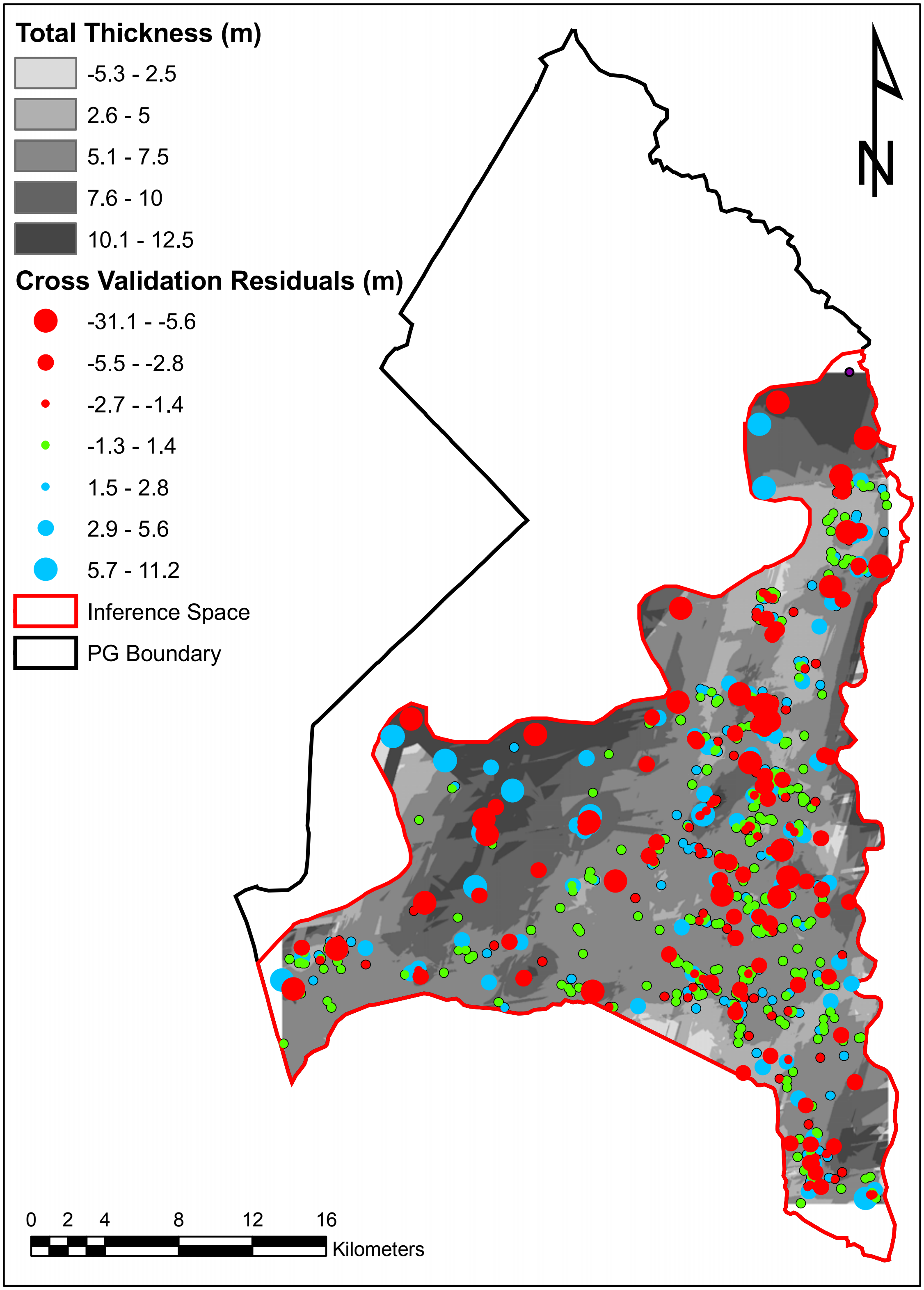


Fig. 3-8e. Thickness map using the universal kriging function with the cross validation residuals included.

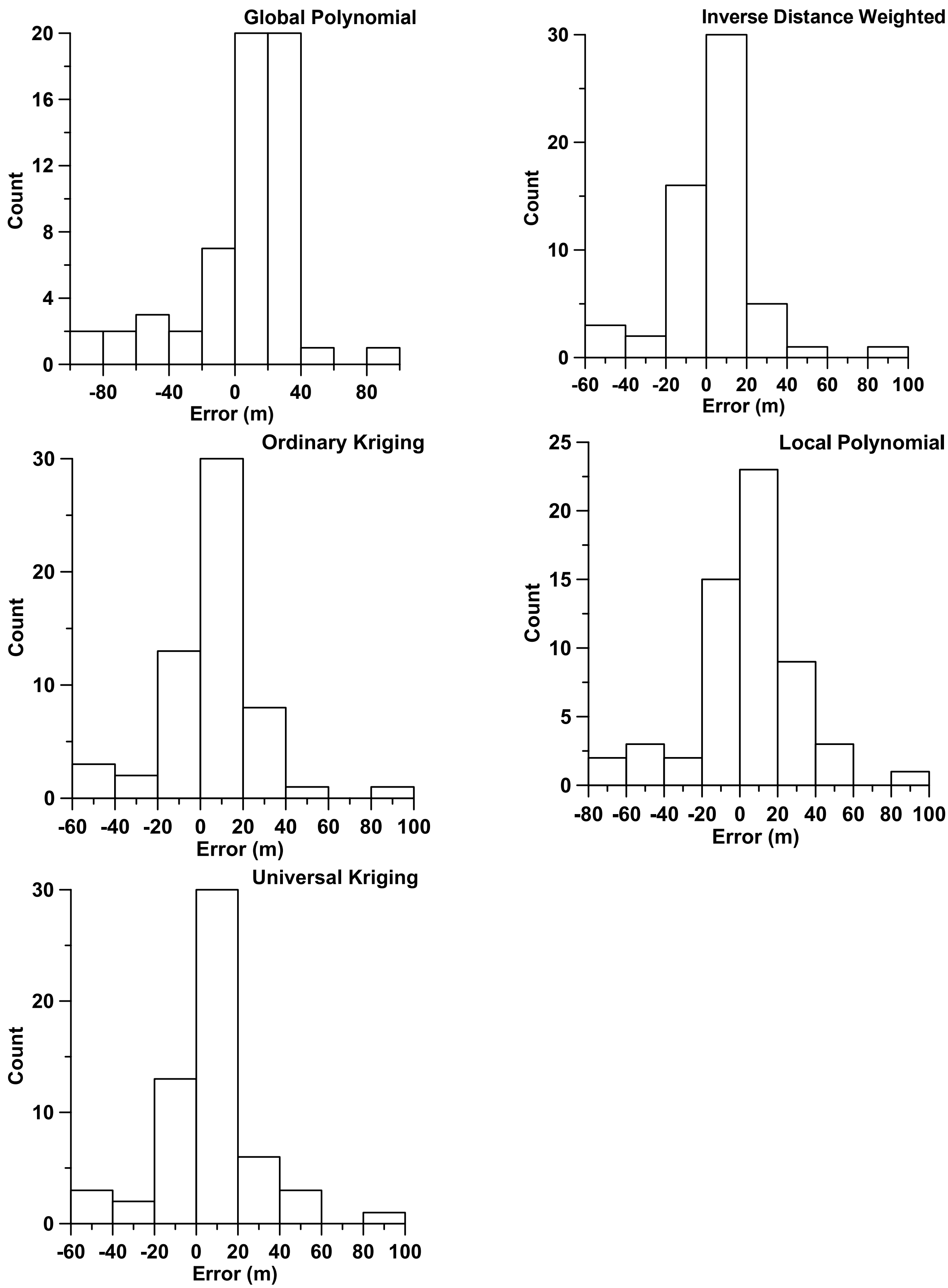


Fig. 3-9a Histograms of the validation residuals for each interpolation method for the bottom elevation from the 50 georeferenced water well log dataset.

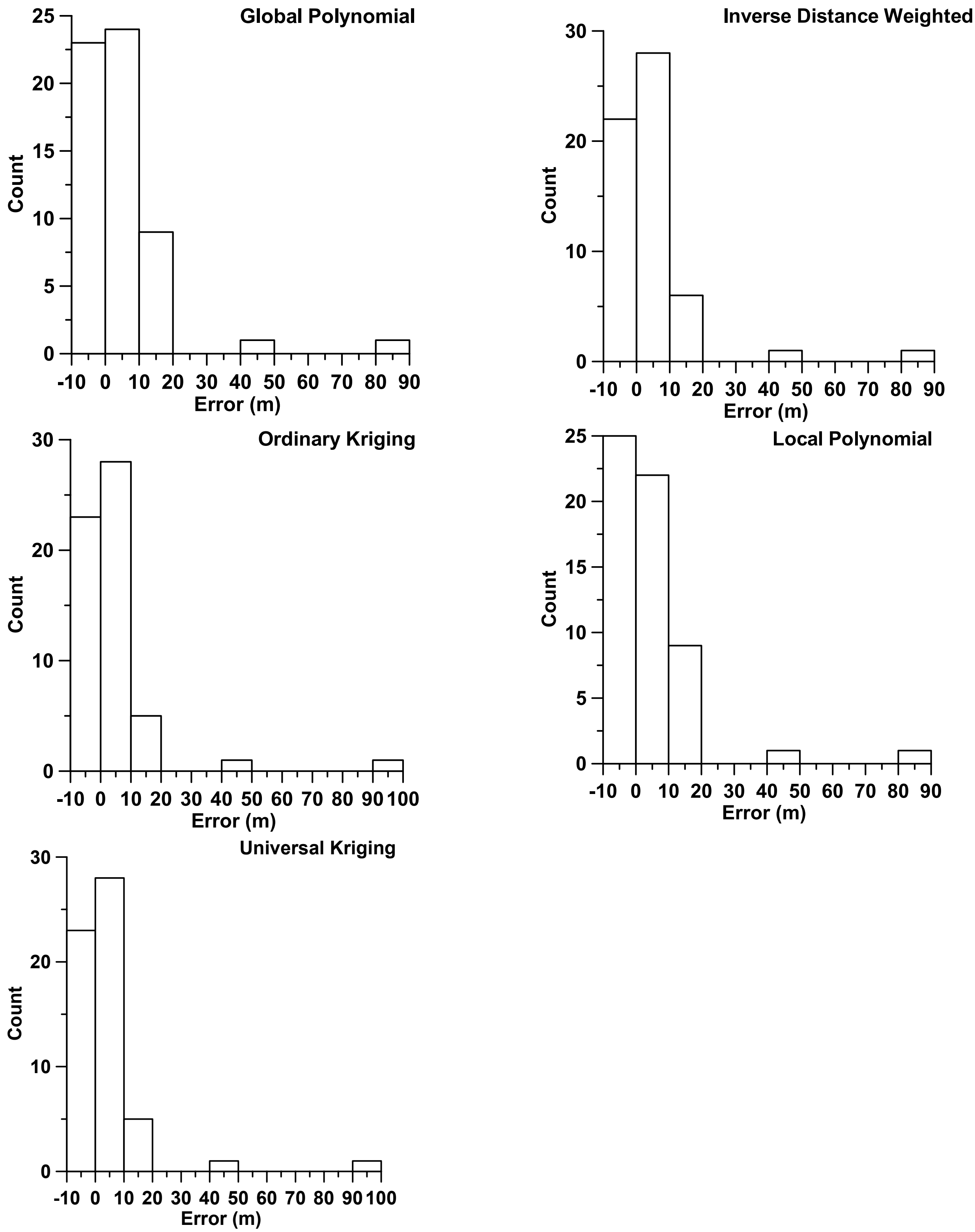


Fig. 3-9b. Histograms of the cross validation residuals for each interpolation method for the thickness from the 50 georeferenced water well log dataset.

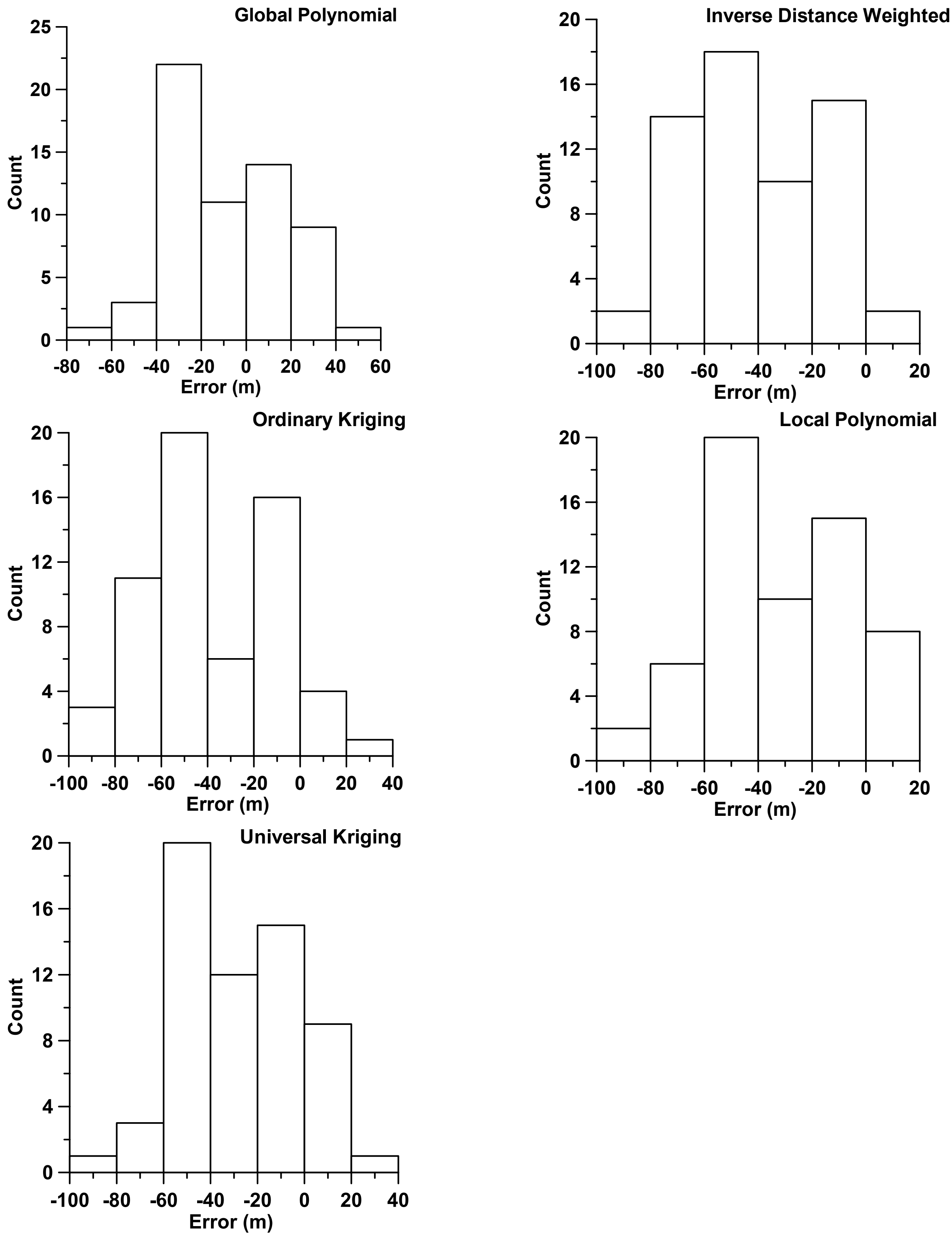
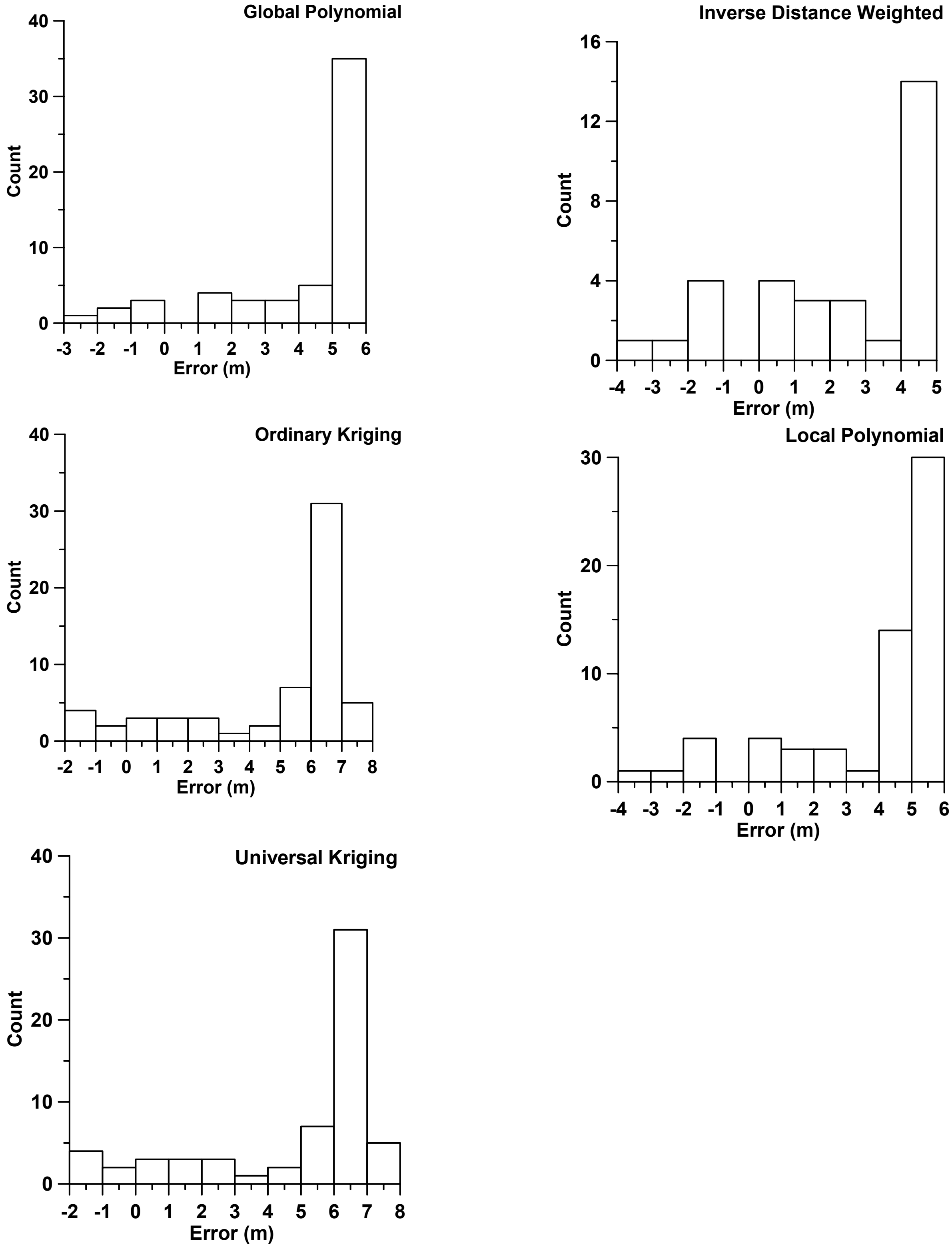


Fig. 3-10a. Histograms of the cross validation residuals of each interpolation method using the bottom elevation from the 61 deep cores dataset.



3-10b. Histograms of the cross validation residuals for each interpolation method using the thickness from the 61 deep cores dataset.

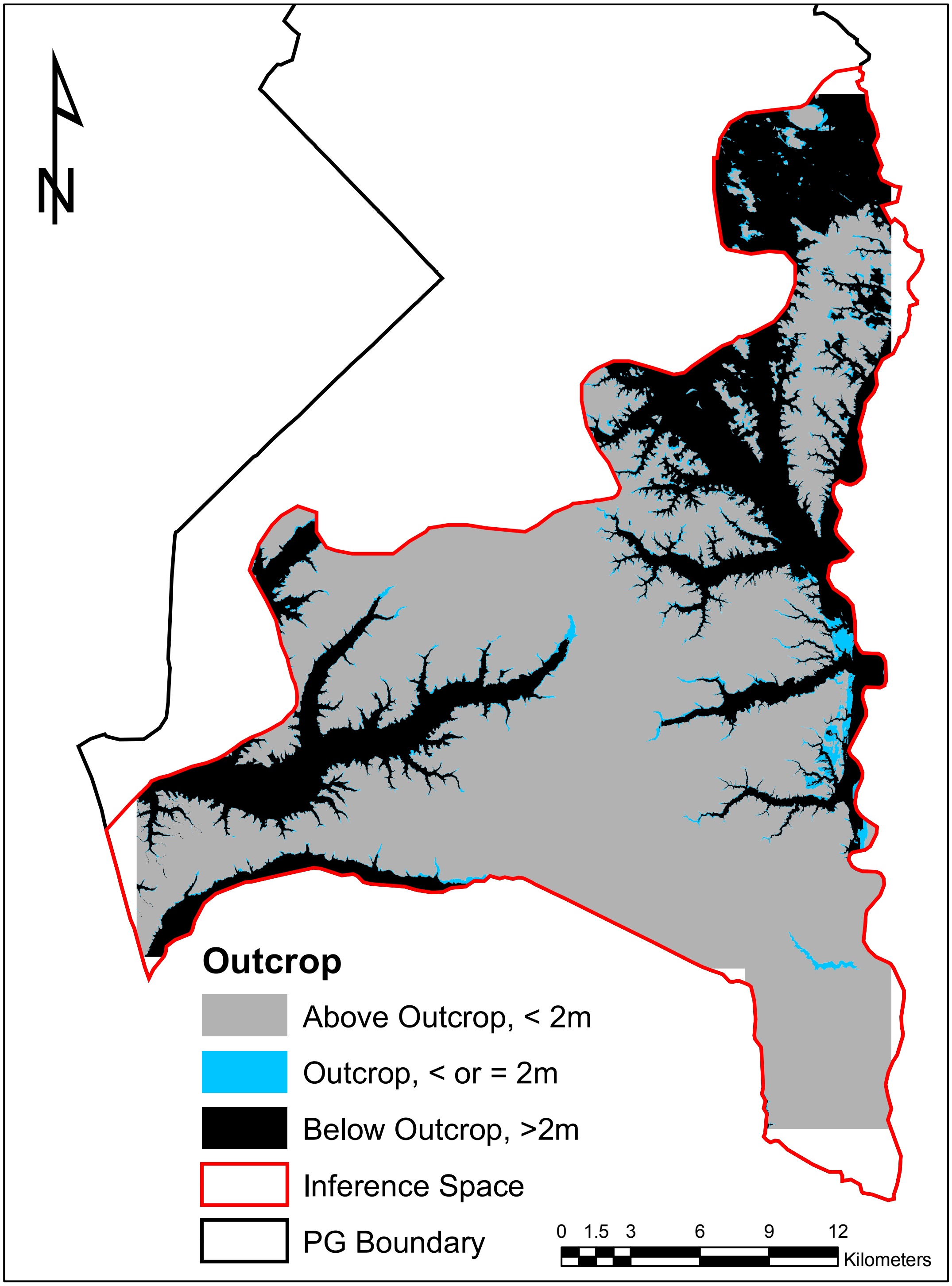


Fig. 3-11. Outcrop map of the Marlboro Clay formation using the global polynomial mapping method. Depths $\leq$ 2m are considered an outcrop.

Appendix A

Potential volume change (PVC), particle-size, and pH analyses of Marlboro Clay samples from the auger borings dataset.

Pedon	Swell Index (kg m^{-2})	PVC Rating	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Texture	pH
AB1	14,393	Marginal	120	560	320	Silty Clay Loam	3.9
AB2	16,137	Marginal	390	430	180	Loam	3.7
AB3	14,974	Marginal	170	600	230	Silt Loam	3.3
AB4	9,741	Noncritical	530	250	220	Sandy Clay Loam	3.8
AB5	8,578	Noncritical	540	250	210	Sandy Clay Loam	3.9
AB6	13,811	Marginal	490	140	370	Sandy Clay	4.1
AB7	14,974	Marginal	190	290	520	Clay	4.0
AB8	12,067	Marginal	470	190	340	Sandy Clay Loam	3.5
AB9	14,393	Marginal	170	550	280	Silty Clay Loam	3.1
AB10	14,974	Marginal	230	440	330	Clay Loam	3.7
AB11	10,322	Marginal	680	130	190	Sandy Loam	3.7
AB12	12,648	Marginal	250	400	350	Clay Loam	3.8
AB13	14,393	Marginal	180	450	370	Silty Clay Loam	3.3
AB14	14,393	Marginal	150	500	350	Silty Clay Loam	3.5
AB15	14,393	Marginal	200	450	350	Clay Loam	3.7
AB16	8,578	Noncritical	200	590	210	Silt Loam	3.6
AB17	12,067	Marginal	320	310	370	Clay Loam	3.8
AB18	10,322	Marginal	340	430	230	Loam	3.8
AB19	12,648	Marginal	330	480	190	Loam	4.0
AB20	6,252	Noncritical	680	190	130	Sandy Loam	3.7
AB21	14,974	Marginal	70	460	470	Silty Clay	4.0
AB22	16,137	Marginal	30	460	510	Silty Clay	3.9
AB23	16,137	Marginal	50	450	500	Silty Clay	3.9
AB24	15,556	Marginal	560	90	350	Sandy Clay Loam	3.6
AB25	13,230	Marginal	440	220	340	Clay Loam	3.7
AB26	15,556	Marginal	130	450	420	Silty Clay	3.7
AB27	14,974	Marginal	120	530	350	Silty Clay Loam	3.6
AB28	12,648	Marginal	240	450	310	Clay Loam	4.0
AB29	19,045	Marginal	130	450	420	Silty Clay Loam	3.6
AB30	16,137	Marginal	270	370	360	Clay Loam	3.9
AB31	15,556	Marginal	190	310	500	Clay	3.8
AB32	12,648	Marginal	550	210	240	Sandy Clay Loam	4.0
AB33	12,067	Marginal	330	350	320	Clay Loam	5.0
AB34	14,974	Marginal	240	380	380	Clay Loam	4.2
AB35	15,556	Marginal	70	670	260	Silty Clay Loam	3.5
AB36	16,137	Marginal	60	470	470	Silty Clay	3.5
AB37	16,719	Marginal	30	520	450	Silty Clay	3.6
AB38	16,137	Marginal	230	360	410	Clay	3.7

Mean	13,796	273	390	337	3.8
Min	6,252	30	90	130	3.1
Max	19,045	680	670	520	5.0

PVC was run on every sample regardless of clay percentage

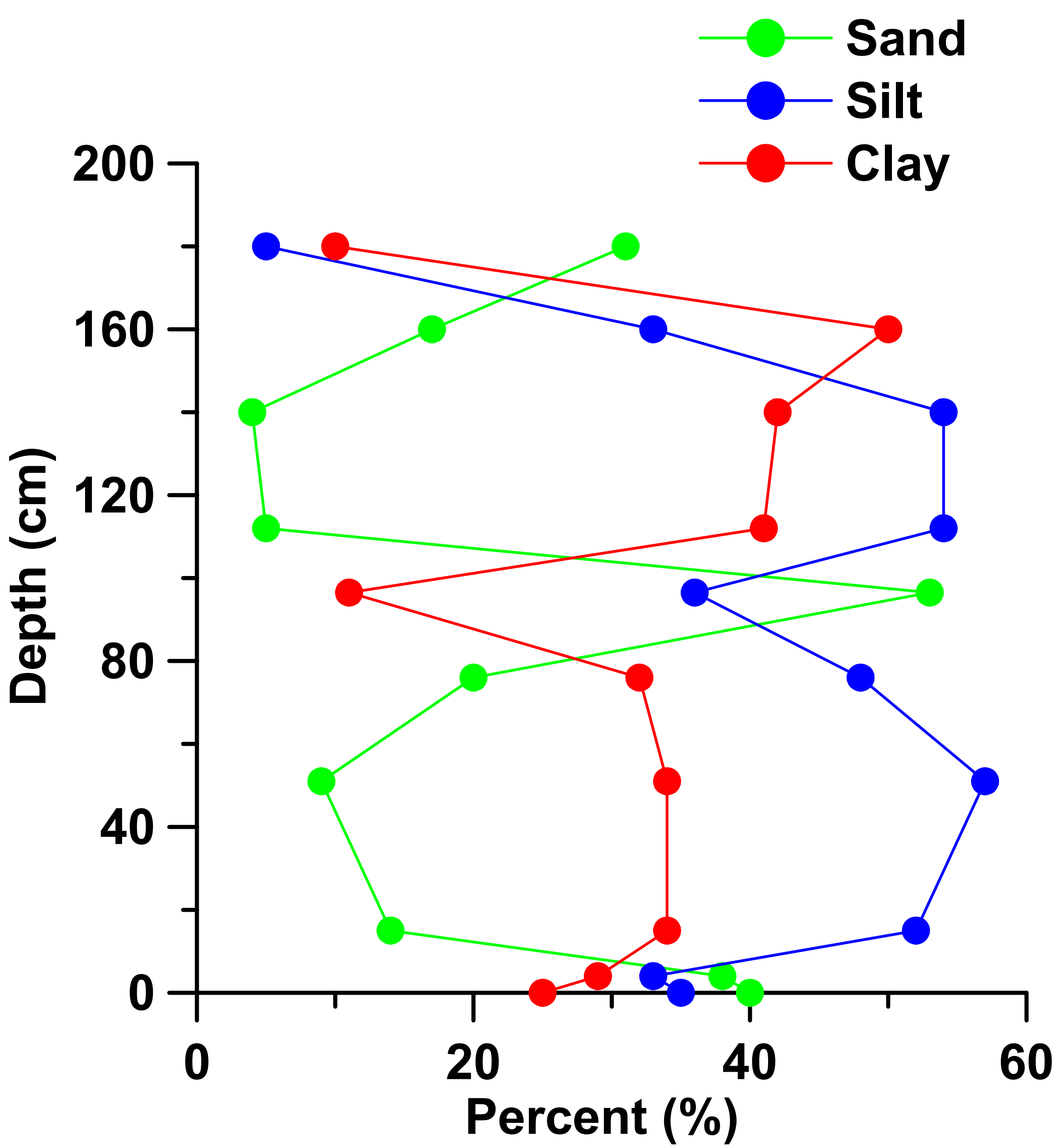
Potential Volume Change (PVC), particle-size, and pH analyses of unweathered Marlboro Clay from the deep cores dataset.

Boring #	Depth (m)	Swell Index (kg m^{-2})	PVC Rating	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Textural Class	pH
BC-1	8.8-15.8	19,045	Marginal	170	690	140	Silt Loam	5.6
BC-2	2.4-8.2	21,371	Critical	90	670	240	Silt Loam	5.1
BC-3	4.0-9.4	19,626	Marginal	70	700	230	Silt Loam	3.6
BC-4	.60-8.2	23,697	Critical	20	600	380	Silty Clay Loam	6.3
BC-5	2.4-7.9	23,115	Critical	10	640	350	Silty Clay Loam	6.2
BC-6	2.4-7.0	21,952	Critical	60	650	290	Silty Clay Loam	4.9
B-45	3.7-7.9	19,626	Marginal	150	680	170	Silt Loam	2.7
Mean		21,205		81	661	257		4.9
Min		19,045		10	600	140		2.7
Max		23,697		170	700	380		6.3

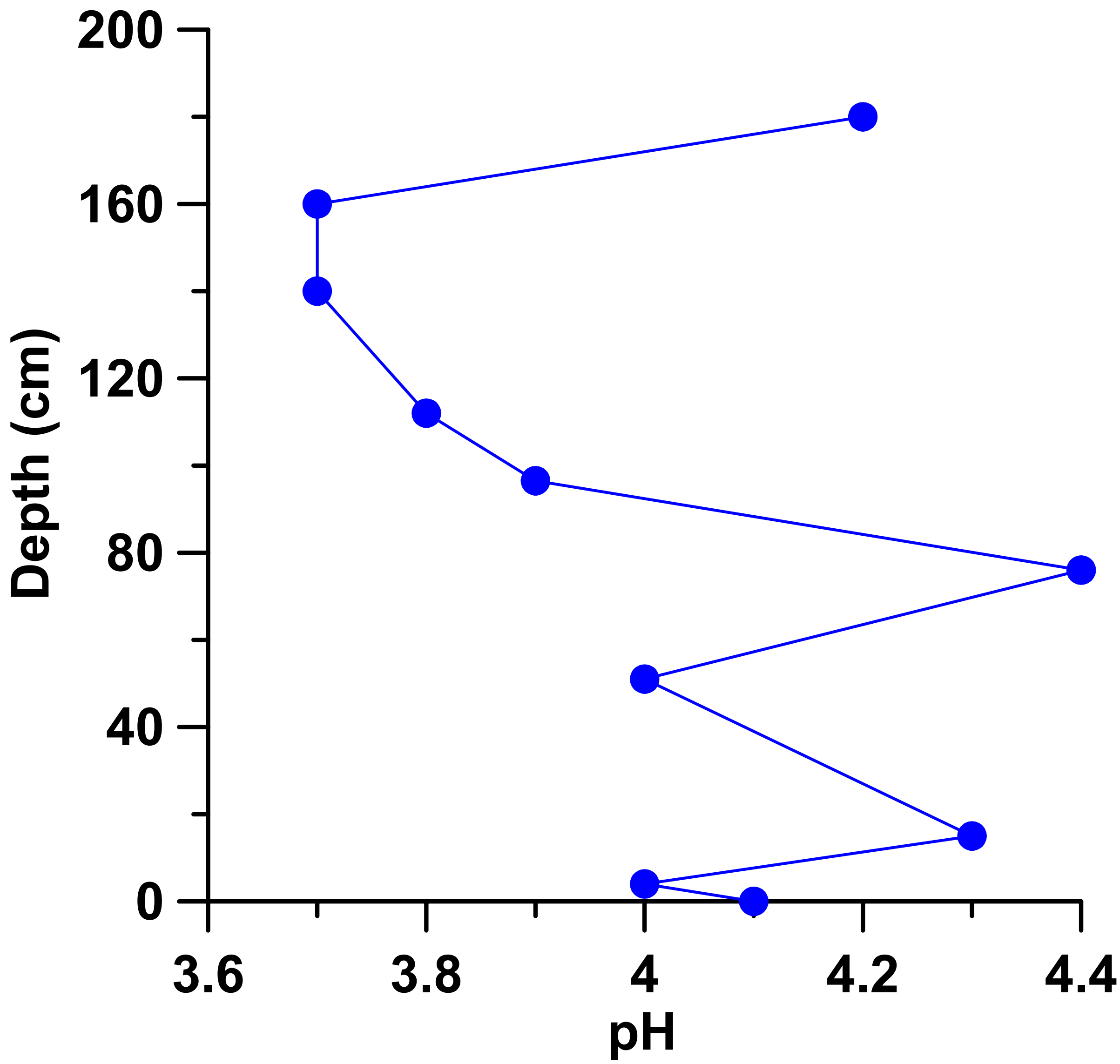
PVC was run on all samples regardless of clay percentage.

Potential volume change of Christiana subsoil's (Wagner, 1976).

Lab. No	Depth cm	Swell Index lbs/sq ft	PVC Category	Texture Sand%	Silt%	Clay%
Profile 1, site 26						
4591	23-41	3600	Critical	19.7	41.5	38.8
4598	108-133	4350	Critical	4.9	43.7	51.3
4604	209-237	5075	Very Critical	6.0	42.2	49.3
Profile 2, site 38						
4609	23-38	100	Noncritical	45.0	38.1	16.9
4613	102-120	4600	Critical	7.3	52.7	40.0
4617	181-207	3900	Critical	15.4	47.8	36.8
Profile 3, site 27						
4674	31-41	3350	Critical	13.1	55.0	31.9
4680	108-128	2150	Marginal	9.0	62.4	28.6
4687	227-242	2000	Marginal	31.8	43.7	24.5
Profile 4, site 32						
4757	20-36	3650	Critical	15.2	39.7	37.1
4761	99-115	3250	Critical	17.2	34.7	48.1
4769	216-242	2900	Marginal	25.0	45.2	29.8



Line graph of the particle size analysis from soil pit B samples mapped as the Howell series.



Line graph of the pH analysis from soil pit B samples mapped as the Howell series.

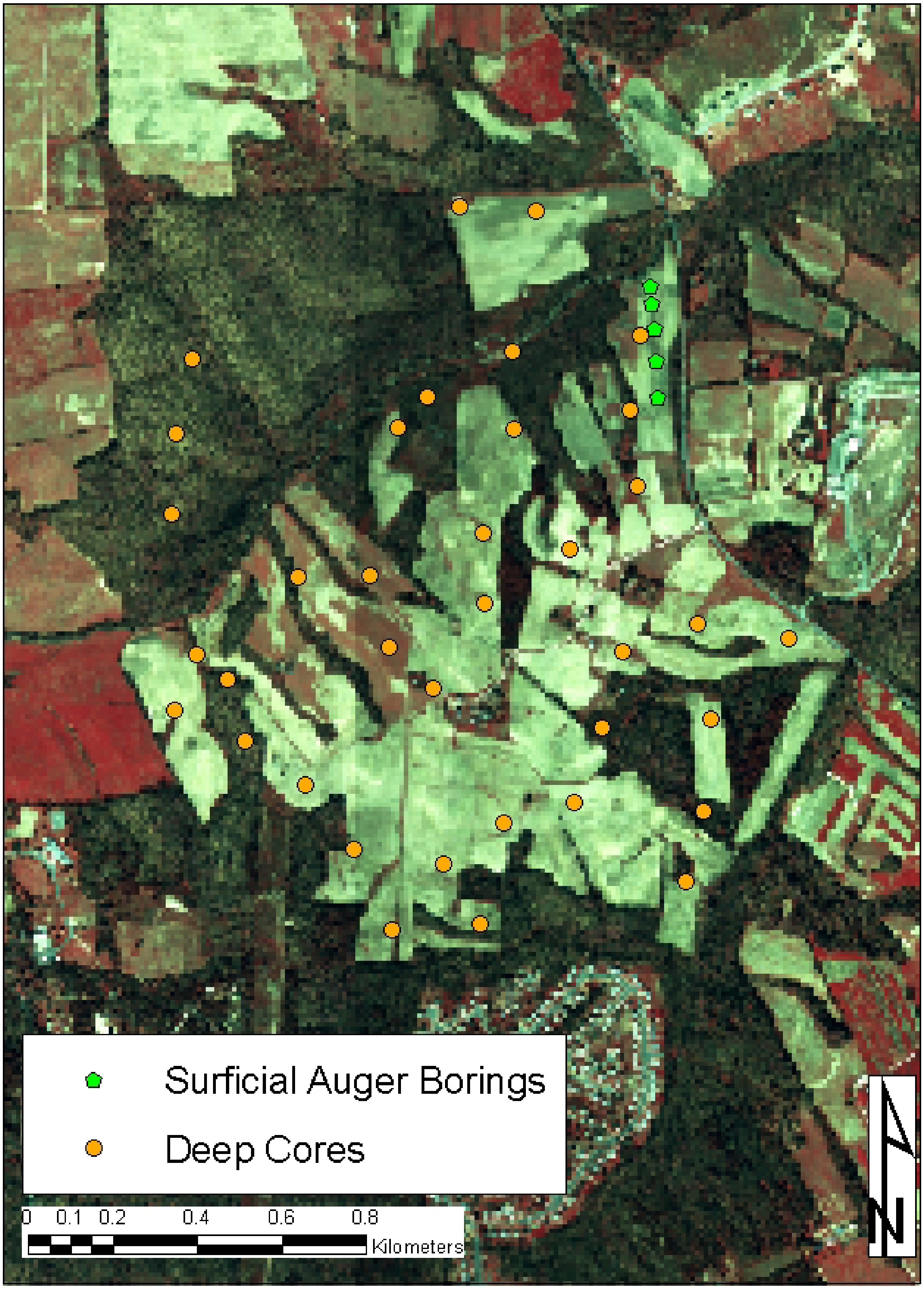
Appendix B

Summary of the sampled deep cores dataset with the Marlboro Clay present.

	Mean (m)	Median (m)	Minimum (m)	Maximum (m)
Bottom Depth	9.2	8.2	7.0	15.9
Total Thickness	11.3	8.0	2.0	29.0

Summary of the unsampled deep cores dataset with and without Marlboro Clay present.

	Bottom Depth (m)	Total Thickness (m)
Mean	1.7	1.0
Median	0	0
Minimum	0	0
Maximum	15.2	8.5
# of Cores with Marlboro Clay	12	
# of Cores without Marlboro Clay	42	



Arial photograph showing the locations of 61 deep cores and 5 auger borings in the intensive sampling zone.

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