Plate 4: Thickness and Geology of the Potomac Formation—Expanded Explanation
City of Alexandria, VA and Vicinity

By Tony Fleming, February 2008

Introduction

The Potomac Formation is a heterogeneous assemblage of ancient river deposits consisting chiefly of unconsolidated and poorly consolidated sands, silts, clays, and small amounts of gravel, along with localized zones of diamictons of uncertain origin. It is the dominant geologic unit in the City of Alexandria. It crops out or is close to the surface everywhere west of Old Town and Del Ray except for a small strip along Holmes Run in the extreme western section of the city, where it has been stripped off by erosion to expose the underlying bedrock. The Potomac Formation also forms the large majority of the Coastal Plain section beneath Old Town and Del Ray, but is covered in that area by thick, younger alluvial deposits of the Potomac River, referred to herein as the "Old Town terrace".

Plate 4 illustrates the geology of the Potomac Formation via a series of informal, geologically- and geographically-defined local units, and by contours depicting the overall thickness of the formation. The map shows the distribution of these local members along the eroded surface that comprises the top of the formation. Typically, the unit present at the top of the formation does not extend all the way to the base, and will overlie one or more of the other units. For example, the Cameron Valley sand, which constitutes the base of the formation, appears to be present above bedrock throughout the city, even though it is covered by younger members at many places. The cross sections shown on plates 2A-C illustrate the vertical sequence stratigraphy of the Potomac Formation, from its eroded upper surface down to bedrock.

Significance of the Potomac Formation

The Potomac Formation comprises the great bulk of the geologic section above bedrock in the city. It begins as a feather edge in Fairfax County, just beyond the western city limits, and thickens rapidly eastward, exceeding 400 feet in thickness near the waterfront at the southern end of Old Town. The formation continues to thicken east and southeast of the city, exceeding 1,000 feet beneath parts of Prince Georges County, MD, and 600 feet in southeastern Fairfax County. The Cretaceous age of the formation was conclusively established by Brenner (1963), who made extensive studies of fossil pollen and spores in the Potomac Group [1] in Maryland, and found that the lower parts of the unit are early Cretaceous, whereas the upper parts are late Cretaceous. The section that underlies Alexandria represents the lowest part of the formation, and is thought to be entirely of early Cretaceous age; however, the precise time during the early Cretaceous when the section was deposited is not well constrained, so its age could, in theory, range anywhere from ~144 to 100 million years (ma).

[1]-in Maryland and DC, the Potomac is considered by geologists to constitute a group composed of several distinct formations. In Virginia, these individual formations are not recognizable, and the Potomac is considered to be of formation rank only. It is referred to as the Potomac Formation in this report.

The Potomac Formation is especially important in the highlands of the city west of the Old Town terrace. The rugged topography of this section, as well as its overall relief (~280 feet above sea level), is largely developed on the Potomac. Differential erosion of contrasting lithologies within the Potomac has produced a variety of distinct landforms and surficial sediments throughout the highlands. The Potomac also is the source of most of the water on and beneath the landscape. Sandy units are the sources of numerous springs and seeps that supply the base flow of most streams, ravines, and wetlands, while large bodies of sand (and some gravel) that make up the base of the formation constitute the principal aquifer system throughout the city, and the only one capable of yielding large volumes of potable water to wells. At one time, not that many decades ago, this aquifer system was the primary source of water in the city, and someday, it may again be called upon to augment the current water supply from the Potomac River. From a civil and environmental engineering standpoint, the Potomac Formation is a study in contrasts, consisting of highly varied sediment bodies that possess radically different properties. Historically, so-called "marine clays" (a lingering historical misnomer) have posed a particular engineering challenge to construction and slope stability because they typically consist of expandable-lattice clay minerals that, in combination with abundant fractures and seasonally-varied pore pressures, commonly lead to serious slope failures and structural stability issues. Indeed, many major slopes in the city owe their morphology to prehistorical (and, in many cases, ongoing) landslides that have been shaping the landscape for thousands of years. Finally, the Potomac Formation, or surficial sediments derived from it, are the substrate for many of the remaining natural communities preserved in the city, whose distinctiveness is often directly related to the character of the underlying material and the landforms developed on it.

Previous Studies

There have been innumerable studies of the Potomac Formation throughout the mid-Atlantic region since it was first named by McGee (1886); this section summarizes only those in the immediate study area. One of the earliest efforts to systematically characterize the Potomac Formation was made by Lester Frank Ward of the U.S. Geological Survey (USGS), who examined the formation throughout the mid-Atlantic region and subdivided it into a variety of units. His publication "The Potomac Formation" (Ward, 1894) appears to be the first to at least briefly touch on the character of the unit within the City of Alexandria: "North of Hunting Creek and Cameron Run, vast quantities of this sand (referring to pebbly, arkosic sand of his "Rappahanock Series") occur in the hills from the river westward for 4 or 5 miles". The same publication also describes Ward's discovery of a species of the fresh-water mussel *Unio* in Chinquapin Hollow, at that time the lowest horizon any shelled fossil organism had been found in the Potomac.

During the first half of the 20th century, N.H. Darton of the USGS carried out comprehensive studies and geologic mapping of the Potomac Formation and the underlying bedrock surface throughout the greater Washington region (e.g., Darton, 1947, 1950, 1951; Keith and Darton, 1901). Although Darton made no attempt to subdivide the formation in northern Virginia, many of his seminal observations still stand today, and the abundant data he collected and systematically archived (e.g., Darton, 1950) continue to be of great value to modern geology, including the current study.

In the 1970's, the USGS launched a major geologic mapping initiative focused on Fairfax County, which resulted in the publication of numerous 1:24,000 geological maps (geological quadrangles, or "GQ's"; e.g., Drake and Froelich, 1986, 1997; Fleming and others, 1994) that encompassed all of the surrounding jurisdictions. Most of the City of Alexandria lies within the Alexandria 7.5-minute quadrangle, which was never published as a separate geological map. The geology of the quadrangle is included at a much reduced scale (1:48,000) in an open-file geological map (Drake and others, 1979) of Fairfax County, VA. On the published GQ's, the Potomac Formation is typically subdivided into two "lithofacies": sand and clay, as on the Annandale Quadrangle (Drake and Froelich, 1986), which encompasses the far western part of the city. On the 1:48,000 regional compilation, however, the whole of the Potomac Formation within Alexandria City, with limited exceptions, is not differentiated into lithofacies, and is shown only as "varicolored silt and clay, interbedded with sand, pebbly sand, and gravel…".

The USGS mapping initiative led to a host of other publications on the Potomac Formation, nearly all of which are open-file reports dealing with various aspects or issues of the unit (e.g., ground water availability, slope stability, etc). Two reports of particular value to understanding the geology of the Potomac and its implications for land use in Alexandria include "Folio of geologic and hydrologic maps for land-use planning in the Coastal Plain of Fairfax County, VA, and vicinity" by A.J. Froelich (1985) and "Engineering geology and design of slopes for Cretaceous Potomac deposits in Fairfax County, VA, and vicinity" by S.F. Obermeier (1984). The former includes numerous small-scale maps (1:100,000) showing different aspects of the Potomac Formation, including interpretations of the percentage of sand in each 100-foot interval of the formation above bedrock, based on widely scattered borehole and outcrop data. The report also contains many valuable, archival water-level data for the city. However, the basic depiction of areal geology in this publication remains unchanged from the initial mapping, that is, most of the city is shown as "undivided Potomac Formation". The second publication describes the geologic features, structures, and engineering properties of clays in the Potomac in great detail, and includes chapters by geotechnical engineers that provide case studies and observations pertinent to slope stability and foundation issues. Although the publication does not specifically focus on the city, the information it contains is enormously relevant, both to current engineering concerns and to an understanding of the evolution of the modern landscape.

<u>Data Sources and Methods</u>

How the Map Was Made: All of the maps and reports mentioned above acted as sources of baseline data, serving as a starting point for the mapping done in this study. The map shown in plate 4, however, is a completely different kind of interpretation based mainly on new data from within and adjacent to the city, collected for the specific purpose of this study. Foremost among the data collected during the present study are: 1) extensive sets of geotechnical borings obtained from the city and VDOT; and 2) numerous observations of the Potomac Formation made in natural outcrops and excavations concentrated in parts of the city west of the Old Town terrace. The locations of the various data used for all aspects of this study are shown on Plate 1: Map Showing the Distribution and Sources of Data. The characteristics of these data, including their strengths and limitations, have been described at length elsewhere, specifically in the expanded explanation of Plate 1 and three associated databases, and to a lesser extent in the expanded explanation of Plate 3". Therefore, these descriptions are not repeated here; only a few comments pertinent to the Potomac Formation are noted below.

The section of the geologic column occupied by the Potomac Formation is bounded by major erosion surfaces known as unconformities, each of which represents a hiatus in the geologic record. The base of the formation, for example, lies on the bedrock surface, whose configuration is shown on plate 3. Since the youngest bedrock in Alexandria is of early Ordovician age (roughly 450 ma.), some 300 million years of "missing" geologic time is represented by the boundary between the bedrock and the base of the Potomac Formation, which is no older than 144 ma. The top of the formation is bounded by a variety of erosion surfaces that range in age from late Tertiary to Recent. These younger erosion surfaces are represented by the bases of several upland river terraces that cap the Alexandria highlands, by the base of the massive Old Town terrace in the lower parts of the city, and by the modern landscape in places where the Potomac Formation has been exposed by Pleistocene and Recent erosion. The contours showing the thickness of the Potomac Formation represent the interval between these fundamental bounding erosion surfaces, and were derived by taking the difference between the elevation of the modern landscape (or base of the river terraces, as appropriate) and the underlying bedrock surface. The map showing the topography of the bedrock surface (plate 3) figured directly in this process, and to a large extent, the thickness contours shown in plate 4 depend directly on the interpretation of bedrock topography.

The Potomac Formation is generally well exposed in many outcrops throughout the highlands of the city. Although few of these exposures are of any great size, they (or the characteristic soils and natural communities developed on the different units within the Potomac) nevertheless are sufficiently numerous to form the backbone of the mapping. They provide the basic visual reference for the formation and its component parts and structures; perhaps more importantly, they allow a reasonable measure of the internal sedimentary variability at different horizons and locations within the formation, a condition widely cited by earlier studies, and one which has posed a major impediment to accurately and systematically characterizing the formation into different sub-units. Lithologic and engineering descriptions from geotechnical borings at hundreds of sites provide the crucial third dimension needed to identify the thickness, lateral continuity, and basic character of the map units defined herein, and their relationship to the major landforms. Data from older water wells collected by previous USGS studies (e.g., Darton, 1950, Johnston, 1961, Froelich, 1985) were less useful to this exercise, primarily because only a tiny percentage of such wells have detailed formation logs that describe what lithologies were penetrated at various depths when a given well was constructed. Nevertheless, a few of these older wells do have such information attached to them, and turned out to be of considerable value.

It was decided at the outset of this project that a different system, employing modern concepts of sedimentary environments and basins, was needed to characterize the Potomac Formation. Whereas the two-fold "sand-clay" lithofacies mapping employed in the latest generation of USGS maps is certainly a major improvement over early efforts, it is nevertheless limited in its descriptive abilities. The Potomac Formation represents the evolution of a very large and complex river system, characterized by a variety of depositional environments that shifted through both time and space. In such an environment, bodies composed purely, or even mostly, of "sand" and "clay", while they do exist, are not the norm. Instead, depositional units are more likely to consist of specific groupings of lithologies, arranged in a particular architecture, and exhibiting characteristic sedimentary structures, which collectively reflect the specific environment in which they were laid down. Such groupings of sedimentary bodies are known as "sedimentary facies". An example would be a series of strata, each of which consists of a sequence of closely interbedded pebbly sands, fine muddy sand, silts, and clays that, with some local variation, generally define a fining-upwards sequence. Each such sequence might be characteristic of a single major flood deposit on the surface of a large point bar, while the entire group of strata, in toto, represents the accretion of the point bar. Another example might be a stack of thick bodies of medium sands with large-scale trough cross beds and pebbly lenses at their bases, punctuated locally by disrupted lenses of clayey or pebbly silt. Such a sequence would represent a series of bars in the thalweg of a river channel. As these limited examples show, the depositional units may or may not be characterized by any one particular lithology or grain size; rather, it is the overall environment of the unit that determines the gross characteristics. Moreover, some units are defined by their variability. Stated a bit differently, for some of the map units, it is the nature of lithological variation itself that is of utmost importance.

There are, of course, a number of practical limitations to this approach, most of which would apply to any system of mapping. For example, outcrops are limited in size, geographic distribution, and clarity of the exposure; likewise, sedimentary structures are seldom, if ever, described from engineering boreholes. The nature of the drilling process used in most geotechnical investigations limits the preservation and recognition of such features, even if their description happened to be a primary goal of the subsurface exploration. Similarly, the boundaries between different facies are often transitional, or gradational, and are seldom displayed prominently in outcrop because the transition typically occurs over distances much greater than that of a single exposure. Nevertheless, using a holistic, basin-based approach to visualize past sedimentary environments and define rock units provides a utilitarian and practical way not only to define map units, but to extrapolate their geometries and boundaries from places where data are robust, into and across areas of limited or less certain information. This technique, known broadly as "basin analysis", has been used rather successfully in the exploration for both petroleum and ground water resources.

Application of this method in the present study led to the recognition of a half dozen major mappable units in the Potomac Formation in Alexandria, and several other sub-units within those. Map units were given informal local names to facilitate familiarity and discussion, and to make them more user-friendly for local problem solving. Each unit is named for the characteristic lithology(ies) present, and for a well-known place in the city where the unit is predominant in the landscape.

Data Limitations: In general, definition of map units is much better in the southern and western parts of the city, where exposures and borehole data are concentrated, and where a readily observable correspondence between map units and landforms is evident. Some other parts of the map area, however, ranging from relatively small enclaves to quite large tracts, contain sparse outcrops and/or few or no boreholes, resulting in poor definition of Potomac Formation geology. Two sizable areas are particularly problematic in this regard: 1) the northeastern part of the highlands, generally corresponding to the largely residential area east of Quaker Lane and north of King Street. Most of the area lacks geotechnical boring sites, and the few boring records that are available are shallow, sometimes not penetrating below the base of the younger upland terraces that cap the area. However, there are relatively widespread, if small, outcrops in a few ravines and other places in the area, which at least makes it possible to make a general determination of the nature of the Potomac Formation there; and 2) the entire area beneath the Old Town terrace, which is blanketed by Pleistocene and Recent alluvium to depths of 50-100 feet or more. There are no outcrops in this area, and the vast majority of geotechnical borings do not penetrate to the top of the Potomac Formation. Although there are records for many older deep wells in the area, only one of these has a detailed lithological log. As many as a dozen other deep wells in Old Town were mapped by Froelich (1985) as to the percentage of sand in each 100-foot interval, but the source of basic well data upon which these interpretations are based is not entirely clear, because none of these wells is reported to have a well log (Johnston, 1961). Nevertheless, these data do give a sense of the composition of the top of the Potomac Formation at some places, and suggest that some of the units mapped in the adjacent highlands continue beneath the Old Town terrace; however, they are not sufficiently robust to determine the stratigraphy in detail, so most of the Potomac Formation at depth in this area remains poorly known.

Another crucial caveat is that the map units shown on plate 4 should be regarded as having strictly local significance. No attempt was made to map the Potomac Formation much beyond the city limits, nor are these map units expected to extend far into other jurisdictions. The sedimentary environments represented by these units are part of a much larger system that changed through time and space, and it is entirely reasonable to believe that different environments may have existed in different places at any given time during the deposition of the Potomac. Although a number of broad trends can be almost universally recognized in the Potomac Formation, on a regional scale the formation is an amalgamation of hundreds or thousands of different sediment bodies, most of which are of local extent and importance. In other words, the units defined herein only have local meaning, and it would be unwise to presume that they can be mapped elsewhere.

Geology of the Potomac Formation

General Observations: Stated simply, the Potomac Formation in the City of Alexandria is the product of a large river system whose scale may have significantly exceeded that of the modern Potomac River. Some of the features left by this system are impressively large. The Arell clay, for example, is a massive, wedge-shaped body that appears to fill an equally enormous oxbow. Only a fraction of this lacustrine deposit appears to be preserved, suggesting that the abandoned channel it filled could have been well over a mile in width and ten or more miles long. Such bodies typically are not the result of a small river or a system of smaller streams operating over long temporal periods (one model that has been suggested for the Potomac Formation). The sedimentary record observed in the city also suggests that the river system evolved over time from a low-sinuousity, relatively higher-gradient situation dominated by sandy facies to a meandering, lower-gradient river in a broad alluvial plain, with a greater proportion of muddy sediment.

Another key aspect of the Potomac Formation is that, at least in Alexandria, it is entirely of fluvial origin. None of it is “marine” (another persistent misconception that has lingered for decades, mainly as applied to so-called “marine” clays), nor does the evidence found in this study suggest that any of it is deltaic, estuarine, or even tidally influenced. All of the various lithologies, facies, sedimentary structures, and their geometric relationships to one another can be readily explained as the result of a large river system. This interpretation is in keeping with those of other workers, notably Brenner (1963), who found that the pollen assemblages in the formation are indicative of a terrestrial environment of deposition, and Froelich (1985), who was also emphatic about the fluvial origin of the formation in northern Virginia. It is also consistent with the limited macro-fossil evidence available from the city and adjoining areas, all of which points to a fresh-water origin. In Alexandria, the Potomac Formation might best be described as outwash that originated from the uplands to the west.

Most observers agree that the Piedmont was the principal source of sediment for the Potomac Formation. This is based on the abundance and proportions of certain major and accessory minerals, particularly potassium feldspars and various heavy minerals derived from Piedmont metamorphic and igneous rocks, such as garnet, staurolite, epidote, and zircon (e.g., McCartan, 1989); it also stems from the abundance of mica, vein quartz, and other lithologies that clearly came from local source rocks. Certain aspects of the clay mineralogy also suggest a primarily Piedmont source terrain. On the other hand, some of the sediment clearly came from further west of the Piedmont: some of the gravelly beds in the Potomac Formation within the map area, as well as the Barcroft diamicton, contain prominent *Skolithos*-bearing quartzites of upper Cambrian age from the Blue Ridge, as well as clasts that look suspiciously like Paleozoic sandstones from the Valley and Ridge province, an observation also made by Ward (1894). To some extent, this observation is in conflict with studies of the ages of zircon populations in the Coastal Plain (e.g., Naeser and others, 2004; Southworth and others, 2006), which indicate that that *late Tertiary* drainage did not breach the Blue Ridge until the Miocene. This conflict is not intractable, however, because the zircon observations do not necessarily mean that the drainage basin was limited to east of the Blue Ridge for the entire period of time extending back to the late Mesozoic: the roughly 80 million years that elapsed between deposition of the lower Potomac and the Miocene is a vast span of geologic time during which the landscape and its drainage patterns could have, and probably did change repeatedly. There is no reason to assume that a river system as large as the one that deposited the Potomac Formation could not have extended far to the west of the modern Blue Ridge.

Lithologies and Map Units: The data collected during this study are sufficient to allow the Potomac Formation to be subdivided into six informal local members, or lithofacies, which appear on plate 4. From bottom to top, these include:
1) the Cameron Valley sand[2], a series of widespread, arkosic channel sands, sandy point bars, and fine grained overbank deposits that collectively form the base of the formation everywhere in the map area. This unit is further subdivided into several sub-units, as described later in this report;
2) the Lincolnia silty clay, a thick, laterally extensive series of mostly silty and clayey overbank deposits that probably represent the accretion of a large, distal floodplain atop the coarser-grained Cameron Valley channel deposits. The lower part of this unit contains the unusual Barcroft diamicton, a possible weathering horizon composed of a framework of coarse pebbles, cobbles, and boulders set in a fine-grained matrix that locally displays soil horizonation and organic layers;
3) the Winkler sand, a group of isolated but locally thick bodies of medium-coarse arkosic sand that probably were originally connected as an integrated system of channels incised into the Lincolnia floodplain, but have since become isolated by erosion and truncation across the top of the formation;
4) the Chinquapin Hollow fine sandy clay, a heterogeneous assemblage of fine sands, silts, and sandy clays that occur in small, fining-upwards, planar-bedded packages suggestive of a large, fine- to medium-grained point bar;
5) the Arell clay, an elongate, wedge-shaped deposit of nearly pure lacustrine clay, thought to have been deposited in an oxbow lake that may have wrapped around the point bar represented by the Chinquapin Hollow member; and
6) the Shooters Hill gravel, an isolated erosional outlier of gravelly arkose that overlies the Arell clay and is probably the remnant of a high-energy bar deposited in a channel.

A key petrologic aspect of the Potomac Formation is that most of the sands are now moderately to extremely clayey, but were not always so: they were originally either lithic arkoses or arkosic quartz arenites, but subsequent in-situ weathering of the feldspar for millions of years has resulted in the development of considerable diagenetic kaolin and montmorillonite, which partially fill the interstices between the remaining sand grains. The clayey texture typically imparts a stiff consistency to the sands, causing them to stand up in steep banks, ledges, and bluffs.

All of the Potomac sediments are overconsolidated from moderately deep burial by younger sediments that have since been stripped off by erosion. None, however, are systematically lithified into rock, though some sands are weakly to moderately well cemented by purplish red hematite (so-called “bog iron”) and orange hematite—iron oxides deposited by chemically-reduced ground water encountering oxygenated conditions. Some ledges of the Cameron Valley sand along Holmes Run, for example, are sufficiently cemented that they could be considered as sandstone. Overall, however, the Potomac Formation is more accurately described as consisting of unconsolidated sediments, because it is easily excavated by a pocketknife at most places.

[2] Descriptive terms used herein as textural modifiers, such as “fine sandy clay”, “clay”, and “silty clay”, follow the standardized nomenclature for soil taxonomy and textural classification (e.g., the “textural triangle”) set forth by the US Department of Agriculture (Soil Conservation Service, 1975).

Cameron Valley sand (C): This unit crops out widely along the north side of the Cameron, Backlick, and lower Holmes Run Valleys, where it locally exceeds 200 feet in thickness. It is also well exposed at places along the south side of Four Mile Run, particularly between Shirley Highway and Barcroft Park in southern Arlington County, where it forms large steep bluffs bordering the valley bottom. Four sub-units are recognized, though precise boundaries between them are generally difficult to define. The lower part of the Cameron Valley sand (map unit **Cs**) consists almost entirely of clayey, medium, arkosic sand dominated by medium- to large-scale trough and planar cross beds. Close to the bedrock surface, the unit is commonly micaceous. Some beds consist of coarse sand, but the unit seldom is pebbly, except for a few thin lenses at the base of cross bed sets, which probably represent a lag deposit. The predominant cross-bed dips observed in numerous outcrops indicate an east to southeast direction of stream transport, which suggests that individual sand bodies are likely to be elongated in the same direction. The largest cross beds observed are about 6 feet in height, though few exposures are sufficiently tall to expose the full heights of the sets.

Most of sub-unit **Cs** was likely deposited in transverse bars in the thalweg of a large, moderate-energy river of probable low sinuousity. Many beds contain clasts of greenish gray clayey silt, which range from tiny chips and balls to large slabs up to 3 feet in length, and which locally can be seen emanating from thin, disrupted beds of the same. The silt beds are drapes deposited during periods of waning water flow. There were probably more such beds deposited, but few are likely to have been preserved in this relatively energetic sedimentary regime. Excellent examples of this sub-unit can be seen in the many large ledges that extend downstream along Holmes Run from the bedrock overlap at Paxton Street to the Backlick Run confluence.

A variant of this sub-unit (map unit **Cg**) occurs at scattered places along and near the base of the formation, and consists of fine to medium gravelly sand and sandy gravel in beds up to 6 feet thick, interbedded with generally thinner lenses of light tan to green sandy and silty clay. The thinnest clay beds are commonly disrupted, and the granular units frequently contain many clay clasts. The gravel is typically disorganized and poorly sorted; in a few places, pebble and boulder beds embedded in the underlying silty clay are present. Some beds are better sorted than others, and a few of the sandiest exhibit planar cross stratification. This unit is typically found in close proximity to the bedrock surface, and the dominant type of gravel consists of frosted vein quartz derived from local Piedmont bedrock. Other types of local Piedmont bedrock are also common, as are *skolithos*-bearing sandstones and quartzites from the Blue Ridge. This sub-unit may have formed in marginal point bars deposited in eddies either close to an original valley wall or in the lees of bedrock obstructions; parts of it may contain colluvial material or debris flows. Good examples of this facies can be seen along Four Mile Run at Barcroft Park (southern Arlington County), and in a ravine below North Chambliss Street in Dora Kelley Park (exposure #153).

A third sub-unit, represented by map unit **Cc**, consists of large plugs of gray silt and silty clay. This unit is not well exposed in the city and is known chiefly from subsurface borings in the Cameron and Four Mile Run bedrock valleys and their tributaries (see plate 3). A particularly thick and extensive body occupies the north side of the modern Four Mile Run valley in the vicinity of Shirley Highway (GTB sites 66-67), while other bodies are defined by borings along the Capital Beltway west of Telegraph Road and near Cameron Regional Park, respectively. A rather extensive body of similar material crops out sporadically just beyond the city limits in the vicinity of South Van Dorn Street and the Capital Beltway. Most of the body is in Fairfax County and the best exposures are in an unnamed ravine below Oakwood Street, west of South Van Dorn, where it is interbedded with Barcroft diamicton in its lower part, just above the contact with the basal part of the Cameron Valley sand (exposure #164). This body occupies the horizon where the Lincolnia silty clay occurs on the north side of the Cameron Valley, and may be correlative, though a direct connection cannot be established at this time. Other similar bodies are likely present elsewhere in the city, but remain undetected.

The upper part of the Cameron Valley sand is best developed in and near the Cameron and Four Mile Run bedrock valley systems. It is denoted by map unit **Cv**, and consists of large masses of medium sand similar to unit Cs, but locally contains more and larger interbedded silty clay units, particularly higher in the section. Medium to coarse, trough cross-bedded sands associated with this sub-unit crop out at several places in the Cameron valley, including large exposures along Duke Street (exposures 5 and 41) and along Wheeler Street (exposures 1 and 24); above Four Mile Run, similar sands are reported from the geotechnical borings (site #69) around the Shirley Highway x Quaker Lane interchange, and could be inferred from slumped exposures on the lower hillsides along Valley Drive in Parkfairfax (exposure #53). Like sub-unit Cs, the upper part of the Cameron Valley sand is also interpreted to have formed in the thalwegs of one or more large river channels, but the larger volume of fine grained sediment interbedded with these sands suggests deposition occurred as the river valleys and the bedrock valleys beneath them became nearly completely alluviated not long before the channels were abandoned.

The Cameron Valley sand thickens dramatically eastward across the map area, from just a thin feather edge in the far west to more than 200 feet near Quaker Lane and Four Mile Run, and near Wheeler and Duke Streets. Some of the thickening is the result of post-depositional tilting and erosion (e.g., the thin feather edge of the unit in the westernmost part of the city is clearly truncated by erosion), but some is original: the observed thickness of the unit beneath the Lincolnia silty clay ranges from less than 50 to nearly 200 feet. The boundary between the upper and lower sub-units (Cs and Cv) is difficult to define, because no consistent horizon (such as a persistent clay unit) or stratigraphic marker is recognized between them, with the possible exception of the silty clay body in Fairfax County near South Van Dorn Street and the Capital Beltway. Where possible, the boundary is drawn where nearby outcrop or subsurface data generally suggest an upward increase in the volume of fine-grained sediment; elsewhere, it is arbitrarily defined by the 100-foot thickness contour. In this part of northern Virginia, the Cameron Valley sand generally corresponds to what has been described as the "lower aquifer" of the Potomac Formation (e.g., Johnston and Larson, 1977; Froelich, 1985).

Lincolnia silty clay (L): This unit forms the surface of the Potomac Formation over a large area in the western part of the city, and holds up numerous slopes and bluffs above ravines in that area. The majority of this area is covered by sediments of the Dowden terrace and associated colluvium, so most information about the unit comes from engineering borings and excavations. The portion of the outcrop area in the Lucky Run drainage is strongly dissected, creating a few hillside exposures. But the Lincolnia silty clay is generally not a strong outcrop maker, and most of the area it occupies is heavily urbanized, so most exposures are small and principally limited to the beds of a few undisturbed ravines. The best extant exposure of the unit is in the head of an unnamed ravine in Chambliss Park, south of Chambliss Street and less than 100 feet below the dead end of Scott Street, in the northwest part of the city. Other exposures occur in the bed of Lucky Run in the Stonegate Scenic Easement, just downstream of Braddock Road.

The predominant lithology is massive to slabby-looking, greenish-gray to tan silty clay and clayey silt. Primary sedimentary structures are very difficult to recognize, especially in the most massive exposures, which often appear completely unstratified. Stratification is most readily evident where very thin sheets of fine and medium sand—presumably crevasse splays—occur in outcrops. Some of the slabbier-looking material contains hints of a fine, planar lamination and an incipient fissility, presumably developed parallel to lines of stratification. Thin lignitic material is sometimes seen when the sediment is split open along the fissility. The slabby-bedded types often contain some fine and very fine sand admixed with the silt and clay. Small to medium sized bodies of clayey (arkosic) medium sand are moderately common in the Lincolnia silty clay, as observed in exposures and reported in a significant number of engineering borings. Most of these bodies are less than 5 feet thick and rarely extend more than a few tens of feet laterally. They are probably crevasse splays—arcuate to fan-shaped sand sheets deposited on the surfaces of floodplains downstream of breaches in natural levees.

The more massive, clayey parts of the unit are exceedingly tough, and commonly exhibit well-developed, regularly-spaced vertical or near vertical fractures. This type of material often exhibits prominent oxidation haloes along the joints, and a reddish-gray mottling of the blocks between the fractures. The joints clearly facilitate vertical movement of oxygenated ground water downward into the clay, enhancing the depth of the weathering profile. Excellent examples of this phenomenon were observed in two excavations, one adjacent to Shirley Highway in Lincolnia (exposure #55), and the other in a hillside behind the Beauregard Street parking garage (exposure #9). N values reported in geotechnical borings are typically high in the Lincolnia silty clay, indicating a very stiff to hard consistency.

On average, the Lincolnia silty clay is about 50-60 feet thick, but the thickness varies considerably, ranging from as little as ten feet in some geotechnical borings to apparently more than 100 feet in the vicinity of Lucky Run. The Lincolnia appears to be draped conformably over an irregular surface on the underlying Cameron Valley sand, which in turn appears to affect its thickness directly. At other places, large parts of the Lincolnia section are cut out by wedge-like bodies of Winkler sand. The boundary with the underlying Cameron Valley sand is locally sharp, based both on observations in ravines and on engineering borings. At places, however, the middle and upper parts of the Cameron Valley sand contain lenses of silty clay very similar to the Lincolnia, suggesting the two are probably genetically related. The most likely possibility is that the Lincolnia represents overbank sediment deposited on a broad, stable floodplain that developed when the active river channel(s) that deposited the underlying Cameron Valley sand migrated some distance away from the map area.

The Lincolnia silty clay appears to be restricted to the western half of the city. Along Four Mile Run Valley, it could not be traced eastward beyond Parkfairfax; there, it appears to become indistinct among the heterogeneous sediments of the Chinquapin Hollow member. In the Cameron Valley, it appears to be cut out by the massive Arell clay near Dalecrest.

The Lincolnia silty clay forms a prominent confining unit wherever it is present, commonly separating the underlying Cameron Valley sand ("lower Potomac aquifer") from the overlying Winkler sand. The clayey Lincolnia undoubtedly is responsible for the perched water table that is commonly observed (or reported in borings) in the Winkler sand. The network of fractures and thin sand seams in the unit promote a considerable amount of ground-water circulation, however, because the unit invariably appears wet in exposures, with ground water visibly discharging from open fractures, and it is often described as "wet" in geotechnical borings. In a few cases where borings that terminated in the Lincolnia were left open for 24 hours or more, a water table was usually reported prior to boring closure, presumably the result of inflow from fractures or thin sand seams. The Lincolnia also appears highly susceptible to landsliding, and bluffs developed on it typically exhibit abundant scars from prehistoric and modern slope failures. An excellent example may be seen along the west side of North Van Dorn Street between Holmes Run Parkway and Landmark Shopping Center (exposure #11). In many geotechnical borings, the unit is described as "fissured" or "slickensided", attesting to its instability, and the large majority of the unit is classified as "fat clay" (CH), reflecting a preponderance of highly expandable clay minerals.

Barcroft diamicton (B): A completely different and exceptional lithology—the Barcroft diamicton—occurs in the lowest part of the Lincolnia silty clay at several places. The diamicton is named for excellent exposures in a stormwater gully at Barcroft Park in southern Arlington County, directly below Claremont Elementary School. The diamicton consists of moderately rounded to strongly faceted clasts embedded in a fine-grained matrix. The clasts range from large pebbles up through boulders, the largest observed being about 18 inches in length. The clasts consist entirely of quartz-rich varieties, primarily vein quartz, quartzite, and sandstone. Many of the latter contain prominent *Skolithos* trace fossils, indicating that they are derived from late Cambrian Antietam Sandstone from the Blue Ridge area. Some of the clasts have a markedly bulletized shape, and many are slightly to moderately pitted. None are striated, as far as is known. The clasts typically do not occur in organized beds or lenses, rather they appear to be distributed within the fine grained matrix, or to form random pockets that look like classic framework cobble- or boulder-gravels.

The matrix is even more enigmatic. It consists of extremely hard heavy loam or clay loam, much of it with a greenish gray gleyed color and abundant wood fragments. At the type locality, the matrix has a "striped" appearance, created by alternating bands of brown and green material up to several inches thick, interspersed with at least 5 distinct organic horizons. These are paleosols, and have similarities with the "accretion gleys" described by Follmer (1982, 1983) at the classic Sangamon interglacial type area in south-central Illinois.

The diamicton at Barcroft Park is on the order of 15 or more feet thick, and overlies typical hard silty clay of the Lincolnia member and/or medium sand of the lower Potomac Formation (Cameron Valley sand), and is in turn overlain unconformably by intensely oxidized Tertiary(?) gravel that caps the Chinquapin Village terrace (see plate 5). Outcrops of similar diamicton were observed in at least four other places, all but one being at about the same stratigraphic horizon: Fort Williams Park, about 600 feet upstream from Duke Street (exposure #247); Stonegate easement, from about 150-400 feet below Braddock Road (exposure #78); Clermont Woods Park, in the heads of twin ravines near the top of the park (exposure #131); and an unnamed ravine below Oakwood Street (exposure #164), where the diamicton forms a prominent "falls" along the creek. The first two sites are within the city limits, while the latter two are on the south valley wall of Cameron Run in Fairfax County. In all four of these other locations, the diamicton is clearly interbedded with typical Potomac Formation lithologies, chiefly green-gray silty clay, and lesser fine clayey sand.

The origin of the diamicton is problematic. There is no evidence of glaciation; none of the material exhibits striations or the internal fabric characteristic of basal till, nor is it associated with other deposits normally found in glaciated areas, such as braided stream deposits (outwash). The material could represent debris flows, but such an origin does not adequately explain either the faceted shapes of the clasts or the repetitive horizonation and gleyed appearance of the matrix. An alternate explanation might be a stranded bar, or lag, of extremely coarse clasts that were left behind after a high energy flood winnowed out all of the fines. Subsequently, the area was entirely abandoned by any active river channels, leaving the bar as a weathering surface that was exposed to the elements for thousands of years, producing ventifacts (wind shaped clasts). The matrix may represent a series of accretion gleys that accumulated very slowly in this environment, perhaps as dust on a wind-swept plain, or fine-grained backwater deposits on a distal floodplain, which became trapped in the large voids between the clasts. The water table may have been sufficiently close to the surface in this environment (presumably an alluvial plain) to produce the gleyed colors and to prevent organic matter, such as wood, from being oxidized and destroyed.

Winkler sand (W): The Winkler sand is named for the sharp, fin-like ridge adjacent to Shirley Highway in the extreme eastern part of the Winkler Botanical Preserve. The hillsides of this ridge are extraordinarily sandy and acidic, and support a classic acid sand forest of stunted chestnut oak, mountain laurel, and heaths. This unit forms a series of small to medium-sized bodies concentrated in a northeast-to-southwest-trending belt that generally parallels Shirley Highway from the King Street interchange southwards to Duke Street. Outcrop is poor in this highly urbanized area, and the distribution of these bodies is largely deduced from a combination of the excellent geotechnical borings on and near Shirley Highway, landforms, small soil exposures, and remnants of highly acidic natural communities.

The characteristic lithology is medium to coarse, well-sorted, somewhat arkosic quartz sand, plus or minus quartz pebbles. Some strata are described as gravel in a few geotechnical borings. Few exposures were found, the best being in tree throws on the hillsides in the botanical preserve, an old cut on the steep hillside above a parking lot on the west side of Beauregard Street, almost directly opposite Roanoke Lane (exposure #38), and an old, steep cut on the west side of South Reynolds Street (exposure #84). Pebbly sand with large trough cross beds could be discerned at the Beauregard Street locality, but the degree of slumping and weathering precluded more detailed observation. Similar features were inferred from the slumped exposures on the steep hillside north of Fort Reynolds (exposure #46) in South Fairlington. A steep, clean face was exposed in an excavation near Beauregard and Armisted Streets, and showed 3- to 5-ft tall sets of trough cross beds with a southerly dip vector.

The various bodies of Winkler sand occur within one of the most highly dissected parts of the Alexandria landscape, and their distribution suggests that, prior to Pleistocene incision, they formed a unified body that may have trended in a southerly direction. Based on geotechnical borings, most of these bodies appear to be highly wedge shaped in profile, and some are remarkably thick, exceeding 100 feet (e.g., GTB sites 22 and 49); this, combined with their coarse texture, suggests they originated in an energetic river channel that cut across the floodplain surface marked by the Lincolnia silty clay. At some places, these bodies are deeply incised into the Lincolnia silty clay, and in at least one location, into the underlying Cameron Valley sand: the body mapped in the vicinity of Beauregard and Armisted Streets, above the west side of Holmes Run, has cut completely through the Lincolnia silty clay. This relation can be seen in the excellent set of geotechnical borings at that site (#2), and indicates that the Winkler has coalesced with the underlying Cameron Valley sand to produce a very thick composite sand section in that area. It seems likely that similar cut outs may occur elsewhere, but are simply not apparent from the current distribution of borings and exposures.

The overall geometry of these bodies suggests an erosional unconformity at the base of the Winkler sand, though the amount of elapsed time between deposition of the Lincolnia floodplain and the Winkler may not have been large. It is entirely possible that the channel(s) in which the sand was deposited may have even been contemporaneous with the latter parts of the Lincolnia silty clay, though evidence bearing on this question is scant. In any event, the Winkler sand probably formed as a stack of transverse bars in such a channel. The Winkler sand appears to be limited to the area described above; it could not be traced east of INOVA hospital, where it appears to be cut out by the Arell clay, nor east of South Fairlington, where it appears to merge into the highly varied Chinquapin Hollow member.

The Winkler is the cleanest and best sorted sand observed during this study. It contains remarkably little clay in some places, suggesting that it originally did not contain a great deal of feldspar. It forms a locally important aquifer, and is frequently reported to have a perched water table developed in it at geotechnical boring sites. Springs discharging from this unit appear to be the source of water for several perennial ravines, including those at two important natural areas in the city: the Winkler Botanical Preserve, and the ravine at Hospital Woods. The unit may also crop out in a narrow strip along the slopes at Seminary Woods, thus accounting for the abrupt appearance of a gravelly, acid soil and corresponding natural community there. Ground water discharging from the Winkler sand along its contact with the underlying Lincolnia silty clay has locally caused it to become cemented by purplish-red hematite, producing characteristic slabs of "bog iron" that mark the trace of the contact along hillsides.

Chinquapin Hollow fine sandy clay: This unit occupies most of the northeastern quadrant of the highlands, and is named for exposures in Chinquapin Hollow, where the whole suite of lithologies that comprise the unit can be seen in a compact area. In some ways, this is a "default" map unit in that it is defined as much by the area it underlies as by lithology. And, from a geological standpoint, both the area and the map unit are the most poorly defined of any area or named map unit in the city. Outcrops are confined to a few relatively natural ravines, the largest of which are upper Taylor Run (Chinquapin Hollow), Timber Branch, the stream in Monticello Park, and an unnamed ravine west of Russell Road below St. Agnes School. Engineering borings are few and far between, and none are more than about 35 feet deep—barely enough to extend through the younger sediments that make up the high-level river terraces capping the upland surfaces in this area. The paucity of data is compounded by the marked heterogeneity of the sediments exposed in outcrop, which typically involve almost every combination of sand, silt, and clay in a single stream exposure. If anything, this map unit is defined by its considerable variability.

The most common lithology appears to be very fine sandy clay. It is typically greenish-gray to buff-colored, plane-laminated, and locally striped, or variegated in earthy tones. The variegations appear to be caused by slight differences in the sand-clay ratio between adjacent laminae, which result in modest permeability contrasts that cause some laminae to be oxidized while others remain in a reduced, or gleyed, state. The largest laminae are about an inch thick, sometimes slightly greater, and some appear to be graded. These laminated-looking units are typically associated with a host of other lithologies, the most common of which are greenish-gray to variegated silty clay, and stiff, elastic, gray, organic silts. Beds of clayey fine sand up to several feet thick are also present, some of which exhibit sets of small-scale planar cross beds. It is often very difficult to distinguish very clayey sands from very sandy clays in the unit, and the two types frequently appear to grade into one another. Some of the exposures in Chinquapin Hollow and Monticello Park appear to consist of repetitive, fining-upwards sequences, each about an inch or less thick, which consist of very fine clayey sand at the base and gummy silt or silty clay at the top. Scattered lenses of granule sand or fine pebbles also occur sparingly. Lignite, cypress fragments, and disseminated organic matter (typically found in the silts) are all abundant at places in the unit. Larger beds or zones of fine-medium sand as well as gummy silty clays, some apparently several tens of feet thick, can also be found at places, but are generally not common and are not traceable over any great lateral extent, perhaps owing to poor exposure.

The heterogeneous assemblage of sediments that comprise the Chinquapin Hollow member may represent a medium-energy floodplain that developed on the surface of a large point bar. The graded, upward-fining sequences are suggestive of individual flood events. Each event caused the bar to accrete vertically. The larger sand bodies may be small channels that developed on the surface of the bar, whereas the thicker clay beds may be plugs filling some of those same channels after they were abandoned. The prevalence of gleyed colors, along with the presence of cypress and abundant organic matter, implies a frequently wet or waterlogged soil, which is consistent with a low surface not far above water level, such as a broad, low-lying point bar. Alternatively, the entire unit may simply represent a broad floodplain surface marginal to a river channel, but a point bar origin better fits the geometric relationship of this unit to the arcuate Arell clay, as outlined in the next section.

The thickness of the Chinquapin Hollow member is not known because its base is nowhere defined by boreholes or outcrops, while its upper surface is truncated by erosion. The apparent thickness is at least 120 feet, based on the fact that the lowest known outcrops of the unit occur at an elevation of about 60 feet, while the highest part of the unit as defined by a few boreholes at TC Williams high school is at an elevation of almost 180 feet. This estimate, however, does not take into account the overall tectonically-induced dip of the Potomac Formation, which is difficult to determine at this horizon given the lack of definitive stratigraphic markers. Assuming the unit occupies the entire elevation differential of the massive Mt Ida scarp above Del Ray, and considering that the base of the unit at that location could easily lie at an elevation significantly less than 60 feet, then 120 feet is an entirely reasonable minimum thickness.

The relationship of this unit to the Cameron valley sand, Lincolnia silty clay, and Winkler sand is obscure. The map pattern in the vicinity of Parkfairfax and South Fairlington suggests that the Chinquapin Hollow may unconformably overlie these units, but a large-scale facies change to the Winkler sand also is a possibility. Relations are especially obscure adjacent to lower Four Mile Run, where the unit appears to be in contact with the upper part of the Cameron Valley sand over the thalweg of the buried bedrock valley. There, it is conceivable that the entire sequence could simply be part of a large valley fill that grades up from coarser channel sands at the base, through the increasingly silty interval of the upper Cameron Valley, and into the finer grained floodplain deposits of the Chinquapin Hollow. It also seems likely that the unit extends beneath the Old Town terrace below Del Ray, based simply on its geographic proximity, but a near complete lack of deep subsurface data for Del Ray makes such an interpretation speculative. Obviously, less is known about all these relations than is known, and a substantial amount of new subsurface and outcrop data is needed before a satisfactory interpretation can be worked out.

The Chinquapin Hollow sediments are the source of many small springs and seeps, which appear in abundance along just about any reach of stream where the unit is exposed. The unit is undoubtedly characterized by a complicated ground-water flow regime marked by multiple perched water tables and complex and unpredictable interfingering and cut-outs of more and less permeable strata. The unit is much sandier than either the Lincolnia silty clay or the Arell clay and, therefore, is much less subject to landslides and slope stability issues. That said, the occasional appearance of larger clay bodies, along with scattered landslide scars on some of the steep side slopes, indicate that it is not immune to these issues. In places where sands and clays of moderate thickness are interbedded, high pore pressures can develop in the saturated sand units beneath fractured clay lenses, literally wedging the clay units loose and causing slope failures to develop along fractures. For more on this process, refer to Obermeier (1984) and Sterrett and Edil (1982).

Arell clay: The Arell clay is a thick wedge of probable lacustrine sediment that consists of nearly pure clay at many places. It is named for exposures in the steep bluff above Duke Street off the end of Arell Court. In map plan, the clay forms an elongate body that extends from Shirley Highway to Old Town, with its long axis roughly aligned with Seminary Road and Janneys Lane. Its center of mass lies near the summit of Quaker Lane, above Duke Street.

The Arell clay is relatively well defined in outcrop, subsurface borings, and geomorphically. This large mass of clay forms some of the most rugged topography anywhere in the city. It is largely responsible for the steep topography of the major escarpment that runs from Pegram Street southward to the Masonic temple and separates the Alexandria highlands from the Cameron Valley. Dissected areas on the clay are characteristically marked by grades in excess of 35% and by long, steep hillsides that exhibit much evidence of past and present landsliding. A few of the steepest scarps are near vertical, particularly where slopes have failed along steeply dipping fractures.

The characteristic lithology is massive clay. Where unweathered, the clay is typically dark bluish-gray or greenish-gray in color, but within 20 feet of the surface, it is more commonly mottled in tones of brownish-red and greenish gray. Most samples of the clay are wet, even relatively close to the surface. No sedimentary structures have been observed in the clay, though a few exposures on the west branch of Taylor Run exhibit a coarse, slabby layering that may be mimicking lines of stratification. The core of the unit contains very little sand, either as discrete bodies or admixed into the matrix. Likewise, geotechnical borings seldom mention any sand in descriptions of the unit. Zones of silty clay are more common and are typically somewhat lighter in color. Small sheetlike sand bodies are slightly more numerous near the edges and close to the base of the map unit, but are by no means common. Excellent examples of the Arell clay can be seen in numerous exposures along the west branch of Taylor Run in Chinquapin Park. Very similar clay is well exposed in a series of large outcrops for several hundred feet downstream of the old service road, about halfway down the ravine in Clermont Woods Park in Fairfax County, but it is unclear whether the clay exposed there is correlative with the Arell.

The thickness of the Arell clay cannot be determined directly because its upper surface is truncated by erosion. No single boring penetrates the entire extant thickness of the unit, but a combination of several boring sites and outcrops located between the summit of Quaker Lane and Wheeler Avenue (below Duke Street) span the entire section and indicate that the clay is some 110-120 feet thick there. Not a speck of sand is reported within this interval in any of these borings. East of Quaker Lane, the base of the unit falls in elevation, while its upper surface becomes truncated by upland river terraces at progressively lower elevations, leading to a diminution of its apparent thickness in that direction. However, the thickness appears to increase abruptly east of the mouth of Taylor Run; geologic relations in that area strongly suggest the presence of a normal fault or steep flexure, across which the thickness appears to increase by 50 percent. Data from water wells and geotechnical borings in the vicinity of the Masonic Temple indicate the base of the unit lies well below the floodplain surface of Cameron Run, and the total thickness may approach 150 feet. This value may come closest to representing the actual thickness, because the top of the clay appears to be defined by the unconformable contact with the overlying Shooters Hill gravel on the hilltop above the temple.

The Arell clay appears to unconformably overlie all other named map units in the Potomac Formation except for the Shooters Hill gravel, although its relationship to the Chinquapin Hollow unit is equivocal. In the major escarpment along its southern side, the base of the clay descends sharply eastward at an angle greater than the regional dip of the Potomac Formation, cutting across the contacts between the Winkler sand, Lincolnia silty clay, and Cameron Valley sand. Near its western edge, the clay truncates the Lincolnia silty clay and Winkler sand. A large part of the northern margin of the body is in contact with the Chinquapin Hollow unit. The nature of this contact is difficult to interpret, but the overall map pattern and cross-sectional profile of the clay suggest it is filling an asymmetrical, bathtub-like hole scoured out of all the other units, in other words, an abandoned meander. The main characteristics of the clay—its massive apperance, nearly pure clay composition, the near complete absence of sand from large parts of the body, and its deep, channel-like shape—collectively suggest that it is a lacustrine deposit filling an oxbow lake that developed in a large, abandoned river channel at considerable distance from any active river channel(s).

It seems virtually certain that the Arell clay continues below the Old Town terrace, but its dimensions there are problematic to define with any degree of precision, due to the paucity of lithologic logs available for the many old wells in the industrial part of town. Nevertheless, the weight of the evidence suggests that the clay bends sharply north in southern Old Town before continuing northeastward beneath the Potomac Yards and northern Old Town (see "***Beneath Old Town and Del Ray***", below): of the small percentage of geotechnical borings deep enough to penetrate the top of the Potomac Formation, most report clay at the base of the Old Town terrace, and are concentrated along a northeast-trending belt. If this interpretation is correct, the Arell clay would then form a strongly hook-shaped, or oxbow-like body that loops broadly around the Chinquapin Hollow point bar. Such an architecture is consistent with the likely origin of the clay as a lacustrine body that formed in a quiet oxbow. Small sheet-like sand bodies that occur sparingly near the northern margins of the unit would likely represent crevasse splays or sheet floods that occasionally spilled into the edges of the oxbow during times of major floods.

The consistency of the Arell clay ranges from very stiff to hard. In geotechnical borings, the unit exhibits some of the highest N values of any interval in the Potomac Formation, comparable to some of the densest sand units. Fractures are ubiquitous in outcrops, and typically occur in sets of widely-spaced, steeply dipping cross joints. The joints are often marked by wide oxidation haloes and deposits of iron oxides along their apertures. The clay is typically described as "fissured" and "slickensided" in most geotechnical borings. Permeability is exceedingly low—the clay is frequently noted as "wet" in borings, and outcrop samples have a pronounced plastic consistency when molded by hand. Seepage of ground water from fractures is occasionally noted in exposures at low positions in the landscape. Not surprisingly, the unit yields only sparse amounts of ground-water discharge, resulting in ravines that are typically dry for much of the year. Montmorillonite is abundant in the clay, leading to high shrink-swell characteristics and a typical designation as "fat clay" in geotechnical reports. These properties result in considerable instability of slopes developed on the clay: as noted earlier, virtually all of the steep slopes are dotted by prominent scarps that mark the heads of past failures. Several prominent landslides were observed on this unit during the course of the project. Due to the hard consistency of the material, failures tend to occur as coherent rotational slump blocks, although places where the clay had mostly liquefied into debris flows during failure were also noted.

Shooters Hill gravel: Little is known about this poorly exposed unit, which forms one or more small, erosional remnants between Ivy Hill Cemetery and Shooters Hill. The unit is almost entirely concealed beneath the younger gravel of the Beverley Hills terrace that caps this hilltop, and because of its superficial resemblance, it easily blends in with the terrace gravel. It would likely have gone unrecognized except for a combination of several small, superficial exposures and shallow borings, in which the thickness of the granular sediment atop the terrace appeared anomalously large.

There are no clean exposures of this unit. Based on a few bare spots on the upper slopes at the cemetery, and descriptions from the bottoms of 4 boreholes, the principal lithology is medium to coarse, clayey sand and/or gravel. The sand is reported to be silty and dense, a characteristic of the Potomac Group. The clay content is likely derived from weathering of feldspar in the sand fraction. The sand is yellowish brown, which likely reflects a strong degree of weathering in the hilltop position it occupies. Similar sand was exposed in an archaeological dig along the side of Shooters Hill in early 2007. At Ivy Hill, the gravel is composed of moderately well rounded quartz pebbles up to an inch long.

The thickness of the Shooters Hill gravel is not known because the top of the unit is truncated by erosion and the base was not reached in any boreholes. Its extant thickness is probably minimal, however, possibly less than 15 feet, based on the fact that clay-rich soil more characteristic of the Arell clay appears on the hillside at Ivy Hill, just below the aforementioned exposures. It may be slightly thicker at Shooters Hill, but only marginally so because a deep well located at the reservoir, about 35 feet vertically below the archaeological site, was reported by Froelich to penetrate clay (the Arell clay of this report) from the surface down to 130 feet or more.

The significance of the Shooters Hill gravel to the local history of the Potomac Formation is not clear, due to its limited extent and exposure. It physically overlies the Arell clay, most likely along a local unconformity. It seems to represent the reestablishment of a more energetic river channel following the quiescent period represented by the Arell clay, but whether this was simply a localized feature or an environmental change of more widespread importance is unknown. There is one other possibility, namely that the unit is a lag at the base of the Beverley Hills terrace, perhaps derived from reworking of older Potomac sediment by the Potomac River when the terrace was deposited. From an environmental and ecological standpoint, the Shooters Hill gravel is likely to have soil-forming, hydrologic, and engineering qualities similar to those of the overlying terrace gravel.

Beneath Old Town and Del Ray: The lowlands that make up the eastern part of the city are dominated by the widespread "Old Town" terrace, a late Pleistocene artifact of the modern river. The alluvial sediments that make up the terrace are almost everywhere greater than 50 feet thick, and exceed 100 feet in some places, putting the top of the Potomac Formation out of reach of the typical depths of most geotechnical borings. Of the hundreds of individual borings that have been made in the terrace, perhaps a few dozen penetrate the upper part of the Potomac Formation. Most of these are located in the Potomac Yards and at a few major building sites where the terrace alluvium is somewhat thinner, chiefly near the inboard edge of the terrace and close to the mouth of Cameron Run. These "holes of fortune" are supplemented by rudimentary descriptions of several deep wells provided by Froelich (1985), consisting of the percentage of sand in each 100-foot interval penetrated by the well, and by one detailed formation log acquired by Johnston (1961) for a deep industrial well at the northernmost tip of Old Town. Collectively, these data are generally too few, too shallow, and too far between to allow the three-dimensional stratigraphy of the Potomac Formation to be worked out to a degree that might enable reliable correlation with the units mapped in the highlands to the west.

On the other hand, enough is known to suggest, in a general way, the gross composition (e.g., sand vs clay) of the Potomac Formation along its truncated surface beneath some parts of the Old Town terrace. This is particularly true beneath Potomac Yards, where a swath of borings several miles long and up to a half mile wide provides at least a limited picture. This evidence, coupled with the aforementioned descriptions from several deep wells, offers a tantalizing glimpse of what may be a very large body of clay that underlies most of southwestern Old Town and extends northeastward obliquely across Potomac

Yards to the Potomac River. The part of the body below southwestern Old Town actually is reasonably well confirmed from several major building sites near the mouth of Cameron Run, where borings up to 100 feet deep penetrate a substantial thickness of hard, massive, "fat" clay beneath the younger alluvium. These sites are directly on line with the trend of the Arell clay in the adjacent uplands, and the clay in the borings can be traced directly into the Arell beneath and along the north side of the Cameron Valley. The area where clay is consistently reported at the top of the Potomac Formation is shown by the line pattern on plate 4. Interestingly, this area coincides reasonably well with structural projections from the adjacent uplands, which suggest that, if the Arell clay is present beneath the Old Town terrace, this is where it should be found. Based on the possible presence of this clay body, it can also be inferred that the top of the Potomac Formation beneath Del Ray is most likely composed of sediments belonging to the Chinquapin Hollow member. Nevertheless, for all the reasons outlined above, the interpretations of the Potomac Formation shown on plate 4 for a large part of Old Town and Del Ray must be regarded as highly speculative.

Paleo-environmental reconstruction of the Potomac depositional system: The architecture of the map units described above appears to record a repeated cycle of establishment, abandonment, and reestablishment of major river channels in the Alexandria area during early Cretaceous time. The earliest events, recorded by the Cameron Valley sand, suggest that a major river system became established along the east- to southeast-dipping bedrock surface, initially occupying and alluviating major bedrock valleys. As the valleys became filled with sandy sediment, the channels migrated laterally, depositing sediment over other parts of the bedrock surface. These early channels probably had limited sinuousity, based on a predominance of transverse bedforms with paleocurrent vectors consistently pointing down the slope of the bedrock surface, and probably interacted with irregularities on the bedrock surface. Abundant mica in some of the lowest strata suggests that the bedrock may have been deeply weathered by the time the channels became established. Once the bedrock valleys were largely filled, the channels probably migrated laterally with relative ease, because the early sediments generally lack appreciable fine-grained sediment, whose cohesiveness tends to stabilize stream banks and thus localize river channels in one place for long periods.

A significant change in this regime appears to have occurred with the appearance of the Lincolnia silty clay. This sequence of fine grained overbank sediment was deposited in a relatively low-energy, and presumably low-gradient, floodplain. The size and thickness of this deposit suggests that the floodplain was broad and that deposition occurred at considerable distance from any large, active river channels. A few small sheet-like and channelized sand bodies within the unit probably represent a combination of crevasse splays and small auxiliary channels that were active during extremely big floods, and perhaps, small alluvial fans deposited by tributaries that debouched onto the floodplain. Over the axes of the Cameron and Four Mile Run bedrock valleys, however, major river channels persisted well into "Potomac time", judging by the accumulation of thick stacks of sand bodies in elongated, down-valley trends in both places. Relations between the upper unit of the Cameron Valley sand, which accumulated in these channels, and the

Lincolnia silty clay, which was probably marginal to them, are not entirely clear but suggest that the two units could be facies equivalents that formed at about the same time.

The regime changed again with the reestablishment of one or more high energy channels atop the Lincolnia floodplain, at least one of which is preserved in the coarse-grained Winkler sand. Although subsequent erosion of this unit has left a fragmentary and possibly biased record, the map pattern suggests that the channel in which the Winkler sand was deposited trended more nearly south, as compared to the more easterly trends of earlier channels and sand bodies in the Cameron Valley sand. It is, of course, impossible to know how much of the Winkler sand has been stripped off, and whether the apparent southerly trend of Winkler sand bodies is simply an artifact of erosion.

The Chinquapin Hollow fine sandy clay marks a rather different environment that the earlier units. The predominantly fine- to medium-grained material of this unit may have been deposited over a long period of time on the surface of a broad point bar, or perhaps a marginal floodplain. The relationship of these sediments to the older units is obscure, but it seems possible that the Chinquapin Hollow is considerably younger than either the Cameron Valley sand or the Lincolnia silty clay, and could also be younger than the Winkler sand. An appealing hypothesis is that the Chinquapin Hollow unit formed a large point bar during Winkler time, and grew on the inside of a very broad meander cut by a substantial river channel. Eventual abandonment of the meander and plugging of both of its ends by point bar sediment led to the development of a large oxbow lake in which the Arell clay was subsequently deposited.

The Arell clay is a thick mass of remarkably uniform, massive clay, in which there is little sand except along the margins. Such a body (in the context of the terrestrial setting of the Potomac Formation) almost has to be of lacustrine origin, and its deposition presumably spans a large period of time. What remains of this distinctive mass of clay is fragmentary, having been severely modified by subsequent Tertiary and Pleistocene erosion. It appears that a large part of lower Cameron Valley was excavated out of Arell clay. The body may well have extended significantly further westward, past the present limits of erosion. Of particular interest is the intriguing possibility, suggested by a few dozen geotechnical borings and deep wells, that the clay may extend beneath Old Town in a *northeastward* direction, outlining a broadly hooked-shape form that may define the axis of a large oxbow. Such a feature, if it exists, would be of substantial scale—at least several miles long and some two miles wide. Perhaps not so coincidentally, the oxbow would outline the margins of the muddy sediments of the Chinquapin Hollow unit, encircling the southern edge of the original point bar around which the meandering channel developed.

The succession of map units in the city seems to record an overall upward and eastward diminishing of grain size in the Potomac Formation, an observation consistent with trends observed in many other places throughout the region. Whether this represents a change in sediment supply, a progressive slackening of regional gradients during Potomac time, or both, is not known. One possibility suggested by the types of sedimentary facies observed here is that the basin may have become progressively filled, or alluviated over time, thus transforming itself from a more robust, Piedmont-type system of discrete river channels into a broad, relatively flat alluvial plain. The abundance of cypress debris throughout the formation, but especially in the upper portions, implies that a relatively swampy environment persisted for much of the period. No evidence was found, however, which would suggest that any of this system was tidally influenced, at least not at this location.

Early Cretaceous – Recent Tectonics

The significance of Cretaceous through Recent tectonics and faulting in the mid Atlantic region, and its documentation, are described in some detail in the discussion of plate 3, and will not be repeated here. The purpose of this section is to outline places where such deformation is recognized or suspected to affect the Potomac Formation in and near the city. Some of these localities display prominent faults that cut the Potomac Formation, while others are places where the map pattern or other relationships suggest that the formation has been deformed either by faults or flexures.

Faults were observed at the following places:

1. Dora Kelley Park, at the confluence of two ravines below North Chambliss Street (exposure #153). Bedrock saprolite is upthrown over the base of the Potomac Formation along a steeply-dipping reverse fault, with about 5-6 feet of apparent displacement. The fault appears to strike a few degrees west of north, with the west side being upthrown. The fault lies along the trace of the Holmes Run aeromagnetic lineament, shown on plate 3 and described therein.
2. Chinquapin Hollow, approximately 500 feet downstream from the Chinquapin Recreation Center (exposure #125). At least two thrust faults are visible in outcrops along the north bank of Taylor Run. The faults cut the Chinquapin Hollow fine sandy clay, and dip between 25 and 45 degrees to the southeast. The southeast sides of both faults are thrust over the northwest sides. The amount of displacement cannot be determined due to a lack of clear stratigraphic markers, but the sediments on either side of the fault planes are contorted, folded, and pulled apart. This zone of faulting lies directly on a strong topographic lineament that separates higher and lower portions of two terraces (the Seminary and Chinquapin Village terraces), in which the southeasterly portions of both terraces appear to be downthrown some 20-40 feet, based on observable offset of the bases of both terraces (see #6 below).
3. Clermont Woods Park (Fairfax County), directly across the valley from Cameron Run Regional Park (exposure #132). This thrust fault is the largest fault observed in outcrop during this study. The fault plane dips northward at 25-30 degrees and is marked by a prominent zone of breccia. The fault is entirely within clay units of the Potomac Group. Lignite-bearing banded clay is thrust over more massive olive green clay. Total displacement is not known. Although it is some 2-3 miles distant from the faults in Chinquapin Hollow, this locality generally aligns with the same lineament described in #2 above.
4. Brenman Park, in a large ledge of Cameron Valley sand, located just below the dam on the north bank of Backlick Run, directly opposite the end of Somerville Street (exposure #42). In the downstream part of the exposure the beds are tilted downstream at about 5-10 degrees. The strata in the lowermost end of the outcrop are

tectonically distorted: a recumbent antiform leans nearly horizontally downstream, and the strata are increasingly chaotic as they disappear beneath debris and rip rap at the end of the exposure. It seems probable that a thrust or reverse fault whose west side has moved up may lie just downstream (east) of the ledge.

A thrust fault reported by Froelich (1985) near the head of Timber Branch could not be located during the present study. In addition, faulting and/or flexuring is indirectly suggested at the following places:

5. Along Duke Street, approximately coincident with College Park, the eastward dip of the bedrock surface and overlying Potomac beds increases markedly from west to east. This suggests the hingeline of a homoclinal flexure is located roughly coincident with Cambridge Street. The steep dip continues eastward to the mouth of Taylor Run. At that location, the thickness of the Arell clay, as seen in cross section, appears to increase abruptly, while its base also declines some 25-30 feet in elevation over an anomalously short distance. In the lowermost part of Taylor Run Park, just above Duke Street, the uppermost part of the Cameron Valley sand occupies the floor of the valley, and appears to be juxtaposed against the Arell clay, which underlies the incredibly steep hillside east of the valley. Further south, borings along the Capital Beltway indicate that a thick body of sand—apparently the Cameron valley—terminates abruptly against a thick unit of clay, which can be traced directly into the Arell clay in the adjacent upland. All of these relations imply some sort of steeply-dipping fault—either a normal fault or reverse fault—runs roughly north-south through this area. The evidence is sufficient to postulate such a fault on plates 4 and 5.
6. At Fort Williams Park, coarse grained, trough cross-bedded sandstone crops out in a series of ledges located approximately 1,100-1,200 feet upstream of Duke Street (exposure #'s 250-251). The entire cross bed sets are tilted steeply westward at 15-20 degrees, which is highly anomalous, considering that the whole Potomac Formation is tilted noticeably the other direction in virtually every other outcrop in the city. This location is directly aligned with the lineament described in #2 above, and with the faults observed in Chinquapin Hollow. The strong tilting of these beds implies some sort of nearby fault or flexure. In addition, the map pattern in the immediate area suggests that strata to the northwest are uplifted relative to strata to the southeast. For example, medium-coarse sand closely resembling the upper Cameron Valley sand crops out at an unexpectedly high elevation on a steep, acid hillside along Fort Williams Drive (exposure #252), forming a small sandy ridge seemingly surrounded by Arell clay. Further to the northeast, the trace of the inferred fault follows a strong topographic lineament, across which both the Seminary and Chinquapin Village terraces are offset, with strata to the northwest apparently uplifted by 20-30 feet. All of the anomalous features observed along the trace of this lineament, including the known fault zone in Chinquapin Hollow, are collectively sufficient to postulate the northeast-trending fault zone shown on plates 4 and 5, which is informally dubbed the Fort Williams fault.
7. Along Four Mile Run in the vicinity of Shirley Highway, geotechnical borings show a massively thick plug of silt and clay appearing abruptly on the north side of Four Mile Run at a very low horizon in the Potomac—nearly on the bedrock surface—

whereas, along the entire south valley wall, this interval is sand. It is conceivable that the clay is a block of Lincolnia silty clay—prominent in the bluffs just to the west—which has been downdropped on a fault. This locality also coincides with an increase in the gradient of the bedrock surface from west to east. On the other hand, it is entirely possible that the clay is simply a fine-grained facies localized on the far north margin of the Four Mile Run bedrock valley (whereas the thick sand units are developed nearer to the thalweg). In the absence of more definitive evidence, including outcrop evidence, no fault is currently postulated at this location on the map, and the clay unit is considered as a fine-grained facies of the Cameron Run sand.

References

Brenner, G.J., 1963. Spores and pollen of the Potomac Group of Maryland: Maryland Geological Survey Bulletin 27, 215 pp.

Darton, N.H., 1947. Sedimentary formations of Washington, D.C. and vicinity: U.S. Geological Survey map, scale 1:31,680.

Darton, N.H., 1950. Configuration of the bedrock surface of the District of Columbia and vicinity: U.S. Geological Survey Professional Paper 217. 42 pp plus 4 plates.

Darton, N.H., 1951. Structural relations of Cretaceous and Tertiary formations in part of Maryland and Virginia: Geological Society of America Bulletin, v. 62, p. 745-780.

Drake, A.A., Jr., and Froelich, A.J., 1986. Geologic Map of the Annandale Quadrangle, Fairfax County, Virginia: U.S. Geological Survey Geologic Quadrangle Map GQ-1601. Scale 1:24,000.

Drake, A.A., Jr., and Froelich, A.J., 1997. Geologic Map of the Falls Church Quadrangle, Fairfax and Arlington Counties and the City of Falls Church, Virginia: U.S. Geological Survey Geologic Quadrangle Map GQ-1734. Scale 1:24,000.

Drake, A.A., Jr., and others, 1979. Preliminary Geologic Map of Fairfax County, Virginia: U.S. Geological Survey Open-File Report 79-398. Scale 1:48,000.

Fleming, A.H., Drake, A.A., Jr., and McCartan, L., 1994, Geologic Map of the Washington West Quadrangle, District of Columbia, Montgomery and Prince Georges Counties, Maryland, and Arlington and Fairfax Counties, Virginia: U.S. Geological Survey Geologic Quadrangle Map GQ-1748, Scale 1:24,000.

Follmer, L.R., 1982. The geomorphology of the Sangamon surface - spatial and temporal attributes, *in* C. Thorn, ed., Space and Time in Geomorphology: Binghamton Symposia in Geomorphology, Int'l Series 12, Allen and Unwin, London, p. 117-146.

Follmer, L.R., 1983. Sangamonian and Wisconsinan pedogenesis in the Midwestern United States, *in* S.C. Porter, ed., Late Quaternary Environments of the United States, v.1, The Late Pleistiocene. Univ. Minnesota Press, Minneapolis, p. 138-144.

Froelich, A.J., 1985. Folio of geologic and hydrologic maps for land-use planning in the Coastal Plain of Fairfax County, Virginia, and vicinity: U.S. Geological Survey Miscellaneous Investigations Series Map (IMAP) I-1423. Scale 1:100,000.

Keith, A.A., and Darton, N.H., 1901. Description of the Washington quadrangle (DC-MD-VA): U.S. Geological Survey Atlas, Folio 70, 7 pp, scale 1:62,500

Johnston, P.M., 1961. Geology and ground-water resources of Washington, D.C. and vicinity - well records and data tables: U.S. Geological Survey Open-File Report 61-79.

Johnston, R.H., and Larson, J.D., 1977. Potentiometric surface maps and water-level change map, 1960-1976, for the lower aquifer of the Cretaceous Potomac Group in Fairfax County, VA: U.S. Geological Survey Open-File Report 77-284, 7 pp., 3 maps, scale 1:48,000

McCartan, Lucy, 1989. Atlantic Coastal Plain sedimentation and basement tectonics southeast of Washington, D.C.: American Geophysical Union, 28th International Geological Congress, field trip guidebook T214, Washington, D.C., 25 pp.

McGee, W.J., 1886. Geologic formations underlying Washington and vicinity: Rept. Health Officer of the District of Columbia for the year ending June 30, 1885, by Dr. S. Townsend, p.19-21, 23-35.

Naeser, N., Naeser, C., Southworth, S., Morgan, B., and Schultz, A., 2004. Paleozoic to recent tectonic and denudation history of rocks in the Blue Ridge province, central and southern Appalachians—evidence from fission-track thermochronology: Geological Society of America Abstracts with Program, v. 36, no.2, p. 114.

Obermeier, S.F., 1984. Engineering geology and slope design of the Cretaceous Potomac deposits in Fairfax County and vicinity, Virginia: U.S. Geological Survey Bulletin 1556. 88 p.

Soil Conservation Service, 1975. Soil Taxonomy-a basic system of soil classification for making and interpreting soil surveys: US Department of Agriculture, Agriculture Handbook No. 436, 754 pp.

Southworth, S., Drake, A.A., Jr., Brezinski, D., Wintsch, R., Kunk, M., Aleinikoff, J., Naeser, C., and Naeser, N., 2006. Central Appalachian Piedmont and Blue Ridge tectonic transect, Potomac River corridor, *in* Pazzaglia, F.J., ed., Excursions in geology and history: field trips in the middle Atlantic states: Geological Society of America Field Guide 8, p. 135-167.

Sterrett, R., and Edil, T.B., 1982. Ground water flow systems and stability of slope: Ground Water, v. 20(1), p. 5-14.

Ward, L.F., 1894. The Potomac Formation: U.S. Geological Survey Ann. Report 15C, 1894, pp. 313-397.