**Question 02.05.01-46**

In CCNPP Unit 3 FSAR Section 2.5.1.1.4.4.4.2, Brandywine Fault System, the text states (p.2.5-47): "The mapped trace of the Brandywine fault system coincides with the western margin of the Taylorsville basin (Mixon, 1977) (Hansen, 1986) (Wilson, 1990). This observation lead Mixon and Newell (Mixon, 1977) to speculate the origin of the Brandywine fault system may be related to the reversal of a pre-existing zone of crustal weakness (i.e., Taylorsville Basin border fault)."

Please expand on this discussion of the Brandywine fault system that includes the origin and tectonic setting of the fault system. Include whether the Brandywine fault is the Taylorsville basin boundary fault, whether it reactivated in a compressional stress field during Cenozoic time, and whether there is any research that interprets the faults as reactivated Paleozoic (Pz) faults.

**Response**

Available data suggest that the Brandywine fault system developed in Cretaceous and early Tertiary time after the 'rift-to-drift' transition had ended in the site region and the Atlantic passive continental margin had begun to develop (Schlische, 2003; Schlische et al., 2003; Withjack et al. 2005). A maximum horizontal compressive stress oriented generally east-southeast – west-northwest is required to produce the northeast-trending reverse faults associated with the Brandywine fault system (Jacobeen, 1972; Wilson and Fleck, 1990). This stress state is likely related to the 'ridge push' forces on the passive margin (Withjack et al., 2005) and is similar to the present-day stress field of east-northeast - west-southwest maximum horizontal compression (Zoback and Zoback, 1989).

The Brandywine fault system, along with the Skinker's Neck anticline and Port Royal fault zone to the south (Section 2.5.1.1.4.4.4.3), are roughly coincident with the western boundary of the Taylorsville basin as shown in FSAR Figures 2.5-22 and 2.5-25. Within northern Virginia, the extent of the basin is well defined based on seismic lines, geologic mapping, and boreholes, but it is less well-defined in southern Maryland where the western margin of the basin is inferred from aeromagnetic anomalies, gravity data, and sparsely spaced borehole data (Jacobeen, 1972; Milici et al., 1991, 1995; LeTourneau, 2003) (Figure 2.5-23). The Brandywine fault system is generally coincident with (within 1.0 to 2.5 miles [2 to 4 kilometers]) and parallel to the aeromagnetic and gravity anomalies used to define the western boundary of the Taylorsville basin (Benson 1992), but they do not precisely coincide. For example, the Brandywine fault system has a slightly more northerly strike in places and crosses the margin of the basin 30 miles (50 km) west-northwest of the CCNPP site. Jacobeen (1972) reports that deep test wells encountered granitic basement and Triassic rift deposits on both the east and west sides of the Brandywine fault system. For both basement types to be located on either side of the fault requires a complex fault zone juxtaposing different basement lithologies that may represent reactivation of on a pre-existing Tertiary fault (Jacobeen, 1972).

As discussed in response to RAI 130, Question 02.05.01-43, both the Richmond and Taylorsville basins, where exposed, are bound on the west by the northeast-striking, southeast-dipping Paleozoic Hylas shear zone (FSAR Figures 2.5-10 and 2.5-23). Bedrock mapping indicates that the Hylas shear zone was reactivated as an extensional fault to accommodate the growth of the basins during Triassic rifting (Bobyarchick and Glover; 1979; LeTourneau, 2003). It is uncertain, but probable, that the Hylas shear zone continues to the northeast beneath the

Coastal Plane and continues to coincide with the northwest margin of the Taylorsville basin, but this has not been proven with direct evidence. By extension, it is possible that the northeastern continuation of the Paleozoic Hylas shear zone was reactivated in the Triassic as a rift-bounding normal fault, and then was again reactivated as a reverse fault to form the Brandywine fault zone in the Late Cretaceous and early Tertiary (Mixon and Newel, 1978; Mixon et al., 2000).

References:

Bobyarchick, A. and Glover, L., 1979, Deformation and Metamorphism in the Hylas Zone and Adjacent Parts of the Eastern Piedmont in Virginia, Geological Society of America Bulletin, Volume 90, p 739–752. Jacobeen, F. Jr, 1972, 1972, Seismic Evidence for High Angle Reverse Faulting in the Coastal Plain of Prince Georges and Charles County, Maryland, Maryland Geological Survey, Information Circular No. 13.

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LeTourneau, P., 2003, Tectonic and climatic controls on the stratigraphic architecture of the Late Triassic Taylorsville Basin, Virginia and Maryland, in P. Olsen, eds., The great rift valleys of Pangea in eastern North America, Sedimentology, Stratigraphy and Paleontology, Volume 2, p 12-58.

Milici, R., Bayer, K., Pappano, P., Costain, J., Coruh, C., Cahit, J., 1991, Preliminary geologic section across the buried part of the Taylorsville basin, Essex and Caroline Counties, Virginia: Virginia Division of Mineral resources Open File Report 91-1, p 31.

Milici, R., Costain, J., Coruh, C., and Pappano, P., 1995, Structural Section Across the Atlantic Coastal Plain, Virginia and Southeasternmost Maryland, Virginia Division of Mineral Resources, Publication 140, 2 plates.

Mixon, R. and Newell, W., 1978, The Faulted Coastal Plain Margin at Fredericksburg, Virginia, Tenth Annual Virginia Geology Field Conference,

Mixon, R., Pavlides, L., Powars, D., Froelich, A., Weems, R., Schindler, J., Newell, W., Edwards, and Ward, L., 2000, Geologic Map of the Fredericksburg 30' x 60' Quadrangle, Virginia and Maryland, U.S. Geological Survey, Geologic Investigations Series Map I- 2607.

Schlische, 2003, Progress in Understanding the Structural Geology, Basin Evolution, and Tectonic History of the Eastern North America Rift System, in P. LeTourneau and P. Olsen, eds., The Great Rift Valleys of Pangea in Eastern North America, Volume 1, R. Schlische, 2003.

Schlische, R.W., Withjack, M.O. and Olsen, P.E., 2003, Relative timing of CAMP, rifting, continental breakup, and inversion: tectonic significance, by The Central Atlantic Magmatic Province: in Hames, W.E., McHone, G.C., Renne, P.R., and Ruppel, C., eds., American Geophysical Union Monograph 136, p. 33-59.

Wilson, J. and Fleck, W., 1990, Geology and Hydrologic Assessment of Coastal Plain Aquifiers in the Waldorf Area, Charles County, Maryland, Maryland Geological Survey, Report of Investigations No. 53, 138 p., 8 plates.

Withjack, M., Schlische, R., and Olsen, P., 1998, Diachronous rifting drifting, and inversion on the passive margin of eastern North America: An analog for other passive margins, American Association of Petroleum Geologist Bulletin, Volume 82, p 817-835.

Withjack, M.O., and Schlische, R. W., 2005, A review of tectonic events on the passive margin of eastern North America: in Post, P., ed., Petroleum Systems of Divergent Continental Margin Basins: 25th Bob S. Perkins Research Conference, Gulf Coast Section of SEPM, p. 203-235.

Zoback, M. and Zoback, M., 1989.Tectonic Stress Field of the Coterminous United States, in L. C. Pakiser and M. D. Mooney, eds., Geophysical Framework of the Continental United States, Geological Society of America Memoir 172, p 523–539.

**COLA Impact**

FSAR Section 2.5.1.1.4.4.4.2, Brandywine Fault System, will be revised as shown in Enclosure 3 in a future revision of the COLA.

**Question 02.05.01-47**

In CCNPP Unit 3 FSAR Section 2.5.1.1.4.4.4.5, Hillville Fault Zone, the text states, "The 26 mi (42 km) long, northeast-striking fault zone is composed of steep southeast-dipping reverse faults that align with the east side of the north-to northeast-trending Sussex-Currioman Bay aeromagnetic anomaly (i.e. SGA, Figure 2.5-22)."

a. Please plot the Hillville fault on Figure 2.5-10 and on Figure 2.5-11.

b. Is there any other data beyond the seismic reflection line supporting the extension/projection of the fault from the seismic line to the northeast of the CCNPP?

c. The text also states (p. 2.5-50), "The fault zone is interpreted as a lithotectonic terrane boundary that separates basement rocks associated with Triassic rift basins on the west from low-grade metamorphic basement on the east (i.e., Sussex Terrane/Taconic suture of Glover and Klitgord, (Glover, 1995a) (Figure 2.5-17) (Hansen, 1986)." Does the seismic reflection data show offset on the basement/Coastal Plain contact? Also, does the seismic reflection profile allow for the interpretation of rift basin reflectors beneath the CP Section either to the east or west of the fault zone?

**Response**

a. As requested, FSAR Figures 2.5-10 and 2.5-11 have been revised to include the trace of the Hillville fault (Hansen, 1986).

b. There are no additional data that would support an extension/projection of the Hillvillle fault to the northeast of the CCNPP site. As discussed in the response to RAI 71, Question 02.05.01-18[5], abundant shallow seismic reflection data acquired and interpreted by Coleman et al. (1990) in Chesapeake Bay intersect the northeast projection of the Hillville fault. Coleman et al., (1990) make no mention of encountering the Hillville fault in their interpretation of the seismic data. The extent of shallow seismic reflection data collected by Colman et al. (1990) is shown in FSAR Figure 2.5-29. In addition, a structure contour map of the top of the Eocene Piney Point-Nanjemoy Aquifer published by the Maryland Geological Survey (Achmad and Hansen, 1997) indicates that the Hillville fault zone does not offset this regionally recognized stratigraphic marker (FSAR Figure 2.5-14).

c. Seismic line St. M-1 from Hansen (1978) was provided previously to the NRC in the response to RAI 71, Question 02.05.01-18[5]. As described in FSAR Section 2.5.1.1.3.3.3.5 and further described in response to RAI 130, Question 02.05.01-55, Hansen (1978) interprets the offset in the basement double reflector to be about 250 feet. Hansen describes the reflections within the Coastal Plane Potomac group as being discontinuous which prohibits definitive upward extension of the interpreted Hillville fault into the Late Cretaceous sediments. However, the reflection data suggests possible dragging at the fault margins within the Potomac group sediments resulting in a queried fault drawn in the section up to a depth of about 1,700 feet.

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[5] G. Gibson (UniStar Nuclear Energy) Letter UN#09-152 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated April 15, 2009.

References:

Achmad, G. and H.J. Hansen, Hydrogeology, model simulation, and water-supply potential of the Aquia and Piney Point-Nanjemoy Aquifers in Calvert and St. Mary's Counties, Maryland, Department ofNatural Resources, Maryland Geological Survey Report of Investigations No. 64, 197 p., 1997.

Colman, S.M., Halka, J.P., Hobbs, C.H., Mixon R.B., Foster, D.S., Ancient channels of the Susquehanna River beneath Chesapeake Bay and the Delmarva Peninsula, Geological Society of America Bulletin, Vol. 102, p. 1268-1279, 1990.

Hansen, H.J., Upper Cretaceous (Senonian) and Paleocene (Danian) Pinchouts on the South Flank of the Salisbury Embayment, Maryland and their relationship to antecedent basement structures, Department of Natural Resources Maryland Geological Survey Report of Investigations No. 29, 36 p., 1978.

Hansen, H.J. and Edwards, J., The Lithology and Distribution of Pre-Cretaceous basement rocks beneath the Maryland Coastal Plain, Department of Natural Resources Maryland Geological Survey Report of Investigations No. 44, p 27, H. Hansen and J. Edwards Jr, 1986.

**COLA Impact**

FSAR Figures 2.5-10 and 2.5-11 have been modified as shown in Enclosure 3 and will be incorporated into a future revision of the COLA.

**Question 02.05.01-48**

In CCNPP Unit 3 FSAR Section 2.5.1.1.4.4.4.6, Unnamed Fault beneath Northern Chesapeake Bay, Cecil County, Maryland (p 2.5-51) the text briefly describes a young fault near CCNPP and cites Pazzaglia's interpretation.

a. Please explain in more detail the basis for Pazzaglia's interpretation and include pertinent figures to illustrate his technical points, including geologic maps and river terrace cross sections. Please include Pazzaglia's latest publications on this feature and the geology of the area (see http://www.lehigh.edu/~fjp3/reprints.html).

b. The text then states, "This fault is unconfirmed based on the lack of direct supporting evidence. First, the fault has not been observed as a local discontinuity on land. Second, the correlation of gravels is permissible based on the data, but has not been confirmed by detailed stratigraphic or chronologic studies. Geologic mapping of the area (Higgins, 1986) shows Miocene Upland gravels along the northeast mouth of the Susquehanna River where Pazzaglia (Pazzaglia, 1993) maps the Quaternary Pennsauken Formation."

   Please provide further explanation of your statements that discount Pazzaglia's interpreted fault. Include geologic maps, cross sections or other kinds of figures to illustrate your counterpoints to Pazzaglia's interpretation. Please explain Higgins' 1986 alternative interpretation of the geology in the area. Please provide a small, detailed portion of the available LiDAR (Light Detection and Ranging) data in a figure to show this portion of the Chesapeake Bay shorelines and landscape, with the trace of the interpreted fault trace posted.

**Response**

a. Pazzaglia's interpretation of a fault (FSAR Figure 2.5-25) is based on declared vertical elevation differences of the early Pleistocene Turkey Point beds between the Coudon Farm terrace, and the Turkey Point, Grove Point, and Betterton localities in Cecil County (Figure 1). Specifically:

   *The Turkey Point beds at Turkey Point, Grove Point, and Betterton lie 6 – 8 m higher than at the mouth of the Susquehanna River...These elevation disparities suggests ~8 m of post-early Pleistocene offset along a northeast-southwest – trending fault beneath the upper Chesapeake Bay."(Pazzaglia, 1993b; p. 1632).*

   The early Pleistocene Turkey Point beds unconformably overlie the Pliocene Pensauken Formation (Pazzaglia, 2006). Central to Pazzaglia's interpretation of a fault is the argument that the Turkey Point beds at Coudon Farm terrace correlate with, and are equivalent to, the Turkey Point beds at Turkey Point State Park (TPSP), 10 km distant to the east (Figures 1 and 2). The fault interpretation relies on the argument that the depositional base of Turkey Point beds should lie at very similar elevations over the lateral distances in the map area, or at least dip gently eastward (Figure 2).

   More specifically, Pazzaglia interprets the Turkey Point beds at the mouth of the Susquehanna River (i.e., Coudon Farm terrace) and at TPSP as genetically-related fluvial terrace deposits based on petrographic and lithostratigraphic analysis (Pazzaglia 1993a, 1993b). Based on petrography (e.g., increased staurolite content) and correlation of interpreted lithologic facies (lithofacies) in field exposures, Pazzaglia (1993a, b; 2006) argues that the Turkey Point beds are derived from the Susquehanna River, and therefore the elevations of the base of the Turkey Point beds between Coudon Farm terrace and Turkey Point, Grove Point, and Betterton should be at correlative elevations. Because Pazzaglia interprets a disparity in elevation of the Turkey Point beds between Coudon Farm terrace west of Northeast River embayment (Figure 1 and 2) and TPSP, Grove Point, and Betterton, Pazzaglia speculates a tectonic fault as a mechanism for producing the apparent offset. The specific basis or elevation datum for calculating the vertical disparity is not defined by Pazzaglia (1993a; 1993b; 2006)

b. Part 1

FSAR Section 2.5.1.1.4.4.4.6 states: "This fault is unconfirmed based on the lack of direct supporting evidence. First, the fault has not been observed as a local discontinuity on land".

If the unnamed fault was active during the Quaternary and shows as much as 8 m of vertical displacement as interpreted by Pazzaglia (1993b), there would be a corresponding on-land geomorphic expression of deformation of Quaternary sediment (e.g., topographic scarps, offset stratigraphic units, deformational warping of deposits) along strike of the postulated fault. No such deformation was observed during site aerial reconnaissance, through analysis of LiDAR elevation models, or through existing geologic maps (Higgins, 1986), and subsurface geological analysis. These analyses indicate that the postulated fault is not present.

FSAR Section 2.5.1.1.4.4.4.6 also states: "Second, the correlation of gravels is permissible based on the data, but has not been confirmed by detailed stratigraphic or chronologic studies. Geologic mapping of the area (Higgins, 1986) shows Miocene Upland gravels along the northeast mouth of the Susquehanna River where Pazzaglia (Pazzaglia, 1993) maps the Quaternary Pennsauken [sic] Formation."

A central argument to Pazzaglia's interpretation of a fault is that the Turkey Point beds that overlie the Pensauken Formation at Coudon Farm terrace (1 km east of Perryville; Figure 1) are, in fact, genetically-related, equivalent and correlative to the Turkey Point beds at TPSP, Grove Point, and Betterton. It is important to recognize that the Coudon Farm terrace is the only location west of the Northeast River embayment that Pazzaglia maps the Pensauken Formation and interprets the presence of overlying Turkey Point beds. Moreover, the Turkey Point beds of Pazzaglia (1993a, b; 2006) have not been demonstrated to be a mappable geologic unit of significant lateral extent west of the postulated fault (Figure 1), and therefore are not adequate or reliable tectonic strain gages.

Additionally, Pazzaglia (1993b) uses soil profile characteristics as a partial basis for correlation of the Turkey Point beds at TPSP to the deposits at Coudon Farm (Pazzaglia, 1993b; Tables 2a and 2b; p.1628). The soil profile descriptions are graphically presented in Figure 3. Figure 3 demonstrates a number of inconsistencies in the soil characteristics between the two sites. First, the development of clay films, a proxy for soil age (Birkeland, 1999), is not consistent across sites, with the Coudon Farm site having less well-developed clay films. Second, the described soil colors are not consistent across sites, suggesting differences in parent material and/or degree of weathering that would argue against correlable deposits. Third, the thicknesses of the soil columns are not consistent across sites, with the column at Turkey Point State Park greater than a meter thicker than at

Coudon Farm. Fourth, the interpreted soil horizon type, thickness, and character are not consistent across sites. For example at Coudon Farm terrace, the column possesses two buried soil horizons whereas at TPSP three buried soil horizons are present (Figure 3). Fifth, the interpreted lithofacies within the Turkey Point beds shows distinct differences across sites. For example, lithofacies L3 at Coudon Farm is 35 cm thick and only possesses horizon Ap (Figure 3). In contrast, lithofacies L3 at Turkey Point State Park is 83 cm thick, contains five separate horizons, as well as possesses a buried soil horizon (Figure 3). Further, lithofacies L2 is 12 cm thick and an absence of buried soil horizons at Coudon Farm whereas at TPSP lithofacies L2 is 237 cm thick with a buried soil horizon as well as weathered parent material. These discrepancies in the soil profile descriptions lead us to challenge the correlation and equivalence of the Turkey Point bed deposits at Coudon Farm terrace and TPSP are not valid. If the deposits at the mouth of the Susquehanna River are not genetically-related to those at TPSP, then elevation disparities between the deposits at Coudon Farm terrace and TPSP are permissible, and do not require a fault.

Lastly, a cross section developed along Pazzaglia's (1993a) section based on recent LiDAR data (Figure 4) shows that there are elevation differences of the top of the Pensauken Formation. However, the important elevation strain marker is the base of the deposit, rather than the top or surface, because the surface can be exposed to post-depositional weathering processes that may alter the surface topography. Because the absolute elevation of the base of the either the Pliocene Pensauken Formation or the early Pleistocene Turkey Point are specifically not defined by Pazzaglia (1993b; 2006), verification of the declared vertical elevation disparities between these deposits is not possible, and does not provide direct evidence to support the interpretation of a fault. The cross section (Figure 5a) also includes 30 m cell size bathymetric data from NOAA that shows no warping, scarps, offsets, or deformation of the Chesapeake Bay bottom consistent with the absence of faulting. In addition, cross sections produced by Pazzaglia (1993b) do not illustrate offset of the Turkey Point beds (Figure 2).

As stated in the above quoted FSAR text, Pazzaglia's interpretation of a fault remains unproven based on analysis of the existing data. Further, Pazzaglia's mapping and correlation (1993a; 1993b, 2006) have not been confirmed by independent studies.

Part 2

Higgins' (1986) interpretation of geology in the area shows parallels and differences to Pazzaglia (1993b; 2006). Both authors illustrate similar distributions of the Potomac Group sediments, the Talbot and Kent Island Formations, and have similar interpretations of the Pensauken Formation on the Elk Neck and Delmarva Peninsulas (Figures 1 and 5). The chief interpretive difference is that Higgins (1986) groups Miocene and early Pliocene fluvial sediments into a single unit, (map unit Tu, Upland Gravel; Figure 4) whereas Pazzaglia (1993b) identifies and delineates the Bryn Mawr Formation as well as the informal Perryville Formation commonly corresponding to Higgins's (1986) Upland Gravel (map unit Tu). Further, at the mouth of the Susquehanna River, Pazzaglia (1993b) interprets and maps Pensauken Formation deposits (Figure 1) where Higgins (1986) interprets and maps Upland Gravel (Figure 5). A map showing Higgins's geologic interpretations and Pazzaglia's interpretations is presented in Figure 5. The geologic explanation is shown on Figure 5. Lastly, the fault inferred by Pazzaglia (1993) is not mapped by Higgins (1986).

Part 3

Figure 6 shows the available LiDAR (Light Detection and Ranging) data in this portion of Cecil County Maryland with Chesapeake Bay shorelines and landscape, and Pazzaglia's (1993b) interpreted fault trace (approximately located). Figure 6 also shows 30 m cell size bathymetric data from NOAA.

References:

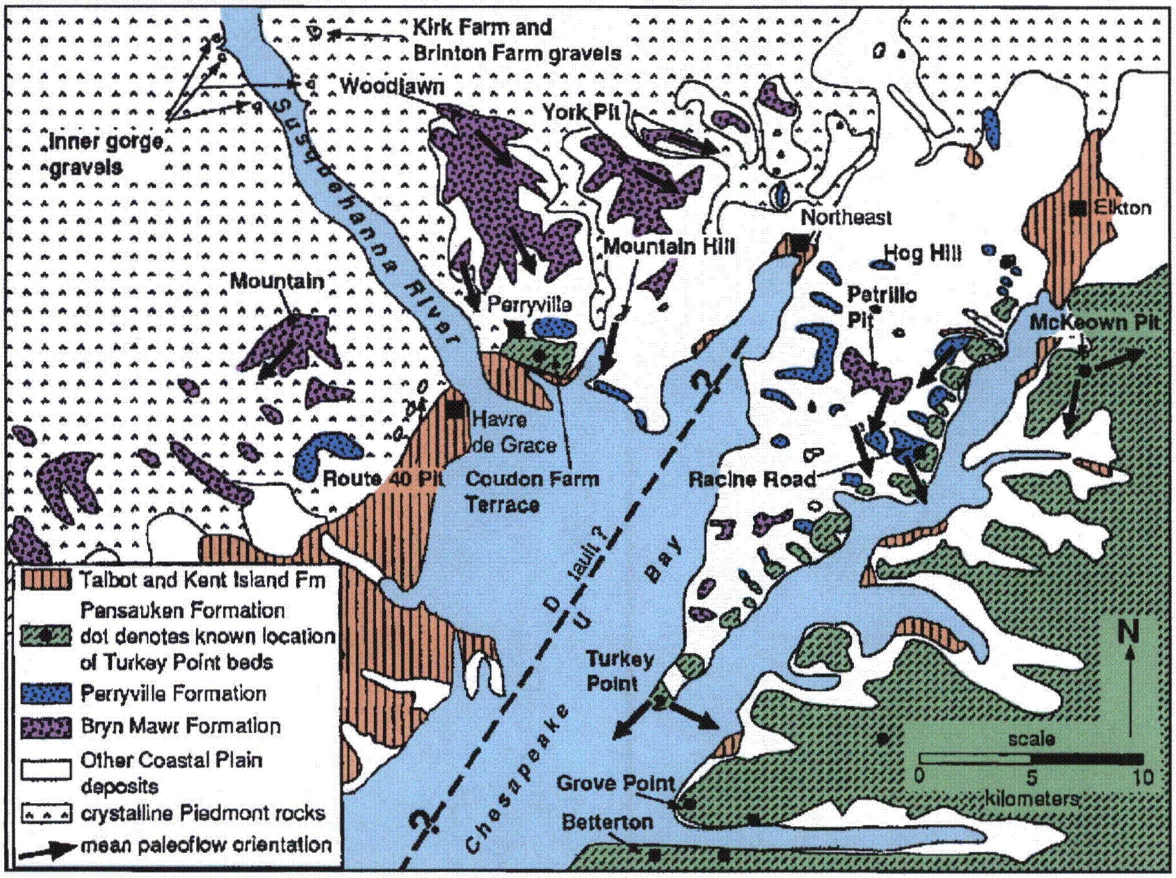
Birkeland, 1999. Soils and Geomorphology, third edition. Oxford University Press, New York, p.429

Higgins, 1986. Geologic Map of Cecil County, State of Maryland, U.S. Geological Survey, 1 sheet, Scale 1:62500, M. Higgins and L. Conant, 1986

Pazzaglia, 1993a. Fluvial terraces of the lower Susquehanna River, Geomorphology, Volume 8, p 83-113, F. Pazzaglia and T. Gardner, 1993.

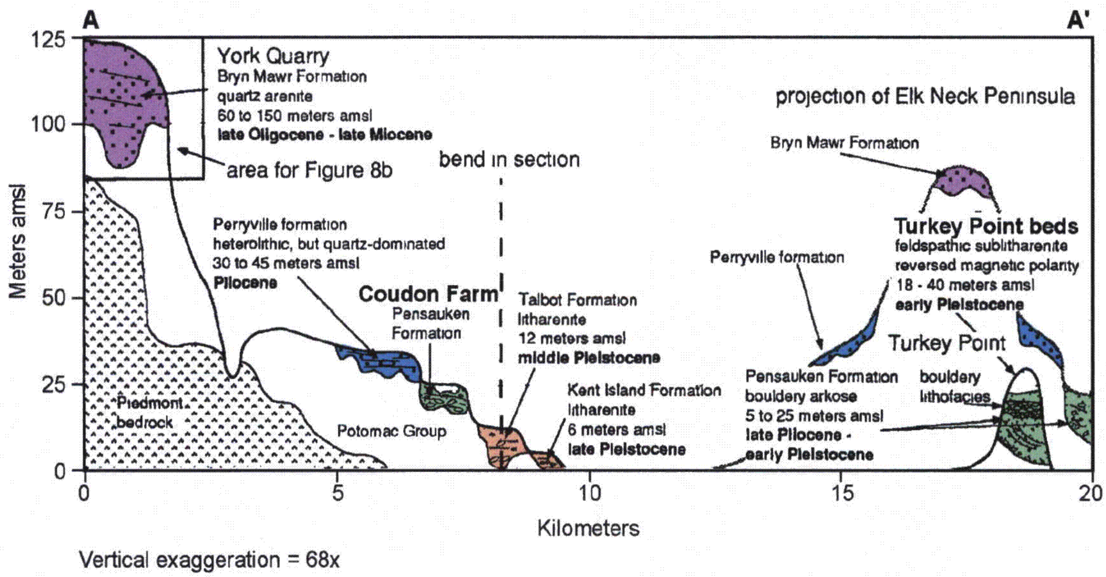
Pazzaglia, 1993b. Stratigraphy, petrography, and correlation of late Cenozoic middle Atlantic Coastal Plain deposits: Implications for late-stage passive-margin geologic evolution, Geological Society of America Bulletin, Volume 105, p 1617-1634, F. Pazzaglia, 1993.

Pazzaglia, 2006. Rivers, Glaciers, landscape evolution, and active tectonics of the central Appalachians, Pennsylvania and Maryland, Geological Society of America, Field Guide 8. F. Pazzaglia, D. Braun, M. Pavich, P. Bierman, N. Potter Jr., D. Merritts, R. Walker, D. Germanoski, 2006.

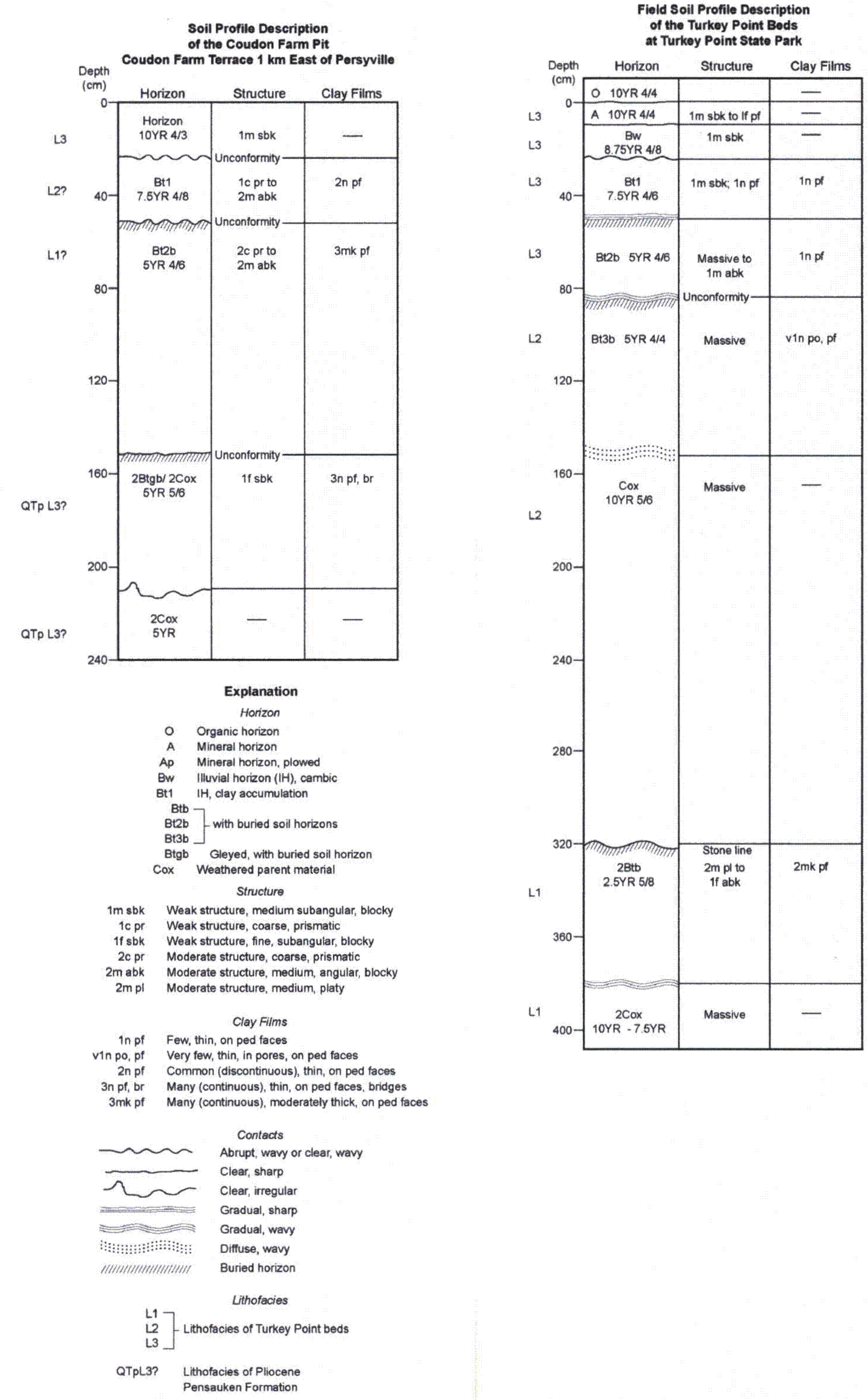



Generalized geologic map of a portion of Cecil and Harford Counties, Maryland (modified from Owens, 1969 and Conant, 1990). Fault location and relative offset is inferred from elevation of Pensauken Formation and Turkey Point beds. [Figure caption from Pazzaglia, 1993b].

**Question 02.05.01-48 Figure 1 – Geologic Map by Pazzaglia (1993b)**

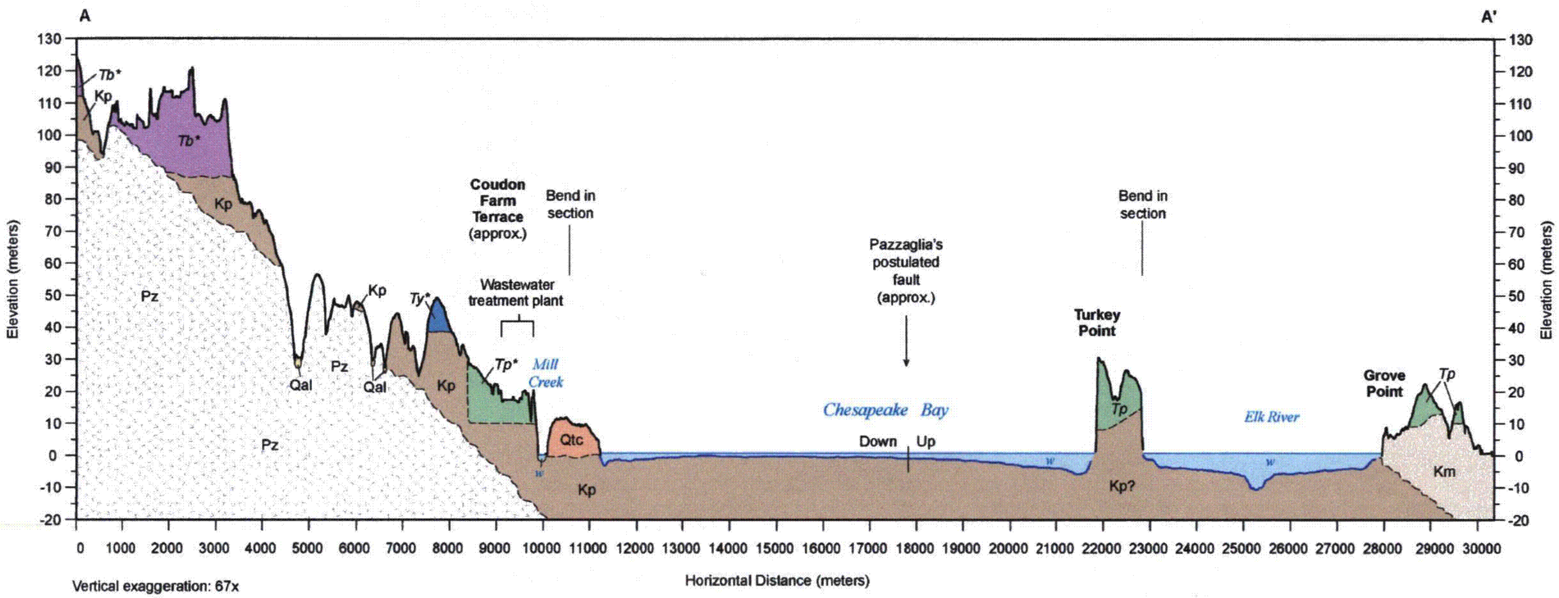



**Question 02.05.01-48 Figure 2 – Geologic Cross Section by Pazzaglia (1993b)**




**Question 02.05.01-48 Figure 3 – Soil Profile Descriptions of Turkey Point Beds by Pazzaglia (1993b)**

# Question 02.05.01-48 Figure 4 – Geologic Cross Section A-A'




## Explanation

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| w | Water | Tp | Pensauken Formation | Km | Matawan Group | Pz | Lower Palezoic meta-volcanic rocks, undifferentiated |
| Qal | Alluvium | Ty | Perryville Formation (Pazzaglia, 1992a; b) | Kp | Potomac Group | | |
| Qtc | Talbot Formation | Tb | Bryn Mawr Formation (Pazzaglia, 1993a; b) | | | | |

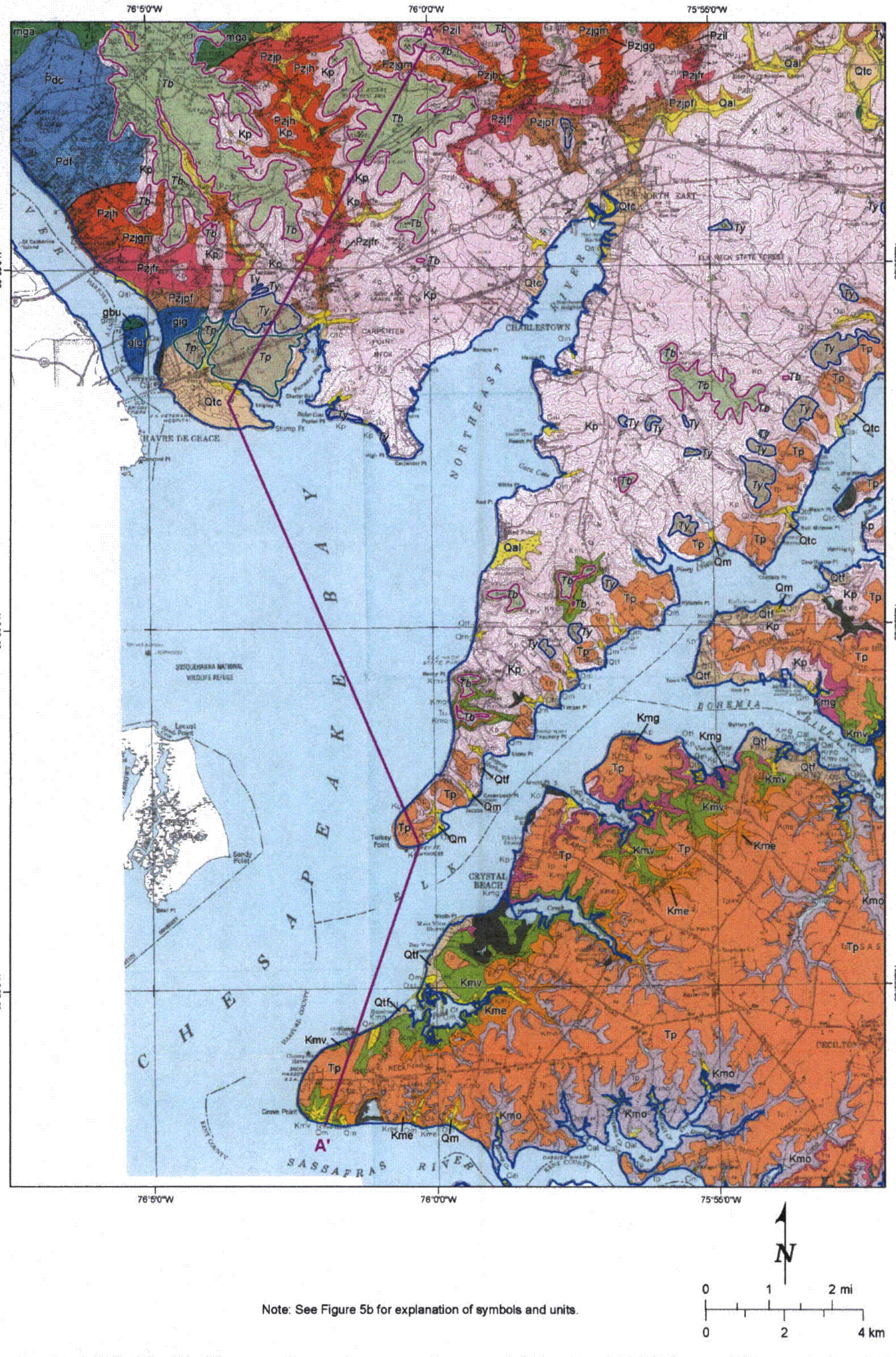
*Symbols*

Topography from LiDAR

Bathymetry from NOAA

* Indicates Higgins map unit Upland gravel (Tu).

Notes: 1. Geologic units from generalized from Higgins except where indicated by *.
2. See Figure 5 for cross section location.
3. Deposit basal elevation from LiDAR data.




Note: See Figure 5b for explanation of symbols and units.

**Question 02.05.01-48 Figure 5a – Comparison of Higgins (1986) and Pazzaglia (1993b) Geologic Mapping**

Question 02.05.01-48 Figure 5b – Comparison of Higgins (1986) and Pazzaglia (1993b) Geologic Mapping (Explanation)

## Explanation

*Symbols*

Cecil County shoreline

A — A' Location of cross section

*Units by U.S.G.S (by Higgins and Conant, 1986)*

### SEDIMENTARY ROCKS

- Qm — Tidal marsh deposits
- Qal — Alluvium
- Qtc — Coarse-grained facies, Talbot Formation
- Qtf — Fine-grained facies Talbot Formation
- Tp — Pensauken Formation
- Tu — Upland gravel
- Kmo — Monmouth Group
- Kme — Matawan Group
- Kmv — Merchantville Formation
- Kmg — Magothy Formation
- Kp — Potomac Formation

### METASEDIMENTARY ROCKS

- mga — Metagraywake with amphibolite

### METAVOLCANIC ROCKS

- Pzjh — Happy Valley Branch Member James Run Formation
- Pzjp — Principio Creek Member, James Run Formation
- Pzjgg — Gilpins Falls Member, greenstone, James Run Formation
- Pzjgm — Gilpins Falls Member, pillow metabasalt, James Run Formation
- Pzjgs — Gilpins Falls Member, chlorite schist James Run Formation
- Pzjl — Little Northeast Creek Member James Run Formation
- Pzjfr — Frenchtown Member James Run Formation
- Pzjpf — Principio Furnace Member, James Run Formation

### FELSIC PLUTONIC ROCKS

- pdc — Port deposit gneiss: coarse-grained phase
- pdf — Port Deposit gneiss: fine-grained phase
- gig — Gneiss on Garrett Island

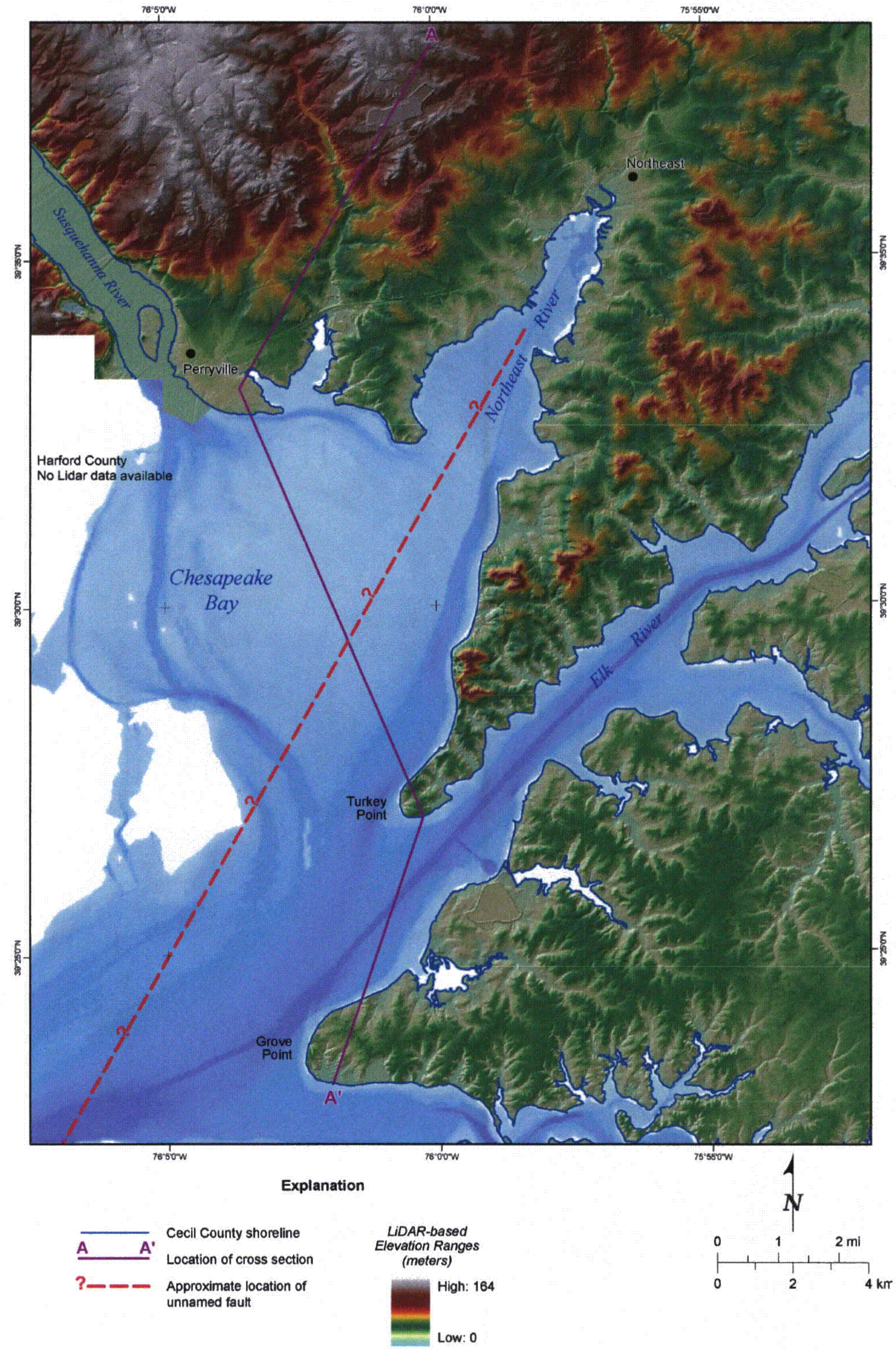
### MAFIC PLUTONIC ROCKS

- gbu — Gabbrioc rocks, undifferentiated

*Units by Pazzaglia (1993b)*

- Tb — Bryn Mawr Formation
- Tp — Pensauken Formation
- Ty — Perryville Formation

**Figure 5b. Comparison of Higgins (1986) and Pazzaglia (1993b) geologic mapping (Explanation)**




Note: 30-meter cell size bathymetric data from NOAA.

**Question 02.05.01-48 Figure 6 – LiDAR Elevation Showing Trace of Pazzaglia's Fault**

**COLA Impact**

The COLA FSAR will not be revised as a result of this response.

**Question 02.05.01-49**

In CCNPP Unit 3 FSAR Section 2.5.1.1.4.4.4.7, Unnamed Monocline beneath Chesapeake Bay, the text states, "Based on these physiographic, geomorphic and geologic observations, McCartan (McCartan, 1995) infer the presence of a fold along the western shore of Chesapeake Bay (Figure 2.5-25)."

a. Please explain how McCartan justifies the monocline on the west shore of the Patuxent river.

b. In the same FSAR section, the text states, "Field and aerial reconnaissance, coupled with interpretation of aerial photography and LiDAR [Light Detection and Ranging] data (see Section 2.5.3.1 for additional information regarding the general methodology), conducted during this COL study, shows that there are no geomorphic features indicative of folding directly along the western shores of Chesapeake Bay." The LiDAR data presented in the FSAR, Figure 2.5-26, is at the wrong scale to examine the features discussed in this section. Please provide a LiDAR figure at a larger scale to see details of topography and post McCartens monoclines, Pazzaglia's faults, and Hansen's Hillville fault on the LiDAR.

**Response**

a. The response to RAI 71, Question 02.05.01-32[6] addressed some aspects of this question.

McCartan (McCartan, 1995) does not cite specific evidence for the buried monocline on the west shore of the Patuxent River and beneath the Chesapeake Bay. The interpretation is based primarily on changes in thickness of subsurface stratigraphic beds derived from sparse regional borehole data (2 boreholes separated by 23 miles). McCartan (1995) also cites the following two lines of argument for inferring the presence of flexures: (1) "First the bay has a peculiar physiography."; (2) "Second, the contrasting highlands west of the bay and lowlands east of the bay are most easily explained by differential uplift."

With respect to stratigraphic thickness changes, mapping and interpretation of limited borehole data, McCartan (1995) shows an apparent change in thickness of the Miocene Choptank Formation across the Patuxent River (see FSAR Figure 2.5-40 for Cross Section A-A' of McCartan (1995)). Cross-section A-A' (McCartan, 1995) shows the thickness of the Choptank Formation as about 130 feet (40 meters) west of the river and about 65 feet (20 meters) east of the river. McCartan (1995) also shows the Miocene St. Mary's Formation that overlies the Choptank Formation as absent west of the Patuxent River. However, mapping by Glaser (2003) shows the St. Mary's Formation at an elevation of 100 feet on both sides of the river. In light of the mapping by Glaser (2003) the stratigraphic thickness changes suggested by McCartan (1995) are not supported.

McCartan (1995) also qualifies interpretations of subsurface stratigraphy by noting, "The lack of deep drill cores immediately east of Chesapeake Bay precludes good control of stratigraphic interpretations." As discussed in Response NRC RAI 71, Question 02.05.01-32[6], Part B, Item 1, deep core borings on the line of the cross section are located near the western shore of Chesapeake Bay (Ca-Ed-23) and 21 miles (35 km) to the

[6] G. Gibson (UniStar Nuclear Energy) Letter UN#09-152 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated April 15, 2009.

northeast near the east shore of the Delmarva Peninsula (DO-Ce-88). In that distance the Tertiary stratigraphic section increases from 570 feet (175 meters) thick in the west to 810 feet (250 meters) thick in the east. Other cross sections in McCartan (1995) account for similar changes in thickness by a gradual thickening of units to the south or east.

Also discussed in the Response to RAI 71, Question 02.05.01-32[7], Part B, Item 3, compelling evidence for the absence of folding in mid-Tertiary units beneath the Patuxent River comes from a structure contour map of the top of the Piney Point Formation in Achmad (1997). The Achmad (1997) map, reproduced as FSAR Figure 2.5-14, shows structural contours every 50 feet (15 meters), constrained by multiple borings. The contours are evenly spaced, marking a gradual dip to the southeast. A flexure like the one shown by McCartan (1995) in cross section A-A', where the Piney Point Formation is inferred to dip as much as 45 degrees and resulting in sharp drop of approximately 150 feet (46 meters), would result in a zone of closely spaced structural contours. The absence of any increased dip in the structural contours of Achmad (1997) argues against the presence of a monoclinal flexure as inferred by McCartan (1995).

b. The attached Figures 1, 2, and 3 are LiDAR elevation maps at larger scales compared to FSAR Figure 2.5-26. As requested, the figures show additional detail of topography. Figure 1 is presented at approximately 1:155,000-scale, and shows McCartan's (1995) hypothesized monoclines and Hansen's (1986) Hillville fault,. The monocline axes are not shown on the map by McCartan (1995); however their map-surface locations from cross-sections are indicated with a triangle symbol on Figure 1. The unnamed fault of Pazzaglia (1993) is located some 70 miles (113 km) from the site and it is not practical to include it with the other features at the requested larger scale. A LiDAR map showing Pazzaglia's unnamed fault is presented on a figure in response to RAI 130, Question 02.05.01-48.

   Figures 2 and 3 are LiDAR-derived elevation maps at 1:62,500-scale, with Figure 2 emphasizing the terraces along the Patuxent River, and Figure 3 emphasizing similar terraces along the Potomac River. Both Figures 2 and 3 display colored slope maps derived from the LiDAR data, and also show the projected surface trace of Hansen's (1986) Hillville fault.

   Added to Figures 2 and 3 are black hachured lines that delineate the back edge (i.e., geologic contact laterally distal to the present-day river) of the Pleistocene lowland terrace deposits of McCartan (1995). Pleistocene terrace deposits of McCartan (1995) include terraces Q2 (youngest) through Q5 (oldest); terrace Q1 is Holocene (Table 1). The terraces locally are mantled by colluvium that forms an apron of sediment shed from the adjacent higher topography (Figures 2 and 3). The colluvium is mapped by McCartan (1995) as map unit QTc. The colluvium is interpreted as late Cenozoic (McCartan, 1995), but is only constrained in age qualitatively by map pattern relationships. The terrace back edge of unit QTc commonly delineates the geologic contact between Tertiary bedrock and Quaternary sediments, and is expressed in the topography as a distinct break in slope and elevation change.

   Along the Patuxent River, the projected trace of the Hillville fault underlies terrace Q4 south of the river and deposit QTc north of the river (Figure 2). Thus, the Hillville fault along the

[7] G. Gibson (UniStar Nuclear Energy) Letter UN#09-152 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated April 15, 2009.

Patuxent River underlies deposits that are at least 180,000 years old (Table 1). The terrace surfaces and the back edges of the terraces do not show vertical offset or deformation that suggests active faulting or folding.

Along the Potomac River, the projected trace of the Hillville fault underlies terrace Q3 which is at least 70,000 years old (Table 1), as well as unit QTc (Figure 3). The terrace surfaces of Q3 are not offset or deformed where they overlie the trace of the fault (Figure 3). Further, the fault does not offset or deform the back edge of the Quaternary sediments where in contact with Tertiary rocks.

These topographic and geomorphic observations along both the Patuxent and Potomac Rivers (Figures 2 and 3) argue for the absence of recent tectonic movements on the Hillville fault.

References:

Achmad, 1997. Hydrogeology, model simulation, and water-supply potential of the Aquia and Piney Point-Nanjemoy Aquifers in Calvert and St. Mary's Counties, Maryland, Department of Natural Resources, Maryland Geological Survey Report of Investigations No. 64, 197 p., G. Achmad and H. Hansen, 1997.

Glaser, 2003c. Geologic Map of the Cove Point Quadrangle, Calvert County, Maryland, Maryland Geological Survey, 1:24,000 scale, J. Glaser.

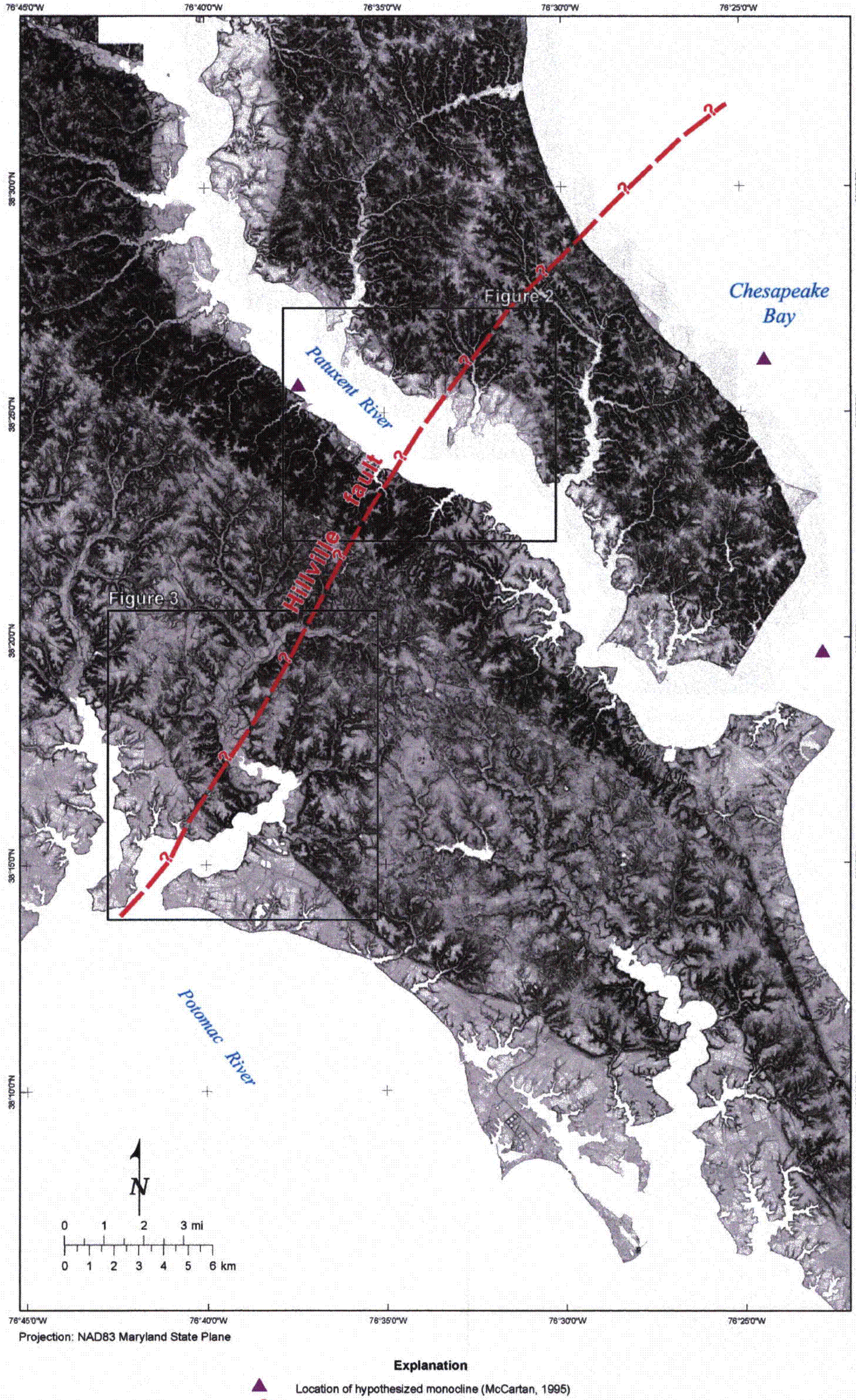
Hansen, 1986. The Lithology and Distribution of Pre-Cretaceous basement rocks beneath the Maryland Coastal Plain, Department of Natural Resources Maryland Geological Survey Report of Investigations No. 44, p 27, H. Hansen and J. Edwards Jr, 1986.

McCartan, 1995. Geologic Map and Cross Sections of the Leonardtown 30 X 60 minute quadrangle, Maryland and Virginia. U.S. Geological Survey Open-file report OFR 95-665, p 38, 1 plate, L. McCartan, W. Newell, J. Owens and G. Bradford, 1995.

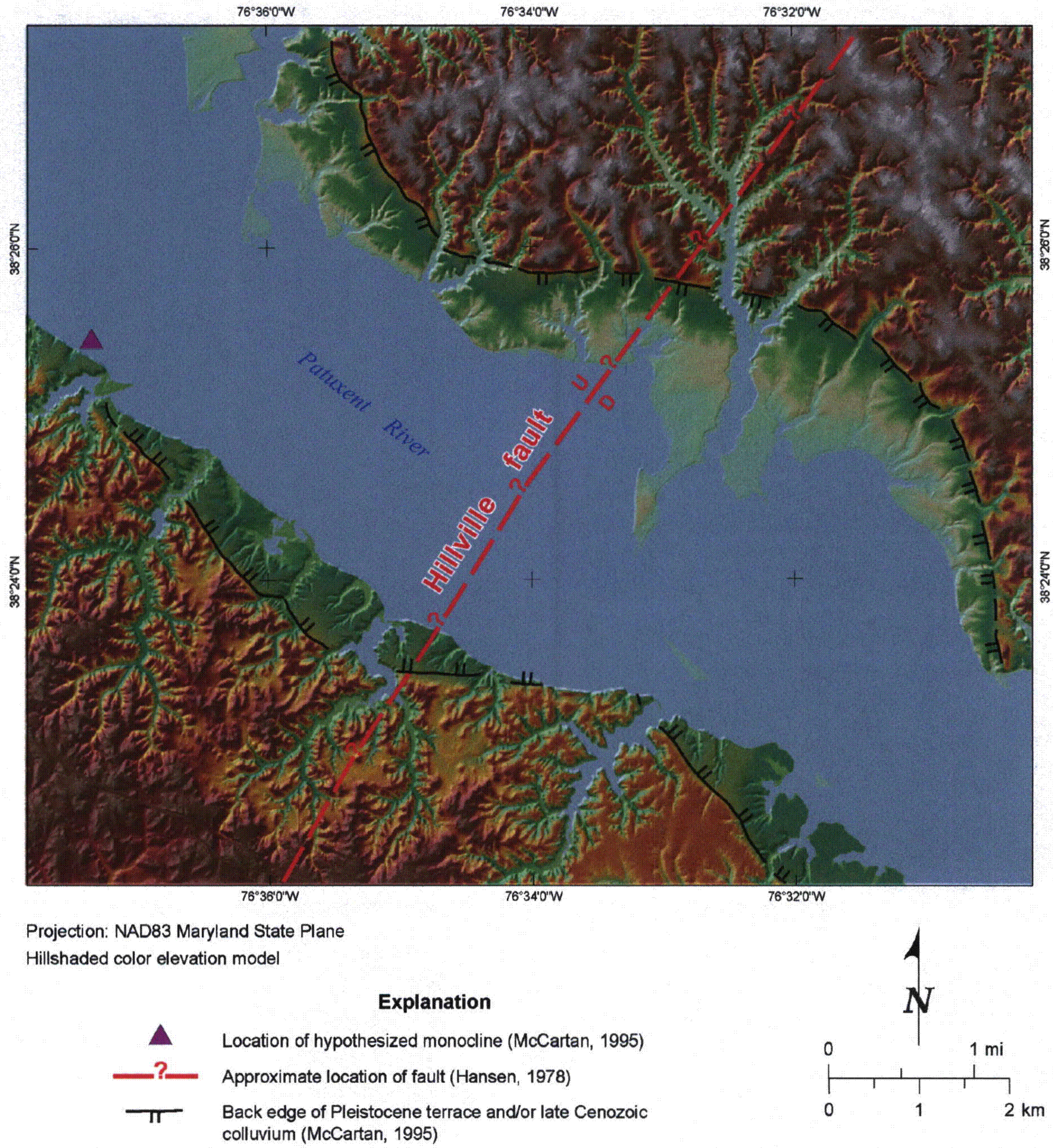
Pazzaglia, 1993. Stratigraphy, petrography, and correlation of late Cenozoic middle Atlantic Coastal Plain deposits: Implications for late-stage passive-margin geologic evolution, Geological Society of America Bulletin, Volume 105, p 1617-1634, F. Pazzaglia, 1993.

**Table 1 – Terrace Ages from McCartan (1995)**

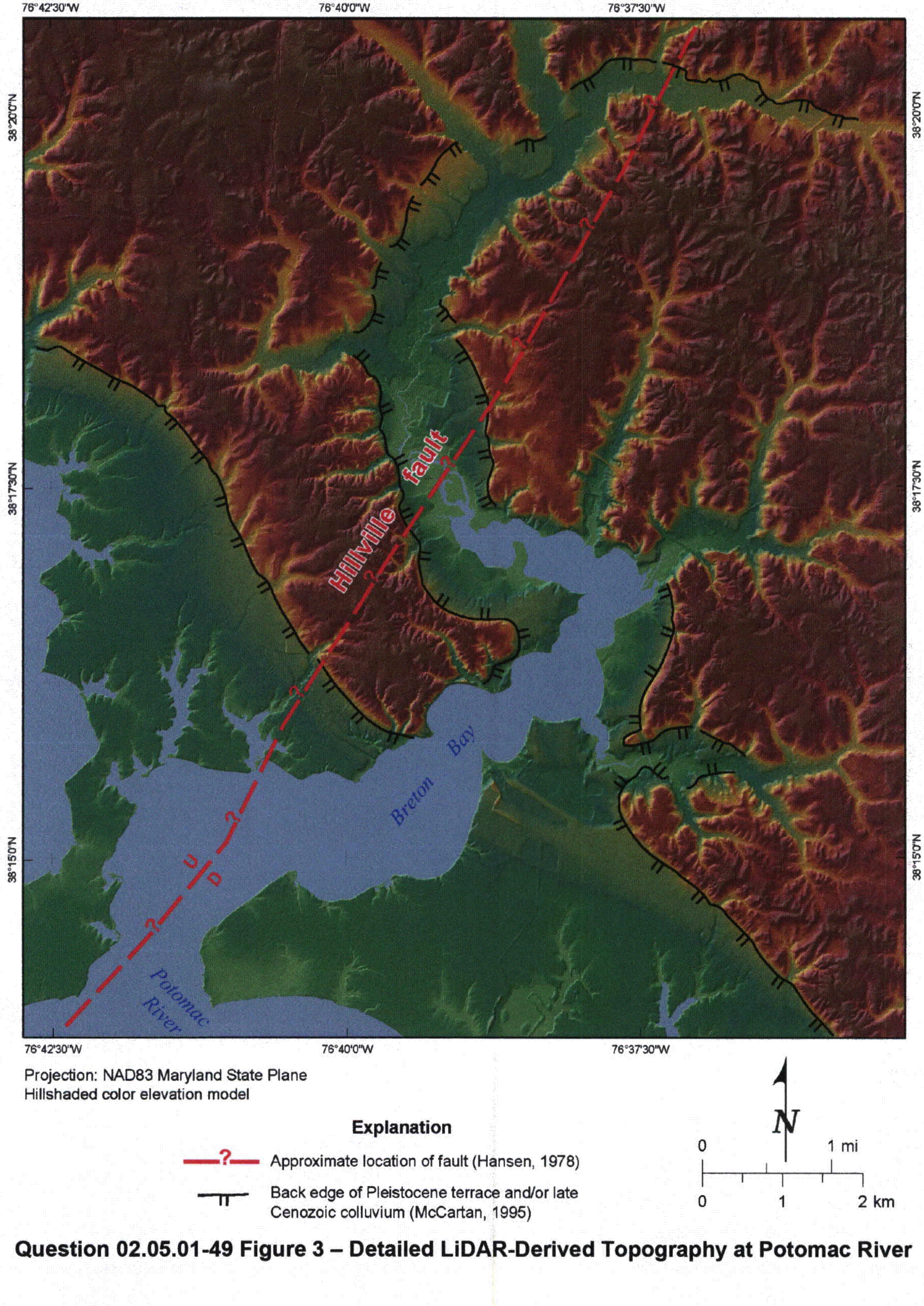
| Terrace | Age | Dating Technique |
|---|---|---|
| Q5 | 450,000 | Uranium Disequilibrium Series |
| Q4 | 180,000 | Uranium Disequilibrium Series |
| Q3 | 70,000 | Uranium Disequilibrium Series |
| Q2 | 24,000 – 36,000 | Radiometric Carbon |
| Q1 | Holocene | |




**Question 02.05.01-49 Figure 1 – LiDAR-Based Slope Map**




**Question 02.05.01-49 Figure 2 – Detailed LiDAR-Derived Topography at Patuxent River**




**Question 02.05.01-49 Figure 3 – Detailed LiDAR-Derived Topography at Potomac River**

**COLA Impact**

The COLA FSAR will not be revised as a result of this response.

**Question 02.05.01-50**

In CCNPP Unit 3 FSAR Section 2.5.1.1.4.4.4.8, Unnamed Folds and Postulated Fault within Calvert Cliffs, Western Chesapeake Bay, Calvert County, Maryland, the text states (p. 2.5-54), "The hypothesized fault is not exposed in the cliff face and is based entirely on a change in elevation and bedding dip of Miocene stratigraphic boundaries projected across the fluvial valley of Moran Landing. Kidwell (Kidwell, 1997) postulates that the fault strikes northeast and exhibits a north-side down sense of separation across the geologic units (Miocene through Quaternary). With regard to the apparent elevation changes for the Pliocene and Quaternary unconformities, these can be readily explained by channeling and highly irregular erosional surfaces (Figure 2.5-30)."

a. Please provide additional explanation, along with illustrations and maps, to illustrate how the Kidwell interpretation can be discounted and must be interpreted as an erosional surface rather than as a tectonic structure.

b. In the same FSAR section, the text states, "Field and aerial reconnaissance, coupled with interpretation of aerial photography and LiDAR [Light Detection and Ranging] data (see Section 2.5.3.1 for additional information regarding the general methodology), conducted during the CCNPP Unit 3 investigation shows that there are no geomorphic features indicative of potential Quaternary activity developed in the Pliocene-Quaternary surfaces along a southeast projection from Chesapeake Bay across the Patuxent and Potomac Rivers (Figure 2.5-26)." Please provide a legible, enlarged version of Figure 2.5-26 so that the specific geomorphic features associated with Pliocene-Quaternary surfaces can be examined.

**Response**

a. Several aspects of this question and response have been discussed in the response to RAI 71, Question 02.05.01-27[8] which is summarized below. In response to the specific question posed here, several points of clarification along with further discussion regarding the hypothesized structures reported by Kidwell (1997) are provided.

   As discussed in the response to RAI 71, Question 02.05.01-27[8], 1.2 mi (1.9 km) south of the site, Kidwell (1997) interprets the existence of a 3 to 12 ft (0.9 to 3.7 m) elevation change in post-St. Mary's Formation sediments by extrapolating unit contacts across the approximately 0.6 mile wide (1 km) gap in cliff exposure at Moran Landing (FSAR Figures 2.5-25 and 2.5-30). As illustrated in FSAR Figure 2.5-30, the post- St. Mary's Formation sediments, including the Pleistocene cliff top gravels (Kidwell, 1997 and dark green color on FSAR Figure 2.5-30) are incised by fluvial erosion into the top of the St. Mary's Formation surface (purple color on FSAR Figure 2.5-30) as exhibited by the deep and narrow geometry in the subsurface near Rocky Point, Conroy Landing, and Western Shorelines locations. The sedimentary facies filling these troughs are channelized sand, further supporting a fluvially eroded origin to the surface. Furthermore, field investigations performed as a part of the FSAR investigations confirm an erosional unconformity at the basal contact of the post- St. Mary's Formation, and any potential variation in the elevation of this contact or thickness of the gravels cannot be used to infer stratigraphic offsets. Similar late Quaternary fluvial

[8] G. Gibson (UniStar Nuclear Energy) Letter UN#09-227 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated May 1, 2009.

deposits have been noted in Cecil County Maryland. At those locations, the Pleistocene deposits possess a number of buried unconformities with abrupt contacts interpreted as erosional (i.e., beveled) surfaces associated with late Cenozoic fluvial geomorphic processes (e.g., Pazzaglia, 2006).

The underlying units of the Miocene St. Mary's formation are also interpreted by Kidwell (1997) as having 6 to 10 ft (2 to 3 m) changes in elevation across Moran landing. Similar subtle elevation variations in Miocene strata characterized along a near-continuous exposure south of Moran Landing contain similar vertical and lateral dimensions as to the inferred elevation change across Moran Landing; however, the features are interpreted as subtle warps and not faults by Kidwell (1997). As summarized in the response to RAI 71, Question 02.05.01-27[9], the geometric similarities and the association of St. Marys deposits at Little Cove Point with those north and south of Moran Landing, where there is an absence of continuous exposure, strongly suggests that elevation change of Miocene strata across Moran Landing should be characterized as a subtle warp and not a fault.

Subtle warps in sedimentary deposits can result from numerous non-tectonic origins such as differential compaction of sediments over preexisting topography, soft sediment deformation, lateral facies changes, or localized diagenetic reactions (Davies et al., 2009; Laubach et al., 2000). Such processes are common in sedimentary basins and also constitute a reasonable mechanism for undulatory relief on geological disconformity surfaces.

b. As requested by the NRC staff, the attached Figures 1 and 2 are LiDAR elevation maps at larger scales compared to FSAR Figure 2.5-26. These figures show additional detail of the topography along the Patuxent River and southern Calvert County. Both figures show McCartan's (1995) hypothesized monoclines, Hansen's (1986) Hillville fault, and the location of landmarks used for geographic reference by Kidwell (1997) (FSAR Figures 2.5-26 and 2.5-30).

Figure 2 displays a hillshaded colored elevation map emphasizing the geomorphology of terraces along the Patuxent River. Black hachured lines delineate the back edge (i.e., geologic contact laterally distal to the present-day river) of the Pleistocene lowland terrace deposits of McCartan (1995). Pleistocene terrace deposits of McCartan (1995) include terraces Q2 (youngest) through Q5 (oldest); terrace Q1 is Holocene (see response to RAI 130, Question 02.05.01-49, Table 1). The terrace back edges commonly delineate the geologic contact between Tertiary bedrock and Quaternary sediments, and are expressed in the topography as a distinct break in slope and elevation change. The approximate area of the hypothesized northeast-striking fault by Kidwell (1997) is delineated by the region shaded red extending to the southwest from Moran landing.

Along the Patuxent River, the projection of the hypothesized fault by Kidwell (1997) along a southwestern trend from Moran Landing suggests the trace of the fault underlies terrace Q3 on both sides of the river (Figure 2). Thus, the Kidwell fault along the Patuxent River underlies deposits that are at least 70,000 years old (see response to RAI 130, Question 02.05.01-49, Table 1). The terrace surfaces of Q3 are not offset or deformed where they overlie the approximated trace of the fault (Figure 2). Further, the terrace back edges

[9] G. Gibson (UniStar Nuclear Energy) Letter UN#09-227 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated May 1, 2009.

display smooth arcuate map patterns typical of fluvial erosion by a meandering river system and do not show offset or deformation that suggests active faulting or folding.

These topographic and geomorphic observations along the Patuxent River (Figure 1) argue for the absence of recent tectonic movement on the hypothesized fault by Kidwell (1997).

References:

Davies, R.J., Ireland, M.T., and Cartwright, J.A., 2009, Differential compaction due to irregular topography of a diagenetic reaction boundary: a new mechanism for the formation of polygonal faults; Basin research, Volume 21, No. 3, 354 – 359.

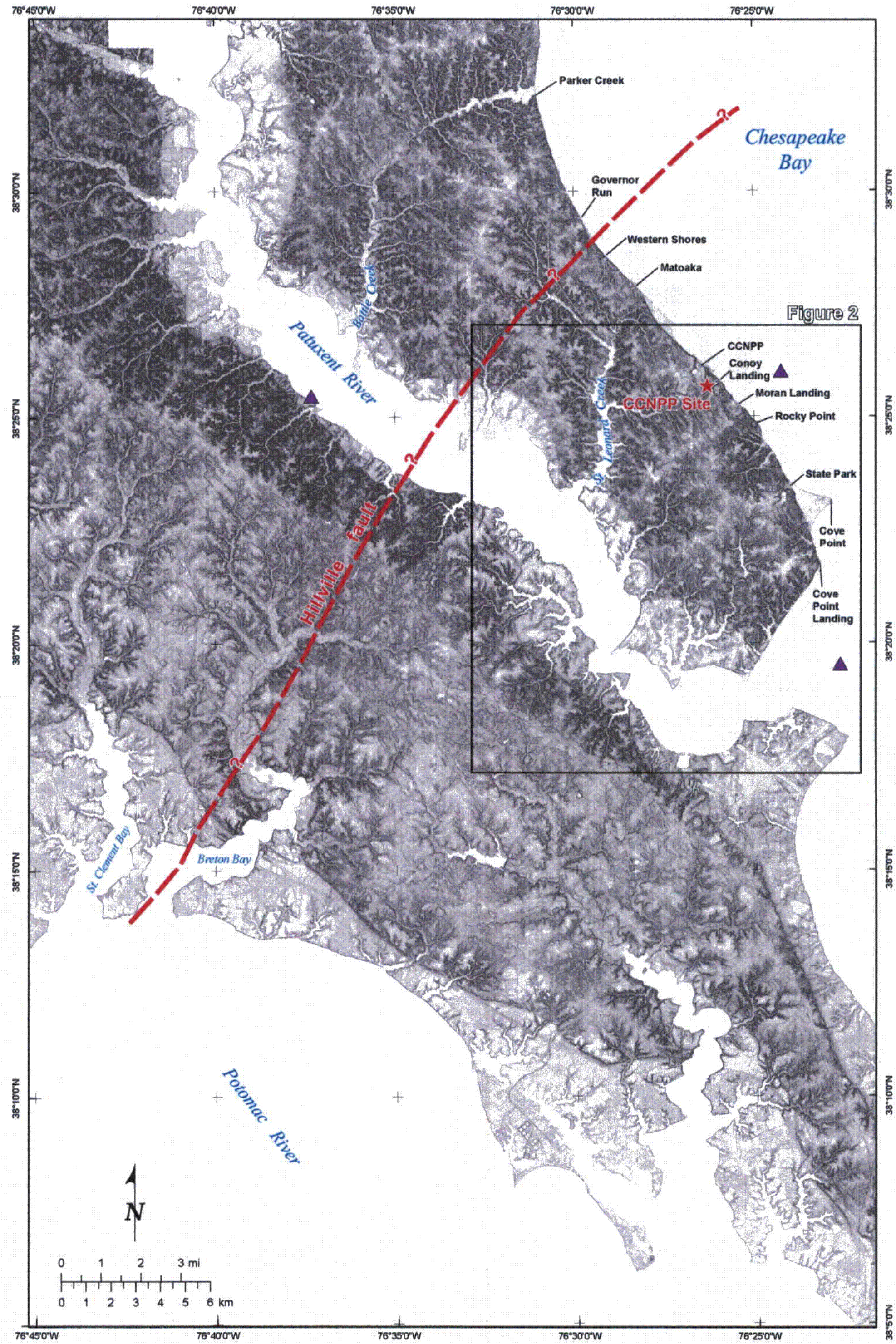
Kidwell, S., 1997, Anatomy of Extremely Thin Marine Sequences Landward of a Passive-MarginHinge Zone: Neogene Calvert Cliffs Succession, Maryland, Journal of Sedimentary Research, Volume 67, Number 2, p 322-340.

Laubach, S.E., Schultz-Ela, D.D., Tyler, R., 2000, Differential compaction of interbedded sandstone and coal; in Forced Folds and Fractures, Ameen, M.S., and Cosgrove, J.W., (eds), Geological Society of London, Special Publication, 169, 51 – 60.

McCartan, L., Newell W., Owens, J., and Bradford, G., 1995, Geologic Map and Cross Sections of the Leonardtown 30 X 60 minute quadrangle, Maryland and Virginia. U.S. Geological Survey Open-file report OFR 95-665, p 38, 1 plate.

Pazzaglia, D., Braun, Pavich, M., Bierman, P., Potter Jr., N. , Merritts, D., Walker R., and Germanoski, D., 2006, Rivers, Glaciers, landscape evolution, and active tectonics of the central Applalacians, Pennsylvania and Maryland, Geological Society of America, Field Guide 8. F.

Enclosure 1
UN#09-389

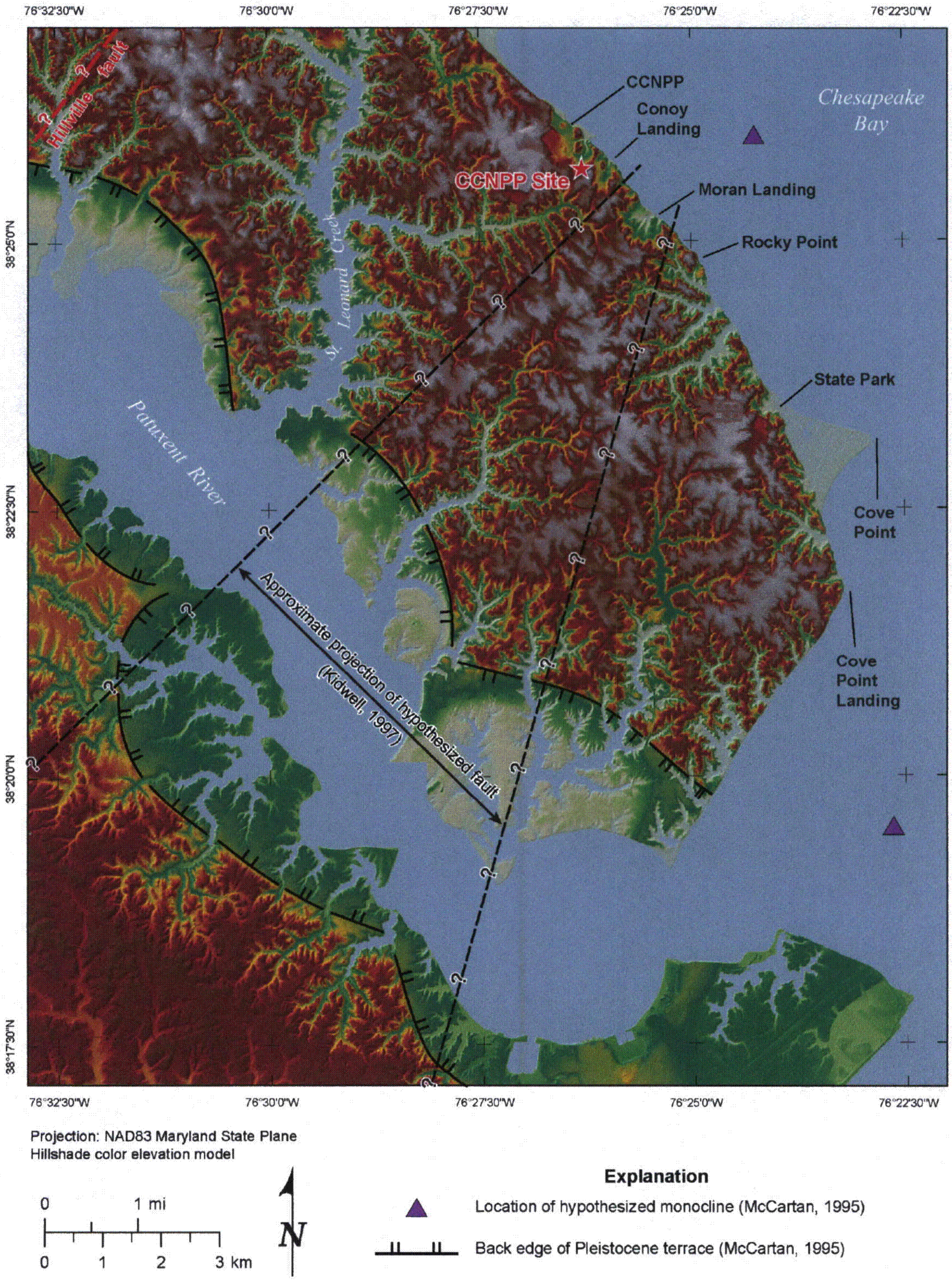




**Explanation**

Location of hypothesized monocline (McCartan, 1995)

Approximate location of fault (Hansen, 1978)

**Question 02.05.01-50 Figure 1 – LiDAR Based Slope Map**




**Question 02.05.01-50 Figure 2 – Detail LiDAR-Derived Topography along Patuxent River and Calvert Peninsula**

**COLA Impact**

FSAR Section 2.5.1.2.4, Site Area Structural Geology, and Section 2.5.3.2.3, Stratigraphic Undulations and Hypothesized Fault, will be revised as shown in Enclosure 3 in a future revision of the COLA.

**Question 02.05.01-51**

The following requests pertain to CCNPP Unit 3 FSAR Section 2.5.1.1.4.4.5, Quaternary Tectonic Features.

a. On page 2.5-56, the text states, "The Everona-Mountain Run fault zone and Stafford fault of Mixon (Mixon, 2000) also are discussed in detail in previous Section 2.5.1.1.4.4.2 (Paleozoic Structures) and Section 2.5.1.1.4.4.4.1 (Tertiary Structures)." Please discuss any evidence of Quaternary movement on either of these faults.

b. In FSAR Section 2.5.1.1.4.4.5.1, Fall Lines of Weems (1998), the text states, "In summary, based on review of published literature, field reconnaissance, and geologic and geomorphic analysis performed previously for the North Anna ESP application, the fall lines of Weems (1998) are erosional features related to contrasting erosional resistances of adjacent rock types, and are not tectonic in origin, and thus are not capable tectonic sources." The Dominion (2004b) work challenged of the existence of the northern segment of the fall lines. Please provide more geologic details about the Dominion work, both text and figures, in order for staff to evaluate the impact specifically to CCNPP Unit 3.

c. In FSAR Section 2.5.1.1.4.4.5.2, Everona-Mountain Run Fault Zone, the text states, "The Mountain Run fault zone is located along the eastern margin of the Culpeper Basin and lies approximately 71 mi (114 km) southwest of the site (Figure 2.5-17 and Figure 2.5-31)." Figures 2.5-17 shows the Everona-Mountain run fault zone in relation to the Blue Ridge province and the Potomac melange but does not show relationship to the Culpeper Basin. Figure 2.5-31 shows the fault as a triangle adjacent to the Fall Lines of Weems. Please provide a figure to adequately illustrate the position of this fault in relation to the Culpeper Basin as discussed in this section at an appropriate scale to support the text.

d. On page 2.5-42, in a previous discussion of this fault in FSAR Section 2.5.1.1.4.4.2.1, the fault is described as underlying the Culpeper basin. Please resolve/integrate the descriptions in FSAR Sections 2.5.1.1.4.4.2.1 and FSAR Section 2.5.1.1.4.4.5.2.

e. On page 2.5-57, the text states, "The northeast-striking Mountain Run fault zone is moderately to well-expressed geomorphically (Pavlides, 2000). Two northwest-facing scarps occur along the fault zone, including: (1) the 1 mi (1.6 km) long Kelly's Ford scarp located directly northeast of the Rappahannock River and; (2) the 7 mi (11 km) long Mountain Run scarp located along the southeast margin of the linear Mountain Run drainage." These observations/interpretations appear to be in conflict with more recent work done for the North Anna ESP, in which Dominion (2004a) concluded that the scarps are not fault scarps but resulted from fluvial erosion. Please integrate the earlier interpretations of Pavlides with Dominion's more recent work for the North Anna ESP.

f. On page 2.5-57, the text states, "The Everona fault is located about 0.5 mi (0.8 km) west of the Mountain Run fault zone." Please provide a figure showing the lithotectonic units of the Everona fault and the Mountain Run fault system on the same map to support the discussion in the text. Please locate the CCNPP site on the figure if possible.

g. On page 2.5-58, the text states, "Based on the findings of the previous studies performed for the North Anna ESP and approval by the Nuclear Regulatory Commission (NRC, 2005), it is concluded that the Everona-Mountain Run fault zone is not a capable tectonic source." The

NRC made conclusions about the North Anna ESP for the Mountain Run fault zone. The CCNPP Unit 3 FSAR is linking the Everona fault to that system. Please clarify fault zone nomenclature in all relevant FSAR sections.

**Response**

a. This question pertains to the one-sentence paragraph that follows the numbered list of potential Quaternary tectonic features in Section 2.5.1.1.4.4.5. This sentence was intended to direct the reader to additional discussion of these structures in previous section of the FSAR text. Evidence of Quaternary movement on both of these faults is discussed in the FSAR text. Section 2.5.1.1.4.4.5.2 addresses the Everona fault and Mountain Run fault zone, and Section 2.5.1.1.4.4.5.3 addresses the Stafford fault of Mixon et al. (2000). This sentence will be deleted in a future revision of the COLA.

b. In the FSAR text for CCNPP, the Dominion (2004b) work is summarized in three sentences. The second paragraph in Section 2.5.1.1.4.4.5.1 (Fall Lines of Weems (1998)) includes the following:

*The North Anna ESP study concludes that that the individual fall zones of Weems (1998) may not be as laterally continuous as previously interpreted. For instance, stratigraphic, structural and geomorphic relations across and adjacent to the Weems (1998) fall zones can be readily explained by differential erosion due to variable bedrock hardness rather than Quaternary tectonism (Dominion, 2004b). Furthermore, there is no geomorphic expression of recent tectonism, such as the presence of escarpments, along the trend of the fall lines between drainages where one would expect to find better preservation of tectonic geomorphic features.*

The above text summarizes two of the primary arguments from a 24-page response by Dominion (2004b) to the NRC, addressing a request to, "Please provide additional justification to confirm or disprove the seven fall lines defined by Weems [1998] as a capable tectonic source." (Dominion, 2004b). Additional details from that 24-page response is provided below; organized in four parts: (1) Summary of analytical approach, (2) Validity and independent evaluation of methodology, (3) Evaluation of river terraces across the Central Piedmont and Nutbush Fall Lines, and (4) Independent geomorphic analysis of the Tidewater and Central Piedmont Fall Lines.

1. Summary of Analytical Approach Used by Weems (1998)

Weems (1998) analyzed longitudinal profiles of rivers in the Piedmont and Blue Ridge provinces of North Carolina and Virginia. He determined that discrete reaches along individual streams were marked by rapids and/or falls, with locally steeper gradients than adjacent upstream and downstream reaches. These reaches of steeper gradients Weems (1998) defined as fall zones. Some of the fall zones are more than 10 miles long, and in some cases Weems (1998) combined multiple steep reaches along a river into a single fall zone with a width of up to 20 miles. Weems (1998) defined apparent alignments of fall zones in a direction sub-parallel to the NE-SW-trending structural grain of the Appalachians to be fall lines. In addition to the traditional Fall Line (termed "Tidewater Fall Line" by Weems) that separates the Piedmont from the Coastal Plain, Weems (1998) interpreted that six other laterally continuous fall lines also are present west of the Tidewater Fall Line in the Piedmont and Blue Ridge provinces. From east to west, these include the Nutbush, Durham, Central Piedmont, Western Piedmont, Blue Ridge, and Great Smokey fall lines. These fall lines are shown in FSAR Figure 2.5-31 and also in Figure 1 of this RAI response. Figure 1 is taken directly from the North Anna ESP application RAI response (Dominion, 2004b), with the addition of the CCNPP site on the figure for reference.

Weems (1998) discussed three hypotheses for the origins of the fall lines in the Blue Ridge and Piedmont provinces:

1) Variable erosion across linear belts of rocks of varying hardness;
2) Late Cenozoic climatic and sea level fluctuations, producing "waves" of headward-retreating nick points that are expressed as fall zones and fall lines; and
3) Localized neotectonic uplift along fall lines.

Weems (1998) rejected the first two hypotheses and instead concluded that tectonic uplift "is the dominant cause of the existing Piedmont fall lines" because neither differential rock erosion nor regional creation of nickpoints by climate-driven changes in fluvial parameters could "adequately explain the observed patterns." Apparently, Weems (1998) adopted a tectonic interpretation primarily because he considered the alternative interpretations to be less compelling, and not because of direct evidence supporting a tectonic origin.

2. Validity and Independent Evaluation of Weems (1998) Methodology

The lack of formal, consistent criteria makes it very difficult to independently reproduce Weems' delineation of individual fall zones, or the correlations of fall zones on individual streams as laterally continuous fall lines. In particular, the proposed model for the lateral continuity of fall lines for hundreds of miles along trend in the Blue Ridge and Piedmont provinces is based on subjective assessments of some steep stream reaches as "anomalous" fall zones.

3. Evaluation of River Terraces Across Central Piedmont and Nutbush Fall Lines

The only evidence in support of late Cenozoic tectonism cited by Weems (1998) consists of locally steepened reaches in the longitudinal profiles of Pliocene terraces along the Roanoke and Staunton Rivers in southern Virginia. These profiles are shown in Figure 2, which is taken from the Dominion (2004b) report and Figure 10 in Weems (1998). Weems (1998) presents profiles of three Pliocene fluvial terraces along the Roanoke and Staunton Rivers that he interprets to show down-to-the-east warping across the Central Piedmont and Nutbush fall lines. From youngest to oldest, the terraces are located at heights of about 60 ft, 140 ft, and 200 ft above the modern stream channel. As depicted by Weems (1998), there is about 60 ft of structural relief in the terraces across the fall zones. It should be noted, however, that the 60 ft of relief occurs across a horizontal distance of about 17 miles. This relief in Weems' terrace profiles presented at ~500X vertical exaggeration appears to define a distinct east-facing warp or scarp in the terraces. However, 60 ft of relief in 17 miles is equivalent to an approximately 0.04° change in the gradient of the terrace surfaces. Localized displacement on a fault is not a plausible explanation for producing a sustained 0.04° increase in gradient across a horizontal distance of 17 miles.

If the deflections in the Roanoke River and Pliocene terraces represent tectonic deformation and the fall lines represent previously unrecognized active fault zones deforming the earth's surface, as suggested by Weems (1998), then this interpretation implies an east-side-down sense of slip on the causative faults. Given the NE-SW orientation of the principal horizontal compressive stress in the Central and Eastern United States (Zoback and Zoback, 1989), it is considered highly unlikely that any of the abundant east-dipping thrust faults within the Appalachian crust have been reactivated to form the fall lines of Weems (1998). East-dipping Appalachian thrust faults would most likely reactivate with dextral and reverse components of slip in the current stress regime, rather than a normal sense of slip that would be needed to form the down-to-the-east warping interpreted from the terrace profiles.

4. Independent Geomorphic Analyses

Independent geomorphic analyses of the Tidewater Fall Line and Central Piedmont Fall Line were evaluated in northern Virginia by Dominion (2004b). The analyses were designed to: (1) confirm the presence and exact location of the fall lines as fall zones on major rivers; and (2) evaluate geologic and geomorphic relationships to determine whether late Cenozoic deformation has occurred along the fall lines, as postulated by Weems (1998).

To assess the presence or absence of Quaternary tectonic activity along the Tidewater Fall Line, a detailed longitudinal profile of the Rappahannock River was constructed across the fall zone at Fredericksburg, Virginia (Figure 3, taken from Dominion, 2004b). Also plotted were elevations of remnants of a regressive late Pliocene marine sand, which caps upland surfaces of the inner Coastal Plain in northern Virginia, and specifically underlies the relatively flat, accordant summit surfaces north and south of the Rappahannock River, upstream and downstream of Fredericksburg. Although there is some scatter in the elevations of the late Pliocene marine sand remnants on the profile, they generally define an east-sloping surface with a constant gradient that crosses the Tidewater fall zone on the Rappahannock River without obvious east-down deflection. The gradient of the late Pliocene marine sand surface is similar to that of the modern Rappahannock River upstream of the fall zone. If this interpretation that the Pliocene marine sand is not deformed is correct, then development of the fall zone in the river, which clearly postdates deposition of the late Pliocene marine sand, must be due to non-tectonic geomorphic processes.

A profile of the South Anna River was also constructed to better understand the significant width of the Tidewater Fall Line depicted by Weems (1998) and the location of lithologic changes along the profile (Figure 4, from Dominion, 2004b). The Tidewater Fall Line defined by Weems (1998) extends nearly 18 miles and includes a prominent steep fall zone east of the Taylorsville basin and a more subtle gradient change near the eastern margin of the basin. It is not clear why Weems (1998) interpreted these multiple gradient changes as a single fall zone and not two different fall zones. A strong correlation between bedrock lithology and gradient can be observed on the profile in Figure 4. The steepest reach of the river corresponds to the portion flowing across the Petersburg granite (Mpg). The labeling of the PzHy and Mpg map symbols in Figure 4 should be switched). The Coastal Plain portion of the river exhibits the gentlest gradient and is underlain by Potomac Formation (Kp) and Alluvium (Qal). The strong correlation between gradient changes and contrasting rock types appears to support a non-tectonic interpretation of the formation of the Tidewater Fall Line.

Weems (1998) cites "anomalous gradient-to-bedrock-hardness" relationships in the Triassic Culpeper Basin along the Rappahannock and Rapidan Rivers as evidence that the Central Piedmont Fall Line is not controlled by differential bedrock erosion. However, based on analysis of geologic and topographic maps, as well as detailed profiling of the

Rappahannock and Rapidan Rivers in this region, it is concluded that the gradient location is not anomalous with respect to bedrock hardness (Figures 5 through 8, taken from Dominion, 2004b). The fall zones along the rivers occur in Jurassic igneous and Paleozoic metamorphic rocks east of the basin, and not within the Triassic basin sediments.

On the Rappahannock River, the fall zone that Weems (1998) associates with the Central Piedmont Fall Line occurs about 1 km west of the eastern Culpeper basin boundary. Detailed profiles indicate that the western two-thirds of the fall zone is underlain by Jurassic diabase intrusive rocks, which crop out extensively in the eastern Culpeper basin (Figures 5 and 6). Based on these relations, the diabase is interpreted to be more resistant to erosion than the basin sediments, and that it is acting as a bedrock "sill", which controls the base level of erosion in the basin to the west. Because rivers erode headward, the Rappahannock is only able to incise its channel in the basin as rapidly as it can erode through the diabase along its eastern (downstream) margin. If the Triassic basin sediments are softer and less resistant to erosion than the diabase, then the river will tend to cut laterally back and forth in the basin upstream of the diabase, producing an area of low relief and low gradient upstream of the fall zone.

A detailed topographic and geologic profile reveals that the increased gradient along the Rapidan River as it exits the Culpeper Basin are associated with Paleozoic metamorphic rocks, not Triassic basin sediments as stated by Weems (1998) (Figure 7, taken from Dominion (2004b). It appears that the crystalline rocks act as "sills" to control the local base level of the river and promote lateral planation in the basin upstream. The observed increase in gradient as the Rapidan River leaves the basin can be explained without invoking down-to-the-east tectonic deformation along the Central Piedmont Fall Line.

Other geomorphic relations along the along the eastern margin of the Culpeper Basin are contrary to the interpretation of late Cenozoic east-side-down tectonic deformation along the Central Piedmont Fall Line. The eastern Culpeper basin is bordered by higher ridgelines and hills that form a broad, northwest-facing escarpment along the Mountain Run fault zone (Figure 8, taken from Dominion (2004b). Parts of this escarpment are recognized as the "Kelly's Ford scarp" and the "Mountain Run scarp." Elevations of the floor of the Culpeper basin, estimated from 1:24,000-scale topographic maps, range from about 290 ft to 320 ft. The elevations of the summit ridges and hills comprising the top of the escarpment directly east of the basin range from about 380 ft to 410 ft, indicating about 100 ft of down-to-the-west topographic relief across the Central Piedmont Fall Line. This is opposite to the east-side-down sense of tectonic displacement inferred by Weems (1998) to create the fall lines or gradient increases along Rapidan and Rappahannock Rivers as they exit the basin.

5. Summary

Based on a critical evaluation of Weems (1998), as well as an independent analysis of the Central Piedmont and Tidewater Fall Lines in northern Virginia, the "fall lines" described by Weems (1998) are not as well defined and laterally continuous as originally proposed, and in fact lack geomorphic expression typical of laterally continuous, tectonically active faults and folds. For example, if individual fall zones are created by down-to-the-east warping or fault displacement, then a more pronounced expression of warping or faulting should be preserved in the interfluves because continued incision along rivers would tend to eradicate the evidence of deformation. In general, however, down-to-the-east topographic escarpments are not observed along the proposed fall lines between rivers in the Piedmont and Blue Ridge provinces. In the specific example of the eastern Culpeper basin, the topographic escarpment faces west, opposite the direction predicted by Weems' (1998) tectonic model for formation of the fall zones (Figure 8). Although the local Culpeper basin escarpment is inconsistent with Weems' (1998) tectonic model, it is consistent with the differential erosion of the Triassic Culpeper Basin strata relative to the Paleozoic metamorphic and Jurassic igneous rocks to the east. Similarly, there is no east-facing escarpment expressed in the remnants of the late Pliocene marine sand along the Tidewater Fall Line (Figure 3), which would be expected if the fall zones on rivers like the Rappahannock are formed by localized east-side-down folding or faulting.

Based on the evaluation of stratigraphic, structural and geomorphic relations across and adjacent to the fall zones described by Weems (1998), it is concluded that:

1) Positive evidence is lacking for a neotectonic origin of individual fall zones;
2) Positive evidence exists for no Quaternary deformation across the "Tidewater Fall Line;"
3) Regional geomorphic relations provide indirect evidence for a lack of east-side-down deformation along the "Central Piedmont Fall Line" adjacent to Culpeper Basin; and
4) Differential erosion due to variable bedrock hardness appears to be a more plausible explanation for the formation of individual fall zones rather than Quaternary tectonics.

The above information from Dominion (2004b) summarizes the bases for interpreting the Fall Lines of Weems (1998) as erosional features, related to contrasting erosional resistances of adjacent rock types, and for concluding that they are not tectonic in origin.

c. The spatial relationship between the Mountain Run fault zone and the Culpeper basin is shown in FSAR Figure 2.5-10 (Map of Mesozoic Basins), FSAR Figure 2.5-16 (Regional Strip Maps Showing Tectonostratigraphic Divisions), and in the revised FSAR Figure 2.5-9. Section 2.5.1.1.4.4.5.2 will be revised to direct readers to these more appropriate figures.

   The relationship between the Mountain Run fault zone and the Culpeper basin is discussed explicitly in FSAR Section 2.5.1.1.4.4.3, Mesozoic Tectonic Structures, as part of the response to RAI 130, Question 02.05.01-43. The generally southeast-dipping Mountain Run fault zone extends southwestward for about 75 miles from the southeast end of the Culpeper basin to near Scottsdale, Virginia (Pavlides, 1994; Pavlides, 2000), with the northeast end of the Mountain Run fault zone forming the southeast boundary of the Culpeper basin. This geologic relationship as mapped by Mixon et al. (2000) is shown in FSAR Figure 2.5-9 in Enclosure 3.

d. The NRC question refers to an apparent inconsistency in the FSAR text regarding statements concerning the relationship between the Mountain Run fault zone and the Culpeper basin. FSAR Section 2.5.1.1.4.4.2.1 (Appalachian Structures), paragraph 6, stated, "In the site region, the Mesozoic Culpeper basin overlies the Mountain Run-Pleasant Grove fault system..." In contrast, FSAR Section 2.5.1.1.4.4.5.2 (Everona-Mountain Run Fault Zone), paragraph 1, stated, "The Mountain Run fault zone is located along the eastern margin of the Culpeper Basin..."

   As mapped by Hibbard et al. (2006) and Horton et al. (1991) at a regional scale (e.g., FSAR Figure 2.5-9) and by Mixon et al. (2000) at a more detailed scale (Figure 9), a portion of the southeast margin of the Culpeper basin is bounded by the northeast end of the Mountain Run fault zone. Farther northeast, the Mountain Run fault zone projects into unfaulted strata of the Culpeper basin, as the eastern margin of the basin trends more easterly than the Mountain Run fault. Also, the eastern and northeastern margins of the Culpeper basin are mapped as a depositional contact between basin strata and rocks of the Potomac terrane (Horton et al., 1991; Hibbard et al., 2006; Schlische, 2003) (FSAR Figure 2.5-9). This depositional contact at the northeastern end of the Culpeper basin also crosses the Pleasant Grove fault, the northeast continuation of the Mountain Run fault zone according to major lithotectonic boundaries (Hibbard et al., 2006). Based on these map relations, the Mountain Run fault zone locally bounds the Culpeper basin and locally is overlain by the continental deposits of the Culpeper basin.

The FSAR text will be revised to clarify the key relationships and provide further discussion. Section 2.5.1.1.4.4.2.1 will be modified to remove the statement about the relationship between the Mountain Run fault zone and the Culpeper basin. FSAR Section 2.5.1.1.4.4.3 (Mesozoic Tectonic Structures) will be modified to include a description of the local fault relationship between the Mountain Run fault zone and the margin of the Culpeper basin. FSAR Section 2.5.1.1.4.4.5.2 will be revised to focus on the evidence concerning the presence or absence of Quaternary tectonic activity on the Mountain Run fault zone.

e. The NRC highlights an apparent contradiction in the FSAR text concerning the geomorphic expression of the Mountain Run fault zone. The FSAR text in Section 2.5.1.1.4.4.5.2, paragraph 3, describes the geomorphic expression of the Kelly's Ford and Mountain Run scarps as presented by Pavlides (1994; 2000). Although Pavlides (1994; 2000) argued that the geomorphic expression reflected late Cenozoic, and possibly Quaternary, tectonic activity, more recent studies by Dominion (2004a) for the North Anna ESP concluded that the Kelly's Ford and Mountain Run scarps were more likely formed by differential erosion only and not by neotectonic activity.

   The FSAR will be revised to more clearly distinguish between the observation that the Kelly's Ford and Mountain Run scarps are geomorphically distinctive lineaments and the interpretation that the scarps are probably formed by differential erosion only as argued by Dominion (2004a), and not related to neotectonic activity as suggested by Pavlides (1994; 2000).

f. The relationship between the Everona fault and the Mountain Run fault zone is presented in the response to RAI 130, Question 02.05.01-41. As explained in the response to that question, the Everona fault is an informal name given by Crone and Wheeler (2000) to a fault exposed at a single location near the town of Everona, Virginia. This northwest-dipping fault that was exposed in a temporary cut and documented first by Pavlides et al. (1983) is located within the generally southeast-dipping Mountain Run fault zone. The location of the Everona fault exposure relative to the surrounding Mountain Run fault zone and simplified tectonostratigraphic units are shown in Figure 9 (revised FSAR Figure 2.5-9 in Enclosure 3). As shown on this map from Mixon et al. (2000) and described by Pavlides et al. (1989), the Mountain Run fault zone dips southeast and is developed primarily within mélange rocks of the Potomac terrane (including the Mine Run Formation) of the Piedmont province, although locally the zone of shearing extends across the tectonostratigraphic terrane boundary and involves the continental margin-affiliated True Blue Formation strata. The fault exposed near Everona offsets saprolitized phyllite of the True Blue Formation (Blue Ridge province)

(Pavlides, 1994), and plots at or near the northwest margin of the Mountain Run fault zone (Figure 9).

The NRC noted that the FSAR text states, "The Everona fault is located about 0.5 mi (0.8 km) west of the Mountain Run fault zone." Given the relationships shown by Mixon et al. (2000) and the discussion of Pavlides (1994), this statement should be revised. A more specific clarification is that the Everona fault exposure is located near the northwestern boundary of the Mountain Run fault zone, and is about 0.4 mi (0.6 km) northwest of the Mountain Run scarp, as mapped by Mixon et al. (2000) and as discussed by Pavlides (1994). The FSAR text will be revised to clarify the spatial relationship between the Everona fault exposure, the Mountain Run fault zone, and the Mountain Run scarp.

g. The nomenclature for the Everona fault exposure and the Mountain Run fault zone is discussed in the response to RAI 130, Question 02.05.01-41, and has been discussed briefly above within part (f.) of the response to this RAI question. The relevant FSAR sections will be modified to provide the FSAR text with clear distinction and definitions of the Everona fault (Pavlides et al., 1983; Crone and Wheeler, 2000), the scarps identified within the Mountain Run fault zone by Pavlides (1986; 1994; 2000), and the Mountain Run fault zone.

The RAI also refers to the FSAR text that concludes the "Everona-Mountain Run" fault zone is not a capable tectonic source based on the findings by Dominion (2004a) and the NRC (2005) for the North Anna ESP application. In this question, the NRC points out that the work done for the North Anna ESP by Dominion (2004a) specifically addresses the Mountain Run and Kelly's Ford scarps that are within the Mountain Run fault zone. The work by Dominion (2004a) does not address the fault exposed near the town of Everona, Virginia, informally named the Everona fault by Crone and Wheeler (2000). The specific information available regarding the Everona fault exposure is discussed in more detail below.

The Everona fault was exposed in a temporary cut near the town of Everona, Virginia and characterized in a meetings abstract as a northward-dipping, south-southwestward directed fault that offset a basal debris flow gravel layer, underlying saprolite, and overlying solum (e.g., the upper part of the soil profile)(Pavlides et al., 1983). Pavlides et al. (1983) characterized the age of the offset as "no older than late Tertiary" based on unweathered greenstone cobbles, and estimated the amount of displacement of the basal gravel-saprolite contact to be about 1.5 meters (4.9 feet). Since the initial abstract, the fault exposure near Everona has been mentioned only briefly in seven publications (Pavlides, 1986; Prowell, 1988; Manspeizer et al., 1989; Pavlides, 1994; Crone and Wheeler, 2000; Wheeler, 2006; Bobyarchick, 2007). These publications differ slightly on the stated age of the basal gravel layer, which vary from "Pleistocene (?)" or "post-Pliocene" to "Late Tertiary." Also, there is some ambiguity about the orientation of the fault, although the clearest statement comes from Crone and Wheeler (2000) who state the fault strikes N55°E and dips 55°NW at the base of the exposure.

From a review of the available published data, no new work has been published on the Everona fault since the initial exposure and its documentation in the 1983 abstract by Pavlides et al. (1983). Subsequent descriptions of the fault in the literature refer to the same exposure. This suspicion was confirmed by interviews with experts (including W. Newell, M. Pavich, coauthors of the original investigation), who stated that no new work had been performed on the Everona fault since the documentation of the original exposure.

In an attempt to review the Everona fault exposure for the CCNPP Unit 3 COL application, the site was visited on October 23, 2006 as directed by one of the original coauthors of the abstract (M. Pavich, U.S.G.S., personal communication to S. Thompson, October 20, 2006). As described by M. Pavich, the site is occupied by a horticultural nursery near Road 627 directly southwest of Everona that has been in continuous operation since about 1983. As suspected by M. Pavich, the original exposure was covered by construction of greenhouses and/or other structures related to the nursery. Additional reconnaissance on the grounds of the nursery did not reveal any natural exposures of significance, and no evidence of faulting, either through geomorphic expression or direct exposure, was encountered.

Figure 10 shows the site of the Everona fault exposure in a series of three panels in an attempt to document the location of the exposure as precisely as possible and understand its location relative to the Mountain Run fault zone and Mountain Run scarp. Panel A) shows an aerial photo view of the Everona area and the nursery footprint near the time of the field visit (October 29, 2006 aerial photograph) The image in panel A) also shows the approximate channel of Mountain Run and the approximate location of the Mountain Run scarp according to Pavlides (1994) and Mixon et al. (2000). Small numbered orange dots in the image represent GPS waypoints collected during the field reconnaissance. Panel B) shows the same area in a November 25, 1982 Landsat™ multispectral satellite image. The low-resolution Landsat™ image shows a rectangular area with very bright reflectance relative to the surrounding cultivated areas that corresponds to the eastern end of the modern facility. The bright rectangle is interpreted to represent the site of the nursery in late 1982, which may include existing facilities and/or areas excavated for the nursery. The area of this high-reflectance rectangle probably includes the Everona fault exposure documented by Pavlides et al. (1983). In panel B), a symbol is approximately located for a fault exposure with a N55°E strike and 55°NW dip (this orientation follows the description of Crone and Wheeler (2000)). Panel B) also shows the approximate locations of the Mountain Run channel and the Mountain Run scarp of Pavlides (1994) and Mixon et al., 2000).

Panel C) of Figure 10 shows the portion of the Mixon et al. (2000) geologic map that coincides with the image extent in panels A) and B). Figure 11 shows a portion of the map explanation from Mixon et al. (2000) for interpreting map units and symbols. The map in panel C) shows the approximate location and extent of the nursery footprints circa 1982 and 2006, and shows the approximate location and orientation of the fault exposure as in Panel B). The map clearly shows that the exposure is located within or near the northwest margin of the Mountain Run fault zone as mapped by Mixon et al. (2000), and that the fault exposure is inferred to be located within the True Blue formation that is affiliated with the Blue Ridge province. The dotted line within the alluvium-filled valley of Mountain Run presumably coincides with a concealed fault boundary that separates the True Blue formation to the northwest and the mélange of the Mine Run Complex (Piedmont province) to the southeast. From the descriptions of Pavlides (1994) and Pavlides (2000), the Mountain Run scarp is plotted to coincide with the southeast margin of the Quaternary alluvium within the Mountain Run. Figure 10 shows the Everona fault to be about 0.4 miles (about 2000 feet) northwest of the Mountain Run scarp.

Based on the available published data, the field reconnaissance, and discussions with experts, there are no significant new data regarding the fault exposure near Everona since the original abstract published by Pavlides et al. (1983). In addition, as described by Crone and Wheeler (2000), no geomorphic expression is associated with the Everona fault. The basic information regarding the Everona fault exposure was available to the EPRI teams for their consideration in the EPRI model. The publications that have mentioned the Everona fault exposure since 1986 have reported the orientation of the fault, the measured displacement, and the approximate timing of displacement based on the same original information. There is no published information to suggest the fault has been mapped along strike from the initial exposure. Thus, no revision to the EPRI model is recommended to account for the Everona fault. The FSAR text will be revised to clarify the discussion of the Everona fault.

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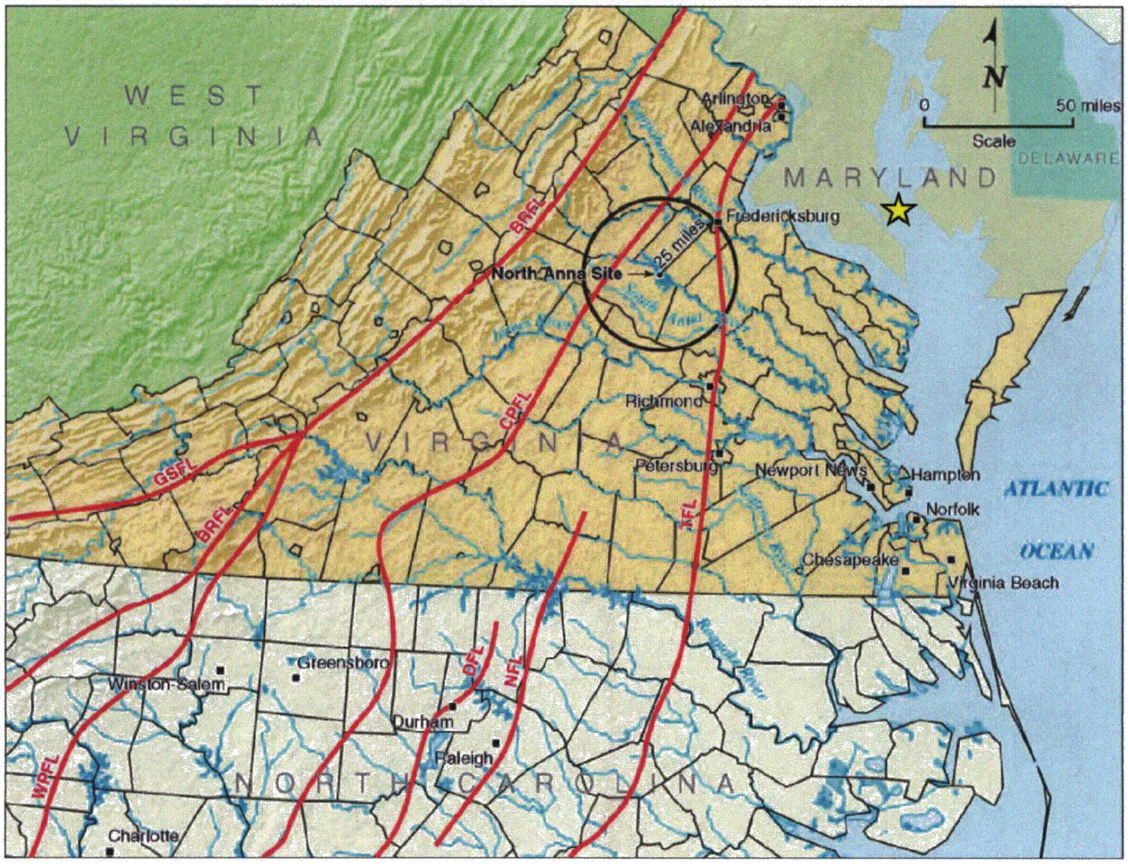
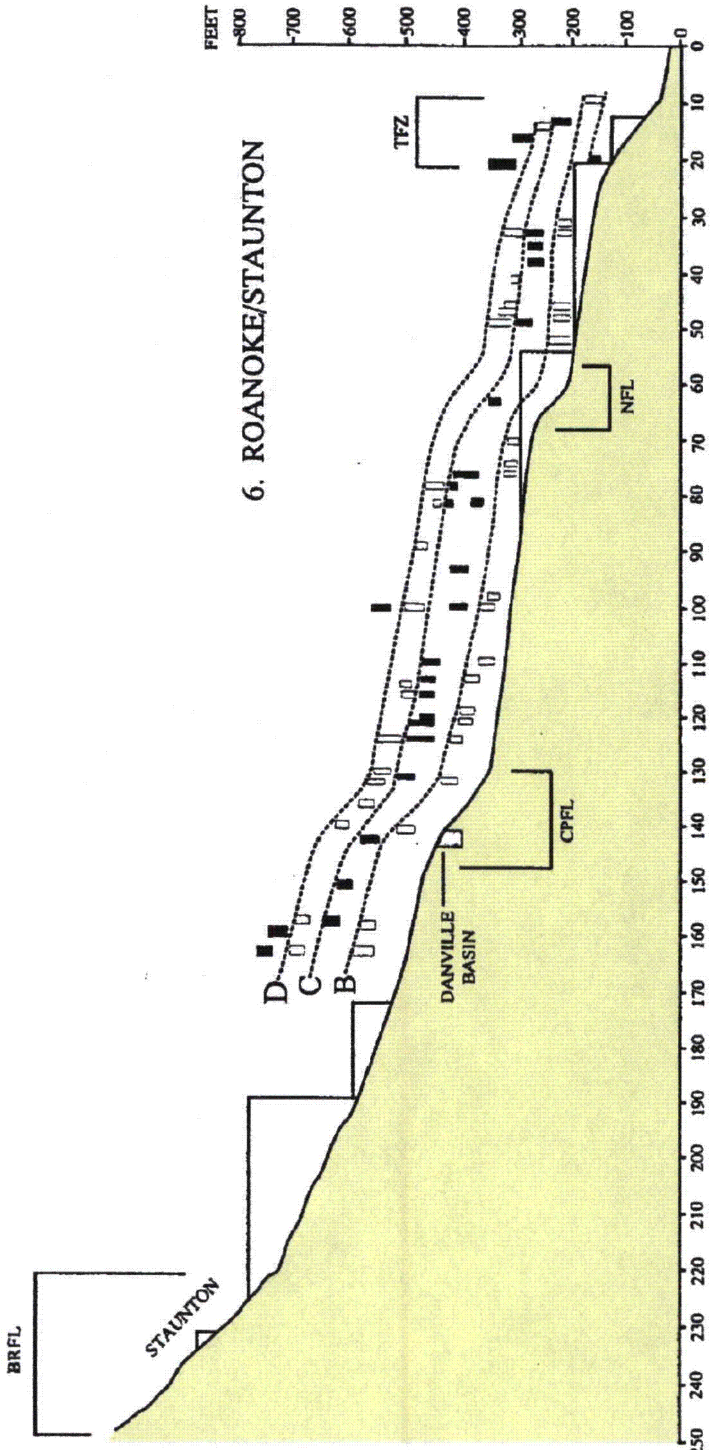
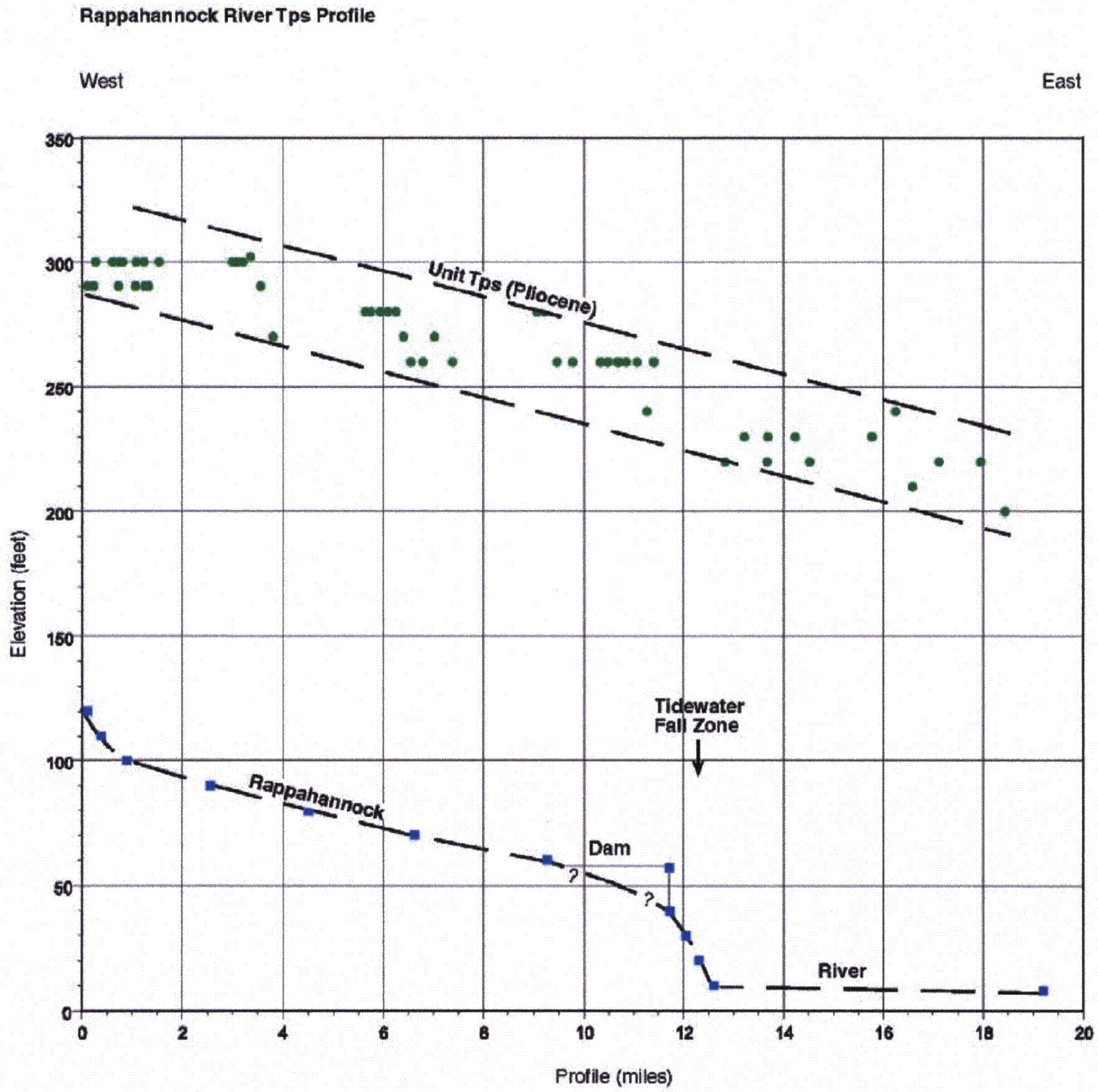


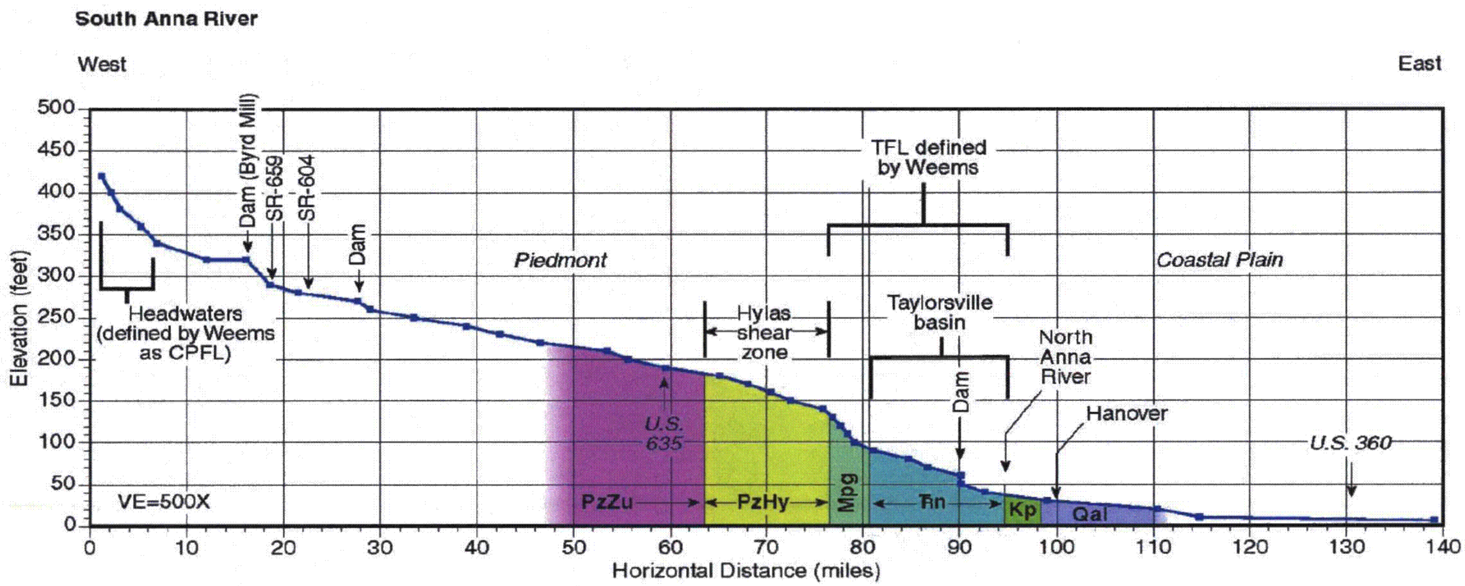

**Question 02.05.01-51 Figure 1 – Approximate locations of fall lines proposed by Weems (1998). From east to west the fall lines include the Tidewater Fall Line (TFL), Nutbush Fall Line (NFL), Durham Fall Line (DFL), Central Piedmont Fall Line (CPFL), Western Piedmont Fall Line (WPFL), Blue Ridge Fall Line (BRFL), and the Great Smokey Fall Line (GSFL). The location of the CCNPP, Unit 3, is shown as a yellow star. Modified from Dominion (2004b).**




**Question 02.05.01-51 Figure 2 – Profiles of three late Cenozoic terraces (B, C, and D) of the Roanoke River (from Weems, 1998). BRFL = Blue Ridge Fall Line; CPFL = Central Piedmont Fall Line; NFL = Nutbush Fall Line; TFZ = Tidal Fall Zone. Reproduced from Dominion (2004b)**



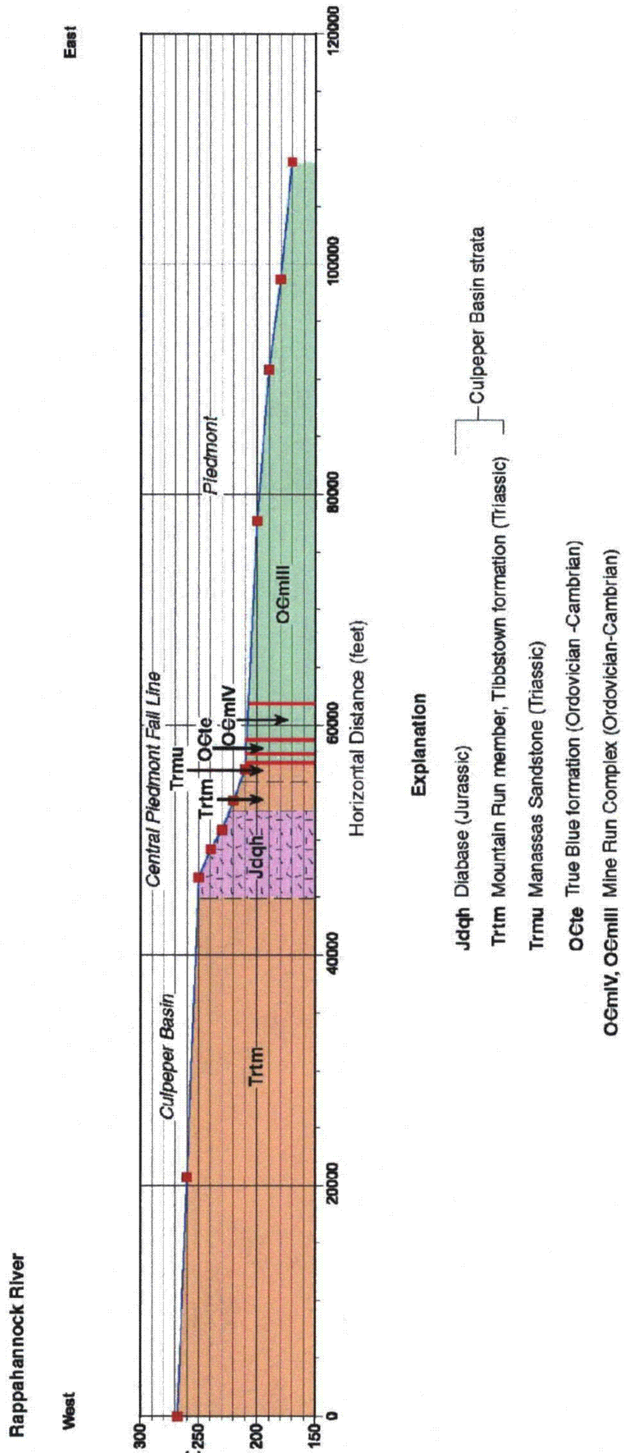

**Question 02.05.01-51 Figure 3 – Longitudinal profiles of the Rappahannock River and the Pliocene Tps unit across the Tidewater fall line at Fredericksburg. The Tps surface has a constant gradient and extends across the fall zone in the river without obvious east-down deflection. Reproduced from Dominion (2004b).**




**Explanation**

| | |
|---|---|
| **Qal** | Pleistocene terrace deposits and Holocene alluvium |
| **Kp** | Potomac formation (Cretaceous) |
| **Ћn** | Newark supergroup, undivided; deposits of the Taylorsville Basin (Triassic) |
| **PzHy** | Petersburg Granite (Mesozoic) |
| **Mpg** | Hylas Zone Clastic Rock (Paleozoic) |
| **PzZu** | Metasedimentary and metaigneous rocks, undifferentiated (Paleozoic) |

**Question 02.05.01-51 Figure 4 – Longitudinal profile of the South Anna River across the Central Piedmont Fall Line (CPFL) and Tidewater Fall Line (TFL) of Weems (1998). Geology from Mixon et al. (1989). Reproduced from Dominion (2004b).**




**Question 02.05.01-51 Figure 5 – Longitudinal profile of Rappahannock River across eastern Culpeper Basin margin showing faults in red. Geology from Mixon et al. (2000). Reproduced from Dominion (2004b).**

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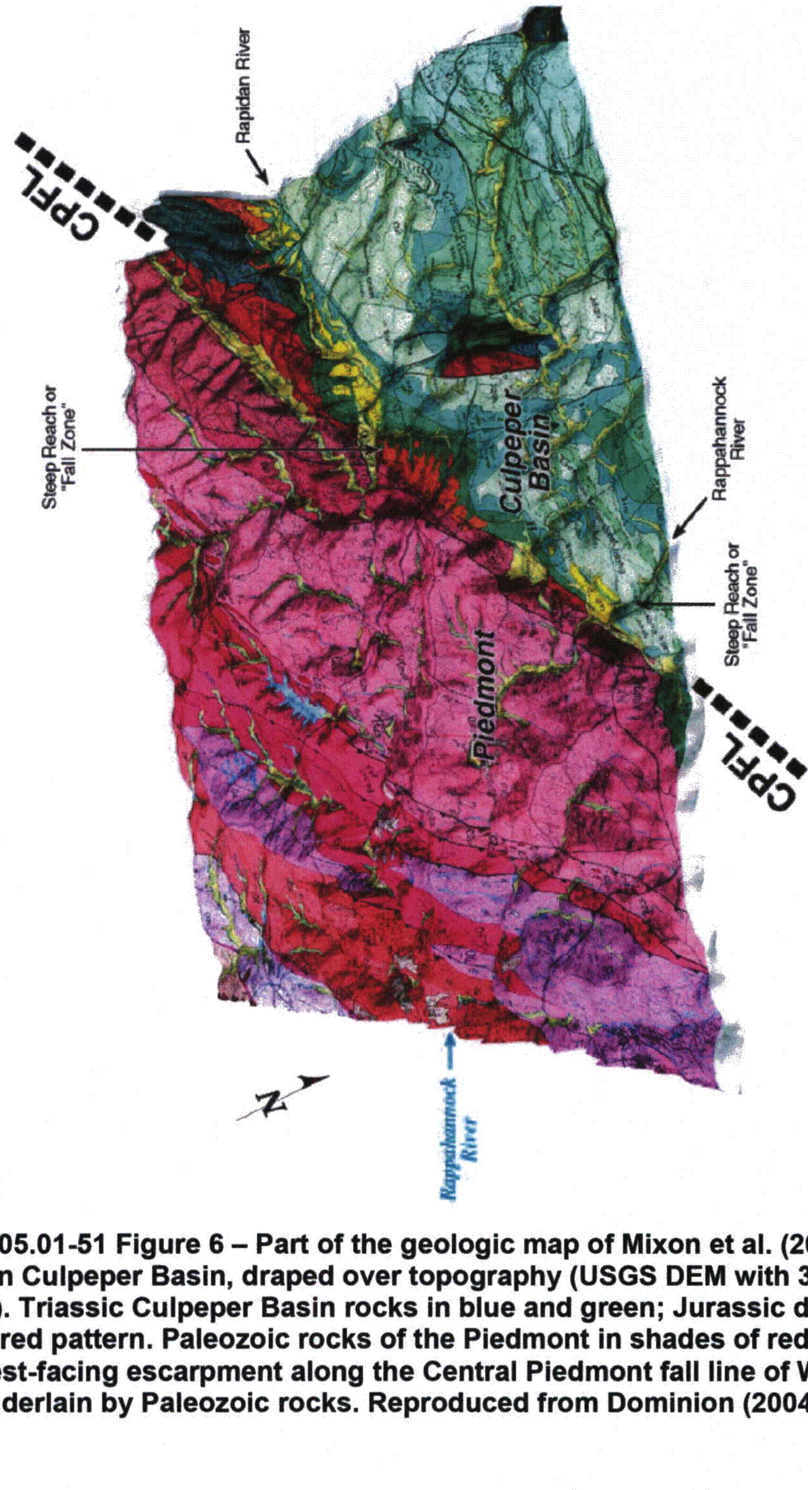
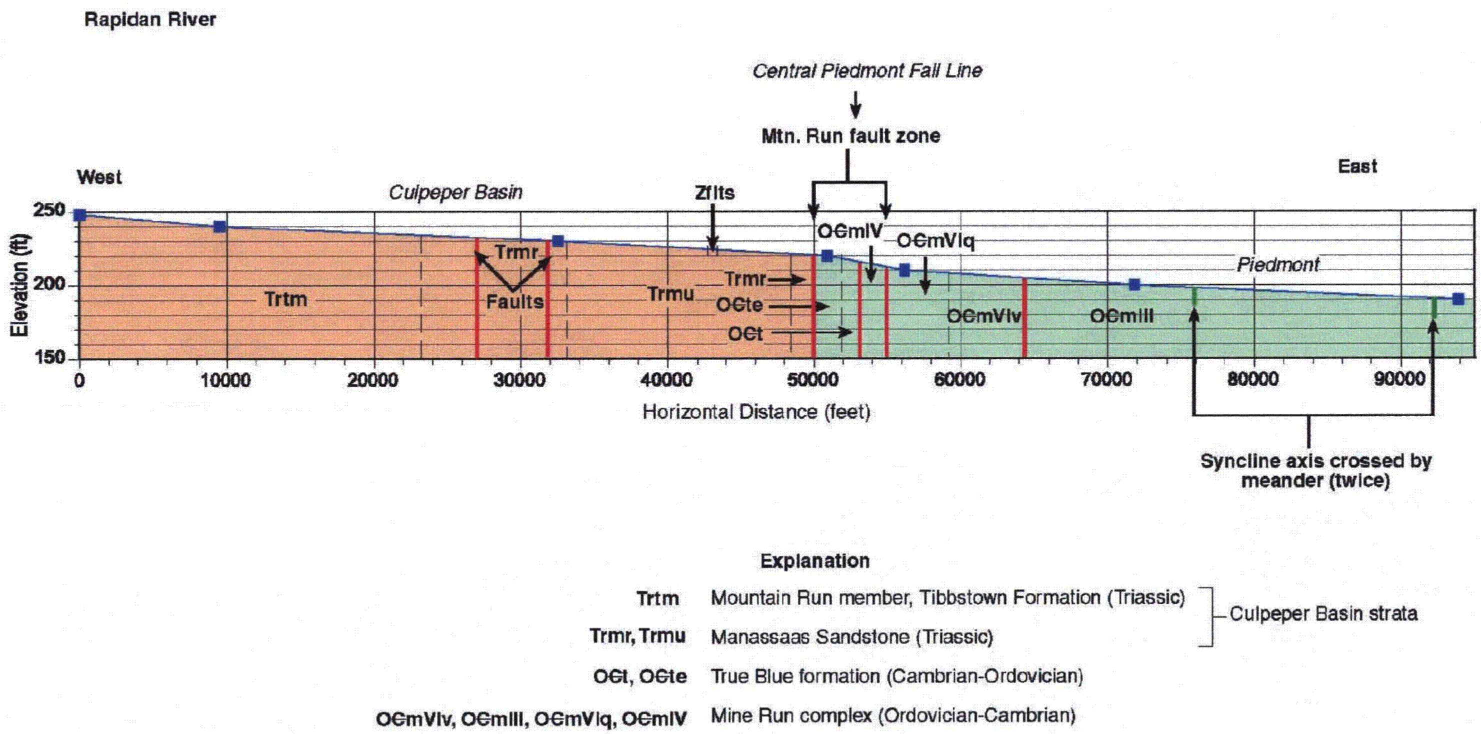
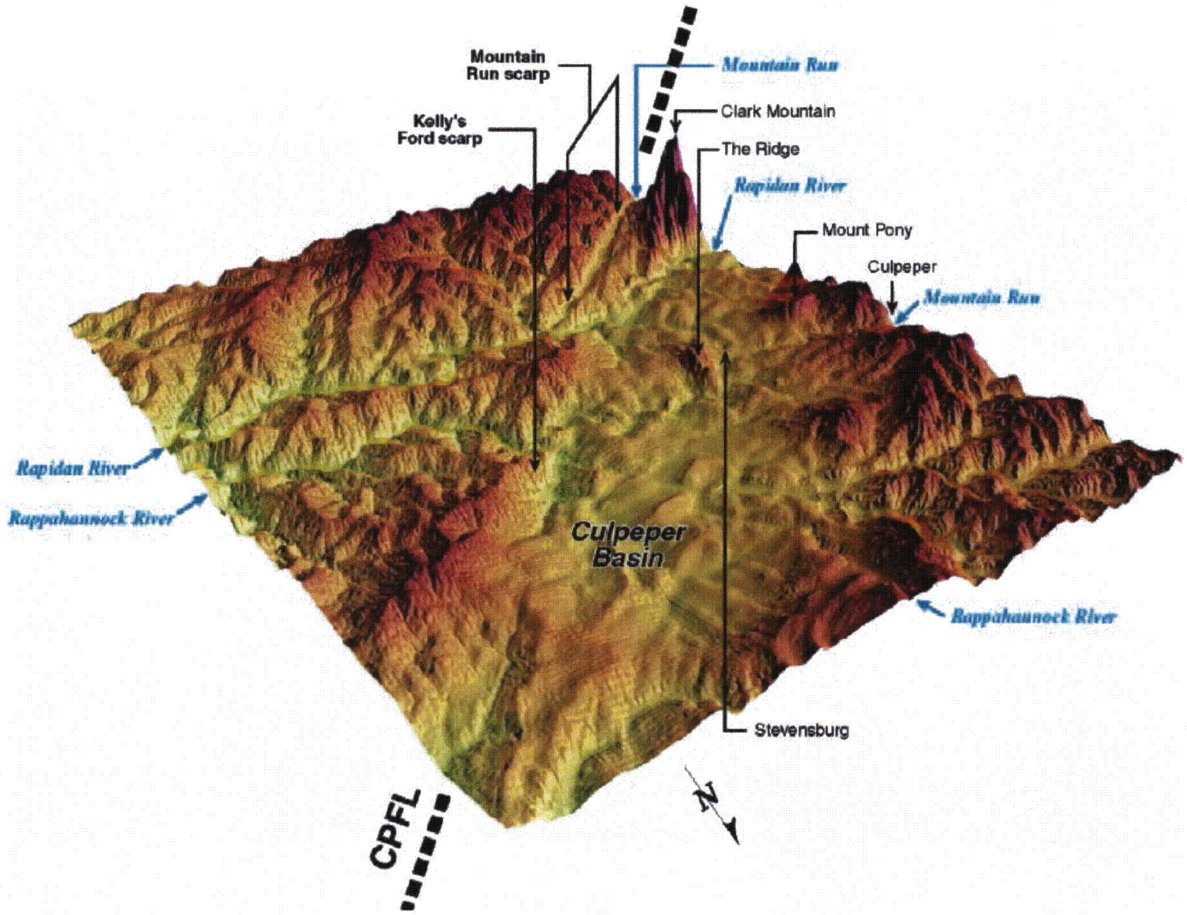


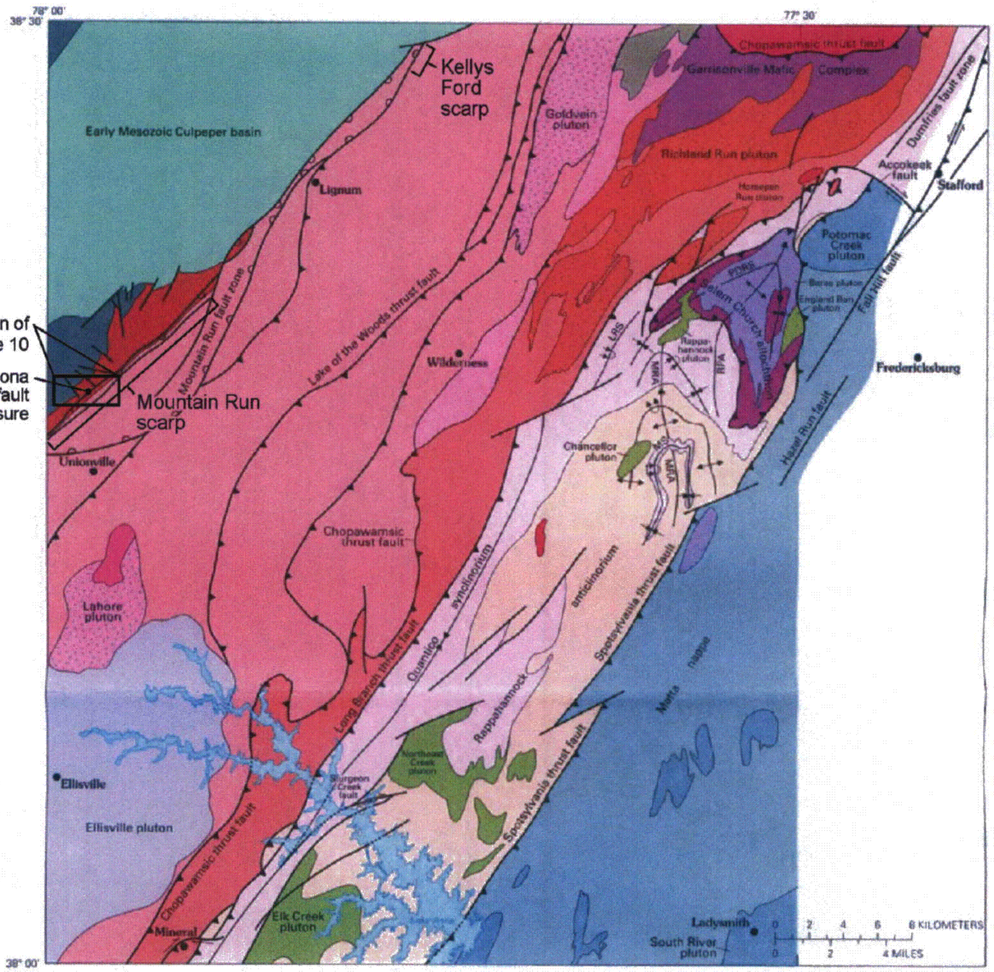

**Question 02.05.01-51 Figure 6 – Part of the geologic map of Mixon et al. (2000) covering the eastern Culpeper Basin, draped over topography (USGS DEM with 30x vertical exaggeration). Triassic Culpeper Basin rocks in blue and green; Jurassic diabase is light bluish with red pattern. Paleozoic rocks of the Piedmont in shades of red and purple. Note northwest-facing escarpment along the Central Piedmont fall line of Weems (1998), underlain by Paleozoic rocks. Reproduced from Dominion (2004b).**

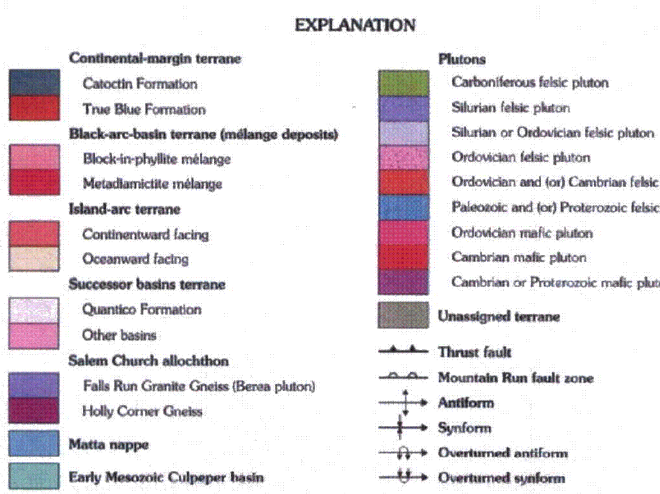



**Question 02.05.01-51 Figure 7 – Longitudinal profile of Rapidan River across eastern Culpeper Basin margin showing faults in red and fold axes in green. Geology from Mixon et al. (2000). Reproduced from Dominion (2004b).**



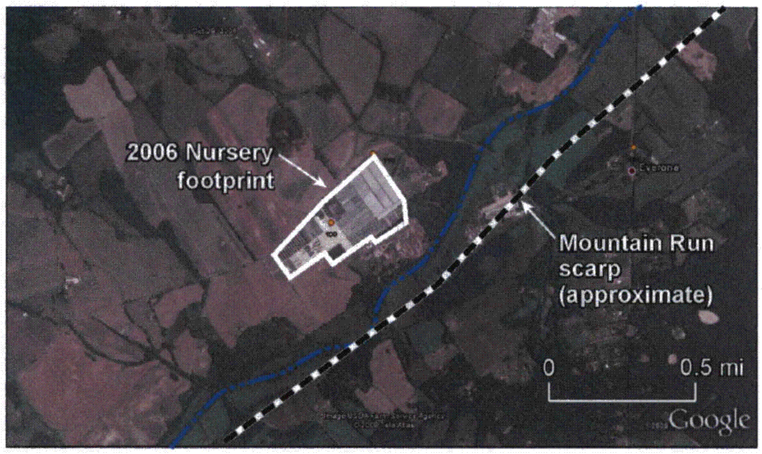

**Question 02.05.01-51 Figure 8 – Oblique view to the southeast of topography (USGS DEM with 30x vertical exaggeration) along the Culpeper Piedmont Fall Line (CPFL) of Weems (1998), at the latitude of Culpeper Basin. Not the broad, northwest-facing topographic escarpment along the fall line. Reproduced from Dominion (2004b).**



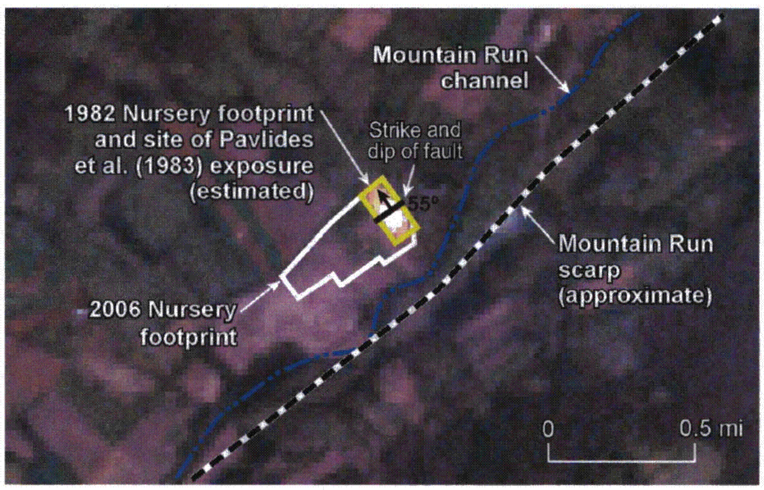




Notes:
1. Modified from Mixon et al. (2000).
2. The Mountain Run fault zone is in the northwest portion of the map and separates mélange deposits of the Piedmont province against continental margin rocks of the Blue Ridge province and strata of the Early Mesozoic Culpeper basin.
3. The Everona fault exposure, Mountain Run scarp, and Kellys Ford scarp are indicated.

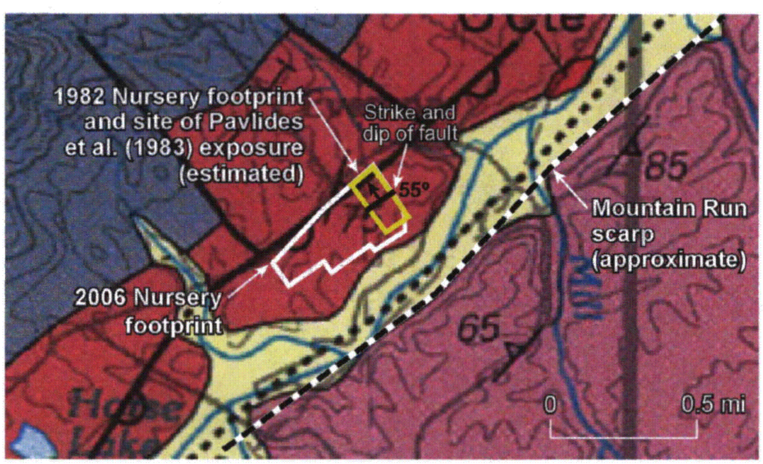
**Question 02.05.01-51 Figure 9 – Simplified tectonostratigraphic map of the Fredericksburg 30' x 60' Quadrangle map by Mixon et al. (2000). Reproduced from Dominion (2004b)**




A) October 29, 2006 (Google Earth)

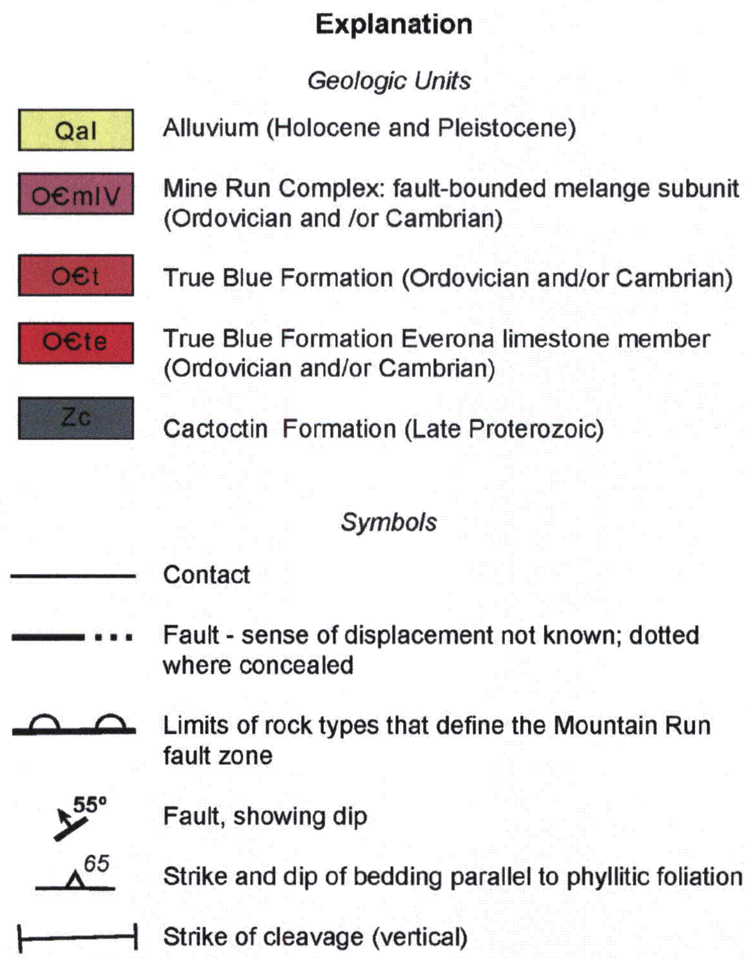



B) November 25, 1982 (Landsat TM scene L4016033_03319821125)




C) Geologic Map (Mixon et al., 2000). See Figure 11 for map explanation.

**Question 02.05.01-51 Figure 10 – Aerial photograph, satellite image, and geologic map of the Everona fault exposure site, 1982 to 2006.**




Note: Map units and symbols from Mixon et al. (2000)

**Question 02.05.01-51 Figure 11 – Explanation to accompany the map in Figure 10 C), based on Mixon et al. (2000).**

## COLA Impact

FSAR Section 2.5.1.1.4.4.5, Quaternary Tectonic Features, will be revised as shown in Enclosure 3 in a future revision of the COLA.

**Question 02.05.01-52**

The following requests pertain to CCNPP Unit 3 FSAR Section 2.5.1.1.4.4.4, Tertiary Tectonic Structures and 2.5.1.1.4.4.5, Quaternary Tectonic Features.

a. In CCNPP Unit 3 FSAR Section 2.5.1.1.4.4.5.3, Stafford Fault of Mixon, et al. the text states: "No new significant information has been developed since 1986 regarding the activity of the Stafford fault system with the exception of the response to an NRC RAI for the North Anna ESP (Dominion, 2004a)." The statement above appears to contradict the statements about this fault on p. 2.5-46 that describe ages of movement based on Mixon's 2000 work on various individual faults of this system. Please resolve the apparent discrepancy.

b. FSAR Section 2.5.1.1.4.4.5.4 describes the structural and neotectonic aspects of the Ramapo Fault System. There are many newer papers that describe structural/neotectonic investigations as well as analysis of emerging seismic patterns. Please provide more details about the history of associated seismicity, including a review of the scientific literature for this section such as: Sykes et al, 2008, Bulletin SSA, vol 98, no 4, pp 1696-1719; Withjack et al, 1998 (this FSAR); Schlische, 2003, (this FSAR); Schlische and Withjack, 2005, GSA Bulletin, v. 117, no. 5/6, pp 823-832. Also, please provide more detailed figures than are currently provided in Figures 2.5-10 and 2.5-31.

c. In FSAR Section 2.5.1.1.4.4.5.6, New York Bight Fault, the text (p 2.5-60) states, "Seismic reflection profiles indicate that the fault originated during the Cretaceous and continued intermittently with activity until at least the Eocene." Benson, 1992 shows a fault on the seaward side of a continental shelf Mesozoic basin, named the New York Bight basin. He cites Hutchinson et al, 1986. Please expand the discussion on this fault to include the geologic and tectonic setting. Please explain how the seismic reflection information suggests movement on a fault from Cretaceous through Eocene.

d. In FSAR Section 2.5.1.1.4.4.5.7, Cacoosing Valley Earthquake Sequence, the text states, "Focal mechanisms associated with the main shock and aftershocks define a shallow subsurface rupture plane confined to the upper 1.5 mi (2.4 km) of the crust." Please describe the orientations of the nodal planes and the interpreted fault movement type.

e. In FSAR Section 2.5.1.1.4.4.5.8, New Castle County Faults, the text states, "The New Castle faults are characterized as 3 to 4 mi (4.8 to 6.4 km) long buried north and northeast-striking faults that displace an unconformable contact between Precambrian (PC) to Paleozoic (Pz) bedrock and overlying Cretaceous deposits." Please clarify the meaning of this statement. Does the fault offset PC and Pz rock or does the fault penetrate up to and including Cretaceous layers?

f. In FSAR Section 2.5.1.1.4.4.5.8, the text also states, "On the basis of geophysical and borehole data, coupled with Vibroseis™ profiles, Spolijaric (Spolijaric, 1973) (Spolojaric, 1974) interprets a 1 mi (1.6 km) wide, N25°E-trending graben in basement rock. The graben is bounded by faults having displacements on the order of 32 to 98 ft (10 to 30 m) across the basement-Cretaceous boundary (Spoljaric, 1972)." Please provide more details and figures for this discussion that show the surface projection (map) of the graben structure. Include the Delaware Geo Survey infomation: seismic lines, trench locations and trench cross sections.

g. In FSAR Section 2.5.1.1.4.4.5.14, East Coast Fault System, the following statement is made about the East Coast Fault Zone and the Charleston source (page 2.5-64): "A review of the seismic sources that contribute 99% of the seismic hazard to the CCNPP shows that the Charleston source is not a contributor." This statement seems to be contradicted by another statement in FSAR Section 2.5.2.2 (page 2.5-99), which reads: "Although the Charleston source lies outside the site region (200-mi radius), a preliminary sensitivity analysis performed for the CCNPP Unit 3 site shows that this source is a significant contributor of low frequency (1 Hz) ground motion, and thus the Charleston source has been included in the PSHA study for the site." Please clarify the apparent contradiction between these two statements and revise the FSAR accordingly.

**Response**

a. The apparent inconsistency noted in this RAI question appears to be due to confusion regarding the scientific research presented within Mixon et al. (2000). The map and accompanying text of Mixon et al. (2000) is not a presentation of original research and results but is primarily a compilation of previously published research and related conclusions on the Stafford fault. As such, the publication year of 2000 does not represent the publication date of the original work that is synthesized within Mixon et al. (2000). For example, the majority of the work summarized within Mixon et al. (2000) related to the Stafford fault was originally published in the 1970s and 1980s (e.g., Mixon and Newell, 1977, 1978; Newell et al., 1976). Mixon et al. (2000) is referenced throughout FSAR Section 2.5.1 because it provides a good summary of these earlier studies. Also, in some sections of the FSAR where activity on the Stafford fault is discussed (e.g., third paragraph of Section 2.5.1.1.4.4.4.1) references are provided to the summary work of Mixon et al. (2000) and the original work of Mixon and Newell (1978). Therefore, there is no contradiction or inconsistency in the statement made within FSAR Section 2.5.1.1.4.4.5.3 that, "No new significant information has been developed since 1986 regarding the activity of the Stafford fault system with the exception of the response to an NRC RAI for the North Anna ESP."

b. The most recent, comprehensive, and up-to-date discussion of seismicity within the region surrounding the Ramapo fault zone is that of Sykes et al. (2008). The work of Sykes et al. (2008) was not available during development of the CCNPP FSAR, but much of the work upon which Sykes et al. (2008) expanded upon was available and was reviewed as part of the FSAR preparation (e.g., Kafka et al., 1985; Kim, 1998; Nottis, 1983; Nottis and Mitronovas, 1983; Sbar et al., 1970; Seeber and Armbruster, 1986, 1988, 1991; Seeber et al., 1993; Yang and Aggarwall, 1981). Subsequent to its publication in late 2008, the Sykes et al. (2008) paper was reviewed for the CCNPP site, and it was concluded that the paper does not contain any information that requires revisions to the conclusions within the FSAR regarding the Ramapo fault.

The Sykes et al. (2008) paper is essentially a compilation that presents a: (1) seismicity catalog for the greater New York-Philadelphia area that is slightly updated from previous studies, and (2) discussion of the tectonic setting of the microseismicity (Figure 1). The portion of the paper that is relevant to the Ramapo fault zone is Sykes et al.'s (2008) discussion of the Ramapo Seismic Zone (RSZ). The RSZ was identified before the EPRI-SOG study (EPRI, 1986-1989) as a region with an apparent increased rate of seismicity west of the Ramapo fault in northern New Jersey and southern New York (Aggarwal and Sykes, 1978; Ratcliffe, 1971, 1980). As discussed in FSAR Section 2.5.1.1.4.4.5.4, earthquakes within the RSZ were originally used to support the hypothesis that the Ramapo fault was an active structure (Aggarwal and Sykes, 1978), but subsequent studies conclusively demonstrated that the Ramapo fault has not been active since the Jurassic (Ratcliffe, 1980; Ratcliffe and Burton, 1984; Ratcliffe et al., 1990; Stone and Ratcliffe, 1984). Sykes et al. (2008) describe the RSZ as a zone approximately 7.5 mi (12 km) wide, extending to depths of 9.3 mi (15 km), and trending northeast for approximately 80 mi (130 km) from northern New Jersey to southern New York (Figure 2). The instrumentally located earthquakes within the RSZ have magnitudes less than mb 3.0 (Sykes et al., 2008). The only earthquake with mb > 3.0 is the historical mb 4.3 earthquake of 30 October 1783 (Figure 1). However, uncertainty in the location of this earthquake is thought to be as much as 100 km (62 mi) (Sykes et al., 2008) raising significant suspicion as to whether the event occurred within the RSZ.

Earthquakes within the RSZ occur within the highly deformed middle Proterozoic to early Paleozoic rocks to the west of the Mesozoic Newark basin (Sykes et al., 2008). Sykes et al. (2008) ambiguously hypothesize that this seismicity indicates that, "... more than one fault, likely many, must be involved in generating its earthquakes...," suggesting that there are many active faults within the RSZ that are causing the observed seismicity. However, neither Sykes et al. (2008), nor any other researcher (e.g., Kafka et al., 1985; Ratcliffe, 1980; Ratcliffe and Burton, 1984; Ratcliffe et al., 1990; Stone and Ratcliffe, 1984; Wheeler, 2005, 2006, 2008; Wheeler and Crone, 2001), have identified distinct faults on which they believe the earthquakes may be occurring.

The other papers cited within the RAI question do not discuss the topic of seismicity related to the Ramapo fault zone, but instead they discuss the broad-scale tectonic history of the Atlantic margin as related to the formation of Mesozoic basins during the opening of the Atlantic Ocean (e.g., Schlische, 2003, 2005; Withjack et al., 1998). This evolution of the Atlantic margin is discussed in detail in FSAR Sections 2.5.1.1.2.7 and 2.5.1.1.4.1.2. The papers cited within the RAI question do not directly discuss potential Quaternary activity of the Ramapo fault, but the papers do generically discuss border faults located along the west side of Atlantic margin Mesozoic basins, such as the Newark Basin (see Response to RAI 130, Question 02.05.01-43). The northernmost border fault of the Newark basin is the Ramapo fault. This indirect discussion of the Ramapo fault is the only association of these papers with the fault. The discussion of basin bounding faults primarily focuses on two aspects: (1) whether the border faults were syn- or post-depositional (Schlische, 2003, 2005), and (2) the history of reactivation of some border faults as reverse and strike-slip faults (Schlische, 2005; Withjack et al., 1998). These general topics are discussed in FSAR Section 2.5.1.1.4.1.2. Importantly, the papers cited within this RAI question (Schlische, 2003, 2005; Withjack et al., 1998) present no information regarding the absence or presence of Quaternary on the boarder faults, and, therefore, have little relevance to the discussion of potential seismicity within the Ramapo fault zone or capability of the Ramapo fault.

c. The New York Bight fault is an approximately 31 mile (50 km) long north-northeast trending fault located offshore of Long Island, New York (Hutchinson and Grow, 1985) (FSAR Figure 2.5-31 and Figure 3 from the response to RAI 71, Question 02.05.01-24[10]). The near vertical fault exhibits down-to-the-west-displacement. It is unclear from existing geophysical data if the fault has normal or reverse motion (Hutchinson and Grow, 1985). Seismic reflection

[10] G. Gibson (UniStar Nuclear Energy) Letter UN#09-152 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated April 15, 2009.

profiles reveal as much as 357 ft (109 m) of displacement across the top of Paleozoic basement and as much as 236 ft (72 m) across reflectors of probable Eocene age (Figure 3 from the response to RAI 71, Question 02.05.01-24[11]). The age of the Eocene deposits was determined by correlation of the seismic profiles with nearby borehole data. A major unconformity separating Eocene and Miocene rocks overlying the fault is undeformed. No offsets in Quaternary sediments were interpreted by Hutchinson and Grow (1985) or Schwab et al. (1997a and 1997b). Therefore, the youngest recognized faulting is Eocene age but possibly as young as Oligocene. The age of the oldest displaced Cretaceous strata is more ambiguous but is tentatively correlated with the Upper Cretaceous Raritan Formation (Hutchinson and Grow, 1985).

The early Mesozoic rifting of Africa and North America produced numerous syn-rift basins along the east coast of North America (Schlische, 2003) (FSAR Section 2.5.1.1.4.1.2). The New York Bight basin is one such basin located immediately east of the New York Bight fault (Hutchinson et al., 1986) (FSAR Figure 2.5-10). The basin geometry is defined by a prominent magnetic high and a positive gravity anomaly immediately south of Long Island, New York (see FSAR Figures 2.5-20 and 2.5-21). On the basis of seismic reflection data, Hutchinson et al. (1986) interpret the basin to be structurally controlled by block faulting in the crystalline basement accompanied by syn-rift Mesozoic sedimentation. There is no evidence that the basin bounding faults in the crystalline basement extend into the overlying Cretaceous sediments.

The offshore coastal plain sediments displaced by the New York Bight fault were deposited along the passive continental margin following Mesozoic rifting. Although not explicitly stated in the published literature (Hutchinson and Grow, 1985 and Schwab et al. 1997a and 1997b), the association of the New York Bight fault along the western edge of the New York Bight basin suggests late Cretaceous through Eocene reactivation of the early Mesozoic basement fault. Similar reactivation has been recognized in other areas of the coastal plain (Schlische, 2003; Withjack et al. 1998). As summarized above, based on correlation of nearby bore hole data with seismic reflectors, the New York Bight fault is interpreted to offset deposits as young as Eocene; however the relationship between the early Mesozoic basin and post Mesozoic faulting remains unclear (Hutchinson and Grow, 1985).

d. The sequence of earthquakes occurring within the Cacoosing Valley near Reading, Pennsylvania, between 1993 and 1997 was studied in detail by Seeber et al. (1998). Seeber et al. (1998) determined a focal mechanism for the mainshock using broadband waveforms and estimated a composite focal mechanism for the mainshock using 41 early aftershocks. Seeber et al. (1998) state that the composite focal mechanism from aftershocks is also the best fit to the waveform data. Seeber et al. (1998) report the nodal planes of this focal mechanism as follows:

| | **Strike** | **Dip** | **Rake** |
|---|---|---|---|
| Plane 1 | 135 ° | 54 ° | 55 ° |
| Plane 2 | 5 ° | 48 ° | 128 ° |

[11] G. Gibson (UniStar Nuclear Energy) Letter UN#09-152 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated April 15, 2009.

Seeber et al. (1998) also report that the mainshock was characterized by predominantly reverse slip along the first nodal plane with a lesser component of left-lateral motion.

e. The New Castle County faults were identified by Spoljaric (1972; 1973) using offsets in structural contours for the top of the early Paleozoic Wilmington Complex crystalline basement (Figure 1b). As discussed in Section 2.5.1.1.4.5.8 Spoljaric (1972; 1973) states that there is no direct evidence that the faults extend into the overlying Cretaceous sediments.

f. As summarized in FSAR Section 2.5.1.1.4.4.5.8, the Delaware Geological Survey conducted a three stage study (McLaughlin et. al., 2002) to investigate the potential for near-surface extension of the basement faults hypothesized by Spoljaric (1972, 1973) in the vicinity of New Castle, Delaware (Figure 2a, FSAR Figure 2.5-31). The first phase of the McLaughlin et al. (2002) study was a seismic reflection and refraction survey (NCRS-1) conducted at a high angle to the hypothesized strike and surface projection of the New Castle County faults of Spoljaric (1972, 1973) (McLaughlin et al., 2002) (Figure 2a). The resulting seismic sections imaged bedded sediments within 1500 ft (457 m) of the ground surface that are interpreted as being disrupted by faulting (Figure 2c). The second phase of the study consisted of exploration drilling and down-hole geophysics to evaluate the inferred faults in the seismic reflection and refraction profiles. Borings were located above the upward projection of faults interpreted from the seismic data (Figure 2 a-c). Correlation of the geophysical logs failed to identify the shallow (< 500 ft depth) faulting interpreted from the McLaughlin et al. (2002) seismic study (Figure 2b). The final phase of the study included the excavation and documentation of five paleo-seismic trenches located in areas directly up dip of faults interpreted in the seismic survey (Figure 2a and b). The trenches exposed unfaulted and undeformed Cretaceous Potomac Formation indicating the absence of near-surface faulting associated with the New Castle faults (McLaughlin et al., 2002) (Figure 3-7). Based on these results the authors determined that shallow faulting is likely not present in the area.

g. The apparent contradiction noted in this RAI question is due to a lack of specificity in the FSAR statements quoted within this RAI question. The statements are intended to highlight the fact that as part of the original EPRI-SOG study (EPRI, 1989), the EPRI-SOG characterizations of the Charleston seismic zone (EPRI, 1986-1989) were determined to not contribute to the hazard at CCNPP Units 1 and 2. In contrast, as part of the CCNPP Unit 3 FSAR efforts, sensitivity studies demonstrated that the updated Charleston source characterization does contribute to the site hazard. This difference is not a contradiction because the two source models for the Charleston seismic zone (the EPRI-SOG and updated) are different (see FSAR Section 2.5.2.2.2.7 for additional details). The FSAR text will be modified to clarify this issue.

References:

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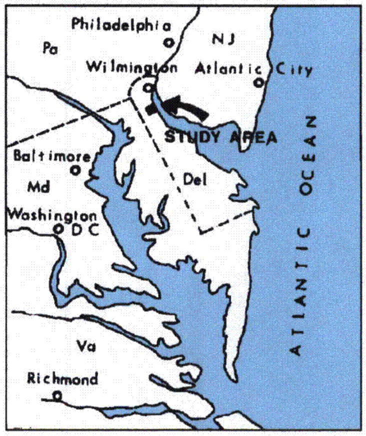
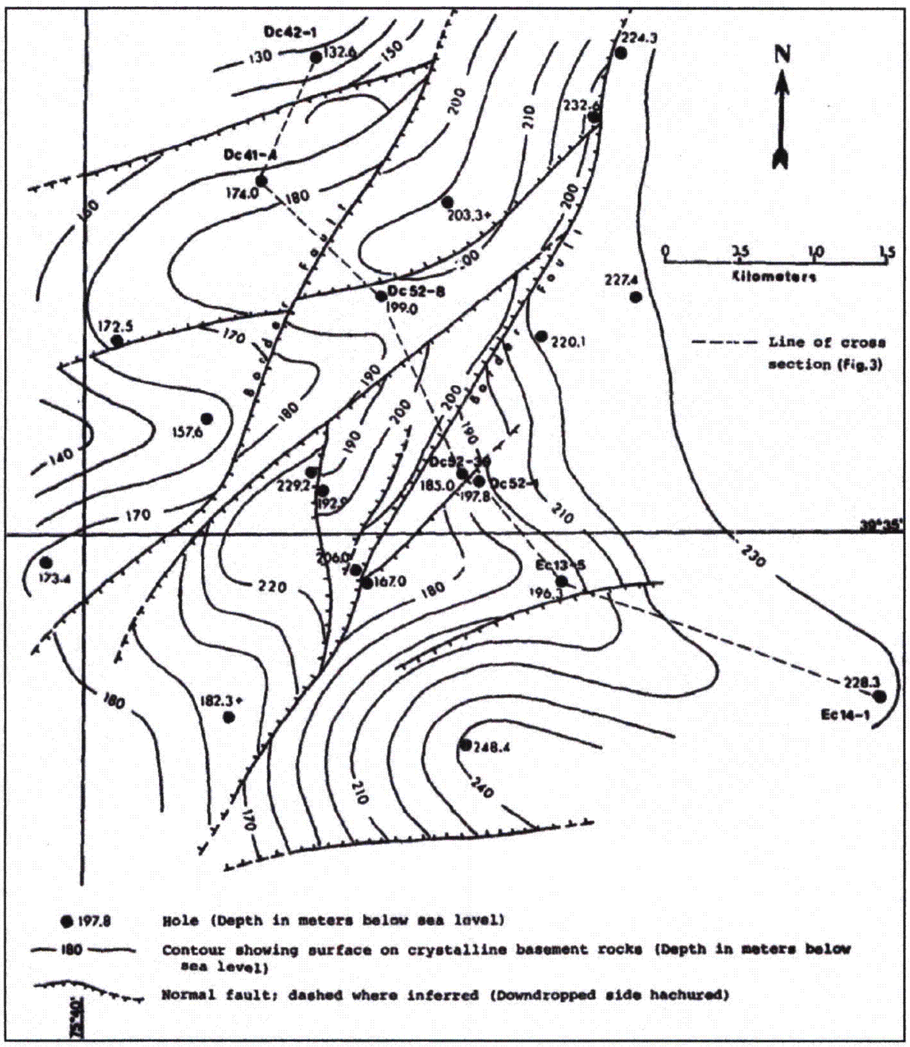
A)




Location of study area.

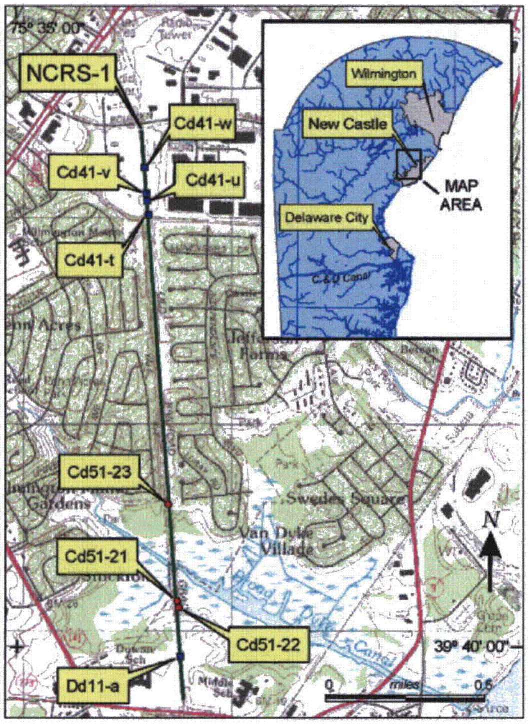
B)




Structural map of the top of crystalline basement.

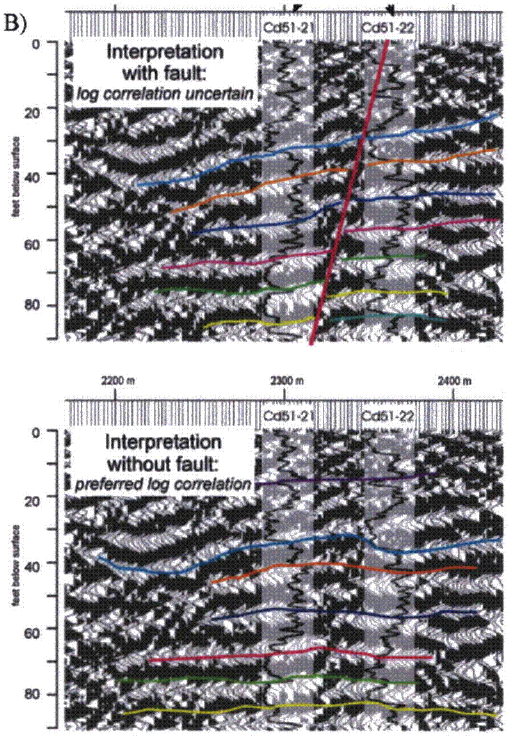
**Question 02.05.01-52 Figure 1 – Figures from Spoljaric (1977)**

A)



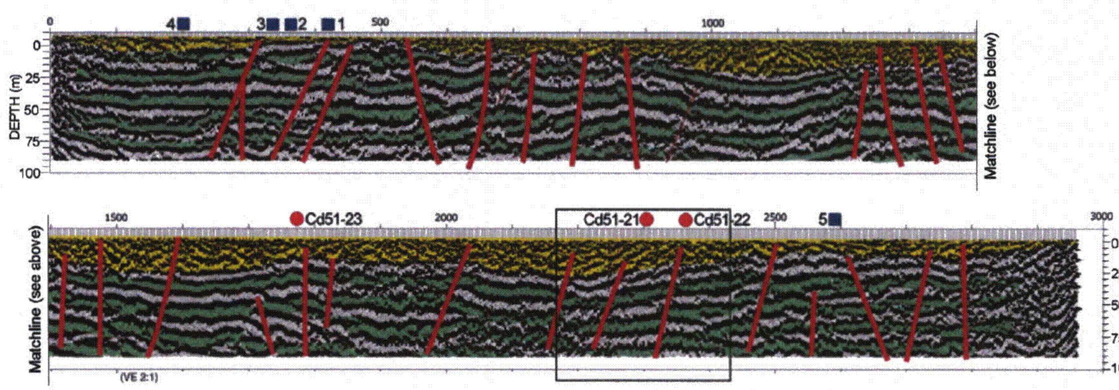

Location of seismic lines, boreholes, and trenches

B)



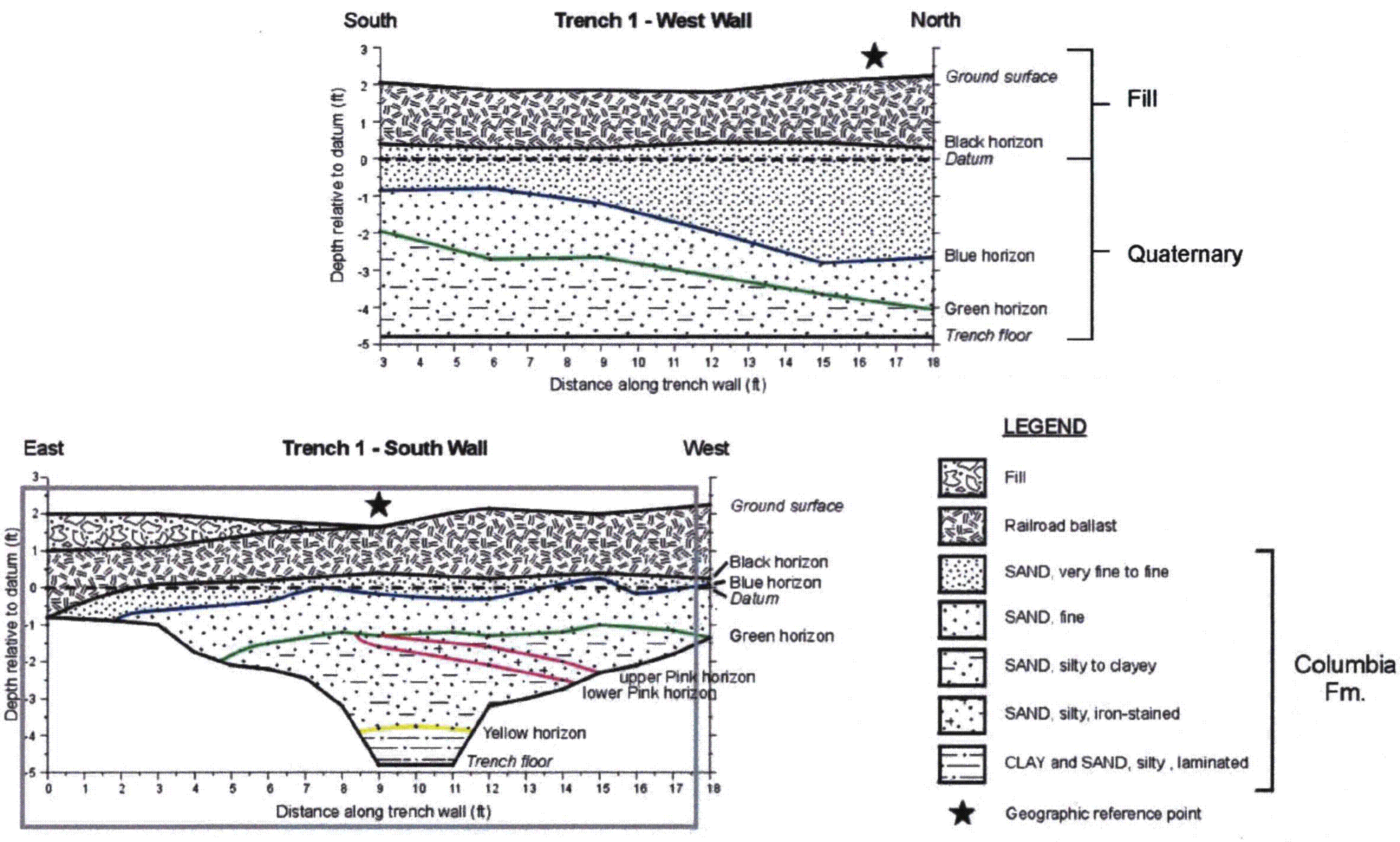

Alternative structural - stratigraphic interpretations for correlations between wells Cd51-21 and Cd51-22. Gamma logs are overlain on part of the depth-converted NCRS-1 seismic line. Geophysical log correlations are more reasonable with no fault between the two wells.

C)



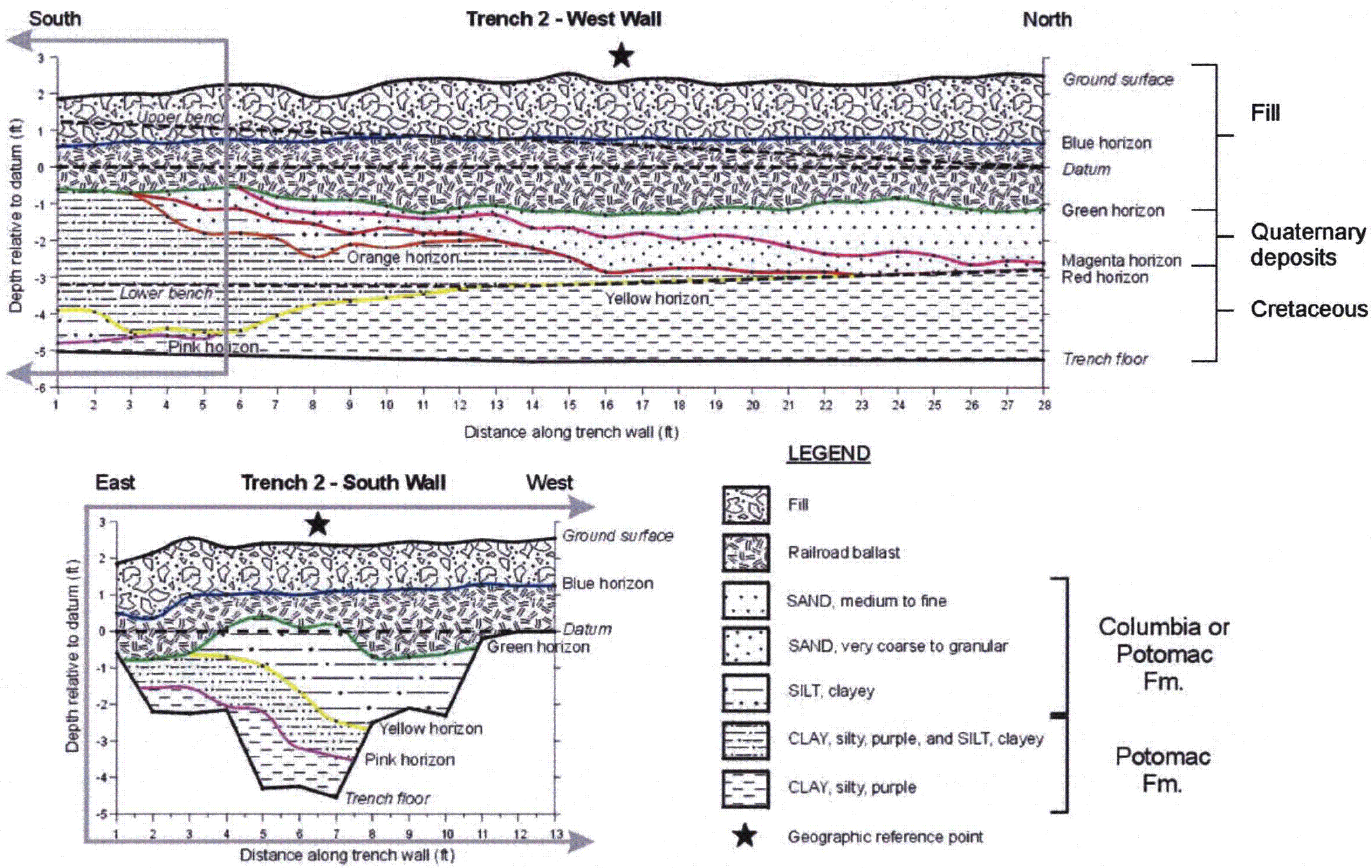

Original interpretation for the depth-section for the NCRS-1 sesimic line (Catchings et al., 2000). Trench locations are indicated by blue squares, boreholes by red circles, and interpreted faults by red lines. Horizontal scale represents meters from north end of line. Location of section shown in Figure 2B is indicated by the boxed area near 2300 m.

**Question 02.05.01-52 Figure 2 – Figures from McLaughlin et al. (2002)**



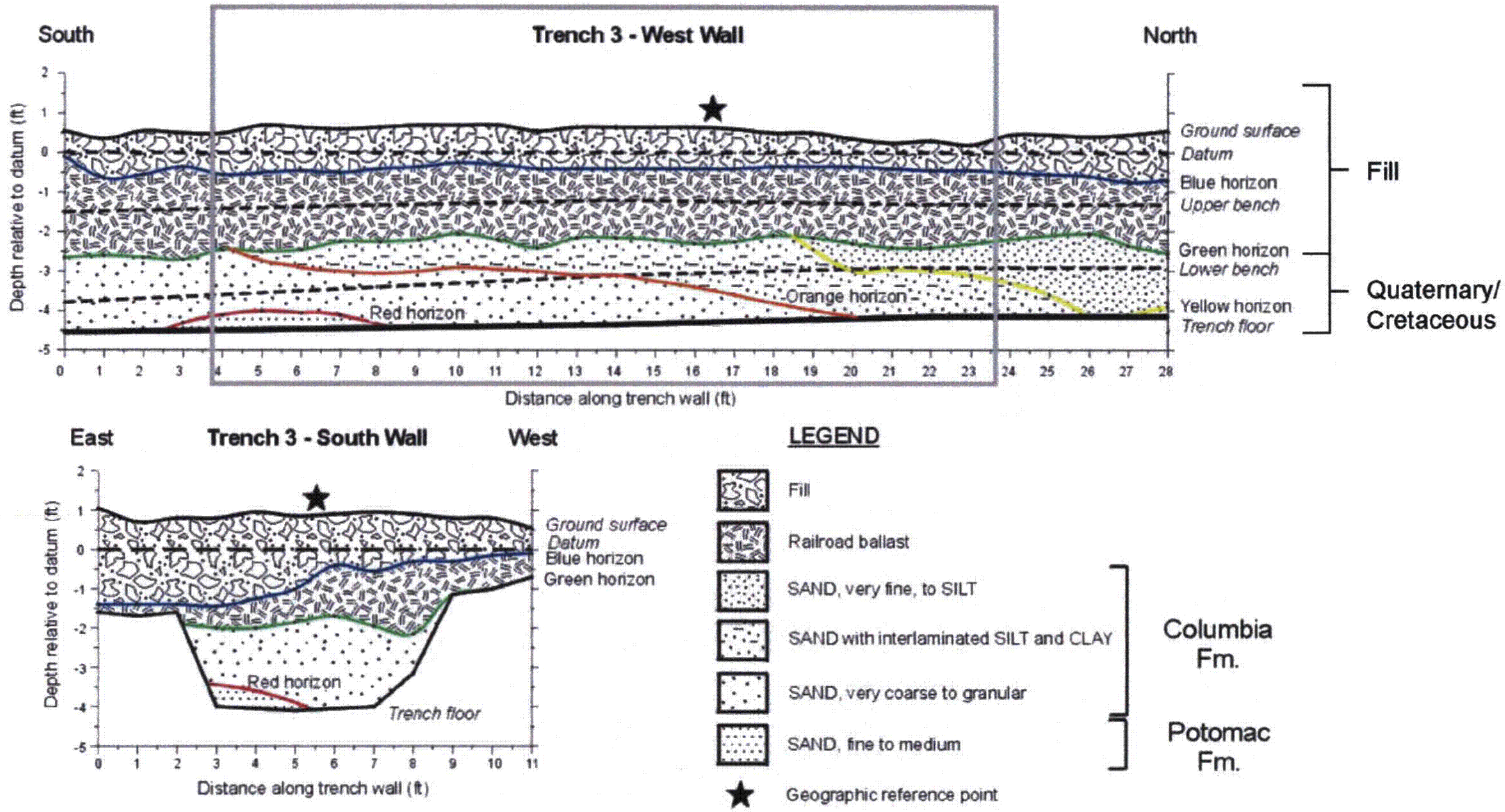

Note: Trench locations shown on Figures 2A and 2C.

**Question 02.05.01-52 Figure 3 – Trench (Cd41-t) (South and West Walls) from McLaughlin et al. (2002)**



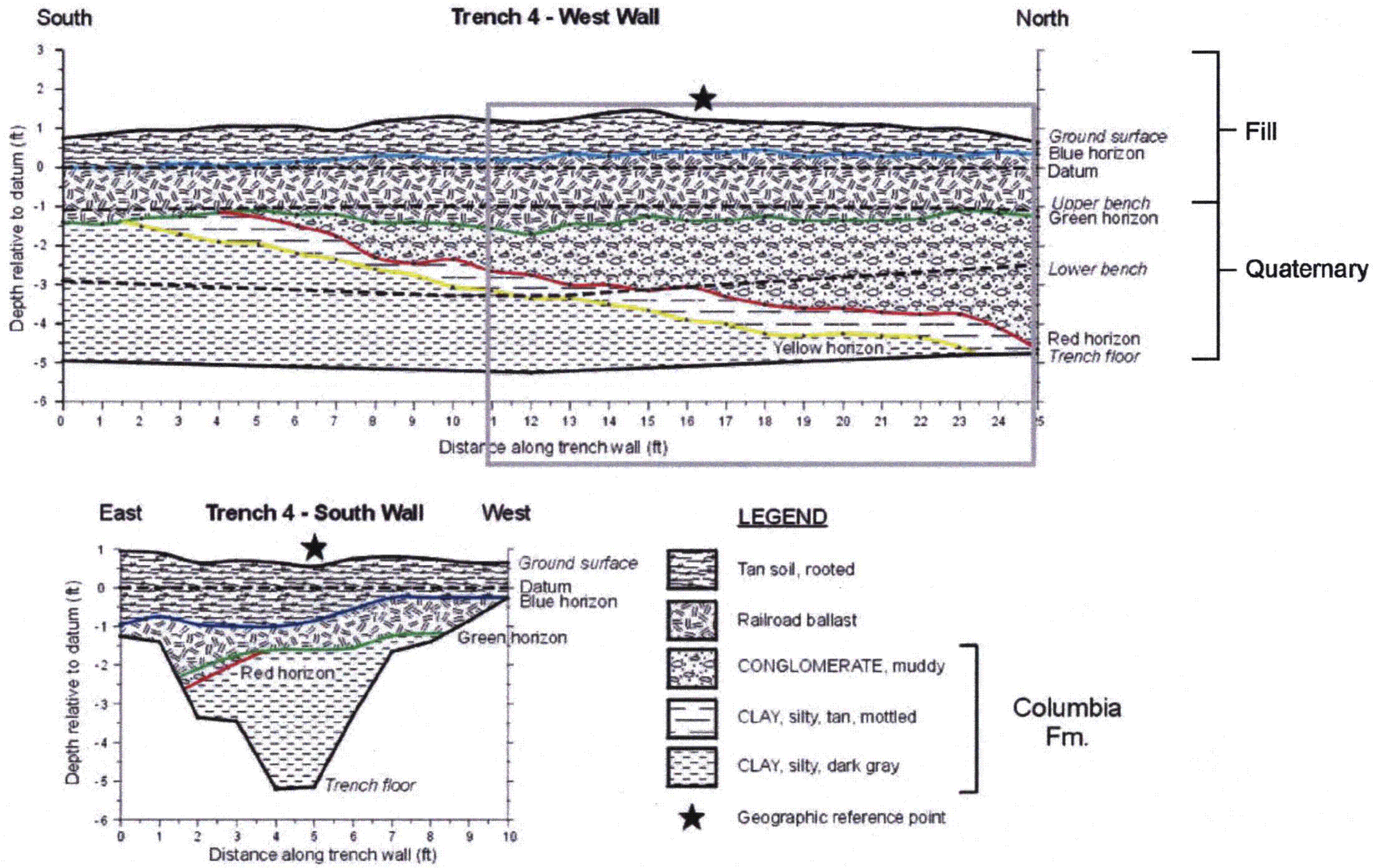

Note: Trench locations shown on Figures 2A and 2C.

**Question 02.05.01-52 Figure 4 – Trench 2 (Cd41-u) (South and West Walls) from McLaughlin et al. (2002)**



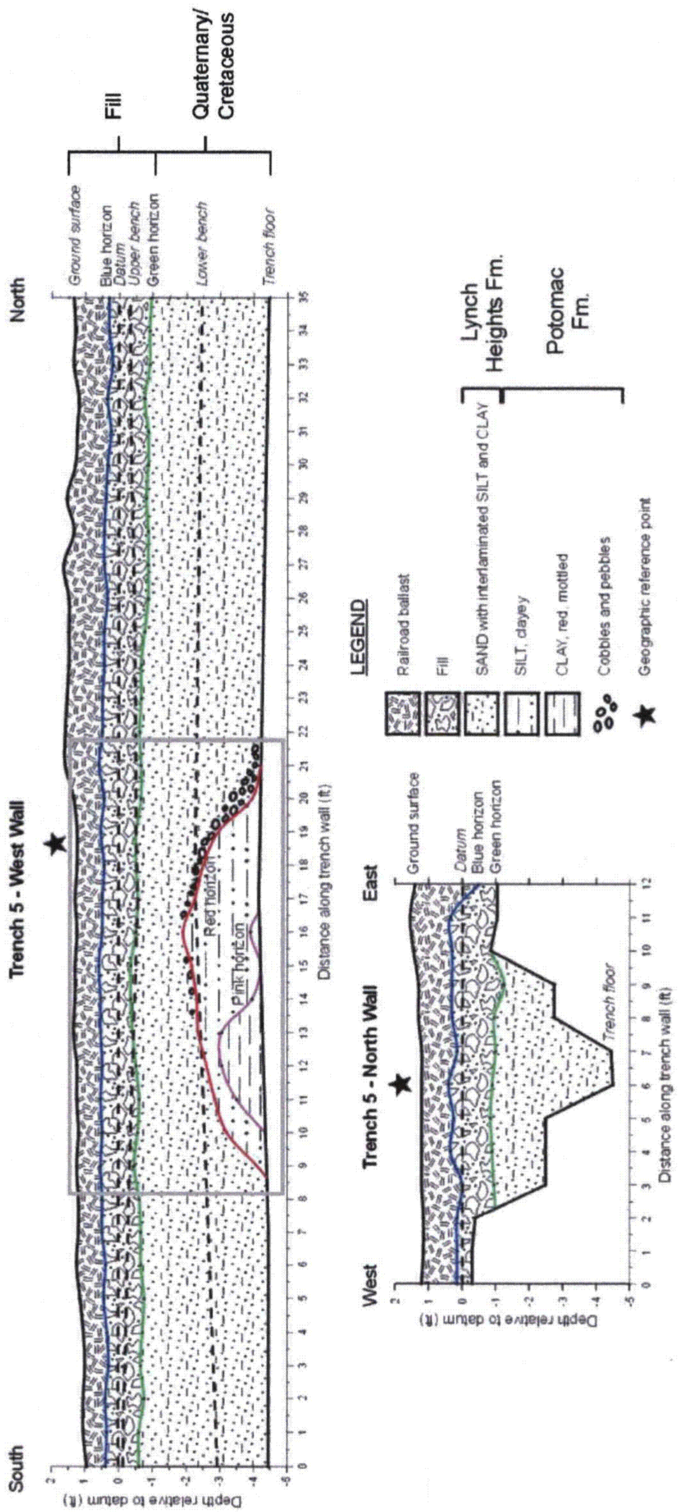

Note: Trench locations shown on Figures 2A and 2C.

**Question 02.05.01 Figure 5 – Trench 3 (Cd41-v) (South and West Walls) from McLaughlin et al. (2002)**




Note: Trench locations shown on Figures 2A and 2C.

**Question 02.05.01-52 Figure 6 – Trench 4 (Cd41-w) (South and West Walls) from McLaughlin et al. (2002)**




Note: Trench locations shown on Figures 2A and 2C.

Question 02.05.01-52 Figure 7 – Trench 5 (Dd11-a) (North and West Walls) from McLaughlin et al. (2002)

**COLA Impact**

FSAR Section 2.5.1.1.4.4.5.8, New Castle County Faults, will be revised as shown in Enclosure 3 in a future revision of the COLA.

**Question 02.05.01-53**

In CCNPP Unit 3 FSAR Section 2.5.1.1.4.5, Seismic Sources Defined by Regional Seismicity, the text provides information on 2 seismic sources within the CCNPP 200 mile radius.

a. Please provide geologic information about the geologic and tectonic setting for seismic sources contributing significantly to the CCNPP evaluation for the new, updated Charleston source, the Newark-Gettysburg Rift basins, and the Connecticut Basin.

b. In FSAR Section 2.5.1.1.4.5.1 the text provides information about the Central Virginia Seismic Zone. Please provide additional illustrations of the various interpretations of several investigators presented by the applicant for this source including: seismicity, locations of Spotsylvania fault, diabase dike swarm, 2 paleoliquefaction sites, Shenandoah fault and Norfolk fracture zone. In addition, illustrate the size and depth distribution of the earthquake catalog for this source, indicating the likely depth of the Appalachian detachment.

c. In FSAR Section 2.5.1.1.4.5.2, the text provides information about the Lancaster Seismic Zone (LSZ). The text states, "The seismic zone is about 80 mi (129 km) long and 80 mi (129 km) wide and spans a belt of allochthonous Appalachian crystalline rocks between the Great Valley and Martic Line about 111 mi (179 km) northwest of the CCNPP site (Figure 2.5-31)." Figure 2.5-31 only shows Earthquakes and a numerical symbol. Please illustrate the tectonic/geologic setting of this seismic zone. Include focal mechanisms, the boundaries of the Great Valley, Martic line and other geo/tectonic features discussed in the text for the LSZ.

d. In FSAR Section 2.5.1.1.4.5.2 (p.2.5-66), the FSAR provides information on the Cacoosing Earthquake sequence and states, "These dikes are associated with many brittle faults and large planes of weakness suggesting that they too have an effect on the amount of seismicity in the Lancaster seismic zone. Most of the seismicity in the Lancaster Seismic Zone is occurring on secondary faults at high angles to the main structures of the Appalachians." Please provide a reference for this interpretation.

**Response**

a. The geologic and tectonic settings for the updated Charleston source and the Newark-Gettysburg Rift basins are described in FSAR Section 2.5.2.2.1.7, Characterization of the Central Virginia Seismic Zone, and Section 2.5.1.1.4.4.3, Mesozoic Tectonic Structures, respectively. Please refer to the proposed revision of FSAR Section 2.5.1.1.4.4.3 developed in response to RAI 130, Question 02.05.01-43.

   The Connecticut Basin seismic source (47) was developed by the Dames & Moore EPRI SOG Team (FSAR Figure 2.5-46) and represents a potential earthquake source from reactivated Mesozoic basin faults (EPRI, 1986). The northern extent of seismic source 47 includes the mapped portions of the Connecticut Valley basin exposed in Connecticut and Massachusetts (Schlische, et al., 2003). Source 47 also includes regions south of the mapped extent of the Connecticut Valley basin. This geometry was intended to capture other poorly constrained or hypothesized buried basin(s) south of the Connecticut Valley basin (FSAR Figure 2.5-46). For example, the southwestern extent of the Connecticut basin source zone (47) encompasses the Taylorsville and Richmond basins (FSAR Figures 2.5-10 and 2.5-46). However, the Dames & Moore team does not provide any independent data or justification that supports the interpretation of a Mesozoic basin under the site or the connection between the Connecticut Valley, Taylorsville, and Richmond basins as a single source zone.

As discussed in FSAR Section 2.5.1.1.4.4.3, Triassic rift basins developed during rifting of Pangea in the Late Triassic and Early Jurassic forming the western margin of the Atlantic Ocean (Schlische et al., 2003). The approximately 124 mi (200 km) long and 19 mi (30 km) wide north-striking Connecticut Valley basin is located about 270 miles (430 km) north-northeast of the CCNPP Unit 3 site in Connecticut and Massachusetts (Figure 2.5-10) (Schlische and Olsen, 1990). The deposits within the basin include Triassic through Jurassic sedimentary rock with interbedded early Jurassic lava flows. The primary border fault is located on the eastern margin of the basin and dips west (Schlische, 2003). Swanson (1986) summarizes evidence suggesting that the main basin-bounding fault (Mineral Hill fault) is localized along a preexisting silicified fault zone of possible late Paleozoic age. Wheeler (2005) synthesizes published information on the eastern border fault and concludes that faulting has not been demonstrated in the Quaternary sediments of the Farm River marsh.

b. In the above RAI question part b, the NRC staff has requested several additional illustrations to provide further documentation of concepts discussed in the FSAR text regarding the Central Virginia Seismic Zone (CVSZ) (Figure 2.5-51). Figure 1 contains much of the above requested information and includes: 1) pre- and post-1986 seismicity, 2) Spotsylvania fault (Hibbard et al., 2006), 3) paleoliquefaction sites of Obermeier and McNulty (1998), and 4) the hypothesized Shenandoah fault (Marple and Talwani, 2004) and Norfolk fracture zone. Figure 2 is a reproduction from Coruh et al. (1988) who discuss the diabase dike swarm and Figure 3 illustrates the Shenandoah fault and the Norfolk fracture from Marple and Talwani (2004). Below is a description of these figures to help clarify the discussion in the FSAR text regarding the CVSZ (Figures 1-3).

As discussed in FSAR Section 2.5.1.1.4.5.1, Coruh et al. (1988) made correlations between earthquake hypocenters and potential seismogenic structures imaged in the I-64 seismic reflection profile. The location of the I-64 profile is shown on Figure 1 and the automatic line drawing display of the seismic reflection data is shown on Figure 2. Coruh et al. (1988) projected 26 hypocenters with an approximate vertical error of less than 5 km onto the seismic data (Figure 2). Using Figure 2, Coruh et al. (1988) correlate two zones of seismicity and with two geologic structures. In one case, a zone of west-dipping hypocenters coincides with a series of west-dipping reflectors along the western flank of a roof antiform between Stations 1300 and 1700 (marked by 'B') (Figures 1 and 2). In the second correlation, a zone of weak seismic reflectors, interpreted as a Mesozoic diabase dike swarm, is coincident with a diffuse pattern of seismicity between stations 2050 and 2250. This zone of diffuse seismicity (marked by 'D') contains five hypocenters and appears to continue across the deeper Moho reflectors. On the basis of the seismicity and seismic reflection data, Coruh et al. (1988) argue for the presence of two different seismogenic structures (e.g., a fold and a dike swarm), rather than a single seismic source within the CVSZ. They continue that "the earthquake activity in central Virginia seismic zone may be detachment-related only on the west flank of the roof of the antiform" p.750 (Coruh et al., 1988).

The depth to the Appalachian detachment (BDT) and the depth to the Moho (M) are shown on Figure 2 at a depth of approximately 19 to 20 km and 35 to 40 km, respectively. Projection of pre- and post-EPRI seismicity compiled for the CCNPP Site study onto the I-64 seismic reflection data (Figure 2c) illustrates that seismicity is generally less than 16 km deep and is located above the Appalachian detachment imaged by the seismic line (Coruh et al., 1998).These results generally agree with those discussed by Wheeler (1992), but indicate the seismicity in the CVSZ is located above the Appalachian Detachment, at least as shown on Figure 2. FSAR Text will be revised to incorporate this change.

Marple and Talwani (2004) infer a correlation between CVSZ seismicity and the hypothesized Shenandoah fault (Figures 1 and 3). The authors infer that the Shenandoah fault represents an on-land extension of the offshore Norfolk fracture and lies buried beneath Paleozoic allochthonous terranes (Figure 3). In this model, the Shenandoah fault offset the Stafford fault zone of Marple (2004) and the hypothesized East Coast Fault System (ECFS) of Marple and Talwani (2000) during the Alleghanian Orogeny. They contend that the CVSZ seismicity is a result of compression in the present-day stress field at the bend formed between the ECFS and the Stafford fault of Marple (2004) by the Shenandoah fault.

The hypothesis presented by Marple and Talwani (2004) has several sources of uncertainty. First, extensive review and analysis of the Marple and Talwani (2000) paper by Dominion (2004) found little evidence to support the existence of the northern segment of the ECFS. As discussed in FSAR Section 2.5.1.1.4.4.5.14, NRC staff agreed with this assessment (NRC, 2005). Second, the Stafford fault system is not considered a capable tectonic source and the extension of the fault system from Virginia to New Jersey is supported by limited data (see FSAR Section 2.5.1.1.4.4.4.1). Third, the existence of the Shenandoah fault (named by Marple and Talwani [2004]) is also based on limited and scattered data including: 1) interpretation of regional gravity anomalies; 2) a single on-land seismic reflection profile; 3) focal mechanisms of CVSZ seismicity oriented northwest; 4) a series of northwest-striking Jurassic and Eocene dikes; and 5) a basement fault shown in an offshore seismic-reflection profile. These observations are widely distributed across central Virginia, West Virginia, and offshore, and are linked by the inferred fault hypothesized of the authors (Figure 3).

In summary, as described in FSAR Sections 2.5.1.1.4.4.1, 2.5.1.1.4.4.5.3, and 2.5.1.1.4.4.5.14 there are little data to support the northern segment of the ECFS, the extension of the Stafford fault system by Marple (2004) to the northeast from Virginia, and only scattered data to support the existence of the Shenandoah fault. Thus, many of the underlying assumptions used by Marple and Talwani (2004) to develop their arguments (e.g., the existence of the northern segment of the ECFS) are poorly supported by available data and thus, their conclusions explaining the cause of CVSZ seismicity are difficult to evaluate.

The FSAR text will be revised to provide citations for these interpretations.

c. As requested by NRC staff, several figures are attached to this response from seminal papers by Armbruster and Seeber (1987) and Seeber et al. (1998) on the Lancaster Seismic zone (LSZ) that illustrate the geologic and tectonic setting of the area. Figures 4 through 9 illustrate features related to the LSZ previously discussed in FSAR Section 2.5.1.1.4.5.2. The tectonic and geologic setting of the LSZ is illustrated in Figures 4 and 5, including the earthquake epicenters which define the LSZ, as well as the Great Valley, Martic Line, Gettysburg Basin, Newark Basin and the structural provinces of the region (Wise and Faill, 2002) (Armbruster and Seeber, 1987). Figure 5 includes historical earthquake epicenters (e.g., pre-instrumentation) compiled by Armbruster and Seeber (1987) from newspaper accounts of felt earthquakes in the area. Figure 5 also shows the north-south trending Mesozoic fractures and dikes discussed in the FSAR text and hypothesized by Armbruster and Seeber (1987) to be accommodating present-day east-northeast – west-southwest compressional stress (Zoback and Zoback, 1989).

Focal mechanisms from the two largest instrumented earthquakes in the LSZ, namely the 16 January, 1994 Cacoosing earthquake (mb 4.6) and the 23 April 1984 Martic earthquake (mb 4.1), are shown in Figure 6. As discussed in the FSAR text, Seeber et al. (1998) infer that the Cacoosing earthquake sequence was triggered by the flooding of a quarry based on the coincidence of the quarry and the earthquake sequence. The spatial relationship between the Cacoosing earthquake hypocenters and the flooded quarry is shown in Figures 7 and 8.

Figure 9 shows the epicenters of the 1984 Martic line earthquake and the surface projection of the inferred rupture plane. As discussed in the FSAR text, Armbruster and Seeber (1987) inferred that the rupture plane strikes at high angles to the main Appalachian structures but is roughly parallel to a prominent Rockhill Jurassic dike.

d. Armbruster and Seeber (1987) interpret the Mesozoic fractures and dikes to be accommodating present-day east-northeast – west-southwest compressional stress. Both Armbruster and Seeber (1987) and Seeber et al. (1998) interpret the LSZ seismicity to be occurring on secondary faults at high angles to the main structures of the Appalachians.

The FSAR text will be revised to provide citations for these interpretations.

References:

Armbruster, J., and Seeber, L, 1987, The 23 April 1984 Martic Earthquake and The Lancaster Seismic Zone In Eastern Pennsylvania, Bulletin of the Seismological Society of America, Volume 77, Number 2, p 877-890.

Coruh, C., Bollinger, G., and Costain, J., 1988, Seismogenic Structures in the Central Virginia Seismic Zone, Geology, Volume 16, p 748-751.

Dominion, 2004, Response to 6/1/04 RAI 2.5.1-5, 2.5.1-6, 2.5.3-2, and 2.5.1-5, Letter No. 5, U.S. Nuclear Regulatory Committee, Serial No. 04-347, and Docket No. 52-008.

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Marple, R., 2004, Relationship of the Stafford fault zone to the right-stepping bends of the Potomac, Susquehanna, and Delaware Rivers and related upstream incision along the U.S. Mid-Atlantic fall line; in Southeastern Geology, Volume 42, Number 3, p 123-144.

Marple, R., and Talwani, P., 2000, Evidence for a Buried Fault System in the Coastal Plain of the Carolinas and Virginia - Implications for Neotectonics in the Southeastern United Sates, Geological Society of America Bulletin, Volume 112, Number 2, p 200–220.

Marple, R. and Talwani, P., 2004, Proposed Shenandoah Fault and East Coast-Stafford Fault System and Their Implications for Eastern U.S. Tectonics, Southeastern Geology, Volume 43, Number 2, p 57-80.

Nuclear Regulatory Commission (NRC), 2005, Safety Evaluation Report for an Early Site Permit (ESP) at the North Anna ESP Site – NUREG-1835,

Obermeier, S. and McNulty, W., 1998, Paleoliquefaction Evidence for Seismic Quiescence in Central Virginia During the Late and Middle Holocene Time (abs), Eos Transactions of the American Geophysical Union, Volume 79, Number 17, p S342.

Schlische, R.W., Withjack, M.O. and Olsen, P.E., 2003, Relative timing of CAMP, rifting, continental breakup, and inversion: tectonic significance, by The Central Atlantic Magmatic Province: in Hames, W.E., McHone, G.C., Renne, P.R., and Ruppel, C., eds., American Geophysical Union Monograph 136, p. 33-59.

Schlische, R.W., and Olsen, P.E., Quantitative filling model for continental extensional basins with applications to early Mesozoic rifts of eastern North America, Journal of Geology, 98, p. 135-155, 1990.

Seeber, L., Armbruster, J., Kim, W., Barstow, N. and Scharnberger, C., 1998, The 1994 Cacoosing Valley earthquakes near Reading, Pennsylvania: A shallow rupture triggered by quarry unloading, Journal of Geophysical Research, Volume 103, Number B10, p 24,505 - 24,521.

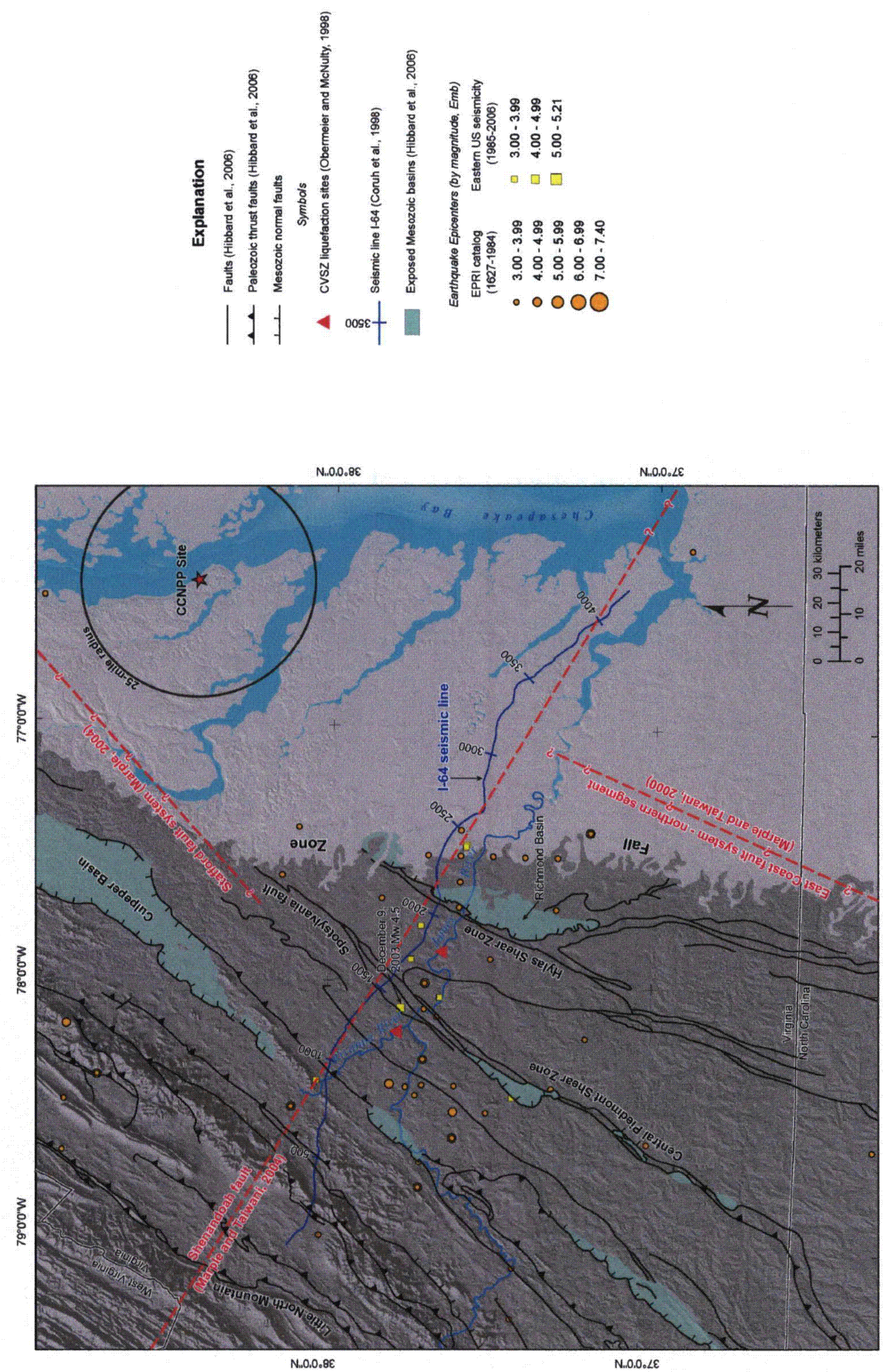
Swanson, M.T., 1986, Preexisting fault control for Mesozoic basin formation in eastern North America, Geology, v. 14 p. 419-422.

Wheeler, R., 2005, Known or Suggested Quaternary Tectonic Faulting, Central and Eastern United States—New and Updated Assessments for 2005, U.S. Geological Survey Open-File Report 2005-1336, p. 8-10.

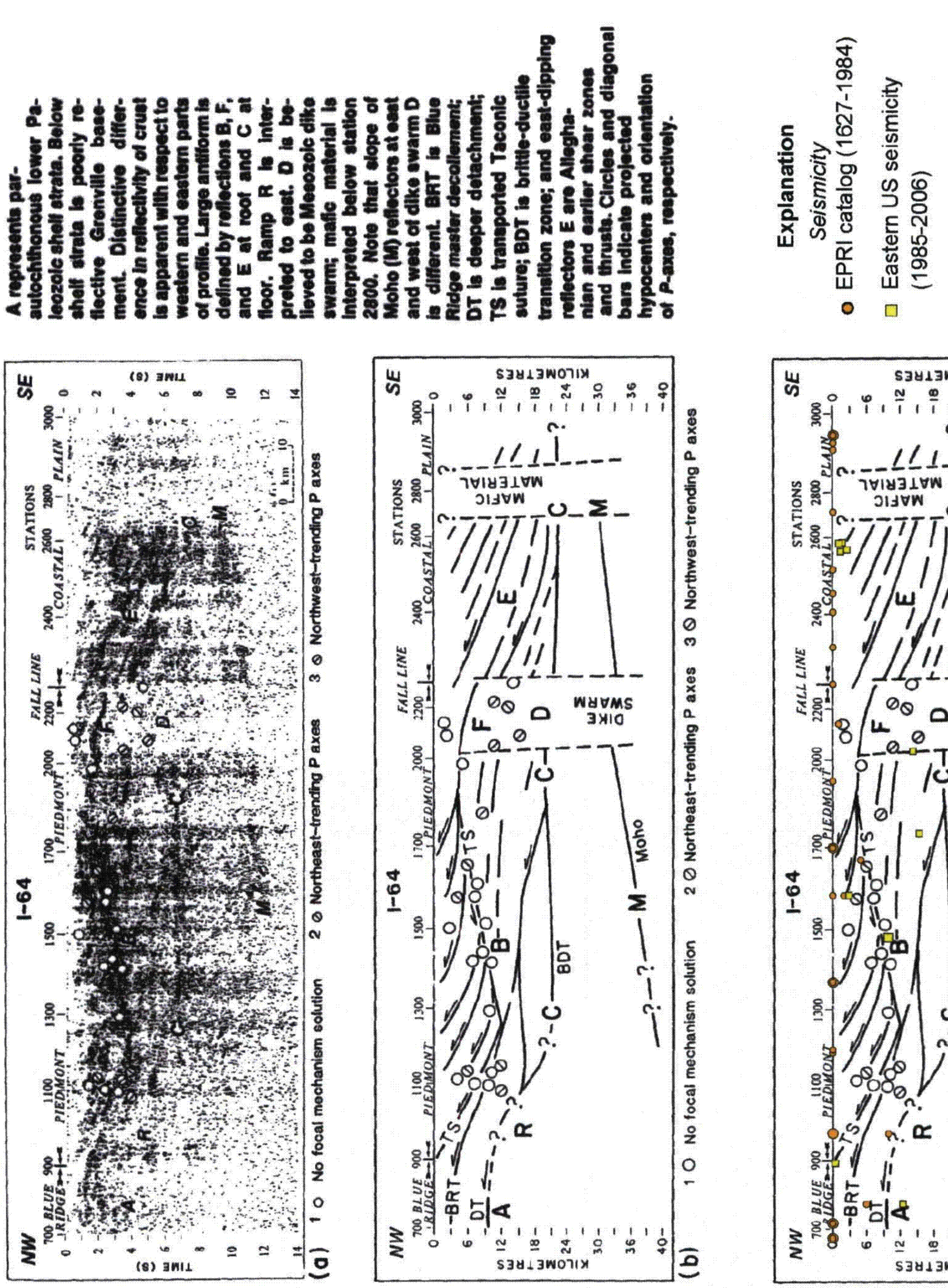
Wheeler, R., and Johnston, A., 1992, Geologic Implications of Earthquake Source Parameters in Central and Eastern North America, Seismological Research Letters, Volume 63, Number 4, p 491–505.

Wise, D., and Faill, R., 2002, Lancaster Transverse Seismic Zone (Pennsylvania): Strain Concentration at Lateral Ramps of Basement Nappes (?), Northeastern Geology and Environmental Sciences, Vol. 24, No. 3, p. 171-175.

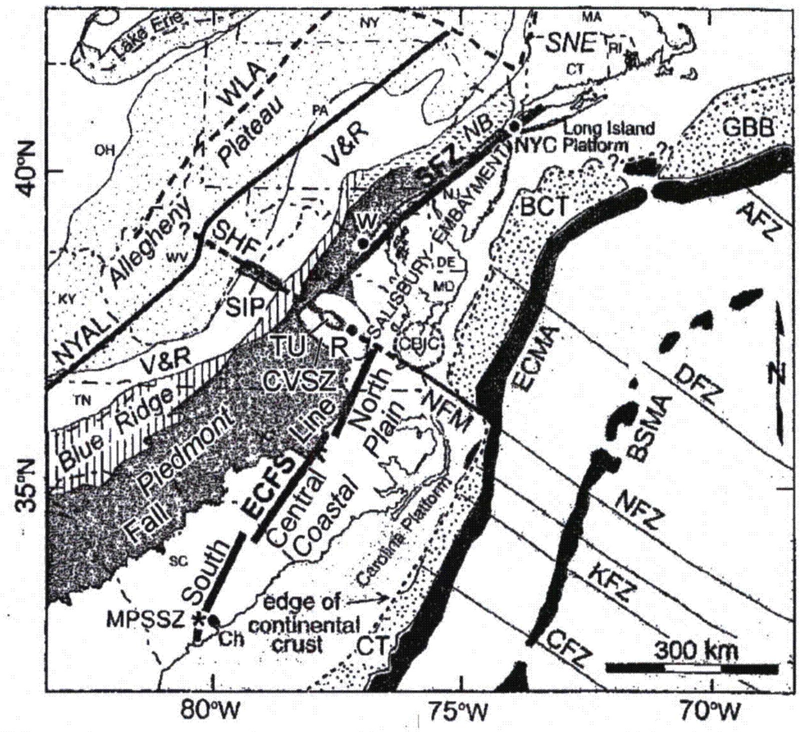
Zoback, M. and Zoback, M., 1989, Tectonic Stress Field of the Coterminous United States, in L. C. Pakiser and M. D. Mooney, eds., Geophysical Framework of the Continental United States, Geological Society of America Memoir 172, p 523–539.




**Question 02.05.01-53 Figure 1 – Central Virginia Seismic Zone illustrating seismicity, principal faults, liquefaction site and the I-64 seismic line**




**Question 02.05.01-53 Figure 2 – A) Central part of automatic line drawing of I-64 seismic reflection data. B) Simplified cross section modified from Coruh et al. 1998. C) Simplified cross section with seismicity from Figure 1 projected onto I-64 seismic line.**




**Question 02.05.01-53 Figure 3 – Locations of the proposed East Coast-Stafford Fault Systems (ECFS), Stafford Fault Zone (SFZ), Norfolk Fracture Zone (NFZ), and the Shenandoah Basement Fault (SHF). Modified from Marple and Talwani, 2004).**

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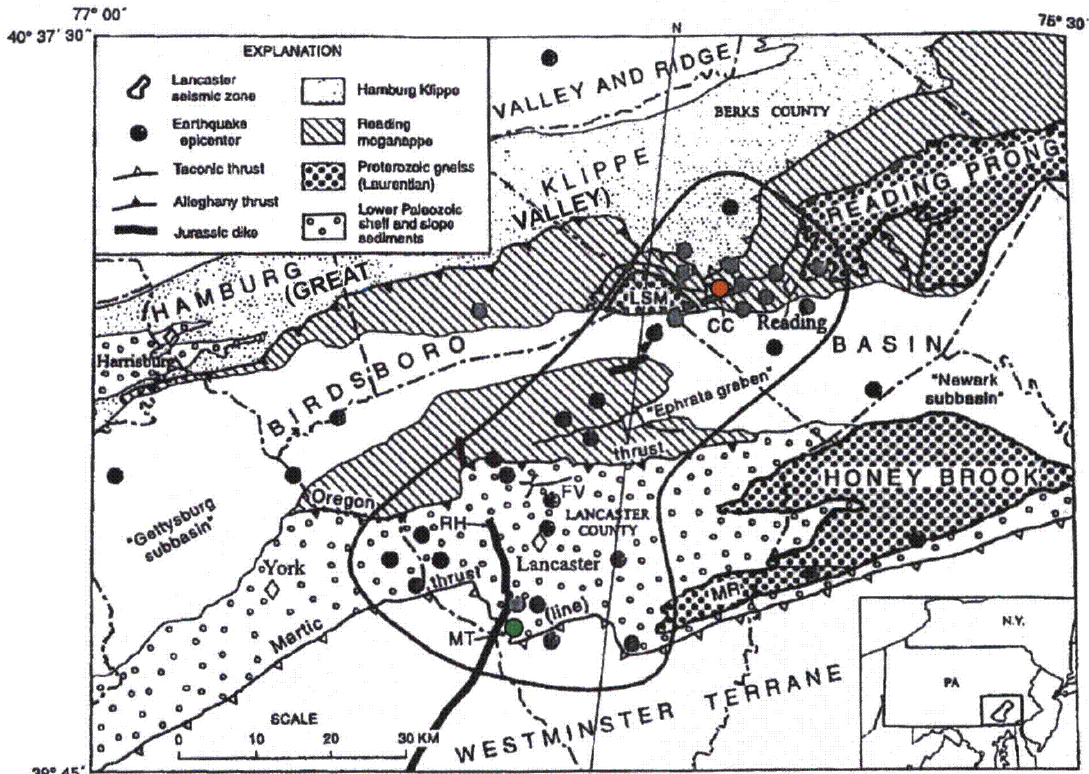
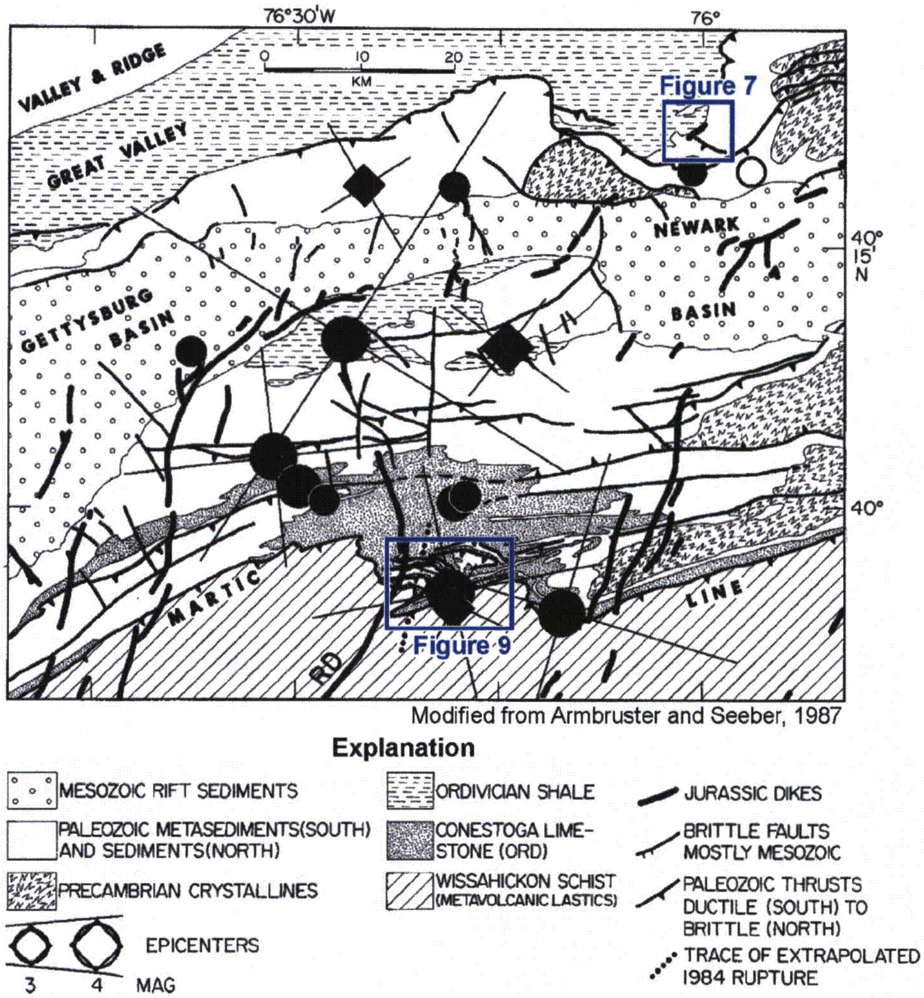


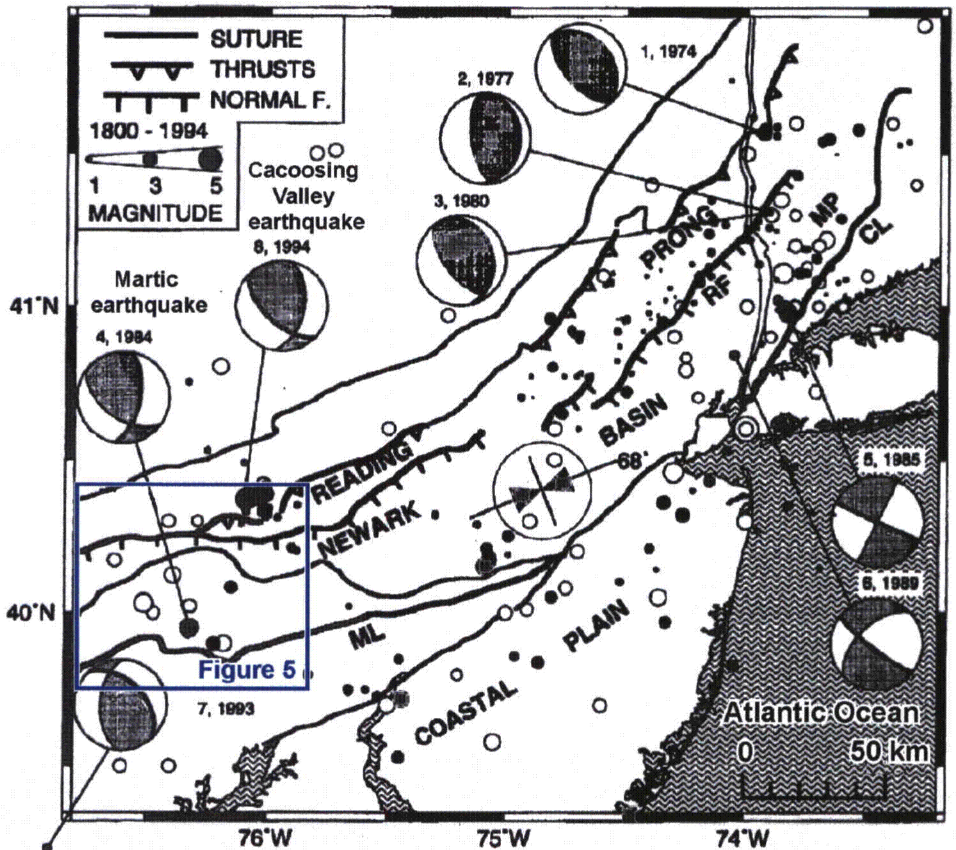

RH–Rockhill dike
FV–Fruitville faults
LSM–Little South Mountain
CC–Cacoosing Valley event(1994)
MR–Mine Ridge
MT–Martic event(1984)

Modified from Wise and Faill, 2002

**Question 02.05.01-53 Figure 4 – Structural provinces and features of the Lancaster seismic zone (encircled by black line). 1984 Martic earthquake shown in green and 1994 Cacoosing Valley earthquake shown in orange. Epicenter data from Armbruster and Seeber (1987), Seeber et al. (1998) and Faill (2001). Modified from Weiss and Faill (2002).**

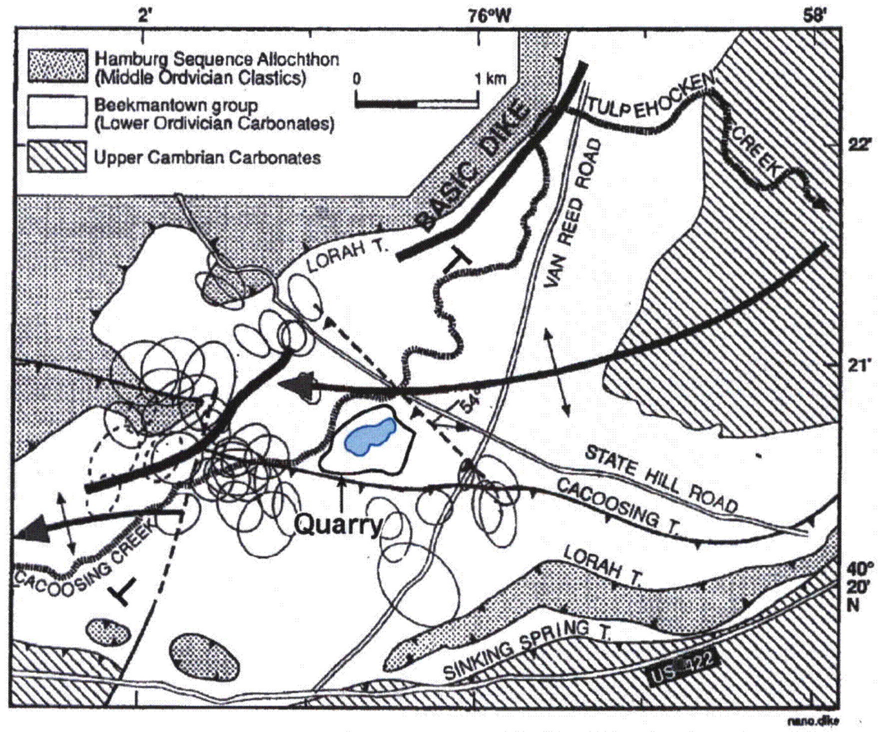



**Question 02.05.01-53 Figure 5 – The Lancaster seismic zone in its structural setting. Location outlined in Figure 6. Circles are historical earthquake epicenters compiled from newspaper searches, diamonds are instrumental epicenters. Both epicenter types have error bars where applicable. The dotted line indicates the extrapolated trace of the 1984 Martic earthquake rupture. Modified from Armbruster and Seeber (1987).**



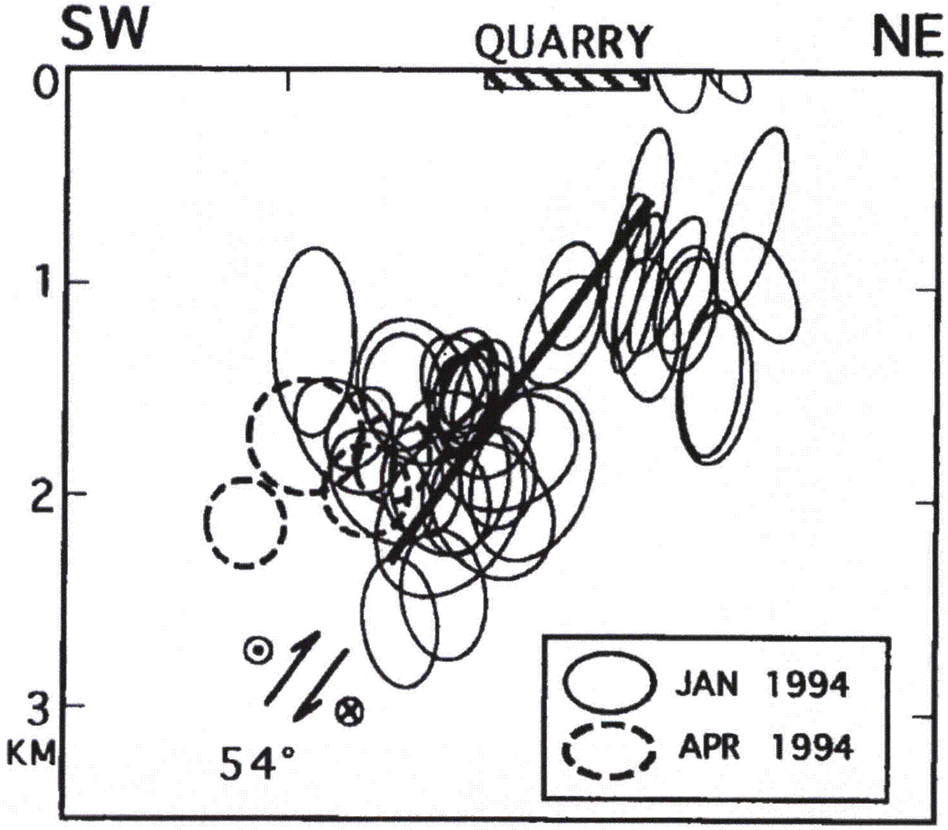

Modified from Seeber et al., 1998

**Question 02.05.01-53 Figure 6 – Epicenters, kinematics of seismogenic faults, and stress orientation in the context of major Appalachian structures along the Atlantic seaboard from southern New York to southeastern Pennsylvania. Epicenters are from the catalog of the National Center of Earthquake Research (NCEER' open circles 1800-1970, magnitudes >=3.0) and from the Lamont-Doherty Seismic Network (filled circles, 1970-1994, magnitudes >= 1.0). The rupture plane for seven of the eight focal mechanisms (thicker nodal plane; lower hemisphere projections) are inferred from after shock distribution and/or from structural correlation. RF is Ramapo fault; ML is Martic Line; CL is Camerons Line; and MP is Manhattan Prong. Modified from Seeber et al. (1998).**



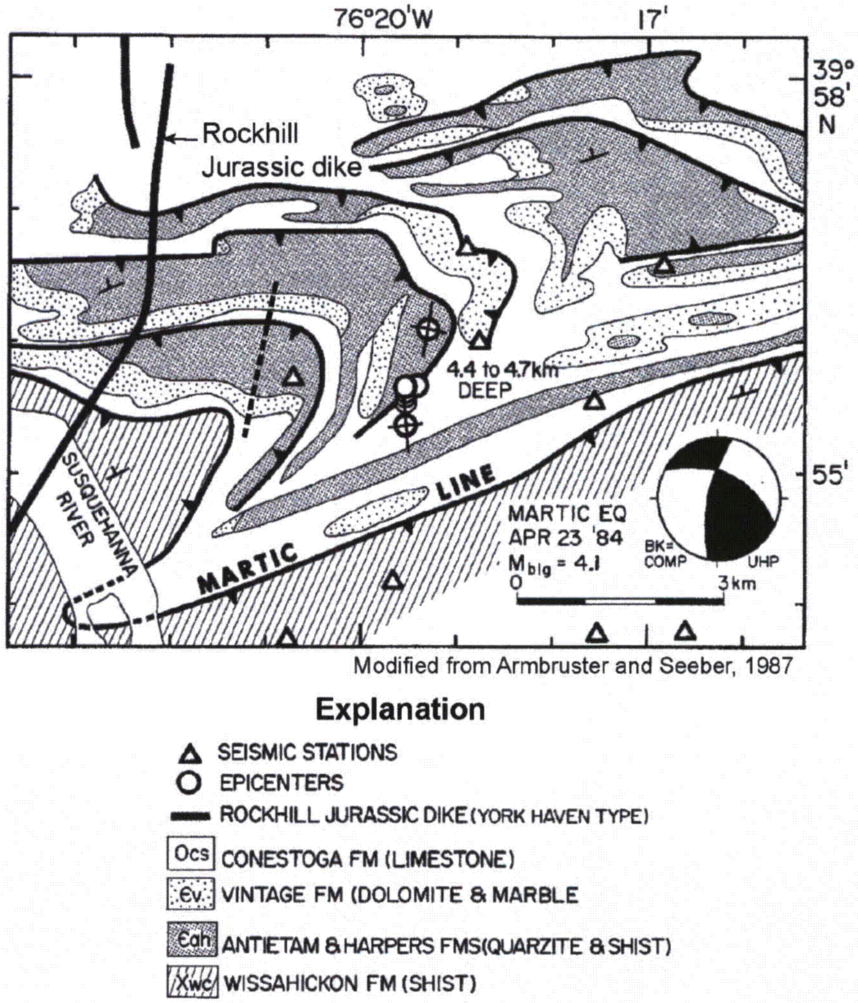

Modified from Seeber et al., 1998

**Question 02.05.01-53 Figure 7 – Map of hypocenters from a temporary local network of analog and digital seismographs operated for 5 days, starting 2 days after the January 16, 1995 Cacoosing Valley mainshock. Epicenters are represented by 90 confident ellipses: from January 18-23 (solid) and from a 3-day deployment in May (dashed). Shallow dipping faults are thrusts (barbs on hanging wall side). The dashed fault trace is the surface expression of the inferred rupture. The flooded area of the quarry is shown in blue. Figure 8 cross section is located by opposing bars. Modified from Seeber et al. (1998).**




Modified from Seeber et al., 1998

**Question 02.05.01-53 Figure 8 – Section (no vertical exaggeration) perpendicular to inferred rupture plan of the January 16, 1994 Cacoosing Valley earthquake, showing hypocenters as confidence ellipses (same data as Figure 7 where section is located by opposing bars). The plan through the hypocenters indicates the inferred main rupture. The quarry is located on the hanging wall block of the reverse fault. Modified from Seeber et al. (1998).**




**Question 02.05.01-53 Figure 9 – Surface structural features along the Martic Line and the April 23, 1984 Martic Line earthquake represented by the seven most accurate after-shock epicenters and by a composite fault-plane solution. Representative horizontal error estimates (axes of horizontal projection of error ellipsoids) are shown for the two epicenters are the opposite ends of the aftershock zone. The fault plane striking NNE with right-lateral and reverse slip is parallel to the trend of the aftershocks and is the inferred plane of rupture. The dashed line is the surface trace of this plane. The plane is discordant with Paleozoic structures associated with the Martic Line, but it is parallel and only 2 km from the trace of the Rockhill Jurassic dike. Modified from Armbruster and Seeber (1987).**

**COLA Impact**

FSAR Section 2.5.1.1.4.5.1, Central Virginia Seismic Zone, and Section 2.5.1.1.4.5.2, Lancaster Seismic Zone, will be modified as shown in Enclosure 3 as part of a future revision.

**Question 02.05.01-54**

CCNPP Unit 3 FSAR Section 2.5.1.2.2 provides information about the site area geologic history. Three quotations out of the text follow. First, the text states, "Sparse geophysical and borehole data indicate that the basement rock beneath the site may consist of exotic crystalline magmatic arc material (Glover, 1995b)." The text also states, "Tectonic models discussed in Section 2.5.1.2.4 hypothesize that the crystalline basement was accreted to the pre-Taconic North American margin during the Paleozoic along a suture that lies about 10 mi (16 km) west of the site (Figure 2.5-17 and Figure 2.5-23)." The text also states, "The Queen Anne Basin was originally postulated by Hansen (1988) and was considered to underlie the site (Horton, 1991). However, this interpretation does not appear to be supported by most of the borehole data and current interpretations (Section 2.5.1.2.4)."

The basement beneath the CCNPP and in the vicinity is geo/tectonically complex because of an extended tectonic history and further complicated by limited data. Please provide a more developed discussion about what is directly below the CCNPP with respect to the concept of extended continental crust and transitional continental crust and about the various interpretations of the positions of Mesozoic rift basins and their boundary faults. Please clarify why the final interpretation of "no basin" below the site is the preferred interpretation. Please verify that the most current research has been taken into account.

**Response**

The NRC has requested several points of clarification, as follows:

a. Please provide a more developed discussion about what is directly below the CCNPP site with respect to the concept of extended continental crust and transitional continental crust and about the various interpretations of the positions of Mesozoic rift basins and their boundary faults;
b. Please clarify why the final interpretation of 'no basin' below the site is the preferred interpretation; and
c. Please verify that the most current research has been taken into account.

a. As requested by NRC staff, additional discussion about the crustal structure directly below the CCNPP site and the history of early Mesozoic rifting is provided in the proposed revision to the FSAR text as part of the response to RAI 130, Question 02.05.01-43. The uncertainties about the nature of the basement directly below the site is addressed in the proposed revision to FSAR Section 2.5.1.2.2, Site Area Geologic History, Section 2.5.1.2.3, Site Area Stratigraphy, and Section 2.5.1.2.4, Site Area Structural Geology, as shown in Enclosure 3. Additional discussion about the positions of Mesozoic rift basins and their boundary faults is also provided in the response to RAI 130, Question 02.05.01-43.

b. This part of the RAI question asks for verification of a statement made concerning the presence or absence of the Queen Anne basin directly beneath the CCNPP site. The alternate hypothesis for 'no basin' under the site is based on:

1) As discussed in Section 2.5.1.1.3.2.1, Crystalline Rocks (Late Precambrian and Paleozoic), as part of the response to RAI 130, Question 02.05.01-36, Hansen and Edwards (1986) interpret three belts from borehole data and aeromagnetic and gravity

anomalies mapped in Maryland (FSAR Figure 2.5-11). The "Inner Belt" has lithologies and geophysical characteristics similar to the adjacent, exposed Piedmont. The "Middle Belt" corresponds to a region of anomaly free magnetic gradients with potential buried Mesozoic basins and the Outer Belt contains diverse lithologies such as gneisses, schists, mafic intrusives and metavolcanics rocks (Hansen and Edwards, 1986). Hansen and Edwards (1986) present a systematic treatment and interpretation of the geophysical data that appears to be more consistent than similar interpretations by Benson (1992). In Hansen and Edwards (1986), the CCNPP site is located in the "Outer Belt" and not underlain by a basin (FSAR Figure 2.5-11).

2) Communications with P. LeTourneau (2006) indicated that the connection between the Queen Anne and Taylorsville basins is no longer an accepted interpretation and that he does not believe that there is a continuous rift basin extending from Virginia into Maryland (Peter Letourneau, Wesleyan University, personal communication, 2006).

3) As discussed in the response to RAI 71, Question 02.05.01-26[12] and RAI 130, Question 02.05.01-43, Benson (1992) presents only weak evidence for the southern extension of the Queen Anne basin under the site. Collectively, this review of existing data and discussion with local experts led us to the "preferred" hypothesis as stated in the FSAR.

A further review of publications and additional correspondence with experts suggests that the presence or absence of a Mesozoic rift basin directly beneath the site is equivocal because there simply are no data upon which to base a compelling, conclusive argument. Relevant literature reviewed show that the site is located east or southeast of the Taylorsville basin, which is relatively well resolved beneath the Coastal Plain based on seismic, borehole, gravity, and magnetic data (LeTourneau, 2003). However, compilations of Mesozoic rift basins beneath the Coastal Plain are inconsistent regarding the presence, location, and extent of the Queen Anne basin that is shown to be located either beneath or adjacent to the site. There are no boreholes or seismic data beneath the site to conclusively resolve the presence or absence of Mesozoic rift basin deposits beneath the site, and gravity and magnetic data do not offer a compelling constraint.

c. The most current research and available literature regarding Mesozoic rifting is incorporated to clarify revised FSAR Sections 2.5.1.2.2, 2.5.1.2.3, and 2.5.1.2.4.

To ensure a complete literature review, during preparation of the original FSAR text and this RAI response, experts in Mesozoic rifting and Maryland geology were contacted. Experts were either interviewed via telephone or contacted through written correspondence. Below is a list of those interviewed, their affiliation, and date and mode of the correspondence.

[12] G. Gibson (UniStar Nuclear Energy) Letter UN#09-152 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated April 15, 2009.

| | | | |
|---|---|---|---|
| Peter Letourneau | Wesleyan University | 08/21/2006<br>08/12/2009 | Written Correspondence<br>Written Correspondence |
| Joseph P. Smoot | U.S. Geological Survey | 10/26/2006<br>08/17/2009 | Written Correspondence<br>Written Correspondence |
| Catherine B. Enomoto | U.S. Geological Survey | 08/14/2009 | Written Correspondence |
| Robert E. Weems | U.S. Geological Survey | 08/13/2009 | Telephone and Written Correspondence |
| David Andreason | Maryland Geological Survey | 10/24/2006 | Written Correspondence |
| Martha Withjack | Rutgers University | 08/28/2009 | Written Correspondence |

Many of these interviews focused on whether any new research has been conducted or data collected that might provide more definitive information to evaluate the geometry of the Queen Anne basin shown by Benson (1992). The consensus from those interviewed is that there are no new data to constrain the southern geometry of the Queen Anne basin that includes the CCNPP site area. As discussed in response to RAI 71, Question 02.05.01-31[13], experts were also contacted to discuss their knowledge on the structural and geologic setting of Chesapeake Bay and the eastern seaboard of the United States. These experts include: Richard Harrison, David Russ, David Powars, Wayne Newell, Lucy McCartan, Wylie Poag, Milan Pavich, and Steve Schindler (U.S. Geological Survey). In addition, UniStar representatives visited the Maryland Geological Survey (MGS) and discussed similar topics with geologist John Wilson who provided additional references related to studies performed by former MGS geologist Harry Hansen.

In addition to the personal correspondence with experts, UniStar reviewed the summary report of a recent workshop on Southeastern U.S. Mesozoic Rift Basins entitled, "2009 Southeast U.S. Mesozoic Rift Basins Energy Resources Potential Workshop." The comprehensive bibliography provided by this workshop (Lassestter and Enomoto, 2009) was reviewed and it was determined that the pertinent data has been incorporated into the revised responses.

References:

Benson, 1992. Benson, R. N. Map of Exposed and Buried Early Mesozoic Rift Basins/Synrift Rocks of the U.S. Middle Atlantic Continental Margin, Delaware Geological Survey Miscellaneous Map Series No. 5, 1992.

Hansen, H., and Edwards, J. Jr, 1986, The Lithology and Distribution of Pre-Cretaceous basement rocks beneath the Maryland Coastal Plain, Department of Natural Resources Maryland Geological Survey Report of Investigations No. 44, p 27.

Lassestter, W.L. Jr., and Enomoto, C.B., 2009, 2009 Southeast U.S. Mesozoic Rift Basins Energy Resources Potential Workshop, Co-Sponsors: Virginia Department of Mines, Minerals and Energy and the U.S. Geological Survey Convened Marsh 19-20, 2009, Charlottesville, Virginia, 18 p.

LeTourneau, P., 2003, Tectonic and climatic controls on the stratigraphic architecture of the Late Triassic Taylorsville Basin, Virginia and Maryland, in P. Olsen, eds., The great rift

[13] G. Gibson (UniStar Nuclear Energy) Letter UN#09-152 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated April 15, 2009.

valleys of Pangea in eastern North America, Sedimentology, Stratigraphy and Paleontology, Volume 2, p 12-58.

LeTourneau, 2006. Peter Letourneau, Wesleyan University, personal communication, 2006.

**COLA Impact**

FSAR Section 2.5.1.1.4.1.2, Mesozoic and Cenozoic Passive Margin Evolution, Section 2.5.1.2.2, Site Area Geologic History, Section 2.5.1.2.3, Site Area Stratigraphy, and Section 2.5.1.2.4, Site Area Structural Geology, will be revised as described in Enclosure 3 in a future revision of the COLA.

**Question 02.05.01-55**

CCNPP Unit 3 FSAR Section 2.5.1.2.4, Site Area Structural Geology, provides a description of the nearby Hillville fault.

a. The text states on p. 2.5-75, "A seismic line imaged a narrow zone of discontinuities that vertically separate basement by as much as 250 ft (76 m) (Hansen, 1978)." Please provide this seismic reflection line and provide a more thorough discussion about the interpretation of the seismic line.

b. The text states, "The Hillville fault may represent a Paleozoic suture zone that was reactivated in the Mesozoic and Early Tertiary." Please provide the reference for this interpretation. Please explain whether or not the Hillville fault is a basin boundary fault that could dip beneath the CCNPP. Please plot the fault on Figure 2.5-10.

c. The text states, "Based on stratigraphic correlation between boreholes within Tertiary Coastal Plain deposits, Hansen and Edwards (Hansen, 1986) ..." Please provide an illustration of the correlated boreholes.

d. The text states, "The unnamed monoclines are not depicted on any geologic maps of the area, including those by the authors, but they are shown on geologic cross sections that trend northwest-southeast across the existing site and south of the CCNPP site near the Patuxent River (McCartan, 1995) (Figure 2.5-25)." Please check the reference to Figure 2.5-25 or whether Figure 2.5.-40 should be listed as the reference.

**Response**

a. A copy of seismic reflection profile St. M-1 from Hansen (1978) was provided to the NRC in the response to RAI 71, Question 02.05.01-18[14].

As summarized in FSAR Section 2.5.1.1.4.4.4.5, Hillville Fault Zone, and the response to RAI 71, Question 02.05.01-18[14], St. M-1 was an approximately 3 mile long seismic line located 9 miles west-southwest of the site. The survey was undertaken to investigate possible basement structures related to the Sussex Currioman aeromagnetic anomaly that may be present at the basement coastal plain contact. Hansen (1978) provides only a limited discussion on the interpretation of seismic line St. M-1, which in part is due to the poor resolution of reflectors above and below the basement contact. Hansen (1978) concludes that "A reasonable interpretation of the record section suggests that two basement terranes have been juxtaposed by high angle faulting with the south block uplifted about 250 feet relative to the north." Hansen goes on to describe the reflectors above basement and associated with the Early Cretaceous Potomac Group as being discontinuous which prohibits definitive upward projection and interpretation of faulting. Below the basement/Coastal Plain reflectors are of similar quality to those above, which prevent interpretation of the underlying geologic deposits. Hansen (1978) does suggest possible dragging at the fault margins within the Potomac group rocks resulting in a queried fault drawn in the section up to a depth of about 1,700 feet. Flat-lying mid-Paleocene stratigraphy

[14] G. Gibson (UniStar Nuclear Energy) Letter UN#09-152 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated April 15, 2009.

shown in borehole data compiled by Hansen and Edwards (1986) suggests that fault activity had ceased by the early-Paleocene (see response c).

b. As requested, FSAR Figure 2.5-10 has been revised to include the trace of the Hillville fault (Hansen and Edwards, 1986).

Hansen and Edwards (1986) speculate that the Hillville fault may represent a "reactivated structural discontinuity" between "crustal blocks". Given the current geologic paradigm within the site region, the Hillville fault may represent a Paleozoic thrust fault or suture. The FSAR will be revised to clarify the discussion.

A discussion of the uncertainties associated with the presence of Mesozoic basins and basin-bounding faults is provided in the previous response to RAI 71, Question 02.05.01-26[15]. This RAI states that the assessment of the Hillville fault as a basin boundary fault, and the down-dip projection of the fault plane relative to the CCNPP site, is inconclusive based on the available data. Besides the single seismic reflection profile St. M-1 of Hansen (1978) there are no other data to indicate down-dip geometry of the fault. The strike of the fault is inferred solely from the fault's coincidence with the Sussex Currioman Bay aeromagnetic anomaly (e.g., Salisbury geophysical anomaly, FSAR Figure 2.5-22). Thus, it is unclear from the available data whether or not the Hillville fault represents the eastern or western boundary of a Mesozoic basin or some other structure entirely. Regardless of whether or not the Hillville fault dips beneath the site, there are no additional data developed since the EPRI-SOG study that suggests the Hillville fault is a capable tectonic source, and there is no impact to the seismic source characterization.

c. The FSAR text quoted in the question was summarized from Hansen (1978) and Hansen and Edwards (1986) who hypothesize that the stratigraphic pinchouts may have been structurally controlled by late-Cretaceous to early-Paleocene activity along the Hillville fault. As requested by the NRC, an example regional stratigraphic cross-section of the Coastal Plain section from Hansen (1978) is attached as Figure 1. The cross section illustrates pinchouts of the late-Cretaceous to early-Paleocene stratigraphy in the vicinity of St Mary's and Calvert Counties. In addition, the cross-section illustrates the flat-lying Aquia Formation, which suggests that any movement on the Hillville fault had ceased by the mid-Paleocene. FSAR Figure 2.5-13 presents a cross section from Achmad and Hansen (1997) which also displays stratigraphic pinchouts in late-Cretaceous to early-Paleocene stratigraphic units and the overlying almost flat-lying Aquia Formation.

d. As requested, the reference to FSAR Figure 2.5-25 in above quoted FSAR text was checked and verified as correct. The figure highlights the location of the monoclines from McCartan et al. (1995) as shown on FSAR Figure 2.5-25 as triangles.

References:

Achmad, G. and H.J. Hansen, Hydrogeology, model simulation, and water-supply potential of the Aquia and Piney Point-Nanjemoy Aquifers in Calvert and St. Mary's Counties, Maryland, Department ofNatural Resources, Maryland Geological Survey Report of Investigations No. 64, 197 p., 1997.

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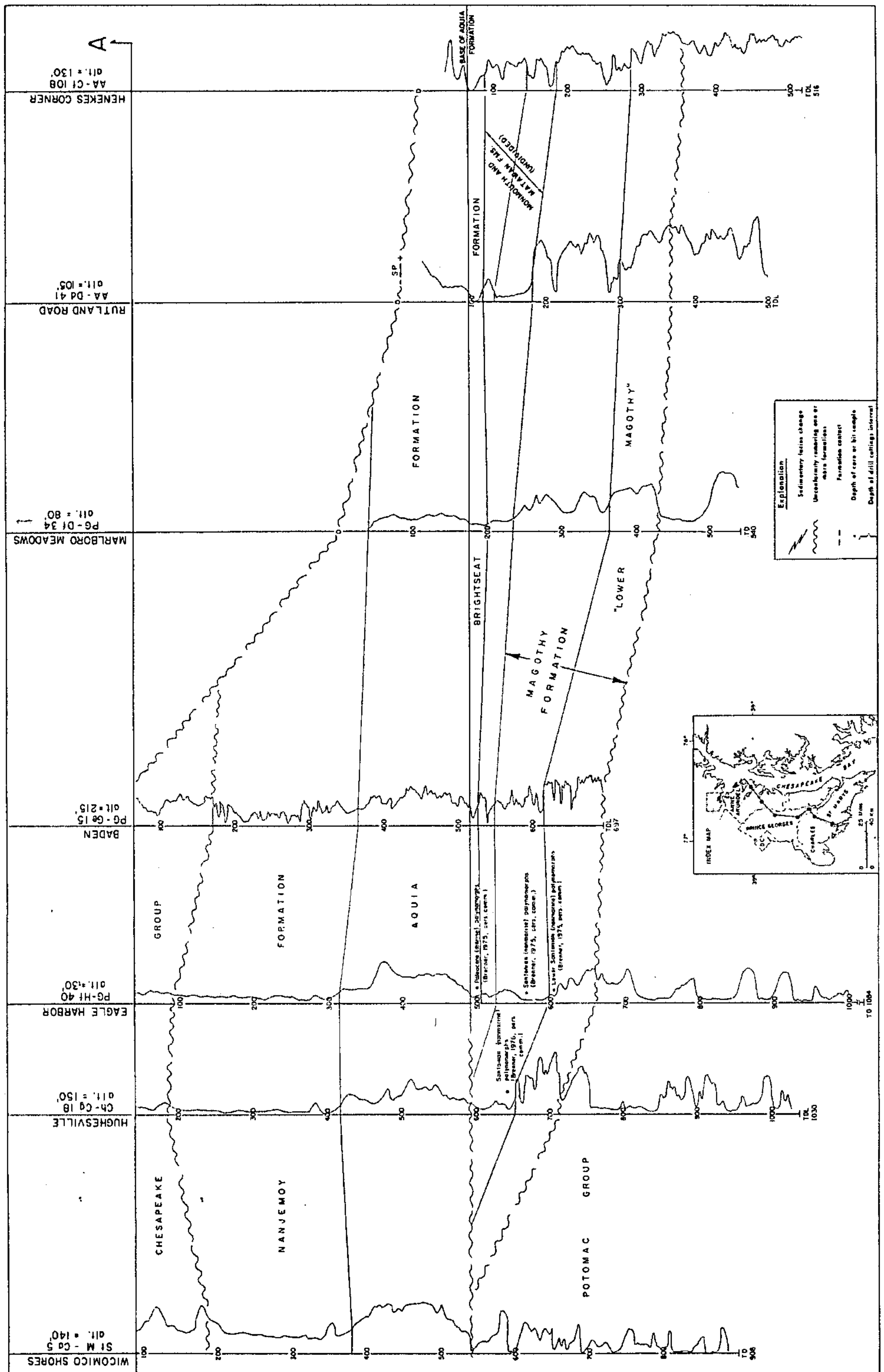
[15] G. Gibson (UniStar Nuclear Energy) Letter UN#09-152 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated April 15, 2009.

Hansen, H.J., Upper Cretaceous (Senonian) and Paleocene (Danian) Pinchouts on the South Flank of the Salisbury Embayment, Maryland and their relationship to antecedent basement structures, Department of Natural Resources Maryland Geological Survey Report of Investigations No. 29, 36 p., 1978.

Hansen, H.J. and Edwards, J., The Lithology and Distribution of Pre-Cretaceous basement rocks beneath the Maryland Coastal Plain, Department of Natural Resources Maryland Geological Survey Report of Investigations No. 44, p 27, H. Hansen and J. Edwards Jr, 1986.

McCartan, L., Newell, W., Owens, J. and Bradford, G., Geologic Map and Cross Sections of the Leonardtown 30 X 60 minute quadrangle, Maryland and Virginia. U.S. Geological Survey Open-file report OFR 95-665, p 38, 1 plate, 1995.

Enclosure 1
UN#09-389
Page 158




from Hansen and Edwards, 1986

**Question 02.05.01-55 Figure 1 – Stratigraphic cross section A-A' extending from eastern Anne Arundel County to SW St. Mary's County, Maryland**

**COLA Impact**

The COLA FSAR will not be revised as a result of this response.

**Question 02.05.01-56**

In CCNPP Unit 3 FSAR Section 2.5.1.2.6.3, Deformational Zones, the text states, "Excavation mapping is required during construction and any noted deformational zones will be evaluated." Please elaborate on your plans to map the excavation as any deformation features identified must be assessed for potential surface rupture and ground motion.

**Response**

Future excavations for safety-related structures will be geologically mapped and photographed by experienced geologists. Unforeseen geologic features that are encountered will be evaluated. Although a specific excavation mapping method has not been identified, it is likely that a photogrammetric mapping technology will be used.

**COLA Impact**

The COLA FSAR will not be revised as a result of this response.

**Enclosure 2**

**Response to NRC Request for Additional Information, RAI No. 134, Basic Geologic and Seismic Information, Questions 02.05.01-57 through 02.05.01-61, Calvert Cliffs Nuclear Power Plant Unit 3**

**RAI No. 134**

**Question 02.05.01-57**

On page 2.5-56, Calvert Cliffs Nuclear Power Plant (CCNPP) Unit 3 Final Safety Analysis Report (FSAR) Section 2.5.1 states, "The fault zone consists of a broad zone of sheared rocks, mylonites, breccias, and phyllites of variable width." Please elaborate on this statement. Do you mean phyllonites?

**Response**

The broad zone of deformation which defines the Mountain Run Fault Zone contains both phyllonites and phyllites (Pavlides, 2000). As reported by Pavlides, 2000 p.8, the Mountain Run Fault zone occupies a broad zone of "variable width which at different places contains sheared rocks, phyllonites, mylonites, breccias, and phyllites having fish-scale structure." The proposed changes to FSAR Section 2.5.1.1.4.4.5.2, Everona-Mountain Run Fault Zone, in response to RAI 130, Question 02.05.01-51, clarify this issue.

Reference:

Pavlides, L., 2000. Geology of the Piedmont and Blue Ridge Provinces, Chapter II of the pamphlet to accompany the U.S. Geological Survey, Geologic Investigations Series Map I-2607.

**COLA Impact**

FSAR Section 2.5.1.1.4.4.5.2, Everona-Mountain Run Fault Zone, will be modified as shown in Enclosure 3 in a future revision of the COLA.

**Question 02.05.01-58**

CCNPP Unit 3 FSAR Section 2.5.1 states (p 2.5.-58), "The Stafford fault (Mixon, 2000) is discussed in more detail in Section 2.5.1.1.4.4.4.1 (Stafford Fault System). The northern extension of the Stafford fault system as proposed by Marple (#16 on Figure 2.5-31) is discussed in Section 2.5.1.1.4.4.5.15."

Please explain why the Stafford fault is discussed under Tertiary Tectonic Structures (p. 2.5-46) and also under Quaternary Tectonic structures (p. 2.5-58). Also, there is no Section 2.5.1.1.4.4.5.15. Please provide the correct reference to the discussion of the northern extension of the Stafford fault system.

**Response**

As discussed in FSAR Section 2.5.1.1.4.4.4, Tertiary Tectonic Structures, and Section 2.5.1.1.4.4.5, Quaternary Tectonic Features, there is no compelling evidence for Quaternary activity of the Stafford Fault system (Mixon, 2000)(Dominion, 2004)(NRC, 2005)(Wheeler, 2005). The Stafford fault system is included in the Quaternary Tectonic features Section 2.5.1.1.4.4.5.3 to: 1) acknowledge Wheeler's (2005) inclusion of the fault zone into his database "Known or Suggested Quaternary Tectonic Faulting, Central and Eastern United States"; 2) reiterate that the fault is not Quaternary active; and 3) designed primarily to redirect the reader to Section 2.5.1.1.4.4.4, Tertiary Tectonic Structures, where there is a detailed discussion of the Stafford Fault system.

The reference to FSAR Section 2.5.1.1.4.4.5.15 is incorrect. The Stafford fault system by Marple (2004) is discussed in Section 2.5.1.1.4.4.4.1, Stafford Fault of Mixon, et al., Section 2.5.1.1.4.4.5.3, Stafford Fault of Mixon, et al., and Section 2.5.1.1.4.4.5.14, East Coast Fault System.

References:

Dominion, 2004, Response to 6/1/04 RAI 2.5.1-5, 2.5.1-6, 2.5.3-2, and 2.5.1-5, Letter No. 5, U.S. Nuclear Regulatory Committee, Serial No. 04-347, and Docket No. 52-008.

Marple, R., 2004, Relationship of the Stafford fault zone to the right-stepping bends of the Potomac, Susquehanna, and Delaware Rivers and related upstream incision along the U.S. Mid-Atlantic fall line; in Southeastern Geology, Volume 42, Number 3, p 123-144.

Mixon, 2000. Geologic Map of the Fredericksburg 30' x 60' Quadrangle, Virginia and Maryland, U.S. Geological Survey, Geologic Investigations Series Map I-2607, R. Mixon, L. Pavlides, D. Powars, A. Froelich, R. Weems, J. Schindler, W. Newell, L. Edwards, and L. Ward, 2000.

NRC, 2005, Safety Evaluation Report for an Early Site Permit (ESP) at the North Anna ESP Site – NUREG-1835, Nuclear Regulatory Commission, September 2005.

Wheeler, R., 2005, Known or Suggested Quaternary Tectonic Faulting, Central and Eastern United States – New and Updated Assessments for 2005, U.S. Geological Survey, Open File Report 2005-1336, p 37.

**COLA Impact**

FSAR Section 2.5.1.1.4.4.4.1, Stafford Fault of Mixon, et al., and Section 2.5.1.1.4.4.5.3, Stafford Fault of Mixon, et al., will be revised as shown in Enclosure 3 in a future revision of the COLA.

**Question 02.05.01-59**

CCNPP Unit 3 FSAR Section 2.5.1 states that (p 2.5-59), "First, a modified velocity model and a carefully re-evaluated earthquake catalog refined the location of the earthquakes previously inferred as aligned with the Ramapo fault, and demonstrated that approximately half of the reported earthquakes occur near the margins of the Newark Basin, far from the Ramapo fault, but still within the Ramapo fault system proper (Kafka, 1985) (Thurber, 1985) (Wheeler, 2006)."

Please explain how the 50 percent of the earthquakes aligned with the fault indicate that there is no Quaternary activity on the system. Also, please explain where the relocated earthquakes are still within the fault system proper and how this impacts understanding of the seismogenic aspects of the Newark basin and all associated faults with that basin.

**Response**

This RAI questions raises two issues summarized here as:

1. Explain how the 50% of earthquakes aligned with the Ramapo fault indicate that there is no Quaternary activity on the fault; and
2. Explain how and where the other 50% of the earthquakes were relocated and how this evaluation impacts understanding of the seismogenic aspects of the Newark basin and associated faults.

Each of these issues is discussed below.

Part 1:

The FSAR text that is the subject of this RAI question is in Section 2.5.1.1.4.4.5.4, Ramapo Fault System, and discusses research on the Ramapo fault. Specifically, the discussion of "50% of earthquakes" is referring to the work of Kafka et al. (1985). Kafka et al. (1985) analyzed 61 earthquakes occurring within the greater New York and New Jersey areas from 1974 to 1983. Considering only those earthquakes (15 in total) with magnitudes greater than $m_{bLg}$ 2.0, Kafka et al. (1985) concluded that "...about half of the earthquakes studied occurred within 10 km of the Ramapo fault system," and all of these earthquakes near the fault have magnitudes less than $m_{bLg}$ 3.0. The FSAR text does not make the statement that the earthquakes of the Kafka et al. (1985) study that are within 10 km of the Ramapo fault indicate that there is no Quaternary activity on the fault. The relevance of the Kafka et al. (1985) paper is discussed in the revised FSAR Section 2.5.1.1.4.4.5.4 as presented in response to RAI 134, Question 02.05.01-61.

Part 2:

The earthquakes discussed within Kafka et al. (1985) that are not within 10 km of the Ramapo fault and have magnitudes greater than $m_{bLg}$ 2.0 are located as follows (Figure 1):

- Three earthquakes are located within the coastal plain southwest of Long Island and east of the Newark basin;
- One earthquake is located within the Newark basin near the Hudson River and Manhattan;
- Two earthquakes are located within the Manhattan Prong; and

- One earthquake is located west of the Reading Prong near the north end of the Ramapo fault.

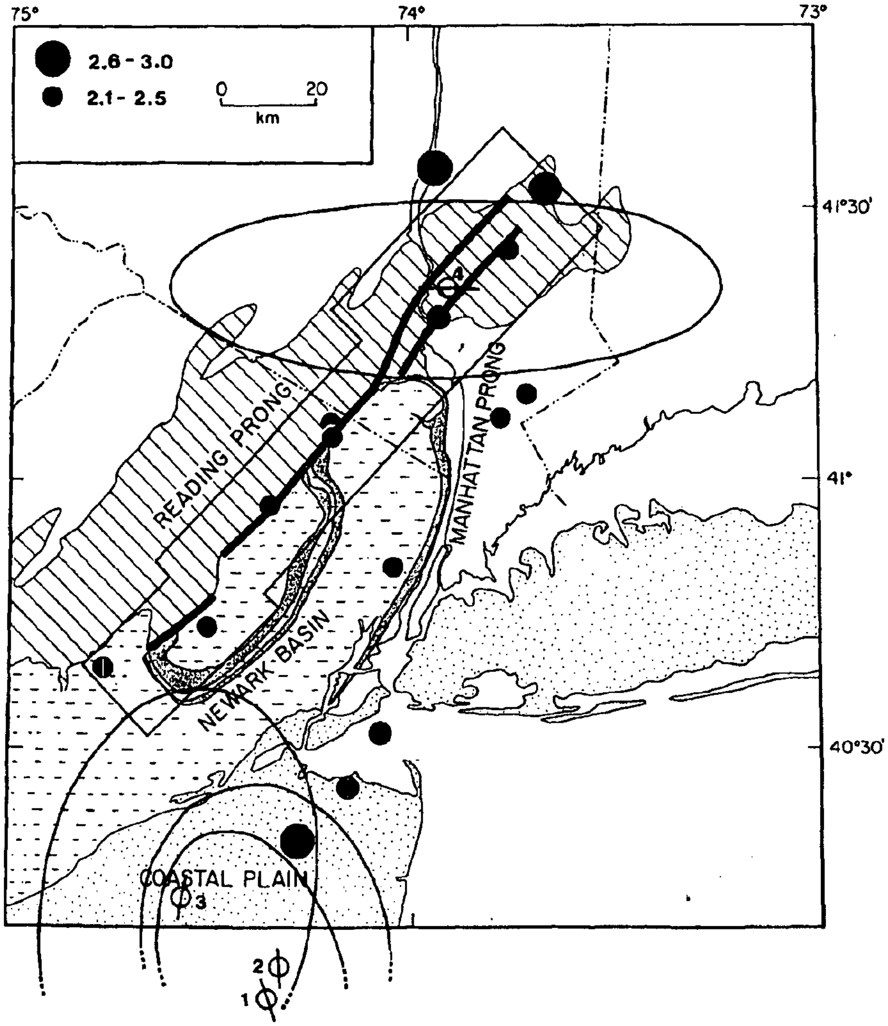
In the simplest sense, the occurrence of these earthquakes indicates that the crust within which these earthquakes occur is capable of having earthquakes with magnitudes of at least magnitude $m_{bLg}$ 3.0. These events have no impact on the understanding of the seismogenic aspects of the Newark basin and faults associated with the basin for the CCNPP site because:

- These earthquakes cannot be directly related to any distinct geologic structure (e.g., fault).
- The magnitudes of the earthquakes are all less than the minimum magnitude considered in the hazard analyses (mb 5.0). Therefore, the earthquakes do not suggest the existence of a seismic source not considered by the EPRI-SOG study.
- The general pattern of these earthquakes is consistent with earthquakes within the EPRI (1986) seismicity catalog (see FSAR Figure 2.5-52).
- These earthquakes were identified and known prior to the EPRI (1986) study.

References:

Electric Power Research Institute (EPRI), 1986, Seismic hazard methodology for the central and eastern United States, NP-4726.

Kafka, A.L., Schlesinger-Miller, E.A., and Barstow, N.L., 1985, Earthquake activity in the greater New York City area: Magnitudes, seismicity, and geologic structures Bulletin of Seismological Society of America, v. 75, p. 1285-1300.




**Question 02.05.01-59 Figure 1 – Distribution of earthquakes with $m_{bLg}$ > 2.0 as presented within Figure 8 of Kafka et al. (1985). Filled circles are earthquakes with locations determined by Kafka et al. (1985), and open circles with error ellipses are earthquakes from the early instrumental record that were not part of the analysis presented by Kafka et al. (1985)**

## COLA Impact

No COLA changes are necessary.

**Question 02.05.01-60**

CCNPP Unit 3 FSAR Section 2.5.1 states (p 2.5-59) that: "In summary, several papers infer that evidence for Quaternary deformation exists near the Ramapo fault zone (Nelson, 1980) (Newman, 1983) (Newman, 1987) (Kafka, 1989) . . . ."

Please provide more details about these papers that find evidence for Quaternary deformation. In previous paragraphs, only the Aggarwal and Sykes 1978 findings that concluded the fault system is likely active are cited.

**Response**

The NRC has requested a more detailed discussion of several papers that report evidence for Quaternary deformation along the Ramapo fault (Nelson, 1980) (Newman, 1983) (Newman, 1987) (Kafka, 1989). This additional detail is provided as part of the response to RAI 134, Question 02.05.01-61.

References:

Kafka, A.L., Winslow, M.A., and Barstow, N.L., 1989, Earthquake activity in the greater New York city area - A faultfinder's guide, in Weiss, D., ed., New York Geological Association 61st Annual Meeting Field Trip Guidebook: Middletown, New York, p. 177-203.

Nelson, S., 1980, Determination of Holocene fault movement along the Ramapo fault in southeastern New York using pollen stratigraphy: Geological Society of America Abstracts with Programs, v. 12, p. 75.

Newman, W.S., Cinquemani, L.J., Sperling, J.A., Marcus, L.F., and Pradi, R.R., 1987, Holocene neotectonics and the Ramapo fault zone sea-level anomaly: A study of varying marine transgression rates in the lower Hudson estuary, New York and New Jersey, in Nummedal, D., Pilkey, O.H., and Howard, J.D., eds., Sea-Level Fluctuation and Coastal Evolution, Society of Economic Paleontologists and Mineralogists, Special Publication No. 41, p. 97-111.

Newman, W.S., Cinquemani, L.J., Sperling, J.A., and Pardi, R.R., 1983, Holocene neotectonics of the lower Hudson Valley: Geological Society of America Abstracts with Programs, Abstract 16786, v. 15, p. 148.

**COLA Impact**

FSAR Section 2.5.1.1.4.4.5.4, Ramapo Fault System, will be revised as shown in Enclosure 3 in a future revision of the COLA.

**Question 02.05.01-61**

CCNPP Unit 3 FSAR Section 2.5.1 states (p 2.5-59), "Besides the presence of microseismicity within the vicinity of the Ramapo fault zone, there is no clear evidence of Quaternary tectonic faulting (Crone, 2000) (Wheeler, 2006), thus the Ramapo fault system is assigned a Class C designation by Crone and Wheeler (Crone, 2000)."

Please provide a complete discussion of the microseismicity associated with the Ramapo fault zone. Provide some illustrations (geologic fault, the earthquake locations in cross section and in map view). Please discuss how microseismicity is not evidence for active faulting on this structure. The Crone and Wheeler papers are compilations of the work of others and do not reflect original field work. Please use original field work research in your discussion.

Is the seismicity now associated with the Ramapo fault system and the seismicity of the relocated earthquakes that are within or nearby the Newark basin part of a seismic source that will impact the CCNPP seismic evaluation? Please provide an integrated discussion of all the research that might actually precipitate a modification to the EPRI models.

**Response**

As discussed in the introduction to FSAR Section 2.5.2, Vibratory Ground Motion, and in detail in Section 2.5.2.2, Geologic and Tectonic Characteristics of Site and Region, NRC Regulatory Guide 1.208 (NRC, 2007) was used as the primary guidance in developing the seismic source characterization for the CCNPP Unit 3 COLA. This guidance states:

> "... seismic sources and data accepted by the NRC in past licensing decisions may be used as a starting point" for the PSHA (page 14, RG 1.208)."

RG 1.208 also provides guidance stating that site-specific geological, geophysical, and seismological studies should be conducted to determine if these accepted source models adequately describe the seismic hazard for the site of interest given any new data developed since acceptance of the original models. The guidance from RG 1.208 describing this review process includes language such as the following:

> "The results of these [site-specific] investigations will also be used to assess whether new data and their interpretation are consistent with the information used in recent probabilistic seismic hazard studies accepted by NRC staff" (RG 1.208, page C-1).
>
> ". . . determine whether there are any new data or interpretations that are not adequately incorporated into the existing PSHA databases" (RG 1.208, page 11).

The key issue identified within the RG 1.208 guidance is that new data should be evaluated as to whether or not the accepted, starting point model "adequately" describes, or is "consistent" with, the new data.

For CCNPP Unit 3, the EPRI (EPRI, 1986) source characterizations are used as the base source models. As guided by RG 1.208, an extensive review of available information and data developed since the EPRI study was conducted as part of the CCNPP Unit 3 effort to determine if the EPRI source characterizations were inconsistent with or not adequate to describe the newer data. This review with respect to the Ramapo fault is presented in detail in several places, including FSAR Section 2.5.1.1.4.4.5.4, the response to RAI 134, Question 02.05.01-59, the response to RAI 71, Question 02.05.01-22[16], and the response to RAI 130, Question 02.05.01-52. As is stated in these materials, there has been no new information developed since the EPRI study that would require a revision to the EPRI source characterizations of the Ramapo fault. The text in the FSAR will be revised to provide a more detailed discussion of the Ramapo fault to support the conclusion that there is no new information that has been developed since the EPRI study that requires modifications to the EPRI.

References:

Electric Power Research Institute (EPRI), 1986, Seismic hazard methodology for the central and eastern United States, NP-4726.

NRC, 2007, Reg. Guide 1.208: A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion, US NRC, p. 53.

**COLA Impact**

FSAR Section 2.5.1.1.4.4.5.4, Ramapo Fault System, will be revised as shown in Enclosure 3 in a future revision of the COLA.

[16] G. Gibson (UniStar Nuclear Energy) Letter UN#09-227 to Document Control Desk (NRC), "Response to Request for Additional Information for the Calvert Cliffs Nuclear Power Plant, Unit 3, RAI No. 71, Basic Geologic and Seismic Information, RAI No. 72, Vibratory Ground Motion" dated May 1, 2009.

UN#09-389

**Enclosure 3**

**Response to NRC Request for Additional Information, Proposed Changes to Final Safety Analysis Report Section 2.5.1, Basic Geologic and Seismic Information**

## 2.5 GEOLOGY, SEISMOLOGY, AND GEOTECHNICAL ENGINEERING

{This section of the U.S. EPR FSAR is incorporated by reference with the following departure(s) and/or supplement(s).

This section presents information on the geological, seismological, and geotechnical engineering properties of the CCNPP3 site. Section 2.5.1 describes basic geological and seismologic data, focusing on those data developed since the publication of the Final Safety Analysis Report (FSAR) for licensing CCNPP Units 1 and 2. Section 2.5.2 describes the vibratory ground motion at the site, including an updated seismicity catalog, description of seismic sources, and development of the Safe Shutdown Earthquake and Operating Basis Earthquake ground motions. Section 2.5.3 describes the potential for surface faulting in the site area, and Section 2.5.4 and Section 2.5.5 describe the stability of surface materials at the site.

Appendix D of Regulatory Guide 1.165, "Geological, Seismological and Geophysical Investigations to Characterize Seismic Sources," (NRC, 1997) provides guidance for the recommended level of investigation at different distances from a proposed site for a nuclear facility.

- The site region is that area within 200 mi (322 km) of the site location (Figure 2.5-1).
- The site vicinity is that area within 25 mi (40 km) of the site location (Figure 2.5-2).
- The site area is that area within 5 mi (8 km) of the site location (Figure 2.5-3).
- The site is that area within 0.6 mi (1 km) of the site location (Figure 2.5-4).

These terms, site region, site vicinity, site area, and site, are used in Sections 2.5.1 through 2.5.3 to describe these specific areas of investigation. These terms are not applicable to other sections of the FSAR.

The geological and seismological information presented in this section was developed from a review of previous reports prepared for the existing units, published geologic literature, interpretation of aerial photography, and a subsurface investigation and field and aerial reconnaissance conducted for preparation of this application. Previous site specific reports reviewed include the Preliminary Safety Analysis Report (BGE, 1968) and the Independent Spent Fuel Storage Installation Safety Analysis Report (CEG, 2005). A review of published geologic literature was used to supplement and update the existing geological and seismological information. In addition, relevant unpublished geologic literature, studies, and projects were identified by contacting the U.S. Geological Survey (USGS), State geological surveys and universities. The list of references used to compile the geological and seismological information is presented in the applicable section.

Field reconnaissance of the site and within a 25 mi (40 km) radius of the site was conducted by geologists in teams of two or more. Two field reconnaissance visits in late summer and autumn 2006 focused on exposed portions of the Calvert Cliffs, other cliff exposures along the west shore of Chesapeake Bay, and roads traversing the site and a 5 mi (8 km) radius of the CCNPP site. Key observations and discussion items were documented in field notebooks and photographs. Field locations were logged by hand on detailed topographic base maps and with hand-held Global Positioning System (GPS) receivers.

Aerial reconnaissance within a 25 mi (40 km) radius of the site was conducted by two geologists in a top-wing Cessna aircraft on January 3, 2007. The aerial reconnaissance investigated the geomorphology of the Chesapeake Bay area and targeted numerous previously mapped geologic features and potential seismic sources within a 200 mi (322 km) radius of the CCNPP site (e.g., Mountain Run fault zone, Stafford fault system, Brandywine fault zone, Port Royal fault zone, and Skinkers Neck anticline). The flight crossed over the CCNPP site briefly but did not circle or approach the site closely in order to comply with restrictions imposed by the Federal Aviation Administration. Key observations and discussion items were documented in field notebooks and photographs. The flight path, photograph locations, and locations of key observations were logged with hand-held GPS receivers.

The investigations of regional and site physiographic provinces and geomorphic process, geologic history, and stratigraphy were conducted by Bechtel Power Corporation. The investigations of regional and site tectonics and structural geology were conducted by William Lettis and Associates.

This section is intended to demonstrate compliance with the requirements of paragraph c of 10 CFR 100.23, "Geologic and Seismic Siting Criteria" (CFR, 2007).}

## 2.5.1 BASIC GEOLOGIC AND SEISMIC INFORMATION

The U.S EPR FSAR includes the following COL Item in Section 2.5.1:

> A COL applicant that references the U.S. EPR design certification will use site-specific information to investigate and provide data concerning geological, seismic, geophysical, and geotechnical information.

This COL Item is addressed as follows:

{This section presents information on the geological and seismological characteristics of the site region (200 mi (322 km) radius), site vicinity (25 mi (40 km) radius), site area (5 mi (8 km) radius) and site (0.6 mi (1 km) radius). Section 2.5.1.1 describes the geologic and tectonic characteristics of the site region. Section 2.5.1.2 describes the geologic and tectonic characteristics of the site vicinity and location. The geological and seismological information was developed in accordance with the following NRC guidance documents:

- Regulatory Guide 1.70, Section 2.5.1, "Basic Geologic and Seismic Information," (NRC, 1978)
- Regulatory Guide 1.206, Section 2.5.1, "Basic Geologic and Seismic Information," (NRC, 2007) and
- Regulatory Guide 1.165, "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion," (NRC, 1997).

### 2.5.1.1 Regional Geology (200 mi (322 km) radius)

This section discusses the physiography, geologic history, stratigraphy, and tectonic setting within a 200 mi (322 km) radius of the site. The regional geologic map and explanation as shown in Figure 2.5-5 and Figure 2.5-6 contain information on the geology, stratigraphy, and tectonic setting of the region surrounding the CCNPP site (Schruben, 1994). Summaries of these aspects of regional geology are presented to provide the framework for evaluation of the geologic and seismologic hazards presented in the succeeding sections.

Sections 2.5.1.1.1 through 2.5.1.1.4 are added as a supplement to the U.S. EPR FSAR.

### 2.5.1.1.1 Regional Physiography and Geomorphology

The CCNPP site lies within the Coastal Plain Physiographic Province as shown in Figure 2.5-1 (Fenneman, 1946). The area within a 200 mi (322 km) radius of the site encompasses parts of five other physiographic provinces. These are: the Continental Shelf Physiographic Province, which is located east of the Coastal Plain Province, and the Piedmont, Blue Ridge, Valley and Ridge and Appalachian Plateau physiographic provinces, which are located successively west and northwest of the Piedmont Province (Thelin, 1991).

Each of these physiographic provinces is briefly described in the following sections. The physiographic provinces in the site region are shown on Figure 2.5-1 (Fenneman, 1946). A map showing the physiographic provinces of Maryland, as depicted by the Maryland Geological Survey (MGS), is shown on Figure 2.5-7.

#### 2.5.1.1.1.1 Coastal Plain Physiographic Province

The Coastal Plain Physiographic Province extends eastward from the Fall Line (the physiographic and structural boundary between the Coastal Plain Province and the Piedmont Province) to the coastline as shown in Figure 2.5-1. The Coastal Plain Province is a low-lying, gently-rolling terrain developed on a wedge-shaped, eastward-dipping mass of Cretaceous, Tertiary, and Quaternary age as shown in Figure 2.5-5 and Figure 2.5-6, which are unconsolidated and semi-consolidated sediments (gravels, sands, silts, and clays), that thicken toward the coast. This wedge of sediments attains a thickness of more than 8,000 ft (2,430 m) along the coast of Maryland (MGS, 2007). In general, the Coastal Plain Province is an area of lower topographic relief than the Piedmont Province to the west. Elevations in the Coastal Plain Province of Maryland range from near sea level to 290 ft (88 m) above sea level near the District of Columbia - Prince Georges County line (Otton, 1955).

Four main periods of continental glaciation occurred in the site region during the Pleistocene. Glaciers advanced only as far south as northeastern Pennsylvania and central New Jersey as shown in Figure 2.5-5 and Figure 2.5-6. However, continental glaciation affected sea level and both coastal and fluvial geomorphic processes, resulting in the landforms that dominate the Coastal Plain Province.

In Maryland, the MGS subdivides the Coastal Plain Physiographic Province into the Western Shore Uplands and Lowlands regions, the Embayment occupied by the Chesapeake Estuary system, and the Delmarva Peninsula Region on the Eastern Shore of the Chesapeake Bay as shown in Figure 2.5-7. In the site region and vicinity, geomorphic surface expression is a useful criterion for mapping the contacts between Pliocene and Quaternary ~~units as shown in Figure 2.5-5 and Figure 2.5-6~~. These geomorphic features appear to be mappable only on the more detailed county (1:62500) or quadrangle (1:2400) scales. For example, geomorphic surface expression is one of the criteria used by McCartan (McCartan, 1989b) to map the contact between Pliocene and Quaternary units in St. Mary's County. Constructional surface deposits define the tops of estuarine and fluvial terraces and erosional scarps correspond with the sides of old estuaries (McCartan, 1989a) (McCartan, 1989b). In some areas, the physiographic expression of terraces that might have formed in response to alternate deposition and erosion during successive glacial stages is poorly defined (Glaser, 1994) (Glaser, 2003c). Sea levels were relatively lower during glacial stages than present-day, and relatively higher than present-day during interglacial stages. Deposition and erosion during periods of higher sea levels led to the formation of several discontinuous Quaternary-age stream terraces that are difficult to correlate (McCartan, 1989a). The distribution of Quaternary surficial deposits in the CCNPP site area and site location is discussed in Section 2.5.1.2. Northeast of the Chesapeake Bay, the Western Shore Uplands Region consists of extensive areas of relatively

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little topographic relief, less than 100 ft (30 m). The Western Shore Lowlands Region located along the west shore of Chesapeake Bay and north of the Western Shore Uplands Region as shown in Figure 2.5-7 is underlain by interbedded quartz-rich gravels and sands of the Cretaceous Potomac Group and gravel, sand, silt and clay of the Quaternary Lowland deposits. During glacial retreats, large volumes of glacial melt-waters formed broad, high energy streams such as the ancestral Delaware, Susquehanna, and Potomac Rivers that incised deep canyons into the continental shelf. Southwest of the Chesapeake Bay, marine and fluvial terraces developed during the Pliocene and Pleistocene. As a result of post-Pleistocene sea level rise, the outline of the present day coastline is controlled by the configuration of drowned valleys, typified by the deeply recessed Chesapeake Bay and Delaware Bay. Exposed headlands and shorelines have been modified by the development of barrier islands and extensive lagoons (PSEG, 2002).

#### 2.5.1.1.1.2 Continental Shelf Physiographic Province

The Continental Shelf Physiographic Province is the submerged continuation of the Coastal Plain Province and extends from the shoreline to the continental slope as shown in Figure 2.5-1. The shelf is characterized by a shallow gradient of approximately 10 ft/mi to the southeast (Schmidt, 1992) and many shallow water features that are relicts of lower sea levels. The shelf extends eastward for about 75 to 80 mi (121 to 129 km), where sediments reach a maximum thickness of about 40,000 ft (12.2 km) (Edwards, 1981). The eastward margin of the continental shelf is marked by the distinct break in slope to the continental rise with a gradient of approximately 400 ft/mi (Schmidt, 1992).

#### 2.5.1.1.1.3 Piedmont Physiographic Province

The Piedmont Physiographic Province extends southwest from New York to Alabama and lies west of, and adjacent to, the Coastal Plain Physiographic Province as shown in Figure 2.5-1. The Piedmont is a rolling to hilly province that extends from the Fall Line in the east to the foot of the Blue Ridge Mountains in the west as shown in Figure 2.5-1. The Fall Line is a low east-facing topographic scarp that separates crystalline rocks of the Piedmont Province to the west from less resistant sediments of the Coastal Plain Province to the east (Otton, 1955) (Vigil, 2000). The Piedmont Province is about 40 mi (64 km) wide in southern Maryland and narrows northward to about 10 mi (16 km) wide in southeastern New York.

Within the site region, the Piedmont Province is generally characterized by deeply weathered bedrock and a relative paucity of solid rock outcrop (Hunt, 1972). Residual soil (saprolite) covers the bedrock to varying depths. On hill slopes, the saprolite is capped locally by colluvium (Hunt, 1972).

In Maryland, the Piedmont Province is divided into the Piedmont Upland section to the east and the Piedmont Lowland section to the west, which is referred to as a sub-province in some publications as shown in Figure 2.5-7. The Piedmont Upland section is underlain by metamorphosed sedimentary and crystalline rocks of Precambrian to Paleozoic age. These lithologies are relatively resistant and their erosion has resulted in a moderately irregular surface. Topographically higher terrain is underlain by Precambrian crystalline rocks and Paleozoic quartzite and igneous intrusive rocks. The Piedmont Lowland section is a less rugged terrain containing fault-bounded basins filled with sedimentary and igneous rocks of Triassic and Early Jurassic age.

#### 2.5.1.1.1.4 Blue Ridge Physiographic Province

The Blue Ridge Physiographic Province is bounded on the east by the Piedmont Province and on the west by the Valley and Ridge Province as shown in Figure 2.5-1. The Blue Ridge Province, aligned in a northeast-southwest direction, extends from Pennsylvania to northern Georgia. It varies in approximate width from 5 mi (8 km) to more than 50 mi (80 km) (Hunt, 1967). This province corresponds with the core of the Appalachians and is underlain chiefly by more resistant granites and granitic gneisses, other crystalline rocks, metabasalts (greenstones), phyllites, and quartzite along its crest and eastern slopes.

#### 2.5.1.1.1.5 Valley and Ridge Physiographic Province

The Valley and Ridge Physiographic Province lies west of the Blue Ridge Province and east of the Appalachian Plateau Province as shown in Figure 2.5-1. This is designated as the Valley and Ridge Province in Maryland as shown in Figure 2.5-7. Valleys and ridges are aligned in a northeast-southwest direction in this province, which is between 25 and 50 mi (40 and 80 km) wide. The sedimentary rocks underlying the Valley and Ridge Province are tightly folded and, in some locations, faulted. Sandstone units that are more resistant to weathering are the ridge formers. Less resistant shales and limestones underlie most of the valleys as shown in Figure 2.5-5 and Figure 2.5-6. The Great Valley Section of the province as shown in Figure 2.5-7, to the east, is divided into many distinct lowlands by ridges or knobs, the largest lowland being the Shenandoah Valley in Virginia. This broad valley is underlain by shales and by limestones that are prone to dissolution, resulting in the formation of sinkholes and caves. Elevations within the Shenandoah Valley typically range between 500 and 1,200 ft (152 and 366 m) msl. The western portion of the Valley and Ridge Province is characterized by a series of roughly parallel ridges and valleys, some of which are long and narrow (Lane, 1983). Elevations within the ridges and valleys range from about 1,000 to 4,500 ft (305 to 1,372 m) msl (Bailey, 1999).

#### 2.5.1.1.1.6 Appalachian Plateau Physiographic Province

Located west of the Valley and Ridge Province, the Appalachian Plateau Physiographic Province includes the western part of the Appalachian Mountains, stretching from New York to Alabama as shown in Figure 2.5-1. The Allegheny Front is the topographic and structural boundary between the Appalachian Plateau and the Valley and Ridge Province (Clark, 1992). It is a bold, high escarpment, underlain primarily by clastic sedimentary rocks capped by sandstone and conglomerates. In eastern West Virginia, elevations along this escarpment reach 4,790 ft (1,460 m) (Hack, 1989). West of the Allegheny Front, the Appalachian Plateau's topographic surface slopes gently to the northwest and merges imperceptibly into the Interior Low Plateaus. Only a small portion of this province lies within 200 mi (322 km) of the CCNPP site as shown in Figure 2.5-1.

The Appalachian Plateau Physiographic Province is underlain by sedimentary rocks such as sandstone, shale, and coal of Cambrian to Permian age as shown in Figure 2.5-5 and Figure 2.5-6. These strata are generally subhorizontal to gently folded into broad synclines and anticlines and exhibit relatively little deformation. These sedimentary rocks differ significantly from each other with respect to resistance to weathering. Sandstone units tend to be more resistant to weathering and form topographic ridges. The relatively less resistant shales and siltstones weather preferentially and underlie most valleys. The Appalachian Plateau is deeply dissected by streams into a maze of deep, narrow valleys and high narrow ridges (Lane, 1983). Limestone dissolution and sinkholes occur where limestone units with high karst susceptibility occur at or near the ground surface.

### 2.5.1.1.2 Regional Geologic History

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The geologic and tectonic setting of the CCNPP site region is the product of a long, complex history of continental and island arc collisions and rifting~~, which spanned a period of over one billion years and formed the Appalachian Mountains (Appalachian Orogen) extended continental crust and coastal plain as shown in Figure 2.5-8. This history of deformation~~

imparts a pre-existing structural grain in the crust that is important for understanding the current seismotectonic setting of the region. Episodes of continental collisions have produced a series of accreted terranes separated, in part, by low angle detachment faults. The geologic history, as deduced from subsurface exploration, rock and rock / sediment exposures, structural and stratigraphic relationships, and geophysical evidence, spans a period of more than one billion years (1000 Ma). The geologic history includes the formation of the Grenville Mountains, the Appalachian Mountains, and associated island arc and microcontinental terranes that have been accreted to the existing mid-Atlantic continental margin. The top of the Grenville Mountains have been eroded and buried beneath younger rocks, but their bases underlie much of the eastern North America continental margin. Exposed remnants of the Grenville Mountains are found where overlying rocks have been worn away by erosion and the scraping action of glaciers. In the northeast, the Grenville rocks are exposed in the Adirondacks, the Hudson and Jersey Highlands, Manhattan and Westchester in New York, the Green Mountains of Vermont, the Reading Prong of Pennsylvania, and the Berkshire Hills of Massachusetts. The Appalachian Mountains include deformed rock of the Appalachian Plateau, Valley and Ridge, Blue Ridge, and rocks of the New England physiographic provinces, including Proterozoic through Paleozoic metamorphosed thrust sheets and plutons. The Appalachian Mountains are disrupted by subsequent development of Mesozoic (Late Triassic and Early Jurassic) rift basins filled with igneous and sedimentary rocks, and basalt dikes and sills that intruded both rift basins and surrounding Piedmont crystalline basement exposed in the hilly, subdued topography of the Piedmont physiographic province. The eastward dipping clastic wedge of Cenozoic sediments overlaps some of the Piedmont and New England physiographic provinces and covers the entire Coastal Plain province. This variation in lithologies results in varied terrane that is reflected in the physiographic provinces of the region, as shown in Figure 2.5-1.

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This geologic history of the region is discussed within the context of tectonostratigraphic terranes shown in Figure 2.5-9. Episodes of continental collisions have produced a series of accreted terranes separated, in part, by low angle detachment faults or juxtaposed by higher-level normal faulting. Episodes of extension have reactivated many earlier structures and created new ones. The deformation of these terranes through time imparts a pre-existing structural grain in the crust that is important for understanding the current seismotectonic setting of the region.

Sources of seismicity may occur in the overlying, exposed, or buried terranes or may occur along structures within the North American basement buried beneath the accreted terranes or overthrust plates. That isTherefore, regional seismicity may not be related to any known surface structure. Intervening episodes of continental rifting have produced high angle normal or transtensional faults that either sole downward into detachment faults or penetrate entirely through the accreted terranes and upper crust. Understanding the geologic history, including of the evolution and the geometry of these crustal faults, therefore, is important for identifying potentially active faults and evaluating the distribution of historical seismicity within the tectonic context of the site region. Based on the geologic history presented here, the seismic implications of geologic structures and the current state of strain in the region are discussed in Sections 2.5.1.1.2.8, 2.5.1.1.3.2.1, and 2.5.2.2.

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Major tectonic events recognized in the site region include five compressional orogenies (Grenville, Potomac, Taconic, Acadian and Alleghany) and two extensional episodes (Late Precambrian rifting to produce the Iapetus Ocean and Mesozoic rifting to produce the Atlantic Ocean)(Faill, 1997a). Extension probably occurred, perhaps of less scale and duration, between each of the compressional episodes (resulting in the opening of the Rheic and Theic oceans, for example). These compressional and extensional episodes began to be recognized in the 1970s through 1980s and are depicted in Figure 2.5-8, modified from Hatcher, 1987. While direct

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evidence of these deformational events is visible in the Appalachian Plateau, Valley and Ridge, Blue Ridge, and Piedmont and New England physiographic provinces, itother evidence is buried beneath the cCoastal pPlain sediments in the site region butand is inferred based onfrom geophysical data, as described in Section 2.5.1.1.4.3, and borehole data as described in
RAI 130 02.05.01-34 Section 2.5.1.1.3. The site region is located currently on the passive, divergent trailing margin of the North American plate following the last episode of continental extension and rifting. Each of these tectonic events is described in the following paragraphs.The current stress regime of this region is discussed in Section 2.5.1.1.4.2. The history of orogenic events is described below.

### 2.5.1.1.2.1 Grenville Orogeny

The earliest of the compressional deformational events (orogenies) recorded in the rocks of North America is the Grenville orogeny that occurred during Middle to Late Precambrian (Proterozoic) time, approximately one billion years ago, as a result of the convergence of the ancestral North American and African tectonic plates. During this orogeny, various terranes were accreted onto the edge of the ancestral North American plate, forming the Grenville Mountains (Faill, 1997a), which were likely the size of the present day Himalayas (Fichter, 2000). The Grenville orogeny was followed by several hundred million years of tectonic quiescence, during which time the Grenville Mountains were eroded and their basement rocks exposed. In Virginia and Maryland, the Grenville basement rocks are exposed in the Blue Ridge Province and portions of the Piedmont Province (Fichter, 2000). This appears to be represented in Maryland by the Middletown Valley biotite granite gneiss in the Blue Ridge Province and the Baltimore Gneiss in the eastern Piedmont Province.The earliest compressional event (orogeny) recorded in the exposed rocks of the mid-Atlantic continental margin is the Grenville orogeny. Prior to the Grenville compressional event, a 'supercontinental' landmass known as Hudsonland (also known as Columbia) is postulated to have included the Laurentian craton (Pesonen, 2003). On the basis of purely paleomagnetic data, this supercontinent consisted of Laurentia, Baltica, Ukraine, Amazonia and Australia and perhaps also Siberia, North China and Kalahari. Hudsonland existed from 1830 Ma to ca. 1500–1250 Ma (Pesonen, 2003). The interior of the Laurentian craton experienced plutonism in the 1740 to 1504 Ma time frame and Hudsonland began to split apart and volcanic arcs were form between 1300 and 1250 Ma. A
RAI 130 02.05.01-34 composite arc belt or microcontinent was formed by about 1200 Ma in the Panthalassa-type ocean basin. (Carr, 2000; Murphy, 2004). This set the stage for the Grenville orogeny.

The Grenville orogeny occurred during Middle Proterozoic time, approximately one billion years ago (1000 Ma). Two phases of compression are recognized, from ca. 1080-1030 Ma and 1010-980 Ma (Carr, 2000). A composite arc or micro-continent was thrust over the eastern Laurentian margin. The uplifted terranes were dissected and exhumed by normal faulting before ca. 1040 Ma. Despite a long pre-Grenvillian tectonic and plutonic history, the present crustal architecture and much of the seismic reflectivity were acquired during the 1080-980 Ma phase of compression and extension. (Carr, 2000).

The Grenville orogeny was the result of the convergence of the ancestral North American craton (Laurentia) with proto-African tectonic plates. During this orogeny, various terranes were accreted onto the edge of Laurentia, forming the Grenville Mountains (Faill, 1997a) and the supercontinent of Rodinia (Thomas, 2006). The Grenville Mountains were likely the size of the present day Himalayas (Carr, 2004). Convergence around the periphery of the Laurentian craton produced a series of mountain ranges offset by transform boundaries.

Intrusive Grenville rocks of the north-central Appalachians are exposed in the Piedmont physiographic province of central Maryland, southeastern Pennsylvania and northern NewJersey (Figure 2.5-201). In the north-central (Maryland and Pennsylvania)

Appalachians, these massifs are separated by the Pleasant Grove-Huntingdon Valley shear zone (PGHV) into external and internal massifs (Figure 2.5-201) (Faill, 1997a). External massifs include the Reading Prong, Honey Brook Upland, Mine Ridge, and Trenton Prong. The stratigraphy of the external massifs is described in more detail in Section 2.5.1.1.3.1.1. Internal massifs include the Brandywine and Baltimore massifs (Figure 2.5-204). The stratigraphy of the internal massifs is described in more detail in Section 2.5.1.1.3.1.2. Other small external massifs are recognized throughout the area (Faill, 1997a).

External massifs are allochthonous massifs that were emplaced by Taconic or Alleghany age thrusts and are now surrounded by Paleozoic and Mesozoic age rocks. External basement massifs (closer to the foreland) in the central and northern Appalachians expose Mesoproterozoic rocks that are likely derived from the nearby craton and mark the eastern edge of Laurentia. They are important because they record the Neoproterozoic rifting of Rodinia (Figure 2.5-205) and the Paleozoic collisions of arcs and continents that eventually formed the supercontinent of Pangea (Karabinos, 2008 and Hatcher, 2004). Internal basement massifs are located in the internal parts of an orogen and can be derived from a number of sources, not necessarily from the nearby craton (Hatcher, 2004).

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The Grenville orogeny was followed by several hundred million years of tectonic quiescence, during which time the Grenville Mountains were eroded and their basement rocks exposed. The stratigraphy of Grenville remnants found within a 200-mile (322-kilometer) radius of the CCNPP site is described in more detail in Sections 2.5.1.1.3.1. Eventually, the supercontinent of Laurentia underwent a major rifting episode that led to the opening of the Iapetus Ocean (Figure 2.5-8) in late Precambrian time, 590–550 Ma (van Staal, 1998). Evidence of rifting can be found in the presence of metamorphosed mafic dikes (for example, the Chesnutt Hill Formation in the western New Jersey Highlands) (Gates, 2004) and the Catoctin and Swift Run formations in central Virginia (Bartholomew, 2004). Continued rifting produced a great basin off the Laurentian margin (the Theic or Rheic oceans) (Figure 2.5-203 and Figure 2.5-206) in which thousands of meters of quartz arenites and limestones/dolomites, including stromatolites, were deposited in shallow (e.g. Frederick Valley Chilhowee Group Weverton Formation) to deep waters (e.g. Great Valley Chilhowee Group Loudon Formation) on the continental slope and shelf platform (Cleaves, 1968) (Cecil, 2004). Further offshore in the deep water of the continental rise, fine-grained rocks (such as the Westminster terrane) were deposited as carbonates interspersed with turbidite deposits. Turbidites of the Potomac terrane were deposited even further offshore in a trench setting (Southworth, 2004). As discussed in Section 2.5.1.1.2.4, all of these units were metamorphosed, deformed, and intruded by plutons in the Ordovician Taconian orogeny (Drake, 1989)(Figure 2.5-9).

### 2.5.1.1.2.2 Late Precambrian Rifting

Following the Grenville orogeny, crustal extension and rifting began during Late Precambrian time, which caused the separation of the North America and African plates and created the proto-Atlantic Ocean (Iapetus Ocean). Rifting is interpreted to have occurred over a relatively large area, sub-parallel to the present day Appalachian mountain range (Faill, 1997a) (Wheeler, 1996). This period of crustal extension is documented by the metavolcanics of the Catoctin, Swift Run, and Sams Creek formations (Schmidt, 1992). During rifting, the newly formed continental margin began to subside and accumulate sediment. Initial sedimentation resulted in an eastward thickening wedge of clastic sediments consisting of graywackes, arkoses, and shales deposited unconformably on the Grenville basement rocks. In the Blue Ridge and western Piedmont, the Weverton and Sugarloaf Mountain quartzites represent late Precambrian to early Cambrian fluvial and beach deposits. Subsequent sedimentation included a transgressive sequence of additional clastic sediments followed by a thick and extensive sequence of carbonate sediments. Remnants of the rocks formed from these sediments can be found within the Valley and Ridge Province and Piedmont Province (Fichter, 2000). In the western Piedmont, the sandy Antietam Formation was deposited in a shallow sea. In the Valley and Ridge Province, a carbonate bank provided the environment of deposition for the thick carbonates ranging from the Cambrian Tomstown Dolomite through the Ordovician Chambersburg Formation. In the eastern Piedmont, the Setters Formation (quartzite and interbedded mica schist) and the Cockeysville Marble have been interpreted as metamorphosed beach and carbonate bank deposits that can be correlated from Connecticut to Virginia. Accumulation of this eastward thickening wedge of clastic and carbonate sediments is thought to have occurred from the Middle to Late Cambrian into Ordovician time (PSEG, 2002).

### 2.5.1.1.2.3 Late Precambrian to Early Cambrian Orogenies (Potomac/Penobscot Orogency)

~~Fossil fauna, detailed geologic mapping, petrologic investigations, and radiometric age dates indicate that the Virgilina orogeny is a Late Proterozoic-earliest Cambrian compressional deformation event that may have involved the accretion of a crustally juvenile Carolina zone to a more crustally evolved Goochland zone in the Carolinas and southern Virginia (Hibbard, 1995) as shown in Figure 2.5-8. Island arc rifting in the Carolina zone might have been associated with the Virgilina orogeny. It is possible that the Virgilina orogeny deformed the Mather Gorge Formation in the central Piedmont of Maryland and northern Virginia. The Sykesville Formation in the same area contains olistoliths of Mather Gorge phyllonite (Drake, 1999). Because the Sykesville Formation was folded prior to the emplacement of the Early Ordovician Falls Church Intrusive Suite and Occoquan Granite, that folding, originally interpreted as a result of the Penobscot orogeny, is now believed to have formed as a result of the Cambrian to earliest Ordovician Potomac orogeny. The deformation, metamorphism and west-directed thrusting affected the western portion of the Piedmont in the Potomac River Valley (Hibbard, 1995) (Drake, 1999).~~

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~~During Late Cambrian time, as the now tectonically stable continental margin continued to subside, micro-continents and volcanic arcs, characteristic of an intra-oceanic island arc terrane, began to develop in the proto-Atlantic Ocean as a result of east-directed oceanic subduction and initial closing of the proto-Atlantic. The Penobscot orogeny (documented in the Maritime Provinces of Canada) is thought to have been caused by crustal convergence and accretion of these volcanic arcs thrust over micro-continents along the North American plate margin as shown in Figure 2.5-8. This orogeny is considered to represent the beginning of the convergent phase in the closing of the proto-Atlantic Ocean (Fichter, 2000). Subsequent convergent phases in the closing of the proto-Atlantic include the Taconic and Acadian orogenies and the Allegheny orogeny that finally closed the proto-Atlantic in the Permian.~~ The Potomac orogeny is the earliest Paleozoic age orogeny recorded in the north-central Appalachians. It is recognized along the western margin of the Piedmont province and is considered distinct from the Penobscot orogeny of the northern Appalachians and the Virgilian orogeny of Northern Carolina (Hibbard and Samson, 1995). The orogeny is dated from Late Cambrian to Early Ordovician and occurred a considerable distance from the North American continental margin, as the magmatic arc(s) in the Theic ocean (including the Jefferson and Smith River terranes) were obducted over the Brandywine microcontinent (Figure 2.5-207). The orogeny started with the magmatic arcs overriding the forearc sediments of the White Clay nappe and the Liberty Complex. The Wilmington Complex in Delaware and southeast Pennsylvania overrode the Glenarm Wissahickon Formation of the White Clay nappe (Figure 2.5-200, Figure 2.5-201 and Figure 2.5-202) and the Potomac-Philadelphia terrane. This obduction created the peak metamorphism of the Potomac orogeny in this part of the north-central Appalachians and possibly generated the Arden Pluton within the Wilmington Complex (Faill, 1997a).

This obduction of the combined Wilmington Complex (Figure 2.5-202), White Clay nappe and Philadelphia terrane over the Brandywine microcontinent continued for some time, although petrologic and microprobe evidence indicates that the schists of the White Clay nappe had cooled somewhat before the amalgamate was thrust over the Brandywine microcontinent on the Doe Run fault (Figure 2.5-200 and Figure 2.5-201). The weight of the obduction is considered to have caused the microcontinent to descend (Figure 2.5-207) raising temperatures and pressures in the massifs, especially in the West Chester massif, which occupied the lowest structural level in the amalgamation (Faill, 1997a).

Around the Baltimore microcontinent, a similar amalgamation was occurring. The westward advancing magmatic arc (James Run volcanics) and ophiolites (Baltimore Mafic Complex) produced a precursory mélange (Morgan Run Formation and the potentially equivalent Sykesville Formation) (Figure 2.5-200 and Figure 2.5-201) in the accretionary wedge to the west. The accretionary wedge and magmatic arc were obducted onto the eastern portion of the Baltimore microcontinent which subsequently became submerged (Figure 2.5-200 and
RAI 130 02.05.01-34 Figure 2.5-201). During the thrusting, the Morgan Run Formation was elevated and provided a source of clasts for the associated Sykesville diamictite. The Ellicott City Granodiorite (west of Baltimore) was subsequently emplaced deep within the thickened crust between the Baltimore Mafic complex and metasediments (Faill, 1997a).

The southward extension of the Potomac Orogeny is represented by the Cambrian age Chopawamsic metavolcanics and associated mélanges of an accretionary / forearc complex. The one difference between the north-central and southern portions of theAppalachian orogeny is that microcontinents are not generally associated with the northcentral Chopawamsic or Jefferson terranes (Figure 2.5-9). The Sauratown Mountains anticlinorium and the Goochland terrane of the eastern Piedmont may have a similar history to that of the north-central Appalachians. Lithic and metamorphic evidence of the Goochland gneisses indicate that the Goochland terrane was probably derived from the North American craton (Laurentian origin) and had an emplacement history quite different from that of the Baltimore and Brandywine internal massifs (Faill, 1997a).

### 2.5.1.1.2.4 Taconic Orogeny

The Taconic orogeny occurred during Middle to Late Ordovician time and was caused by
RAI 130 02.05.01-34 continued collision of micro-continents and volcanic arcs with the eastern North America margin along an eastward dipping subduction zone during progressive closure of the ~~proto-Atlantic~~lapetus Ocean ~~as shown in~~ (Figure 2.5-8). Taconic terranes are preserved today in the Piedmont in a series of belts representing island-arcs and micro-continents. They include the Chopawamsic terrane~~belt~~, the Carolina / Albemarle arc, ~~Slate belt, the Eastern Slate belt,~~ the Goochland-Raleigh terrane~~belt as shown in Figure 2.5-9 (Bledsoe, 1980) (Fichter, 2000)~~, and the
RAI 130 02.05.01-34 Sussex Terrane, directly west of the CCNPP site, as shown in Figure 2.5-9. These ~~Taconic~~ terranes are ~~considered~~thought to have collided with, and accreted to, eastern North America craton at different times during the Taconic orogeny (Horton, 1991; Glover, 1997~~Fichter and Baedke, 2000~~). Closer to the CCNPP site, the central Piedmont in Northern Virginia, Maryland, and Pennsylvania contains several belts of rocks whose age is unknown and/or whose relation to
RAI 130 02.05.01-34 the pre- or synorogenic rocks of the Taconic ~~O~~orogen is uncertain (Drake, 1999). These stratigraphic units include the Wissahickon Formation, which is now recognized in the Potomac Valley as three distinct lithotectonic assemblages (Drake, 1999). Other stratigraphic units, whose ages range from Late Proterozoic to Late Ordovician and contain indications of Taconic deformation, include various units in the Ijamsville Belt, the Glenarm Group Belt, which includes the Baltimore Gneiss, the Potomac terrane that was thrust over the Glenarm Group belt, and the Baltimore mafic complex to the east as shown in Figure 2.5-9 (Horton, 1989)-

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~~(Bledsoe, 1980)~~ (Fichter, 2000). Additional details on the complex stratigraphy of the Taconic orogen in the Piedmont ~~are contained in~~were described by Drake (Drake, 1999).

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Accretion of the island-arcs and micro-continents to the eastern margin of North America created a mountain system, the Taconic Mountains, that became a major barrier between the ~~proto-Atlantic~~Iapetus Ocean to the east and the carbonate platform to the west. The growth of this barrier transformed the area underlain by carbonate sediments to the west into a vast, elongate sedimentary basin, the Appalachian Basin. The present day Appalachian Basin extends from the Canadian Shield in southern Quebec and Ontario Provinces, Canada, southwestward to central Alabama, approximately parallel to the Atlantic coastline (Colton, 1970). The formation of the Appalachian Basin is one of the most significant consequences of the Taconic orogeny in the region defined by the Valley and Ridge Province and Appalachian Plateau Province. The Taconic mountain system was the source of most of the siliclastic sediment that accumulated in the Appalachian Basin during Late Ordovician and Early Silurian time. Many of these units are preserved closest to the CCNPP site in the Valley and Ridge Province. A continent-wide transgression in Early Silurian time brought marine shales and carbonate sedimentation eastward over much of the basin, and a series of transgressions and regressions thereafter repeatedly shifted the shoreline and shallow marine facies. Carbonate deposition continued in the eastern part of the basin into Early Devonian time (Faill, 1997b).

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The type region of the Taconic orogeny in the northern Appalachians records the obduction of one or more volcanic arcs onto the eastward-dipping Ordovician Laurentian (Iapetan) margin. However, the southern Appalachians record late Cambrian initiation of a westward dipping subduction zone and Ordovician development of an arc-backarc system along the Laurentian margin, reflecting an extensional, not collisional, orogenesis. The limit of this Middle Ordovician extensional regime is currently unknown, but determining its northeastern extent is important in paleotectonic reconstructions of the Laurentian margin for the early Paleozoic (Barineau, 2008).

#### 2.5.1.1.2.5 Acadian Orogeny

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The Acadian orogeny ~~(Figure 2.5-8) was caused by the collision of the micro-continent Avalon with eastern North America during the Middle to Late Devonian Period.~~ began in early Devonian time and ended at the beginning of Mississippian time. Accretion of a composite Goochland-Avalonia terrane to Laurentia at c. 421 Ma and the subsequent accretion of Meguma between 400 and 390 Ma were probably responsible for the Acadian orogeny and continuing Devonian orogenesis (van Staal, 1998). The 1 billion year old (1000 Ma) Goochland terrane, possibly a displaced fragment of Laurentia (Bartholomew and Tollo, 2004) had been sutured to the Avalonia terrane in the Taconian orogeny (Sheridan, 1993).

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At its peak, the orogeny produced a continuous chain of mountains along the east coast of North America and brought with it associated volcanism and metamorphism. ~~Remnants of the Avalon terrane (the Acadian Mountains) can be found in the Piedmont Province within the pre-existing Taconic Goochland belt, Carolina Slate belt, and the Chopawamsic belt (Fichter, 2000).~~ The Acadian orogeny ended the largely quiescent environment that dominated the Appalachian Basin during the Late Ordocician and into the Silurian, as vast amounts of terrigenous sediment from the Acadian Mountains were introduced into the basin and formed the Catskill clastic wedge in Pennsylvania and northeastern New York as shown in Figure 2.5-5, Figure 2.5-6, and Figure 2.5-8. ~~Thick accumulations of clastic sediments belonging to the Catskill Formation are spread throughout the Valley and Ridge Province (Faill, 1997b). During the Mississippian Period, the Acadian Mountains were completely eroded, and the basement rocks of the Avalon terrane were exposed (Fichter, 2000).~~Vast amounts of terrigenous sediment from the Acadian Mountains were introduced into the Catskill foreland basin during the Middle and Late Devonian and formed the Catskill clastic wedge sequence in Pennsylvania and New York. Thick accumulations of clastic sediments belonging to the Catskill Formation are spread throughout the Valley and Ridge Province (Faill, 1997b). The Catskill clastic wedge is representative of fluctuating shorelines and prograding alluvial environments along the western margin of the Acadian upland. This regressional sequence is represented in the sedimentary record with turbidites, slope deposits, alternating shallow marine and nonmarine sediments and alluvial plain fining-upward sequences (Walker, 1971, Faill, 1997b and USGS, 2008). The pebbles and sand grains of the Catskill Formation in New York, Pennsylvania and Maryland are mostly composed of metamorphic and granitic rock fragments, feldspar, mica and quartz. The red color is due to the presence of a small percentage of iron oxide between the grains (Dolt and Batten, 1988). The regressive sequence in the region is bounded above and below by marine transgressions which are represented by basal black shale overlain by gray shales and mudstones capped by small amounts of siltstone (Bridge, 1994; Huber, 2000). The Catskill clastic wedge was the site of the greatest accumulation of sediment in the region depositing as much as 7,000 feet of sediment (USGS, 2008). The sediments are the thickest in the east and grow progressively thinner westward and southward into the central Appalachian Basin region (Figure 2.5-200). In general, the Acadian Orogeny was superimposed upon terranes affected or formed by the Taconic Orogeny (Figure 2.5-200) RAI 130 02.05.01-34

By Mississippian time, the Acadian Mountains had been denuded because the source material for the Catskill Delta was depleted and sedimentation ceased.

#### 2.5.1.1.2.6 Allegheny Orogeny

The Allegheny orogeny occurred during the Late Carboniferous Period and extended into the Permian Period. The orogeny represents the final convergent phase in the closing of the RAI 130 02.05.01-34 proto-AtlanticIapetus Ocean in the Paleozoic Era (Figure 2.5-8). Metamorphism and magmatism were significant events during the early part of the Allegheny orogeny. The RAI 130 02.05.01-34 Allegheny orogeny was caused by the collision of the North American and proto-African plates, and it produced the Allegheny Mountains. As the African continent was thrust westward over North America, the Taconic and Acadian terranes became detached and also were thrust RAI 130 02.05.01-34 westward over Grenville basement rocks (Fichter, 2000Mulley, 2004). The northwest movement of the displaced rock mass above the thrust was progressively converted into the deformation of the rock mass, primarily in the form of thrust faults and fold-and-thrust structures, as seen in the Blue Ridge and Piedmont Plateau Provinces. The youngest manifestation of the Allegheny orogeny was northeast-trending strike-slip faults and shear zones in the Piedmont Province. The extensive, thick, and undeformed Appalachian Basin and its underlying sequence of carbonate sediments were deformed and a fold-and-thrust array of structures, long considered the classic Appalachian structure, was impressed upon the basin. The tectonism produced the Allegheny Mountains and a vast alluvial plain to the northwest. The Allegheny Front along the eastern margin of the Appalachian Plateau Province is thought to represent the westernmost extent of the Allegheny orogeny. Rocks throughout the Valley and Ridge Province are thrust faulted and folded up to this front, whereupon they become relatively flat and only slightly folded west of the Allegheny Front (Faill, 1998).

#### 2.5.1.1.2.7 Early Mesozoic Extensional Episode (Triassic Rifting)

Crustal extension during Early Mesozoic time (Late Triassic and Early Jurassic) marked the opening of the Atlantic Ocean (Figure 2.5-8). This extensional episode produced numerous RAI 130 02.05.01-34 local, closed basins ("Triassic basins") along eastern North America continental margin (Figure 2.5-9) (Faill, 1998). The elongate basins generally trend northeast, parallel to the pre-existing Paleozoic structures (Figure 2.5-10). The basins range in length from less than 20 mi (32 km) to over 100 mi (161 km) and in width from less than 5 mi (8 km) to over

50 mi (80 km). The basins are exposed in the Piedmont Lowland of Maryland and Northern Virginia (Gettysburg and Culpeper Basins) and are also buried beneath sediments of the Coastal Plain and the continental shelf. The exposed and buried Mesozoic basins identified in Figure 2.5-9 are described more fully in FSAR Section 2.5.1.1.3.4.The closest exposed basin to the site, the Gettysburg Basin, extends northeast from the Frederick Valley at the south end of the basin into Pennsylvania. Valleys in these Mesozoic basins are developed on sandstone and shale units and trend northeast-southwest, parallel to the strike of the bedrock.

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Generally, the Mesozoic rift basins are asymmetric half-grabens with principal faults located along the western margin of the basins. Triassic and Jurassic rocks that fill the basins primarily consist of conglomerates, sandstones, and shales interbedded with basaltic lava flows. At several locations, these rocks are cross-cut by basaltic dikes. The basaltic rocks are generally more resistant to erosion and form local topographically higher landforms. In the Frederick Valley, the younger Mesozoic units are deposited on Ordovician age limestone units subject to dissolution and karst development. Areas in the Fredrick Valley underlain by limestone subject to dissolution have relatively low relief compared to the higher and more rugged terrain underlain by intrusive and extrusive rocks consisting predominantly of diabase and basalt (Brezinski, 2004).The Mesozoic rift basins along the length of the North American Atlantic margin are related to one of the largest intrusive systems in the world, the Central Atlantic Magmatic Province (CAMP) (de Boer, 2003). The CAMP intrusives were emplaced before the breakup of Pangea, during the embryonic stage of continental rifting. Correlative dike swarms are found in the western and southeastern margins of the African continental margin and the northern part of the South American continental margin (representing the "Early Jurassic Circum-Atlantic Dike System") (de Boer, 2003). The dikes of the Circum-Atlantic swarm show a convergence pattern, with a focal point near the present-day Blake Plateau, near Florida (present coordinates).

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Subsidence of the rift basins was initiated ca. 230 Ma prior to the magmatic event. Dike intrusion began in the northern (New England) section of the North American continental margin. Most of the dikes along the length of the CAMP were emplaced between 205 and 195 Ma. Similar ages are found for dike swarms in Iberia, Africa and South America. de Boer (2003) summarizes various models proposed for the production of the voluminous magma that created the dike swarms. One proposal has a single hotspot plume, located near Florida (present coordinates) beneath the Blake Plateau. Another model proposed two hot spots, one off Florida and the other in the Gulf of Maine. Another model proposes that magmas were derived from multiple, rather than localized, sources below the rift valleys. The results of de Boer (2003) analyses of the anisotropy of magnetic susceptibility across the CAMP suggest that the overall radiating pattern ofthe circum-Atlantic dikes support a plume source in the vicinity of the Blake Plateau (de Boer, 2003).

The episode of crustal extension that produced the Mesozoic rift basins of the mid-Atlantic region is believed to have ended and the Atlantic margin stabilized as a passive margin before Eocene time (see discussion in Section 2.5.1.1.4.1.2).

### 2.5.1.1.2.8 Cenozoic History

The Early Mesozoic extensional episode gave rise to the Cenozoic Mid-Atlantic spreading center. The Atlantic seaboard presently represents the trailing passive margin related to the spreading at the Mid-Atlantic ridge. Ridge push forces resulting from the Mid-Atlantic spreading center are believed to be responsible for the northeast-southwest directed horizontal compressive stress presently observed along the Atlantic seaboard.

During Cenozoic time, as the Atlantic Ocean opened, the newly formed continental margin cooled and subsided, leading to the present day passive trailing divergent continental margin. As the continental margin developed, continued erosion of the Appalachian Mountains produced extensive sedimentation within the Coastal Plain. The Cenozoic history of the Atlantic continental margin, therefore, is preserved in the sediments of the Coastal Plain Province, and under water along the continental shelf. The geologic record consists of a gently east-dipping, seaward-thickening wedge of sediments, caused by both subsidence of the continental margin and fluctuations in sea level. Sediments of the Coastal Plain Province cover igneous and metamorphic basement rocks and Triassic basin rift deposits.

During the Quaternary Period much of the northern United States experienced multiple glaciations interspersed with warm interglacial episodes. The last (Wisconsinan) Laurentide ice sheet advanced over much of North America during the Pleistocene. The southern limit of glaciation extended into parts of northern Pennsylvania and New Jersey, but did not cover the
RAI 130 02.05.01-34 CCNPP site vicinity (Figure 2.5-5 and Figure 2.5-6). South of the ice sheet, periglacial environments persisted throughout the site region (Conners, 1986). Present-day Holocene landscapes, therefore, are partially the result of geomorphic processes, responding to isostatic uplift, eustatic sea level change, and alternating periglacial and humid to temperate climatic conditions (Cleaves, 2000).

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Recent studies demonstrate that widespread uplift of the central Appalachian Piedmont and subsidence of the Salisbury Embayment represents first-order, flexural isostatic processes driven by continental denudation and offshore deposition. Studies indicate that the mid-Atlantic margin experiences an average, long-term denudation rate of approximately 10 m/m.y., and the Piedmont has been flexurally upwarped between 35 and 130 meters in the last 15 m.y. (Pazzaglia, 1994). This Piedmont upwarp and basin subsidence are accommodated primarily by a convex-up flexural hinge, physiographically represented by the Fall Zone. The current state of resulting stress on the Atlantic margin lithosphere is discussed more fully in Section 2.5.1.1.2.8 and 2.5.1.1. 4.4.

#### 2.5.1.1.3 Regional Stratigraphy

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This section contains information on the regional stratigraphy within each of the physiographic provinces. The regional geology and generalized stratigraphy within a 200 mi (322 km) radius of the CCNPP site is shown on Figure 2.5-5 and Figure 2.5-6. This section contains information on the regional stratigraphy within a 200-mile (322-km) radius of the CCNPP site. The regional geology and generalized stratigraphy within this area is shown on Figure 2.5-5 and described in Figure 2.5-6. For an illustration of regional stratigraphy, see Figure 2.5-209 through Figure 2.5-213. In this FSAR section, the description of pre-Silurian (pre-Taconian) stratigraphic units is organized by tectonostratigraphic affinity to Laurentian continental characteristics or by affinity to oceanic, island arc, or exotic microcontinent terranes. Figure 2.5-9 provides one interpretation of these tectonostratigraphic terranes within a 200-mile radius of the CCNPP site. The pre-Silurian terranes are described in FSAR sections 2.5.1.1.3.1, The Laurentian Realm, 2.5.1.1.3.2, The Iapetan Realm, and 2.5.1.1.3.3, The Peri- Gondwanan Realm. Silurian through Jurassic stratigraphic units are described in FSAR Section 2.5.1.1.3.4, The Pangean Realm. Finally, post-rifting Cretaceous, Tertiary and Quaternary sediments that drape the basement rocks across the Piedmont, Coastal Plains, and continental shelf of the mid-Atlantic margin are described in FSAR Section 2.5.1.1.3.5, Post-Pangean Sediments.

FSAR sections 2.5.1.1.3.1 through 2.5.1.1.3.5 are supported by corresponding stratigraphic columns that correlate regional stratigraphic names across the 200-mile (322 kilometer) radius of the CCNPP site. The stratigraphic units that comprise the Laurentian, Iapetan, and Peri-Gondwanan realms are correlated in Figure 2.5-209 and Figure 2.5-210. The description of stratigraphic units in FSAR Sections 2.5.1.1.3.1 through 2.5.1.1.3.3 refer to the map symbols on Figure 2.5-9. The post-Silurian through Jurassic stratigraphic units described in FSAR Section 2.5.1.1.3.4 are regionally correlated in Figure 2.5-211. The Cretaceous through Holocene stratigraphic units described in FSAR Section 2.5.1.1.3.5 are regional correlated in Figure 2.5-213.

A tectonostratigraphic map such as Figure 2.5-9 is by definition interpretive; both of the nature of boundaries, and in terms of the nature of tectonostratigraphic units. Some of the affinities depicted in Figure 2.5-9, which was based on work through 1991, have subsequently been questioned (Glover 1997, for example). According to Hibbard, the pre-Silurian Appalachian orogen is composed of three realms: Laurentian, Iapetan, and peri-Gondwanan (Hibbard, 2007). The three realms acquired their defining geologic character before the Late Ordovician. The Laurentian realm is composed of all rocks deposited either on or immediately adjacent to ancient proto-North America supercontinent known as Rodinia (see discussion in FSAR Section 2.5.1.1.2.1)at the close of the Grenville orogeny. The Laurentian realm formed the western flank of the Appalachian orogen. The Iapetan realm is a collection of terranes of oceanic and volcanic arc affinity that were caught between the Laurentian and peri-Gondwanan realm during Appalachian orogenesis. The peri-Gondwanan realm along the southeastern flank of the orogen formed near the supercontinent Gondwana and is exotic with respect to Laurentian elements. Only one terrane within a 200-mile (322-kilometer radius of the CCNPP site, the Raleigh-Goochland terrane, defies easy classification into this scheme. For the present discussion, it will be placed in the Iapetan realm.

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According to Hibbard (2006), the Laurentian realm is represented by terranes found west of the Pleasant Grove-Huntington Valley fault system (Figure 2.5-23) (incorrectly referred to as the Pleasant Valley shear zone on the Hibbard 2006 map). Peri-Laurentian and Iapetan realm terranes are found west of the Central Piedmont- shear zone (including the Spotsylvania fault). The Peri-Gondwanan realm (Carolina and related terranes) is found east of the Central Piedmont shear zone (Figure 2.5-23). See FSAR Section 2.5.1.1.4.4.2.1, Appalachian Structures, for a description of these two regional structures.

#### 2.5.1.1.3.1 The Laurentian Realm

The stratigraphic units within a 200-mile (322-kilometer) radius of the CCNPP site provide a history of the growth of the proto-North American continental margin within the past billion years. It is a history of recycling and redistribution of Mesoproterozoic crust of Laurentia, accretion and subsequent deformation of oceanic crust, volcanic arcs and microcontinents related to ancient oceans, and probable capture and subsequent deformation of portions of other supercontinents (such as the Pan-African Avalon terrane in the northern Appalachians and Suwannee terrane in the southern Appalachians, for example) by the North American continental margin.

Precambrian-age Grenville rocks of the north-central Appalachians outcrop in central Maryland, southeastern Pennsylvania and northern New Jersey (Figure 2.5-209). These exposures are metamorphic massifs that were emplaced on Taconic or Allegheny orogenic thrusts and are now surrounded by Paleozoic and Mesozoic age rocks. In the north-central Appalachians these massifs are separated by the Pleasant Grove-Huntingdon Valley shear zone (Figure 2.5-23) into external and internal massifs (Figure 2.5-201) (Faill 1997a). External basement massifs are blocks of older crust that are incorporated into the more external (foreland-ward) parts of an orogen, whereas internal basement massifs are blocks of older crust that are located in the internal parts of an orogen (Hatcher, 1983). External massifs are more likely to be derived from the nearby craton, but internal massifs can be derived from a variety of locales, not necessarily from the nearby craton, so they can be either proximally derived or parts of exotic terranes, such as the remains of the microcontinent that originated from the South America craton (Gondwana) (Faill, 1997a) (Figure 2.5-203).

Laurentian terrane (undivided): Tectonostratigraphic map (Figure 2.5-9) unit "L"

Almost half of the exposed landmass within a 200-mile (322-kilometer) radius of the CCNPP site is composed of ancestral North America, or Laurentia terrane together with probable related terranes deformed during the Grenville orogeny (see Section 2.4.1.1.2.1). The undifferentiated Laurentia terrane shown in Figure 2.5-9 includes a number of Mesoproterozoic massifs, rift-related Late Proterozoic clastic sedimentary and volcanic sequences, and deformed Paleozoic shelf and platform strata.

Chesapeake terrane: Tectonostratigraphic map (Figure 2.5-9) unit "ch"

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The character of the Chesapeake terrane and its position at the outer limits of the mid-Atlantic continental margin has raised a great deal of interest regarding its affinities. The detected presence of the Chesapeake terrane in boreholes along the central Atlantic Coast implies some relationship to the broad gravity low [tectonostratigraphic map (Figure 2.5-9) unit "g3"] known as the Salisbury gravity anomaly (Faill 1998). Gravity and magnetic data, seismic reflection profiles, and drill hole data are interpreted to indicate that Laurentian crust of Grenville age underlies the New Jersey Coastal Plain as far south as Cape May (Maguire 2003). The tectonostratigraphic map (Figure 2.5-9) indicates that this terrane continues south beneath the coast of Virginia to about the Virginia-North Carolina line. Rb/Sr age dates indicate that the basement terrane was created 1025±0.035 Ma. Basement lithologies are similar to exposed Grenville-age rocks of the Appalachians and perhaps most importantly, the $TiO_2$ and $Zr/P_2O_5$ composition of metagabbro in the Chesapeake terrane overlap those of Proterozoic mafic dikes in the New Jersey Highlands. These new findings support the interpretation that Laurentian basement extends southeast as far as the continental shelf in the U.S. mid-Atlantic region. The subcrop of Laurentian crust under the mid-Atlantic Coastal Plain implies unroofing by erosion of the younger Carolina (Avalon) supracrustal terrane. Dextral-transpression fault duplexes may have caused excessive uplift in the Salisbury Embayment area during the Alleghanian orogeny (Sheridan 1998).

#### 2.5.1.1.3.1.1 External Massifs

Grenville basement rocks are exposed in the cores of en echelon massifs which are interpreted to be allochthonous (Rankin, 1989) or para-autochthonous (Drake, 1989) and have been carried westward (current coordinates) by Taconian thrusting.

The external massifs include the Reading Prong, Honey Brook Upland, Mine Ridge, Trenton Prong and Blue Ridge massifs (Figure 2.5-201 and Figure 2.5-202). Following are brief descriptions of these massifs from Faill (1997a).

Reading Prong: Tectonostratigraphic map (Figure 2.5-9) unit "L," located immediately east of the Hamburg terrane

The Reading Prong extends from western New England southwestward across southern New York, northern New Jersey, and terminates in the vicinity of Reading, Pennsylvania in the "Little" South Mountain (Figure 2.5-201). Rocks of the Reading Prong consist of a variety of metamorphic and igneous rocks including quartzofeldspathic and calcareous metasediments, sodium-rich gneisses and amphibolites, granites and mafic plutonic rocks. The terrane, extending from the New Jersey Highlands to Reading, Pennsylvania, is underlain by a Middle

Proterozoic assemblage of intrusive plutonic rocks and migmatites, metasediments, rocks of probable volcaniclastic origin and charnockitic rocks of unknown origin (Drake, 1989).

The Hexenkopf complex is part of the Reading Prong in Pennsylvania. It apparently represents the oldest basement rocks of the Reading Prong and is overlain by the Losee Metamorphic Suite, a largely sodic plagioclase and quartz series of granofels, granitoid,and foliated rocks. The Losee Suite is overlain in turn by a sequence of quartzofeldspathic and calcareous metasedimentary rocks. The rocks in this part of the Reading Prong are considered to be a part of Laurentia, and resemble the rocks of the Honey Brook massif but not the rocks in the internal or other external massifs to the south.

Honey Brook Upland: Tectonostratigraphic map (Figure 2.5-9) unit "L," located immediately north of the Westminster terrane

The Honey Brook Upland consists mainly of amphibolite to granulite facies, felsic to mafic gneisses having sedimentary, volcanic and/or volcaniclastic protoliths. The graphitic metasediments are interlayered with felsic gneisses in some areas. These rocks are somewhat similar to the rocks of the Reading Prong and the Adirondacks in northern New York, but the lenticular ultramafites in both the Honey Brook Uplands and Mine Ridge are not present in the Reading Prong. The Honey Brook Upland, Mine Ridge and the Trenton Prong are the southeastern most external basement massifs in the central Appalachians (Drake,1989). The Honey Brook Upland overlies undated, but presumably Middle Proterozoic rocks.

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Granulite gneisses appear to be the oldest rocks in the massif, and are associated with, and probably intruded by, the Honey Brook anorthosite. The layered gneiss has both light and dark phases which are interpreted to be metamorphosed volcanics (Rankin, 1989). The layered gneiss appears to be younger than the granulite gneiss and the anorthosite. Amphibolite is found within both the layered gneiss and in the Pickering Gneiss, a coarsely crystalline highly variable rock characterized by abundant graphite and pods of marble. The intrusive rocks that characterize the Reading Prong are missing from the Honey Brook Upland.

Mine Ridge: Tectonostratigraphic map unit "L," located immediately south and west of the Honey Brook Upland

The Mine Ridge consists of amphibolite-facies felsic to mafic gneisses mixed with sedimentary and volcaniclastic protoliths and is similar to parts of the Honey Brook Upland. The presence of ultramafites in both the Mine Ridge and Honey Brook is considered to indicate either a Precambrian age oceanic provenance or tectonic emplacement along offshore and continental margin rocks. There is no evidence in the literature that there are intrusives in the Mine Ridge Anticline.

Trenton Prong: Tectonostratigraphic map (Figure 2.5-9) unit "L" located just south of the Newark Basin near Trenton, Pennsylvania

The Trenton Prong (or Trenton massif) consists of Grenville-age graphitic schists and intermediate grade gneiss with some mafic gneiss and the lithologies are similar to the schists and gneiss of the Honey Brook. The Trenton Prong contains Mesoproterozoic metagabbro, charnockite, and metadacite/tonalite, unconformably overlain by biotitebearing quartzo-feldspathic gneiss, calc-silicate gneiss, and minor marble. (Maguire, 2003). The rocks are unconformably overlain on the south by the Cambrian Chickies quartzite (Figure 2.5-209).

Blue Ridge Anticlinorium: Tectonostratigraphic map (Figure 2.5-9) unit "L," located immediately west of the Little North Mountain Fault (Figure 2.5-23)

The Blue Ridge Anticlinorium contains the largest area of exposed Laurentian crust in the Appalachians. The Grenville rocks south of Pennsylvania are dominantly derived from plutonic igneous rocks with locally stratified rock protoliths. The interpretation of these local protoliths is questionable as they could be strongly deformed dikes as well as metasedimentary rocks (Rankin, 1989). The northern-most exposure of Grenville rocks in the Blue Ridge complex occurs in northern Virginia and Maryland, north of the Potomac River.

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Above the Grenville basement rocks of the Blue Ridge Anticlinorium terrane, a clastic wedge began to form in late Precambrian time. It was intruded by basalts, presumably still related to the Iapetan rifting. The resulting terrane consists of stratified metasedimentary rocks and meta-basalts of Late Precambrian and Early Paleozoic age. The earliest sediments were siliciclastic and quartzose deposits derived from the Laurentian craton to the northwest (current coordinates). These sediments include the Chilhowee Formation within the Catoctin rift basins, the Hardyston quartzite in the Reading Prong, the Chickies, Harpers and Araby formations in Maryland, and the Weverton, Loudon, Antietam, and Harpers formations in Virginia. Some of these clastic sediments were trapped on the continental margin but some were deposited on the continental slope and deeper water in the Theic Ocean (Faill, 1997a). The clastic wedge progressively overlapped the Grenville basement rocks exposed to the northwest. Siliciclastic sediments were eventually replaced by carbonate deposition during the Early Cambrian. The eastern (present coordinates) margin of the shelf spalled large fragments of carbonate shelf deposits downslope, forming a slope-facies Conestoga Limestone. The carbonate bank, with local influx of sand and silt from the northwest (present coordinates), persisted for the next 100 ma. The carbonates varied in thickness across the platform, reflecting the impact of epeirogenic structural arches and basins (Faill, 1997a). In addition, the shelf-to-bank transition appears to have migrated back and forth in the central Laurentian continental margin because of the superposition of shelf over bank (such as slope-facies Vintage Limestone over Chilhowee clastics in Pennsylvania and slope-facies Conestoga over shelf carbonates further to the northwest (Faill, 1997a).

Eventually, the carbonate bank began to subside at different rates across its area probably also due to epeirogenic movements of the crust and the proximity to the shelf edge. This disparate subsidence produced locally different depositional environments, where contrasting carbonate sequences accumulated. These differences are reflected in the character of the Cumberland Valley, Lebanon Valley, Schuylkill and Lehigh Valley sequences (Figure 2.5-209 and Figure 2.5-210.

The initial closing of the Theic Ocean began in Middle Cambrian but the approaching tectonism did not affect the carbonate shelf until Middle Ordovician. Initial shelf response to the closure of the Theic Ocean was the Knox unconformity (Figure 2.5-200 and Figure 2.5-201). The magnitude of the Knox unconformity decreases from northwest to southeast and may non-existent from central Pennsylvania to northern Virginia because the stratigraphic section there appears to be uninterrupted (Faill, 1997a).

The Late Precambrian to Ordovician clastic wedge sediments and igneous intrusives were deformed during three successive orogenies (the Taconic, the Acadian and the Alleghanian (see FSAR Sections 2.5.1.1.2.4 through 2.5.1.1.2.6). Throughout those orogenic events, post-Silurian sediments were shed across the uplifted terranes and deposited in basins resulting from orogenic crustal flexure and faulting. These post-Silurian sediments are described in FSAR Sections 2.5.1.1.3.4.

The stratigraphic units of the Valley and Ridge physiographic province of the central Appalachians is composed of Grenvillian crystalline basement rocks overlain by pre-Silurian clastic and carbonate bank deposits similar to those of the Blue Ridge described above. The initial clastic and carbonate bank deposits may have eroded from the northern Valley and Ridge (represented by the Knox unconformity). Further south, in the Virginia and North Carolina portions of the Valley and Ridge, deposition was continuous (Faill, 1997a) through the Lower Devonian, as the effects of the closure of Iapetus moved progressively westward in the Taconic orogeny. The stratigraphy of these post-Silurian units is described in FSAR Section 2.5.1.1.3.3.1.

#### 2.5.1.1.3.1.2 Internal Massifs or Peri-Laurentian Microcontinents

The Internal Massifs in the north-central Appalachians include the Brandywine massifs in southeastern Pennsylvania and the Baltimore massifs in central Maryland. Following are descriptions of these massifs from Faill (1997a).

Brandywine Massifs: Tectonostratigraphic map (Figure 2.5-9) unit "L" and (Figure 2.5-201) unit "2"

The Brandywine massifs include the West Chester, Avondale, and Woodville bodies and possibly the gneiss in the Mill Creek "dome" (Figure 2.5-202). These four massifs comprise the Brandywine terrane of southern Pennsylvania.

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The West Chester massif consists predominantly of quartzofeldspathic granulites of variable composition and pyroxene granulites of dioritic to olivine-gabbroic composition, metamorphosed to granulite facies during the Grenville orogeny and later recrystallized to amphibolite facies. There is little information available on the gneisses of the Avondale, Woodville and Miller Creek massifs. The Brandywine gneisses of the internal massifs are quite different lithologically from the gneisses of the external massifs in that they lack large Precambrian age intrusions, charnockitic rocks are not present in the massifs and Late Precambrian dikes in the internal massifs do not have the Catoctin-affinity chemistry present in the dikes in the gneisses north of the Pleasant Grove-Huntingdon Valley shear zone (Figure 2.5-23). These differences are considered to infer that the massifs may not have been derived from the ancestral North America craton (Laurentia) but from the remains of a microcontinent that originated from the South America craton (West Gondwana) (Faill, 1997a) (Figure 2.5-203).

The gneisses of the Avondale, Woodville and Miller Creek massifs are unconformably overlain by a siliciclastic and carbonate sequence of the Setters and Cockeysville Formations, which constitute the lower part of the Glenarm Group. This group was originally defined to include the Wissahickon schist, Peters Creek Formation, Cardiff Conglomerate, and Peach Bottom Slate and underlie much of the Piedmont Province in Maryland, Delaware, Pennsylvania, and New Jersey and under the Coastal Plain to the southeast. The age of the Glenarm Group remains indeterminate, although Late Precambrian to Early Paleozoic is now generally assumed for most of the group.

Baltimore Massifs Tectonostratigraphic map (Figure 2.5-9) unit "ib"

The Baltimore Massifs lie in central Maryland clustered around the city of Baltimore (Figure 2.5-201). Seven gneiss-cored anticlines compose the Baltimore gneisses, which consist largely of layered quartzofeldspathic gneiss of granitic to granodioritc composition and are considered to be metamorphosed felsic and intermediate to mafic volcaniclastic rocks. Subordinate lithologies include amphibolite, augen gneiss, biotitehornblende gneiss and massive granitic gneiss. These gneisses are thought to represent multiple episodes of deformation in recumbent folds. These rocks are typically surrounded by carbonate and perhaps the basal clastics, forming a link between the Mesoproterozoic basement and the Avondale anticline of the Brandywine massif to the north.

Like the Brandywine gneisses, the Baltimore gneisses are different lithologically from the gneisses of the external massifs in that they lack the large Precambrian-age intrusions and charnockitic characteristics, indicating that the Baltimore massifs may also have been derived from the remains of a microcontinent that originated from the South American craton (Figure 2.5-203).

The Baltimore massifs, like several of the Brandywine massifs, are overlain unconformably by the lower Glenarm, Setters and Cockeysville Formations. In Maryland, the Cockeysville Formation is overlain by the Loch Raven schist. The Baltimore massifs and their sedimentary cover comprise the Baltimore terrane (Figure 2.5-201).

### 2.5.1.1.3.1.3 Laurentian Rift Sequences

Catoctin Rift

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The Catoctin rift (Figure 2.5-203, Figure 2.5-204, and Figure 2.5-206) is part of the Late Precambrian age intracontinental rift system sub-parallel to the eastern margin of the Laurentian craton. Rocks of the Catoctin rift are largely associated with the Blue Ridge massif, as mapped from Charlottesville, Virginia to south central Pennsylvania. The exposed rock of the Catoctin rift in Virginia, Maryland and Pennsylvania include the volcanic rocks of the Catoctin Formation (Schmidt, 1993) and the overlying sedimentary clastics of the Chilhowee Group. In Virginia and Maryland, the Catoctin volcanics are mostly basalts and are present on both flanks of the Blue Ridge anticlinorium (known in Maryland as the South Mountain). In Maryland, the volcanics overlie the Precambrian-age Grenville basement rocks whereas south of the Potomac River the Catoctin volcanics are underlain by 702-704 Ma rift-filling sediments of the Fauquier Group. Northward intoPennsylvania the volcanics are predominantly rhyolite and form the exposed core of South Mountain. Catoctin volcanics are not present above the gneisses of the Honey Brook, Reading Prong and Trenton Prong massifs, suggesting that these massifs were outside the Catoctin rift. Metabasalt dikes in these eastern massifs, however, are geochemically very similar to the Catoctin volcanics of South Mountain in Pennsylvania.

Rome Trough

The Rome Trough (Faill, 1997a) extends from eastern Kentucky northeastward through West Virginia and southwestern Pennsylvania and disappears in north central Pennsylvania (Figure 2.5-203, Figure 2.5-204, and Figure 2.5-206). It is the result of crustal extension that occurred primarily during Middle and Late Cambrian time. The trough is bounded on the northwest and southeast by steep normal faults that become listric at depth where they merge with the thrusts that originated during the Grenville orogeny. In the northcentral Appalachians, the lithology of the sediments that fill the trough is unknown. Correlative rocks outside the trough, however, consist of dolomite, limestone, sandstone and shale.

### 2.5.1.1.3.1.4 Laurentian Continental and Shelf Sediments

Early Cambrian-Early Ordovician Passive Margin Sequences

The oldest deposits on the Laurentian continental margin are Late Precambrian to Early Cambrian age siliciclastic and quartzose sediments derived from the exposed craton to the northwest (current coordinates). Continued subsidence of the continental margin through the

Cambrian caused the quartzose facies to transgress westward and a carbonate shelf to develop behind (Figure 2.5-206 and Figure 2.5-207). Once the carbonate shelf formed, supplies of siliciclastic sediment from the Laurentian craton slowed (Faill, 1997a).

In southern Virginia, the basal siliciclastic and quartzose sediments are Early Cambrian in age and become progressively younger to the northwest. In northwestern Pennsylvania the oldest of these rocks are Middle Cambrian in age and in southern Ohio they are Early Ordovician. The Chilhowee sequence which is thickest in the Catoctin rift becomes progressively thinner toward the shelf edge (Figure 2.5-206). The Hardyston quartzite in the Reading Prong and the Lowerre quartzite in the Manhattan Prong in southern New York are much thinner across the New Jersey arch and into southern New England (Cheshire Quartzite) and thicken again in west central Connecticut (Faill, 1997a).

In Maryland, the first sediments deposited were sands which later became the Weverton and Sugarloaf Mountain quartzites. These were deposited during the Late Precambrian or Early Cambrian time followed by the Harpers, Urbana and Ijamsville formations. Sands and thin mud of the Setters Formation were deposited on the shelf edge together with the sands of the Antietam Formation. Farther offshore, mud and silt deposits would later become the Araby and Cash Smith formations (Schmidt, 1993).

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Siliciclastic deposition near the shelf edge of the north-central Appalachians was replaced by carbonate deposition during the Early Cambrian (Figure 2.5-206 and Figure 2.5-207), indicative of either a decreased volume of siliciclastic deposits and/or a northwestward migration of the shoreline. In Maryland and Virginia, the carbonate-rimmed continental shelf graded into a carbonate ramp. In Maryland, the thick accumulations of limestones and dolomites include all of the formations between the Tomstown Dolomite and the Chambersburg formations, with the exception of the Waynesboro Formation (Schmidt, 1993). In southern New York, the shelf edge in the Manhattan Prong is represented by the Inwood Marble, which is correlated with the Wappinger Limestone, north of the Manhattan Prong. The carbonate bank edge or rim presently lies roughly along a line from White Marsh Valley north of Philadelphia to Lancaster and southwestward through Hanover and then through Frederick, Maryland (Figure 2.5-201). The current location of the carbonate bank edge in the latter area is due to thrusting during the Taconic and Alleghany orogenies (Faill 1997a).

Late Ordovician Drowning Margin Sequences

Subsidence of the continental shelf was not uniform. In northwestern Pennsylvania, the clastic/carbonate sequence thickens considerably to the southwest (Figure 2.5-206). The sequence becomes thinner to the north in southeastern New York as well as to the west and northwest and thickens again farther north in the Champlain Valley. Near the shelf edge, the sequence thins to the northeast over the New Jersey arch and to the southwest over the Virginia arch. These thinner sequences and the inferred arches have been related to the New York and Virginia promontories (Faill, 1997a).

An unconformity (Figure 2.5-207) extending from eastern Pennsylvania to western Massachusetts during the Early and Middle Cambrian produced locally different environments of deposition. The variations are shown in several stratigraphic sequences including the Cumberland Valley, Lebanon Valley, Schuylkill, and Lehigh Valley sequences (Figure 2.5-204 and Figure 2.5-207). While initial tectonic events in the Theic Ocean may have started in the Middle Cambrian, it was not until the Middle Ordovician that the carbonate shelf was significantly affected. The Knox unconformity (Figure 2.5-207) developed as a result of flexural bulge during the Middle Ordovician. Rocks as old as Late Cambrian were eroded and subsequently overlain by Chazyan carbonates. The magnitude of the unconformity decreases to the southeast and is possibly absent from central Pennsylvania to northern Virginia where the stratigraphic sequence is uninterrupted. The Blackriveran unconformity affected Llanvirn to Early Caradoc rocks along the shelf margin from south-central Pennsylvania into New Jersey. In west-central New York and southeastern Ontario it occurs as an east-west trending arch under Lake Ontario and into the southwestern Adirondacks where approximately 1 km of shelf sequence from the Upper Cambrian age Potsdam Formation to the top of the Beekmantown Group was eroded form the arch crest. The arch was then unconformably overlain by the widespread Lowville Formation (Blackriveran) and Trenton units (Faill, 1997a).

#### 2.5.1.1.3.2 The Iapetan Realm

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Based on a compilation of core and cuttings descriptions from wells that penetrated the buried basement complex in the Maryland Coastal Plain and on regional magnetic and gravity data, Hansen (1986) interprets three distinct belts of crystalline rock underlying Cretaceous sediments (Figure 2.5-11). The "Inner Belt" has lithologies and geophysical characteristics similar to the adjacent, exposed Piedmont. As such, this belt appears to be similar to rocks that had been mapped as part of the Wissahickon Group, Baltimore Mafic Complex and the James Run Formation. Rocks of the Middle Belt do not crop out in Maryland but, based on along-strike projections, appear to be similar to the Fredericksburg Complex and Petersburg Granite in Virginia. Although schist or phyllite was logged in borehole CH-BE 57 (Figure 2.5-11), and CH-DA 6-14 toward the southeast, this belt appears to consist of more gneissic and granitic rocks. The Middle Belt in Maryland appears to be characterized by a relatively smooth, anomaly-free, magnetic gradient. The Outer Belt contains diverse lithologies such as gneisses, schists, mafic intrusives and metavolcanics rocks. En echelon geophysical anomalies are truncated at the contact with the Middle Belt. Hansen (1986) interpret the geophysical data as indicating that the Outer Belt may have been accreted to the main North American plate subsequent to the Taconic Orogeny.

#### 2.5.1.1.3.2.1 Iapetan Slope and Abyssal Deposits

*2.5.1.1.3.2.1.1 Iapetan Continental Slope and Rise Deposits*

Hamburg terrane: Tectonostratigraphic map (Figure 2.5-9) unit "ah"

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The Hamburg terrane is an allochthonous continental slope and rise sequence of the Laurentian margin. The Hamburg terrane, located in southeastern Pennsylvania, is one of the southernmost of the Taconic klippen that are so prominent in the central and northern Appalachians (Figure 2.5-9) (Hatcher, 2007). Like the Westminster terrane, the rocks of the Hamburg terrane are Late Proterozoic to Early Cambrian in age. The Hamburg terrane has been tectonically thickened and has been inferred to represent an Early Paleozoic subduction complex. The terrane is composed of alternating sequences of sandstone, siltstone, olive-green mudstone (~85%), and red, purple and light green mudstone, deep water limestone, and radiolaria-bearing siliceous mudstone and chert. Minor proportions of pebble and boulder conglomerate and mafic intrusive and extrusive igneous rocks are also present (Lash, 1989). The generally coarsening-upward sequence has been interpreted as reflecting a migration from an abyssal plain on oceanic crust to a trench (Lash, 1989). Later analyses of the pebble/boulder conglomerate and intrusive and extrusive igneous rocks suggest that minor portions of the Hamburg terrane are para-autochthonous, with deposition of Late Ordovician siliciclastics and igneous rocks produced and erupted during complex plate interactions with subduction of the Laurentian margin beneath the Taconic arc (Figure 2.5-209 and Figure 2.5-210, Middle Ordovician). The Hamburg terrane was emplaced into the foreland basin (Martinsburg formation) on the Yellow Breeches fault (Figure 2.5-23) early in the Taconic orogeny (Ganis, 2005).

During Early and Middle Cambrian the transition between continental shelf and slope shifted back and forth. This shifting is evident from the presence of Vintage Limestone over Chilhowee clastics in southern Lancaster County and the Conestoga Formation over shelf carbonates farther to the northwest (Figure 2.5-206). The presence of Upper Cambrian and Ordovician shelf carbonates in central Lancaster County, however, indicate that this slope edge did not shift any further to the north (Faill, 1997a).

In Maryland, the transition between continental shelf and slope is considered to be somewhat different. From Early Cambrian to Middle Ordovician the slope edge migrated eastward towards the Octoraro Sea. The change from deep to shallow water facies of the Upper Cambrian Frederick limestone suggests a carbonate ramp rather than a reef rim. To the northeast, the correlative transition during Late Cambrian to Middle Ordovician is hidden under Westminster terrane siliciclastics south of the Martic Line in Pennsylvania and under Mesozoic and/or Cenozoic age rocks farther east in New Jersey (Figure 2.5-201). This lack of exposure of shelf to slope deposits within the north-central Appalachians led to a decade long controversy over- whether the Martic Line represents a conformable contact or a thrust fault (Faill, 1997a).

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The Martic Line, east of the Susquehanna River, is the surface trace of the contact between the Lower Paleozoic carbonates of Chester and Lancaster Valleys and the siliciclastic rocks to the south (Figure 2.5-201). West of the Susquehanna River, west of Long Level in York County and southwestward into Maryland, the Martic Line does not correspond to the siliciclastic-carbonate boundary but rather was mapped between two predominantly pelitic assemblages. It is now generally considered that the Martic Line along the south edge of Chester Valley represents an early Taconic thrust fault which carried the Lower Paleozoic Octoraro Formation over the Conestoga Formation and the other Lower Paleozoic carbonates (Figure 2.5-207) with superposed late Alleghany transpressional shear zones. Along the Martic Line trace southwest of Mine Ridge, the relations are complicated by multiple thrusts and repetitious stratigraphy. An apparent break in the Conestoga Formation supports the interpretation of a thrust fault. West of the Susquehanna River the southern edge of the carbonate shelf is hidden under the Alleghany-age Stoner thrust sheet. The Martic Line disappears farther southwestward under the southeastern portion of the Gettysburg basin. It reappears in central Maryland as a thrust fault between the slope shales and siltstones of the Cash Smith and Araby formations below and the slightly older Ijamsville and Urbana Formations above (Faill, 1997a).

#### 2.5.1.1.3.2.1.2 *Iapetan Abyssal Deposits*

Octoraro Sea

Translational movement in the Theic Ocean positioned the Brandywine and Baltimore microcontinents east (present coordinates) of the Laurentian craton creating the Octoraro Sea (Figure 2.5-206), its size throughout the Cambrian mainly dependent on the positions of these microcontinents. The apparent absence of carbonate shelf deposits southeast of the Martic Line is considered to indicate that the Octoraro Sea had already formed by the Early Cambrian. The Peters Creek Formation occupied the southeastern part of the sea and suggests a continental source consisting of interlayered sequences of quartzites, psammites, and pelites. The Jonestown Basalt in the Hamburg klippe and the Sams Creek Metabasalt in the western Piedmont of Maryland (Schmidt, 1993) and Pennsylvania suggest either an oceanic or highly-attenuated transitional continental/oceanic source (Faill, 1997a).

The sediments and volcanics deposited in the Octoraro Sea now make up the Westminster terrane (Figure 2.5-201). It is comprised of three segments, the Martinsburg segment, the

Octoraro segment, and the Peters Creek segment. The Martinsburg segment includes the Urbana, Ijamsville, and Marburg Formations. The Octoraro segment includes Sams Creek, Gillis, Pretty Boy, and the Octoraro formations and is separated from the Marburg segment in Maryland by the Linganore thrust. The Peters Creek segment includes the Peters Creek Formation only (Faill, 1997a; Schmidt, 1993).

Westminster terrane: Tectonostratigraphic map (Figure 2.5-9) unit "aw"

The Westminster terrane of Maryland and Pennsylvania includes rocks previously described as Ijamsville-Pretty Boy-Octoraro terrane (Horton, 1989). This terrane consists of pelitic schist or phyllite, characterized by albite porphyroblasts, and a green and purple phyllite unit.

The rocks of the Westminster terrane have been interpreted to be a slope-rise deep-water prism related to the initial rifting of the Theic Ocean. At some point during the initial rifting, the Brandywine and Baltimore microcontinents (Section 2.5.1.1.3.1.1.2) moved independently within the Theic Ocean between the eastern cratonic margin and developing magmatic arc(s) (Figure 2.5-203). The Octoraro Sea is a proposed arm of the Theic Ocean, between the Laurentian margin and the South American craton (Faill, 1997a). The sediments that accumulated in the sea, mostly from the microcontinents, now constitute the Westminster terrane (Figure 2.5-201).

The rocks are probably correlative with rocks in the Hamburg terrane of Pennsylvania (Drake, 1989; Horton, 1991). The Westminster terrane rocks were metamorphosed to greenschist facies, assembled as a thrust sheet, and finally folded and contractually inverted during the Taconic orogeny (Southworth, 2006).

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The Westminster terrane is comprised of three segments, the Marburg segment, the Octoraro segment, and the Peters Creek segment (Figure 2.5-201). The Marburg includes the Urbana, Ijamsville, and Marburg formations. The Octoraro segment includes Sams Creek, Gillis, Pretty Boy, and the Octoraro formations and is separated from the Marburg segment in Maryland by the Linganore thrust. The Peters segment includes the Peters Creek Formation only (Figure 2.5-209 and 2.5-210) (Faill, 1997a; Schmidt, 1993).

While the metamorphic overprint of Westminster terrane rocks shows evidence of Early Silurian and Middle Devonian thermal events, the highest temperature steps of the age spectrum of these rocks record ages that are consistent with cooling from Grenvillian metamorphism (Mulvey, 2004). The Westminster terrane is thought to have been thrust over the unmetamorphosed, Cambro-Ordovician Frederick Valley Limestone along the Martic Line fault onto the Laurentian margin during the Ordovician Taconic orogeny. (Mulvey, 2004). Later, rocks of the Potomac terrane were transported westward onto rocks of the Westminster terrane along the Pleasant Grove fault (Figure 2.5-23). The Pleasant Grove fault is a ductile shear zone as much as 1 to 2 km wide that initially formed as a thrust fault during deformation associated with the Ordovician Taconian orogeny (Drake, 1989).

Theic Ocean

The Theic Ocean beyond the Brandywine and Baltimore microcontinents was an oceanic basin. Parts of several separate structural bodies that existed in the Theic Ocean were obducted onto the North American continental margin during the Taconic orogeny, some of which were assembled during the Potomac orogeny. These structural bodies each represent a different Theic component and include the Philadelphia terrane, the Wilmington Complex, White Clay nape and Cecil Amalgamate (Figure 2.5-202). Following are descriptions of these structural bodies from Faill (1997a).

Philadelphia terrane

The Philadelphia terrane in southeastern Pennsylvania (Figure 2.5-201 and Figure 2.5-202) consists mostly of the Wissahickon Formation, a group of schists and gneisses whose pelitic and psammitic layering indicate accumulation of siliciclastic sediments in a basin environment, possibly as turbidites. The general homogeneity of the Wissahickon throughout the Philadelphia terrane indicates that the part of the Theic Ocean from which the terrane came, was an open basin. The lack of true amphibolites in the terrane indicates that it developed at some distance from any magmatic source. The presence of Springfield Granodiorite and Lima Granite in the Wissahickon Formation suggest a possible affinity with the Ellicott City Granodiorite in Baltimore, Maryland. The present northern contact of the Philadelphia terrane is the Huntington Valley fault (Figure 2.5-201). Initial contacts of the Philadelphia terrane were considered to be thrust faults but the evidence to support this has either been obscured, covered or destroyed by later deformation. The southeastern boundary of the terrane is hidden under Coastal Plain sediments. The early contact between the terrane and the Brandywine terrane to the west was obscured by Taconic shearing along the Rosemont fault. The contact with the White Clay nappe farther south is hidden under the Wilmington Complex.

White Clay Nappe

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The White Clay Nappe (Figure 2.5-201 and Figure 2.5-202) consists of pelitic and psammitic schists and gneisses of the "Glenarm Wissahickon," so named because in the past they have been related to the Wissahickon of the Philadelphia terrane and formed part of the Glenarm Series. The White Clay Nappe schists and gneisses are lithologically similar to the metasedimentary micaceous and quartzose schists and gneisses of the Wissahickon Formation of the Philadelphia terrane. However, they are separated from the Philadelphia terrane by the Rosemont fault and so associated with ultramafic bodies. On the northwest side, the nappe rocks are in fault contact with the Brandywine massifs, they overlie the Cockeysville and Setters Formations in the western part of the massifs and lie directly on massif gneisses in the east. Evidence suggests that the White Clay nappe was probably generated out of the accretionary wedge that accumulated in front of the northwestward moving magmatic arc. The nappe rocks were subsequently carried on the Doe Run thrust over the massifs of the Brandywine terrane.

Cecil Amalgamate

The Cecil Amalgamate lies mostly in Maryland, southeast of the Westminster and Baltimore terranes and southwest of the White Clay nappe (Figure 2.5-202). A portion of it, the Liberty Complex, lies between the Westminster and Baltimore terranes (Figure 2.5-201). It occupies northern Cecil County, eastern and northern Harford County, and southern Baltimore County. The Liberty Complex crosses northern Baltimore County into Carroll County where it passes southward into the Potomac terrane, which is a complex of thrust sheets and sedimentary mélanges that extend southward into northern Virginia. The Cecil Amalgamate consists of five separate lithic assemblages, the Liberty Complex, the Baltimore Mafic Complex, a metasedimentary sequence, the James Run Formation and the Port Deposit Tonalite. All of these five separate assemblages, while quite distinct lithologically, all have characteristics that relate them to a magmatic arc origin.

The Liberty Complex is the northwestern-most assemblage of the Cecil Amalgamate and consists of the Morgan Run Formation and the younger Sykesville Formation. The assemblage is considered to represent an accretionary wedge accumulated in front of a westward advancing magmatic arc. Fragments of basalt, amphibolite and ultramafics from the magmatic arc were deposited in the Morgan Run schist, while blocks from the Morgan Run were incorporated into the Sykesville metadiamictitic mélange. The combined Morgan Run-Sykesville assemblage was thrust over the Baltimore terrane to its present location between Baltimore and Westminster terranes.

The Baltimore Mafic Complex lies southeast of the Baltimore and Westminster terranes and includes the Aberdeen block (Figure 2.5-201). It consists of a layered sequence of ultramafic, cumulate mafic and mafic intrusives, and volcanic rocks. It has many of the characteristics of an ophiolite sequence, but evidence suggests that it may not be derived from typical depleted oceanic crust as it contains contamination from continental material. The Baltimore Mafic Complex probably developed in a magmatic arc setting over a subduction zone with its contamination coming from subducted continental sediment from nearby microcontinents.

South of the main body of the Baltimore Complex (Figure 2.5-201) lies a belt of metasedimentary rocks which consist of pelitic schists, diamictites, and metagraywackes. The clasts in the diamictites are reported to match lithically the metavolcanics of the James Run Formation and the felsic rocks of the Port Deposit Tonalite indicating that they accumulated in close proximity to both. This metasedimentary belt is reportedly included within the Potomac terrane and Morgan Run Formation in a couple of publications.

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The James Run Formation is the southeastern-most belt of the Cecil Amalgamate (Figure 2.5-201) and consists of a sequence of mostly felsic to intermediate rocks of bimodal volcanic, hypabyssal, and volcaniclastic origin. The rocks of the James Run Formation have been associated with the Chopawamsic terrane because of the lithological similarities between the James Run rocks and the rocks of the Chopawamsic terrane. However, an alternate interpretation is that the James Run Formation has a greater chemical affinity to the Baltimore Mafic Complex than to the Chopawamsic Formation (Faill, 1997a).

Within the metasedimentary belt and the James Run Formation is the Port Deposit Tonalite, a metamorphosed felsic pluton (Figure 2.5-201). It has a gradational contact with the James Run Formation and is chemically similar to these volcanics. It is considered to be the extrusive equivalent of the James Run and pre-dates the Taconic orogeny; a post-Taconic shallow granodiorite/granite (the Basin Run Granitoid) reportedly lies to the northwest.

#### 2.5.1.1.3.2.2 Iapetan Oceanic Crust Remnants

Variously sized bodies of ultramafic rocks are found within the Baltimore Gneiss, all parts of the Wissahickon Formation, and the Peters Creek Schist and variably tectonized schist. They are primarily serpentinite, ranging in color from dark green to yellow-green. Steatite, chlorite-talc schist, anthophyllite schist, pyroxenite, and norite are also present. The relationships between the ultramafic and surrounding rocks, and between the ultramafic bodies themselves, are unclear. The age of these rocks is also uncertain. The largest bodies lie along and near the Rosemont Fault. Other concentrations of ultramafic rocks are close to the boundary between the Avondale Anticline and West Chester Massif, and to the Cream Valley Fault. The remaining small bodies are scattered through the surrounding rocks with no apparent pattern. Examples of possible obducted oceanic crust include the Bel Air-Rising Sun terrane [Tectonostratigraphic map (Figure 2.5-9) unit "ob"] and the Sussex terrane [Tectonostratigraphic map (Figure 2.5-9) unit "os"].

A newly identified remnant of the Siluro-Devonian ocean crust is the Cat Square terrane (Merchat, 2007). The Cat Square terrane is located just south of the Virginia-North Carolina border southwest of the Milton terrane. It is bound on the west by the Brevard fault zone (southern extension of the Bowens Creek fault) and on the east by the central Piedmont suture (Figure 2.5-23). The terrane consists of metapsammite and pelitic schist that was intruded by Devonian anatectic granitoids. Rare mafic and ultramafic rocks occur in the eastern Cat Square terrane. The metapsammite and pelitic schist may represent turbidites derived from approaching highlands on both sides of the closing ocean.

#### 2.5.1.1.3.2.3 Iapetan Volcanic Arc Terranes

The volcanic arcs accreted along the mid-Atlantic margin of North America consist of a collection of terranes that generally display first-order similarities with respect to lithic content and depositional-crystallization ages; however, each of these terranes records differences with respect to the proportions of different rock types, isotopic signatures of magmatic rocks, and tectonothermal histories that distinguish one terrane from another. The components of the zone can be crudely divided on the basis of tectonothermal imprint. Some elements have remained at upper crustal levels throughout their history, experiencing mainly low-grade metamorphism and simple structural imprints and thus are designated "suprastructural" terranes; primary structures are commonly preserved in these terranes, thus allowing for the establishment of stratigraphic sequences (Hibbard, 2003). Suprastructural terranes include the Wilmington, Chopawamsic, Milton, Carolina / Albemarle, Spring Hope, and Roanoke Rapids terranes (Figure 2.5-9). Locally some of these terranes display higher grade metamorphism and complex structural geometries. The accreted island arc terranes are described in the following paragraphs.

Wilmington terrane: Tectonostratigraphic map (Figure 2.5-9) unit "cw"

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The Wilmington terrane consists of granulite grade felsic to mafic gneisses presently exposed in northern Delaware and adjacent Pennsylvania (Figure 2.5-201 and Figure 2.5-202). The complex is considered to have formed in the lower portion of a magmatic arch that developed over an eastward dipping subduction zone in the ocean basin as early as the Middle Cambrian. Its emplacement over the Philadelphia terrane, White Clay nappe, and Brandywine Avondale massif occurred during the Late Proterozoic-Early Cambrian Potomac orogeny (Faill, 1997a).

Chopawamsic and Milton terranes: Tectonostratigraphic map (Figure 2.5-9) unit "vcp" and "um," respectively

The Early Cambrian Chopawamsic terrane and its southeastward extensions, the Milton terrane, comprise a broad central part of the Piedmont Province extending from southeast Delaware to North Carolina. The Chopawamsic and Milton terranes consist predominantly of meta-sedimentary and meta-volcanic rocks. The Chopawamsic terrane includes the Ta River (Virginia) and James Run (Maryland) metamorphic suites (Figure 2.5-209). The Ta River and James Run metamorphic suites consist of a sequence of amphibolites and amphibole-bearing gneisses with subordinate ferruginous quartzites and biotite gneiss. Rocks of the Ta River Metamorphic Suite are generally thought to be more mafic and to have experienced higher-grade regional metamorphism than the rocks of the Chopawamsic Formation (Spears, 2002).

The Chopawamsic and Milton terranes are interpreted to be vestiges of island-arc(s) that were accreted to ancestral North America during the Taconic orogeny (Figure 2.5-208). The terranes consist of sequences of felsic, intermediate and mafic meta-volcanic rocks with subordinate meta-sedimentary rocks. The Chopawamsic and Milton terranes (and others described later in this section) are regarded as exotic, or suspect, terrains that formed ocean-ward from the Laurentian continental margin. Recent U-Pb studies consistently yield Ordovician ages for

Chopawamsic volcanic rocks. Rb-Sr and U-Pb dating of granite plutons give late Ordovician ages (Spears, 2002). Detrital zircon ages for the Arvonia and Quantico overlap sequences indicate deposition in early Devonian/late Silurian.

Figure 2.5-9, based on the Horton map (1991) correctly shows the regional extent of the Milton terrane as a southern extension of the Chopawamsic terrane. However, the map legend indicates that the Milton terrane represents an accreted portion of continental crust, distinct from the volcanic arc affinity of the Chopawamsic terrane. Subsequent analytical work shows conclusively that the Milton terrane rocks are isotopically, geochemically, and geochronologically equivalent to the Chopawamsic terrane in the central Virginia Piedmont (Henika, 2006).

Within the 200-mile (322-kilometer) radius of the CCNPP site, the Chopawamsic transitions to the Milton terrane south-southeast of Richmond, Virginia (Figure 2.5-9). The Chopawamsic and Milton terranes are bounded on the west by the Brookneal northeast-trending dextral shear zone (Figure 2.5-23) and its northern extension, the Chopawamsic thrust fault (Figure 2.5-23). Further south, the Milton terrane is overlain on the east by sediments of the Mesozoic Dan River-Danville Basin (tectonostratigraphic map unit "$Mz_3$"), bounded to the west by a down-to-the-east normal fault. To the east, the Goochland terrane overrides the Chopawamsic and Milton terranes along the Spotsylvania thrust fault. The Chopawamsic and Milton terranes, as well as the contiguous Potomac terrane on the east, are intruded by the Ordovician Occoquan pluton (tectonostratigraphic map unit "$p_1$"), the Ellisville pluton (tectonostratigraphic map unit "$p_2$"), and Tanyard Branch pluton (tectonostratigraphic map unit "$p_3$"). These are "stitching" plutons whose age dates provide a maximum age of terrane assembly (Howell, 1995) (see discussion of Paleozoic plutons in Section 2.5.1.1.3.2.2).
RAI 130 02.05.01-37 Unconformably overlying the Chopawamsic and Milton terranes and their intruded plutons are in-folded remnants of a Paleozoic overlap sequences, the Arvonia Formation (tectonostratigraphic map unit "$O_1$") and Quantico Formation (tectonostratigraphic map unit "$O_2$"), consisting of slates, phyllites, schists, and quartzites (see description of Paleozoic overlap sequences in Section 2.5.1.1.3.2.1)

#### 2.5.1.1.3.2.4 Iapetan Disrupted (Infrastructural) Terranes

Some terranes have been subjected to either middle or lower crustal conditions at some time(s) during their history and are thus considered as "infrastructural" terranes; most of these terranes are imprinted by both amphibolite facies or higher metamorphism and complex deformational geometries; primary structures have generally been obliterated in these terranes, thus precluding the establishment of any stratigraphy (Hibbard, 2003). Terranes with infrastructural character within a 200-mile (322-kilometer) radius of the CCNPP site include Potomac composite terrane, the Jefferson terrane, the Smith River terrane, the Falls Lake, and Raleigh - Goochland, terranes

Potomac composite terrane: Tectonostratigraphic map (Figure 2.5-9) unit "dp"

The Potomac terrane is characterized by a stack of mainly metaclastic thrust sheets and intervening mélanges with ophiolitic remnants (Horton, 1989). The Potomac terrane has been divided into Mather Gorge, Sykesville, and Laurel formations. The protoliths of the three formations were interpreted to be Neoproterozoic to Early Cambrian distal slope deposits and olistostromes (Drake, 1989). The three formations are separated by major north-northeast–striking faults (Drake, 1989). Multiple foliations are common and composite foliations are strongest in phyllonitic rocks close to these fault zones.

The relationship between the Smith River allochthon and the Potomac terrane is unknown, although it is likely that the north end of the Smith River allochthon structurally overlies the Potomac terrane. Slices of the Potomac Terrane from central Virginia to the New York Bight appear to have been dextrally transposed along the Brookneal shear zone in Virginia (Figure 2.5-23) and its continuation northeastward.

Jefferson terrane: Tectonostratigraphic map (Figure 2.5-9) unit "dje"

The Jefferson terrane contains mainly metaclastic rocks with subordinate amphibolite and meta-ultramafic rocks that structurally underlie the allochthon. The age of rocks in the Jefferson terrane is unknown, although traditionally they have been viewed to be Neoproterozoic to early Paleozoic (Faill, 1997a). The terrane has been thrust over the Laurentia cover sequence on the Creek Fault and was, in turn, overthrust by the Smith River terrane by the Chatham Fault (Figure 2.5-9).

Smith River terrane: Tectonostratigraphic map (Figure 2.5-9) unit "ds"

The Smith River allochthon is in a southern Appalachian belt of metaclastic rocks that has traditionally been considered to be of peri-Laurentian origin. New Th-U-Pb monzonite ages confirm that the allochthon was involved in an Early Cambrian tectonothermal event. and The presence of ca. 1000 Ma Detrital zircons indicate that the terrane is exotic with respect to adjacent Laurentian rocks and could have a Gondwanan source, because Detrital and xenocrystic zircons of this age are also found in Appalachian peri-Gondwanan crustal elements (Hibbard, 2003). The allochthon may form a new link between the Appalachians and the Pampean terrane of western South America; in addition, its position in the orogen has implications for recent models of the opening of the Iapetus (Hibbard, 2003).

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The Smith River terrane includes the structurally underlying Bassett Formation and the structurally overlying Fork Mountain Formation; the contact between the units appears to be conformable, although there is no evidence preserved that indicates their stratigraphic sequence (Conley, 1973). Both units are dominated by biotite paragneiss; the Fork Mountain Formation also includes matrix-supported breccias that have been favorably compared to some of the mélanges in the Potomac terrane (Horton, 1989). The only age constraint for these units is that they are intruded by the Martinsville intrusive suite. (Hibbard, 2003)

Falls Lake terrane: Tectonostratigraphic map (Figure 2.5-9) unit "df"

The Falls Lake terrane is a small allochthonous unit found in Grenville County, North Carolina, just at the limit of the 200-mile (322-kilometer) radius of the CCNPP site. The western boundary of the Falls Lake terrane is thrust over the eastern edge of the upper greenschist facies Carolina/Albemarle arc along the ductile normal Upper Barton Creek fault while western boundary of the Spring Hope terrane is thrust over the eastern boundary of the Falls Lake terrane along the Nutbush Creek Fault (Figure 2.5-9 and Figure 2.5-23). In Grenville County, a greenschist facies pluton of the Carolina / Albemarle terrane contains a variety of relict igneous features including greenstone, metagabbro, and meta-ultramafic blocks similar to the amphibolite facies Falls Lake terrane.

Goochland or Raleigh / Goochland terrane: Tectonostratigraphic map (Figure 2.5-9) unit "cg"

The Goochland terrane (also known as the Raleigh-Goochland terrane of Hibbard,2003) stretches southward from Fredericksburg, Virginia, to the North Carolina state line east of the Spotsylvania fault (discussed in Section 2.5.1.1.4.4.2) (Frye, 1986) (Figure 2.5-9). The Goochland belt (Virginia) is composed predominantly of granulite facies (high grade) metamorphic rocks and the Raleigh belt (North Carolina) is composed of sillimanite (very high grade) metamorphic rocks (Hibbard, 2007). The Goochland-Raleigh terrane is interpreted to be a microcontinent that was accreted to ancestral North America during the Taconic orogeny. Some geologists believe that the micro-continent was rifted from ancestral North America during the proto-Atlantic rifting while others believe that it formed outboard of ancestral North America (exotic or suspect terrane). Rocks of the Goochland-Raleigh belt are considered to be the oldest rocks of the Piedmont Province and bear many similarities to the Grenville age rocks of the Blue Ridge Province (Spears, 2002).

The Po River Metamorphic Suite and the Goochland terrane, that lie southeast of the Spotsylvania fault, make up the easternmost part of the Goochland-Raleigh terrane. The Po River Metamorphic Suite was named after the Po River in the Fredericksburg area and comprises amphibolite grade (high grade) metamorphic rocks, predominantly biotite gneiss and lesser amounts of hornblende gneiss and amphibolite (Pavlides, 1989). The age of this unit is uncertain, but it has been assigned a provisional age of Precambrian to Early Paleozoic (Pavlides, 1980). The Goochland terrane was first studied along the James River west of Richmond, Virginia, and contains the only dated Precambrian rocks east of the Spotsylvania fault. It is a Precambrian granulite facies (high grade) metamorphic terrane.

### 2.5.1.1.3.3 The Peri-Gondwanan Realm

#### 2.5.1.1.3.3.1 Peri-Gondwanan Microcontinents

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Avalonia or the Avalon terrane has been identified as a microcontinent of peri-Gondwanan affinity (Faill, 1998). Remnants of Avalonian continental crust are not found within the 200-mile (322-kilometer) radius of the CCNPP site. However, exposures in the northern Appalachians indicate that the Carolina volcanic arc terrane was accreted to the Avalonia terrane before the amalgamated microcontinent impinged of the North Atlantic continental margin. The impingement of the amalgamated microcontinent added to the intensity of the collision during the Alleghanian orogeny. Only southeastward (current coordinates) translated portions of the Carolina arc are found within the 200-mile radius of the CCNPP site. Therefore, the discussion of this terrane is limited to the volcanic arc terranes described in the next section FSAR Section 2.5.1.1.3.3.2. The other identified peri-Gondwanan microcontinent, the Suwannee terrane of the southern Appalachians, is only found outside the 200-mile radius of the CCNPP site and is not discussed further.

#### 2.5.1.1.3.3.2 Peri-Gondwanan Volcanic Arcs

Carolina terrane: Tectonostratigraphic map (Figure 2.5-9) unit "vca"

The Carolina terrane extends southward from southern Virginia to central Georgia, while the Eastern Slate belt is located predominantly in North Carolina, east of the Goochland-Raleigh belt (Figure 2.5-9). Both the Carolina and Eastern Slate belts are composed of greenschist facies (low grade) metamorphic rocks (Hackley, 2007), including metagraywacke, tuffaceous argillites, quartzites, and meta-siltstones (Glover, 1997). The Carolina and Eastern Slate belts are interpreted to be island-arcs that were accreted to ancestral North America during the Taconic orogeny. The island-arcs are interpreted to have been transported from somewhere in the proto-Atlantic Ocean, and are therefore considered to be exotic or suspect terranes. Rocks of the Carolina and Eastern Slate belts generally are considered to be Early Paleozoic in age. Granitic and gabbro-rich plutons that intrude the belts generally are considered to be Middle to Late Paleozoic in age).

New analytical work shows that the Milton terrane and Carolina terrane are distinct and unrelated crustal blocks, separated by a significant shear zone, the Hyco shear zone, a segment of the central Piedmont shear zone (Henika, 2006).

Hatteras terrane: Tectonostratigraphic map (Figure 2.5-9) unit "uh"

The Hatteras terrane is a pluton-rich belt of amphibolite metamorphic grade metaigneous rocks that range in composition from tonalite gneiss with mafic amphibolite layers through quartz monzonite to granite to cordierite-bearing granite. The rocks have a compositional range appropriate for magmatic arcs on continental crust. The western boundary is an abrupt transition to greenschist facies volcaniclastic rocks and may be a fault. Rb/Sr whole-rock ages of 583±46 Ma for the granite and 633±61 Ma for the quartz monzonite. Except for the younger age, the Hatteras terrane is compositionally similar to the eastern high-grade continental basement of the mid-Atlantic states. The plutonic and sub-volcanic to volcanic nature and age span of the Hatteras terrane rocks is consistent with those of the Carolinian terrane (Glover, 1997).

In the Carolinas, magmatic arc rocks are continuous across the Piedmont and under the coastal plain from west of Charlotte, North Carolina, to Cape Hatteras. In Virginia the Piedmont nappes of Goochland Grenville basement are warped into an antiformal structure that plunges southward beneath the Carolinian terrane magmatic arc rocks near Raleigh North Carolina (Glover, 1997). Glover (1997) goes on to state that "The Carolinian terrane is broken by faults and interrupted by Mesozoic basins (Keppie, 1989), but there is little evidence to suggest that it comprises more than a single exotic terrane. Recent maps of the Atlantic Coastal Plain basement (Thomas, 1989; Keppie; 1989) generally agree. Horton (1991), however, split Carolinia into five terranes but consider several to be possible extensions of adjacent volcanic 'terranes.'" RAI 130 02.05.01-37 Based on the Glover (1997) analysis, this FSAR section groups the Chopawamsic and Milton terranes, the Carolina / Albemarle arcs, and the Hatteras terrane together as possibly correlative accreted volcanic arc terranes built on continental crust.

#### 2.5.1.1.3.4 The Pangean Realm

##### 2.5.1.1.3.4.1 Paleozoic Pangean Sediments

The Paleozoic orogenies eventually led to the formation of the Pangean supercontinent by Late Paleozoic time. The closure of the Iapetus/Theic oceans beginning in the Middle Ordovician was accompanied by the loading onto the Rodinian (see discussion in FSAR Sections 2.5.1.1.3 and 2.5.1.1.2.1) continental margin of thrust sheets. These thrust sheets included microcontinental, abyssal and volcanic arc terranes. This loading likely led to a crustal bulge that uplifted the cratonward portion of carbonate platform in the northern Appalachians causing erosion (the Knox unconformity) of carbonate platform sediments that were shed westward into a foreland basin. On the opposite side of the bulge, subsidence was occurring. Twenty-plus ash falls that thickened southwestward were deposited across the carbonate shelf of the orogenic belt during the Upper Ordovician (the Millbrig K-bentonite, for example). Based on thicknesses of these units, the source of these volcanic deposits is believed to have been off the coast of South Carolina (present coordinates), from a magmatic arc or the Baltica continent colliding with Laurentia (Faill, 1997a).

As the Taconic orogeny reached greater intensity in the central Appalachians, the Brandywine and Baltimore microcontinents began to impinge on the Laurentian margin, leading to subsidence along the continental shelf. Carbonate shelf deposition was replaced by pelitic sedimentation (Martinsburg and Reedville formations (Figure 2.5-209). Pelitic units were soon replaced by coarser siliciclastic sediments (Bald Eagle, Juniata and Tuscarora formations) derived from uplifted terranes to the southeast (Figure 2.5-211) (Faill, 1997a). The start of regional deposition of these coarse siliciclastics ended the 100 ma of carbonate shelf deposition on the Laurentian margin. The area of subsidence widened during the Taconic orogeny, spreading northwestward with deposition of the Reedsville shale, for example. Deposition of these marine units spread as far westward (current coordinates) as far north as Ontario and as far west as the Mid-continent (Faill, 1997a). As the Octoraro Sea continued to close, crustal fragments and supracrustal rocks were thrust onto the Laurentian margin, generating several nappes and producing widespread metamorphism. Events associated with the collapse of the Octoraro basin included the development of the Martic thrust, emplacement of the Hamburg klippe, creation of the Reading meganappe system, and the obduction onto the Laurentian margin of microcontinent/magmatic arc packages, previously assembled within the Octoraro basin (Faill, 1997a).

East of the Susquehanna river, oceanic basin sediments were thrust over the Conestoga slope and carbonate shelf sediments. Further south, in south-central Pennsylvania and central Maryland, equivalent Octoraro and related sediments were thrust over pelitic and carbonate slope deposits along the Linganore thrust fault. A deeper thrust, probably still affecting Octoraro basin sediments but not oceanic crust, provided the mechanism by which the Reading meganappe system was emplaced. (Faill,1997a). The depth limit of this thrust is based on the lack of ophiolitic material in the resulting nappe. This lower thrust fault, however, was probably responsible for the inclusion of slivers of Laurentian continental basement into the interleaved and stacked thrust sheets.

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The Appalachian basin developed as a consequence of the Taconic orogeny, which produced a crustal downwarp cratonward of new highlands to the west (present coordinates) uplifted as a result of crustal bulging. The initial deposits in the basin included molasse deposits of conglomerate, sandstone, siltstone, and shales of the Shagawunk Formation and its lateral facies, the Bloomsburg delta. A series of transgressions and regressions repeatedly shifted the shore zone and shallow marine facies. The lagoonal-tidal Wills Creek and laminated limestones of the Tonolway formations (Figure 2.5-211) accumulated in the Late Silurian. The Appalachian basin continued to receive sediments nearly uninterrupted through the remainder of the Paleozoic. Sedimentation in the basin accelerated as a result of Silurian through Permian orogenies.

The Acadian orogeny (Figure 2.5-8) was caused by the collision of the microcontinent Avalon with eastern North America during the Middle to Late Devonian Period. At its peak, the orogeny produced a continuous chain of mountains along the east coast of North America and brought with it associated volcanism and metamorphism. The Acadian orogeny ended the largely quiescent environment that dominated the Appalachian Basin during the Late Ordovician and into the Silurian, as vast amounts of terrigenous sediment from the Acadian Mountains were introduced into the basin and formed the Catskill clastic wedge in central Pennsylvania and northeastern New York (Figure 2.5-200). Vast amounts of terrigenous sediment from the Acadian Mountains were introduced into the Catskill foreland basin during the Middle and Late Devonian and formed the Catskill clastic wedge sequence in Pennsylvania and New York. Thick accumulations of clastic sediments belonging to the Catskill Formation are spread throughout the Valley and Ridge Province (Faill, 1997b). The Catskill clastic wedge is representative of fluctuating shorelines and prograding alluvial environments along the western margin of the Acadian upland. This regressional sequence is represented in the sedimentary record with turbidites, slope deposits, alternating shallow marine and non-marine sediments and alluvial plain fining-upward sequences (Walker, 1971, Faill, 1997b and USGS, 2008). The pebbles and sand grains of the Catskill Formation in New York, Pennsylvania and Maryland are mostly composed of metamorphic and granitic rock fragments, feldspar, mica and quartz. The red color is due to the presence of a small percentage of iron oxide between the grains (Dolt, 1988). The regressive sequence in the region is bounded above and below by marine transgressions which are represented by basal black shale overlain by gray shales and mudstones capped by small amounts of siltstone (Bridge, 1994 and Huber, 2000). The Catskill clastic wedge was the site of the greatest accumulation of sediment in the region, depositing as much as 7,000 feet of sediment (USGS, 2008). The sediments are the thickest in the east and grow progressively thinner westward and southward into the central Appalachian Basin region (Figure 2.5-200). In general, the Acadian Orogeny was superimposed upon terranes affected or formed by the Taconic Orogeny (Dolt, 1988) (Figure 2.5-200).

The Catskill clastic wedge in the central Appalachians is overlain by cyclothems of the Mississippian Pocono Group (Figure 2.5-211), consisting predominantly hard gray massive sandstones, with some shale. In the Eastern Panhandle of Maryland, the Pocono Group has been divided into the Hedges, Purslane, and Rockwell formations unconformably overlain by the Greenbrier and Mauch Chunk formations. The Mississippian stratigraphic units in northern Virginia and West Virginia, and western Maryland/Delaware includes the Rockville and Burgoon/Purslane Sandstone unconformably overlain by the Greenbrier and Mauch Chunk formations.

Sediments of the Mississippian Pocono Group are overlain by cyclothems in the Pennsylvanian Pottsville Group (Figure 2.5-211). The Pottsville Group consists predominantly of sandstones, some of which are conglomeratic, interbedded with thin shales and coals. In eastern Pennsylvania, the Pennsylvanian stratigraphic units include the Pottsville Group and overlying Allegheny, Glenshaw, Casselman, and Monongahela formations. In Maryland and Delaware, the Pennsylvanian stratigraphic units consist of the Pottsville Group and overlying Allegheny, Conemaugh and Monongahela formations. The Pottsville Group is known only from the southwestern portion of Virginia and the southeastern portion of West Virginia (outside the 200-mile (322-kilometer) radius of the CCNPP site). There, the Pottsville is known as the Pocahontas, New River, and Kanawha formations (Stewart 2002). Interestingly, the Late Mississippian Mauch Chunk Group north of Bluefield, Virginia at the state border with West Virginia, evidence is found of a paleoseismite, including clastic sand dikes and slumps, probably associated with the Alleghany orogeny (Stewart 2002).

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#### 2.5.1.1.3.4.2 Late Paleozoic Plutons

Late Paleozoic plutons were the result of the final orogeny (the Alleghany orogeny) that contributed to the formation of the Pangean supercontinent. Plutonism was widespread across the Appalachian orogen. Some of the plutons were intruded into paraautochthonous and allochthonous terranes that had been accreted during previous orogenies and provide a means of dating the minimum age of emplacement of the thrusted units. These plutons are termed "stitching" plutons. Some of the major "stitching" plutons and the terranes they affected are described below.

Occoquan pluton: Tectonostratigraphic map (Figure 2.5-9) unit "$p_1$"

The Occoquan pluton is a granite-granodiorite-tonalite body that is medium- to coarsegrained with rare xenoliths and exhibits moderate to strong metamorphic foliation and mineral lineation by quartz rods and mica layers. The pluton intrudes the upper part of the Wissahickon Schist and the Chopawamsic Formation.

Ellisville pluton: Tectonostratigraphic map (Figure 2.5-9) unit "$p_2$"

The Ellisville pluton is a large granodiorite body that intrudes the high metamorphic grade rocks of the Hatcher Complex and the lower-grade rocks of the Chopawamsic Formation. Most of the pluton is porphyritic granodiorite with minor foliation, but the body is sheared along the southern margin along the James River.

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#### 2.5.1.1.3.4.3 Mesozoic Rift Sequences

The Mesozoic rift basins within a 200-mile (322-kilometer) radius of the CCNPP site are identified collectively in Figure 2.5-9 as map unit "$Mz_3$" and individually in Figure 2.5-10 with numerical designators.

~~Coastal Plain Physiographic Province~~

~~Pre-Cretaceous Basement Rock~~

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As described in the subsection on Cenozoic History (Section 2.5.1.1.2.8~~7~~), early Mesozoic rifting and opening of the Atlantic Ocean was followed by ~~the~~ sea floor spreading and the continued opening of the Atlantic Ocean during ~~the~~ Cenozoic time. Continued erosion of the Appalachian Mountains and the exposed Piedmont produced extensive sedimentation within the Coastal Plain Province that includes the CCNPP site region.

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The non-marine and marine sediments deposited in the Coastal Plain Physiographic Province overlie what are most likely foliated metamorphic or granitic rocks, similar to those cropping out in the Piedmont approximately 50 mi (80 km) to the northwest (Figure 2.5-5 and Figure 2.5-6). A combination of erosion, downwarping, and faulting resulted in an undulatory, east-dipping basement surface with local slope variations that underlies the Coastal Plan Province. The Pre-Cretaceous basement bedrock is only encountered in the Coastal Plain Province by borings designed to characterize deep aquifers above the underlying basement rock. ~~The closest borehole to the CCNPP site that penetrates the basement rock is located in St. Mary's County about 13 mi (21 km) south of the site (Figure 2.5-11).~~ Hansen~~It has been indicated~~ (Hansen, 1986) indicates that most of the borings that penetrate coastal plain sediments and extend to the underlying basement have encountered metamorphic or igneous rocks. For example, well DO-CE 88 in Dorchester, County located approximately 24 mi (39 km) east of the CCNPP site was drilled into gneissic basement rock at 3,304 ft (1,007 m) in depth (Figure 2.5-11). Based on the characteristics summarized in FSAR Section 2.5.1.1.3.2.1, this lithology is within the Outer Belt of the terranes underlying the Coastal Plain sequence. Well QA-EB 110, in Queen Anne's County, located 38 mi (61 km) north of the CCNPP site, was drilled to explore for deep freshwater aquifers. This well was drilled into basement at a depth of 2,518 ft (767 m). The basement rock was only sampled in the drill cuttings and suggests a gneiss/schist from the mineralogy present, (i.e., biotite, chlorite, and clear quartz). This crystalline sample lies within the Middle Belt terrane.

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Regional geophysical and scattered borehole data indicate that a Mesozoic basin might be present in the site vicinity, buried beneath Coastal Plain sediments. Triassic clastic deposits, indicative of a possible rift basin, were penetrated in Charles County (well CH-CE 37), located over 20 mi (32 km) west of the site, for an interval of 99 ft (30 m), returning samples of weathered brick red clay and shale. Hansen (1986) reports the occurrence of siltstones, sandstones, and clays in several borings north of this well within Prince Georges County. These samples appear to represent continental deposits within the buried Taylorsville Basin. The

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Inner Belt as defined by Hansen (Hansen, 1986) may contain portions of a buried Mesozoic basin or basins similar to the Neward-Gettysburg terrane to the Northwest (Figure 2.5-9). FSAR Section 2.5.1.1.4.4.3 contains further discussions of potential Mesozoic extensional (rift) basins buried beneath coastal plain sediments.

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Diabase was cored in the closest deep boring (SM DF 84) to the CCNPP site that penetrated the Pre-Cretaceous basement. The boring is located in Lexington Park, St. Mary's County, about 13 mi (21 km) south of the CCNPP site (Hansen, 1984) (Figure 2.5-11). ~~A statement regarding the presence of the diabase was made~~Hansen (Hansen, 1984) states:

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As no other basement lithologies were encountered, it is presently not known whether the diabase is from a sill or dike associated with the rift-basin sediments or whether it is cross-cutting the crystalline rocks. The diabase is apparently a one-pyroxene (augite) rock, which Fisher (1964~~, p. 14~~) suggests is evidence of rapid, undifferentiated crystallization in a relatively thin intrusive body, such as a dike.

The occurrence of Mesozoic rift-basin rocks in St. Mary's and Prince George's County are further discussed (Hansen, 1986): "The basins that occur in Maryland are all half-grabens with near-vertical border faults along the western sides. The strata generally strike north-easterly, but, in places, particularly in the vicinity of cross-faults, strike may diverge greatly from the average."

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Exposed Mesozoic rift basins found within a 200-mile (322-kilometer) radius of the CCNPP site include the Culpepper Basin, the Deep River Basin, the Gettysburg Basin, the Newark Basin, the Oatlands-Studley Basin, the Richmond Basin, and the Taylorsville Basin. Buried Mesozoic rift basins, inferred from geophysical studies or borehole drilling within a 200-mile radius of the CCNPP site, include New York Bight Basin, the Queen Anne Basin, the Delmarva Basin, the Norfolk Basin, and other unnamed basins identified in Figure 2.5-9 and Figure 2.5-10. All of the exposed rift basins identified above belong to the Newark Supergroup. Instead of describing individual stratigraphic units within each basin, the following is a brief description of the rift basin formation associated with the Eastern North America Magmatic Province (discussion in Section 2.5.1.1.2.7), and a more specific discussion of the Newark Basin Supergroup lithologies.

The Newark Supergroup consists largely of poorly-sorted non-marine sediments deposited within rift basins along the mid-Atlantic margin. The typical lithologies are conglomerate, arkosic sandstone, siltstone, and shale. Most of the strata are red beds that feature ripple marks, mud cracks, and rain drop imprints; dinosaur footprints are common, though actual body fossils are very rare. Some of the strata are detailed to the level of varves, with indications of Milankovitch cycles. The Triassic stratigraphy of a typical Newark Group basin consists of a basal fluvial unit overlain by lacustrine strata. The deepest lakes occur near the base of the lacustrine succession and then gradually shoal upward. This Triassic sequence is referred to as the "tripartite stratigraphy" (Schlische, 2003). The tripartite stratigraphy is generally overlain by an Early Jurassic age sequence of lava flows and intercalated lacustrine (commonly deep-water) strata overlain in turn by shallow lacustrine strata and, in some cases, by fluvial strata (Schlische, 2003). Based on basin geometry, onlap geometry, and major stratigraphic transitions, the basins grow wider, longer, and deeper through time. Sediment supply appears to keep pace with basin subsidence. Transition from fluvial to lacustrine appears to be a consequence of gradual growth of basin length and width (Schlische, 2003).

The Mesozoic rift basins along the length of the North American Atlantic margin are related to the Eastern North America Magmatic Province (de Boer, 2003). Subsidence of the rift basins was initiated ca. 230 Ma. The orientation of the rift basin follows the general axis of deformation of the Appalachian orogen, including changes along strike related to promontories and recesses. This likely indicates that crustal thinning took advantage of pre-existing deep crustal features such as a major translithospheric suture zone, possibly related to the edge of the Grenvillian basement.

~~Because of the depth of Coastal Plain sediments, the basement rock type beneath the CCNPP site must be inferred based on surrounding borings and geophysical data. The presence and character of basement rock beneath the CCNPP site is discussed further in Section 2.5.1.2.~~

#### 2.5.1.1.3.5 Post-Pangean Sediments

##### 2.5.1.1.3.5.1 Upper Mesozoic Stratigraphic Units~~Cretaceous Stratigraphic Units~~

Regionally, coastal plain deposits lap onto portions of the eastern Piedmont~~. In Stafford, Prince William, and Fairfax counties in Virginia Lower Cretaceous Potomac Formation sediments were deposited unconformably on a narrow belt of Ordovician Quantico Slate and on the Cambrian Chopawamsic Formation~~ (Mixon, 2000). ~~The Potomac Formation occurs on Proterozoic to Cambrian metamorphic and igneous rocks in the Washington DC area (McCartan, 1990).~~East of the Fall Line, the Coastal Plain sediments range from Early Cretaceous to Quaternary in age and consist of interbedded silty clays, sands, and gravels that were deposited in both marine and non-marine environments. These sediments dip and thicken toward the southeast. Whereas the basement surface dips southeast at about 100 ft/mi in Charles County, west of the CCNPP site, a marker bed in the middle of the Cretaceous Potomac Group dips southeast at about 50 ft per mile (McCartan, 1989a). This wedge of unlithified sediments consists of Early Cretaceous terrestrial sediments and an overlying sequence of well-defined, Late Cretaceous, marine stratigraphic units. These units from oldest to youngest are summarized in the following paragraphs.

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~~The Lower Cretaceous Potomac Group overlies a complex suite of basement rocks that includes strata as young as Triassic. Jurassic units appear to be missing north of the Norfolk Arch (Hansen, 1978) (Figure 2.5-12). The undulatory and east-dipping basement surface that underlies the Coastal Plain resulted from a combination of downwarping, erosion, and faulting. This has led to local variations in the slope of the bedrock surface. The Coastal Plain sediments deposited east of the Fall Line, range from Early Cretaceous to Quaternary in age and consist of interbedded silty clays, sands, and gravels that were deposited in both marine and non-marine environments. These sediments dip and thicken toward the southeast. Whereas the basement surface dips southeast at about 100 ft/mi in Charles County, west of the CCNPP site, a marker bed in the middle of the Cretaceous Potomac Group dips southeast at about 50 ft per mile (McCartan, 1989a). This wedge of unlithified sediments consists of Early Cretaceous terrestrial sediments and an overlying sequence of well-defined, Late Cretaceous, marine stratigraphic units. These units from oldest to youngest are summarized in the following paragraphs.~~

The Lower Cretaceous strata of the Potomac Group consists of a thick succession of variegated red, brown, maroon, yellow, and gray silts and clays with interstratified beds of fine to coarse gray and tan sand. The Potomac Group occurs on Proterozoic to Cambrian metamorphic and igneous rocks in the Washington DC area (McCartan,1990).In the Baltimore-Washington area, the Potomac Group is subdivided from oldest to youngest into the Patuxent, Arundel, and Patapsco Formations. This subdivision is recognizable in the greater Washington-Baltimore area where the clayey Arundel Formation is easily recognized and separates the two dominantly sandy formations (Hansen, 1984). This distinction is less pronounced to the east and southeast where the Potomac Group is divided into the Arundel/Patuxent formations (undivided) and the overlying Patapsco Formation. At Lexington Park, Maryland, the clayey

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beds that dominate the formation below a depth of 1,797 ft (548 m) are assigned to the Arundel/Patuxent Formations (undivided) (Hansen, 1984).

At the Lexington Park well, located about 13 mi (21 km) south of the CCNPP site (Figure 2.5-11), about 30 ft (9 m) of a denser, acoustically faster, light gray, fine to medium clayey sand occurs at the base of the Potomac Group and might represent an early Cretaceous, pre-Patuxent Formation. These sediments might correlate with the Waste Gate Formation encountered east of Chesapeake Bay in the DOE Crisfield No. 1 well (Hansen, 1984).

The Patapsco Formation contains interbedded sands, silts, and clays, but it contains more sand than the overlying Arundel/Patuxent Formations (undivided). The contact is marked by an interval dominated by thicker clay deposits. The Arundel/Patuxent Formations (undivided) are marked by the absence of marine deposits. The Mattaponi Formation was proposed (Cederstrom, 1957) for the stratigraphic interval immediately above the Patapsco Formation. An identified interval (Hansen, 1984) as the Mattaponi (?) is now recognized as part of the upper Patapsco Formation. ~~In general, it appears that downwarping associated with the Salisbury Embayment (Figure 2.5-12) began early in the Cretaceous and continued intermittently throughout the Cretaceous and Tertiary periods. Deposition apparently kept pace, resulting in a fluvial-deltaic environment. Biostratigraphic data from test wells on the west side of Chesapeake Bay indicate that Upper Cretaceous sediments reach maximum thickness in Anne Arundel County and show progressive thinning to the south. This appears to reflect deposition within the downwarping, northwest-trending Salisbury Embayment during the Cretaceous (Hansen, 1978). In southern Calvert County, the Upper Cretaceous Aquia Formation rests unconformably on Lower Cretaceous sediments (Figure 2.5-13). Thinning and overlapping within the Upper Cretaceous interval suggests that the northern flank of the Norfolk Arch was tectonically active during late Cretaceous time (Hansen, 1978) (Figure 2.5-12).~~

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The Upper Cretaceous Magothy Formation <u>Figure 2.5-213</u> is approximately 200 ft (61 m) thick in northern Calvert County but becomes considerably thinner southward at the CCNPP site and pinches out south of the site and north of wells in Solomons and Lexington Park, Maryland (Hansen, 1996) (Achmad, 1997) (Figure 2.5-13). This pattern also appears to reflect thicker deposition in the Salisbury Embayment. The Magothy Formation is intermittently exposed near Severna Park, Maryland, and in the interstream area between the Severn and Magothy Rivers. This outcrop belt becomes thinner to the south in Prince Georges County. The Magothy consists mainly of lignitic or carbonaceous light gray to yellowish quartz sand interbedded with clay layers. The sand is commonly coarse and arkosic and in many places is cross bedded or laminar. Pyrite and glauconite occur locally (Otton, 1955).

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The upper Cretaceous Matawan and Monmouth formations <u>(Figure 2.5-213)</u> are exposed in Anne Arundel County, Maryland. While the Matawan is absent in Prince Georges County, the Monmouth crops out in a narrow belt near Bowie, Maryland. Exposures of these formations have not been identified in Charles County. These formations are inseparable in sample cuttings and drillers' logs and are undifferentiated in southern Maryland (Otton 1955) (Hansen, 1996). They consist mainly of gray to grayish-black micaceous sandy clay and weather to a grayish brown. Glauconite is common in both formations and fossils include fish remains, gastropods, pelecypods, foraminifera, and ostracods. The presence of glauconite and this fossil fauna indicate that the Matawan and Monmouth are the oldest in a sequence of marine formations. These formations range in thickness from a few feet or less in their outcrop area to more than 130 ft (40 m) at the Annapolis Water Works (Otton, 1955). The formations thin to the west and average about 45 ft (14 m) in Prince Georges County. The combined formations along with the Brightseat Formation form the Lower Confining Beds (Section 2.4.12) that become progressively thinner from southern Anne Arundel County through Calvert County to St. Mary's County where this hydrostratigraphic unit appears to consist mainly of the Brightseat Formation (Hansen, 1996).

#### 2.5.1.1.3.5.2 Tertiary Stratigraphic Units

The Brightseat Formation is exposed in a few localities in Prince Georges County and contains foraminifera of Paleocene age (Figure 2.5-213). This unit is relatively thin [up to about 25 ft (8m)] but occurs widely in Calvert and St. Mary's counties. It is generally medium and olive gray to black, clayey, very fine to fine sand that is commonly micaceous and / or phosphatic (Otton, 1955; Hansen, 1996). It can be distinguished from the overlying Aquia Formation by the absence or sparse occurrence of glauconite. It generally contains less fragmental carbonaceous material than the underlying Cretaceous sediments (Otton, 1955). The Brightseat Formation is bounded by unconformities with a distinct gamma log signature that is useful for stratigraphic correlation (Hansen, 1996). The Late Paleocene Aquia Formation (Figure 2.5-213) was formerly identified as a greensand due to the ubiquitous occurrence of glauconite. This formation is a poorly to well sorted, variably shelly, and glauconitic quartz sand that contains calcareous cemented sandstone and shell beds. The Aquia Formation was deposited on a shoaling marine shelf that resulted in a coarsening upward lithology. This unit has been identified in the Virginia Coastal Plain and underlies all of Calvert County and most of St. Mary's County, Maryland (Hansen, 1996). The Aquia Formation forms an important aquifer as discussed in Section 2.4.12. The Late Paleocene Marlboro Clay (Figure 2.5-213) was formerly considered to be a lower part of the early Eocene Nanjemoy Formation but is now recognized as a widely distributed formation. The Marlboro Clay extends approximately 120 mi (193 km) in a northeast-southwest direction from the Chesapeake Bay near Annapolis, Maryland to the James River in Virginia. Micropaleontological data indicate a late Paleocene age although the Eocene-Paleocene boundary may occur within the unit (Hansen, 1996). The Marlboro Clay is one of the most distinctive stratigraphic markers of the Coastal Plain in Maryland and Virginia. It consists chiefly of reddish brown or pink soft clay that changes to a gray color in the subsurface of southern St. Mary's and Calvert Counties. Its thickness ranges from 40 ft (12 m) in Charles County to about 2 ft (60 cm) in St. Mary's County (Otton, 1955). However, the thickness is relatively constant from Anne Arundel County south through the CCNPP site to Solomons and Lexington Park, Maryland (Figure 2.5-13). The apparent localized thickening in Charles County might represent a local depocenter rather than a broader downwarping of the Salisbury Embayment relative to the Norfolk Arch (Figure 2.5-12).

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The lower part of the overlying Early Eocene Nanjemoy Formation (Figure 2.5-213) is predominantly a pale-gray to greenish gray, glauconitic very fine muddy sand to sandy clay. This formation becomes coarser upward from dominantly sandy silts and clays to dominantly clayey sands. The gradational contact between the two parts of the Nanjemoy is defined on the basis of geophysical log correlations (Hansen, 1996). In southern Maryland the Nanjemoy Formation ranges in thickness from several ft in its outcrop belt to as much as 240 ft (73 m) in the subsurface in St Mary's County (Otton, 1955) (Figure 2.5-13).

The Middle Eocene Piney Point Formation (Figure 2.5-213) was recognized (Otton, 1955) as a sequence of shelly glauconitic sands underlying the Calvert Formation in southern Calvert County. The contact with the underlying Nanjemoy Formation is relatively sharp on geophysical logs, implying a depositional hiatus or unconformity (Hansen, 1996). The Piney Point Formation ranges in thickness from 0 ft (0 m) in central Calvert County to about 90 ft (27 m) at Point Lookout at the confluence of the Potomac River and Chesapeake Bay (Hansen, 1996). The Piney Point Formation contains distinctive carbonate-cemented interbeds of sand and shelly sand that range up to about 5 ft (1.5 m) in thickness (Hansen, 1996) and a characteristic fauna belonging to the Middle Eocene Jackson Stage (Otton, 1955). This unit is recognizable in the subsurface in Charles, Calvert, St. Marys, Dorchester, and Somerset Counties in Maryland and in Northumberland and Westmoreland Counties in Virginia but has not been recognized at the surface (Otton,1955). The work of several investigators were summarized (Hansen, 1996) who identified a 1 to 4 ft (30 to 122 cm) thick interval of clayey, slightly glauconitic, fossiliferous olive-gray, coarse sand containing fine pebbles of phosphate. This thin interval of late Oligocene age occurs near the top of the Piney Point Formation and appears to correlate with the Old Church Formation in Virginia. This formation appears to thicken downdip between Piney Point and Point Lookout (Hansen, 1996). The absence of middle Oligocene deposits in most of the CCNPP site region indicates possible emergence or non-deposition during this time interval. Erosion or nondeposition during this relatively long interval of time produced an unconformity on the top of the Piney Point Formation that is mapped as a southeast dipping surface in the CCNPP site vicinity (Figure 2.5-14).

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Renewed downwarping within the Salisbury Embayment resulted in marine transgression across older Cretaceous and Eocene deposits in Southern Maryland. The resulting Miocene-age Chesapeake Group consists of three marine formations; from oldest to youngest these are the Calvert, Choptank and St. Marys Formations (Figure 2.5-213). The basal member of the group, the Calvert Formation, is exposed in Anne Arundel, Calvert, Prince Georges, St. Mary's and Charles Counties. Although these formations were originally defined using biostratigraphic data, they are difficult to differentiate in well logs (Hansen, 1996) (Glaser, 2003a). The basal sandy beds are generally 10 to 20 ft (3 to 6 m) thick and consist of yellowish green to greenish light gray, slightly glauconitic fine to medium, quartz sand. The basal beds unconformably overlie older Oligocene and Eocene units and represent a major early Miocene marine transgression (Hansen, 1996). The overlying Choptank and St. Marys formations are described in greater detail in Section 2.5.1.2.3.

The Upper Miocene Eastover Formation and the Lower to Upper Pliocene Yorktown Formation occur in St. Mary's County and to the south in Virginia (McCartan, 1989b) (Ward, 2004). These units appear to have not been deposited to the north of St. Mary's County and that portion of the Salisbury Embayment may have been emergent (Ward, 2004).

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Surficial deposits in the Coastal Plain consist, in general, of two informal stratigraphic units: the Pliocene-age Upland deposits and the Pleistocene to Holocene Lowland deposits (Figure 2.5-213). ~~These deposits are mapped (Mc Cartan, 1989a) (MaCartan, 1989b) as two units of Upper Pliocene fluvial Upland Gravels. It was recognized~~ McCartan (McCartan, 1989b) recognized that an Upper Pliocene sand with gravel cobbles and boulders that blankets topographically high areas in the southeast third of St. Mary's County. The Upland Deposits are areally more extensive in St. Mary's County than in Calvert County (Glaser, 1971). The map pattern has a dendritic pattern and since it caps the higher interfluvial divides, this unit is interpreted as a highly dissected sediment sheet whose base slopes toward the southwest (Glaser, 1971) (Hansen, 1996). This erosion might have occurred due to differential uplift during the Pliocene or down cutting in response to lower base levels when sea level was lower during period of Pleistocene glaciation.

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~~McCartan (1989b) differentiates three Upper Pleistocene estuarine deposits, Quaternary stream terraces, Holocene alluvial deposits and colluvium in St. Mary's County. The Lowland deposits in southern Maryland were laid down in fluvial to estuarine environments (Hansen, 1996) and are generally found along the Patuxent and Potomac River valleys and Chesapeake Bay. These deposits occur in only a few places along the eastern shore of Chesapeake Bay. The Lowland deposits extend beneath Chesapeake Bay and the Potomac River filling deep, ancestral river channels with 200 ft (61 m) or more of fluvial or estuarine sediments (Hansen, 1996). These~~

deep channels and erosion on the continental slope probably occurred during periods of glacial advances and lower sea levels. Deposition most likely occurred as the glaciers retreated and melt waters filled the broader ancestral Susquehanna and Potomac Rivers.

#### 2.5.1.1.3.5.3 Plio-Pleistocene and Quaternary Stratigraphic Units

As stated previously, surficial deposits in the Coastal Plain consist, in general, of two informal stratigraphic units: the Pliocene-age Upland deposits and the Pleistocene to Holocene Lowland deposits. McCartan (1989b) differentiates three Upper Pleistocene estuarine deposits, Quaternary stream terraces, Holocene alluvial deposits and colluvium in St. Mary's County. The Lowland deposits in southern Maryland were laid down in fluvial to estuarine environments (Hansen, 1996) and are generally found along the Patuxent and Potomac River valleys and Chesapeake Bay. These deposits occur in only a few places along the eastern shore of Chesapeake Bay. The Lowland deposits extend beneath Chesapeake Bay and the Potomac River filling deep, ancestral river channels with 200 ft (61 m) or more of fluvial or estuarine sediments (Hansen, 1996). These deep channels and erosion on the continental slope probably occurred during periods of glacial advances and lower sea levels. Deposition most likely occurred as the glaciers retreated and melt waters filled the broader ancestral Susquehanna and Potomac Rivers.

Piedmont Physiographic Province

There are two distinct divisions to the rocks of the Piedmont Physiographic Province. The first is a set of predominantly Late Precambrian and Paleozoic age crystalline rocks and the second is a set of Early Mesozoic (Triassic) age sedimentary rocks deposited locally in down-faulted basins within the crystalline rocks (Section 2.5.1.1.1) (Fichter, 2000) (Figure 2.5-5, Figure 2.5-6, and Figure 2.5-10).

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Crystalline Rocks (Late Precambrian and Paleozoic)

Crystalline rocks of the Piedmont Province primarily occur within the Piedmont Upland section. The crystalline rocks consist of deformed and metamorphosed meta-sedimentary, meta-igneous, and meta-volcanic rocks intruded by mafic dikes and granitic plutons (Markewich, 1990). The rocks belong to a number of northeast-trending belts that are defined on the basis of rock type, structure and metamorphic grade (Bledsoe, 1980) and are interpreted to have formed along and offshore of ancestral North America (Pavlides, 1994). From east to west the main lithotectonic belts are: the Goochland-Raleigh belt; the Carolina and Eastern slate belts; the Chopawamsic and Milton belts; and the Western/Inner Piedmont belt (Bledsoe, 1980) (Fichter, 2000) (Figure 2.5-9). The stratigraphy of the crystalline rock in these lithotectonic belts are discussed in the following paragraphs.

Goochland-Raleigh Belt

The Goochland-Raleigh belt stretches southward from Fredericksburg, Virginia, to the North Carolina state line east of the Spotsylvania fault (presented in Section 2.5.1.1.4.4.2) (Frye, 1986) (Figure 2.5-9). The Goochland belt (Virginia) is composed predominantly of granulite facies (high grade) metamorphic rocks and the Raleigh belt (North Carolina) is composed of sillimanite (very high grade) metamorphic rocks (Fichter, 2000). The Goochland-Raleigh belt is interpreted to be a microcontinent that was accreted to ancestral North America during the Taconic orogeny. Some geologists believe that the micro-continent was rifted from ancestral North America during the proto-Atlantic rifting while others believe that it formed outbound of ancestral North America (exotic or suspect terrane). Rocks of the Goochland-Raleigh belt are considered to be the oldest rocks of the Piedmont Province and bear many similarities to the Grenville age rocks of the Blue Ridge Province (Spears, 2002).

The Po River Metamorphic Suite and the Goochland terrane, that lie southeast of the Spotsylvania fault, make up the easternmost part of the Goochland-Raleigh belt. The Po River Metamorphic Suite was named after the Po River in the Fredericksburg area and comprises amphibolite grade (high grade) metamorphic rocks, predominantly biotite gneiss and lesser amounts of hornblende gneiss and amphibolite (Pavlides, 1989). The age of this unit is uncertain, but it has been assigned a provisional age of Precambrian to Early Paleozoic (Pavlides, 1980). The Goochland terrane was first studied along the James River west of Richmond, Virginia, and contains the only dated Precambrian rocks east of the Spotsylvania fault. It is a Precambrian granulite facies (high grade) metamorphic terrane.

Carolina Slate and Eastern Slate Belts

The Carolina Slate belt extends southward from southern Virginia to central Georgia, while the Eastern Slate belt is located predominantly in North Carolina, east of the Goochland-Raleigh belt (Figure 2.5-9). Both the Carolina and Eastern Slate belts are composed of greenschist facies (low grade) metamorphic rocks (Fichter, 2000), including meta-graywacke, tuffaceous argillites, quartzites, and meta-siltstones (Bledsoe, 1980). The Carolina and Eastern Slate belts are interpreted to be island arcs that were accreted to ancestral North America during the Taconic orogeny. The island arcs are interpreted to have been transported from somewhere in the proto-Atlantic Ocean, and are therefore considered to be exotic or suspect terranes. Rocks of the Carolina and Eastern Slate belts generally are considered to be Early Paleozoic in age. Granitic and gabbro-rich plutons that intrude the belts generally are considered to be Middle to Late Paleozoic in age (Bledsoe, 1980).

Chopawamsic Belt, including Milton and Charlotte Belts

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The Chopawamsic belt, and its southeastward extensions, the Milton and Charlotte belts comprise a broad central part of the Piedmont Province from Virginia to Georgia (Figure 2.5-9). The belt is interpreted to be part of an island arc and consist predominantly of meta-sedimentary and meta-volcanic rocks.

The Chopawamsic belt, also referred to as the "Chopawamsic Volcanic Belt" (Bailey, 1999) and the "Central Virginia Volcanic-Plutonic Belt (Rader, 1993) takes its name from exposures along Chopawamsic Creek in northern Virginia. The belt trends northeastward from the North Carolina state line, crosses the James River between Richmond and Charlottesville and continues northeastward to south of Washington D.C., where it is covered by Coastal Plain deposits. The Chopawamsic belt is bounded on the west by the Chopawamsic fault and on the east by the Spotsylvania fault (Section 2.5.1.1.4). The Chopawamsic belt is interpreted to be an island arc that was accreted to ancestral North America during the Taconic orogeny (Figure 2.5-8). The Chopawamsic belt is regarded as an exotic or suspect terrain. Rocks in the Chopawamsic belt are Early Paleozoic in age. Recent U-Pb studies consistently yield Ordovician ages for Chopawamsic volcanic rocks and Rb-Sr and U-Pb dating of granite rocks give late Ordovician ages (Spears, 2002).

The Chopawamsic belt is comprised of the Chopawamsic Formation and the Ta River Metamorphic Suite. The Chopawamsic Formation and the Ta River Metamorphic Suite are interpreted to have formed as an island arc. The Chopawamsic Formation is interpreted to have formed as the continent-ward side of the island arc and the Ta River Metamorphic Suite as the ocean-ward side (Pavlides, 2000). The Chopawamsic Formation consists of a sequence of felsic, intermediate and mafic meta-volcanic rocks with subordinate meta-sedimentary rocks. The Ta River Metamorphic Suite consists of a sequence of amphibolites and amphibole-bearing gneisses with subordinate ferruginous quartzites and biotite gneiss. Rocks of the Ta River Metamorphic Suite are generally thought to be more mafic and to have experienced higher-grade regional metamorphism than the rocks of the Chopawamsic Formation (Spears, 2002).

The Chopawamsic Formation and Ta River Metamorphic Suite are unconformably overlain by the Quantico and Arvonia Formations. The Quantico and Arvonia Formations consist of meta-sedimentary rocks including slates, phyllites, schists, and quartzites. These meta-sedimentary rocks are considered to have been deposited in successor basins after the subjacent terranes were eroded and formed depositional troughs. Rocks of the Arvonia Formation are exposed in the Arvonia and Long Island synclines, while rocks of the Quantico Formation are exposed in the Quantico syncline. Rocks of the Arvonia, Long Island, and Quantico synclines form three belts across the central Virginia Piedmont, the Quantico synclines to the southeast and the Arvonia and Long Island synclines to the north (Spears, 2002).

The Chopawamsic Formation and the Ta River Metamorphic Suite are intruded by a number of granite plutons. The number of plutons and their relation to one another, however, remains uncertain (Spears, 2002). Rocks of the Falmouth Intrusive Suite intrude the Ta River Metamorphic Suite and Quantico Formation in the form of dikes, sills, and small irregular intrusions (Pavlides, 1980).

Western/Inner Piedmont Belt/Baltimore Terrane

The Western Piedmont belt, referred to as the Inner Piedmont belt in some publications, extends southward from Pennsylvania, where it has been designated as part of the Baltimore Gneiss and Glenarm Group (Baltimore terrane) through North Carolina and into Georgia (Figure 2.5-9). It is composed of greenschist facies (low grade) and amphibolite facies (high grade) meta-sedimentary rocks. These meta-sedimentary rocks enclose blocks of meta-basalt, ultramafic rocks, granite and other quasi-exotic lithologies and are called mélanges (Pavlides, 2000). These mélanges are interpreted to have formed in a Cambrian-Ordovician back-arc or marginal basin that lay on the continent-ward side of an island-arc terrane (Pavlides, 1989). The Baltimore terrane, a Middle Proterozoic metamorphosed sequence of felsic to intermediate rocks (Horton, 1989), consists of the Baltimore Gneiss and its cover sequence, the Glenarm Group, which consists of the basal Setters Formation, the Cockeysville Marble and the pelitic Loch Raven Schist. Mineral assemblages within the Glenarm Group indicate that it was metamorphosed during the Paleozoic (Horton, 1989). The Potomac terrane (not shown on Figure 2.5-9 due to scale) was thrust upon the Baltimore terrane during the Taconic orogeny.

Two distinct types of mélange deposits occur within a collage of thrust slices in the Western Piedmont belt. The first type is a block-in-phyllite mélange that constitutes the Mine Run Complex of Virginia. It consists of a variety of meta-plutonic, meta-volcanic, mafic, and ultramafic blocks enclosed within a matrix of phyllite or schist and meta-sandstones of feldspathic or quartz meta-graywacke. The Mine Run complex is interpreted to consist of four imbricated thrust slices, each with its own distinctive exotic block content (Pavlides, 1989).

The second mélange type within the Western Piedmont belt is a meta-diamictite and contains a less extensive variety of exotic blocks, the most common being mafic and ultramafic blocks. The exotic blocks are enclosed in a micaceous quartzofeldspathic matrix, which has contemporaneously deposited schist and quartz-lump fragments as its characterizing features.

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~~Several varieties of meta-diamictite have been recognized in Virginia and described as the Lunga Reservoir and Purcell Branch Formations (Pavlides, 1989).~~

~~The mélanges of the Western Piedmont are overlain unconformably by Ordovician age meta-sedimentary rocks and are intruded by Ordovician age and Late Ordovician or Early Silurian age felsic plutons, such as the Lahore and Ellisville plutons (Pavlides, 1989).~~

~~Ijamsville Belt/Westminster Terrane~~

~~The Ijamsville-Pretty Boy-Octoraro terrane is more currently known as the Westminster terrane (Horton, 1989). This belt consists of pelitic schist or phyllite characterized by albite porphyroblasts and a green and purple phyllite unit. Rocks of the Ijamsville/Westminster terrane were interpreted to comprise a tectonic assemblage of undated rocks of the rise and slope deepwater deposits of the Iapetus Ocean that were thrust onto the Grenville-age Blue Ridge Province along the Martic overthrust during the Taconic orogeny (Drake, 1989) (Horton, 1989).~~

~~Sedimentary Rocks (Early Mesozoic)~~

~~Mesozoic sedimentary rocks of the Piedmont Province occur primarily within the Piedmont Lowland section (Figure 2.5-10). The sediments were deposited in a series of northeast-trending basins described below in Section 2.5.1.1.4.4.3. Sediments filling the basins include intermontane fanglomerates, fresh-water limestone, mudstones, siltstones and sandstones, and basic igneous intrusive dikes and sills and lava flows (Markewich, 1990). The Lower Mesozoic sediments deposited in these basins usually are referred to as Triassic basin deposits, although the basins are now known to also contain Lower Jurassic rocks.~~

~~Surficial Sediments (Cenozoic)~~

~~Surficial sediments in the Piedmont Province consist of residual and transported material. The residual soils have developed in place from weathering of the underlying rocks, while the transported material - alluvium and colluvium - has been moved by water or gravity and deposited as unconsolidated deposits of clay, silt, sand, and gravel (Carter, 1976). Surficial sediments in the Piedmont Upland section are interpreted to be the product of Cenozoic weathering, Quaternary periglacial erosion and deposition, and recent anthropogenic activity (Sevon, 2000).~~

~~Residual soil in the Piedmont Province consists of completely decomposed rock and saprolite. Residual soils occur almost everywhere, except where erosion has exposed the bedrock on ridges and in valley bottoms. Saprolite comprises the bulk of residual soil in the Piedmont Province and is defined as an earthy material in which the major rock-forming minerals (other than quartz) have been altered to clay but the material retains most of the textural and structural characteristics of the parent rock. The saprolite forms by chemical weathering, its thickness and mineralogy being dependent on topography, parent rock lithology and the presence of surface and/or ground water (Cleaves, 2000).~~

~~Relief affects the formation of soils by causing differences in internal drainage, runoff, soil temperatures, and geologic erosion. In steep areas where there is rapid runoff, little percolation of water through the soil and little movement of clay, erosion is severe and removes soil as rapidly as it forms. Gently sloping areas, on the other hand, are well drained and geologic erosion in these areas is generally slight. The characteristics of the underlying rock strongly influence the kind of changes that take place during weathering. Because of differences in~~

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~~these characteristics, the rate of weathering varies for different rock types. The igneous, metamorphic and sedimentary rocks of the Piedmont Province are all sources of parent material for the soils.~~

~~Colluvium in the Piedmont Province occurs discontinuously on hilltops and side slopes, while thicker colluvium occurs in small valleys lacking perennial streams. Alluvium is present in all valleys with perennial streams (Sevon, 2000).~~

~~Blue Ridge Physiographic Province~~

~~The Blue Ridge Physiographic Province is underlain by a broad, northeast-trending, structurally complex metamorphic terrane (Mixon, 2000). In the site region, the Blue Ridge occurs southward from south-central Pennsylvania through Virginia (Figure 2.5-1). The Blue Ridge terrain consists of stratified meta-sedimentary rocks and meta-basalts of Early Paleozoic and Late Precambrian age and an underlying gneissic and granitic basement-rock complex of Middle to Late Precambrian age (Figure 2.5-5 and Figure 2.5-6).~~

~~Valley and Ridge Physiographic Province~~

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~~The Valley and Ridge Physiographic Province is underlain primarily by layered sedimentary rock that has been intensely folded and locally thrust faulted. The sedimentary rocks range in age from Cambrian to Pennsylvanian. The valley areas within the Great Valley (Figure 2.5-7) are underlain predominantly by thick sequences of limestone, dolomite and shale. The upland areas of the Valley and Ridge Province (Appalachian Mountains) to the west are underlain predominantly by resistant sandstones and conglomerates, while the lowland areas are underlain predominantly by less resistant shale, siltstone, sandstone and limestone (Colton, 1970) (Figure 2.5-5 and Figure 2.5-6).~~

~~Appalachian Plateau Physiographic Province~~

~~The Appalachian Plateau Physiographic Province is underlain by rocks that are continuous with those of the Valley and Ridge Province, but in the Appalachian Plateau the layered rocks are nearly flat-lying or gently tilted and warped, rather than being intensely folded and faulted. Rocks of the Allegheny Front along the eastern margin of the province consist of thick sequences of sandstone and conglomerate, interbedded with shale, ranging in age from Devonian to Pennsylvanian. Rocks of the Appalachian Plateau west of the Allegheny Front are less resistant and consist of Permian age sandstone, shale and coal (Lane, 1983) (Hack, 1989) (Figure 2.5-5 and Figure 2.5-6).~~

#### 2.5.1.1.4 Regional Tectonic Setting

In 1986, the Electric Power Research Institute (EPRI) developed a seismic source model for the Central and Eastern United States (CEUS), which included the CCNPP site region (EPRI, 1986). The CEUS is a stable continental region (SCR) characterized by low rates of crustal deformation and no active plate boundary conditions. The EPRI source model included the independent interpretations of six Earth Science Teams and reflected the general state of knowledge of the geoscience community as of 1986. The seismic source models developed by each of the six teams were based on the tectonic setting and the occurrence, rates, and distribution of historical seismicity. The original seismic sources identified by EPRI (1986) are thoroughly described in the EPRI study reports (EPRI, 1986) and are summarized in Section 2.5.2.2.

Since 1986, additional geological, seismological, and geophysical studies have been completed in the CEUS and in the CCNPP site region. The purpose of this section is to summarize the current state of knowledge on the tectonic setting and tectonic structures in the site region and to highlight new information acquired since 1986 that is relevant to the assessment of seismic sources.

A global review of earthquakes in SCRs shows that areas of Mesozoic and Cenozoic extended crust are positively correlated with large SCR earthquakes. Nearly 70% of SCR earthquakes with M 6 occurred in areas of Mesozoic and Cenozoic extended crust (Johnston, 1994). Additional evidence shows an association between Late Proterozoic rifts and modern seismicity in eastern
RAI 71 North America (Johnston, 1994) (Wheeler, 1995) (Ebel, 2002). Paleozoic and older crust
02.05.01-25 extended during the Mesozoic ~~extended crust~~ underlies the entire 200 mi (322 km) CCNPP site region (Figure 2.5-15). However, as discussed in this section, there is no evidence for late Cenozoic seismogenic activity of any tectonic feature or structure in the site region (Crone, 2000) (Wheeler, 2005). Although recent characterization of several tectonic features has modified our understanding of the tectonic evolution and processes of the mid Atlantic margin, no structures or features have been identified in the site region since 1986 that show clear evidence of seismogenic potential greater than what was recognized and incorporated in the EPRI study (EPRI, 1986) seismic source model. A study by Schulte and Mooney (Schulte, 2005) reassessed the correlation between earthquakes and extended and non-extended SCRs using an updated SCR earthquake catalog. Based on their analysis, Schulte and Mooney made
RAI 71 numerous observations and conclusinos that largely support the conclusions of Johnston et al.
02.05.01-3 (Johnston, 1994). In particular, Schulte and Mooney concluded that:

- Extended SCR crust on has slightly more earthquakes than non-extended SCR crust, and
- The largest SCR earthquakes (Mw > 7.0) occur predominantly within the extended crust

The following sections describe the tectonic setting of the site region by discussing the: (1) plate tectonic evolution of eastern North America at the latitude of the site, (2) origin and orientation of tectonic stress, (3) gravity and magnetic data and anomalies, (4) principal tectonic features, and (5) seismic sources defined by regional seismicity. Historical seismicity occurring in the site region is described in Section 2.5.2.1. The geologic history of the site region was discussed in Section 2.5.1.1.2.

#### 2.5.1.1.4.1 Plate Tectonic Evolution of the Atlantic Margin

The Late Precambrian to Recent plate tectonic evolution of the site region is summarized in Section 2.5.1.1.2 and in Figure 2.5-8. Most of the present-day understanding of the plate tectonic evolution comes from research performed prior to the 1986 EPRI report (EPRI, 1986). Fundamental understanding about the timing and architecture of major orogenic events was clear by the early 1980's, after a decade or more of widespread application of plate tectonic theory to the evolution of the Appalachian orogenic belt (e.g., (Rodgers, 1970) (Williams, 1983)). Major advances in understanding of the plate tectonic history of the Atlantic continental margin since the EPRI study report (EPRI, 1986) include the organization of lithostratigraphic units and how they relate to the timing and kinematics of Paleozoic events (e.g., Hatcher, 1989) (Hibbard, 2006) (Hibbard, 2007) and the refinement of the crustal architecture of the orogen and passive margin (e.g., (Hatcher, 1989) (Glover, 1995b) (Klitgord, 1995)).

The following subsections divide the regional plate tectonic history into: (1) Late Proterozoic and Paleozoic tectonics and assembly of North American continental crust, (2) Mesozoic rifting and passive margin formation, and (3) Cenozoic vertical tectonics associated with exhumation, deposition, and flexure.