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2.5 GEOLOGY, SEISMOLOGY, AND GEOTECHNICAL ENGINEERING

2.5.1 Geologic Characterization Information

The geological and seismological information presented in this subsection was developed from a review of previous reports for the proposed Clinch River Breeder Reactor, published geologic literature, and interpretations of data obtained as part of the surface and subsurface field investigations.

This subsection demonstrates compliance with the requirements of 10 CFR 100.23(c). Information on the geological and seismological characteristics of the Clinch River Nuclear (CRN) site region (200-mile [mi] radius), site vicinity (25-mi radius), site area (5-mi radius), and site location (0.6-mi radius) is presented in this subsection. Subsection 2.5.1.1 describes the geologic and tectonic characteristics of the site region and for stratigraphy, the site vicinity. Subsection 2.5.1.2 describes the geologic and tectonic characteristics of the site vicinity, site area and site location. The geological and seismological information was developed in accordance with NRC guidance documents Regulatory Guide (RG) 1.206, *Combined License Applications for Nuclear Power Plants (LWR Edition)* and RG 1.208, *A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion*. NUREG-0800, *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition*, Section 2.5.1, provides guidance for the development of Subsection 2.5.1.

2.5.1.1 Regional Geology (within the 200-Mile Regional Radius)

2.5.1.1.1 Regional Physiography and Geomorphic Processes

2.5.1.1.1.1 Regional Physiography and Topography

The site region is defined as the area within a 200-mi radius of the CRN Site (Figure 2.5.1-1). The CRN Site is located in the Valley and Ridge physiographic province. The area within a 200-mi radius of the CRN Site includes six physiographic provinces. These include, from west to east: the Central Lowlands province, Interior Low Plateaus province, the Appalachian Plateaus province, including the Cumberland Plateau at the latitude of the site region, the Valley and Ridge province, the Blue Ridge province, and the Piedmont province (Figure 2.5.1-1). Each of these six physiographic provinces is described below in terms of their physiography and geomorphology. A more detailed discussion is provided for the Valley and Ridge physiographic province in which the CRN Site is located.

2.5.1.1.1.1.1 Central Lowlands Physiographic Province

The Central Lowlands physiographic province is generally located in the northern Midwest but also extends through Oklahoma into north-central Texas (Reference 2.5.1-1). The Central Lowlands physiographic province is subdivided into several sections. A small portion of the Till Plains section of southeast Indiana, within the Ohio River Valley, is located on the northwestern boundary of the site region radius as shown on Figure 2.5.1-1.

The southern portion of the Central Lowlands province, located within the site region, is characterized by flat to gently-rolling glacial landforms including till plains, end moraines, ground moraines, recessional moraines, and outwash plains, along with some isolated lacustrine deposits. The local relief is up to 76 meters (m) (250 feet [ft]). Paleozoic bedrock, consisting of relatively flat-lying carbonate and clastic strata, is exposed locally, particularly along steep slopes associated with drainage networks. Pleistocene glacial deposits were deposited on a dissected bedrock surface with buried stream valleys (Reference 2.5.1-2). The southern portion of the Central Lowlands province, within the 200-mi site region radius is differentiated from other

regions in the province to the north and the west by well-developed stream systems (e.g., Ohio River and its tributaries) with a significant history of erosion. In the southern portion, older landscapes have been differentiated from younger landscapes on the basis of soil development, depth of leaching, and degradation of glacial landforms (e.g., Cincinnati, Ohio). However, these landscapes may have also been eroded by hillslope processes, especially those that allowed the movement of the active layer on low slopes when permafrost was present. These processes have resulted in a rolling terrain atypical of other regions within the province (Reference 2.5.1-3). Karst conditions in the Central Lowlands province can occur where terrain is underlain by Paleozoic carbonate rock. An example of a recognized karst region in the Central Lowlands is the Muscatatuck Plateau of southeastern Indiana. Karst has developed in this northwestern portion of the site region on limestones of Silurian and Devonian age (Figure 2.5.1-2) (Reference 2.5.1-4).

2.5.1.1.1.1.2 Interior Low Plateaus Physiographic Province

The Interior Low Plateaus province is situated within the western portion of the CRN site region radius (Figure 2.5.1-1). The eastern boundary of the Interior Low Plateaus province corresponds with the westernmost extent of Pennsylvanian strata of the adjacent Cumberland Plateau (Reference 2.5.1-5). The mean elevation of the Interior Low Plateaus is lower than the Cumberland Plateau, with summit levels that gradually decrease from approximately 1400 ft msl to approximately 500 ft msl from east to west. The Interior Low Plateaus are structurally similar to the Cumberland Plateau, consisting of broad, gentle folds with nearly horizontal strata throughout. In contrast to the late Paleozoic strata of the Cumberland Plateau, strata from the Interior Low Plateaus range in age from Ordovician through Silurian-Devonian. Because Pennsylvanian rocks are preserved only toward the east, greater uplift toward the west is suggested, associated with exposures of Ordovician strata within the Nashville Dome and Cincinnati Arch (Figure 2.5.1-3) (Reference 2.5.1-6). The Interior Low Plateaus province is about 300 by 300 mi in size and covers most of central Tennessee and central Kentucky (Figure 2.5.1-1). Along its boundary with the Appalachian Plateaus province (in Kentucky and Tennessee) is a west-facing escarpment that is composed of sandstones of early Pennsylvanian age.

The Interior Low Plateaus Province is underlain predominantly by Ordovician and Mississippian carbonate rocks onto which moderate karst (topography) is developed. Karst is created by large-scale dissolution of these carbonate rocks resulting in the formation of numerous large caverns. One example of the result of this process is Mammoth Cave, the largest documented cavern in the world, located within Mammoth Cave National Park in west-central Kentucky (Reference 2.5.1-7). Many caves in the region, like fluvial terraces, have preserved a local and/or regional geomorphic history including cycles of erosion, downcutting of associated rivers and streams as a product of glacially-induced climatic changes during the Pleistocene epoch and/or uplift during the late Miocene epoch. Periods of erosion caused by increased precipitation, corresponding to maximum glaciation, lead to the deposition of alluvium, including stream terraces and decreased stream gradients on a regional scale. Conversely, uplift during the Miocene and decreased precipitation, erosion and subsequent sediment load during intraglacial periods produced downcutting and/or incision of stream courses (References 2.5.1-8 and 2.5.1-9).

2.5.1.1.1.1.3 Appalachian Plateaus Physiographic Province

The Appalachian Plateaus physiographic province includes the western part of the Appalachian Mountains, stretching from New York to Alabama. The Appalachian Plateaus physiographic province is bounded on the west by the Interior Low Plateaus and on the east by the Valley and Ridge province. The Appalachian Plateaus physiographic province extends from northwestern New York to central Alabama. From its maximum width of more than 200 mi through

Pennsylvania and Ohio, it begins to narrow in eastern Kentucky, spanning approximately 30 mi wide (east-west) in portions of Tennessee. The Appalachian Plateaus physiographic province is made up of gently-deformed and unmetamorphosed sedimentary rocks, including sandstone, siltstone, shale, and coal, of Permian to Cambrian age (Figure 2.5.1-1).Typically, rocks of Silurian through Permian Age (middle to late Paleozoic) are exposed at the surface.

This province is essentially a broad syncline (synclinorium) in rocks of Late Paleozoic age, bounded on all sides by escarpments that reflect the regional synclinal structure. The stratigraphy is nearly horizontal with typical plateau structure, but the formations are so elevated and dissected that terrain is typically mountainous (Reference 2.5.1-6). These strata are generally subhorizontal to gently-folded into broad synclines and anticlines, reflecting little deformation compared to the Valley and Ridge province to the east. Rocks within this province exhibit lithologic variation from each other with respect to resistance to weathering. Sandstone units tend to be more resistant to weathering and form topographic ridges, whereas less resistant limestones, shales, and siltstones weather preferentially and underlie most valleys. Limestone dissolution and sinkholes occur where limestone units with high karst susceptibility are at or near the ground surface (Reference 2.5.1-10). The Appalachian Plateaus physiographic province is deeply dissected by streams into a maze of deep, narrow valleys and high narrow ridges.

The Appalachian Plateaus ground surface slopes gently to the northwest and is juxtaposed next to the Interior Low Plateaus at a westward-facing escarpment. The Allegheny Front, along the southeast margin of the Appalachian Plateaus, is the topographic and structural boundary between the Appalachian Plateaus and the Valley and Ridge province (Reference 2.5.1-11). The Allegheny Front 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 4790 ft msl (Reference 2.5.1-12). West of the Allegheny Front, the Appalachian Plateaus' topographic surface merges imperceptibly into the Interior Low Plateaus.

The Appalachian Plateaus physiographic province includes the Cumberland Plateau within the 200-mi radius boundary (Figure 2.5.1-3). The Cumberland Plateau is distinguished from the Interior Low Plateaus Province to the west and the Valley and Ridge Province to the east by its relatively high topography and contrasting structural style. Both its eastern and western boundaries are defined by outward-facing escarpments. The western boundary is defined by the western extent of Pennsylvanian strata in the Cumberland Plateau (Reference 2.5.1-5), while the eastern boundary is demarcated by several Valley and Ridge thrust faults, klippes, and windows (Figure 2.5.1-3). In eastern Tennessee, the eastern boundary coincides with a complex series of faults and folds (Reference 2.5.1-13).

In Tennessee and Alabama, the Cumberland Plateau section is generally composed of the resistant Pottsville Formation of Pennsylvanian age, which consists of alternating beds of sandstone, siltstone, and shale with coal seams. Topographic elevations within the Cumberland Plateau section generally increase to the north, rising from approximately 2000 ft msl near the Tennessee-Alabama border to greater than 3000 ft msl in central and northern Tennessee and 4000 ft in West Virginia and Virginia, before decreasing into Maryland and Pennsylvania. The eastern boundary of the Cumberland Plateau section is the Cumberland escarpment which marks the change from the broad open folds in the Cumberland Plateau to the close folding with marked faulting in the Valley and Ridge. The linearity of the Cumberland escarpment contrasts with the dissected character of the scarp on the west side of the Plateau (Reference 2.5.1-1).

2.5.1.1.1.1.4 Valley and Ridge Physiographic Province

The CRN Site is located in the Valley and Ridge physiographic province (Reference 2.5.1-1). The Valley and Ridge physiographic province is bordered to the west by the Appalachian Plateaus physiographic province (Cumberland Plateau) and to the east by the Blue Ridge physiographic

province (Figure 2.5.1-1). The Valley and Ridge extends for 1200 mi, from the Saint Lawrence Lowlands and eastern New York in the north to central Alabama in the south. It ranges from 14 to 80 mi in width and is 40 to 50 mi wide in Alabama and northwestern Georgia (Reference 2.5.1-1). The boundary between the Appalachian Plateaus and the Valley and Ridge is an abrupt topographic rise known as the Allegheny Front in Pennsylvania and the Cumberland Escarpment in Tennessee and Virginia. The Cumberland Escarpment is capped by sandstone and conglomerate which are more resistant to erosion than the underlying limestone, siltstone, shale, and coal. This contrast in resistance is expressed geomorphically as a belt of cliffs and narrow crested valleys. The CRN Site is located approximately 10 mi east of the Cumberland Escarpment, which is locally named Walden Ridge. The topographic relief of the Walden Ridge portion of the Cumberland Escarpment in eastern Tennessee is approximately 1000 feet above the terrain of the Valley and Ridge to the east. Walden Ridge is breached by a series of thrust faults including the Pine Mountain fault, the westernmost of the Valley and Ridge thrust faults (Reference 2.5.1-12).

The general features (Reference 2.5.1-14) that distinguish this province from adjacent areas are: (1) parallel ridges and valleys commonly aligned from northeast to southwest; (2) topography caused by erosion of interstratified weak and strong formations that are exposed at the surface by exhumation of a relatively strongly folded and faulted terrain; (3) a few major transverse superimposed streams with subsequent streams forming a trellis-like drainage pattern (drainages are mostly dendritic in the headwaters and trellis downstream); (4) many ridges with accordant summit levels suggesting a history of erosion; and (5) many water and wind gaps through resistant ridges. The southern Valley and Ridge of Thornbury (Reference 2.5.1-14) is similar to the northern section but differs from the northern section by having (1) more exposed thrust faults; (2) lower ridges; and (3) more distinct longitudinal river systems. In Tennessee and Alabama, ridges are generally approximately 1000 ft msl in elevation and sometimes reach 1500 ft msl elevation (Reference 2.5.1-15). In the northern part of the province, ridges sometimes exceed 4000 ft msl elevation.

Anticlinal valleys, anticlinal ridges, synclinal valleys, synclinal ridges, homoclinal valleys, and homoclinal ridges are six possible topographic expressions of the geologic structure commonly encountered in the Valley and Ridge province (Reference 2.5.1-6). Folds are strongly compressed and the degree and intensity of faulting generally increases southward. At the latitude of the CRN Site, the Valley and Ridge is dissected by approximately 16 major (significant) thrust faults (Reference 2.5.1-16).

The geomorphology of the Valley and Ridge province is a direct result of differential weathering and erosion of different folded and faulted Paleozoic sedimentary rocks (Figures 2.5.1-3, 2.5.1-19, and 2.5.1-27). In the Valley and Ridge province, ridges are composed of more resistant sandstone, siltstone, dolomite and limestone with relatively higher silica content. Valleys are commonly composed of soluble limestone formations and easily-erodible shale formations. Valley formation may also be attributed to erosion and physical weathering along thrust faults, where present (Reference 2.5.1-9). Elevations within the ridges and valleys range from about 1000 to 4500 ft msl (Reference 2.5.1-17).

The Valley and Ridge province is composed of Paleozoic sedimentary formations ranging from 30,000 to 40,000 ft thickness. The rocks within this province are tightly folded and, in many locations, faulted. The eastern boundary of the Valley and Ridge province marks a change from folded, lesser-deformed Paleozoic sedimentary rocks to more penetratively deformed Precambrian rocks in the Blue Ridge.

Drainage patterns in the Valley and Ridge province generally follow the northeast-southwest trend of topography. However, segments of major rivers cut across the regional topographic alignment following deeply entrenched, ancient stream courses. Four rivers including the Powell,

Clinch, Holston and French Broad join to form the Tennessee River after flowing many miles in northeast-southwest-trending valleys. Most of the site vicinity (25-mi radius) lies within the Tennessee River drainage basin. The Tennessee River flows southwest across eastern Tennessee, eventually changing to a northerly stream course and merging with the Ohio River at the Kentucky-Illinois border. Within the site area the Clinch River meanders in a westerly direction in an entrenched course that cuts across the regional topography. The Clinch River joins the Tennessee River approximately 16 river mi downstream (west-southwest) from the CRN Site.

2.5.1.1.1.1.5 Blue Ridge Physiographic Province

The Blue Ridge province is bounded on the northwest by the Valley and Ridge physiographic province and to the southeast by the Piedmont physiographic province. The Blue Ridge province is aligned in a northeast-southwest direction and extends from southeastern Pennsylvania to northern Georgia. The province varies in approximate width from 5 mi (8 km) to more than 50 mi (80 km) at its widest extent in western North Carolina through eastern Tennessee (Reference 2.5.1-6).

This province represents the core of Appalachian Mountains. It is composed of granites and granitic gneisses and more resistant crystalline rocks, generally occupying upper ridge crests. Less resistant rocks (metasedimentary lithologies) such as phyllites schist, slate, and metasiltstone are generally on slopes. Harder, more massive, metasedimentary rocks, such as metagreywacke, may also occupy ridgetops. Metavolcanic rocks, such as greenstone, are generally located on lower ridgecrests. The rocks of the Blue Ridge province date to the Precambrian and Paleozoic and were deposited on the basement rocks of the North American continent (Figures 2.5.1-2 and 2.5.1-11).The province is a metamorphosed basement/cover sequence consisting of igneous (granitic) and low to high-grade metamorphic rocks that have been complexly folded, faulted, penetratively deformed, and intruded. These rocks record multiple late Proterozoic to late Paleozoic deformation events (Reference 2.5.1-18). Thomas (Reference 2.5.1-19) describes the Blue Ridge as an elongate external basement massif along which late Precambrian syn-rift sedimentary and volcanic rocks, as well as older basement rocks, have been translated and deformed by younger compressional structures, especially large-scale Alleghanian (late Paleozoic) thrust faults.

The Blue Ridge physiographic province is a deeply dissected mountainous area of numerous steep mountain ridges, intermontane basins, and steep v-shaped valleys that intersect at all angles and give the area its rugged mountainous character. The Blue Ridge contains the highest elevations and the most rugged topography in the Appalachian Mountain system of eastern North America. Within North Carolina, 43 peaks exceed 6000 ft in elevation, including Mount Mitchell, North Carolina, the highest point (6684 ft msl) in the Appalachian Mountains. In addition, 82 peaks are between 5000 and 6000 ft in elevation.

The east-facing Blue Ridge escarpment separates the highlands of the Blue Ridge from the lower-relief Piedmont province in the southern Appalachians. The Blue Ridge escarpment is about 300 mi in length and averages 1000 to 1650 ft in elevation. The lithologies and tectonic evolution of the Blue Ridge are described in Subsections 2.5.1.1.2 and 2.5.1.1.4.

2.5.1.1.1.1.6 Piedmont Physiographic Province

The Piedmont province is located southeast of the Blue Ridge province and is bordered on the southeast by the Atlantic Coastal Plain, outside of the site region radius (Figure 2.5.1-1). The Piedmont physiographic province extends southwest from New York to Alabama. The Piedmont province is about 40 mi wide in Maryland and narrows northward to about 10 mi wide in southeastern New York. The Piedmont is characterized by gently-rolling, well-rounded hills and

long, low ridges. The Piedmont is a seaward-sloping land surface varying in width from about 10 mi in southeastern New York to almost 125 mi in South Carolina, and has the lowest topographic relief of the Appalachian provinces. Elevation of the western boundary ranges from about 200 ft msl in New Jersey to over 1800 ft msl in South Carolina. Along the boundary between the Piedmont and the Coastal Plain (Fall Line), elevations range from 500 to 800 ft, gradually rising to the west to about 1700 ft at the foot of the Blue Ridge (Reference 2.5.1-20). 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 (References 2.5.1-21 and 2.5.1-22).

Within the site region, the Piedmont province is generally characterized by deeply-weathered bedrock and a relative paucity of solid rock outcrop (Reference 2.5.1-6). Residual soil or saprolite covers the bedrock to varying depths. However, publications and detailed geologic mapping during the past 45 years indicate that outcrops of relatively fresh rock occur in the banks of streams and small creeks. Both residual soils and saprolite are soils derived from the in situ weathering of metasedimentary and metaigneous parent bedrock, with the latter exhibiting bedrock structural characteristics, including, but not limited to, relict bedding planes, lineations, foliations, joints and fractures. On hillslopes, saprolite may be capped locally by colluvium (Reference 2.5.1-23).

Most of the rocks in the Piedmont province are gneiss and schist, with minor marble and quartzite, and were derived from metamorphism of older sedimentary and volcanic rocks. Late Proterozoic, Ordo-Silurian, Devonian, and late Paleozoic granite are also present. Some less intensively metamorphosed rocks, including considerable slate, occur along the eastern part of the province from southern Virginia to Georgia.

The Piedmont physiographic province is divided on the basis of its geologic history and lithology into different lithotectonic associations. Mesozoic basins within the Piedmont are located east of the 200-mi radius site region and are discussed further in Subsection 2.5.1.1.2. Subsections 2.5.1.1.2 and 2.5.1.1.4 contain detailed discussions of the lithologies, tectonic evolution and structural geology of the Piedmont.

2.5.1.1.1.2 Fluvial Processes

Climate shifts during the Pleistocene resulted in significant changes in the types, rates and intensity of geomorphic processes. Upland soils underwent several cycles of denudation during periods of maximum glaciation. Landforms on slopes and other sensitive landforms were periodically stripped down to hard rock or resistant saprolite while other less sensitive areas were hardly affected. Freeze-thaw during Wisconsinan time along with periods of winter freezing and downward melting of the surface in the spring destabilized many upland soils. The longest period of soil instability was between 18,000 and 25,000 years ago when glaciers extended south to their maximum extent in southern Ohio. Large volumes of soil flowed downslope as mud and debris flows, filling topographic lows and choking stream valleys and river channels (Reference 2.5.1-14). Regionally, many rivers may also have been unable to transport increased sediment load and may have aggraded their channels, producing widening floodplains with braided streams and damming of tributaries. Other streams that were choked by sediments were forced into other pathways through topographically-lower outlets. Stream piracy was common during the Pleistocene as stream networks eroded headwardly in response to increased rates of precipitation (Reference 2.5.1-5). Records of these processes are preserved in age-dated fluvial terraces that include chert gravels eroded from uplands and other stream rounded gravels deposited on bedrock residuum. A detailed discussion of fluvial geomorphic processes, as they relate to the site, including Pleistocene geomorphic processes related to the formation of entrenched meanders and fluvial terraces of the Tennessee River watershed (including the

Clinch River) is contained in Subsection 2.5.1.2.1, Local Physiography and Geomorphic Processes.

2.5.1.1.1.3 Regional Karst Processes and Occurrence

Karst is a terrain with distinctive hydrology and morphology created through the dissolution of soluble rock (Reference 2.5.1-7). The process of dissolution, where weakly acidic groundwater reacts with soluble (carbonate) rock over long periods of time, creates underground drainage systems and associated karst landscape features. The distribution of soluble carbonate rock within 200-mi radius site region is shown on Figure 2.5.1-4. The list of world-wide karst landscape features is extensive, and the characteristics of these features vary with the geologic, hydrologic, tectonic, and climatic setting. However, the fundamental feature common to all karst areas is the presence of an underground drainage system created through the dissolution of soluble rock. Geologic hazards in karst terrains may include ground subsidence or collapse, rapid underground drainage, irregular soil-bedrock contact, and deep weathering along bedding planes, joints, fractures, and faults. In the site region, the presence of extensive carbonate strata (Figure 2.5.1-4) in a temperate climate with abundant rainfall has led to intense chemical weathering and landscapes produced by dissolution of soluble carbonate rock (limestone and dolomite) and karst formation, containing one or more characteristics of karst as mentioned above. This subsection summarizes the nature of karst development and karst features in the site region.

Karstification is the process created by chemical dissolution when weakly acidic groundwater circulates through soluble rock. CO_2 from the atmosphere is fixed or converted in the soil horizon to an aqueous state, where it combines with rainwater to form carbonic acid, which readily dissolves carbonate rock. Root and microbial respiration in the soil further elevates carbon dioxide partial pressure, increasing acidity (lowering pH). In humid, temperate to subtropical regions such as Tennessee, abundant vegetation, high rainfall, and high atmospheric CO_2 values favor the rapid dissolution of the preexisting limestone. Karst features develop from a self-accelerating process of water flow along well-defined pathways. As the water percolates downward under the force of gravity, it dissolves and enlarges the pore or fracture space in the rock through which it flows. These pathways also include bedding planes, joints, fractures, and faults. Enlarging the fracture allows it to carry more water, which increases the dissolution rate. As the fracture becomes larger and transmits more water, it begins to capture drainage from the surrounding rock mass. This process creates areas where the rock is highly eroded with very little dissolution around it, creating a very jagged appearance to the soil and bedrock interface.

Karstification can occur at the ground surface resulting in sinkholes. Sinkholes create depressions that can be filled with water or sediment. There are four main types of sinkholes common to the southeastern United States (Figure 2.5.1-6):

- Solution sinkholes occur where limestone is exposed at the ground surface or is covered with a thin mantle of material (1A on Figure 2.5.1-6). Dissolution is concentrated at the surface and along joints, fractures, or other openings in the rock. The development of such features is accomplished by a slow drop of the ground surface that results in the formation of a depression that is commonly filled with organic-rich sediments. These sinkholes typically manifest themselves as bowl-shaped depressions at the ground surface.

- Cave-collapse sinkholes occur where a solution cavity develops in the limestone to a size such that the rock material cannot support its own weight (1B on Figure 2.5.1-6). The result is generally a sudden collapse of the limestone rock into the cavity. These sinkholes are common in areas where limestone is close to the ground surface and under water-table conditions, with accelerated dissolution occurring in limestone zones at and just below the water table.

- Cover-collapse sinkholes form from the collapse of unconsolidated deposits or residual soil over dissolutioned bedrock (1F on Figure 2.5.1-6). Soil slowly filters through enlarged joints in the rock into solution cavities below. A void forms at the base of the soil which gradually slopes upward as soil is lost from below. The ground surface gradually subsides forming a subsidence sinkhole (1C on Figure 2.5.1-6), or where the soil is dense and cohesive, the progressively thinning soil bridge over the void eventually collapses (1F on Figure 2.5.1-6).

- Cover-subsidence sinkholes occur where the overburden is comprised of unconsolidated and permeable sands (1E on Figure 2.5.1-6). They form when the sand slowly moves downward into space formerly occupied by other sediments, which have already moved downward into space formerly occupied by limestone that has been removed by dissolution. These sinkholes generally develop gradually. Cover-collapse and cover-subsidence sinkholes are the most common type of sinkholes documented in the Valley and Ridge province (Reference 2.5.1-25).

Karst features are common throughout the Appalachians and the Central Lowlands physiographic province wherever carbonate bedrock (limestone, dolomite, or marble) occurs. Weary (Reference 2.5.1-26) maps the extent of carbonate rock types and describes styles of karst terrain within the site region. Karst features and processes in the two most extensive karst terrains, labeled FFC and GC on Figure 2.5.1-4 are summarized below. These two terrains occur in the Valley and Ridge and the Interior Low Plateaus physiographic provinces, respectively, shown on Figure 2.5.1-1.

The geomorphology within the site region is characterized as a karst landscape wherever carbonate bedrock is present in the near-surface through chemical weathering of solutionable carbonate bedrock. Two distinct, but related, karst terrains dominate the site region, Valley and Ridge and Interior Low Plateaus provinces (Figure 2.5.1-4), and they are discussed in detail below. Both form in Paleozoic carbonate strata under similar climatic and vegetative conditions, and in landscapes characterized by long-term erosion. Differing geologic structure, however, has led to major differences in karst characteristics, especially cave development (Figure 2.5.1-5). Caves in the folded and faulted rocks of the Valley and Ridge are relatively short as the dominantly Cambrian to Ordovician carbonate strata are folded, and interbedded with clastic strata. Cave passages tend to be controlled by bedding planes, joints, fractures, and faults, and major passages are oriented parallel to strike. In contrast, caves in the gently-dipping to flat-lying rocks of the Interior Low Plateaus develop extensive and complex horizontal branchwork passages, especially in the thick Mississippian limestone units. Multiple levels of passages are preserved beneath a caprock of clastic rock, with each level corresponding to a pause in stream incision. Both karst terrains feature extensive sinkhole development where carbonate strata underlie the soil cover.

Refer to Subsection 2.5.1.1.5.1 for discussion of regional karst hazards.

2.5.1.1.1.3.1 Karst in the Valley and Ridge Province

Karst in the Valley and Ridge province, which includes the CRN Site, forms in folded and faulted Paleozoic carbonate rocks, labeled FFC on Figure 2.5.1-4. These rocks form a linear band running southwest to northeast through the states of Alabama, Georgia, Tennessee, Kentucky, Virginia and West Virginia, Maryland, Pennsylvania, New Jersey, and New York. Karst landscape features in the Valley and Ridge include sinkholes, caves, springs, seeps, and sinking streams.

Shofner et al., (2001 Reference 2.5.1-25) (Figure 2.5.1-5) shows the general distribution of sinkholes in the Valley and Ridge province of Tennessee. Cover-collapse sinkholes are the most common in this province. Cover-collapse and cover-subsidence sinkholes are a primary cause of damage to homes and infrastructure in the region (Reference 2.5.1-27). Loss of material at the

bedrock-soil interface results in soft or loose soils and voids. However, as the authors indicate, "…although similar geologic conditions appear to favor both sinkhole development and cave formation, the actual processes involved in the development of these two types of features seems to be only weakly related."

Weary (Reference 2.5.1-26) notes, "Where carbonates are thick and extensive, cave systems may be long and complex. Where thin and interbedded with non-carbonates, caves are small and short." In this province, caves are common, but tend to be relatively small (less than a few kilometers in length), as the carbonate strata are folded and interbedded with siliciclastic strata. The tectonic history of the region has produced a series of imbricate thrust sheets that repeat stratigraphy and results in a lack of horizontal continuity perpendicular to strike. Consequently, most cave passages are oriented parallel to strike with their geometries exemplifying structural control, such as passages oriented along bedding strike, joints, or joint-bedding plane intersections. According to Sutherland's (Tennessee Cave Survey) cave count about 9,839 caves are known in Tennessee, of which approximately 15 percent are located in the Valley and Ridge province (Reference 2.5.1-28).

2.5.1.1.1.3.2 Karst in the Interior Low Plateaus Province

North and west of the Valley and Ridge province in central Tennessee, Kentucky, and northern Alabama, a second distinct karst terrain occurs in gently folded to flat-lying Paleozoic limestone and dolomite of the Interior Low Plateaus physiographic province. Labeled GC on Figure 2.5.1-4, this karst terrain forms in an area of thick carbonate units that have a flat-lying to gentle dip. Similar to the Valley and Ridge, the land surface exhibits extensive areas of solution, collapse, and cover-collapse sinkholes wherever carbonate rocks are near the surface. Sinkhole frequency in Tennessee is reported by Shofner et al. (Reference 2.5.1-25) and shown on Figure 2.5.1-5. Sinkholes are especially common in the Eastern Highland Rim sub-province where thick, solutionable, limestone strata are exposed at the surface.

According to the cave count by physiographic province exclusively, the Tennessee Cave Survey reports approximately 84 percent of known caves in Tennessee within the Interior Low Plateaus province and Appalachian Plateaus provinces combined (Reference 2.5.1-28). The flat-lying structure allows for the development of very long complex caves with branch-work patterns. Mammoth Cave, Kentucky, located 130 mi northwest of the site, is the longest cave in the world with 400 mi of surveyed passages (Reference 2.5.1-29). At Mammoth Cave, thick sequences of almost flat-lying Mississippian limestone, protected from erosion beneath a sandstone caprock, have combined to create an extensive and complex cave system with a branch-work pattern. Major cave passages form near the water table, cutting across the gently dipping bedding planes.

During the Quaternary period, the region experienced gradual erosion and landscape lowering, as streams cut down through the bedrock in response to possible tectonic uplift as interpreted by White (Reference 2.5.1-30); however, this may also be attributed to non-tectonic mechanisms. Slope processes and karst dissolution gradually removed rock at the surface and subsurface (Reference 2.5.1-30). Studies of cave sediments in passages left dry by stream incision indicate that the present fluviokarst landscape of the Cumberland Plateau began forming in the Miocene (References 2.5.1-8 and 2.5.1-30). At Mammoth Cave, multiple passage levels, each graded to a former level of the Green River, record the episodic downcutting of the river from the Miocene to the present, based on radiometric dating of relict Green River deposits (References 2.5.1-31 and 2.5.1-32). This process has left a series of abandoned dry passages that increase in age with elevation. Vertical shafts and slots formed by downward-moving vadose water connect the levels. Similar caves occur in Tennessee; the longest in the state is 38 mi in length (Reference 2.5.1-29). Subsection 2.5.1.2.5.1 contains a detailed characterization of karst at the CRN site area.

2.5.1.1.2 Regional Geologic History and Tectonic Evolution

The CRN Site lies just west of the main axis of the northeast-southwest-trending Appalachian orogenic belt, which extends nearly the entire length of eastern North America from Newfoundland, Canada to central Alabama (Figure 2.5.1-7). The Appalachian orogenic belt is the product of at least three Paleozoic orogenies (Figures 2.5.1-8 and 2.5.1-9). These orogenies consisted of periods of tectonic contraction and associated metamorphism and magmatism, related to the opening and closing of several proto-Atlantic oceans along the eastern margin of ancestral North America (Laurentia). Three primary Appalachian orogenic events influenced the geology and structure of the CRN site region: the Middle Ordovician Taconic orogeny, the Early Devonian to Mississippian Acadian/Neoacadian orogeny, and the Pennsylvanian to Permian Alleghanian orogeny (e.g., Reference 2.5.1-34) (Figures 2.5.1-8 and 2.5.1-9). A more thorough discussion of the lithotectonic terranes (regional-scale fault-bounded fragment of oceanic or continental material with a discrete tectonic history relative to adjacent terranes) that comprise the southern Appalachian orogen is provided in Subsection 2.5.1.1.4.

Prior to the Paleozoic Appalachian orogenies, the eastern (present-day geographic configuration) Laurentian margin was deformed and metamorphosed during the Grenville orogeny, which involved the amalgamation of the supercontinent Rodinia at approximately 1.1 giga annum (Ga). Blue Ridge and Piedmont terranes, described in Subsections 2.5.1.1.3 and 2.5.1.1.4, record the Grenville orogeny, but based on lead isotopic data, central and southern Appalachian Grenvillian rocks may have a South American (Amazonian) rather than Laurentian origin (Reference 2.5.1-34). Rodinia began to rift apart at approximately 735 mega annum (Ma), and although the opening of the Iapetus ocean associated with Rodinia's terminal breakup occurred during the late Neoproterozoic, based on the age of the Catoctin metavolcanics (560-570 Ma; Reference 2.5.1-36). This rifting event produced an irregular continental margin controlled by northwest-striking transform faults, which strongly dictated the stratigraphic thickness of rift-facies successions (e.g., Ocoee Supergroup) in the southern Appalachian Blue Ridge (e.g., Reference 2.5.1-37). Additionally, the rifted margin framework that developed during the breakup of Rodinia also acted as a template for the distribution of the Paleozoic orogenies, and the present-day sinuous trace of the Appalachian mountain belt is a direct result of the rifted Laurentian margin geometry (Figure 2.5.1-10) (e.g., Reference 2.5.1-38).

The rifted Laurentian margin transitioned to a passive margin sometime in the early Cambrian; this transition is commonly associated with deposition of shallow-marine Chilhowee Group strata (Reference 2.5.1-39). In the Blue Ridge province southeast of the site vicinity, Chilhowee Group rocks are conformably overlain by the Shady Dolomite, which signifies the development of a stable continental shelf by the early Cambrian (Reference 2.5.1-42). The stratigraphically higher Rome Formation conformably overlies the Shady Dolomite, although it was nonconformably deposited on crystalline (Grenvillian) basement in more proximal positions (Figure 2.5.1-11). The overlying Conasauga and Knox Groups represent the Cambrian – Ordovician carbonate platform that developed on the passive Laurentian margin.

The eastern Laurentian margin evolved into a collisional environment during the Middle Ordovician (480-460 Ma) Taconic orogeny, which involved the accretion of several peri-Laurentian island arcs and oceanic tracts (now the central Blue Ridge terranes) to the margin (e.g., References 2.5.1-43, 2.5.1-44, and 2.5.1-45) (Figure 2.5.1-9). Orogenic activity along the margin resulted in clastic input from the east into the Appalachian foreland basin. This pulse of clastic sedimentation resulted in relatively thick deposits of the Sevier clastic wedge that now overlie the carbonate successions that dominated the Cambrian-Ordovician stratigraphy (References 2.5.1-46 and 2.5.1-47).

Tectonic loading along the Laurentian margin associated with the Taconic orogeny resulted in uplift and erosion of portions of the carbonate platform (Knox unconformity)

(Reference 2.5.1-48). The Knox unconformity also coincides with a eustatic sea level low (Reference 2.5.1-49), although variations in the magnitude of the unconformity and age relationships in the southern Appalachians indicate local tectonic control (References 2.5.1-48 and 2.5.1-50).

The following Devonian-Mississippian Acadian/Neoacadian orogeny (415-355 Ma) was the result of diachronous northeast to southwest accretion of the Carolina superterrane as it overrode the Laurentian margin (References 2.5.1-34, 2.5.1-44 and 2.5.1-52). The Carolina superterrane is an amalgamation of Neoproterozoic-Cambrian continental and oceanic volcanic arc terranes that formed proximal to Gondwana (composite Africa and South America) (Reference 2.5.1-53). Evidence that supports Devonian-Mississippian accretion of the Carolina superterrane includes: (1) prograde, upper amphibolite-facies metamorphism of the Inner Piedmont occurred during that time interval (References 2.5.1-44, 2.5.1-52, 2.5.1-54, and 2.5.1-55); (2) a distinct pulse of anatectic plutonism in the eastern Inner Piedmont that coincides with peak metamorphism (References 2.5.1-52, 2.5.1-55, and 2.5.1-56); (3) regional-scale structural patterns that indicate orogen-parallel channel flow at mid-crustal depths was coincident with peak Devonian-Mississippian metamorphism (References 2.5.1-51 and 2.5.1-57); (4) a suite of Late Silurian-Devonian subduction-related bimodal plutonic rocks (Concord Plutonic Suite) occur along the western flank of the Carolina superterrane, which supports east-dipping subduction of ocean crust beneath the Carolina superterrane at that time (References 2.5.1-52, 2.5.1-58, 2.5.1-59, and 2.5.1-60); (5) detrital zircons as young as Late Silurian occur in the Cat Square terrane (see Subsection 2.5.1.1.4), which precludes earlier accretion of the Carolina superterrane; and (6) a series of thick Devonian-Mississippian clastic successions in the central and southern Appalachian foreland that progressively become younger to the southwest throughout the central to southern Appalachians. These clastic units include the Catskill, Price-Pocono, and Bordon-Grainger clastic wedges, and the Chattanooga Shale through eastern Tennessee and are located within the Valley and Ridge province just southeast of the site region (References 2.5.1-53, 2.5.1-61, 2.5.1-62, 2.5.1-63, and 2.5.1-64). Alternatively, several studies have suggested Late Ordovician-Early Silurian accretion of the Carolina superterrane (termed the Cherokee orogeny, Reference 2.5.1-65) based on: (1) paleomagnetic data that indicate Laurentia and the Carolina superterrane have been at similar latitudes since the Ordovician (References 2.5.1-66 and 2.5.1-67); (2) the Late Ordovician Tuscarora unconformity in the Appalachian foreland (Reference 2.5.1-68); (3) Late Ordovician-Silurian $^{40}Ar/^{39}Ar$ cooling ages from the Carolina terrane (References 2.5.1-66, 2.5.1-67, and 2.5.1-69); and (4) Late Ordovician-Silurian plutonic rocks in the western Inner Piedmont and eastern Blue Ridge (References 2.5.1-70 and 2.5.1-71). Although Devonian-Mississippian accretion is more strongly supported by available evidence, a more complex tectonic scenario may be necessary to encompass all available data regarding the accretion of the Carolina superterrane to the eastern Laurentian margin.

The Pennsylvanian to Permian Alleghanian orogeny marks the terminal collisional event in the Appalachian orogen, and was the result of the diachronous dextral transpressive collision between Gondwana and Laurentia that formed the supercontinent Pangea (Figures 2.5.1-9 and 2.5.1-12). Plutonism, metamorphism, and deformation in the crystalline interior of the Appalachians related to the Alleghanian orogeny began as early as approximately 340 Ma, although the main pulse of orogenesis in the interior of the Appalachians occurred 300-320 Ma (References 2.5.1-52 and 2.5.1-72). The later stages of the Alleghanian orogeny involved a clockwise-rotational component that produced a more head-on collision in the southern Appalachians (Reference 2.5.1-73). This resulted in the emplacement of the Blue Ridge-Piedmont megathrust sheet onto the Laurentian shelf, which drove deformation in the Valley and Ridge and accommodated more than 400 km (approximately 250 mi) of crustal shortening (Figures 2.5.1-9 and 2.5.1-12) (References 2.5.1-73 and 2.5.1-74). Uplift of the mountain chain at this time resulted in the deposition of thick successions of shallow marine to immature fluvio-deltaic siliciclastic rocks in the Appalachian basin. These most notably include

the Gizzard, Crab Orchard Mountains, and Crooked Fork Groups in the CRN site region (see Subsection 2.5.1.1.3). Deposits associated with the Alleghanian clastic wedge blanket the Appalachian Plateau from central Alabama through northern Pennsylvania (e.g., References 2.5.1-34 and 2.5.1-75).

The Mesozoic breakup of Pangea was a protracted event. In the southern Appalachians, evidence of extension, basin filling, deformation and magmatism associated with continental rifting spans an approximately 30 million year time period from the Middle Triassic to the earliest Jurassic (e.g., References 2.5.1-76, 2.5.1-77, 2.5.1-78, and 2.5.1-79). The oldest basal conglomerates and siliciclastics in northeast-southwest-trending rift basins were deposited in the Middle Triassic (~230 Ma), and deposition in these basins continued into Late Triassic time (References 2.5.1-77 and 2.5.1-80). A brief period of basin inversion, reverse-sense reactivation of preexisting border faults, and shortening of basin deposits occurred in the latest Triassic, which is hypothesized to represent the rift-to-drift transition (References 2.5.1-77, 2.5.1-78, and 2.5.1-80). Features associated with this episode of post-depositional shortening are truncated by undeformed diabase dikes of the Central Atlantic Magmatic Province (CAMP), which intruded along the Atlantic margins of both Americas and Africa within a few million years of the Triassic-Jurassic boundary (202-198 Ma; References 2.5.1-81 and 2.5.1-82; Figure 2.5.1-13). Withjack et al. (Reference 2.5.1-78) suggested the emplacement of CAMP was the result of compressive stresses generated during the initial stages of ridge push, as the continents surrounding the newly opened Atlantic ocean transitioned from states of tension to compression (Reference 2.5.1-83).

CAMP diabase dikes mostly trend northwest (290-345) in the southern Appalachians, and rotate to a more northerly and northeast trend in the central Appalachians (Figure 2.5.1-13). A narrow north-south-trending fanned swarm of CAMP diabase dikes also occurs in the Carolinas, although the age and geochemical composition of these dikes is indistinguishable from the more abundant northwest-trending set (Reference 2.5.1-84). CAMP dikes share mutually overprinting crosscutting relationships with numerous silicified, relatively small-displacement faults across the Blue Ridge and Piedmont terranes throughout the southern Appalachians (Figure 2.5.1-13). This crosscutting relationship indicates overall coeval emplacement of these features over the brief duration of CAMP magmatism (References 2.5.1-85, 2.5.1-86, and 2.5.1-87). Huebner and Hatcher (Reference 2.5.1-87) demonstrate sinistral shear-sense for several silicified faults in central Georgia based on the geometry of interpreted dilational step-overs, which kinematically corresponds to a proposed clockwise rotation of Africa relative to North America during the breakup of Pangea (Reference 2.5.1-88). Silicified fault orientations vary across the orogen, generally occurring in groups trending 050-070, 015-020, 305-325, and east-west (References 2.5.1-85 and 2.5.1-87). The wide variation of orientations of these features that occurred over this brief time period may be the result of an unstable stress field during the incipient stages of continental drift (References 2.5.1-84 and 2.5.1-87).

A growing body of evidence indicates possible late-stage Tertiary (Miocene?) uplift of the southern and central Appalachians (e.g., References 2.5.1-89, 2.5.1-90, 2.5.1-91, 2.5.1-92, 2.5.1-93 and 2.5.1-94). Evidence that supports Miocene rejuvenation of elevated Appalachian topography includes: (1) Increased siliciclastic accumulation rates along the offshore Atlantic margin (References 2.5.1-89 and 2.5.1-95); (2) results of thermochronologic analyses that indicate an episode of rapid uplift in the Miocene (References 2.5.1-90 and 2.5.1-96); (3) steep topographic relief that is not consistent with tectonic quiescence since the Mesozoic, with evidence that relief has increased significantly since the Miocene (References 2.5.1-94 and 2.5.1-98); (4) longitudinal profiles of rivers that drain into the Atlantic steepen significantly near the coast, with no apparent relationship to lithology or structure, indicating a relative base level drop that does not correspond to any eustatic event (Reference 2.5.1-95); (5) late Mesozoic to Eocene sedimentary traps that occur far inboard of the current Fall Line (landward extent of Coastal Plain onlap), including shallow marine deposits at elevations 300 m (984 ft) above

present-day sea level (Reference 2.5.1-93); and (6) episodic downcutting of the Green River from the Miocene to the present, based on radiometric dating of relict Green River deposits (References 2.5.1-31 and 2.5.1-32). The causative mechanism driving this uplift is not well understood, and is commonly attributed to unconstrained epeirogenic processes (e.g., References 2.5.1-94 and 2.5.1-95).

2.5.1.1.3 Regional Stratigraphy

As stated in Subsection 2.5.1.1.1, the 200-mi radius CRN site region comprises, from west to east, parts of the Central Lowlands, Interior Low Plateaus, the Appalachian Plateaus, the Valley and Ridge, the Blue Ridge, and the Piedmont physiographic provinces (Figure 2.5.1-1). The site region is comprised of geologic formations that include sedimentary rocks ranging in age from Cambrian to recent sediments with igneous and metamorphic rocks in the Blue Ridge and Piedmont that are Proterozoic to Paleozoic age (Figures 2.5.1-19, Sheet 1 and 2.5.1-19, Sheet 2). Lithotectonic terranes are shown with respect to physiographic provinces on Figure 2.5.1-18, Sheet 1. The geology within the 25-mi radius site vicinity is shown on Figure 2.5.1-27. Plate 1 in Part 8 of the application is a more detailed site vicinity geologic map and incorporates recent interpretations of geologic data (Reference 2.5.1-97). The stratigraphic column in Figure 2.5.1-14 supports this greater level of detail. The site vicinity is comprised of sedimentary rock units within the Valley and Ridge and Appalachian (Cumberland) Plateau provinces. The regional stratigraphy is described in the following subsections, from oldest to youngest, starting with the site vicinity and expanding the discussion to units that occur within the other physiographic provinces within the site region. This subsection includes information on local stratigraphy and lithology within the site vicinity but outside the 5-mi radius site area. The site area stratigraphy and lithology are described in Subsection 2.5.1.2.3 based on the units mapped at the site and cored during the subsurface investigation.

2.5.1.1.3.1 Valley and Ridge Province

The CRN Site is located within the southwestern portion of the Valley and Ridge province. In the site vicinity, this province is underlain predominantly by lower to middle Paleozoic sedimentary rocks (Figures 2.5.1-27 and 2.5.1-14). The Paleozoic section consists of four major subdivisions: a basal, mainly clastic transgressive unit; a thick, extensive Cambrian to Ordovician carbonate shelf sequence; a thin, laterally variable shelf sequence of Ordovician to Lower Mississippian carbonate rocks and thin clastic units; and a Middle Mississippian to Pennsylvanian synorogenic clastic wedge. This sedimentary rock sequence was deposited on what has been interpreted as Grenvillian continental crust. The Grenville Province basement is composed primarily of gneisses, granites, amphibolites, and other igneous and metamorphic rocks ranging in age from more than 2 Ga to approximately 980 Ma (Figure 2.5.1-2) based on province-wide geochronology studies (Reference 2.5.1-99). Although they have been deformed by Paleozoic orogenies, the rocks of the Blue Ridge province (Subsection 2.5.1.1.3.5) are Mesoproterozoic inliers interpreted as reworked amphibolite- to granulite –facies metamorphic rocks representative primarily of the Grenville orogeny and the crystalline basement beneath the CRN Site (Reference 2.5.1-99). Figure 2.5.1-35 presents a geologic cross section through the CRN Site area to illustrate the relationship between Paleozoic stratigraphy, northwest-directed Alleghanian thrust faults, and underlying Grenville basement rocks. An alternative interpretation that demonstrates the relationship between stratigraphy, structure, and shear wave velocities from the basement to the ground surface is also provided to support the discussion of site response (see Figures 2.5.1-62 and 2.5.1-63). Additionally, the lithologic descriptions of the stratigraphic units above the basement and below the Chickamauga Group, detailed in this section, support the site response analysis described in Subsection 2.5.2.5.

The Lower Cambrian Rome Formation is composed primarily of red, green and yellow shale, siltstone, and sandstone, with minor amounts of gray dolomite, limestone, and evaporite. It has a

mapped maximum exposed thickness of about 1200 ft (Reference 2.5.1-100). However, the maximum thickness of this unit is not precisely known due to tectonic duplication resulting from thrust faulting and resulting truncation. Because the Whiteoak Mountain thrust fault is located within the lower Rome Formation (Apison Shale member), a thicker section of the Rome Formation is present on the Whiteoak Mountain thrust sheet compared with the thinner section within the Copper Creek thrust sheet (Reference 2.5.1-9) (Figure 2.5.1-63). Geologic mapping indicates that the Rome Formation can vary in thickness from 122 to 183 m (400 to 600 ft) on the Copper Creek thrust sheet but can be as much as 450 m (1476 ft) thick within the Whiteoak Mountain thrust sheet. According to Rankin et al., (Reference 2.5.1-101) a study of isopach maps suggests a thickness of up to 600 m (1970 ft) of Rome Formation red beds in the Conasauga depocenter in eastern Kentucky. The Rome Formation was deposited directly on crystalline basement rock and comprises the basal transgressive unit with a sediment source to the west. This unit becomes increasingly carbonate rich to the east (i.e., away from the source) (Reference 2.5.1-102). The Rome Formation is thinner toward the west, is absent over the Nashville Dome, but becomes thicker (locally as much as 1000 m [3280 ft] thick) in the Rome Trough (Reference 2.5.1-101). Exposures of the lower Rome Formation within the Whiteoak Mountain thrust sheet are sparse due to thrust faults truncating portions of the unit and to depth of burial. Where exposed, the lower Rome is maroon, green, and yellow-brown micaceous shale. Sandstone and siltstone interbeds are present within the fissile shale. Thin interbeds of argillaceous limestone and dolomite also occur within the lower Rome (Reference 2.5.1-9). The upper Rome Formation consists mainly of interbedded maroon sandstone, siltstone and shale. Distinctive dolomite and dolomitic sandstone intervals have been mapped within the Copper Creek thrust sheet but not in the Whiteoak Mountain thrust sheet. The sandstone units are silica- and hematite-cemented, quartz-rich and occasionally contain glauconite (Reference 2.5.1-9) (Subsections 2.5.1.1.2 and 2.5.1.1.4). The Sandstone member of the Rome Formation was penetrated by two site borings (Subsections 2.5.1.2.3 and 2.5.1.2.4) where it has been thrust over the Moccasin Formation of the Chickamauga Group along the Copper Creek fault. This thrust fault is mapped along strike within the site vicinity (Figure 2.5.1-29). The sandstone and shale members of the Rome Formation are mapped north of the CRN Site within the Oak Ridge Reservation (ORR) where the Rome has been thrust over younger rocks by a series of thrust faults (Subsection 2.5.1.1.4).

The Middle Cambrian Conasauga Group overlies the Rome Formation and exhibits a regional transition from predominantly clastic sediments in the west to predominantly carbonate deposits in the east (Reference 2.5.1-103). This is interpreted as a transition from the basal marine transgression to a stable carbonate bank environment along the passive Laurentian margin. Lateral facies and thickness changes may be the result of deposition on a surface with paleotopographic highs and lows in the underlying basement and Rome formation (Reference 2.5.1-102). The CRN Site is located in an area where the Conasauga Group consists primarily of calcareous shale interbedded with shaly to silty limestone (Reference 2.5.1-103). According to Rankin et al., (Reference 2.5.1-101) a study of isopach maps suggests a thickness of up to 600 m (1970 ft) of Rome Formation red beds in the Conasauga depocenter in eastern Kentucky. Hatcher et al, (Reference 2.5.1-9) describe the variation of thickness of the Conasauga Group within the site vicinity. Based on thicknesses measured in boreholes, borehole deviation and estimated formation dip, the average thickness of the Conasauga Group within the Whiteoak Mountain thrust sheet in Bear Creek Valley and dipping under the CRN Site is about 557 m (1827 ft) (References 2.5.1-9 and 2.5.1-99) (Figure 2.5.1-63). The Conasauga Group is comprised, from oldest to youngest, of the Pumpkin Valley Shale, the Friendship formation (Rutledge Limestone), Rogersville Shale, Dismal Gap formation (Marysville Limestone), Nolichucky Shale, and Maynardville Limestone (Figures 2.5.1-28 and 2.5.1-63).

Based on mapping at the ORR and in the Valley & Ridge of east Tennessee, sedimentary facies change rapidly within the Conasauga Group. For example, the Friendship and Dismal Gap formations are thinner than the Rutledge and Maryville Limestones farther east and contain 30 to

60 percent clastic material. Based on thickness and higher clastic/lower carbonate content, the stratigraphic nomenclature preferred for the CRN site vicinity is the Friendship and the Dismal Gap formations rather than the Rutledge and Maryville Limestones, respectively (Reference 2.5.1-9).

The contact between the Rome Formation and the overlying Pumpkin Valley Shale is gradational in the CRN site vicinity, from dominantly shale to interbedded shale and sandstone with occasional dolomite in the underlying Rome Formation. The contact is drawn at the bottom of the shaly gray-brown siltstone of the Pumpkin Valley Shale and the top of the uppermost massive to laminated gray-green sandstone of the Rome Formation (References 2.5.1-9 and 2.5.1-99). The two units are otherwise indistinguishable without performing detailed paleontology studies to distinguish the Lower Cambrian *Olenellus* fauna from the Middle Cambrian fauna in the Pumpkin Valley Shale. The gradational nature of this contact is recognizable on shear wave velocity (Vs) suspension logs. However, the Rome Formation and Pumpkin Valley Shale are combined for site response analysis (Figure 2.5.1-63).

Bioturbated maroon-brown and gray to gray-green siltstone and mudstone comprise the lower Pumpkin Valley Shale (Reference 2.5.1-9). The upper Pumpkin Valley Shale consists of red-brown, red-gray, and gray mudstone and shale interbedded with siltstone.

The contact of the Pumpkin Valley Shale with the overlying Friendship formation (former Rutledge Formation) (Figure 2.5.1-63) is characterized by borehole geophysical anomalies (Reference 2.5.1-9). Southeast of the Oak Ridge Reservation, the Friendship formation is dominantly ribbon-bedded carbonate with an upper unit of dolomite. In the ORR and the CRN site vicinity, the Friendship formation is dominantly clastic with some limestone. The base of the Friendship formation is characterized by three coarse-grained limestone beds interbedded with distinctive maroon shale and mudstone. These lithologies produce a very distinct three-pronged pattern on gamma-ray and neutron borehole logs; serving as an excellent stratigraphic marker. The Friendship formation, informally defined in the CRN site vicinity by Hatcher et al. (1992) (Reference 2.5.1-9) consists of light-gray, micritic to coarsely crystalline limestone commonly containing shale partings, interbedded with dark-gray or maroon shale beds.

The contact between the Friendship formation and the overlying Rogersville Shale is abrupt and recognized by the absence of 0.3-m (1-ft) thick limestone beds and the appearance of maroon shale (Reference 2.5.1-9) (Figure 2.5.1-63). The Rogersville Shale is characterized by massive to very thinly bedded non-calcareous mudstone and calcareous to non-calcareous siltstone. The lower part of the Rogersville Shale consists mostly of dark gray mudstone with some thin shale beds. The upper part of the Rogersville Shale consists mostly of maroon shale that contains thin siltstone or argillaceous limestone lenses. Distinctive reddish, massive to thick-bedded mudstone occurs immediately below the contact between the Rogersville Shale and the overlying Dismal Gap formation. This contact occurs at the base of the lowest, comparatively thick limestone bed of the overlying Dismal Gap formation (Reference 2.5.1-9).

Hatcher et al., (Reference 2.5.1-9) informally defined the Dismal Gap formation (formerly the Maryville Limestone) (Figure 2.5.1-63) in the CRN site vicinity as containing 60 to 70 percent clastic material and 30 to 40 percent limestone interbedded with dark gray shale. Calcareous mudstone interstratified with calcarenite and calcareous siltstone comprises the informal lower unit of the Dismal Gap formation. These lithologies appear to occur in cyclical sequences with the tops of cycles marked by an abrupt change to calcareous mudstone. Several relatively limestone-rich beds ranging in thickness from 6 to 12 m (20 to 39 ft) occur throughout the lower member. The upper part of the Dismal Gap formation is characterized by abundant flat-pebble limestone conglomerate. Siltstones, mudstones and shales are interbedded with the conglomerates. The upper contact of the Dismal Gap formation with the Nolichucky Shale is marked by a baseline shift to increasing gamma log values and decreasing neutron log values.

This shift occurs because the top of the Dismal Gap formation contains more limestone than the base of the Nolichucky Shale (Reference 2.5.1-9).

Dark, fissile shales comprise the dominant lithology of the Nolichucky Shale. Intraclastic (flat-pebble) limestone conglomerate interbedded with shale and calcareous siltstone is characteristic of the lower portion of the Nolichucky Shale. The middle portion of this unit is characterized by the occurrence of packstone and grainstone carbonates interbedded with the shale. The upper unit is characterized by laminated limestones and mudstones. Rock core data from the ORR indicate that the contact between the Nolichucky Shale and the overlying Maynardville Limestone can be placed directly below the lowermost massive mottled limestone of the Maynardville Limestone, which coincides with the upper-most occurrence of dark-gray shale containing ribbon-bedded calcareous mudstone (Reference 2.5.1-9) (Figure 2.5.1-63).

In the CRN site vicinity, the Maynardville Limestone varies in thickness from 79 m (259 ft) on the Copper Creek thrust sheet to 127 m (416 ft) on the Whiteoak Mountain thrust sheet (Reference 2.5.1-9). It has been divided into lower Low Hollow and upper Chances Branch dolomite members. The Low Hollow member is generally a ribbon-bedded or mottled dolomitic calcarenite. Thin lenticular beds and olive gray shale partings are common within the ribbon-bedded lithology. The Chances Branch member consists primarily of dolomites and limestones. Where locally present, shale interbeds can be detected by rightward deflections in the gamma-ray borehole log. The gradational contact of the Maynardville Limestone with the overlying Copper Ridge Dolomite in the Knox Group is identified over a 3-m (10-ft) interval by the appearance of mottled to irregularly bedded calcarenite in the upper portion of the Maynardville Limestone and a decrease in calcite content while the dolomite content increases (Reference 2.5.1-9). The Maynardville Limestone and the Knox Group are carbonate units with shear wave velocities consistently higher than 9200 feet per second. Therefore, both units are grouped together for site response analysis (Figure 2.5.1-63).The Upper Cambrian to Lower Ordovician Knox Group overlies the Conasauga Group and is recognized in the Valley and Ridge Province from Alabama to Virginia (Figure 2.5.1-27). Faunal assemblages and lithologies indicate deposition on a regionally extensive Late Cambrian-Early Ordovician continental shelf (Reference 2.5.1-9). The total thickness of this limestone and dolomite sequence ranges from 700 to 1000 m (2000 to 3000 ft) in eastern Tennessee, with the Copper Ridge Dolomite comprising approximately one-third of the total. The Knox Group forms the principal strong (competent) unit supporting the folding and low-angle thrust faulting that occurs throughout the Valley and Ridge Province. Hatcher et al. (Reference 2.5.1-9) support the subdivision of the Knox into five units based on ease of recognition in the field; primarily the characteristics of weathered materials preserved in residual soils (Reference 2.5.1-9). In eastern Tennessee and adjacent states, these include, from oldest to youngest, the Cambrian Copper Ridge Dolomite, and the Ordovician Chapultepec Dolomite, Longview Dolomite, Kingsport Formation and the Mascot Dolomite (Figures 2.5.1-28, 2.5.1-14, and 2.5.1-63).

To support the discussion of the shear wave velocity column in Subsection 2.5.4 and the site response analysis in Subsection 2.5.2.5, the three lower units in the Knox Group are described in detail in this subsection. The Kingsport Formation and Mascot Dolomite, grouped together as the Newala Formation, are described in Subsection 2.5.1.2.3, Local Stratigraphy and Lithology, since that description is based on data obtained during the site investigation.

Medium-grained to coarsely-crystalline, thickly bedded dolomite comprises most of the lower two thirds of the Upper Cambrian Copper Ridge Dolomite. This lithology grades upward into a medium to light-gray, fine-grained, medium- to thick-bedded dolomite similar to the rest of the Knox Group (Reference 2.5.1-9). The Copper Ridge Dolomite is siliceous and tends to be a ridge former in the CRN site vicinity. Quartz sandstone beds are common in the upper part of the formation. The contact with the overlying Chepultepec Dolomite is mapped at the base of a prominent sandy zone.

The Chepultepec Dolomite is less siliceous than the Copper Ridge Dolomite and tends to form valleys between the Chepultepec and Longview dolomites. Light-gray, fine-grained, medium-bedded dolomite, similar to the rest of the Knox Group comprises the Chepultepec Dolomite (Reference 2.5.1-9).

Medium- to light-gray, thin- to medium bedded siliceous dolomite comprises the Lower Ordovician Longview Dolomite. This siliceous dolomite is a ridge-former in the ORR (Reference 2.5.1-9).

Although some researchers have proposed the formation of a peripheral bulge (Reference 2.5.1-104, for example), regional uplift resulting from the Taconic orogeny and/or a drop in eustatic sea level at the end of the Early Ordovician led to the development of an extensive karst landscape; the Knox unconformity (Subsection 2.5.1.1.2). This exposed land surface extended from western Texas to northeastern Canada. Inundation following regional erosion resulted in the deposition of the Middle and Upper Ordovician Chickamauga Group. Regionally, the erosion surface (disconformity) is recognized by the presence of angular dolomitic and red chert (jasper) intraclasts within pale-olive and purplish maroon limestones of the Blackford Formation immediately above the dense fine-grained Mascot Dolomite. Conodont geochronology indicates that the Knox Group south of the City of Oak Ridge has an age of approximately 475 Ma and the overlying Chickamauga Group has an age of approximately 467 Ma (Reference 2.5.1-104). Paleotopographic relief in the Knox unconformity accounts for variable stratigraphic thicknesses and facies variations in the basal Chickamauga units (Subsection 2.5.1.2.3).

The Chickamauga Group consists mainly of limestone toward the northwest and becomes increasingly clastic to the southeast. Its total thickness is more than 600 m (1970 ft) (Reference 2.5.1-105). On geologic maps within the CRN site region, the Chickamauga Group is subdivided into several formations with characteristics and nomenclature that vary between thrust sheets (References 2.5.1-9, 2.5.1-106, 2.5.1-107, and 2.5.1-108). Subdivisions of the Chickamauga Group in the CRN site vicinity are described below from oldest to youngest. The stratigraphy of the Chickamauga Group and the underlying upper Knox Group, derived from site-specific borings and mapping, are described in greater detail in Subsection 2.5.1.2.3.

The White Oak Mountain thrust sheet includes the stratigraphic package that underlies Bear Creek Valley, Chestnut Ridge, Bethel Valley, Haw Ridge, and Melton Valley. The CRN Site is located within Bethel Valley with Chestnut Ridge to the north and Haw Ridge to the south (Subsection 2.5.1.2.1). The stratigraphic column for the White Oak Mountain thrust sheet is shown on Figure 2.5.1-14. The Chickamauga Group is divided into the Blackford Formation, the Eidson and Fleanor members of the Lincolnshire Formation, and the Rockdell, Benbolt, Bowen, Witten, and Moccasin formations (Figure 2.5.1-14).

Hatcher et al. (Reference 2.5.1-9) report that the name Blackford Formation was proposed for a series of conglomerates, red beds, gray shales, dolomites and chert beds that overlie the Knox Group at Blackford, Russell County, Virginia. Most of the Blackford Formation is composed of massive- to thick-bedded purple to dark maroon and olive-gray calcareous siltstone interbedded with subordinate amounts of dark- and light-gray calcarenite. At some locations, a thin bed of pale-olive limestone is overlain by a thin (1 m thick) purple maroon dolomite that in turn is overlain by a thick section of purple to maroon siltstone. Both lower lithologies contain angular dolomitic intraclasts derived from erosion of the underlying Knox Group.

Northeast of the ORR and the CRN Site, the overlying Lincolnshire Formation is subdivided into three members in eastern Tennessee and into Virginia. However, only the Eidson and Fleanor members are recognized in the site vicinity, which is probably the result of lateral facies changes (Reference 2.5.1-9). The Eidson member consists of massive to nodular limestone with bedded

and nodular chert toward the top. It is approximately 20 m (65.6 ft) thick at the ORR and contrasts sharply with the maroon calcareous siltstones of the underlying Blackford Formation and the overlying Fleanor member. The Fleanor member is composed of approximately 75 to 80 m (246 to 262 ft) of maroon, calcareous, shaly siltstone with numerous light-gray limestone beds. The lowermost and uppermost beds within the Fleanor member consist of a thick unit of thinly bedded olive-gray calcareous siltstone, which contrasts with the maroon siltstone that characterizes this unit (Reference 2.5.1-9).

The Rockdell Formation overlies the Lincolnshire Formation in the CRN site region. The type section is located near Elk Garden, Russell County, Virginia. This unit is 80 to 85 m (262 to 279 ft) thick in the site vicinity and underlies the continuous low ridge near the middle of Bethel Valley. Stockdale (Reference 2.5.1-109) and Lee and Ketelle (Reference 2.5.1-110) divide the Rockdell Formation into a lower portion (Unit C) that consists of a light-gray calcarenite, dark-gray calcareous siltstone, fossiliferous nodular limestone, and bird's-eye micritic limestone. This lithology grades upward into dense calcarenite that contains subordinate amounts of bird's-eye micrite and nodular limestone. Bedded and nodular cherts are distinctive in this upper lithology recognized as Unit D by Stockdale (Reference 2.5.1-109) and Lee and Ketelle (References 2.5.1-110 and 2.5.1-9) (See Table 2.5.1-1; Figure 2.5.1-28).

The Benbolt Formation overlies the Rockdell Formation in the CRN site region. The type section of the overlying, relatively heterogeneous, Benbolt Formation is located in Virginia. This unit is relatively heterogeneous and consists of thick interbeds of fossiliferous nodular limestone; unfossiliferous, amorphous micrite within a dark siltstone matrix; dark-gray siltstone; and unfossiliferous calcarenite. The Benbolt Formation is approximately 110 to 115 m (360 to 377 ft) thick in the site vicinity. Where present on the ORR, the uppermost limestone enriched portion is termed the Wardell Formation (Reference 2.5.1-9).

The overlying Bowen Formation is composed of maroon calcareous and shaly siltstone and thin interbeds of light-gray to olive-gray limestone and argillaceous limestone (Reference 2.5.1-9). It was named for exposures in Bowen Cove, Tazewell County, Virginia. The Bowen Formation is 5 to 10 m (16.4 to 32.8 ft) thick in the site vicinity (Reference 2.5.1-9). The maroon color and lithology makes the Bowen an effective marker bed in the site vicinity.

The Witten Formation was proposed to designate a series of interbedded nodular limestone; calcarenite; amorphous, thin-bedded limestone, and siltstone (Reference 2.5.1-9) overlying the Bowen Formation in Virginia and eastern Tennessee. The Witten Formation is approximately 105 to 110 m (344 to 361 ft) thick in Bethel Valley (Reference 2.5.1-9).

The uppermost stratigraphic unit in the Chickamauga Group in the Bethel Valley sequence is the Moccasin Formation. This unit is not completely present in the site vicinity because it is cross-cut and partially removed by the Copper Creek thrust fault. The Moccasin Formation is an olive-gray and pale-maroon calcareous siltstone interbedded with light-gray, fine-grained limestone (Reference 2.5.1-9) (Subsection 2.5.1.2.3). The Rome Formation was emplaced above the Moccasin Formation by thrust faulting Figures 2.5.1-27, 2.5.1-29, 2.5.1-30, and Plate 1, included in Part 8 of the application.

The stratigraphic section in the Kingston thrust sheet, which consists of the Stones River and overlying Nashville groups, effectively demonstrates the stratigraphic variation that can occur between Valley and Ridge thrust sheets (Figure 2.5.1-14). The Stones River Group is composed, from oldest to youngest, of the Pond Spring Formation, the Murfreesboro/Pierce Limestone, the Ridley Limestone, the Lebanon Limestone and the Carters Limestone. The Nashville Group consists of the Hermitage Formation, Cannon Limestone, and Catheys and Leipers Formation. Comparisons of the stratigraphic characteristics and nomenclature used in the two stratigraphic sequences are described in Hatcher et al., (Reference 2.5.1-9).

The Upper Ordovician through Lower Silurian Reedsville Shale, Sequatchie Formation and Rockwood Formation overlie the Chickamauga Group and are composed mainly of a shallow marine clastic sequence including calcareous shale and siltstone with lesser argillaceous limestone (Figures 2.5.1-14 and 2.5.1-28) (References 2.5.1-9 and 2.5.1-108). These units are exposed in the cores of synclines within thrust sheets of the Valley and Ridge.

Lower Paleozoic rocks mapped east of Knoxville, Tennessee are exposed a middle Ordovician syncline, west of the Great Smoky-Miller Cove thrust fault system (Reference 2.5.1-111). From oldest to youngest these units consist of the Cambrian Conasauga Group overlain by the Cambrian to Ordovician Knox Group. The Knox Group is overlain by the Chickamauga Group, which is subdivided locally, from oldest to youngest, into the Lenoir Limestone, Toqua Sandstone member, Athens Shale, Chapman Ridge Sandstone, Chota/Ottosee Formations, Sevier formation, Bays Formation and the Grainger Formation/Chattanooga Shale (Reference 2.5.1-111).

The Upper Devonian through Lower Mississippian Chattanooga Shale is a regionally-extensive bituminous shale that was deposited in a shallow marine setting and represents the distal end of the Acadian clastic wedge (References 2.5.1-9 and 2.5.1-64) (Figures 2.5.1-14 and 2.5.1-28). This unit is generally exposed in synclines within Valley and Ridge thrust sheets.

The Mississippian Fort Payne, Newman Limestone and Pennington formations are shallow marine units that grade upward from carbonates and shales to primarily clastic rocks (Reference 2.5.1-105). These units are exposed in the hanging wall of the Rockwood fault and in the Cumberland Escarpment (Figure 2.5.1-16) and are the uppermost bedrock units exposed in the CRN site region.

2.5.1.1.3.2 Appalachian and Interior Low Plateaus Physiographic Provinces (Cumberland Plateau and Highland Rim)

The Appalachian Plateaus province extends from New York to Alabama and consists of the Allegheny and Cumberland Plateaus in the central and southern Appalachians, respectively. The Cumberland Plateau lies in an elongated northeast-plunging synclinorium between the Nashville Dome to the west and the Valley and Ridge Province to the east (Figure 2.5.1-15). As a result of this structural setting, only lowermost Pennsylvanian coal-bearing beds remain in the southern part of the plateau and younger Pennsylvanian units are preserved to the northeast into Kentucky and Virginia (Reference 2.5.1-112).

The sedimentary record in the Appalachian Plateaus Province comprises the final major cycle of Paleozoic sedimentation in the site region. Deposition began in the Middle to Late Devonian with submergence of an erosional surface that cut across sedimentary units ranging in age from Middle Ordovician to Early Devonian (Reference 2.5.1-112). The basal unit in the Cumberland Plateau and the eastern Highland Rim portion of the Interior Plateaus is the Chattanooga Shale. The lowermost Chattanooga Shale ranges in age from Middle to Late Devonian in age. The base of the Carboniferous System is either within or at the top of the Chattanooga Shale (Reference 2.5.1-112).

Carboniferous strata underlie a large area in eastern and central Tennessee extending westward from limited exposures in the Valley and Ridge across the Cumberland Plateaus to the broad Interior Low Plateaus (Highland Rim in Tennessee). The lower part of the Mississippian section is preserved on the Highland Rim, which forms a crude ellipse around the Ordovician and Silurian strata exposed in the core of the Nashville Dome (Reference 2.5.1-112) (Figure 2.5.1-15). These rocks are generally not extensively deformed or metamorphosed, but are gently-folded.

The lower portion of the Carboniferous strata is composed mainly of carbonate rocks that were deposited on a relatively shallow stable platform to the west, and to the east, consist of terrigenous clastic and carbonate rocks that were deposited in the subsiding Appalachian basin (Figure 2.5.1-16). The upper part of the Carboniferous section consists almost entirely of coal-bearing terrigenous (non-marine) clastic deposits. These strata are interpreted as having been deposited in either coastal barrier island-lagoon or fluvial deltaic depositional environments (Reference 2.5.1-112) (Figure 2.5.1-17). The lower carbonate sequence is separated from the coal-bearing strata by the transitional Pennington Formation. The Pennington Formation is a heterogeneous unit consisting of various lithologies. In general, the lower carbonate rocks and the transitional Pennington Formation are Mississippian and the overlying terrigenous clastic rocks are Pennsylvanian. The Pennsylvanian System can be divided into two parts: a lower sequence of massive sandstones with approximately equal amounts of shale and an upper sequence with thinner sandstones and a large percentage of shale (Reference 2.5.1-113). The Lower Pennsylvanian units within the Cumberland Plateau (site vicinity) are composed of, from oldest to youngest: the Gizzard, Crab Mountain Orchard, and Crooked Fork Groups (Figures 2.5.1-14 and 2.5.1-17). These stratigraphic units consist of interbedded shale, sandstone, siltstone and conglomerate with coal seams. The lower through Middle Pennsylvanian sequence was deposited in a shallow marine deltaic environment and is interpreted as part of the distal Alleghanian clastic wedge. Beyond the site vicinity, the predominantly shaly Pennsylvanian sequence is composed of the Slatestone, Indian Bluff, Graves Gap, Red Oak Mountain, Vowell Mountain, and Cross Mountain formations (Figure 2.5.1-17) (References 2.5.1-112 and 2.5.1-113).

Deformation during the Alleghanian orogeny produced folds and thrust faults that deformed Carboniferous stratigraphic units in geologic structures within the eastern Cumberland Plateau. These structures include, for example, the Chilhowee Mountain belt, the Clinch Mountain belt, Newman Ridge, the Sequatchie anticline and the Pine Mountain block (thrust sheet). Milici et al. (Reference 2.5.1-112) provide detailed discussions of the stratigraphy of each of these structures summarized in Figure 2.5.1-16.

2.5.1.1.3.3 Interior Low Plateaus

The stratigraphy of the Interior Low Plateaus in Tennessee and Kentucky can be subdivided into the eastern and western portions of the highland rim surrounding the Nashville Dome and flanking the Cincinnati Arch (Figures 2.5.1-15 and 2.5.1-19). Middle to Upper Ordovician sedimentary series consisting predominantly of carbonate rocks with subordinate shales and sandstones occur in the core of the Nashville Dome and the Cincinnati Arch. These rocks from youngest to oldest are mapped as the Middle Ordovician Stones River and Nashville Groups and Upper Ordovician Eden, Maysville and Richmond Groups or their stratigraphically correlative units (four USGS open-file report integrated geologic map databases; References 2.5.1-114, 2.5.1-115, 2.5.1-116, and 2.5.1-117.). Silurian and Devonian units have been mapped on the west flank of the Nashville Dome. Limited outcrops of Silurian and Devonian rocks have been mapped at locations surrounding the Cincinnati Arch. As described above for the Cumberland Plateau, the Upper Devonian to Lower Mississippian Chattanooga-Maury Shale is overlain by the Grainger-Ft. Payne sequence shown in Figure 2.5.1-16. Lower Mississippian shales and sandstones continue southwest from southern Tennessee into northern Alabama and northeast into southern Ohio.

2.5.1.1.3.4 Central Lowland

The 200-mi radius CRN site region includes a small portion of the Central Lowland physiographic province in the vicinity of Evansville, Indiana (Figure 2.5.1-1). These rocks consist of a sequence of Mississippian to upper Pennsylvanian carbonate rocks, sandstones and shales.

2.5.1.1.3.5 Blue Ridge Physiographic Province

The Blue Ridge physiographic province in the central and southern Appalachians comprises three lithotectonic subdivisions that provide a useful context for discussing regional stratigraphy. These include the Western, Central and Eastern Blue Ridge, although the Eastern Blue Ridge and Inner Piedmont are commonly considered the same lithotectonic terrane (Tugaloo terrane; Reference 2.5.1-34). Subsection 2.5.1.1.4 contains discussions of post-depositional histories in terms of deformation, metamorphism, plutonism and structural style.

2.5.1.1.3.5.1 Western Blue Ridge

The Western Blue Ridge lithotectonic province extends from northern Georgia into eastern Tennessee and western North Carolina (Figure 2.5.1-18). This belt comprises rocks ranging in age from Neoproterozoic to Cambrian and possibly Ordovician (Reference 2.5.1-118). The Ocoee supergroup, the conglomerate, sandstone, and graywacke of the Chilhowee Group overlain by the Shady Dolomite and Rome Formation collectively overlie the Neoproterozoic siliciclastic rocks of the Great Smoky thrust sheet (Reference 2.5.1-111). The Mineral Bluff Formation consists, in general, of siliciclastic and carbonate rocks deposited on Mesoproterozoic Grenville crust. These stratigraphic units were deposited during the rifting of Rodinia and subsequent development of the Iapetan passive margin (References 2.5.1-34 and 2.5.1-119). In eastern Alabama and western Georgia, the Western Blue Ridge consists of the Talladega Belt, which includes early Cambrian through Middle Ordovician(?) siliciclastic and carbonate rocks that are roughly correlative with Western Blue Ridge rocks to the northeast.

Clastic sequences belonging to the Cambrian Chilhowee Group, Shady Dolomite, and Rome Formation are mapped overlying clastic members of the Neoproterozoic-Cambrian Sandsuck Formation on the Great Smoky thrust sheet of the Western Blue Ridge (Reference 2.5.1-111). These siliciclastic and carbonate rocks represent deposition on the Iapetan passive margin during the rifting of Rodinia (References 2.5.1-34 and 2.5.1-119). This interpretation also appears to apply to the Neoproterozoic metasiltstones, slate, conglomerates and sandstones of the Cades sandstone on the Rabbit Creek thrust sheet as well as the Ordovician Mineral Bluff Formation and underlying Ordovician metasediments on the Greenbrier thrust sheet (Reference 2.5.1-111).

This series of thrust sheets is described in Subsection 2.5.1.1.4.

2.5.1.1.3.5.2 Central and Eastern Blue Ridge

The Central Blue Ridge terranes generally consist of migmatitic metasiliciclastic rocks with abundant mafic-ultramafic complexes. The Eastern Blue Ridge consists principally of the Tallulah Falls Formation, which consists of Neoproterozoic-Cambrian(?) deep-water siliciclastic and mafic volcanic rocks interpreted as deposits on ocean crust and fragments of Grenville basement (Reference 2.5.1-34).

The Eastern Blue Ridge Tallulah Falls Formation is the stratigraphic equivalent of the Ashe (Reference 2.5.1-120) and Lynchburg (Reference 2.5.1-121) Formations in North Carolina and Virginia, and the Ashland supergroup in western Georgia and Alabama (References 2.5.1-122 and 2.5.1-123). These rocks have been metamorphosed to middle- and upper-amphibolite facies, and now consist of biotite paragneiss, pelitic and aluminous schist, and amphibolite; nevertheless, an intact stratigraphy is still discernible (e.g., References 2.5.1-124, 2.5.1-125, and 2.5.1-126). The stratigraphy of Tallulah Falls Formation consists of a lower amphibolite-rich metagraywacke-pelitic schist unit and an upper amphibolite-poor metagraywacke-pelitic schist unit separated by a distinct, regionally continuous aluminous schist unit (References 2.5.1-125 and 2.5.1-127).

Subsection 2.5.1.1.4 contains a description of the metamorphic and igneous lithologies and tectonic evolution of these terranes.

2.5.1.1.3.6 Piedmont Physiographic Province

The Piedmont Province is subdivided into Inner and Outer subprovinces. The Inner Piedmont consists of two lithotectonic terranes, the Tugaloo (Western Inner Piedmont) and Cat Square (Eastern Inner Piedmont) terranes. The Western Inner Piedmont consists of predominantly Neoproterozoic to Middle Ordovician siliciclastic and metavolcanic units (Tallulah Falls Formation) intruded by Ordovician to Silurian plutons. The Eastern Inner Piedmont consists of Silurian to Devonian siliciclastics with latest Silurian to Mississippian felsic igneous rocks Mershat and Hatcher (Reference 2.5.1-53). Subsection 2.5.1.1.4 contains a description of the metamorphic and igneous lithologies and tectonic evolution of these terranes.

The basal stratigraphic unit in the Western Inner Piedmont, like the Eastern Blue Ridge, is the Tallulah Falls Formation. Throughout the western Carolinas, the Tallulah Falls Formation is conformably overlain by Cambrian-lower Ordovician(?) metasiltstone, quartzite, graphitic schist, and impure marble of the Chauga River Formation (e.g., References 2.5.1-128, 2.5.1-129, and 2.5.1-130). This unit thins dramatically to the northeast in the Western Inner Piedmont of the Carolinas and has not been identified in the Eastern Blue Ridge (Reference 2.5.1-131). The Chauga River Formation is unconformably overlain by the Poor Mountain Formation, which consists of a basal laminated amphibolite with an interlayered felsic tuff member that grades upward into feldspathic quartzite, marble, and metatuff (References 2.5.1-130, 2.5.1-131, and 2.5.1-132). The Tallulah Falls Formation was first recognized in the western Carolinas and northeastern Georgia (Reference 2.5.1-133), and may correlate with the Ropes Creek Amphibolite (Reference 2.5.1-52) in eastern Alabama. Ion microprobe analysis of two metatuff units from the upper quartzite member reveal Late Ordovician ages (459 ± 4 and 445 ± 4 Ma; Reference 2.5.1-55). In contrast, metasedimentary rocks of the Eastern Inner Piedmont consist of migmatized metagraywacke and aluminous schist units without a recognizable stratigraphy (References 2.5.1-52 and 2.5.1-53).

The Carolina superterrane corresponds closely with the outer Piedmont physiographic province. The Carolina superterrane comprises an amalgamation of lithotectonic terranes that consist mainly of Neoproterozoic to early Paleozoic volcanic arc, volcanogenic sedimentary, and subarc plutonic components that developed proximal to Gondwana (Reference 2.5.1-134). Subsection 2.5.1.1.4 contains a description of the metamorphic and igneous lithologies and tectonic evolution of these terranes.

2.5.1.1.4 Regional Tectonic Setting

2.5.1.1.4.1 Subdivision of Tectonic Terranes and Physiographic Provinces

Regional tectonic terrane analysis has proven useful in delineating the tectonic history of orogenic belts through geologic time, and has been applied to numerous orogenic systems worldwide (e.g., References 2.5.1-135 and 2.5.1-136). A lithotectonic terrane is a discrete, fault-bounded, allochthonous (formed elsewhere) fragment of oceanic or continental material. A lithotectonic terrane has a distinct tectonic (magmatic, depositional, etc.) history relative to adjacent terranes and is ultimately accreted to a craton at an active plate margin during an orogenic event. Because of the internal homogeneity and regional context of lithotectonic terranes, the application of terrane analysis to orogenic belts has yielded vital clues regarding the tectonic histories recorded along cratonic margins. By definition, many of the physiographic provinces of the Appalachians do not warrant their distinction as separate terranes (e.g., Cumberland Plateau and Valley and Ridge provinces). However, their discrete structural styles and deformational histories necessitate separation in any discussion of their tectonic evolution.

The following subsections, therefore, comprise a hybrid of lithotectonic terranes and physiographic subdivisions to describe the regional tectonic setting of the geology within the 200-mi radius of the CRN Site (Figure 2.5.1-18, Sheet 1). Lithotectonic terrane distinctions in this discussion are based on recent tectonic maps of the southern Appalachians (References 2.5.1-24 and 2.5.1-34) whereas physiographic provinces are based on those defined by Fenneman (Reference 2.5.1-137). Prominent faults and characteristics associated with the framework and emplacement of the lithotectonic terranes are also described in the following subsections. A geologic map that encompasses the site region (200-mi radius) is also included for reference (Figure 2.5.1-19, Sheet 1).

2.5.1.1.4.1.1 Interior Low Plateaus

The Interior Low Plateaus province comprises the western portion of the CRN site region (Figure 2.5.1-18, Sheet 1) (see Subsection 2.5.1.1.1). The eastern boundary of the Interior Low Plateaus province corresponds with the western extent of Pennsylvanian strata of the adjacent Cumberland Plateau to the east (Reference 2.5.1-137). Mean elevation of the Interior Low Plateaus is relatively lower than the Cumberland Plateau, with summit levels that gradually decline westward to approximately 500 ft msl. The Interior Low Plateaus are structurally similar to the Cumberland Plateau, consisting of broad, gentle folds with nearly horizontal strata throughout. In the Interior Low Plateaus province of Tennessee, Kentucky and Ohio, the Cincinnati Arch and Nashville Dome are structural uplifts that expose middle to late Ordovician rocks in their cores and are generally flanked by Silurian and Devonian strata (Figures 2.5.1-1 and 2.5.1-19). The western and eastern Highland Rim portions of the Interior Low Plateaus consist mainly of Mississippian units.

Faulting within the Interior Low Plateaus includes the Shawneetown-Rough Creek fault system of western Kentucky which is located in the western portion of the CRN site region. This fault system is reportedly late Paleozoic in age with moderate displacement of Pennsylvanian and Permian strata recognized at the surface (References 2.5.1-138 and 2.5.1-139), although these authors provide no evidence for a cross-cutting relationship that would delimit a minimum age. Several unnamed faults southwest of Nashville, Tennessee offset Silurian strata, although they are truncated by the pre-Fort Payne Formation (Mississippian) unconformity (Reference 2.5.1-34). Other deformation of strata in this province likely coincides with late Paleozoic shortening related to the Alleghanian orogeny, based on continuity of Late Paleozoic deformation fabrics from the orogenic front through the Interior Low Plateaus province (e.g., Reference 2.5.1-140).

2.5.1.1.4.1.2 Cumberland Plateau

The Cumberland Plateau is distinguished from the Interior Low Plateaus province to the west and the Valley and Ridge province to the east by its relatively high topography and contrasting structural style (see Subsection 2.5.1.1.1). Both its eastern and western boundaries are defined by outward-facing escarpments. The western boundary is defined by the western extent of Pennsylvanian strata in the Cumberland Plateau (Reference 2.5.1-137), while its eastern boundary is demarcated by several Valley and Ridge thrust faults, klippes, and windows (Figure 2.5.1-18, Sheet 1).

Valley and Ridge style deformation is not confined to rocks east of the Cumberland Plateau escarpment. Several faults, specifically the Sequatchie Valley and Ozone faults, and the Pine Mountain and Cumberland Plateau overthrusts propagated into the Cumberland Plateau province during the Alleghanian orogeny (Reference 2.5.1-141). Deformation across the Cumberland Plateau, caused by the late Paleozoic emplacement of the Valley and Ridge province, decreases in intensity from east to west. Evidence of deformation associated with Valley and Ridge emplacement is observed far west of the eastern boundary of the Cumberland

Plateau, and based on twinned calcite in carbonate rocks, far-field effects of this orogeny may occur as far as 1200 km (745 mi) west of that boundary (References 2.5.1-140 and 2.5.1-141).

In addition to the faults described above, the Kentucky River fault system is located near the northern limit of the CRN site region and consists of several discontinuous east-west trending faults that may extend from southern Illinois to western West Virginia (Figure 2.5.1-18, Sheet 1). Van Arsdale (Reference 2.5.1-142) suggested possible Pliocene-Pleistocene activity of this fault system based on offset terrace deposits in several trenches excavated in eastern Kentucky. Slip sense of the identified faults includes strike-slip (dextral and sinistral) and dip-slip (normal and reverse) components (Reference 2.5.1-142). Van Arsdale (Reference 2.5.1-142) could not rule out solution collapse as a formative mechanism for Tertiary deformation, although reverse faults are documented in several trenches and ubiquitous compressional structures may suggest a tectonic origin. Zeng and others (Reference 2.5.1-143) demonstrate that the Kentucky River fault system developed in the Early Carboniferous, based on several distinct carbonate sequences that buttress against this fault system. In their model, the Kentucky River fault system acted as growth faults that created accommodation space, resulting in the deposition of at least six distinct carbonate sequences that span the Early to Middle Carboniferous (Reference 2.5.1-143).

2.5.1.1.4.1.3 Valley and Ridge

The CRN Site is located in the Valley and Ridge physiographic province (Reference 2.5.1-137) (Figure 2.5.1-18, Sheet 1). The Valley and Ridge province has a distinct structural style relative to adjacent terrane/province subdivisions (see Subsection 2.5.1.1.1). The defining characteristics of this province, linear northeast-southwest trending ridges and valleys, are the direct result of differential erosion of Paleozoic strata that has been deformed into an imbricate stack of southeast-dipping thrust sheets. Valley and Ridge province thrust sheets formed above the Proterozoic crystalline basement (called “thin-skinned tectonics”) (Figure 2.5.1-9). Valley and Ridge deformation disrupts strata as young as Late Carboniferous, and is the product of the Pennsylvanian-Permian Alleghanian orogeny, which was the result of the collision between Africa and North America during the formation of the supercontinent Pangea (e.g., References 2.5.1-73 and 2.5.1-128). The absolute age of Valley and Ridge deformation is not well defined, although recent $^{40}Ar/^{39}Ar$ analyses of clay fault gouge (illite) from several major Valley and Ridge faults indicates emplacement occurred 276-280 Ma (Reference 2.5.1-144). In the central Appalachians (central Virginia through central Pennsylvania, approximately 200 Ma CAMP diabase dikes (Reference 2.5.1-81) truncate Valley and Ridge structures, which provide a minimum age for deformation (References 2.5.1-145, 2.5.1-146, 2.5.1-148, and 2.5.1-150).

2.5.1.1.4.1.4 Blue Ridge

The central and southern Appalachian Blue Ridge is a physiographic distinction characterized by the highest topography in the entire Appalachian mountain belt, but it also comprises several lithotectonic terranes, herein separated into the Western, Central, and Eastern Blue Ridge for ease of discussion (Figures 2.5.1-18, Sheet 1 and 2.5.1-18, Sheet 2). This characterization is based on gross lithology, structural style, and similar tectonic histories recorded in these three subdivisions. It should also be noted that the Eastern Blue Ridge and Western Inner Piedmont are commonly portrayed as the same lithotectonic terrane by definition — Tugaloo terrane (Reference 2.5.1-34); however, their post-depositional histories, in terms of deformation, metamorphism, plutonism, and structural style, warrant their distinction in this discussion.

2.5.1.1.4.1.4.1 Western Blue Ridge

The western boundary of the Western Blue Ridge is collectively termed the Blue Ridge thrust, although a number of faults define this boundary through the southern Appalachians. At its southwestern extent in Alabama, this boundary is defined by the Talladega-Emerson fault, which

becomes the Cartersville fault in western Georgia. In northern Georgia, the fault has been termed the Cartersville-Great Smoky fault. The Great Smoky fault becomes the Holston Mountain-Iron Mountain fault in northeastern Tennessee, and is termed the Blue Ridge thrust into southwestern and west-central Virginia (Reference 2.5.1-34).

Rocks of the Western Blue Ridge record a Barrovian-style sequence of metamorphism that increases from sub-chlorite through staurolite grade metamorphism from west to east, decreases to chlorite grade toward the core of the Murphy syncline, then increases again eastward to kyanite grade toward the eastern boundary of the Western Blue Ridge (Reference 2.5.1-44). Penetrative deformation was synchronous with peak metamorphism, and occurred during the 480-460 Ma Taconic orogeny, likely the result of the accretion of the Central Blue Ridge terranes (References 2.5.1-43 and 2.5.1-44).

The Western Blue Ridge is made up of a stack of at least five imbricate thrust sheets, including (from west to east) the Great Smoky, Miller Cove, Gatlinburg, Dunn Creek, and Greenbrier faults (e.g., Reference 2.5.1-147) (Figure 2.5.1-18, Sheet 2). Based on fabric relationships, the Great Smoky, Gatlinburg, and Miller Cove faults post-date metamorphism, and are commonly attributed to Alleghanian emplacement of the Blue Ridge-Inner Piedmont megathrust sheet (e.g., References 2.5.1-73 and 2.5.1-147). The Dunn Creek and Greenbrier faults are ductile faults that were active prior to or during Taconic metamorphism (References 2.5.1-147 and 2.5.1-149), although an Alleghanian overprint has recently been suggested for the Greenbrier fault (Reference 2.5.1-151).

2.5.1.1.4.1.4.2 Central Blue Ridge

The Central Blue Ridge terranes are juxtaposed above the Western Blue Ridge along the early Taconic pre- to syn-metamorphic Hayesville fault (References 2.5.1-44 and 2.5.1-152). The Central Blue Ridge terranes consist of the Cartoogechaye and Cowrock terranes, and the Dahlonega Gold Belt (Figure 2.5.1-18, Sheet 2). The Central Blue Ridge contrasts with the Western Blue Ridge by relatively higher metamorphic grade, gross structural style, and the occurrence of Paleozoic granitic plutons and relatively abundant mafic and ultramafic bodies (e.g., References 2.5.1-119 and 2.5.1-44). The Central Blue Ridge terranes generally consist of migmatitic metasiliciclastic rocks with abundant mafic-ultramafic complexes, with several bodies of Mesoproterozoic basement identified in the Cartoogechaye terrane (Reference 2.5.1-44). Rocks of the Central Blue Ridge were metamorphosed at amphibolite to granulite facies conditions in the Early Ordovician Taconic orogeny, likely related to accretion of these terranes to the Laurentian margin (References 2.5.1-34 and 2.5.1-44). Moecher et al. (Reference 2.5.1-43) reported U-Pb zircon ages of 458 ±1.0 and 460 ± 12 Ma from syn-metamorphic leukosome at Winding Stair Gap (Cartoogechaye terrane) (Figure 2.5.1-18, Sheet 2).

The Cartoogechaye terrane structurally overlies the Cowrock terrane, separated by the Shope Fork-Chunky Gal Mountain fault (References 2.5.1-34 and 2.5.1-44) (Figure 2.5.1-18, Sheet 2). Both the Cartoogechaye and Cowrock terranes overlie the Dahlonega Gold Belt, and were juxtaposed above it along the Soque River fault (References 2.5.1-34 and 2.5.1-44). Metamorphic mineral assemblages in fault-zone mylonites indicate these faults were active under greenschist to upper amphibolite facies conditions, which coincided with metamorphism associated with the Ordovician Taconic orogeny (References 2.5.1-34 and 2.5.1-44). The eastern boundary of the Central Blue Ridge is the Chattahoochee-Holland Mountain fault, which juxtaposes the Eastern Blue Ridge above the Central Blue Ridge terranes. The Chattahoochee-Holland Mountain fault was active during the Taconic orogeny, and based on fault-rock fabrics and crosscutting relationships with the 336 ± 2 Ma Rabun Granodiorite, was reactivated during the Alleghanian orogeny (References 2.5.1-34 and 2.5.1-126).

2.5.1.1.4.1.4.3 Eastern Blue Ridge

The Eastern Blue Ridge is separated from the Western Inner Piedmont by the Brevard fault, one of the largest and most fundamental tectonic boundaries in the southern Appalachian orogen. Even though the same stratigraphic succession, the Tallulah Falls Formation, occurs on either side of the Brevard fault (References 2.5.1-153 and 2.5.1-154), differences in metamorphic age and grade, structural style, in addition to temporally and chemically distinct plutonic suites, occur across this boundary (References 2.5.1-44, 2.5.1-51, 2.5.1-56, and 2.5.1-155). The Brevard fault has a complex and protracted tectonic history that records several episodes of deformation (Reference 2.5.1-154). The earliest deformation recorded along the Brevard fault occurred during the Acadian/Neoacadian orogeny, and involved approximately 200 km (124 mi) of dextral displacement at upper amphibolite-facies conditions (References 2.5.1-51, 2.5.1-154, and 2.5.1-156). The Brevard fault was overprinted under greenschist-facies conditions during the Alleghanian orogeny, with shear-sense indicators in mylonites again suggesting dextral displacement (Reference 2.5.1-154). This episode of deformation is similar in kinematics and metamorphic grade to a suite of early Alleghanian faults termed the Eastern Piedmont Fault System (EPFS; Reference 2.5.1-157), that occupy a broad zone from the Brevard fault eastward to beneath the Atlantic Coastal Plain (Figure 2.5.1-12). The latest phase of deformation along the Brevard fault occurred in the late stages of the Alleghanian orogeny, and involves northwest-directed thrusting under brittle conditions (Reference 2.5.1-154). The Brevard fault is cut by undeformed CAMP diabase dikes, which indicates the fault has not been active since the Mesozoic, approximately 200 Ma (Reference 2.5.1-154).

2.5.1.1.4.1.5 Inner Piedmont

The Inner Piedmont is a composite terrane that consists of the Tugaloo (Western Inner Piedmont) and Cat Square (Eastern Inner Piedmont) terranes (References 2.5.1-52, 2.5.1-53, and 2.5.1-55). They are here combined because of their coupled metamorphic and deformational history. The Western Inner Piedmont consists of predominantly Neoproterozoic-Middle Ordovician siliciclastic and metavolcanic units that were intruded by Ordovician-Silurian plutons, whereas the Eastern Inner Piedmont is made up of Silurian-Devonian siliciclastics with latest Silurian-Mississippian peraluminous felsic igneous rocks (References 2.5.1-52, 2.5.1-53, and 2.5.1-55). These terranes are separated by the Brindle Creek-Jackson Lake fault (References 2.5.1-52 and 2.5.1-55).

In terms of structural style, the Inner Piedmont comprises a gently dipping stack of large, crystalline thrust nappes that were emplaced at peak (upper amphibolite-facies) metamorphic conditions (e.g., References 2.5.1-51, 2.5.1-158, and 2.5.1-159). Regional structural analyses indicate these nappes represent southwest-directed sheath folds that developed during the dextral transpressive accretion of the Carolina superterrane as it overrode the eastern Laurentian margin during the Acadian/Neoacadian orogeny (References 2.5.1-51 and 2.5.1-57). Fabric relationships indicate the Brindle Creek-Jackson Lake fault and other ductile faults that carried thrust nappes were emplaced during peak metamorphism and development of the pervasive fabric in the Inner Piedmont, which occurred 400-355 Ma based on U-Pb zircon-rim ages (References 2.5.1-44, 2.5.1-52, and 2.5.1-160). Carboniferous plutons in the Inner Piedmont (337-302 Ma; References 2.5.1-52, 2.5.1-56, and 2.5.1-72) truncate dominant fabric elements in the Inner Piedmont, which provides a minimum age of pervasive deformation and emplacement of ductile thrust sheets in the Inner Piedmont.

In eastern Alabama through Georgia, the post-metamorphic Towaliga fault separates the Inner Piedmont terranes from the Pine Mountain window, a peri-Laurentian basement block with an associated metasiliciclastic cover sequence (References 2.5.1-87 and 2.5.1-161) (Figure 2.5.1-18, Sheet 1). The Towaliga fault frames the northwestern flank of the Pine Mountain window, then continues through the Inner Piedmont, possibly as far northeast as the Savannah

River (Reference 2.5.1-87). The Towaliga fault has a complex polyphase history, which includes an episode of Alleghanian dextral displacement at upper greenschist-facies conditions associated with the EPFS (References 2.5.1-87, 2.5.1-161, and 2.5.1-162). This phase of faulting truncates post-Acadian (328-301 Ma) granitoids in central Georgia (References 2.5.1-163 and 2.5.1-164) suggest the development of fault rock fabrics occurred at approximately 295 Ma based on Rb-Sr mineral isochron ages. Huebner and Hatcher (Reference 2.5.1-87) suggested that isolated, km-scale rhomboidal pods of silicified cataclasite along the fault trace represent ancient dilational step-overs in a small-displacement, sinistral fault system. This episode of faulting shares mutually overprinting crosscutting relationships with undeformed CAMP diabase dikes, similar to numerous small-scale silicified faults throughout the Inner Piedmont (References 2.5.1-85, 2.5.1-86, and 2.5.1-87). This indicates that deformation along these brittle, silicified faults occurred during the emplacement of CAMP diabase dikes at approximately 200 Ma (Reference 2.5.1-87).

2.5.1.1.4.1.6 Carolina Superterrane

The Carolina superterrane is an amalgamation of lithotectonic terranes that mostly consist of Neoproterozoic-early Paleozoic volcanic arc, volcanogenic sedimentary, and subarc plutonic components (e.g., References 2.5.1-34, 2.5.1-134, and 2.5.1-165) (Figure 2.5.1-18, Sheet 1). The two largest and most prominent terranes in the Carolina superterrane are the Charlotte and Carolina terranes (Reference 2.5.1-134). The boundary that separates the Carolina and Charlotte terranes is commonly depicted as the Gold Hill-Silver Hill fault system References 2.5.1-24 and 2.5.1-34), although several studies indicate stratigraphic continuity across that boundary (e.g., References 2.5.1-69, 2.5.1-166, 2.5.1-167, and 2.5.1-168). These terranes are combined into one unit here to simplify discussion, as their Paleozoic histories are similar.

Peri-Gondwanan affinity of the Carolina superterrane was confirmed with the presence of a Middle Cambrian Atlantic province trilobite (*Acadoparadoxides*) fauna (Reference 2.5.1-169), and is further supported by several pulses of sedimentation, magmatism, deformation, and metamorphism, that do not correspond with Laurentian orogenies (e.g., References 2.5.1-134, 2.5.1-170, and 2.5.1-171). Hibbard and Samson (Reference 2.5.1-171) and Hibbard et al. (Reference 2.5.1-134) summarized the history of Neoproterozoic to earliest Paleozoic tectonic events that occurred independent of Laurentia, and recognized three basic stages of tectonic activity that occurred at 700-600 Ma, 590-560 Ma, and 550-530 Ma. Several Paleozoic orogenic events resulted in metamorphism, fabric development, and plutonism throughout the Carolina superterrane, including an Ordovician-Silurian (termed the Cherokee orogeny; Reference 2.5.1-65), Silurian-Devonian to Mississippian (Acadian-Neoacadian orogeny), and Pennsylvanian-Permian Alleghanian orogeny.

The Carolina superterrane is separated from Laurentian and peri-Laurentian rocks by the Central Piedmont suture, which juxtaposes Carolina superterrane rocks above those native to Laurentia. Timing of deformation along the suture through the Carolinas is middle Carboniferous, based on fabric relationships with syn- and post-deformational plutons along this boundary (Reference 2.5.1-172). At its southern terminus in central Georgia (termed the Ocmulgee fault), pervasive fabric with a minimum age of approximately 328 Ma crosses the suture without disruption, which provides a minimum age of deformation along the fault (Reference 2.5.1-163). Other prominent faults within the Carolina superterrane include the Gold Hill-Silver Hill and Modoc faults. The Gold Hill-Silver Hill fault system records dextral strike-slip displacement that occurred during the Devonian (e.g., References 2.5.1-173, 2.5.1-174, and 2.5.1-175), although it may also record an episode of Late Ordovician sinistral strike-slip (Reference 2.5.1-69). The Modoc fault is considered part of the EPFS, and is thought to be Alleghanian in age based on fabric relationships and kinematic and deformational similarities to other Alleghanian faults (Reference 2.5.1-176).

2.5.1.1.4.2 Regional Geophysical Data

Regional geophysical data, including seismic reflection data and aeromagnetic and gravity surveys, have been paramount to delineating the current distribution of tectonic elements in the southern Appalachians, and have also proven useful in deciphering the tectonic history of the orogen (see Reference 2.5.1-34). Seismic reflection data, collected under the Consortium for Continental Reflection Profiling (COCORP), revealed the continuity of Valley and Ridge reflectors beneath the Blue Ridge and Inner Piedmont, which supports hypotheses that suggest a thin-skinned tectonic style in the southern Appalachians (e.g., References 2.5.1-125 and 2.5.1-177). These data have also been applied to structural interpretations of the Valley and Ridge province, and clearly illustrate that major Valley and Ridge faults propagate from a basal detachment near the basement-cover interface (e.g., Reference 2.5.1-102). Major structures in the Valley and Ridge and western Blue Ridge are generally not visible on aeromagnetic or gravity maps, as they juxtapose rocks with similar densities and magnetic susceptibilities.

Aeromagnetic and gravity surveys collect data that are used to generate anomaly maps, or maps of perturbations in the Earth’s natural magnetic field (or gravity) caused by crustal rocks (Figure 2.5.1-20). These maps are useful in identifying lithotectonic boundaries on a regional scale, identifying plutonic rocks at depth, and have also been valuable in identifying and tracing fault systems, both at the surface and at depth (e.g., References 2.5.1-34 and 2.5.1-74). Aeromagnetic anomaly maps were relied on heavily during the compilation of the Hatcher et al. (Reference 2.5.1-34) tectonic map, which illustrates that many of the major tectonic boundaries in the southern Appalachian orogen are readily identifiable in these data. The simplified tectonic map shown in Figure 2.5.1-18, Sheet 1 is based largely on the Hatcher et al., (Reference 2.5.1-34) subdivisions, which are based on a combination of field geologic evidence and interpretation of aeromagnetic and gravity data.

Arguably the most conspicuous feature in aeromagnetic anomaly maps of the eastern United States is the New York-Alabama (NY-AL) lineament, a feature that is visible for more than 1600 km (994 mi) (References 2.5.1-178 and 2.5.1-179) (Figure 2.5.1-20). The NY-AL lineament is a subsurface feature in crystalline basement rocks, and has been interpreted as a strike-slip fault that could have been active during the Grenville orogeny, the Neoproterozoic-Cambrian rifting of Rodinia, or during one of the Paleozoic orogenies (References 2.5.1-178 and 2.5.1-179). It has also been hypothesized to represent the suture between Laurentian and Amazonian (proto-South American) rocks that were juxtaposed during the Grenville orogeny, based on Pb isotopes from southern Appalachian basement rocks that indicate Amazonian affinity (References 2.5.1-34 and 2.5.1-180) (Figure 2.5.1-20).

Other major structures in the southern Appalachians are especially well-delineated using a combination of gravity and aeromagnetic data. Specifically, the central Piedmont suture is conspicuous in both gravity and aeromagnetic anomaly maps, as it separates generally high-magnetic and high-gravity rocks of the Carolina superterrane (relatively higher mafic content) from adjacent peri-Laurentian rocks to the west (Figure 2.5.1-20). Rounded, high-magnetic anomalies in the western flank of the Carolina superterrane represent the magnetic signature of mafic plutons of the Concord Plutonic suite, which correspond with plutons exposed at the surface and plutons at depth.

The Brevard fault (labeled as 8, in Figure 2.5.1-18 Sheet 1 and Figure 2.5.1-20) is also visible in these data, and although it does not appear to juxtapose magnetically contrasting rocks, it does appear to separate several gravity anomalies, seen by the consistent gravity “low” along the fault (Figure 2.5.1-20). The aeromagnetic lineament that corresponds with the well-defined surface trace of the Brevard fault stretches from western North Carolina through eastern Alabama, and its aeromagnetic signature continues to the southwest beneath the Coastal Plain in Alabama (Figure 2.5.1-20). Numerous curved magnetic anomalies southeast of the Brevard fault in central

Georgia are interpreted to represent macroscopic structures in the polydeformed Inner Piedmont (Reference 2.5.1-34).

The Brunswick Magnetic Anomaly traverses south-central Georgia on an east-west trend, and is interpreted to represent the geophysical signature of the Suwanee suture (References 2.5.1-274, 2.5.1-275, and 2.5.1-276). This zone separates Laurentian crust to the north from Gondwanan-affinity crust to the south, based on geochronologic and isotopic data from igneous rocks collected from deep boreholes (Mueller et al., 1994 Reference 2.5.1-275). This suture is interpreted to be late Paleozoic, related to the Alleghanian orogeny (References 2.5.1-73 and 2.5.1-274).

2.5.1.1.4.3 Distribution of Seismicity and Stress in the Eastern United States

2.5.1.1.4.3.1 Current Stress Regime in the Eastern United States

Maps of present day lithospheric stresses have provided a wealth of information regarding intraplate seismicity in the eastern United States (e.g., References 2.5.1-181, 2.5.1-182, 2.5.1-183, 2.5.1-184, 2.5.1-185, and 2.5.1-306) (Figure 2.5.1-21). Orientation of principal stress directions is derived from measurement of instantaneous strain data gathered from hydraulic fracturing, borehole breakouts, and earthquake focal mechanisms. The stress field in the Central and Eastern United States (CEUS) and southeastern Canada is broad and consistent on the lateral scale of hundreds of kilometers and is generally characterized by a horizontal, compressive, NE–SW trending maximum horizontal stress (Reference 2.5.1-306). Some second-order stress fields that may deviate from the large-scale regional field and that are driven by more localized forces are also observed across the CEUS (Reference 2.5.1-306).

Compilations of stress indicator data published since the 1980s consistently indicate that the maximum compressive principal stress (σ_1) is subhorizontal, and roughly trends NE-SW across large areas of the CEUS (e.g., References 2.5.1-181, 2.5.1-184, 2.5.1-185, and 2.5.1-306) (Figure 2.5.1-21). A domain of relatively uniform NE-SW-trending σ_1, which includes the northern Atlantic states and parts of southern Canada, was defined by Zoback and Zoback (Reference 2.5.1-307) as the mid-plate stress province. A visual average of long-wavelength σ_1 trends in the mid-plate stress province from maps of stress indicators published by Zoback and Zoback (Reference 2.5.1-181) and Heidbach et al. (Reference 2.5.1-184) is about N55°E to N65°E. The uniformity of the NE-SW σ_1 orientation in the mid-plate stress province is statistically robust (Reference 2.5.1-308) and is generally assumed to extend to the southeastern U.S., with the caveat that stress indicator data are relatively sparse in Georgia, Alabama, and Mississippi, and in neighboring areas of South Carolina and Louisiana.

Although the orientation of σ_1 is relatively uniform throughout the mid-plate stress province (subhorizontal, trending roughly NE-SW), the orientations of the intermediate and minimum compressive stresses (σ_2 and σ_3, respectively) are not. In general, σ_3 is the vertical principal axis (thrust faulting) in the central and northern Appalachians, whereas σ_2 is vertical (strike-slip faulting) in the southern Appalachians and Midwestern Plains states (Figure 2.5.1-21, Sheet 2 of 2). A discussion of the possible driving mechanisms that result in the observed regional stress field is presented later in this subsection.

Mazzotti and Townend (Reference 2.5.1-185) define the orientation and shape of the stress ellipsoid (orientation and magnitude of the three principal stress axes) throughout the eastern U.S. by inverting groups of small-earthquake focal mechanisms. Their analysis focuses on areas of relatively higher background seismicity rates, where a sufficient number of focal mechanisms are available to provide an over-determined inversion solution. Areas of elevated seismicity rate closest to the CRN Site include: (1) the Eastern Tennessee seismic zone; (2); the epicentral region of the 1886 Charleston, South Carolina earthquake; and (3) the New Madrid seismic zone

region (Figure 2.5.1-21). The inversion results for these regions indicate that σ_1 is subhorizontal and oriented NE-SW to ENE-WSW, consistent with the regional trend in the mid-plate stress province. σ_3 is vertical in the region surrounding Charleston (Reference 2.5.1-309), whereas the New Madrid and the Eastern Tennessee seismic zones are characterized by vertical σ_2 axes, which are more indicative of strike-slip faulting. Chapman et al. (Reference 2.5.1-194) and Cooley (Reference 2.5.1-310) also present focal mechanisms from the Eastern Tennessee seismic zone that indicate σ_2 locally is vertical and the style of deformation is characterized by strike-slip faulting.

Hurd and Zoback (Reference 2.5.1-306) use the inversion results of Mazzotti and Townend (Reference 2.5.1-185), with an updated catalog of available earthquake focal mechanisms, to produce a map of the regional variation stress-field geometry (Figure 2.5.1-21, Sheet 2 of 2). They report a strike-slip focal mechanism from a M_w 3.8 earthquake that occurred in 2009 in central Alabama approximately 350 km south of the CRN Site, which indicated left-lateral slip on a sub-vertical, WNW-ESE-striking nodal plane (alternatively, right-lateral slip on a NNE-SSW plane). The P-axis for this focal mechanism trends approximately N50°E, which is consistent with the inferred regional NE-SW trend of σ_1 in the mid-plate stress province, and the inferred strike-slip kinematics suggest that σ_2 is vertical and σ_3 is horizontal in the vicinity of the earthquake.

Potential Driving Mechanism of Stresses in the Eastern United States

Zoback and Zoback (Reference 2.5.1-307) note that the consistent NE-SW orientation of σ_1 across very large areas of the interior of the North American plate implies relatively uniform forces acting on its boundaries, and proposed that the dominant source of stress for the mid-plate stress province is ridge-push force from the Mid-Atlantic Ridge. Richardson and Reding (Reference 2.5.1-311) modeled the contributions of several classes of forces to the state of stress in the interior of North America:

- Horizontal stresses arise from gravitational body forces acting on lateral variations in lithospheric density. Richardson and Reding (Reference 2.5.1-311) emphasize what is commonly called the ridge-push force is an example of this class of force. Rather than a line force that acts outwardly from the axis of a spreading ridge, ridge-push arises from the pressure that the positively buoyant, topographically high ridge exerts against the topographically lower and less buoyant lithosphere in the adjacent ocean basins. The horizontal pressure from the ridge results in large compressive stresses in the oceanic lithosphere, which are transmitted elastically into the interior of adjoining continents.

- Shear and compressive stresses are associated with major tectonic plate boundaries like transform faults and subduction zones.

- Shear tractions act on the base of the lithosphere from relative flow of the underlying asthenospheric mantle.

Richardson and Reding (Reference 2.5.1-311) conclude that the NE-SW trend of σ_1 in the central and eastern U.S. dominantly reflects the contribution from ridge-push forces. They estimate the magnitude of ridge-push to be about 2 to 3 x 10^{12} N/m (i.e., the total vertically integrated force acting on a column of lithosphere 1 m wide), which corresponds to average stresses of about 40 MPa to 60 MPa in a 50-km-thick elastic plate. Richardson and Reding (Reference 2.5.1-311) demonstrate that the fit of modeled stress trajectories to the data is improved by adding a modest compressive stress (about 5 to 10 MPa) acting on the San Andreas fault and Caribbean plate boundaries.

The observed NE-SW orientation of σ_1 in the mid-plate stress province is reproduced by models that assume relative flow of the underlying asthenosphere induces a shear stress (i.e., “drag”) on the base of the continental lithosphere (Reference 2.5.1-311). However, Richardson and Reding (Reference 2.5.1-311) and Zoback and Zoback (Reference 2.5.1-307) discount this as a significant contribution to the total stress in the continental interior, because it predicts that the horizontal compressive stress should increase by an order of magnitude, from east to west, across the central U.S. This east-to-west stress increase is not observed. In fact, Hurd and Zoback (Reference 2.5.1-306) demonstrate the magnitude of σ_1, relative to σ_2 and σ_3, is higher in the northeastern U.S. than in the southeastern and central U.S., which essentially contradicts the first-order predictions of the “drag” model. More recent research (Reference 2.5.1-312) suggests there may be a partially molten, low viscosity channel at the base of the lithosphere that mechanically decouples the tectonic plates from the asthenosphere. If this model is valid, then it is unlikely that significant shear stresses in the lithosphere, specifically in the upper crust, are a product of motion relative to the asthenosphere.

Additionally, the orientation of the principal stress axes in the southern Appalachians (specifically, σ_2 vertical) is inconsistent with ridge-push as the lone driving mechanism for the observed stress field. If ridge-push were the sole driving mechanism, then σ_3 should be vertical with nearly horizontal σ_1 and σ_2, similar to what is observed in the central and northern Appalachians (Figure 2.5.1-21, Sheet 2 of 2). While the orientation of σ_1 is consistent with the predicted orientation based on the orientation of the mid-Atlantic Ridge (Reference 2.5.1-307), a subvertical intermediate principal stress axis suggests local buoyancy forces in the southern Appalachians may be contributing to the overall shape and orientation of the regional stress field. Numerous independent studies in recent decades have interpreted Cenozoic epeirogenic uplift of the Southern Appalachians (see Subsection 2.5.1.1.2), and many workers attribute the uplift to mantle processes. Based on recently acquired mantle tomography, Biryol et al. (Reference 2.5.1-313) suggest that foundering of the lower lithosphere beneath west-central Tennessee is driving buoyant uplift of eastern Tennessee, Georgia, and South Carolina (Figure 2.5.1-82). Gravitational body forces acting on the uplifted lithospheric column predictably would generate local horizontal tensile stresses, which in turn could contribute to the subvertical orientation of σ_2 in the southern Appalachians (see discussion and additional references cited in Reference 2.5.1-314). The combination of locally derived upper mantle buoyancy forces and far-field ridge-push forces from the Mid-Atlantic Ridge presents a viable explanation for the observed orientation of the regional stress field in the southeastern U.S. including the site region.

2.5.1.1.4.3.2 Distribution of Seismicity: The Eastern Tennessee Seismic Zone

The CRN Site is situated within a broad zone of elevated activity of historically low-magnitude seismicity in Eastern Tennessee, identified by regional earthquake monitoring over the last several decades. This area, commonly called the ETSZ is an approximately 300 km long and less than 50 km wide (approximately 186 mi and less than 31 mi wide) northeasterly trending band of seismicity within the Valley and Ridge and western Blue Ridge physiographic provinces (References 2.5.1-186 and 2.5.1-279). The ETSZ boundary, as depicted by the USGS in Figure 2.5.2-26 is discussed in Subsection 2.5.2.2.5. The ETSZ underlies eastern Tennessee, and parts of North Carolina, Georgia, and Alabama (References 2.5.1-186, 2.5.1-187, 2.5.1-188, and 2.5.1-189). After the New Madrid seismic zone, the ETSZ has the second highest rate of small (i.e., M<5) earthquakes in the eastern United States (Section 7.3.4.1.2 of Reference 2.5.1-190).

Instrumentally located epicenters in the ETSZ indicate that the overwhelming majority of earthquake hypocenters are located beneath the 5-km (3-mi) thick Appalachian fold-thrust belt in Neoproterozoic basement rocks. The mean focal depth within the ETSZ is approximately 15 km (9 mi) (Reference 2.5.1-186). These earthquakes have been correlated with potential aeromagnetic anomalies, primarily the NY-AL lineament, and associated with alternative tectonic

models (Reference 2.5.1-178, 2.5.1-186, 2.5.1-187, 2.5.1-188, 2.5.1-189, 2.5.1-191; and 2.5.1-192).

Powell et al. (Reference 2.5.1-186) showed that the instrumentally located epicenters of the ETSZ lie close to and east of the NY-AL lineament and west of the Clingman lineament. They associate the aeromagnetic signature of the NY-AL aeromagnetic lineament with a potentially vertical boundary that separates two rock types or crustal blocks. Powell et al. (Reference 2.5.1-186) describe the ETSZ as a possible evolving seismic zone in which slip on north- and east-striking surfaces is slowly coalescing into a northeast-striking strike-slip shear zone near the juncture between the relatively weak structural block (Ocoee) and the relatively strong crust to the northwest. Strike slip movement along this northeast trending juncture associated with the NY-AL aeromagnetic lineament and a postulated crustal strength contrast is reportedly consistent with the regional stress field (Reference 2.5.1-186). Powell et al. (Reference 2.5.1-186) recognize that earthquakes within the ETSZ cannot be attributed to known faults but suggest the seismicity is in response to the development of a potential incipient crustal fault.

Chapman (Reference 2.5.1-193) and Chapman et al. (Reference 2.5.1-194) used revised hypocenter locations based on an updated three-dimensional (3D) velocity-hypocenter inversion (Vlahovic et al., 1998 Reference 2.5.1-192) to derive focal mechanism solutions for 26 earthquakes in eastern Tennessee. Depths of most earthquakes range from approximately 5 to 22 km (approximately 3 to 14 mi) (Reference 2.5.1-189), indicating nearly all of earthquakes in the ETSZ occur in basement rocks below the depth of the decollement underlying the Appalachian fold-thrust belt (References 2.5.1-194 and 2.5.1-195). Through statistical analyses, Chapman et al. (Reference 2.5.1-194) found the focal mechanism solutions to be bimodal: one group includes right-lateral motion on northerly trending nodal planes and left-lateral motion on easterly trending nodal planes; the second group includes right-lateral motion on northeasterly trending nodal planes and left-lateral motion on southeasterly trending nodal planes. Chapman et al. (Reference 2.5.1-194) propose that the earthquakes have occurred primarily through left-lateral motion on east-west trending faults that are east of and adjacent to the NY-AL lineament and that the preferred orientation of focal mechanism nodal planes and epicenter alignments suggest seismicity is distributed over a series of northeasterly trending en-echelon segments and is structurally controlled by basement faults. Chapman et al. (Reference 2.5.1-189) suggest that these linear segments and the locations of their terminations may reflect basement fault structure that is being reactivated in the modern stress regime by the presence of a weak lower crust and/or increased fluid pressures within the upper to middle crust as evidenced by the anomalously low velocities within the seismic zone. Chapman et al. (Reference 2.5.1-189) suggest a slight correlation may exist between the seismicity, the major drainage pattern, and the general topography of the region, which could result from a hydrological element linkage.

Steltenpohl et al. (Reference 2.5.1-179) attribute seismicity in the ETSZ to the N15°E magnetic grain of hypothesized metasedimentary gneisses of the buried Ocoee block correlative with the Amish anomaly. Additionally, Steltenpohl et al. (Reference 2.5.1-179) proposed that the stress that initiated dextral motion along the NY-AL lineament and the modern stress field are compatible. Long and Zelt (Reference 2.5.1-196), Long and Kaufmann (Reference 2.5.1-197), and Kaufmann and Long (Reference 2.5.1-191) propose an alternative interpretation of seismicity and velocity structures in the ETSZ in which the majority of seismicity is concentrated in areas of low velocity at midcrustal depths and is not associated with major crustal features such as distinct crustal blocks defined by the NY-AL lineament. This alternative model suggests intraplate earthquakes occur in midcrustal zones of weakness that may result from increased fluid content in the crust (Reference 2.5.1-196).

The recently published *Central and Eastern United States Seismic Source Characterization for Nuclear Facilities*, (Reference 2.5.1-190) discusses the ETSZ in general terms as a zone of elevated seismicity and some preliminary paleoseismic results from Vaughn et al. (Reference 2.5.1-198) were cited; however, the region was not modeled as a unique source of Repeated Large Magnitude Earthquakes (RLMEs) (Reference 2.5.1-190) (see Subsection 2.5.2.2). The elevated seismicity rate which defines the ETSZ was included in the Central and Eastern United States (CEUS) Seismic Source Characterization (SSC) model as part of the Paleozoic Extended Crust (PEZ) areal source zone. Spatial smoothing was used to retain the elevated rate of seismicity in the ETSZ region. Since publication of the CEUS SSC report more recent research has been published describing possible paleoseismic evidence for large magnitude ETSZ paleoearthquakes near Douglas Reservoir, approximately 80 km (50 mi) east of the CRN Site (References 2.5.1-199, 2.5.1-200, and 2.5.1-201).

2.5.1.1.5 Regional Non-Seismic Geologic Hazards

2.5.1.1.5.1 Karst Hazards

Carbonate rock dissolution and karst formation is the dominant non-seismic geologic hazard in the CRN site region (Subsection 2.5.1.1.1). This geomorphic process has resulted in extensive cave development in the gently folded and flat lying Mississippian to Pennsylvanian carbonate stratigraphic units in the Cumberland Plateau. This hazard or potential hazard within the Cumberland Plateau occurs from Kentucky southwest into Tennessee and Alabama (Figure 2.5.1-4). The folded and faulted Paleozoic limestones and dolomites in the Valley and Ridge Province contain fractures and, in some locations, fracture cleavage, which provides conduits for fluid flow and enhanced carbonate dissolution. Cave development and geometry tend to show structural control of karst (Subsection 2.5.1.1.1). The karst hazard in the Valley and Ridge Province extends from Virginia southwest into Tennessee, Georgia, and Alabama (Figure 2.5.1-4). Local karst hazards are discussed in Subsection 2.5.1.2.5.

2.5.1.1.5.2 Landslide Hazards

The United States Geological Survey has identified zones of varying landslide susceptibility within the conterminous United States (Reference 2.5.1-202). Since the cessation of deformation that occurred during the late Paleozoic and Mesozoic, erosion has produced steep slopes including the development of canyons throughout the site region (Subsection 2.5.1.1.1). Persistent rainfall followed by more intense precipitation has resulted in damaging debris slides and avalanches (Reference 2.5.1-202). Landslides occur predominantly on weathered rock or colluvial soils on steep slopes. Many of these landslides have occurred on soils derived from weathered Pennsylvanian and Permian sedimentary rocks. Shales, particularly red beds and shale-limestone sequences, weather rapidly into clayey soils when exposed at the earth’s surface. Common forms of mass wasting in the site region consist of rock slides originating from detached rock slabs and translational landslides involving soils containing elevated groundwater under a hydrostatic head. Numerous slow-moving debris slides occur in the Valley and Ridge and Blue Ridge provinces. These slides form in colluvial soils containing rock fragments on slopes underlain by sandstones and metamorphic rocks. As stated in Subsection 2.5.1.1.2, the Interior Low Plateaus and the Cumberland Plateau are underlain by relatively flat-lying Devonian and Mississippian shales, sandstones and limestones. The shale becomes susceptible to landsliding when weathered into clayey soils. Figure 2.5.1-22 is a landslide hazard map of the CRN site region. Figure 2.4.9-5 shows landslide incidence and susceptibility. Both maps indicate that the site is located in an area of moderate susceptibility and low incidence, whereas surrounding areas in the site region range from high to moderate susceptibility.

2.5.1.2 Local Geology

The following subsection presents a summary of geologic conditions of the 25-mi radius site vicinity, 5-mi radius site area, and the 0.6-mi radius site location. Site physiography, geomorphology, geologic history, stratigraphy, structural geology, non-seismic geologic hazards, and engineering geology are discussed. The information presented is based on a review of Clinch River Breeder Reactor Project (CRBRP) reports and documents, Oak Ridge National Lab (ORNL) reports, review of published and unpublished geologic literature, and the results of geotechnical and geologic field investigations conducted at the CRN Site. Geologic investigations, including field reconnaissance, karst mapping, river-terrace mapping, and geomorphic analyses were complemented with high-resolution LiDAR digital elevation data acquired during the site investigation. LiDAR coverage encompasses the 5-mi radius site area, with pixel resolution of 0.5 ft over a total of 168 sq mi. (Figure 2.5.1-23). Geologic field reconnaissance way points are located on Figure 2.5.1-25.

2.5.1.2.1 Local Physiography and Geomorphic Processes

2.5.1.2.1.1 Local Physiography

The site location (0.6-mile radius) is within the western portion of Oak Ridge, Tennessee, in the northwestern Valley and Ridge physiographic province (Figure 2.5.1-1). The Valley and Ridge province is the topographic expression of the structures of the southern Appalachian foreland fold-thrust belt, which formed during the Pennsylvanian to Permian Alleghanian orogeny (Reference 2.5.1-203) (see Subsections 2.5.1.1.2 and 2.5.1.1.4). The CRN site vicinity topography is characterized by northeast–southwest trending ridges and intervening valleys typical of the regional physiographic setting of the Valley and Ridge (Subsection 2.5.1.1.1). The major ridges and intervening valleys within the site vicinity from southeast to northwest are: Copper Ridge/Melton Hill, Bradbury Valley, Dug/Hood/Haw Ridge, Poplar Springs / Bethel Valley, Chestnut Ridge, Bear Creek Valley, Pine Ridge, East Fork Valley and Black Oak Ridge (Figure 2.5.1-24).

The Clinch River follows a meandering south-westerly stream course across the site area with incised water gaps at each of the major ridges that cross the site (Figure 2.5.1-24). Most of the seasonal and perennial tributaries in the major valleys follow stream courses consistent with the current topographic setting. One exception is Poplar Creek, which is a major perennial tributary to the Clinch River that cuts across Black Oak Ridge through a steeply incised valley north of the site. The southeastern third of the CRN site area, 5-mi radius, is characterized by low hills and lacks a major northeast-southwest trending axial valley, but instead has a dendritic drainage pattern. This area is underlain by Knox Group carbonate rocks with karst features that have influenced the local stream network and resulted in sinking streams at several locations. Dug/Haw Ridge, underlain by the Rome Formation, is on the hanging wall of the Copper Creek fault (Subsection 2.5.1.2.4.2.3) and forms the southern high point on the CRN Site peninsula (Figures 2.5.1-23, 2.5.1-29, and 2.5.1-47).

2.5.1.2.1.2 Local Geomorphic Processes

2.5.1.2.1.2.1 Deposition of Colluvium

The Quaternary surficial units at the site are described in Subsection 2.5.3.2.5.1 and are mapped on Figures 2.5.1-26 and 2.5.3-2. Colluvium (Qc) deposits consist of weathered residuum transported by hillslope processes including slopewash and creep. Colluvium is deposited at the toe of hillslopes and in hollows on the hillsides. Colluvium mapped in the site area is largely Holocene in age though Pleistocene age deposits are likely present. The thickness and areal extent of colluvium deposits varies significantly dependent on the subsurface bedrock unit and

slope. The Rome Formation, which erodes primarily by mechanical weathering, produces abundant colluvial deposits which blanket gentle slopes underlain by stratigraphically adjacent units. Carbonate deposits, which erode primarily by chemical processes, tend to only produce areally extensive colluvial deposits if they contain a significant percentage of chert, such as the Longview Dolomite. Colluvium was mapped primarily on the basis of topographic expression, and only the larger bodies are included on Figures 2.5.1-26 and 2.5.1-29.

2.5.1.2.1.2.2 Deposition of Alluvium

Holocene alluvium (Qha) is deposited in hillside gullies and in the principal tributary valleys across the site area (Figures 2.5.1-26 and 2.5.1-29). Unit Qha includes channel bottom alluvium and low terrace deposits that are undivided at the scale of mapping. The unit is composed largely of silt; with sand and gravel present in varying amounts dependent on the local bedrock parent material. Holocene alluvial fan (Qhaf) deposits are present primarily at the mouths of the larger gullies incised into ridges underlain by the Rome Formation. Holocene through Pleistocene alluvial terrace deposits are mapped along larger tributary valleys in the site area including Poplar Creek, the East Fork of Poplar Creek, Bear Creek and Caney Creek in the Broadbury Valley and Young Creek. In these drainages Holocene terrace levels are assigned based on relative topographic positions, with Qht0 representing the historical flood plain. Tributary terraces of probable Pleistocene age were not assigned a relative terrace level (Subsection 2.5.3).

2.5.1.2.1.2.3 Fluvial Terraces

Fluvial terraces are extensively preserved within the site area and record a history of incision likely dating back to the early Pleistocene and possibly into the Tertiary, as observed from field and remote sensing data (Subsection 2.5.3.2.5.2). The local continuity of terraces and correlations of local Clinch River terraces to dates and elevations of regional terraces indicate incision is related to reduced sediment load following the Pleistocene (Reference 2.5.1-203). The elevations and relative ages of fluvial terraces at and near the CRN Site are discussed in Subsection 2.5.3.2.5.2.

2.5.1.2.1.2.4 Karst

Karst has developed in eastern Tennessee, within the 25-mi radius site vicinity and the 5-mi radius site area. Karst development in both the site vicinity and site area is described in Subsection 2.5.1.2.5, *Local Geologic Hazards*. Subsection 2.5.1.2.5, emphasizes detailed investigations in the site area, including previous studies within the ORR, and current studies conducted for the Clinch River Small Modular Reactor (CR SMR) Project.

2.5.1.2.1.3 Local Geomorphic Development

2.5.1.2.1.3.1 Late Tertiary and Early Pleistocene Geomorphic Processes

Although the most recent orogenic event that affected the Valley and Ridge province was the late Paleozoic Alleghanian orogeny, a growing body of evidence indicates the southern and central Appalachians may have been uplifted in the Miocene (see Subsection 2.5.1.1.2). The Miocene uplift may have affected fluvial processes and the development of karst within the site area.

Repeated glacial periods during the middle and early Pleistocene had a strong influence on the geomorphic development of the CRN site vicinity. Each glacial period was marked by a similar cycle of changes in base levels, increased precipitation, erosion, and increased stream discharge and sediment load, (isostatic) uplift and subsidence, resulting in the deposition and later dissection, isolation and/or erosion of stream terraces. Remnants of older terraces from these earlier Pleistocene events are preserved on the ORNL in areas underlain by Knox soils.

Permeable substrates and surface armoring by coarse fragments are two necessary requirements for the preservation of paleosols and also for topographic inversion (Reference 2.5.1-9).

There are several elevations on Chestnut Ridge and Copper Ridge/Melton Hill where ancient soils have been preserved (Reference 2.5.1-9). Recent studies have also recognized Pleistocene terraces in the same area (see Subsection 2.5.3.2.5.2). At an elevation of approximately 350 m (1050 to 1060 ft) and extending to approximately 360 m (1100 ft) along Chestnut Ridge, ancient toe-slope colluvial and alluvial soils of local origin have been preserved on northeastern and eastern slopes (Reference 2.5.1-9). On Melton Hill, ancient alluvium has been mapped at an elevation of nearly 450 m (1350 ft). Ancient main-channel alluvium has also been preserved at similar elevations. Extremely cherty foot-slope/toe-slope colluvium, along with small areas of residual soil, have also been preserved on what are now broad ridge tops on Chestnut Ridge and Melton Hill. Also on Chestnut Ridge, old alluvial soils occur at an elevation of approximately 290 m (875 to 900 ft). Most of the ancient colluvial and alluvial soils are interpreted to date from the late Tertiary to early Pleistocene. The Melton Hill area seems to have a preserved sequence of terrace remnants based on preliminary soils mapping evidence. Remnants of old alluvium are preserved on the Conasauga Group in Melton Valley above White Oak Lake at elevations of approximately 290 m (875 to 900 ft) and at approximately 280 m (840 to 850 ft) (Reference 2.5.1-9). An abandoned Clinch River meander occurs at an elevation of 265 m (800 to 815 ft) while the present elevation of the Clinch River arm of the Watts Bar Reservoir is about 247 m (741 ft).

2.5.1.2.1.3.2 Pleistocene Geomorphic Processes

Climate shifts during the Pleistocene produced significant changes in the types and rates and intensity of geomorphic processes. Upland soils underwent several cycles of denudation in the Pleistocene Epoch, generally corresponding to periods of maximum glaciation.

Some areas of geomorphically-sensitive landforms and soils, especially those on steeper slopes, were periodically stripped down to hard rock or hard saprolite while other less sensitive areas here hardly affected. The latest major episode of denudation occurred during the Wisconsinan, a time period of several thousand years that ended about 12,000 years ago. Numerous freeze-thaw cycles along with periods of deep freezing and downward melting of the surface in the spring, which produced saturated conditions, destabilized many of upland soils. Large volumes of soil flowed downslope as mud and debris flows, filling topographic lows and choking stream valleys and river channels. The Clinch River may also have been unable to transport the increased sediment and may have aggraded its channel, producing a widening floodplain with braided streams and damming of Poplar Creek and other ORR tributaries. Evidence includes the presence of wide spread alluvium and terrace remnants at elevation of 280 m (840 to 850 ft) in several tributary watersheds and on terrace remnants above the present Clinch River. Soil mapping in Melton and Bethel valleys has located the presence of highly dissected terrace remnants along a bend of the Clinch River that are at an elevation of about 280 m (840 ft) and a lower terrace that has an elevation of about 265 m (815 ft). The lower terrace corresponds to the elevation of an abandoned meander of the Clinch River. Incised terrace remnants have been observed.

Stream piracy was common during the Pleistocene. When the Bear Creek floodplain became choked with sediments during the Pleistocene, the stream was forced into lower pathways. Evidence for this process includes chert gravels and other stream-rounded gravels overlying residuum that was part of the bedload. Before stream piracy occurred, large amounts of sediment were deposited in ponded water as an alluvial or deltaic fan that extends to the present-day Bear Creek floodplain. The deltaic fan material covers the underlying silty alluvium and was not covered by loess (Reference 2.5.1-203).

2.5.1.2.1.3.3 Modern (Holocene) Geomorphic Period

The modern age of the Holocene Epoch is defined, for purposes of this report, as beginning about 300 years ago when the activities of European settlers resulted in large-scale deforestation, the beginning of agricultural activities, the onset of anthropogenic-accelerated erosion, and the burial of older Holocene alluvium by fresh sediments. Deforestation and primitive agricultural management practices stripped the vegetative cover off the land and left bare soil exposed to the full force of raindrop impact and runoff (Reference 2.5.1-9). In humid environments, the dominant geomorphic processes are the wearing-away of topographic highs and either the filling of low areas or the transport of sediment away from the local watershed system. These processes are driven by rainfall and the force of gravity. Soil particles are detached by raindrops or overland flow and then are transported downslope to a depositional site or into a stream. This natural process is a relatively slow one whenever there is a vegetative cover on and/or a tree canopy above the soil surface.

The Holocene Epoch covers a time span starting at the end of the Pleistocene (approximately 12,000 years ago) and includes the modern age. In the southeastern U.S., the Holocene has often been thought to have been a benign period with little climate fluctuation. Holocene climate changes, however, have produced periods of geomorphic instability. A result is the burial of Prehistoric Native American habitations on low river terraces by younger sediments between about 2800 and 5000 years ago (Reference 2.5.1-9). There is only minimal evidence of Prehistoric Native American influence on the soils of the CRN site area.

Soils on steeper slopes in the site vicinity derived from the weathering of Conasauga Group and Rome Formation were evidently not cultivated. Steep areas and extremely cherty areas of Knox were evidently not cultivated but may have been pastured for grazing of livestock. Several units within the Chickamauga Group were not cultivated due to high chert content while others were intensely cultivated, which increased erosion and led to the formation of gullies. Evidence that modern age erosion has occurred is revealed in drainageways and floodplains where 50 to 100 centimeters (cm) (20 to 40 in.) or more of modern-age sediment (mostly topsoil, derived from past agriculture and forestry land practices) has covered older Holocene age soils. Some of these areas have been reforested (Reference 2.5.1-9).

Holocene colluvium occurs: (1) in doubly-concave landform segments that occupy foot-slope and toe-slope positions at the base of slopes, (2) as fans at the outlets of headward eroding drainageways, (3) on side slopes in doubly-concave elongated landform segments and (4) in saddles between subwatersheds (Reference 2.5.1-203). Neoglacial Holocene colluvium can overlie: (1) in-place saprolite, (2) the remnants of a truncated older colluvial soil of Holocene or Pleistocene age, or (3) truncated remnants of older residual soils. Colluvium of Neoglacial age was identified only on Conasauga Group soils. Because there was a slight reduction in temperature during this period, which was accompanied by wetter conditions, only highly geomorphically-sensitive soils were destabilized (Reference 2.5.1-9).

2.5.1.2.2 Local Geologic History

The geologic history of the CRN site vicinity is dictated by regional to continent-scale tectonic events that shaped the broader Appalachian orogenic belt during the Neoproterozoic through Paleozoic Eras. The discussion in this section initially focuses on the specific relationships between these tectonic events and the bedrock stratigraphy in the CRN site vicinity. As such, lithologic units have been grouped, for ease of discussion, by similarities in age and depositional setting (Figures 2.5.1-27 and 2.5.1-28) in Subsection 2.5.1.1.3. Several lines of evidence also indicate the present-day elevation of the Appalachian Mountains is the product of a more recent (Miocene?) episode of uplift, which has affected Quaternary stream incision, deposition, and karstification (see Subsection 2.5.1.1.2). More detailed accounts of the regional tectonic

framework are described in Subsections 2.5.1.1.2 and 2.5.1.1.4, and a more detailed account of the structural evolution of the site vicinity is presented in Subsection 2.5.1.2.4.

The CRN Site lies just west of the main axis of the northeast-southwest-trending Appalachian orogenic belt, which extends nearly the entire length of eastern North America from Newfoundland, Canada, to central Alabama. The Appalachian orogenic belt formed during at least three Paleozoic orogenic events related to the opening and closing of several proto-Atlantic oceans along the eastern margin of Laurentia. The three primary Appalachian orogenies that affected the CRN site vicinity occurred in the Middle Ordovician (Taconic orogeny), Early Devonian to Mississippian (Acadian/Neoacadian orogeny), and Pennsylvanian to Permian (Alleghanian orogeny) (see Subsection 2.5.1.1.2). All of these events have strongly influenced the stratigraphy, structure, and tectonic history of the CRN site region, but the foreland fold-and-thrust belt structures of the Alleghanian orogeny are most noticeably expressed in the physiography and geomorphology of the CRN site vicinity.

Prior to the Paleozoic Appalachian orogenic events, the eastern Laurentian (proto-North America) margin was deformed and metamorphosed during the amalgamation of the supercontinent Rodinia (Grenville orogeny) at approximately 1.1 Ga. Paleozoic sedimentary rocks exposed in the CRN site vicinity were deposited on Grenville-age crystalline rocks shortly after the Neoproterozoic (560–570 Ma) breakup of Rodinia and development of a stable continental shelf that faced the Iapetus ocean. Deposition of the stratigraphic succession that comprises the rocks of the CRN site vicinity continued through the late Paleozoic. The character of this stratigraphic package is the product of orogenic events that occurred along the Laurentian margin, in addition to global paleoclimatic and paleoeustatic fluctuations that occurred throughout that time interval (Figure 2.5.1-28). Additionally, Laurentia was at equatorial latitudes throughout the Paleozoic (e.g., Reference 2.5.1-204), which also strongly influenced the stratigraphy in the Appalachian foreland basin. This Neoproterozoic through late Paleozoic sedimentary package formed an eastward-thickening wedge that was telescoped westward during the late Paleozoic Alleghanian orogeny (Reference 2.5.1-73). This deformation was thin-skinned, meaning that shortening of the sedimentary wedge occurred above the crystalline Grenvillian basement rocks on which they were deposited and is discussed later in Subsection 2.5.1.2.4 (e.g., References 2.5.1-9, 2.5.1-128, and 2.5.1-177) (Figure 2.5.1-9).

The basal stratigraphic unit in the CRN site vicinity is the early Cambrian Rome Formation, which nonconformably overlies crystalline Grenvillian basement rocks (Figures 2.5.1-11 and 2.5.1-14). The Rome Formation consists of fine- to medium-grained siliciclastic rocks in the site vicinity and is generally coarser-grained to the northwest and increasingly finer-grained and calcareous to the southeast (e.g., References 2.5.1-15 and 2.5.1-102). Sedimentary structures common to the Rome Formation include mud cracks, raindrop imprints, and ripple marks; the depositional environment for the Rome Formation has subsequently been interpreted to represent a shallow intertidal to supratidal setting (Reference 2.5.1-205).

The early Paleozoic Era was characterized by warm paleoclimate conditions that resulted in long-term sea-level rise through the Cambrian and Middle Ordovician (also called the Sauk Transgression; Reference 2.5.1-49), which is reflected in the stratigraphic succession in the CRN site vicinity (Figure 2.5.1-28). The Rome Formation is conformably overlain by the middle- to late Cambrian Conasauga Group, which consists of fine-grained siliciclastic rocks that become progressively more dolomitic up-section, representing the marine transgression that flooded the continents at this time. Within the site vicinity, the Conasauga Group consists of mostly calcareous shale with interbeds of shaly to silty limestone, with a maximum thickness of approximately 600 m (1970 ft) (References 2.5.1-9 and 2.5.1-105). The Conasauga Group consists of conformable formations that include, from oldest to youngest, the Pumpkin Valley shale, Friendship Formation (Rutledge limestone), Rogersville shale, Dismal Gap Formation (Marysville limestone), Nolichucky shale, and Maynardville limestone (Figure 2.5.1-28) (see

Subsection 2.5.1.1.3). The Conasauga Group has collectively been interpreted to represent deposition in a clastic subtidal to carbonate peritidal environment (Reference 2.5.1-103). The shale and dolomite of the Conasauga Group gently grade upward to predominantly carbonate rocks of the Knox Group, which coincides with a eustatic sea level high that may have been 180 m (590 ft) above present-day msl (Reference 2.5.1-206). The Knox Group was deposited in a peritidal environment on a wide carbonate shelf that covered the passive Laurentian margin during the late Cambrian to Early Ordovician (Figure 2.5.1-28) (e.g., Reference 2.5.1-9). Throughout eastern Tennessee, the Knox Group is generally 700 to 1000 m (2300 to 3280 ft) thick, and includes both dolomite and limestone in its northwestern extent, although is mostly limestone to the southeast (References 2.5.1-105 and 2.5.1-207).

In the Middle Ordovician, a eustatic sea level drop resulted in a regional to global-scale unconformity (Reference 2.5.1-49). In the southern Appalachians, age relationships and variations in the magnitude of the Knox unconformity suggest more localized tectonic control, which has been attributed to the Taconic orogeny (References 2.5.1-48 and 2.5.1-50). Eustatic sea level rose to approximately 200 m (650 ft) above present-day msl following the Knox unconformity (Reference 2.5.1-206), and subsequent inundation of the carbonate shelf resulted in continued peritidal carbonate deposition of the Middle Ordovician Chickamauga Group, which dominates the stratigraphy of the site area.

The Chickamauga Group consists predominantly of limestone in the northwest and becomes increasingly clastic to the southeast, which indicates source detritus derived from the Taconic highlands along the outboard Laurentian margin (References 2.5.1-46, 2.5.1-47, and 2.5.1-208). The Chickamauga Group has a total thickness of over 600 m (1970 ft) (Reference 2.5.1-105). On many 1:24,000 geologic maps, the Chickamauga Group is subdivided into several formations with characteristics and nomenclature that vary between thrust sheets (e.g., References 2.5.1-106, 2.5.1-107, and 2.5.1-108). The CRN Site is on the White Oak Mountain thrust sheet, where lithologies have a greater clastic component and are broken into seven formations, from oldest to youngest these are the: Blackford Formation, Lincolnshire Formation (consisting of the Eidson and Fleanor Shale Members), Rockdell Formation, Benbolt Formation, Bowen Formation, Witten Formation and Moccasin Formation (see Subsections 2.5.1.1.3 and 2.5.1.2.3). Within the Copper Creek thrust sheet (southeast of the White Oak Mountain thrust sheet), the Chickamauga Group is locally subdivided into five formations, from oldest to youngest these are the: Lenoir Limestone, Holston Formation, Chapman Ridge Sandstone, Ottosee shale and Bays Formation (Plate 1, included in Part 8 of the application). In the southeastern most site vicinity, the Chickamauga Group is mapped as the Athens Shale (Plate: 1; Reference 2.5.1-105).

An extensive glaciation event occurred in the Late Ordovician-Early Silurian, which led to a significant drop in eustatic sea level (References 2.5.1-206 and 2.5.1-209). This sea-level low coincides with the waning phases of the Taconic orogeny, or possibly the main pulse of the Cherokee orogeny (see Subsection 2.5.1.1.2). Northeast of the CRN site vicinity, a regional unconformity occurs at this time interval (Tuscarora unconformity), although several studies indicate this unconformity is the result of local tectonic controls versus global eustasy (e.g., References 2.5.1-68 and 2.5.1-210). Renewed siliciclastic input above this unconformity coincided with post-glaciation rising sea levels, and resulted in deposition of the Early Silurian Rockwood Formation in the site vicinity. The Rockwood Formation conformably overlies shales, siltstones and carbonates of the Reedsville Shale and Sequatchie Formation (which conformably overlie the Chickamauga Group; Figure 2.5.1-28), and consists of fine-grained siliciclastic rocks that grade upward to fine- to coarse-grained sandstones (Reference 2.5.1-9). The depositional environment of the Rockwood Formation has been interpreted as a shoreface to shallow marine shelf setting, based on sedimentary structures that include cross-bedding, load casts, and rip-up clasts (Reference 2.5.1-9).

In the site vicinity, the Early Silurian Rockwood Formation is unconformably overlain by the Late Devonian-Mississippian Chattanooga Shale. The Chattanooga Shale is a bituminous dark shale with fauna and sedimentary structures that indicate deposition in a shallow marine setting (References 2.5.1-211 and 2.5.1-212). Its basal unconformity represents a major time gap (possibly 70 Ma), which has been interpreted to be the result of uplift related to the Devonian-Mississippian Acadian/Neoacadian orogeny (Reference 2.5.1-141). The Chattanooga Shale may represent the distal western end of a more extensive clastic wedge to the east that developed during this event (References 2.5.1-9 and 2.5.1-64).

The Chattanooga Shale is conformably overlain by the Mississippian Fort Payne Chert, Newman Limestone, and Pennington Formation (Figure 2.5.1-28). The Fort Payne Chert has been interpreted to represent a basin-filling shoaling upward sequence that initiated in deeper water and became successively shallower up section (Reference 2.5.1-213). These three units collectively are shallow marine units that grade upward from carbonates and shales to primarily clastic rocks (Reference 2.5.1-105), which marks the influence of high eustatic sea-level throughout the Mississippian followed by the onset of the Alleghanian orogeny.

The transition to Pennsylvanian strata in the site vicinity is marked by coarse-grained and conglomeratic siliciclastic strata that indicate deposition in a shallow marine to fluvio-deltaic environment (see Subsection 2.5.1.1.3). These deposits represent the westward progradation of the Alleghanian clastic wedge as the Appalachian Mountains were uplifted during the terminal collision between Laurentia and Gondwana that formed the supercontinent Pangea (see Subsection 2.5.1.1.2). Pennsylvanian strata generally consist of interbedded shale, sandstone, siltstone and conglomerate with prominent coal seams. Deposits associated with the Alleghanian clastic wedge blanket the Appalachian Plateau from central Alabama through northern Pennsylvania (e.g., References 2.5.1-34 and 2.5.1-75).

During the later stages of the Alleghanian orogeny, portions of the Laurentian margin, including crustal blocks that were accreted during previous Paleozoic orogenies, were thrust over the more distal portions of the Paleozoic continental shelf (e.g., References 2.5.1-128 and 2.5.1-177). This block of crustal material is collectively termed the Blue Ridge-Piedmont megathrust sheet (e.g., Reference 2.5.1-73), and it acted as the major indenter that drove Valley and Ridge province deformation in the Appalachian foreland (see Subsection 2.5.1.1.2). In the site vicinity, this resulted in the thin-skinned emplacement of several west-directed thrust sheets that propagated from the Rome Formation at the basement-cover strata interface, which is approximately 3 km (1.9 mi) deep at the CRN Site (Reference 2.5.1-141). Recent $^{40}Ar/^{39}Ar$ geochronologic analyses of fault gouge illite from several Valley and Ridge faults indicates collective emplacement occurred 276-280 Ma (Reference 2.5.1-144).

Following deformation associated with the late Paleozoic formation of Pangea, the CRN site vicinity has been in a period of tectonic quiescence. The rifting of Pangea and opening of the Atlantic Ocean occurred during the Late Triassic to Early Jurassic, although evidence of this event is generally confined to areas closer to the Atlantic Coast. A general consensus among geologists is that the present-day elevation of the Appalachian mountain chain is a relic of uplift during the formation of Pangea, although evidence that supports Tertiary (Miocene?) topographic rejuvenation of the southern and central Appalachians has been growing in recent decades (see Subsection 2.5.1.1.2). This uplift has most likely influenced the development of Quaternary features in the CRN site vicinity (see Subsection 2.5.3).

2.5.1.2.3 Local Stratigraphy and Lithology

The following summary of the stratigraphy and lithology within the CRN Site (Figure 2.5.1-29) is largely based on the description of the geologic units presented in Hatcher et al.

(Reference 2.5.1-9) and Lee and Ketelle (Reference 2.5.1-110), and from site-specific data generated as part of the current site subsurface investigation (Reference 2.5.1-214).

2.5.1.2.3.1 Stratigraphic Nomenclature Approach

The CRN Site is located in Bethel Valley southwest of the ORR. The basic stratigraphic framework for the CRN Site is established by comparison to published descriptions of similar geologic sections located within Bethel Valley (Bethel Valley Section). Lee and Ketelle (Reference 2.5.1-110) completed a study at the ORNL (X-10 Facility) that provides an analog to the CRN Site as it is located directly along strike of the section investigated for the CR SMR Project, approximately 4.5-mi to the northeast. Lee and Ketelle (Reference 2.5.1-110) correlate their findings to the geologic framework established for the ORR by Stockdale (Reference 2.5.1-109), and continued the use of Stockdale's unit designations for the Chickamauga Group (Units A through H). Stockdale's work was based mostly on outcrop observations with limited borehole data. The Lee and Ketelle (Reference 2.5.1-110) study is based on a series of deep core holes completed along a transect perpendicular to geologic strike. The boreholes, along with down-hole geophysical logs, overlap to provide a complete section of the Chickamauga Group in the Bethel Valley Section. Lee and Ketelle (Reference 2.5.1-110) provide detailed lithologic and stratigraphic descriptions for the Chickamauga Group Units A through H.

Hatcher et al. (Reference 2.5.1-9) established the application of formation names to the lettered Chickamauga Group Unit designations. Hatcher et al. (Reference 2.5.1-9) apply the regional stratigraphic nomenclature described in Virginia and eastern Tennessee to the unit designations (Units A-H) of the Chickamauga Group for the Bethel Valley Section, and include general descriptions of the formations. The current investigation adopts Hatcher et al. (Reference 2.5.1-9) stratigraphic nomenclature. Ongoing studies at the ORR and elsewhere in eastern Tennessee may refine these correlations, specifically for the lowermost Chickamauga Units/formation correlations (e.g., Blackford Formation).

The CRN Site stratigraphic boundaries presented on the final boring/coring logs and summarized in Table 2.5.1-1 are primarily established by comparison of field boring/coring log descriptions and rock core samples to the stratigraphic and lithologic descriptions provided by Lee and Ketelle (Reference 2.5.1-110) and by the CRBRP (Reference 2.5.1-100). Natural gamma and electrical conductivity data are also used to identify stratigraphic and lithologic boundaries in borings where downhole geophysical testing was performed. The Chickamauga Group Units have characteristic geophysical (gamma/conductivity) signatures, relative to the unit above or below, that correlate to the lithology and lithological variations of the unit. In general, unit boundaries correlate to distinctive changes in the overall gamma and/or conductivity data observed in the borings logged for the CR SMR Project. These variations are used to refine the boring/coring log descriptions during the technical review of field logs, rock core, and core photographs to establish the boundary depths of the units.

In borings for which no downhole geophysical testing was completed, the field descriptions and core photographs are compared to adjacent borings that have available geophysical data to establish the unit boundaries. Non-geophysical factors used to determine the Chickamauga units and unit boundaries include the presence or lack of chert, and the mode of occurrence, such as chert nodules versus bedded chert (or the thickness of chert beds), the bedding characteristics of the units, the presence or lack of fossils, gross lithologic composition of the unit (i.e. limestone, siltstone, dolomite, or the degree of interbedded limestone, siltstone, and chert), along with the overall appearance and color of individual units. Once the individual Chickamauga Unit (A through H) was established, the regional formation correlation was made per Hatcher et al. (Reference 2.5.1-9). Individual lithologies shown on the CRN Site boring logs are based on the descriptions, observations, and conditions encountered specific to that boring.

2.5.1.2.3.2 Local Stratigraphy

Underlying a mantle of fill/residual soil and weathered bedrock, stratigraphy at the CRN Site comprises rocks of the Lower Cambrian Rome Formation, Middle Cambrian to Lower Ordovician age rocks belonging to the Knox Group and Middle Ordovician age rocks of the Chickamauga Group (Figure 2.5.1-29). The Copper Creek thrust fault, located approximately 0.6 miles south of the power block area, places the Rome Formation over the Ordovician Moccasin Formation of the Chickamauga Group in a hanging wall over footwall geometry (Reference 2.5.1-9). The geologic cross-section shown on Figure 2.5.1-30 illustrates the bedrock structure and succession of stratigraphic units encountered at the CRN Site. Orientated perpendicular to the strike of the bedding planes, rocks belonging to the Knox Group outcrop to the northwest and the progressively younger rocks belonging to the Chickamauga Group outcrop to the southeast (Figure 2.5.1-29). Rocks of the Rome Formation do not outcrop at the site, but they were encountered by two subsurface investigation boreholes. Subsurface Investigation borehole locations and the location of the geologic cross-section depicted in Figure 2.5.1-30 are shown on Figure 2.5.1-31.

A total of 82 geotechnical boreholes (76 in rock) were drilled on the CRN Site as part of the subsurface investigation (Reference 2.5.1-214). The stratigraphic units encountered during drilling at the CRN Site include, from oldest to youngest, the Rome Formation, the Newala Formation of the Knox Group, and the Blackford Formation, Eidson and Fleanor Members of the Lincolnshire Formation, Rockdell Formation, Benbolt Formation, Bowen Formation, and Moccasin Formation of the Chickamauga Group. The Witten Formation, which stratigraphically lies between the older Bowen Formation and the younger Moccasin Formation, was not encountered during the subsurface investigation drilling program. Depth below ground surface of stratigraphic picks for each borehole is presented in Table 2.5.1-2. Average vertical and true stratigraphic unit thickness are shown in Table 2.5.1-3.

2.5.1.2.3.3 Local Lithology

From oldest to youngest, the following descriptions of the bedrock units encountered at the CRN Site are based on an assessment of the subsurface investigation boring logs, geologic mapping, and previous investigations (Reference 2.5.1-214). Lithologic descriptions of the CRN Site stratigraphic units are supplemented with laboratory analytical data, downhole geophysical data, and petrographic data generated during the subsurface investigation, as available (Reference 2.5.1-214). Definitions of lithologic adjectives and modifiers used in the descriptions below are provided in Table 2.5.1-4.

Rome Formation

The Lower Cambrian Rome Formation is the oldest bedrock unit exposed in the 0.6-mi site location (Figure 2.5.1-29). It is composed principally of shale and siltstone, with lesser amounts of sandstone, dolostone, limestone and evaporite (Reference 2.5.1-9). The Rome Formation was deposited directly on crystalline basement from a clastic source to the west, and becomes increasingly carbonate rich to the east (Reference 2.5.1-102). The Rome Formation was encountered in two CRN Site subsurface investigation boreholes (CC-B1 and CC-B2). These boreholes were advanced to locate and characterize the Copper Creek thrust fault on the far southern end of the CRN Site.

At the CRN Site, the Rome Formation is composed of dusky red to weak red to dark reddish gray calcareous siltstone. It is medium strong to strong, laminated to thinly-bedded, and slightly to moderately weathered. Slight to moderate bioturbation and a trace of calcite filled pits are also noted. It is interbedded with little to some laminated to thin gray limestone (micrite) interbeds. At Boring CC-B1, the boring located closest to the Copper Creek fault, approximately 18.4 ft of gray

to olive-gray micritic limestone was encountered at the base of the Rome Formation where it is truncated by the Copper Creek fault. It is medium to strong, laminated to thinly-bedded, slightly to moderately-weathered, and interbedded with little, laminated to thin, dusky-red to olive calcareous siltstone and clayey shale. Slight bioturbation and trace calcite filled pits are also noted. Since only the leading edge of the Copper Creek thrust fault hanging wall was drilled, the thickness of the Rome Formation at the CRN Site is not known.

Approximately 4.3 to 7.4 ft of weathered fault gouge representing the Copper Creek thrust fault is observed between the base of the Rome Formation and the top of the underlying Chickamauga Group Moccasin Formation. It consists of variegated, calcareous, clayey shale and siltstone. The fault gouge is very weak to extremely weak in strength and highly to completely weathered. A few thin interbeds of dolomite-cemented, feldspathic sand lenses with pervasively sheared fabric are present. Northwest-verging rotation of bedding is also observed.

Knox Group – Newala Formation – Kingsport Formation/Mascot Dolomite

Hatcher et al. (Reference 2.5.1-9) report medium to thick white chert beds and chert matrix sandstone in the lower part of the Mascot Dolomite near the contact with the underlying Kingsport Formation. Where this lithology is not present, the combined Kingsport Formation and Mascot Dolomite is called the Newala Formation (Reference 2.5.1-9). This convention is used here (Table 2.5.1-1). The Newalla Formation is a fine- to medium-grained, variegated (gray, pink, and green) crystalline dolomite. Nodular and bedded variegated jasperoidal chert is common, and several 5 to 15 ft thick limestone and dolomitic limestone interbeds are observed. It is typically described on the boring logs as fine- to medium-grained, light olive-gray to light gray and dusky-red to gray, and locally mottled with weak red. It is strong to very strong, moderately to thickly bedded, fresh, with few irregular chert nodules and chert beds with coarse dolomite crystals (gray to gray-brown). Trace healed/filled fractures with indurated clay mineral fill (dark reddish-brown) are noted. Dolomite-healed fractures throughout, trace fossils, trace dolomite-filled pits and vugs (separate/non-touching), stylolites, and weak (delayed) to no reaction to hydrochloric acid (HCl), which signifies relatively low calcium carbonate content, are observed. A thin (less than 1.0 ft) olive gray chert and dolomite-cemented fine- to coarse-grained quartz sandstone with fine gravel-sized rounded chert clasts is also noted.

Limestone interbeds typically consist of gray limestone to dolomitic limestone (micrite) that is strong, laminated to very thinly- and moderately-bedded, locally nodular, slightly-weathered to fresh, and partially dolomitized with dolomite crystals as matrix and along laminations and bedding. Stylolites, trace chert nodules (reddish-brown), healed fractures with calcite/dolomite throughout, trace to few dolomite and calcite filled pits and vugs (separate/non-touching, few open with calcite/dolomite lining), and trace scattered quartz sand grains, and weak to strong HCl reaction are observed.

The Newala Formation was not fully penetrated during the drilling investigation, and its thickness at the CRN Site is not known, but is regionally estimated to be 900–1200 ft (Reference 2.5.1-97). The discomformable and irregular contact between the Newalla and the overlying Blackford Formation is generally indistinctive in the downhole geophysical data with two exceptions. The contact between the crystalline dolomite of the Newala Formation and the micritic limestone of the lower Blackford Formation shows a decrease in the lower Blackford natural gamma signature relative to the Newala Formation in borehole MP-426. Conversely, electrical conductivity shows a marked increase in the lower Blackford in MP-426. Borehole MP-201 shows an increase in the natural gamma and electrical conductivity signature strengths in the upper Blackford Formation micritic limestone above its contact with the Newala Formation crystalline dolomite (Reference 2.5.1-214).

Two Newala Member samples logged in the field as fine- to coarse-grained crystalline dolomite taken approximately 79.0 and 216.5 ft below ground surface from borehole MP-401 were analyzed for carbonate content. These tests yielded 77 percent and 90 percent calcite equivalent, respectively (Reference 2.5.1-214).

Chickamauga Group

Bedrock stratigraphic units of the Middle and Upper Ordovician Chickamauga Group are well researched and understood (Reference 2.5.1-9, 2.5.1-110, 2.5.1-215, and 2.5.1-216). Lithologically diverse and variable, the Chickamauga Group consists mainly of interbedded limestone and siltstone lithofacies. Subdivisions of the Chickamauga Group into the stratigraphic units at the CRN Site follow closely the lithologic descriptions used by Lee and Ketelle (Reference 2.5.1-110) and the nomenclature established by Hatcher et al. (Reference 2.5.1-9). The Chickamauga Group represents deposition on the regionally extensive disconformity at the top of the Knox Group (Reference 2.5.1-9).

Chickamauga Group – Blackford Formation

The Blackford Formation is distinguished on the boring logs as Lower and Upper Blackford. The Lower Blackford, sometimes referred to as the Five Oaks Formation, is only observed in the northern portion of the CRN Site. Average true thickness of the Blackford Formation at the CRN Site is approximately 213 ft (Table 2.5.1-3).

Above its disconformable contact with the Newalla Formation of the Knox Group, the lower facies of the Lower Blackford formation is logged as greenish gray to dark greenish gray to very dark gray, grading to reddish black and dark gray, locally mottled dolomitic limestone (micrite). It is strong, occasionally oolitic, moderately to thickly bedded, fresh, and stylolitic. Trace dolomite-filled pits and weak HCl reaction are also observed. A few coarse sand to fine gravel-sized angular chert fragments and trace subrounded clasts of dolomite and crystalline dolomite are also observed. These chert and dolomite clasts are presumably rip-up clasts derived from the underlying Newala Formation (Reference 2.5.1-9). Laboratory and petrographic analyses were not performed on the Lower Blackford Formation. The upper facies of the Lower Blackford Formation is logged as a dark gray to gray, strong, micritic limestone. It is laminated to moderately bedded, fresh, argillaceous, and demonstrates repeating fining upward sequences with some disturbed bedding. It exhibits a slightly nodular appearance, slight bioturbation, and is interbedded with few, very thin to moderately bedded chert lenses and nodules (reddish brown, very dusky red, and reddish black to gray and very dark gray, a few with red jasper specks). Trace calcite-filled pits and strong HCl reaction are observed.

The Upper Blackford is described as a gray, calcareous siltstone, laminated to moderately bedded, interbedded with little to some limestone with few to little chert beds, lenses and nodules. The calcareous siltstone is logged as black to reddish black to very dusky red to very dark greenish gray, locally mottled with dark gray to dark greenish gray, medium strong to strong, and laminated to moderately bedded and fresh. The Upper Blackford siltstone contains a few to little laminated to moderately interbedded, strong limestones (micrite/ wackestone/ packstone). The interbeds are locally nodular, gray to greenish gray, and dark gray to very dark gray containing a trace to little, very thin to thin jasperoidal chert beds, lenses and nodules (variegated, dark gray to black, brown, olive, orange, and very dusky red, with calcite filled tensional fractures). The interbeds are moderately- to strongly-bioturbated with vertical and horizontal burrows and contain trace calcite filled pits and separate calcite lined (open) vugs. The limestone often exhibits calcite-healed tensional fractures oriented orthogonal to bedding. Strong HCL reactions are noted. Where the lower Blackford Formation is absent and the Upper Blackford Formation directly overlies the Newalla Formation, the basal few feet of the Upper Blackford Formation typically consists of gray to dark greenish-gray micritic limestone and

greenish-gray to dark reddish-brown chert with red specks of jasperoidal chert throughout. Small rip-up clasts of dolomite are also noted. Where the Lower Blackford Formation is present, a transitional 10 to 15 ft thick light gray micritic limestone is typically observed at the base of the Upper Blackford Formation. It is described as strong, very thinly to moderately bedded, fresh, interbedded with few to little laminated to moderately bedded calcareous siltstone, and few very thin to moderately bedded chert lenses and nodules (variegated gray to black, dark brown, dark red, dark grayish-brown, dark reddish-brown, reddish-black and dark olive-gray, most with red jasper specks, and fractured). Slight bioturbation, trace calcite filled pits, and strong HCl reaction are also observed.

A single sample logged in the field as calcareous siltstone and taken approximately 23.5 ft below the top (true depth) of the Upper Blackford Formation from borehole MP-202 was submitted to the laboratory for petrographic examination, X-ray diffraction and thermogravimetric analyses. Results of the petrographic examination are summarized in Table 2.5.1-5. Results of the thermogravimetric analysis indicate the Upper Blackford Formation averages 64.09 weight percent calcium carbonate and 28.26 mass percent insoluble residue. The X-ray diffraction results indicate the major insoluble residue fraction consists of quartz, and the minor fractions consist of muscovite and albite. A second sample logged in the field as calcareous siltstone and taken approximately 69 ft below the top (true depth) of the Upper Blackford Formation from borehole MP-202 was analyzed for carbonate content using ASTM D-4373. This test yielded 39 percent calcite equivalent, indicative of significant calcium carbonate content variability in the Upper Blackford (Reference 2.5.1-214).

The contact between the Upper Blackford Formation and the overlying Eidson Member of the Lincolnshire Formation is recognized by strong positive natural gamma and conductivity signatures in the Blackford Formation relative to the Eidson Member of the Lincolnshire Formation (Reference 2.5.1-214).

Chickamauga Group – Eidson Member of the Lincolnshire Formation

The lower member of the Lincolnshire Formation, the Eidson Member, is described on the boring logs as a gray, medium strong and strong, laminated to thinly bedded, fresh, argillaceous, micritic limestone. The geologic map includes the Eidson Member as part of the Blackford Formation (Figure 2.5.1-29). It exhibits little to some, laminated to thinly interbedded, greenish black to black and very dark gray calcareous siltstone and few, very thin chert lenses and nodules (dark gray to black with calcite-healed tensional fractures orthogonal to bedding). Trace calcite filled pits, sparry calcite "bird's eyes," and stylolites are observed. It is locally fossiliferous with weak to moderate bioturbation and a strong HCl reaction. Average true thickness of the Eidson Member at the CRN Site is approximately 86 ft (Table 2.5.1-3).

Three distinctive marker beds occur within the Eidson Member in all borings at the CRN Site. The marker beds are described here as measured from the distinctive contact between the Eidson Member and the overlying Fleanor Member. Immediately below the contact with the overlying Fleanor Member, 1 to 3 ft of mostly nodular, dark gray, medium strong, very thinly bedded micritic limestone is observed. Consistently occurring approximately 34 ft below the top of the Eidson Member is a second marker bed consisting of 1 to 3 ft of fossiliferous, strongly bioturbated dark gray to very dark gray, limestone (wackestone/packstone). The coarse vertical and horizontal burrows are filled with sparry calcite and calcite. The third marker bed, approximately 55 to 70 ft below the top of the Eidson Member, consists of a zone 5 to 15 ft of light gray to gray micritic limestone exhibiting intense deformation with calcite mineralization (see Subsection 2.5.3.2.2 for further discussion).

A single sample logged in the field as micritic limestone taken approximately 53.5 ft below the top (true depth) of the Eidson Member from borehole MP-202 was submitted to the laboratory for

petrographic examination, X-ray diffraction and thermogravimetric analyses. Results of the petrographic examination are summarized in Table 2.5.1-5. Results of the thermogravimetric analysis indicate the Eidson Member micritic limestone sample consists of 67.42 weight percent calcium carbonate and averaged 28.47 mass percent insoluble residue. X-ray diffraction results indicate the major insoluble residue fractions consists of quartz, with no minor constituents noted. Two Eidson Member samples logged in the field as micritic limestone taken approximately 28 ft and 41 ft below the top (true depth) of the Eidson Member from borehole MP-202 were analyzed for carbonate content using ASTM D-4373. These tests yielded 51 percent and 54 percent calcite equivalent, respectively (Reference 2.5.1-214).

Moving from the micritic limestones of the Eidson Member to the calcareous siltstones of the overlying Fleanor Member, the lithologic contact is recognized by strong positive natural gamma and conductivity signatures in the Fleanor Member relative to the Eidson Member (Reference 2.5.1-214).

Chickamauga Group – Fleanor Member of the Lincolnshire Formation

The Fleanor Member is described on the boring logs as a dusky red to very dusky red, medium strong, laminated to moderately bedded calcareous siltstone with few to little dark gray to very dark gray micritic limestone interbeds and strong HCl reaction. The interbeds are bioturbated with trace calcite filled pits and burrows. The basal 10 ft of the Fleanor Member consistently exhibits a sharp gradation to a dark greenish gray to dark grayish olive calcareous siltstone with the same lithology as described above. Similarly, the top 12 to 23 ft of the Fleanor Member is dark gray to very dark gray to greenish black, slight to moderately bioturbated, calcareous siltstone gradually grading to the dusky red calcareous siltstone that makes up the majority of the Fleanor Member. Average true thickness of the Fleanor Member at the CRN Site is approximately 216 ft (Table 2.5.1-3).

A single sample logged in the field as calcareous siltstone and taken approximately 132 ft above the base (true depth) of the Fleanor Member from borehole MP-202 was submitted to the laboratory for petrographic examination, X-ray diffraction and thermogravimetric analyses. Results of the petrographic examination are summarized in Table 2.5.1-5. Results of the thermogravimetric analysis indicate the Fleanor Member calcareous siltstone sample yielded 42.21 weight percent calcium carbonate and averaged 50.49 mass percent insoluble residue. X-ray diffraction results indicate the major insoluble residue fractions consist of quartz, with the minor constituents consisting of muscovite. A total of three Fleanor Member samples logged in the field as calcareous siltstone taken from borehole MP-202 were analyzed for carbonate content using ASTM D-4373. These tests yielded an average of 32 percent calcite equivalent (Reference 2.5.1-214). One sample of a Fleanor Member micritic limestone interbed from borehole MP-101 yielded 45 percent calcite equivalent (Reference 2.5.1-214).

The natural gamma signature at the contact between the Fleanor Member and the overlying Rockdell Formation is pronounced. The signature is relatively constant; moving upward through the dusky red calcareous siltstones until the dark gray to greenish-black calcareous siltstones at the top of the Fleanor Member are encountered. At this contact, the natural gamma signature steadily decreases until the contact with Rockdell Formation limestones is encountered. At this contact, a pronounced positive kick followed by higher natural gamma signatures relative to the dark gray to greenish black calcareous siltstones at the top of the Fleanor Member is observed in the basal Rockdell Formation (Reference 2.5.1-214).

Chickamauga Group – Rockdell Formation

The Rockdell Formation is predominantly a gray micritic limestone, very thinly- to moderately-bedded, interbedded with few to little calcareous siltstone, trace chert beds, lenses

and nodules, stylolites, fossils and sparry calcite “bird’s eyes.” It is interbedded with thicker (>5 ft thick) calcareous siltstone units. The Rockdell Formation is divided into a lower and upper unit corresponding to Unit C and D of Stockdale (Reference 2.5.1-109) and Lee and Ketelle (Reference 2.5.1-110). Average true thickness of the Rockdell Formation at the CRN Site is approximately 241 ft (Table 2.5.1-3).

Lying above the Fleanor Member of the Lincolnshire Formation, Unit C of the Rockdell Formation is described on the boring logs as a gray to bluish-gray to very dark gray, strong, very thinly to moderately bedded limestone (micrite/ wackestone/ grainstone). It is logged as fresh, with few to little, laminated to very thin and thin, wavy and irregular, shaly, very dark gray to black calcareous siltstone interbeds and trace thin chert beds and nodules. It exhibits a strong HCl reaction and locally exhibits trace fossils, calcite filled pits and vugs/bioturbation.

The contact between the Rockdell Formation Unit C and overlying Unit D is defined as the top of an 11 to 32 ft thick calcareous siltstone in the top of Rockdell Formation Unit C. This siltstone is logged as a black to greenish-black to very dark gray, strong, laminated to very thinly-bedded, fresh, calcareous siltstone. It is interbedded with trace to some, laminated to very thin dark gray micritic limestone. A trace very thin chert beds, lenses, and nodules (dark gray to black) and strong HCl reaction is also observed. The frequency of the limestone interbeds increases with depth.

Unit D of the Rockdell Formation is described on the boring logs as a light brownish gray grading upwards to gray to bluish gray to dark gray, strong, laminated to moderately bedded, fresh, locally argillaceous, predominantly micritic limestone. It is interbedded with few to little laminated to very thin, wispy/irregular and diffuse very dark gray to greenish gray and locally dusky red calcareous siltstone. Trace to few very thin to thin chert beds, lenses, and irregular nodules (light gray to dark gray with calcite healed fracturing) and trace calcite filled pits, burrows and strong HCl reaction are also observed. An approximately 3.0 to 6.0 ft thick very dark gray to greenish-black laminated to very thinly-bedded calcareous siltstone is observed approximately 55 ft below the top of Rockdell Formation Unit D.

A single sample logged in the field as micritic limestone and taken approximately 120 ft below the top of Rockdell Formation Unit D (true depth) from borehole MP-101 was submitted to the laboratory for petrographic examination, X-ray diffraction and thermogravimetric analyses. Results of the petrographic examination are summarized in Table 2.5.1-5. Results of the thermogravimetric analysis indicate the Rockdell Formation Unit D micritic limestone sample yielded 94.48 weight percent calcium carbonate and averaged 2.78 mass percent insoluble residue. X-ray diffraction results indicate the major insoluble residue fractions consist of quartz, with the minor constituent consisting of muscovite. A total of three Rockdell Formation Unit D limestone samples taken from borehole MP-101 were analyzed for carbonate content using ASTM D-4373. These tests yielded results of 45, 62 and 75 percent calcite equivalent (Reference 2.5.1-214). One sample of a Rockdell Formation Unit C micritic limestone from borehole MP-101 yielded 48 percent calcite equivalent (Reference 2.5.1-214).

The natural gamma and conductivity signatures at the contact between the Rockdell Formation and overlying Benbolt Formation are very pronounced. It is recognized by very strong positive natural gamma and conductivity kicks when moving from the Rockdell Formation to the Benbolt Formation (Reference 2.5.1-214).

Chickamauga Group – Benbolt Formation

The Benbolt Formation is a gray limestone, very thinly to moderately bedded, interbedded with few to little shaly calcareous siltstone interbeds, and is locally fossiliferous. It is described on the boring logs as a gray and bluish-gray to dark bluish-gray, strong, very thinly- to thinly-bedded,

locally moderately bedded and nodular limestone (micrite/wackestone). Bedding is roughly planar to wavy becoming wispy/irregular and diffuse with depth. Trace stylolites, trace pyrite replacing fossils, trace calcite filled pits and vugs (separate/non-touching) and strong HCl reaction are observed. Few very thin chert beds, lenses, and nodules (dark gray to black, with calcite filled tensional fractures orthogonal to bedding) are also noted. It is interbedded with little to some laminated to thin, dark gray to very dark gray calcareous siltstone. Average true thickness of the Benbolt Formation is approximately 277 ft (Table 2.5.1-3).

Two distinct relatively thick (>5 ft) calcareous siltstone interbeds are observed in all borings that penetrate the lower portion of the Benbolt Formation. The lowermost interbed is consistently 18.0 to 21.5 ft thick, and on average, its base is observed to lie approximately 16.0 ft above the base of the Benbolt Formation. It is logged as a very dark greenish-gray to greenish-black, laminated to thinly-bedded calcareous siltstone. It is weak to medium strong with moderately bedded appearance and is interbedded with few to little, locally to some, laminated to thin, gray to dark gray micritic limestone.

The upper interbed is consistently 5.9 to 6.8 ft thick and on average the base is observed to lie approximately 44.0 ft above the base of the Benbolt Formation. It is logged as a dark gray to very dark greenish gray, medium strong to strong, laminated to thinly-bedded calcareous siltstone. It is interbedded with little to some laminated to thin gray micritic limestone.

A single sample logged in the field as micritic limestone and taken approximately 79 ft above the base of the Benbolt Formation (true depth) from borehole MP-101 was submitted to the laboratory for petrographic examination, X-ray diffraction and thermogravimetric analyses. Results of the petrographic examination are summarized in Table 2.5.1-5. Results of the thermogravimetric analysis indicate the Benbolt micritic limestone sample yielded 79.93 weight percent calcium carbonate and averaged 16.04 mass percent insoluble residue. X-ray diffraction results indicate the major insoluble residue fractions consist of quartz, with the minor constituents consisting of muscovite and pyrite. A sample logged in the field as calcareous siltstone and taken approximately 35.5 ft above the base (true depth) of the Benbolt Formation from borehole MP-101 was analyzed for carbonate content using ASTM D-4373. This test yielded 27 percent calcite equivalent (Reference 2.5.1-214).

The natural gamma and conductivity signatures at the contact between the Benbolt Formation and overlying Bowen Formation are very pronounced. It is recognized by very strong positive natural gamma and conductivity kicks when moving from the Benbolt Formation to the Bowen Formation followed by elevated responses in the Bowen Formation relative to the Benbolt (Reference 2.5.1-214).

Chickamauga Group – Bowen Formation

The Bowen Formation is a maroon calcareous siltstone overlying the Benbolt Formation. Because of its limited thickness and its distinctive color, Hatcher et al. Reference 2.5.1-9 (1992) describes it as a reliable marker for field and subsurface correlations. A total of only 40.5 ft of Bowen Formation was encountered in two boreholes during the CRN Site subsurface investigation drilling program, and site-specific lithologic information is relatively limited. It is described on the boring logs as a reddish-brown to olive-brown and dark grayish-green, weak to medium-strong, laminated to very thinly-bedded calcareous siltstone. Where encountered, it is slightly weathered, locally highly to moderately weathered, locally bioturbated, and interbedded with some laminated to thinly-bedded light gray micritic limestone.

The upper section of the Bowen Formation is not present at the CRN Site, so its actual thickness is not known. Lee and Ketelle (Reference 2.5.1-110) report a thickness of 21 ft for Unit F, which is equivalent to the Bowen Formation at the ORNL in Bethel Valley (Table 2.5.1-1). Hatcher et al.

Reference 2.5.1-9 (1992) report a thickness of 5 to 10 m (16.4 to 32.8 ft) for the Bowen Formation in Bethel Valley.

Three calcareous siltstone samples were submitted to the laboratory for carbonate content analyses. These tests yielded results of 26, 57 and 88 percent calcite equivalent (Reference 2.5.1-214).

Chickamauga Group – Witten Formation

The Witten Formation was not encountered during the CRN Site subsurface investigation drilling program (Figure 2.5.1-30); therefore, lithologic descriptions from Lee and Ketelle (Reference 2.5.1-110) and Hatcher et al. (Reference 2.5.1-9) are summarized here.

According to Lee and Ketelle (Reference 2.5.1-110), Unit G (equivalent to the Witten Formation) is a variable unit consisting of 319 ft of nodular limestone, calcarenite, thin-bedded limestone and siltstone, and wavy interbedded limestones. They differentiate Unit G into three lithologies. The lower 116 ft of Unit G is described as a light gray, fine to- medium-grained, fossiliferous nodular limestone grading upward to ribbon limestone. The middle 68 ft is defined as a light gray, fine grained, calcarenite which is less fossiliferous than the underlying section. The upper 135 ft of Unit G consists of slightly laminated, interbedded dark gray siltstone and light gray limestone grading upward to light gray, fine to medium grained nodular and ribbon limestone. Lee and Ketelle (Reference 2.5.1-110) indicate that the contact with the overlying Unit H, equivalent to the Moccasin Formation (Table 2.5.1-1), is indistinct and gradational. They place it at a point where siltstone content slightly increases and a pale maroon coloration is noted. Both Lee and Ketelle (Reference 2.5.1-110) and Hatcher et al. (Reference 2.5.1-9) note the similarity in lithology between the lower Witten Formation (Unit G) and upper Benbolt Formation (Unit E). Lee and Ketelle (Reference 2.5.1-110) suggest that the intervening Unit F (Bowen Formation) represents a minor interruption in a generally continuous paleodepositional setting. Hatcher et al. (Reference 2.5.1-9) suggest the Witten Formation and Benbolt might otherwise be mapped together if not for the presence of the intervening maroon Bowen Formation.

Chickamauga Group – Moccasin Formation

The Moccasin Formation was largely removed from the CRN Site by stratigraphic displacement on the Copper Creek fault and is not fully represented in Bethel Valley (Reference 2.5.1-9). It was encountered below the Copper Creek fault in two CRN subsurface investigation boreholes (CC-B1 and CC-B2). It is described on the boring logs as a dark greenish-gray to gray to bluish-gray, medium strong to strong, laminated to moderately bedded, slightly-weathered to fresh, argillaceous, micritic limestone. It is interbedded with some dark reddish-gray to dark greenish-gray, laminated to very thin, clayey calcareous siltstone. Moderate to strong bioturbation, trace calcite filled pits and vugs, trace very thin chert lenses (gray to dark gray), and strong HCl reactions are also observed. The base of the Moccasin Formation was not encountered, therefore, its thickness at the CRN Site is not known.

2.5.1.2.3.4 Karst Evaluation

Data review

A review of the cavity data from the CRN and CRBRP Site drilling programs reveal several trends illustrated in Figures 2.5.1-75 through 2.5.1-77. The data are segregated by geologic formation to assess the likelihood of the presence of cavities, as well as to estimate cavity size within each geologic unit. Each data plot presents the cavity center-point elevation versus cavity length within the borehole. For this analysis, karst cavity data were partitioned into three elevation intervals. Intervals were as follows: (1) above the CRN Site proposed plant grade of elevation 821 ft

NAVD88; (2) between elevations 821 ft NAVD88 and 740 ft NAVD88, the shallowest embedment depth considered and also the Watts Bar Reservoir pool elevation; and (3) lower than elevation 740 ft NAVD88. A comparison of the compiled borehole data shows that the majority of cavities: (1) occur above the elevation 740 ft NAVD88 pool elevation of the Watts Bar Reservoir, and (2) are less than 2 ft in height. The Eidson and Rockdell units show the largest and greatest frequency of cavities. The largest cavity encountered in any borehole has a height of 16.5 ft and occurs at elevation 789 ft NAVD88.

The cavities that occur below the current Watts Bar Reservoir elevation of 740 ft NAVD88, which is the current Watts Bar Reservoir elevation as well as the shallowest embedment depth considered in this investigation, are assumed to reflect dominantly phreatic development below the water table. Cavities in the vadose zone, the area above the water table, may be related to either vadose processes only, or vadose dissolution overprinted on originally phreatic cavities. The relative amount of dissolution attributed to vadose versus phreatic processes in the latter case cannot be determined or quantified from borehole data.

Based on the compiled borehole data, the highest frequency and largest size of cavities occur within the Rockdell and the Eidson units (Table 2.5.1-19, Figure 2.5.1-51). These two units also contain the greatest thicknesses of pure limestone beds relative to other Chickamauga Group strata encountered at the site. More detail regarding the variability of carbonate content by stratigraphic unit is demonstrated in the geophysical logs for these units (Reference 2.5.1-214). Natural gamma radiation increases with the proportion of silt and clay in the formation and the alternating high and low levels reflect the locations of siltstone and limestone beds, respectively (Figure 2.5.1-78; Reference 2.5.1-9). Additionally, carbonate contents were determined from rock core samples during the CRN subsurface investigation (Figure 2.5.1-49). These methods demonstrate the variability of carbonate content both between and within the stratigraphic units at the CRN Site.

The spatial distribution of cavities is consistent with the trends discussed above. A map of boreholes indicating the presence and elevation interval of cavities is presented in Figure 2.5.1-79. Several boreholes within the Rockdell Formation in the south-center of the power block area exhibit cavities in the middle and lower elevation intervals. The boreholes and cavities occur along strike with bedding. However, elevations of individual cavities within this cluster do not appear to correlate directly. Boreholes B-144 and B-145, spaced approximately 33 ft apart, have cavities at elevation 781 ft NAVD88, although connectivity between cavities is uncertain.

Conduit Shape

Karst cavity shapes can vary widely, but their morphology is determined by several basic principles. The three dimensional shape of any cavity is governed by its environment of formation, hydrogeologic setting, and rock characteristics. For example, dissolution within the vadose zone, where water is moving downward toward the water table, tends to create slots, shafts, canyons, and passages oriented down dip or following steep joint planes (Reference 2.5.1-305). By contrast, dissolution within the phreatic zone, where water is moving at and below the water table following the hydraulic gradient, tends to create an integrated conduit system with subhorizontal tubular passages that tend to be circular, the most efficient shape for transmittal of water (Reference 2.5.1-305).

The common phreatic tube shape can be modified by factors such as variations in rock solubility, bed thickness, structural discontinuities, geometry of the fracture pathway where dissolution initiated, and the degree to which the initial fractures have been enlarged (Reference 2.5.1-305). The conduit system follows available fractures in response to the hydraulic gradient and may descend or ascend as needed to respond to that gradient, while at the same time following the

more open or connected fractures. The resulting pathway enlarges by dissolution, tending toward a circular cross section as dissolution proceeds assuming uniform solubility of the rock.

2.5.1.2.3.5 Unconsolidated Soils/Fill/Terraces

Residual soils and backfill encountered in the CRN Site subsurface investigation boreholes are discussed in Subsection 2.5.4.

The characteristics of Quaternary terrace deposits are described in Subsection 2.5.3.

2.5.1.2.4 Local Structural Geology

The structural geology at the CRN Site is a direct function of its position in the Appalachian orogenic system (see Subsections 2.5.1.1.2 and 2.5.1.2.2). The site is located within the foreland fold-thrust belt, which is a structural feature common to orogenic systems worldwide (e.g., Reference 2.5.1-217). Foreland fold-thrust belts are generally characterized by the following attributes: (1) thin-skinned deformation that is taken up largely above a detachment horizon, usually crystalline basement; (2) imbricate thrust faults that propagate from a weak basal layer; (3) an initial wedge geometry that is maintained throughout deformation; and (4) plastic behavior of the entire wedge as a whole (Reference 2.5.1-218). In general, timing of deformation within a foreland fold-thrust belt is progressively younger toward the foreland (exterior part of the orogen), while intensity of deformation is greater toward the hinterland (interior part of the orogen). Faults in a foreland fold-thrust belt propagate through mechanically weak layers at significantly lower angles than through mechanically stronger units, which results in the characteristic ramp-flat geometry.

The Neoproterozoic through late Paleozoic sedimentary package along the eastern Laurentian margin comprises an eastward-thickening wedge that was deposited along a passive oceanic margin directly on southeast-dipping Proterozoic basement (Figure 2.5.1-32). This wedge was telescoped onto the Laurentian margin during the late Paleozoic Alleghanian orogeny, which involved the rotational transpressive collision of Gondwana with Laurentia, resulting in a head-on collision at the latitude of eastern Tennessee (Reference 2.5.1-73; see Figure 2.5.1-12). As this collision ensued, the master Appalachian detachment formed at the brittle-ductile transition toward the hinterland, propagated upward into the relatively weaker Chilhowee Group, and as deformation progressed toward the foreland, propagated up-section into the Rome Formation (e.g., Reference 2.5.1-102) (Figure 2.5.1-32). Throughout the southern Appalachian Valley and Ridge province, the Rome Formation acted as the weak basal layer that the master Appalachian detachment propagated through (e.g., Reference 2.5.1-219). All major Valley and Ridge faults mapped at the ground surface initially propagated from this basal detachment during the Alleghanian orogeny, which is supported by detailed geologic mapping, structural analysis, deep drill core data, and interpretation of seismic reflection data (e.g., References 2.5.1-102, 2.5.1-177, and 2.5.1-220). Therefore, any discussion of the local structural geology at the CRN Site is dependent on an understanding of the overall tectonic development of the Valley and Ridge province.

2.5.1.2.4.1 Macroscopic Structures within the Site Vicinity (25 Mile Radius)

2.5.1.2.4.1.1 Folds

Macroscale folds in the CRN site vicinity are open, upright to overturned kilometer-scale synclines and anticlines with axes that trend parallel to major faults and the strike of lithologic units (References 2.5.1-9, 2.5.1-16, 2.5.1-105, 2.5.1-97, and 2.5.1-216) (Plate 1, included in Part 8 of the application). Fold axes can generally be traced for 0.5 to more than 7 mi throughout the site vicinity, although macroscopic Valley and Ridge folds can locally be traced over much greater

distances. Fold axes are normal to the inferred shortening direction, which supports timing of folding coincident with Alleghanian emplacement of Valley and Ridge thrust sheets (e.g., Reference 2.5.1-221).

2.5.1.2.4.1.2 Faults

The vast majority of faults within the CRN site vicinity can be characterized as bedding-parallel thrusts that formed during thin-skinned deformation of the Appalachian foreland (Reference 2.5.1-222) (see Subsections 2.5.1.1.2 and 2.5.1.2.2; Plate 1, included in Part 8 of the application). The tectonic history of the region, including deformation of late Paleozoic siliciclastic strata, indicates that Valley and Ridge province faults and folds were active during the late stages of the Alleghanian orogeny (e.g., Reference 2.5.1-128). Numerous radiometric age determinations of features associated with deformation and shortening in the Valley and Ridge agree with this timing, and range from 265-290 Ma (e.g., References 2.5.1-75, 2.5.1-100, 2.5.1-168, 2.5.1-223, 2.5.1-224, 2.5.1-225, and 2.5.1-226). Recent $^{39}Ar/^{40}Ar$ analyses of fault gouge illite from several Valley and Ridge faults suggest emplacement occurred 276-280 Ma (Reference 2.5.1-144).

Approximately 11 imbricate thrust sheets comprise the foreland fold-thrust belt at the latitude of the site vicinity, which are soled by several regional-scale master faults (Rome-Saltville, Copper Creek, White Oak Mountain-Clinchport-Hunter Valley-Wallen Valley, Pulaski) (Figures 2.5.1-27 and 2.5.1-33). The faults generally strike northeast, dip toward the southeast, and cumulatively represent greater than 120 km (75 mi) of shortening that occurred during the Alleghanian orogeny (Reference 2.5.1-102 and 2.5.1-223). These thrust sheets contain no basement rocks and are largely unmetamorphosed, unlike Blue Ridge rocks to the east (Reference 2.5.1-75). The geometry, amount of displacement, and timing of individual faults that occur in the site vicinity are discussed below. Where appropriate, genetically related subordinate faults are grouped for discussion.

2.5.1.2.4.1.2.1 Emory River and Bitter Creek Faults

The Bitter Creek and Emory River faults are exposed southwest of the Wartburg basin in the Cumberland Plateau (Figure 2.5.1-27). The Emory River fault strikes notably northwest-southeast and is an oblique strike-slip tear fault that accommodated differential displacement between sections of the northwest-directed thrust belt (References 2.5.1-227 and 2.5.1-228). Tear faults are strike-slip faults that form along the edges of thrust sheets, and are common geologic structures in foreland fold-thrust belts (Reference 2.5.1-280). An analogous and well-studied tear fault in the southern Appalachian foreland fold-thrust belt to the Emory River and Bitter Creek faults is the northwest-striking, late Paleozoic Jacksboro fault. The Jacksboro tear fault is a strike-slip fault that resulted from late Paleozoic thrusting of the Pine Mountain fault (Reference 2.5.1-229 and 2.5.1-281).

A maximum throw of 150 m (492 ft) was estimated on the Emory River fault (Reference 2.5.1-227). The related Bitter Creek fault is a short fault with presumed strike-slip displacement. These faults truncate strata as young as Pennsylvanian (Reference 2.5.1-227), which provides a maximum age of deformation along these structures. Although there are no well-defined constraints that would bracket a minimum age on these specific faults, their geometry and kinematics indicate they are tear faults related to late Paleozoic northwest-directed thrust faulting, similar to the late Paleozoic, Jacksboro tear fault (see 2.5.1-227, 2.5.1-229, and 2.5.1-281).

2.5.1.2.4.1.2.2 Rockwood, Harriman, and Chattanooga Faults

The Chattanooga fault and two associated splay faults (the Rockwood and Harriman faults) yield a complex map pattern in the northwestern portion of the CRN site vicinity (Reference 2.5.1-105) (Figure 2.5.1-27). The Chattanooga fault is a thrust that carries Rome Formation rocks in its hanging wall and soles into the basal detachment (Figure 2.5.1-33). This fault is exposed approximately 7 mi northwest of the site. The minimum estimate of displacement on this structure is 20 km (12.4 mi), based on palinspastic restoration of balanced Valley and Ridge cross-sections (References 2.5.1-102 and 2.5.1-230).

Based on map patterns, structural analysis, and balanced geologic cross-sections, the Rockwood fault is a low-angle footwall-splay of the Chattanooga fault that is exposed northwest of the main trace of the Chattanooga fault, and includes several klippen and windows along its extent (References 2.5.1-141, 2.5.1-230, and 2.5.1-231) (Figure 2.5.1-27). The fault dips a maximum of 30 degrees southeast where it is exposed at the surface, and flattens to essentially horizontal in seismic reflection data at a depth of 60–120 m (200–390 ft) (Reference 2.5.1-231). A minimum displacement estimate for this fault derived from palinspastic restoration of balanced geologic cross-sections is 7 km (4.3 mi), and it may be associated with a triangle zone (an area where blind faults that dip toward the foreland and hinterland form the core of an anticline) at depth (References 2.5.1-230 and 2.5.1-232). The Harriman fault is a minor low-angle splay off of the Rockwood fault, and occurs between the traces of the Rockwood and Chattanooga faults. Northeast of the site vicinity, the Chattanooga fault may transfer displacement to the Pine Mountain thrust via the strike-slip Jacksboro tear fault (Figure 2.5.1-33, Sheet 2) (Reference 2.5.1-141).

2.5.1.2.4.1.2.3 Kingston Fault

The Kingston thrust fault occurs between the Chattanooga and White Oak Mountain faults through eastern Tennessee (e.g., References 2.5.1-102 and 2.5.1-230) (Figures 2.5.1-27 and 2.5.1-33). This thrust is detached in the Cambrian Rome Formation in the southeast and Pennsylvanian rocks to the northwest, reflecting the regional pattern of detachment horizons that step-up stratigraphically to the northwest (Reference 2.5.1-75). A branch of the Kingston fault crosscuts the Chattanooga fault southwest of the site, (near the Georgia-Tennessee border), which indicates the Kingston fault is slightly younger than the Chattanooga fault (Reference 2.5.1-233).

2.5.1.2.4.1.2.4 Beaver Valley Fault

The Beaver Valley fault is at its closest approach approximately 5 mi southeast of the CRN Site. This fault thrusts Cambrian Rome Formation rocks northwestward over Lower and Middle Ordovician rocks (Figure 2.5.1-33) (Reference 2.5.1-234). Bedding in the hanging wall dips southeast between 35 and 70 degrees. Based on its structural attributes, timing of deformation on this structure is late Paleozoic, similar to other major Valley and Ridge thrust faults (Reference 2.5.1-234). The Beaver Valley fault has an estimated minimum displacement of 10 km (6.2 mi) based on restoration of balanced cross-sections (Reference 2.5.1-230). To the southwest, this fault merges with the Saltville and Knoxville faults to form the Rome thrust, which continues into Georgia (Reference 2.5.1-230).

2.5.1.2.4.1.2.5 Saltville Fault

The Saltville fault is major structure that is traceable from Georgia to Virginia (Reference 2.5.1-141). In most of the CRN site vicinity, this fault places Cambrian Rome formation over Ordovician Knox Group rocks in a flat-on-flat geometry. In some locations this structure is associated with gouge, breccia, and cataclasite, which is somewhat rare for Valley

and Ridge thrust faults, and may indicate some reactivation (Reference 2.5.1-141). Through northeastern Tennessee and southwestern Virginia, displacement estimates for the Saltville fault are generally greater than 100 km (62 mi) (References 2.5.1-102 and 2.5.1-230). Near Knoxville, the displacement on the Saltville fault decreases significantly, and slip appears to be transferred to the Beaver Valley fault to the southwest in a classic foreland fold-thrust belt transfer zone (Reference 2.5.1-141). In a foreland fold-thrust belt transfer zone, slip can only be transferred between two faults if they are both rooted in the same detachment (Reference 2.5.1-235). Hnat and van der Pluijm (Reference 2.5.1-144) reported an absolute age of 354 ± 10 Ma for the Saltville fault based on $^{40}Ar/^{39}Ar$ analysis of fault gouge illite, although the authors noted that this age cannot correspond to latest activity on the fault because the fault cuts Mississippian strata that are considerably younger.

2.5.1.2.4.1.2.6 Knoxville Fault

The Knoxville fault is located 17 km (10.5 mi) southeast of the CRN Site (Figure 2.5.1-27). This northwest-vergent thrust juxtaposes Cambrian Copper Ridge Dolomite over Middle Ordovician Chickamauga group rocks in the Saltville thrust sheet (Figure 2.5.1-33) (Reference 2.5.1-236). Structural analyses and palinspastic restoration of balanced cross-sections indicate a minimum of 10 km (6.2 mi) of displacement within the site vicinity (References 2.5.1-102; and 2.5.1-230). Timing of deformation on this structure is likely Pennsylvanian or Permian, similar to other Appalachian foreland fold-thrust belt structures (Reference 2.5.1-236).

2.5.1.2.4.1.2.7 Dumplin Valley, Chestuee and Wildwood Faults

The Dumplin Valley fault is a steeply dipping northwest-vergent thrust fault that soles into the Rome Formation in the site vicinity, although regionally this structure can have a variable geometry at depth (Figure 2.5.1-33) (Reference 2.5.1-141). Throughout the site vicinity, it juxtaposes Cambrian-Ordovician Conasauga Group above Ordovician Knox Group rocks (Figure 2.5.1-27).

The Chestuee fault is located in the footwall of the Dumplin Valley fault and is a relatively low-displacement fault within the suite of thrusts in the Valley and Ridge (Figures 2.5.1-27 and 2.5.1-33). Its displacement diminishes to the southwest toward the Tennessee-Georgia border where it becomes a series of folds in Conasauga group rocks (Reference 2.5.1-230). In some cases, minor faults slightly oblique to the structural grain displace the Chestuee by less than a kilometer (Reference 2.5.1-230). The Dumplin Valley-Chestuee faults are estimated to account for at least 10 km (6.2 mi) of shortening based on restoration of balanced cross-sections (Reference 2.5.1-230).

The Wildwood fault juxtaposes Conasauga group rocks above the Knox group in the hanging wall of the Dumplin Valley fault. Restoration of balanced cross-sections indicates approximately 6 km (3.7 mi) of displacement along the Wildwood fault (References 2.5.1-102, 2.5.1-219, and 2.5.1-230). The Wildwood fault likely contains Rome Formation rocks in the hanging wall at depth, and the Chestuee, Dumplin Valley, and Wildwood faults all likely sole into the Saltville fault approximately 2 km (1.2 mi) below the ground surface (Figure 2.5.1-33) (References 2.5.1-102, 2.5.1-219, and 2.5.1-230).

2.5.1.2.4.2 Macroscopic Structures within the Site Area (5 Mile Radius)

Two major Valley and Ridge thrust faults, the White Oak Mountain and Copper Creek faults, cross through the CRN site area (Figures 2.5.1-34 and 2.5.1-35; Plate 2, included in Part 8 of the application). Additionally, a subordinate small-displacement thrust, the Chestnut Ridge fault, was identified and mapped by Lemiszki et al. (Reference 2.5.1-97).

2.5.1.2.4.2.1 Geophysical Data

Seismic reflection and seismic refraction surveys were conducted at the CRN Site to support the subsurface investigations (Reference 2.5.1-214). The primary objectives of the seismic reflection surveys were to 1) interpret the contact between the Knox Group and overlying Chickamauga Group rocks; 2) interpret the dip of bedding between borehole locations; and 3) identify possible subsurface structures beneath the survey lines. The primary objective of the seismic refraction surveys was to map the depth to bedrock at the site.

2.5.1.2.4.2.1.1 Seismic Reflection Data

Seismic reflection has been a reliable geophysical method for successfully imaging stratigraphy and faults in foreland fold-thrust belts, including the southern Appalachian Valley and Ridge (e.g., References 2.5.1-102 and 2.5.1-316). Hatcher et al. (Reference 2.5.1-102) present numerous balanced geologic cross sections throughout the eastern Tennessee Valley and Ridge Province that rely heavily on seismic reflection data, demonstrating the applicability of this method to delineate the subsurface structural geology in a foreland fold-thrust system. Additionally, Hatcher et al. (Reference 2.5.1-9) present a line drawing of their interpretation of a seismic reflection profile that was acquired along Tennessee Highway 95, approximately 2 mi. northeast of the CRN Site (Figure 2.5.1-83). Hatcher et al. (Reference 2.5.1-9) interpret the Whiteoak Mountain and Copper Creek faults on this profile, based on the mapped locations of the faults relative to the seismic reflection survey line and, for the Whiteoak Mountain fault, strong reflectors in the hanging wall that truncate reflectors in the interpreted footwall (Figure 2.5.1-83). Similar truncations are not visible along the Copper Creek fault in this seismic reflection profile, which is interpreted by Hatcher et al. (Reference 2.5.1-9) to represent parallel bedding above and below the fault (Figure 2.5.1-83, Sheet 2 of 2).

Two seismic reflection surveys, SRL-1 and SRL-2, were conducted at the CRN Site (Reference 2.5.1-214) (also see Subsection 2.5.4.4.2.1). The locations of the seismic reflection survey lines are presented in Figure 2.5.1-29, and the processed P-wave seismic reflection profiles are presented in Figure 2.5.1-36. Data quality decreases on the edges of seismic reflection profiles due to a decrease in data redundancy (fold). Noise contamination, out-of-plane reflectors and spatial aliasing effects are mitigated better in areas with increased fold, due to the statistical effects of signal enhancement associated with increased fold (Reference 2.5.1-214). Noise effects, therefore, are more pronounced at the ends of each line where fold decreases (Reference 2.5.1-214). In Figure 2.5.1-36, orange subvertical lines on the interpreted profiles represent areas where the fold is significantly decreased and the effects of noise contamination do not permit accurate interpretation (Reference 2.5.1-214).

Vertical resolution of seismic reflection data is generally defined as one-quarter of the wavelength (Reference 2.5.1-317). As wavelength is equal to seismic velocity divided by the dominant frequency, the best vertical resolution of seismic reflection profiles SRL-1 and SRL-2 is on the order of approximately 10 m (33 ft), based on assumed seismic compressional wave velocities of 12,500 to 20,000 ft/s (Reference 2.5.1-214) and an assumed signal frequency spectra on the order of 125 Hz. However, wavelength depends on velocities above and below a specific reflector, so a reliable estimate of vertical resolution that covers the entire time sections of both lines is not possible with the current data.

Unmigrated seismic reflection profiles of SRL-1 and SRL-2 (Figure 2.5.1-36, with interpretation and without interpretation) show continuous, moderately southeast-dipping reflectors, which is consistent with geologic observations at the ground surface and from borehole data (Reference 2.5.1-214). The anomalies described below could not be resolved by enhanced stack options, including: spectral whitening; a FX predictive deconvolution enhancement filter; and, finite difference time migration. The survey lines were purposefully extended beyond the area of

the plant site so that migration would not be necessary to obtain the data quality needed beneath the site. In any case, the lengths of the survey lines were constrained by the Clinch River arm of the Watts Bar Reservoir to the south and Chestnut Ridge to the north. Because of these spatial constraints, the survey lines could not have been easily extended to obtain the additional data required to resolve these artifacts. Migration did not add value to the data interpretation in the target area beneath the proposed plant site.

Several anomalies were identified in the seismic reflection profiles; these anomalies are not interpreted to represent geologic features (Figure 2.5.1-36) (Reference 2.5.1-214, Appendix D.2). In SRL-1, three anomalies were encountered (A-1, A-2, and A-3 in Figure 2.5.1-36, Sheet 2). Anomalies A-1 and A-3 represent areas where dip of reflectors changes abruptly near the ends of the line, and are interpreted as artifacts associated with out-of-plane reflectors or spatial aliasing (Figure 2.5.1-36, Sheet 2) (Reference 2.5.1-214, Appendix D-2). Anomaly A-2 distorts the reflector associated with the top of the Knox Group, and is attributed to a tuning phenomenon from resonating dominant frequencies in a wedge-like geologic structure (Figure 2.5.1-36, Sheet 2) (Reference 2.5.1-214, Appendix D-2).

Two additional anomalies are described in SRL-2 (Figure 2.5.1-36, Sheet 4). Anomaly A-4 represents a gap in a prominent reflector, and is attributed to out-of-plane reflectors or spatial aliasing (Reference 2.5.1-214). The lack of offset in the reflectors that flank this gap, in addition to no imaged diffractions in the seismic horizons above or below the anomaly, support the interpretation that this anomaly does not represent a fault (Reference 2.5.1-214). Anomaly A-5 presents as a stair-step feature in the Knox Group horizon, and appears to be related to interference between the seismic reflector and linear noise that bisects the reflector (Figure 2.5.1-36, Sheet 4) (Reference 2.5.1-214).

The Alleghanian thrust faults located within the site area were not identified in geophysical data collected at the site, primarily due to logistical constraints on survey line length (Reference 2.5.1-214). Additionally, the seismic reflection data, combined with seismic refraction and borehole data, did not reveal any evidence for previously unknown blind subsurface structures at the site (Figures 2.5.1-30 and 2.5.1-36; Reference 2.5.1-214).

2.5.1.2.4.2.1.2 Seismic Refraction Data

Six seismic refraction lines were acquired at the CRN Site (Figure 2.5.1-29). The data are presented as seismic tomography models (Figure 2.5.1-86). Such models can be used to resolve complex velocity structure that cannot be imaged using layer-based modelling techniques (Reference 2.5.1-214). The primary objective of the seismic refraction surveys was to map the depth to bedrock in graded and filled areas within the central portion of the site. The data were also reviewed to identify anomalies that might indicate the presence of geologic structures such as blind faults or large karst dissolution features beneath the fill. The resolution of these data is not sufficient to identify small-scale features (less than 10 ft). The results of this review are presented in Subsection 2.5.1.2.5.1.2.

2.5.1.2.4.2.2 White Oak Mountain Fault

The White Oak Mountain fault is located approximately 2 mi northwest of the CRN Site (Figure 2.5.1-34). This is a regional structure that continues both northeast into Virginia and southwest into Georgia. To the northeast it bifurcates into the Wallen Valley and Hunter Valley / Clinchport faults (Figure 2.5.1-33, Sheet 2). This fault juxtaposes Cambrian Rome Formation rocks northwest over a variety of Cambrian to Mississippian footwall strata (Figure 2.5.1-35) (Reference 2.5.1-9). Because of its length, the “bow-and-arrow rule” (fault displacement is proportional to length) would indicate up to 80 km (50 mi) of displacement (References 2.5.1-141 and 2.5.1-230). However, despite its length, minimum displacement estimates from cross-section

reconstructions yield a more modest 10–12 km (6.2–7.5 mi) of slip (Reference 2.5.1-230). Although no radiometric ages have been determined for the White Oak Mountain fault, it is a late Paleozoic fault related to the Alleghanian foreland fold-thrust belt (see Subsections 2.5.1.1.2 and 2.5.1.1.4).

2.5.1.2.4.2.3 Copper Creek Fault

The Copper Creek fault, a major structure of the Valley and Ridge fold-thrust belt, is located within 1 mile of the CRN Site (Figure 2.5.1-34). Throughout the site vicinity, maximum dip of the fault is approximately 34 degrees at the surface, but it flattens at depth to between 5 and 15 degrees (Reference 2.5.1-9). Breccia, cataclasite and gouge in hanging wall rocks of the Copper Creek fault were encountered in several wells that were drilled approximately 3 mi east of the site (JOY-1, DM1, and DM2; locations shown in Reference 2.5.1-9). This fault juxtaposes Cambrian Rome Formation rocks over the Ordovician Moccasin Formation, with a displacement estimate of 12 to 50 km (7.4 to 31 mi) (Reference 2.5.1-9).

The gouge within the fault zone documented in boreholes CC-B1 and CC-B2 (see Figures 2.5.1-29 and 2.5.1-30 for borehole locations) ranged from 1 to 2 m thick, and was composed of highly weathered siltstone and shale derived from hanging wall Rome Formation strata with minor footwall Moccasin Formation limestone (Reference 2.5.1-214). As part of the CRBRP geologic investigation, cataclastic rocks from an exposure of the Copper Creek Fault in a road cut off of I-40 southwest of the site have been dated using the $^{40}K/^{40}Ar$ method; results indicate the last movement along the Copper Creek fault occurred 280-290 Ma. These results are in agreement with a more recently acquired $^{40}Ar/^{39}Ar$ age of 279.5 ± 11.3 Ma determined from fault gouge illite sampled from the Copper Creek fault in northeastern Tennessee (Reference 2.5.1-144).

2.5.1.2.4.2.4 Chestnut Ridge Fault

The Chestnut Ridge fault (CRF) was originally mapped by Lemiszki et al. (Reference 2.5.1-97) as a subordinate, small displacement, thrust fault approximately 1.5 miles long and located 0.5 miles west of the site and southwest of the Clinch River but within the site location (0.6-mile radius). The CRF is mapped as NE-SW trending, striking parallel to bedding and the major through-going thrust faults associated with the Alleghanian orogeny in the Valley and Ridge fold and thrust belt. The CRF is discontinuous and located based primarily on the repetition of geologic units within the Knox Group as determined by mapping loose pieces of bedrock along the ground surface (float mapping). The Kingsport Formation of the Knox Group contains an interval of thick to massive bedded chert which creates a resistant ridge parallel to bedding which makes float mapping of this unit more certain. There is no exposure of the CRF at the ground surface; thus, there are no direct observations of kinematic data from the fault plane.

This previous geologic mapping of the area around the CRF was updated in 2015 by the Tennessee Geological Survey (References 2.5.1-282 and 2.5.1-283). This recent mapping is included on Figures 2.5.1-29, 2.5.1-34, 2.5.1-37 and Plates 1 and 2 in Part 8 of the ESPA. The Tennessee Geological Survey now shows the CRF as extending farther to the northeast, approximately 2000 feet northwest of the site. The total length of the CRF is now mapped as 2.8 miles long, but is limited to the Geologic Map of the Elverton Quadrangle (Reference 2.5.1-282). The neighboring Bethel Valley Quadrangle has not been updated, but the CRF reportedly extends into this area north of the CRN Site. The recent geologic mapping bases the northeast extension of the CRF on a few geologic and geomorphic inconsistencies including; thickening of the Mascot Formation on the neighboring Bethel Valley Quadrangle, a minor topographic ridge, and some bedrock dipping angles that are steeper than the regional trend.

Based on mapping performed for the CRN Site ESPA (see Figure 2.5.1-25), the regional trend and structural style of the CRF is similar to the major through going thrust faults associated with the Alleghanian orogeny in the Valley and Ridge fold and thrust belt. However, the CRF does not juxtapose rock types with significant stratigraphic or temporal differences, nor is it associated with significant structural shortening. The CRF strikes parallel to regional bedding at approximately N50°E and is depicted in Figures 2.5.1-35, 2.5.1-37, and 2.5.1-64 as a southeast-dipping bedding plane thrust fault with relatively minor displacement. Regional mapping of the geometry of more extensively mapped faults, such as the Whiteoak Mountain fault by the Tennessee Geological Survey, suggest the dip of the CRF may steepen from approximately 35° at depth, to approximately 50° near the ground surface based on steeper bedrock dipping angles (Figure 2.5.1-64 and Plate 2 in Part 8 of the ESPA). The relatively steep dip of the CRF can be kinematically described as the result of passive rotation of the hanging wall of the Whiteoak Mountain fault as the hanging wall block climbed the footwall ramp during Alleghanian deformation of the Valley and Ridge. This suggests that the CRF may pre-date much of the motion on the Whiteoak Mountain fault and accommodated crustal shortening along bedding planes due to deformation associated with the Alleghanian orogeny. The CRF and other subordinate faults associated with Paleozoic Alleghanian orogeny in the Valley and Ridge, such as the “unnamed fault” shown on Figure 2.5.1-64 and Plate 2 in Part 8 of the ESPA (Reference 2.5.1-282), are a byproduct of the crustal shortening within the Alleghanian foreland fold-thrust belt.

2.5.1.2.4.3 Mesoscopic Structures within the Site and Vicinity

Mesoscopic data collected at the CRN Site and vicinity (Figure 2.5.1-37; Plate 1, included in Part 8 of the application) includes a combination of field geologic, borehole, and seismic reflection and refraction data (Reference 2.5.1-214). Planar fabric data collected during the site investigation are graphically illustrated with stereographic projection and rose diagrams in Figure 2.5.1-38. Planar fabric data are reported in azimuth notation following right-hand-rule. For example, 045/45 represents a strike of N45°E with a 45-degree dip to the southeast; 225/45 represents the same strike, however, dip is instead to the northwest.

2.5.1.2.4.3.1 Folds

Mesoscale folds in the Valley and Ridge province throughout the site vicinity are primarily buckle folds with inch- to foot-scale wavelengths that formed during shortening that drove foreland fold-thrust belt deformation. Flexural slip and flexural flow folding were both active deformation mechanisms, and their occurrence is dependent on lithology, mechanical strength contrasts, and layer thickness. Mesoscopic folds in the Valley and Ridge are associated with an axial planar cleavage (where developed), and their orientations generally mimic regional-scale structures. Project Management Corporation (PMC) (Reference 2.5.1-100) noted several tight, asymmetric meter-scale folds at the site that were described as overturned with southeast vergence and southwest plunging axes. These folds are no longer visible due to the excavation and backfill related to construction and site closure of the CRBRP. Additionally, structures described as drag folds that ranged from inches to feet in amplitude were described in well logs during the subsurface investigation for the CRBRP (Reference 2.5.1-100).

2.5.1.2.4.3.2 Bedding

Throughout the Valley and Ridge portion of the CRN site vicinity, bedding of Paleozoic strata consistently strikes northeast (mostly between 030–060 degrees) with moderate southeast dips. In general, the strike of primary bedding surfaces is roughly consistent across Valley and Ridge thrust faults. Overall structural style changes significantly toward the northwestern portion of the site vicinity, which includes portions of the Cumberland Plateau physiographic province (see Subsections 2.5.1.1.1 and 2.5.1.1.4 for more detailed discussion of physiographic provinces).

Alleghanian deformation was much less intense within this province; bedding is mostly subhorizontal, with maximum dips on the order of 20 to 25 degrees.

Geologic field mapping and acoustic televiewer (ATV) log data indicate bedding at the site overwhelmingly strikes 050–070 with southeast dips that range between 20 and 50 degrees (References 2.5.1-106 and 2.5.1-97). Mean orientations reported during the CRBR Preliminary Safety Analysis Report (PSAR) Project ranged from 052/31 (derived using 3-point problems) to 052/37 from surface mapping (Reference 2.5.1-100). A recent estimate based on surface mapping and 3-point problems from key horizons in boreholes yielded a similar 052/33. ATV log data of total borehole measurements (n=4733) yielded a mean bedding attitude of 063/33 (Figures 2.5.1-38, Sheet 1 and 2.5.1-38, Sheet 2); orientation between different stratigraphic units was consistent down-hole. Additionally, seismic reflection data supports consistent dip of strata between borehole locations (Figure 2.5.1-36). Geologic cross-sections that were constructed using subsurface contacts observed in boreholes also indicate bedding dips are consistent throughout the site (Figure 2.5.1-30).

2.5.1.2.4.3.3 Fractures

Hatcher et al. (Reference 2.5.1-9) provide an exhaustive review of fractures throughout the Oak Ridge area, and described joint sets by lithology and thrust sheet in which they occur. These distinctions are supported by: (1) evidence that suggests fracture sets predate Valley and Ridge thrusting, and (2) the mechanical dependence of fracture development by lithology. Evidence that supports fracture development occurred prior to Alleghanian shortening and Valley and Ridge thrust sheet emplacement includes: (1) fractures parallel to bedding indicate their orientation is controlled by bedding orientation; (2) fractures are crosscut by bedding-parallel slip surfaces that likely formed during Alleghanian shortening; (3) fractures are offset by mesoscopic faults; and (4) calcite vein fill within fractures throughout the region is commonly twinned (References 2.5.1-9, 2.5.1-216, and 2.5.1-237). Therefore, the present-day orientation of fracture sets represents rotation and translation of their initial geometry that occurred during the Alleghanian emplacement of major Valley and Ridge thrust sheets.

Hatcher et al. (Reference 2.5.1-9) schematically demonstrates a strong dependence of fracture orientation to lithology using a Mohr diagram. Failure envelopes for different lithologies (mechanical strength) influence whether fractures develop in compressive or extensional regime for similar stress magnitudes. The mechanical strengths of different lithologic units also result in slightly different fracture orientations (Reference 2.5.1-9).

Fractures in the site vicinity are primarily extensional (References 2.5.1-215 and 2.5.1-216). Lemiszki (Reference 2.5.1-216) notes that two orthogonal fracture sets occur almost ubiquitously throughout the Oak Ridge area. One strike-parallel that dips perpendicular to bedding, and one that is oriented perpendicular to both strike and dip of bedding. The orientation of these fracture sets consistently rotates with bed orientation, which provides further evidence for their development prior to Alleghanian thrust faulting (References 2.5.1-9 and 2.5.1-216). Lemiszki (Reference 2.5.1-215) also notes that fractures tend to terminate at bed contacts.

Within the site vicinity, three prominent fracture sets were identified in the Copper Creek thrust sheet (Reference 2.5.1-9): (1) 234/55 in the Rome Formation, 241/65 in the Conasauga Group, and 236/80 in the Knox Group; (2) 321/87 in the Rome Formation, 331/89 in the Conasauga Group, and 332/88 in the Knox Group; and (3) 107/84 in the Rome Formation, 106/80 in the Conasauga Group, and 107/81 in the Knox Group. Hatcher et al. (Reference 2.5.1-9) defined two prominent joint sets in the White Oak Mountain thrust sheet: (1) 140/88 in the Rome Formation, 126/54 in the Conasauga Group, 141/87 in the Knox Group, and 148/89 in the Chickamauga Group; and (2) 247/45 in the Rome Formation, 221/40 in the Conasauga Group, 248/56 in the Knox Group, and 233/55 in the Chickamauga Group.

Four prominent fracture sets at the site were identified in the CRBRP PSAR: 052/31, 232/58, 295/75, and 335/85 (Reference 2.5.1-100). In the current investigation, fracture surfaces are defined as planar, discontinuous or irregular, while fracture thickness is described as hairline or open, based on whether there was observed material loss along the joint surface. Of the five sets of discontinuities identified in ATV logs, the two primary fracture sets strike parallel to bedding (Figures 2.5.1-38, Sheet 3 through 2.5.1-38, Sheet 5). The most commonly occurring set consists mostly of discontinuous hairline fractures, with strike parallel to bedding and dip normal to bedding (mean orientation of 240/59) (Figures 2.5.1-38, Sheet 3 through 2.5.1-38, Sheet 5). The subordinate set consists of hairline and open joints that roughly parallel bedding, with a mean orientation of 060/38. Another set of mostly discontinuous, planar hairline fractures roughly parallels strike of bedding, although dips significantly steeper to the southeast (mean orientation 060/73) (Figures 2.5.1-38, Sheet 3 through 2.5.1-38, Sheet 5). Two additional, relatively minor fracture sets consist of mostly planar to discontinuous hairline joints that appear normal to strike, with orientations of 140/74 and 322/73.

2.5.1.2.4.3.4 Shear-Fracture Zones

During the CRBRP site investigation, a structure was identified in the Unit A Limestone (Eidson Member of the Lincolnshire Formation) that was described as an ancient rehealed “shear zone” (Reference 2.5.1-100). The “shear zone” was encountered in 39 boreholes during that investigation, and a surface exposure in the northeastern portion of the site was described in the CRBRP PSAR (Reference 2.5.1-238) (Figure 2.5.1-65). This zone is described as 19 to 46 ft thick, and is on average approximately 35 ft thick (Reference 2.5.1-100). The zone, including slickensides, is conformable with bedding (Reference 2.5.1-238). It is characterized as “a zone of interbed slippage characterized by a combination of slickensides, calcite veins, and 1-in. to 1-ft segments that are either severely warped or brecciated” (Reference 2.5.1-100). The authors concluded that the “shear zone” is a zone of interbed slippage that developed during Alleghanian Valley and Ridge shortening, based on the truncation of calcite-filled fractures by stylolites (Reference 2.5.1-238). Interbed slippage in the zone is estimated to be on the order of inches (Reference 2.5.1-238), although no evidence is provided to support that statement. The definition of the “shear zone” identified in the CRBRP PSAR is refined to clarify that “there are calcite-filled fractures across bedding and small zones of paper-thin slickensides oriented parallel or subparallel to the bedding,” and “the ‘shear zone’ is not a fault breccia nor a fault zone” (Reference 2.5.1-238).

For discussion of this structure, the term shear-fracture zone is adopted based on the following attributes observed in rock core (Figure 2.5.1-90):

- Shear-fracture zones exhibit a relative abundance of calcite veins compared to adjacent rock. Calcite veins appear to be randomly oriented; they are observed at high angles to, and subparallel with bedding. Calcite veins locally appear to be folded or deformed.
- The shear-fracture zones, and calcite veins within the zones, are commonly truncated by stylolites. Stylolites that truncate calcite veins within the shear-fracture zones are variously parallel to bedding, at high angles to bedding, and subvertical. Apparent offsets in veins locally appear to be a function of juxtaposition related to volume loss along stylolite surfaces.
- Within the shear-fracture zones, angular pieces of carbonate rock are locally juxtaposed. Where this occurs, there is no evidence for brecciation by mechanical grain-size reduction (angular host rock fragments with matrix), but instead, the juxtaposition appears to be related to pressure solution.
- Slickenlines occur along bedding planes and less commonly along vein surfaces. However, slickenlines on bedding surfaces or veins are not unique to the shear-fracture zones.

Shear-fracture zones that include the attributes described above are identified in boreholes in the Lincolnshire (Eidson Member), Rockdell, and Benbolt Formations in the current subsurface

investigation (see Subsection 2.5.1.2.6) (Reference 2.5.1-214). The Lincolnshire Formation (Eidson Member) and the Unit A Limestone defined in the CRBRP PSAR are equivalent (see Table 2.5.1-1). These shear-fracture zones are located and characterized in 18 of the 100-, 200-, and 400-series boreholes (Table 2.5.1-17), and are described in more detail in Subsection 2.5.1.2.6.4. Thicknesses are reported to be up to 22 ft (Table 2.5.1-17) (see Subsections 2.5.1.2.4 and 2.5.1.2.6), although the thicker zones reported in the boring investigation (Reference 2.5.1-214) generally do not exhibit shear-fracture zone characteristics over the entire depth interval. In other words, areas of strain that characterize the shear-fracture zones tend to be localized over intervals of only a few feet or less.

The intervals over which shear-fracture zone features occur within the lower Eidson Member of the Lincolnshire Formation are shown on two cross-sections through the site in Figures 2.5.1-66 and 2.5.1-67. These cross-sections show that the shear-fracture zone is conformable to bedding and is, for the most part, laterally continuous across the site. Similarly, the strike-parallel extent of the shear-fracture zone based on boreholes that encountered the shear-fracture zone also suggests lateral continuity, although several boreholes that penetrated the lower Eidson Member of the Lincolnshire Formation did not encounter the shear-fracture zone (Figure 2.5.1-65). Within the Eidson Member, the shear-fracture zone is recognized in boreholes for a distance of about 500 ft parallel to dip direction, and for a distance of about 2,700 ft parallel to strike.

As noted above, additional shear-fracture zone features were also observed up-section in boreholes during this investigation further to the southeast within the Benbolt and Rockdell Formations (Figure 2.5.1-65). These less well-defined shear-fracture zones were not observed in the three boreholes completed for the CRBRP that penetrated these units (References 2.5.1-100 and 2.5.1-238). These shear-fracture zone features share similar characteristics with the shear-fracture zone features in the Eidson Member of the Lincolnshire Formation (Table 2.5.1-17). Within the Rockdell and Benbolt Formations, the shear-fracture zone features are located in the approximately middle third of each unit (Figure 2.5.1-67). The features in the Rockdell Formation define a zone that is roughly conformable with bedding, while the observed features in the Benbolt Formation are not dense or extensive enough to define a zone (Figure 2.5.1-67). As depicted in map view (Figure 2.5.1-65) and cross-section view (Figure 2.5.1-67), neither the Benbolt nor the Rockdell Formation shear-fracture zone features define laterally continuous zones through multiple borings parallel to dip or strike. Instead, the shear-fracture zone features in the Benbolt and Rockdell Formations appear to comprise localized zones of deformation that do not extend continuously for more than a few hundred feet in either the dip-parallel or strike-parallel directions.

Geological mapping during excavation activities related to the CRBRP (Reference 2.5.1-303) reports that the “western shear zone” in the Unit A Limestone (Eidson Member of the Lincolnshire Formation), which is the “shear zone” encountered in CRBRP borings, was not encountered in the Lincolnshire Formation in the floor of the excavation (Reference 2.5.1-303). However, the underlying Unit A Lower Siltstone (Blackford Formation) is reported as “highly deformed by the thrust-and-fold structures” (Reference 2.5.1-303). The observed deformation in the Blackford Formation is interpreted by Drakulich (Reference 2.5.1-303) to represent the up-dip extension of the “western shear zone,” or the “shear zone” reported in the Eidson Member of the Lincolnshire Formation from CRBRP PSAR borings. An implication of this interpretation is that the “shear zone” in the Eidson Member, identified only in exploratory borings and not observed in the Eidson Member in the excavation, ramps down section into the underlying Blackford Formation siltstone (Figure 2.5.1-91, Sheet 3 of 3). In other words, the “western shear zone” of Drakulich (Reference 2.5.1-303) is not observed to correspond to the Eidson Member “shear zone” identified in the CRBRP PSAR (References 2.5.1-100 and 2.5.1-238) or the shear-fracture zone in the current investigation. Drakulich (Reference 2.5.1-303) reports common bedding-parallel slip that locally produces meso-scale folds and bedding-parallel slip, and “thrust-and-fold structures” in the underlying Blackford Formation. Photograph 22 of Reference 2.5.1-303

(Figure 2.5.1-92) documents what appears to be a fault-propagation fold that was exposed in the Equalization Basin excavation (Figure 2.5.1-91, Sheet 2 of 3). Drakulich (Reference 2.5.1-303) specifically notes a lack of deformation in the Lincolnshire Formation.

Slickensided veins at various orientations relative to bedding are common in the Valley and Ridge province. Foreman and Dunne (Reference 2.5.1-237) observed four sets of bed-normal calcite veins in limestones and shales at the Oak Ridge Reservation that are offset 0.8 in. or less by bed-parallel veins. The bed-parallel veins are characterized by slickensides oriented parallel to Alleghanian thrusting. On the basis of calcite twinning, fluid inclusions and cross-cutting relationships, Foreman and Dunne (Reference 2.5.1-237) interpret the development of the bed-normal veins to have occurred in the middle Mississippian during the onset of the Ouachita and Alleghanian orogenies. The bed-parallel veins, which offset the bed-normal veins, are interpreted by Foreman and Dunne (Reference 2.5.1-237) to have developed during the Alleghanian orogeny. Slickensides, oriented parallel to the thrusting direction, are interpreted by Foreman and Dunne (Reference 2.5.1-237) to have formed during movement of the Whiteoak Mountain thrust sheet. Similar features to the bed-normal and bed-parallel veins are common throughout borehole logs of the current investigation (Reference 2.5.1-214), which describe calcite healed tensional fractures oriented orthogonal to and parallel to bedding. Given the similarity in geologic setting, tectonic history, and fracture characteristics, slickensided veins observed in CRN Site borings likely share the same Alleghanian origin and development as the slickensided veins described by Foreman and Dunne (Reference 2.5.1-237).

Lemiszki (Reference 2.5.1-215) observed and briefly described local “shear fractures” that are most common in, but not exclusive to the K-25 site area of the Oak Ridge National Laboratory. The shear fractures are described as single, discrete fractures to wide zones of en echelon fractures and tension gashes with left- and right-lateral shears based on offset of chert marker beds and mineral-filling geometries. That study describes the shears as “commonly perpendicular to bedding,” which is not consistent with descriptions of the “shear zone” observed in the CRBRP (Reference 2.5.1-100 and 2.5.1-238), the bed-parallel veins described by Foreman and Dunne (Reference 2.5.1-237), or the shear-fracture zones as described in the current study (Reference 2.5.1-214). However, the “shear fractures” described by Lemiszki (Reference 2.5.1-215) could be related to the bed-normal veins observed by Foreman and Dunne (Reference 2.5.1-237) and similar features observed in the current study (Reference 2.5.1-214).

The CRBRP study notes that “shear zone” calcite-filled fractures are truncated by stylolites, and concludes the shear-fracture zones formed before or during rock lithification (Reference 2.5.1-238). Stylolites are primarily sedimentary structures that form in response to lithostatic-driven pressure dissolution (Reference 2.5.1-284). The term is typically used to describe bedding parallel “seams” in carbonate rocks that developed diagenetically during burial due to lithostatic pressure (Reference 2.5.1-285). Alternatively, several studies have shown that stylolite “seams” develop perpendicular to maximum compressive stress (e.g., References 2.5.1-285 and 2.5.1-286) and that subvertical stylolites can develop in active compressive margins in response to horizontal compressive stress (References 2.5.1-285, 2.5.1-286, 2.5.1-287 and 2.5.1-288). These subvertical stylolites are referred to as tectonic stylolites. The stylolites observed in the current investigation are generally described as bedding joints that dip between 20 to 40° conformable with bedding (Reference 2.5.1-214). However, subvertical stylolites and stylolites at high angles to bedding are clearly visible in the core (Reference 2.5.1-214), which indicates multiple generations of stylolite formation (diagenetic and tectonic).

The observed orientations and crosscutting relationships of stylolites, among other structures, are key to the characterization of the shear-fracture zones. Truncation of the shear-fracture zones, or calcite veins within the zones, by bedding parallel stylolites 1) demonstrates pre- to

syn-diagenetic development of these zones and precipitation of calcite in veins, and 2) supports stratigraphic (lithologic) control on the development of the shear-fracture zones. Additionally, truncation of calcite veins within the shear-fracture zone by steeply dipping and subvertical stylolites, folding and deformation of calcite veins, and slickenlined vein and bedding surfaces, demonstrate a tectonic overprint on the zone, likely related to Alleghanian shortening related to emplacement of Valley and Ridge thrust faults.

A schematic diagram that depicts the attributes and crosscutting relationships observed within the shear-fracture zones is presented in Figure 2.5.1-68. In summary, the relative abundance of pressure solution features and calcite veins observed in the shear-fracture zones suggests this specific interval within the carbonate stratigraphy was more susceptible to dissolution-precipitation processes relative to adjacent rock. Based on the observed crosscutting relationships with bedding-parallel and subvertical stylolites, these processes were active both during diagenesis and during a post-diagenetic tectonic overprint, likely shortening associated with the Alleghanian orogeny. The observed abundance of pressure-solution features and paucity of evidence for mechanical grain-size reduction suggests strain was primarily accommodated via pressure solution with limited cataclastic flow during Alleghanian shortening and emplacement of the Whiteoak Mountain and Copper Creek thrust sheets. Localized folding of veins suggests intracrystalline plasticity may have contributed to the observed strain in the rocks; these processes have been reported in Valley and Ridge faults that involve carbonate rocks (e.g., Hunter Valley thrust; see Reference 2.5.1-320) even though deformation temperatures are estimated to be below the theoretical threshold for carbonate plasticity (Reference 2.5.1-320).

2.5.1.2.4.4 Characterization of Alleghanian Foreland Fold-Thrust Structures

The different macroscopic structural attributes of Alleghanian Valley and Ridge province thrust faults that occur within the site area, in addition to the shear-fracture zones at the Site, are most likely a function of lithology and their mechanical and chemical responses to stress during deformation. The following synthesis of the thrust faults and other structures related to the late Paleozoic Alleghanian orogeny is presented with respect to the three primary deformation mechanisms that occur in rocks (see Reference 2.5.1-321): 1) brittle cataclasis (i.e., mechanical grain-size reduction); 2) diffusive mass transfer (i.e., pressure solution); and 3) intracrystalline plasticity. While the thrust faults, and likely the shear-fracture zone, were all emplaced during the late Paleozoic Alleghanian orogeny, the faults exhibit distinct mesoscopic attributes that represent variations in the relative contribution of deformation mechanisms to the cumulative strain in the rocks.

In the site area, the Whiteoak Mountain and Copper Creek thrust faults juxtapose lower Cambrian Rome Formation (primarily siliciclastic lithologies) above Middle Ordovician Chickamauga Group carbonate rocks (see Plates 1 and 2 in Part 8 of the ESPA). The Copper Creek fault was encountered in borings CC-B1 and CC-B2 during the CRN Site investigation (Reference 2.5.1-214). The fault zone occurs over a 4 to 7 foot interval in the borings, and includes angular carbonate and siliciclastic fragments in a clayey gouge matrix (Reference 2.5.1-214). This texture represents deformation accommodated via mechanical grain-size reduction during brittle cataclasis. An exposure of the Whiteoak Mountain fault was not visited during the investigation, although a similar style of deformation is expected based on the juxtaposition of similar lithologic units.

The Chestnut Ridge fault of Lemiszki (Reference 2.5.1-282) juxtaposes Middle Ordovician Kingsport Formation rocks above the stratigraphically overlying Mascot Dolomite (Figure 2.5.1-64). This fault is only mapped by stratigraphic repetition; no direct observation of this fault is reported.

As discussed in Subsection 2.5.1.2.4.3.4, zones of localized deformation termed shear-fracture zones were encountered in borings related to the CRBRP investigation (References 2.5.1-100, 2.5.1-238) and in the CRN Site investigation (Reference 2.5.1-214). These zones occur in specific stratigraphic intervals, and are characterized by a relative abundance of calcite veins compared to adjacent rock, locally folded or deformed calcite veins, slickenlined bedding and vein surfaces, and truncation of veins and lithologies at bedding-parallel and subvertical stylolites. Apparent brecciation reported in the shear-fracture zone is not accompanied by evidence that supports mechanical grain size reduction by brittle cataclasis, but instead appears to be juxtaposition of lithologies by pressure solution (see Subsection 2.5.1.2.4.3.4). The observed abundance of pressure-solution features and paucity of evidence for mechanical grain-size reduction suggests localized strain was primarily accommodated via pressure solution with limited cataclastic flow at these specific intervals. Subvertical stylolites indicate dissolution occurred during strong subhorizontal compression, which most likely coincides with shortening and emplacement of Valley and Ridge thrust faults during the Alleghanian orogeny.

2.5.1.2.5 Local Geologic Hazards

This section reviews and assesses potential geologic hazards in the site vicinity (25-mi radius), site area (5-mi radius) and site location (0.6-mi radius). Geologic hazards of primary interest are those that could potentially compromise the safety or integrity of critical facilities at the site.

Karst features and active karst processes are common throughout the site vicinity and include sinkholes, caves, springs, underground drainage, and irregular soil-bedrock contact. Karst dissolution of the carbonate bedrock, which underlies all plant facilities, is the primary geologic hazard of concern.

In addition to karst hazards, other geologic hazards, such as landsliding, deformation zones, zones of alteration or structural weakness, unrelieved residual stresses, and subsidence and settlement resulting from fluid withdrawal or mineral extraction are briefly addressed. Hazards such as landsliding, which are capable of producing surface deformation, are more thoroughly discussed in Subsection 2.5.3, Surface Deformation.

2.5.1.2.5.1 Karst Hazards

In this section, karst processes and features in the site vicinity and area are reviewed, and site-specific geologic and geotechnical data relevant to the assessment of potential karst hazard within the site location are presented. The presence of karst features is documented at the CRN Site, and a thorough examination of the nature, origin, occurrence, and potential hazards posed by karst features and processes is made.

Karst Conceptual Models

To provide background and context, and enable the eventual development of a site-specific karst model, the section begins with a review of conceptual karst models. All karst models entail the same basic principle, the karst landscapes and features are dominantly formed by the dissolution of bedrock by water (Reference 2.5.1-35).

Karst models can be classified by whether they invoke *epigenic* dissolution, *hypogenic* dissolution, or both. Epigenic dissolution occurs as meteoric water descends and flows along a hydrologic gradient underground through the rock, eventually discharging to springs in nearby valleys (Reference 2.5.1-35). Hypogenic dissolution occurs when groundwater ascends from below, independent of recharge from the overlying or immediately adjacent ground surface (Reference 2.5.1-289).

Most of the published literature on karst focuses on *epigenic* karst, formed by descending groundwater. Epigenic karst is formed by water moving from the ground surface down into soluble rock formations, then through them along the hydraulic gradient. Permeability of the regolith and/or rock formations governs the extent to which water is able to penetrate to varying depths. As discussed in Subsection 2.5.1.1.1.3, epigenic karst features develop from a self-accelerating process of water flow among well-defined pathways. As the water flows through the rock, it dissolves and enlarges the pore or fracture space through which it flows. These pathways include bedding planes, joints, fractures, and faults. Enlarging the fracture allows it to carry more water, which increases the dissolution rate, eventually forming a conduit. The location and geometry of dissolution conduits are controlled by the rock composition, rock structure, porosity, amount of fractures and voids, amount of recharge, the hydraulic gradient, and other factors (Reference 2.5.1-290).

Early models of epigenic karst formation view the style of dissolution as a function of the hydrologic zone of formation (Reference 2.5.1-291). *Vadose* dissolution occurs as descending water flows through the unsaturated (vadose) zone from the ground surface down toward the water table, resulting in vertical and steeply pitched dissolution channels. Deep *phreatic* dissolution takes place below the water table in the phreatic zone, from groundwater first descending, moving laterally, then ascending along a hydraulic gradient, resulting in deep caves that follow joints, faults, fractures, and/or bedding planes. Water table dissolution takes place at and just below the water table, resulting in horizontal cave passages.

Ford and Williams (Reference 2.5.1-290) presented a model that accounted for the variation in the depth of dissolution in epigenic phreatic cave formation (Figure 2.5.1-53) as a function of rock properties. They proposed that in rock with abundant fractures and pathways for water flow, dissolution is concentrated in the zone of mixing of meteoric and groundwater at the top of the groundwater table, resulting in an “ideal water table cave” with dominantly horizontal passageways. In rock with few, tight, or widely spaced fractures, water is forced to descend along available fractures before it can continue laterally or upward to follow the hydraulic gradient, forming the deeper and more complex “deep phreatic or *bathyphreatic* cave.”

Latest research by Worthington (Reference 2.5.1-302) proposes that depth of phreatic dissolution is dependent on additional hydraulic, structural, and solubility factors, which can combine to form conduits at very great depths. The decrease in the viscosity of water with depth as temperature increases along the geothermal gradient facilitates efficient flow, an effect that favors deep dissolution in settings with long flow paths and steeply dipping strata.

Studies of karst aquifers by the U.S. Geological Survey (Reference 2.5.1-292) led to the development of a general karst model for the Valley and Ridge province of Tennessee. In this model, shown in Figure 2.5.1-69, epigenic karst processes lead to dissolution throughout the vadose and phreatic zones. Dissolution is most intense in the near surface, and proceeds downward along bedding planes and joints. Phreatic dissolution occurs in both the shallow and deep phreatic zones, with the dominant direction of flow parallel to strike. Dissolution may extend to depths greater than 180 m (600 ft).

Over the last few decades, research on *hypogenic* karst has expanded greatly, and hypogenic features are increasingly recognized in karst environments. The understanding and the definition of hypogenic karst has evolved and been refined over this timeframe. Early definitions of hypogenic speleogenesis linked the process to very specific examples and characteristics, mostly through a geochemical framework associated with hydrothermal waters or oxidation of hydrocarbons (References 2.5.1-290, 2.5.1-293). Hill (Reference 2.5.1-294) demonstrated that large caves in New Mexico such as Carlsbad Caverns were formed by acidic waters charged with hydrogen sulfide derived from hydrocarbons at depth. Defining hypogene speleogenesis has evolved with increasing research on the subject, but the common theme was that dissolution

occurred at depth, essentially decoupled from surficial processes and hydrologic conditions. This theme has persisted, and the following definition presented by Reference 2.5.1-289 is now generally applied. Hypogenic speleogenesis is "the formation of caves by water that recharges the soluble formation from below, driven by hydrostatic pressure or other sources of energy, independent of recharge from the overlying or immediately adjacent surface."

Hypogene dissolution requires a structural setting in which waters can descend to great depths, and then rise up through the soluble formation. Klimchouck (Reference 2.5.1-289) presents a model of an open basin in which both hypogene and epigene dissolution may take place (Figure 2.5.1-70). More often, however, a confining layer forces the water to great depths and creates the opportunity for hypogene dissolution. The rising water is often aggressive i.e. having the ability to dissolve rocks. Water becomes aggressive, for example, through geochemical interaction with deeper strata rich in hydrocarbons, dissolution of carbohydrates to form carbonic acid, or at increased temperatures.

The mixing of fresh water and salt water in coastal settings can also result in hypogene dissolution. Cunningham and Walker (Reference 2.5.1-41) and Cunningham et al. (Reference 2.5.1-318) describe multistoried vertical sag features evident in high resolution seismic reflection profiles from Biscayne Bay, Florida (Figure 2.5.1-84). They interpreted these stacked sag features, which range in diameter from 170 m (560 ft) to 3.2 km (10,500 ft), as evidence for coalesced, collapsed paleocave systems. Cunningham and Walker (Reference 2.5.1-41) proposed two hypogene mechanisms to explain these broad structural sags. They postulate upward flow driven by Kohout convection with dissolution by mixed fresh and saline groundwaters (Figure 2.5.1-85) and/or upward ascension of hydrogen-sulfide-charged groundwater derived from dissolution and reduction of calcium sulfates in deeper strata. Additionally, the faults associated with these collapse features may serve as pathways for upward ground water flow. This setting is highly susceptible to both epigenic and hypogenic karst processes due to the high porosity and permeability of Florida limestones and the frequent mixing of salt water and fresh water in groundwaters near the coast (Reference 2.5.1-295).

Within the Valley and Ridge, Doctor and Orndorff (Reference 2.5.1-296) identify multiple hypogenic characteristics in caves within the central Appalachian Great Valley (AGV) of Virginia. Here, rocks are stratigraphically similar in age, composition, and structure to those at the CRN Site. Steeply dipping strata, folds, and faults account for the availability of deep flow paths and allow for rising of thermal and geochemically altered waters (Reference 2.5.1-297). Doctor and Orndorff (Reference 2.5.1-296) propose that the caves initially formed by hypogene dissolution, were significantly enlarged by deep phreatic dissolution, then selectively modified by water table and vadose dissolution as erosion and landscape lowering gradually exposed them.

The major lines of evidence Doctor and Orndorff present for hypogene dissolution and deep phreatic dissolution of caves in the AGV are (1) the random landscape position of the caves, (2) the complex geometry of cave passages, (3) the presence of many thermal and travertine springs, and (4) the observation of cavities in water wells to depths of more than 1,000 ft. Caves appear to be randomly distributed beneath the landscape without regard for the modern stream networks. Cave elevations do not cluster about stream terrace elevations, nor do they cluster at any elevation that might reflect pauses in regional downcutting. Passages are not related to positions of modern trunk streams. Instead, cave passages are maze-like with vertical extents of over 20 m (76 ft). They follow joints, faults, and bedding planes, and have phreatic features such as cupolas and feeder tubes. Caves are known to occur in isolated hills with no inlets or outlets, far from base level streams. In an interview (Reference 2.5.1-298) and publication (Reference 2.5.1-319), Doctor also noted the presence of exotic mineral deposits, including dog-tooth spar, gypsum, iron, or fluorite, as evidence of hypogene processes (Figure 2.5.1-87). Present-day thermal and travertine springs indicate that hypogene conditions likely still exist at depth, and the presence of very deep dissolution cavities in water wells supports hypogene

dissolution as an ongoing process. Figure 2.5.1-71 shows Doctor and Orndorff's (Reference 2.5.1-296) model of how the interaction of a fault and a fold can result in hypogene dissolution by waters rising along a fault.

In summary, karst models show that dissolution occurs in a variety of hydrogeologic settings. Epigenetic dissolution, by descending and circulating meteoric water, can occur in the vadose zone, in the shallow phreatic zone, and in the deep phreatic zone. Dissolution begins along fractures, faults, and bedding planes, and proceeds to form voids and conduits capable of rapid transmittal of water. Hypogenic dissolution, by water ascending from below, forms conduits and voids with characteristic geometry and mineralogy. These voids can be later modified by epigenetic processes. Either epigenic or hypogenic processes are capable of creating voids and conduits at significant depth below the water table. A karst model for the CRN Site, informed by the above discussions, is presented at the conclusion of Subsection 2.5.1.2.5.1.2.

2.5.1.2.5.1.1 Karst in the Site Vicinity and Area

The site vicinity includes portions of the Valley and Ridge physiographic province and the Appalachian Plateaus province of eastern Tennessee (Subsection 2.5.1.2.1). The Valley and Ridge province of the site vicinity is underlain by northeast-striking folded and faulted sedimentary strata of Cambrian through Silurian age (Figures 2.5.1-27 and 2.5.1-34) as previously described in Subsection 2.5.1.2.3. Karst features are abundant and well-documented in carbonate strata of the Valley and Ridge province. A geologic model for karst development in the Valley and Ridge province was presented in Subsection 2.5.1.1.1.3.1. By contrast, very few karst features lie within the Appalachians Plateau province within the 25-mi CRN Site radius. Pennsylvanian clastic rocks, rather than carbonate rocks, underlie this portion of the Appalachian Plateau province (Figure 2.5.1-4).

Karst development in the Valley and Ridge Province within the 25-mi radius site vicinity is similar to development within the 5-mi radius site area as stratigraphy and geologic structure are consistent through the province. Therefore, the following detailed discussions of karst development focus on the site area.

The 5-mi radius site area falls entirely within the Valley and Ridge physiographic province of Tennessee (Subsection 2.5.1.2.1). Paleozoic strata, folded and faulted during the Alleghanian orogeny, are eroded into a series of parallel ridges and valleys striking northeast as described in Subsection 2.5.1.1.3. The strata are Cambrian to Ordovician in age and include sandstone, siltstone, limestone, and dolomite. Some strata are dominated by a single lithology and others include significant interbeds of other lithologies. Karst development is observed to vary strongly with stratigraphic unit. In general, the thickest and most pure carbonate units host the largest and most abundant karst features. All carbonate units host some karst features. Dissolution rates are variable and are dependent on a number of factors, including, but not limited to: (1) bedrock geochemistry; (2) location of rock relative to water table; (3) fracture density; or localized anthropogenic effects (e.g., acid mine drainage). According to White (Reference 2.5.1-30), estimates of the rate of denudation of karst surfaces by dissolution of carbonate bedrock in the Appalachians is in the range of 30 millimeters per kiloannum.

This section begins with a review of karst-related studies in the site area, much of which has focused on the ORR, owned by the Department of Energy, which adjoins the Tennessee Valley Authority (TVA) CRN Property (Figure 2.5.1-39). These previous studies provide a robust framework and conceptual model for the local karst setting. To extend this understanding to the CRN Site area, a detailed mapping and inventory of karst features of the site area was conducted based on interpretation of high resolution LiDAR-based topographic data obtained in 2013. Presentation of the mapping results is followed by analysis of the distribution of karst features

with respect to stratigraphic unit, and a discussion of the influence of bedrock lithology and structure on karst development in the site area.

Previous Karst-related Studies in the Site Area

Understanding of the local karst setting was advanced significantly by karst characterization efforts within the ORR. The ORR comprises most of the northern half of the 5-mi radius site area (Figure 2.5.1-39). Studies conducted in the 1980s and 1990s include Reservation-wide geologic studies and karst inventory, development of a geologic model for cave development, and site-specific studies that address contaminant fate and transport, ground failures, or site characterization. Primary organizations involved in these studies include ORNL, its contractors, and the University of Tennessee.

A Reservation-wide synthesis of ORR geology was completed by Hatcher et al. (Reference 2.5.1-9). This comprehensive report is composed of nine chapters, each summarizing a different aspect of the geology of the ORR. Relevant to the understanding of karst are chapters on stratigraphy, soils, geologic structure, and hydrogeology. Chapter 3.5 establishes the stratigraphic framework and lithology of the units of the Chickamauga Group which underlie the CRN Site as described in Subsection 2.5.1.2.3. This stratigraphy was based on rock core borings drilled at ORNL, and these unit names and descriptions are applied to the CRN SMR Project rock core. Chapter 4 describes the formation and characteristics of soils. The carbonate units are mantled by mature soils composed of the residuum of the underlying bedrock and colluvium. In addition, flat-bottomed dolines often contain layers of Pleistocene loess, interbedded with colluvium. Geologic structure is summarized in Chapter 5. Faults and joints, along with bedding planes, control the location and orientation of dissolution conduits. Major joint sets are oriented northeast and northwest, with minor north-south and east-west trending sets.

Chapter 7 of Hatcher et al. (Reference 2.5.1-9) describes a conceptual model for groundwater flow developed for the ORR (see Subsection 2.4.12.1.3 for more discussion). In the model the stormflow zone, or soil above rock approximately down to 0.3 to 6.5 ft below the ground surface, accounts for 90 percent or more of water moving through the subsurface (Figure 2.5.1-72). The water table zone, an area 3 to 16 ft thick below the vadose zone, takes up the remaining 10 percent of subsurface flow. Water deeper than this likely moves, if at all, on a scale of thousands of years or more. Separate models are developed for aquitards, dominated by non-carbonate strata, and the Knox aquifer, dominated by carbonate strata. The model notes that in the Knox aquifer a few hydrologically dominant cavity systems control groundwater movement in the saturated zone.

A comprehensive karst inventory of the ORR was conducted by Lemiszki et al. (Reference 2.5.1-239) to help understand the extent of and controls on the karst systems in the Oak Ridge area. Sinkholes, cave entrances, and springs were identified using 1942 aerial photography, detailed field mapping, reviews of existing reports, maps, drilling records, and word-of-mouth. The data were compiled on a topographic base map, as shown in the excerpt in Figure 2.5.1-40. The study concluded that most of the sinkholes occur in the Knox Group, followed by the Chickamauga Group, and the Conasauga Group. Lemiszki et al. (Reference 2.5.1-239) estimated that about 16 percent of the 555 sinkholes mapped were active. Caves occur only in the Knox Group, or the Maynardville Limestone of the Conasauga Group.

Cave development in the ORR was found to be strongly controlled by geologic structure and stratigraphy. Rubin and Lemiszki (Reference 2.5.1-240) synthesize a number of datasets, including karst inventory, cave survey, lithologic, and drilling data, to develop a model for cave development in the Oak Ridge area. Lithology is found to be a major factor; the thicker and purer limestone and dolomite units feature the larger and more extensive solution conduits. Figure 2.5.1-41 shows generalized geology with typical joint and bedding orientations within the

ORR. Site-specific characterization of the karst susceptibility of lithologic units is presented in Subsection 2.5.1.2.5.1.2.

In the Chickamauga Group of the White Oak Mountain Trust Sheet, where the CRN Site is located, Rubin and Lemiszki (Reference 2.5.1-240) find that the Rockdell, Benbolt, and Witten formations are the purest and thickest limestones, and the Fleanor Shale is a major potential barrier to down-dip conduit development. Chert beds, because of their thin bedding and closely spaced fractures, do not tend to inhibit dissolution. Bedding dip, faults, and fractures in the carbonates act as infiltration pathways and sites for potential dissolution. Groundwater flow is constrained by the presence of noncarbonate units, resulting in strike-parallel cave systems.

Downcutting due to fluvial erosion and karstification since the Pliocene has resulted in the preservation of large relict cave segments in resistant carbonate ridges of the Knox Group (Rubin and Lemiszki (Reference 2.5.1-240). Copper Ridge Cave (Figure 2.5.1-40) and Cherokee Caverns, located along strike about 10 mi (16 km) northeast of Copper Ridge Cave, are good examples (Figure 2.5.1-41). The master passages are strike-parallel and approximately horizontal, reflecting their formation in a phreatic environment. Vadose passages, formed above the water table, are oriented down-dip or along joints. A conceptual model for karst systems in the Oak Ridge area (Figure 2.5.1-42) illustrates the relationships among bedding dip, caves, other subsurface conduits, and surface topography (Reference 2.5.1-240). No evidence for hypogene karst processes has been documented in the caves of the Oak Ridge, Tennessee area, although thorough studies have yet to be conducted.

A detailed study of the West Chestnut Ridge site for a proposed waste disposal facility provides insights into the nature of the weathering profile, karst processes, and groundwater flow (Reference 2.5.1-241). West Chestnut Ridge adjoins the northeast boundary of the CRN Site (Figure 2.5.1-39), and is underlain by the Conasauga and Knox Groups. Ketelle and Huff (Reference 2.5.1-241) identify five karst zones that are stratigraphically controlled, each mapped as line of features along strike. Karst features include dolines (sinkholes or closed depressions), solution pans (gentle sunken areas with no topographic closure), open karst throat (funnel where water disappears, also swallow hole and swallet), and a hummocky slope attributed to possible raveling of soil into bedrock cavities. They postulate that some gullies initiate where laterally flowing soil water emerges.

The West Chestnut Ridge site is mantled by thick residuum in which mature soils, classified as paleudults, have developed. The residuum is generally devoid of carbonate minerals, except at its base near the bedrock contact. Based on 10 boreholes, residual soil of variable thickness overlies a zone of cavitose carbonate bedrock with mud and gravel-filled cavities. The cavitose zone ranges in thickness from 0 to more than 100 ft. Vertical cavity dimensions varied from 1 to 16 ft (Reference 2.5.1-241).

Groundwater flow in the West Chestnut Ridge site is strongly affected by karst porosity. Field permeability tests in the soil, bedrock, and weathered bedrock, found that the range in permeability values spanned four orders of magnitude. Dye injected into a swallow hole was detected at three locations along the Clinch River arm of the Watts Bar Reservoir, yielding a flow rate of 790 to 1250 ft/day (240 to 380 m/day), thought to represent the upper bound of groundwater movement for the West Chestnut site (Reference 2.5.1-241). The dye test suggests that subsurface flow may follow strike-parallel conduits during low flow conditions and well-up and rise to additionally flow beneath the surface drainage channels during high flow conditions.

In a separate dye tracing study, conducted in response to a sewer pipe break between buildings 3019 and 3074 at the ORNL (site X-10 on Figure 2.5.1-41), dye was injected into a seven-foot high cavity found beneath the ruptured pipe (References 2.5.1-242 and 2.5.1-243). The cavity had formed in limestone of the Chickamauga Group. Dye moved primarily to the east or

northeast, along strike, consistent with a model of groundwater movement controlled by solution cavities, joints, and fractures.

Evidence of deep groundwater flow has been documented within the ORR. Nativ and others (References 2.5.1-300 and 2.5.1-301) point to the presence of ancient brine at depths of more than 300 ft having geochemical signatures of partial recharge by recent waters, and to the presence of post-bomb contaminants at a depth of approximately 880 ft. Observed temperature and salinity anomalies in shallow groundwater system at ORR may be attributed to upward flow from the deep system. Nativ (References 2.5.1-300 and 2.5.1-301) also postulates that while the frequency of fractures and dissolution conduits generally decrease with depth, there are likely spatial variations where local fracture density increases and that these provide pathways for connectivity between the shallow and deep systems.

Hydrogeologists at the Tennessee Department of Environment and Conservation (TDEC) have noted evidence for connections between the shallow and deep aquifers at the ORR (Reference 2.5.1-299). Contaminants from the ORNL site are observed to flow southwest along strike through the deep aquifer.

The detection of shallow subsurface karst features using geophysical methods was studied by Doll et al., (References 2.5.1-244 and 2.5.1-245). The 1999 study examined the ability of different geophysical methods to detect a mud-filled void extending from 59 to 98 ft (18 to 30 m) depth discovered during installation of monitoring wells near the ORR Y-12 plant. Both microgravity and resistivity methods were able to detect the void. Seismic refraction data were not able to detect the void, but did detect two depressions in the bedrock surface beneath the soil. The Doll et al. (Reference 2.5.1-245) 2005 study evaluated both seismic reflection and seismic refraction data at the ORR. Seismic refraction surveys were conducted to assess the depth to bedrock and identify buried sinkholes, and were used successfully for these applications. Seismic reflection was less successful at detecting voids within the bedrock and was used primarily for mapping geologic structures. Conventional procedures for analyzing the data have inherent assumptions about the nature of the seismic velocity structure that conflict with the typical structures at karst sites, therefore they do not accurately represent the structure of the karst features. Seismic reflection studies were conducted to image bedrock structures such as faults. Karst was found to significantly influence the quality of stacked seismic reflection profiles. Doll et al. (Reference 2.5.1-245) note that similar to seismic refraction, attributes of karst structures, such as steeply dipping boundaries, rough interfaces, and laterally discontinuous interfaces are in conflict with the assumptions inherent in seismic reflection analysis.

Karst Features Inventory of the Site Area

Karst features of the 5-mi site radius (site area) were inventoried to understand the nature and extent of karst development and the distribution of karst features as a function of bedrock lithology, structure, and topography. The inventory is based primarily on the interpretation of LiDAR-based topographic data, but also includes review of the ORR karst inventory and other literature, and field reconnaissance of accessible sinkholes and caves. The results of the inventory include descriptions of the types of karst features present (Table 2.5.1-6), a map of karst features, calculations of depression density for each geologic unit (Table 2.5.1-7), and descriptions of cave passage geometry.

<u>Mapping of Karst Features</u>

Most karst features were mapped through the interpretation of LiDAR-based topographic data. The LiDAR data, along with orthoimagery, were collected in the spring of 2013. Derivative products were prepared in ArcGIS including a bare-earth digital elevation model (DEM), hillshade, contours (1 and 5 ft intervals), and slope map. Identification and delineation of karst

depressions was conducted in ArcGIS, beginning with an automated process to identify topographic depressions, followed by on-screen mapping and editing by geologists. During the editing process, geologists identified a large number of karst depressions that did not meet the minimum criteria used by the automated process (closed depressions at least two feet deep and 100 ft^2 in area). Each additional feature was noted by placing a point in the center of the feature, and classifying it as either a shallow depression, three-sided depression, or two-sided depression, as described in Table 2.5.1-6. Examples of these four depression types are presented in Figure 2.5.1-43. In November of 2013 TVA geologists field checked karst depressions that could be seen from public roads or visited with permission from ORNL (Figure 2.5.1-44). Selected field photographs of karst depressions are shown in Figure 2.5.1-45.

Karst depressions on the TVA CRN Property were mapped based on a combination of LiDAR topographic data, the 1973 site topographic map (Figure 2.5.1-46), and field reconnaissance conducted in July and November of 2013 (Figure 2.5.1-44). Excavation, backfilling, and grading of the site took place in the 1980s associated with the CRBRP (Reference 2.5.1-246). Karst features that had been removed, thus not visible in the 2013 LiDAR data, were identified and delineated from the 1973 CRBRP site topographic map.

Information to assemble the cave entrance inventory was obtained from the ORR karst inventory (Reference 2.5.1-239) and from cave entrance locations shown on USGS 7.5-minute topographic maps (Bethel Valley, Cave Creek, Elverton, and Lenoir City quadrangles). Field reconnaissance in November of 2013 included visits to the entrances of six of the twenty-four caves identified in the inventory. Speleologist Bruce Zerr, who had participated in the ORR karst inventory (Reference 2.5.1-239), provided additional cave information and accompanied the TVA team in the field.

The resulting map of karst features within the site area was compiled as a GIS database. This database provided the basis for the analysis of the distribution of karst features presented in the following section.

Distribution of Karst Depressions

The karst depression inventory identified a total of 2797 karst depressions within the site area, summing all 4 depression categories (Table 2.5.1-7). Of these, 1210 were classified as sinkholes at least 2 ft deep and 100 ft^2 in area. The combined area of the closed depressions meeting these criteria is shown in Table 2.5.1-7. This table also lists the depression data by geologic unit.

A frequently-applied method of assessing the degree of karstification of a landscape is to quantify the occurrence of karst depressions (dolines or sinkholes). While the method quantifies only a single class of karst feature, karst depressions are important not only as indicators of the presence of a subsurface drainage system, but also as topographic features that facilitate rapid entry of water into that system (Reference 2.5.1-247).

White (Reference 2.5.1-247) defined the parameter *depression density*, D_D, as the number of depressions, N_D, per unit area examined, A_K. Similarly, the *area ratio*, R_D, is the sum of the areas of all closed depressions per unit area examined, where $A_{D,i}$, is the area of individual depressions.

Depression density $D_D = N_D/A_K$

Area ratio $R_D = \sum(A_{D,i})/A_K$

The number of depressions can be obtained by identifying and counting the closed depressions on topographic maps. The contour interval on the topographic map limits the depth of the

depression that can be detected; the smaller the contour interval, the greater the number of depressions that can be potentially identified (Reference 2.5.1-247). The use of LiDAR topographic data in mapping of karst depressions can allow identification of depressions as shallow as one foot, allowing the identification of many more depressions than maps with a larger contour interval. Thus, the resolution of the topographic data must be accounted for when comparing different datasets.

Calculation of depression density and similar parameters has been applied in a number of studies in the eastern United States (e.g., References 2.5.1-25, 2.5.1-248, 2.5.1-249 2.5.1-250, and 2.5.1-251). The goal of these studies is to understand the factors governing the distribution and density of sinkholes, and in some cases to assess the hazard of future occurrence. Depression density may be compared spatially with the distribution of different lithologic units, the locations of joints, faults, folds, streams or anthropogenic features to understand the processes responsible for the patterns observed. D. Doctor et al. (Reference 2.5.1-252), in a study of Valley and Ridge karst in Virginia and West Virginia, found that the formation and occurrence of sinkholes and springs is most strongly controlled by bedrock lithology, joints, fold axes, and faults. Shofner et al. (Reference 2.5.1-25) compares sinkhole density with cave locations and found only weak correlation. He concluded that although both sinkholes and caves occur in carbonate rocks, areas with high sinkhole density may have a shallow groundwater table or low relief, restricting the presence of enterable caves, whereas cave entrances may occur on the flank of a bedrock slope beneath a caprock of sandstone, where sinkholes are less likely to occur.

Within the 5-mi radius site area, all mapped depressions, including those categorized as being without complete topographic closure, were included in the calculation of depression density. This metric allows a more complete characterization of surface karst features, and a robust comparison of the degree of karstification among the various units underlying the surface within the 5-mi site radius. Depression density values, however, should not be compared to other studies using different criteria.

The data clearly show concentrations of depressions in certain geologic units (Table 2.5.1-7, Figure 2.5.1-47). Depression density, D_D, was greatest in members of the Knox Group. Between twenty and thirty depressions per square kilometer were observed in the Mascot Dolomite, Longview Dolomite, Chapultepec Dolomite, and Copper Ridge Dolomite. Ten to twenty depressions per square kilometer were observed in four formations of the Stones River Group and in the Kingsport Formation of the Knox Group. The Witten and Rockdell Formation, members of the Chickamauga Group underlying the site footprint, average eight to nine depressions per square kilometer. Other members of the Chickamauga Group featured less than three depressions per square kilometer.

Data for area ratio, R_D or the area of all closed depressions per area of bedrock unit, show similar patterns, with a few significant differences (Table 2.5.1-7). Again, members of the Knox Group and Stones River Group have the highest area ratios, typically 1 to 3 percent. The Witten Formation of the Chickamauga Group, also shows an area ratio in this range. Several wide depressions likely account for this relatively high area ratio. The Longview Dolomite, which has a very high depression density, forms a steep-sided topographic ridge due to the presence of significant chert beds. Due to the steep slopes, depressions are typically of the two-sided and three-sided type that do not count toward the area ratio, thus the Longview Dolomite has a relatively low R_D area ratio. Area ratio data more closely correlate with the density of closed depressions, type D on Table 2.5.1-7.

The above analysis shows that geologic units having the highest depression density and area ratios are those characterized by thick and relatively pure carbonate lithology. These include the Knox Group dolomites, and the more pure limestones of the Chickamauga Group, Stones River

Group, and the Conasauga Group. Units that contain interbedded carbonate and clastic lithologies, such as the Benbolt and Five Oaks formations of the Chickamauga Group have a moderate number to few depressions, and those dominated by clastic material (sandstone, siltstone, shale), have very few to no depressions. The presence of chert in the carbonate does not appear to influence the number of depressions, but may influence the type of depressions present.

Cave Development

Caves in the study area are segments of underground dissolution passages that can be entered from the surface. The observed features of caves can provide information on the extent and patterns of subsurface dissolution that can be applied to passages that may be too small to be explored or that do not intersect the surface. The presence of extensive underground drainage systems is indicated by the presence of surface depressions, springs, and other karst features. As described in Subsection 2.5.1.2.5.1.2, cavities encountered in exploratory boreholes drilled at the site are further evidence of the presence of an underground drainage system.

Cave passages in the region can be placed into two categories based on the groundwater setting (Reference 2.5.1-35). *Vadose* passages form above the water table by water moving downward from the surface toward the groundwater table. Vadose passages tend to follow the steepest available openings such as vertical joints and dipping bedding planes. Their geometry can be described as slots, chimneys, shafts, pits, or canyons. *Phreatic* passages form at or just beneath the water table where groundwater flows laterally in the direction of the hydraulic gradient. The ideal phreatic passage is a tube-shaped conduit, reflecting dissolution on all sides in a water-filled passage. This shape is often modified by the geometry of joints and bedding planes, and the presence of less soluble strata.

As stream incision and landscape lowering proceeded during the late Tertiary and Quaternary, former phreatic passages were abandoned and left as dry cave passages beneath the hills (Reference 2.5.1-31). New phreatic passages formed at the present water table, along with vadose passages that reflect the new subsurface geometry. As the non-active solution passages, vadose or phreatic, come closer to the ground surface, they may partially fill with cave formations such as flowstone and stalagmites, or with soil from the ground surface above. The ceiling or walls may spall, forming breakdown blocks on the cave floor.

Twenty-four caves were identified in the 5-mi site radius, all of which formed in the Copper Ridge Dolomite, Chapultepec Dolomite, or Maynardville Limestone (Figure 2.5.1-47, Table 2.5.1-8). Descriptions of local caves were provided by Peter Lemiszki and Bruce Zerr. In November of 2013, TVA geologists accompanied by Mr. Zerr inspected the entrances of six caves, and conducted a geologic traverse of the interior of one cave (Figure 2.5.1-48). Brief descriptions of these caves and their genesis follow.

Cave Creek Cave is a small cave in the Mascot Dolomite that contains an active stream. Its entrance is located at the base of a bedrock wall at the margin of the valley, where the stream emerges to join the creek that flows through the valley bottom. The main passage extends horizontally northeast along strike beneath the hill of Mascot Dolomite. Several large sinkholes on the hill above probably discharge downward through enlarged vertical joints, the water exiting through Cave Creek Cave. Active stream flow and sediment transport is indicated by the presence of alluvial sand, silt, and fine gravel covering the floor of the cave, and the presence of the stream itself. The ceiling shows fresh dissolution features (Figure 2.5.1-48). This cave is a good example of an active stream passage developed along bedding strike.

Copper Ridge Cave, the largest cave in the site area, begins in a deep sinkhole on a hillside in the Copper Ridge Dolomite (Figure 2.5.1-40). The entrance passage is a stream-carved canyon

that takes local water collected on the hillside then flows underground down-dip for approximately 700 ft (Figure 2.5.1-48). A 400 ft-long linear segment of the entrance passage follows a prominent northwest-oriented joint set. The wall of the entrance passage shows evidence of small-scale dissolution at the intersection of joints and bedding planes (Figure 2.5.1-48). The passage eventually intersects a 40-ft diameter, 700-ft long tube-shaped passage extending along strike (Reference 2.5.1-240). This passage, now more than one hundred feet above the level of the Clinch River, is interpreted to be a relict phreatic passage formed when base level was higher (Reference 2.5.1-253). The passage is closed off by rubble at both ends where it intersects the present ground surface at the margins of two ravines.

Flashlight Heaven Cave is a smaller segment of a similar abandoned horizontal phreatic passage. The cave is a single flattened tube-shaped passage entered from the hillside, approximately 20 ft wide and 100 ft in length (Reference 2.5.1-254). Based on its close proximity to Copper Ridge Cave, this cave may represent a segment of the same system.

Smith Cave, located on the west bank of the Clinch River arm of the Watts Bar Reservoir across from the CRN Property, is also an abandoned segment of a phreatic passage. The entrance is 35 ft above the river where fluvial incision has cut across the passage, exposing it in the bluff. The cave, formed in the Chapultepec Dolomite, extends approximately 350 ft horizontally along strike, and ends in rubble. The passage is 20 to 30 ft wide and its original phreatic shape has been modified by the deposition of flowstone and breakdown of slabs of rock from the ceiling (Figure 2.5.1-48).

Other caves in the area show similar patterns of development. Three small caves at the north margin of the CRN Property occur in the Maynardville Limestone near the contact with the Copper Ridge Dolomite, and a fourth within the Copper Ridge Dolomite. These four caves are small, each less than 300 ft in length. Two are described as relict horizontal phreatic passages oriented along strike. Passage cross-sections are influenced by the dipping bedding planes, and by the partial sediment fill on the floor. The other two caves show passage development both along strike and down-dip. In the vicinity of Melton Hill Dam, a 400 ft-long cave appears to be developed along a northwest-striking joint. This cave passage is fairly linear, oriented northwest. It follows the dip of the bedding, rising gradually from its entrance at the base of the hill, and shows signs of ceiling collapse at the uppermost end.

Summary of Local Karst Development

Field inspection and descriptions of local caves in the 5-mi site area support the geologic model of cave development presented by Rubin and Lemiszki (Reference 2.5.1-240) for the Oak Ridge area. Cave development is strongly controlled by geologic structure and stratigraphy. Lithology is found to be a major factor; the thicker and purer limestone and dolomite units feature the larger and more extensive solution conduits, and the less-pure beds serve as barriers affecting passage size and network geometry. The orientation of the cave passages is influenced by bedding strike and dip, and joint orientation. The larger cave passages are typically relict phreatic passages that formed at the intersection of bedding and the groundwater table, and therefore are parallel to strike. A smaller number of passages are observed to follow northwest-striking joints. Vadose passages are steep to gently dipping and follow both dipping joints and bedding planes as water moves downward through these passages toward the water table.

Due to the long history of landscape lowering, abandoned or relict segments of cave passages are found at various levels beneath the hills of the site area. After abandonment, passages are divided into segments by surface erosion, and may partially fill with sediments, cave formations, and collapsed rock from the ceiling. Presently active phreatic cave passages are generally not accessible due to their position at and below the groundwater table.

The extent to which formation of these caves was initiated under deep phreatic conditions, including hypogenic conditions, is not known. The generally horizontal orientation of the major phreatic passages in the caves documented suggests shallow phreatic dissolution may have played a significant major role in their formation. However, the presence of deep cavities in water wells (Reference 2.5.1-292) suggests that deep phreatic dissolution is also taking place, and may have played a role in the inception of cave formation. No clear evidence of hypogene dissolution has been documented in the site area. Cave passage geometry is consistent with either phreatic or vadose dissolution. Secondary minerals characteristic of hypogene processes, such as travertine springs or exotic minerals in caves, are not documented. Most springs in the Oak Ridge Reservation have water chemistry typical of meteoric water (Reference 2.5.1-299).

2.5.1.2.5.1.2 Karst Processes and Features at the Clinch River Nuclear Site

Documentation of karst features at the site provides the technical basis for the development of a site-specific karst model. This section begins with discussion of the properties of the geologic units expected to influence the occurrence of karst dissolution, including carbonate content, bedding characteristics, and jointing. Karst features at the site are then documented. Features consist primarily of karst depressions (also known as sinkholes or dolines) observed on the ground surface (Figure 2.5.1-37), and cavities encountered in boreholes. The data are based on geologic mapping and field reconnaissance, and on geotechnical investigations conducted for the CRBRP (Reference 2.5.1-100) and the CRN Site. Finally the site-specific karst model is presented.

Karst Susceptibility of Site Stratigraphic Units

The susceptibility of a stratigraphic unit to karst development is strongly dependent on its properties, especially composition, bedding, and jointing characteristics. The following section presents data on the chemical and mineralogic composition of the stratigraphic units present at the site, and describes their bedding and jointing.

<u>Rock Composition</u>

The stratigraphic units of the Chickamauga Group that underlie the site are composed of varying proportions of calcite, dolomite, sand, silt, clay, and chert. The stratigraphic column presented in Figure 2.5.1-37, provides general lithologic descriptions. Within each unit are compositional variations among the different beds. During the 2013 geotechnical investigation, samples were taken from representative beds of each unit for mineralogic, chemical, and petrographic testing. The results of these tests, presented in Table 2.5.1-9, provide information on the percent carbonate (calcite and dolomite), a primary indicator of the susceptibility of a rock type to karst dissolution. Additional mineralogic data from rock core samples drilled for the CRBRP (Table 2.5.1-10) (Reference 2.5.1-100) are incorporated into the analysis.

The data show a range of composition in the site strata tested (Table 2.5.1-9, Sheet 1 and 2.5.1-9, Sheet 2). Significant differences in carbonate content are noted among the stratigraphic units and within each unit, shown graphically in Figure 2.5.1-49. Geologic units with the highest carbonate content are the Mascot Dolomite, the Eidson Member (included in the Blackford Formation in Figure 2.5.1-37), and the Rockdell and Benbolt Formations. The Fleanor Shale, Blackford and Bowen Formations have relatively lower carbonate contents. Regardless, carbonate is a significant component of every stratigraphic unit tested. The variability in carbonate content within any given unit (Figure 2.5.1-49) reflects the alternating interbeds of carbonate-rich and clastic-rich strata observed in the core, and typical of the Chickamauga Group with Bethel Valley (Reference 2.5.1-9). Mineralogic analyses show that the non-carbonate component is dominated by quartz, including silt, sand, and chert, with minor mica, feldspar, iron oxide, and clay.

Bedding and Jointing

Bedding planes, joints, and fracture zones constitute the initial pathways for water to penetrate the rock and begin the process of dissolution. An understanding of their orientations and spacing can help predict likely dissolution patterns. Detailed descriptions of bedding, jointing, and fracture zones are provided in Subsection 2.5.1.2.4.

Borehole contacts show that bedding is consistently oriented N52°E33°SE (Reference 2.5.1-100). Data from borehole contacts also show generally planar bedding contacts between formations within the Chickamauga Group. In contrast, the contact between the Knox Group (Mascot Dolomite) and the Chickamauga Group (Blackford Formation) is irregular at the site scale, reflecting a major erosional unconformity (Figure 2.5.1-73).

Joints encountered in the core are consistent with regional joint sets and with joint orientations recorded in boreholes drilled for the CRBRP (Reference 2.5.1-100). The CRBRP reported primary joint orientations of N52°E37°SE, N52°E58°NW, N25°E80°SW, and N65°W75°N (Reference 2.5.1-100). Discontinuity orientation data from borehole ATV and outcrop measurements collected for the CR SMR Project show that Joint set 1, oriented N60°E59°NW, is the dominant joint set at the site. Joint set 2 has an average orientation of N60°E38°SE. Minor high angle joint sets are oriented at N60°E73°SE, N40°W74°SW, and N38°W73°NE.

Karst-Related Surface Features at the Site

Karst-related surface features at the site include large funnel-shaped and dish-shaped sinkholes, and small holes in the ground. Surface features were identified by both the CRBRP and CRN Site investigations. Inspection of the CRBRP site topographic map (Figure 2.5.1-46) reveals several closed depressions, identified as sinkholes and delineated on the CRBRP site geologic map (Figure 2.5.1-46). Two major sinkhole clusters are identified, one in the Knox Group (at the contact between the Kingsport Formation and Mascot Dolomite) and the other in the Chickamauga Group (Witten Formation) (Figure 2.5.1-45). The CRBRP investigation drilled nine exploratory holes (B-60 through B-68) in the Knox Group sinkhole cluster. Soil thickness was found to vary markedly, from 2 ft at the margin of the sinkholes, to as much as 78 ft within a sinkhole. Solution voids up to four feet high were encountered below the top of rock. The sink area was found to be aligned along a high-angle northeast striking (N52°E) joint set (Reference 2.5.1-100).

The CRBRP map (Figure 2.5.1-50) also shows a line of small holes in the Unit B limestone (Rockdell Formation) along the contact with the Unit A siltstone (Fleanor Shale). The holes are described as one to two feet in diameter and three to ten feet deep, and were interpreted to represent raveling of material into solution-widened joints (Reference 2.5.1-100). One 15-ft-wide sinkhole in the Rockdell Formation was investigated by four boreholes. The top of rock illustrated the irregularity of the limestone rock surface due to solutioning along joints. Soil seams and voids up to three feet in height were encountered in the limestone. No solution, weathering or drilling water losses occurred below the contact with the Fleanor Shale (Reference 2.5.1-100).

Mapping of surface features for the Clinch River ESPA Project using high resolution LiDAR topographic data identified the same two major sinkhole clusters, along with several additional sinkholes. Compare Figure 2.5.1-50 and Figure 2.5.1-37. Field reconnaissance shows that the large sinkhole complex in the Witten Formation consists of a large dish-shaped closed depression approximately 800 ft long by 300 ft wide, elongated along strike. The eastern end of this depression contains a steep-sided swallet with a vertical bedrock wall, corresponding to the prominent joint set striking N52°E. Based on field observations, water appears to collect and sink rapidly into the ground at this location. The western end of the larger depression is dish-shaped with a flat floor (Figure 2.5.1-45). At the time of inspection it was covered with a thin film of silt,

evidence of recent standing water. A small swallet was located at the margin of this depression. Fill now covers the southern portion of the depression.

Grading of the site during the 1980s removed some surface karst features identified by the CRBRP. A complete set of sinkholes identified by both projects is overlain on the 1973 site topographic map in Figure 2.5.1-46.

Karst-Related Subsurface Features at the Site

Karst subsurface features consist of dissolution features formed from movement of vadose and phreatic groundwater along bedding planes and joints within the rock. The primary documentation of these dissolution features comes from boreholes, Boreholes, however, provide a poor indication of the actual extent and geometry of dissolution. Due to their small diameters and the large distances between borings compared to the likely geometry of the dissolution network, boreholes show only a small fraction of the dissolution features present. However, the presence of cavities is a positive indication of the presence of a dissolution network. An understanding of the expected patterns of dissolution must be relied on to complete the picture. The occurrence of cavities in boreholes is analyzed and discussed with respect to elevation and lithologic unit.

Seismic refraction surveys are useful to image near-surface karst features such as an irregular top of bedrock and shallow cavities (References 2.5.1-255 and 2.5.1-256). This method and other geophysical methods are often used in karst terrain to complement borehole analysis. A seismic refraction survey, consisting of six lines, each 500 to 600 ft in length, was conducted at the site to map depth to rock (Figure 2.5.1-29) (Reference 2.5.1-214). These surveys were conducted primarily in areas that had been graded as part of CRBRP construction activities. The soil and rock under the high points had been removed, and fill had been emplaced in the low points to create a planar ground surface. The resulting tomography models, therefore, primarily delineate the top of bedrock and the margins of the fill (Figure 2.5.1-86). The seismic refraction tomography profiles show the general shape of the top-of-rock. Where they can be correlated, the borehole top-of-rock corresponds to a compressional wave velocity (V_p) of 7,000 ft/s to 11,000 ft/s. The thickest fill is shown on Figure 2.5.1-86, Sheet 6, along line SRS-6 located within the 1983 CRBRP excavation. Here, the bottom of the excavation at 712.5 ft MSL corresponds to a V_p of about 11,000 ft/s. No features were observed in the seismic refraction data that could clearly be attributed to karst phenomena.

Additionally, two seismic reflection survey lines were completed at the site during the CRN Site field investigation (Figure 2.5.1-36, Subsection 2.5.1.2.4.2.1). Both seismic reflection profiles show planar beds of uniformly dipping strata. The types of large-scale karst-related stacked sag structures and associated small faults observed in the Biscayne Bay, Florida, seismic reflection profiles (Reference 2.5.1-41) (Figure 2.5.1-84) are not visible in the CRN lines, nor on a seismic reflection profile along Tennessee route 95 on the ORR in the CRN Site vicinity. The uniformity of the planar beds imaged by these seismic reflection profiles is evidence for the lack of any large-scale karst collapse or stacked sag features along these survey lines.

An additional source of subsurface information is documentation of the condition of the rock exposed during the 1983 excavation for the CRBRP foundation. The Fleanor Shale and Rockdell Formation strata were exposed during the excavation. Continuous exposure of rock provides a more robust picture of the dissolution network than borehole data. Geologic mapping and documentation of karst features in the excavation (Reference 2.5.1-303) are summarized below.

Karst Features Observed in Boreholes

Soil borings show an irregular top-of-rock beneath the soil mantle. The soil-rock interface, termed the *epikarst* zone (Reference 2.5.1-7, p. 120) is characterized by an irregular bedrock surface. The epikarst zone represents the dissolution weathering front, where downward penetrating water encounters soluble bedrock. The CRBRP PSAR (Reference 2.5.1-100) reports that the soil-rock contact is typically quite irregular, exhibiting rock pinnacles and intervening gaps. These irregularities are developed by solution-widening along joints and to a lesser degree along bedding planes. The wide range of soil depths over the top of rock reflects these irregularities. Due to grading of the site during the 1980s, the irregular bedrock surface is best expressed in the CRBRP soil borings and in the CRN Site soil borings outside the graded areas. In a few of these CRN Site soil borings, blow counts are observed to decrease with depth consistent with dissolution of the rockhead and loss of the deepest horizons of the soil into slots and cavities in the rock.

Cavities, both open and clay-filled, were encountered in rock core borings drilled at the site. A total of 238 cavities, defined as being at least 0.1 ft in height in the core, were logged in rock core borings, including borings from the CRBRP drilling program (Reference 2.5.1-100) and the CRN Site drilling program (Table 2.5.1-11). Of the 180 rock core borings drilled at the site (104 for the CRBRP and 76 for the CRN Site), 75 borings, or 42 percent, encountered one or more cavities (Table 2.5.1-11). This number should be considered a minimum as not all possible solution features were logged as cavities. The CRBRP borings encountered clay intervals up to 8 ft thick in five borings (Reference 2.5.1-100). The clay was described as similar to the overburden residual soils and interpreted to represent in situ weathering. Alternatively, these intervals could represent cavities that have been filled with soil washed in from above. Weathered and fractured zones were encountered in some CRN Site borings where core losses of 1 to 3 ft took place. Dissolution is likely to have played a role in the weathering of these zones, as the lithologies are calcareous.

The frequency and size of cavities generally decrease with depth, and are observed to be greater in units with higher carbonate content (Figure 2.5.1-49, Figure 2.5.1-51). Cavity size is inferred from the observed height of that cavity in the borehole; cavity height yields no information regarding the lateral extent of that cavity. Cavities were encountered in boreholes drilled in every stratigraphic unit within the footprint of the proposed excavation, including the Blackford Formation, Eidson Member, Fleanor Shale, Rockdell Formation, and Benbolt Formation (Table 2.5.1-11). The number of borings in each unit varied and therefore the number of apparent karst features per unit may not be representative. Regional surface expression of karst is a better indicator of unit susceptibility (Plate 1; Figure 2.5.1-37; Table 2.5.1-7). The greatest number and the apparently largest cavities were encountered in borings in the Rockdell Formation, where over one hundred cavities were encountered, ranging up to 16.5 ft in height. In the Eidson Member, which is similar in composition to the Rockdell Formation but one-third the thickness, 56 cavities were encountered ranging in size up to 11 ft in height. In the interbedded siltstone and limestone of the Blackford Formation 30 cavities were encountered up to 2.5 ft in height. Finally, in the Fleanor Shale, with the lowest carbonate content of the group, 19 cavities were encountered up to 1.4 ft in height.

The distribution of cavities in cross-section illustrates the influence of lithology and bedding planes on karst development (Figure 2.5.1-51). Boreholes from both the CRBRP and the CRN Site are projected onto a plane oriented perpendicular to strike, with cavities indicated by red flags. The largest and most numerous cavities are observed in the Rockdell Formation and Eidson Member. Smaller and fewer cavities were encountered in the Blackford Formation, Fleanor Shale, and Benbolt Formation. Within the Rockdell Formation, the larger cavities appear to be aligned along bedding, suggesting the influence of bedding planes and lithologic variability among individual limestone beds. In two boreholes, the cavities occur within a pure limestone

bed of Rockdell subunit D above the contact with a calcareous siltstone bed at the top of Rockdell subunit C (Figure 2.5.1-51). Here, dissolution appears to be localized in the subunit D limestone as water flows down-dip along the less soluble bed of subunit C. Natural gamma radiation downhole logs show a strong contrast in gamma-ray signal across the subunit C/D contact, suggesting the calcareous siltstone bed has significant clay content, increasing its effectiveness as an impermeable layer.

The frequency of cavities encountered in boreholes increases with increasing elevation, consistent with the generally surface-intensive nature of karst processes. Figure 2.5.1-52 plots the elevation of each cavity encountered by both the CRBRP and CRN Site borehole programs against its length, and shows the percent cavities encountered in the rock core in 50-ft elevation intervals from 600 to 900 ft elevation. The cavity percentage decreases from 9.3 percent between 850 and 900 ft, to 0.2 percent between 650 and 700 ft (Figure 2.5.1-51). No cavities were encountered below 650 ft. Most cavities occur above the level of the Watts Bar Reservoir (740 ft). The concentration of cavities in this zone is consistent with karst dissolution taking place both above the water table (vadose dissolution) and at the water table (shallow phreatic dissolution). Long-term landscape lowering will have raised former phreatic conduits into the vadose zone through time. Thus, some cavities encountered in the present vadose zone may be originally phreatic in origin.

A few important cavities were encountered below the level of the reservoir, as low as 660 ft elevation (Table 2.5.1-10, Figure 2.5.1-52). Assuming that the pre-reservoir groundwater level had been no lower than the bed of the Clinch River, 719 to 720 ft (Reference 2.5.1-100), these cavities formed more than 60 ft below the groundwater table; (i.e., the piezometric surface beneath the hills would have been higher and inclined toward the water surface of the river). The presence of these cavities suggests that deeper groundwater circulation is taking place.

Trends in the frequency of cavities seen in the boreholes at the CRN Site show good correlation with observation well data. The occurrence and size of open fractures is greatest within the first hundred feet of the ground surface approximately (Figure 2.5.1-51, Figure 2.5.1-52). Packer tests at the site indicate that hydraulic conductivity decreases at depths greater than 100 to 150 ft below ground surface (see Subsections 2.4.12.1.4.1, 2.4.12.2.4.1 for additional details) consistent with a decrease in cavity frequency with depth. Additionally, precipitation events result in increased water levels in some observation well clusters in all screened intervals, from the upper screened intervals (15 to 105 ft below ground surface) down to the deep screened intervals (up to 297 ft below ground surface). These data indicate that meteoric water is able to permeate vertically through the formation, suggesting zones of high connectivity in the near surface, but also deeper. These data also suggest that the rate of flow at depth is likely much lower than in near surface elevations, consistent with regional trends.

A number of the cavities encountered in the boreholes were partially to completely filled with clay or soil. Drilling procedures allowed for the collection of soil samples from these cavities. Selected samples were examined visually in the field to gain insights into the origin of this material. At issue was whether the soil constituted residual material derived from dissolution of the adjacent rock, or foreign material transported into the cavity through either a horizontal conduit system or a vertical system of enlarged joints and dipping bedding planes. Most soil samples appeared to be derived either from the residuum of the rock in which they were found, or from the residual soil overburden that may have washed down through a vertical dissolution system.

In a single boring drilled for the CRBRP in the large sinkhole complex in the Knox Group, rounded grains were found in the cavity fill, suggesting possible alluvial transport (Reference 2.5.1-100). This sinkhole complex is aligned with a linear valley that extends across much of the peninsula (Figure 2.5.1-46). The sinks and the linear valley may be relict expressions of a former a phreatic conduit system extending across the peninsula along a

strike-parallel vertical joint. If so, the rounded grains could represent Clinch River alluvium transported through this system.

Fifteen boreholes penetrated shear-fracture zones during the subsurface investigation (Reference 2.5.1-214; see Table 2.5.1-17). Core recovered from 100- and 200-series borings in shear-fracture zones is commonly described as calcite-healed, with rock quality generally described as high with moderate to high core recovery (Reference 2.5.1-214; see Subsection 2.5.1.2.6.4). Shear fracture zones do not appear to be loci for accelerated dissolution relative to adjacent rock.

Karst Features in the CRBRP Excavation

The results of the CRBRP site investigation can be used to enhance and further inform the understanding of the geology and engineering suitability of the CRN Site. Excavations for the CRBRP were virtually complete before the project was cancelled in November of 1983. The excavations were mapped and described in detail prior to backfilling to provide documentation of the geology and structure exposed during the excavation (Reference 2.5.1-303) (Figure 2.5.1-88). Two excavations were made, a large excavation (480 ft long x 360 ft wide, and 100 ft deep) for the nuclear island (Figure 2.5.1-54) and a smaller excavation (180 ft x 180 ft shallow depth) for the Equalization Basin. The nuclear island excavation extended to an elevation of 712.5 ft MSL, with 75-ft-high near-vertical faces on the north, east, and south sides, and a 26-degree slope on the west side (References 2.5.1-100, 2.5.1-246, and 2.5.1-257).

The nuclear island excavation exposed the Fleanor member, a dusky red, shaley, calcareous siltstone with thin interbeds of limestone, over most of the walls and floor. The southeast wall exposed the Rockdell Formation. The Fleanor member exhibited deep chemical weathering of siltstone strata, with minor dissolution of its thin limestone interbeds (Reference 2.5.1-303). The siltstone was fresh at the base of the excavation, but found prone to slaking and disintegration upon exposure to weathering. Joints in the weathered zone at the top of the excavation were open or clay filled, and became less frequent and tight with depth within the unweathered rock. Similarly, the frequency and the extent of dissolution features were found to decrease with depth.

Limestone beds of the overlying Rockdell Formation were exposed on the southeast wall of the nuclear island excavation and contained a concentration of solution cavities at an elevation of approximately 780 ft MSL (Figure 2.5.1-89). The cavities had a maximum radius of a few feet, with lengths ranging “from a few feet to several tens of feet” along discontinuities (Reference 2.5.1-303). Most cavities were partially filled with lateritic clay and silt. Cavities exposed during the excavation were cleaned and plugged with concrete.

The excavation mapping report (Reference 2.5.1-303) does not mention the presence of dissolution cavities within the Fleanor member. A brief statement by geologists Rubin and Lemiszki (Reference 2.5.1-240) confirms that the greatest number and largest cavities occurred in the Rockdell Formation, and comments on small cavities within the Fleanor member as well:

> “…during foundation construction a number of cavities were revealed with average diameters of 0.5 to 1 m. The largest cavities occur in the thick to massive limestone beds of the Rockdell Formation.”… “In addition a surprising number of small cavities are present in the mudstone-rich Fleanor Shale.”

An example of similar small cavities may be the dissolution-enlarged joints observed in thin interbeds of limestone of the Blackford Formation in a road cut exposure in the City of Oak Ridge, Tennessee (Figure 2.5.1-55). Dissolution is restricted to the approximately 1 ft-thick limestone beds, which are bounded between adjacent beds of calcareous siltstone. The cavities are now filled with soil.

The excavation mapping report concluded that the site was suitable for development of the proposed facility or other industrial facilities based on the character of the rock exposed (Reference 2.5.1-303). The planned foundation level of the CRBRP, 714 ft MSL, was below the zone of weathered siltstone observed in the excavation, and the limestone at that elevation was found to be hard and sound. No cavities were described on the floor of the excavation. Any weathered siltstone found to be soft and prone to disintegration and slaking would be mitigated by the planned concrete base mat.

Karst Model for the Site

The conceptual model for karst development at the CRN Site, presented below, is developed to be consistent with concepts, observations and data derived from regional, local, and site-specific studies. The model is partially illustrated in Figure 2.5.1-73 and described by the following points:

1. The bedrock surface beneath the mantle of residual soil is undergoing dissolution from downward penetrating meteoric water, resulting in an irregular top of rock with pinnacles and intervening dissolution slots, or cutters, formed along vertical joints. Soil filling the slots can trickle down into dissolution cavities within the rock, creating voids which may stope upwards through the soil and collapse or subside to form sinkholes.

2. The soil-bedrock interface, termed the *epikarst* (Reference 2.5.1-7, p. 120), is characterized by soft soils, cavities, and shallow groundwater. Rainwater (stormflow) is temporarily stored in the epikarst zone, draining both laterally along the top of bedrock, and downward through enlarged bedrock joints into the deeper karst system.

3. At the CRN Site, evidence of both vadose (above the water table) and phreatic (below the water table) dissolution is present and appears to be controlled by the structure of the subsurface strata (i.e. bedding planes, joints, and fractures). Karst dissolution is clearly evident in the cavities encountered in boreholes and in cavities observed in the walls of the CRBRP excavation.

4. The dominant orientation of phreatic dissolution pathways is strike-parallel. Groundwater flow is constrained by low-carbonate units, resulting in strike-parallel drainage systems. Phreatic conduits are localized in the high-carbonate beds, often near the intersection of a bedding plane or high angle-strike-parallel joint. Additional dissolution pathways occur down-dip following bedding planes and lithologic contacts, and along joints.

5. The thicker and purer carbonate beds have larger and more numerous cavities and sinkholes. The Rockdell, Eidson (member), Benbolt, and Witten formations, the most carbonate-rich units in the Chickamauga Group, have relatively higher numbers of sinkholes and borehole cavities than other units. The Fleanor, Blackford, and Bowen formations the most carbonate-poor units in the Chickamauga Group, have no mapped sinkholes and smaller and fewer borehole cavities than other units.

6. Cavities in the carbonate-poor units occur within thin carbonate interbeds. The siltstone itself is calcareous and weathers primarily by dissolution; however, it leaves a silty residuum which inhibits the development of continuous conduits.

7. Long-term erosion, stream incision, and landscape lowering have resulted in older dissolution passages formed in the phreatic zone being abandoned, segmented, filled with sediment and flowstone, and ultimately collapsed. Rock above the present groundwater table may contain any combination of active vadose passages and abandoned and/or filled vadose and phreatic passages.

8. Borehole data show that subsurface dissolution is most intense near the surface and decreases steadily with depth. Small numbers of cavities are observed below the water table. This is consistent with observations of decreased fracturing frequency and groundwater flow rates with depth in the ORR studies (Reference 2.5.1-9).

9. Direct evidence of hypogene dissolution processes is not documented at the CRN Site or within the ORR. Most evidence is consistent with dissolution by epigenetic processes in the vadose and phreatic zones. This evidence includes the decrease in frequency of fractures and dissolution cavities with depth in boreholes (Reference 2.5.1-214), phreatic passage geometry and morphology of known caves and solution conduits within the ORR (References 2.5.1-240, 2.5.1-244, and 2.5.1-253), and the lack of secondary minerals characteristic of hypogene processes. Springs in the ORR have water chemistry typical of meteoric water (Reference 2.5.1-299), rather than warm, mineral-rich waters of hypogene springs (Reference 2.5.1-296). Finally, seismic reflection profiles across the site show continuous, uninterrupted bedding at depth beneath the site suggesting that large hypogenic karst collapse features are not present, at least along the two dimensional profile lines.

   Lack of evidence for hypogene processes does not necessarily mean these processes were not active in the past or may occur at great depths in the present. Geotechnical explorations and field observations focus on the near-surface. In addition, paleohypogenic karst features may have been significantly modified or erased by more recent epigenic processes.

10. Evidence from local groundwater studies supports deep phreatic dissolution in the CRN site vicinity. The occurrence of deep phreatic processes is consistent with the presence of favorable factors such as long flow paths, steeply dipping strata, faults and/or fractures, rock types that are susceptible to dissolution, and locally confined and/or semiconfined aquifers. Groundwater studies in the ORR area by Nativ and colleagues (References 2.5.1-300 and 2.5.1-301) show contamination of the deep aquifers by hazardous wastes originating on the ORR, indicating relatively rapid penetration of meteoric waters to depths of more than 800 ft (Reference 2.5.1-300). Wolfe et al (Reference 2.5.1-292) note the presence of cavities in water wells to depths greater than 600 feet.

Karst was characterized at the CRN Site by an initial review of regional and local karst literature and data, followed by collection of new data for the site area and the site itself. A number of subsurface investigations were performed at the CRN Site to evaluate the presence or absence of karst. These studies included (1) geotechnical boreholes to a minimum elevation of approximately 260 ft NAVD88 (540 ft depth) and angled boreholes specifically for karst evaluation, (2) two seismic reflection lines, (3) field reconnaissance and mapping of surficial karst features in the site area, (4) consideration of observations from the previous CRBRP excavation, (5) evaluation of hydrothermal activity in the site region, (6) mineralogy and geochemistry of karst features, (7) review of karst models provided by others for the AGV of Virginia, and (8) comparison of karst features at the CRN Site to potential karst analogues in Florida.

To provide a more detailed delineation of karst features below the floor of the proposed excavation, a surface geologic mapping and subsurface exploration program will be implemented during site excavation as described in Subsection 2.5.1.2.6.10.

2.5.1.2.5.1.3 Potential Karst Hazard at the CRN Site

The CRN plant structures may be placed in deep excavations that will likely extend approximately below the level of the Watts Bar Reservoir. Overburden soils and cavities associated with dissolution near the top of rock will be removed during the excavation process. Therefore, there is little hazard of a cover-collapse or subsidence sinkhole, the most common sinkhole type in the site area. However, cavities have been observed in boreholes as deep as

660 ft elevation (Table 2.5.1-11). A complete understanding of the extent and spatial distribution of these cavities or other potential karst cavities contains some uncertainty; however, the significant amount of data collected at the CRN Site during this investigation, as well as during past investigations and excavations, provides a comprehensive understanding of the karst setting within approximately 300 ft of the ground surface.

These cavities pose three types of potential karst hazards to the proposed structures.

First, the potential presence of cavities in the excavation walls below the groundwater table may pose a hazard to the safety of the excavation; Groundwater may discharge from the cavities, making it difficult to maintain a dry excavation, and the water may affect slope stability during construction. If the cavities are small or discharges are small, they may be mitigated, for example, by grouting. If they are large or are discharging large volumes of water, grouting may be difficult or ineffective. A large cavity with a high discharge may represent a segment of an active phreatic passage. The CRBRP (Reference 2.5.1-100) anticipated this potential hazard. However, documentation from the CRBRP excavation into the Fleanor Shale show the excavation to have been relatively dry (Reference 2.5.1-257).

Second, the presence of cavities below the base of the foundation may require mitigation to ensure foundation stability. Small cavities that are exposed in the excavation floor or wall can be mitigated, for example by grouting. Slightly deeper cavities that cannot be seen may be detected using geophysical methods or boreholes in the finished excavation. If detected, engineering analyses can determine the appropriate mitigation for these cavities. Additional measures to confirm understanding of karst hazard at the CRN Site are discussed in Subsection 2.5.1.2.6.10. Final conclusions regarding karst hazard will be based on detailed geologic mapping of the excavations and geophysical surveys at foundation level.

Third, the presence of cavities can enable rapid movement of an accidental release. Accidental releases are evaluated in Subsection 2.4.13.

2.5.1.2.5.2 Other Local Geologic Hazards

Other local geologic hazards are discussed in this section including slope failure, unrelieved residual stresses, and the effects of human activities. Slope failure, or landsliding, is known to occur in the site area especially where slopes are steep. A geomorphic process that results in non-tectonic surface deformation, slope failure is discussed in Subsection 2.5.3, Surface Deformation.

The potential for unrelieved residual stresses in the bedrock or soil can be evaluated from an understanding of the geologic history of the Clinch River area. As described in Subsection 2.5.1.2.4, the CRN Site last experienced major tectonic uplift in the Pennsylvanian and Permian periods during the Alleghanian orogeny, which caused the folding and faulting observed today. At this time the Paleozoic strata on which the site is located were uplifted and gently folded. As described in Subsection 2.5.1.1.4.3.1, the CRN Site is located in the Eastern U.S. stress regime, which is characterized as a broad and consistent stress field. The history of the CRN Site since the Alleghanian orogeny has been one of steady weathering and erosion.

Locally, the stress regime can be characterized as an unloading condition. Weathering and erosion have been relatively slow, allowing for gradual release of stress. Stress relief may be expressed in more closely spaced joints near the surface. There was no past glacial loading. These conditions are not conducive to high residual stresses in the rock.

Human activities such as mining, hydrocarbon extraction, and groundwater withdrawal have the potential to cause surface deformation. The effects of human activities are discussed further in

Subsection 2.5.1.2.6.8. Underground mining tunnels, shafts and adits can collapse, withdrawal of groundwater or hydrocarbons can result in subsidence of the ground surface. In some cases, lowering of the groundwater table may trigger sinkhole formation.

Underground mining and petroleum and gas extraction have not taken place at the site. Open-pit mines and quarries are present in Roane County, extracting limestone, crushed stone and similar products, primarily for the construction industry. No underground mines are present on the CRN Property. Therefore, subsidence due to mining and mineral extraction is not a potential hazard.

Significant groundwater withdrawal is not occurring at the site, and construction and operation plans do not call for significant use of local groundwater. Regardless, the hard limestone bedrock is not susceptible to intergranular subsidence. Therefore, subsidence due to groundwater withdrawal is not a potential hazard.

2.5.1.2.5.3 Evaluation of Local Geologic Hazards

The primary geologic hazard to the CR SMR Project is the potential for karst dissolution processes and features to compromise the safety of the excavation, or the stability of the foundation, or to enable rapid movement of groundwater. It is anticipated that these karst hazards, if present, can be mitigated by geotechnical techniques during the construction process. To more fully describe karst features and enable planning of appropriate mitigation, geologic conditions of the walls and floors of safety-related excavations will be mapped in detail and characterized (Subsection 2.5.1.2.6.10).

2.5.1.2.6 Site Engineering Geology

Evaluation of the engineering geology conditions beneath the power block area at the CRN Site is performed based on a review of existing site-specific reports, geologic and geotechnical investigations and geologic literature.

The CRN Site is founded on bedrock belonging to the Knox and Chickamauga Groups. The discussions that follow focus on geologic features that may affect the bedrock. Engineering soil and rock properties, compressibility and liquefaction potential are discussed in Subsection 2.5.4 and natural and man-made slope stability issues are addressed in Subsections 2.5.3 and 2.5.5, respectively.

2.5.1.2.6.1 Summary of Subsurface Conditions

To evaluate the subsurface conditions at the CRN Site, a subsurface investigation program was executed. A total of 82 geotechnical borings (including the 6 soil borings) (MP 100-series, MP 200-series, MP 400-series, and CC-series) were drilled and sampled. Soil boring and rock coring logs are presented in Appendix B to Reference 2.5.1-214. The locations of the borings are shown on the boring location plan on Figure 2.5.1-31. The ground surface elevation within the power block area ranges from approximately 855 ft North American Vertical Datum of 1988 (NAVD88) (MP-406) to approximately 780 ft NAVD88 (MP-207). Ground surface elevations beyond the power block area in the areas explored ranges from about 855 ft NAVD88 to about 760 ft NAVD88 (MP-407).

The bedrock stratigraphy at the CRN Site is presented in Subsection 2.5.1.2.3. The stratigraphic units underlying the power block area are predominantly the Newala Formation, belonging to the Knox Group, the Blackford Formation, the Lincolnshire Formation (Eidson and Fleanor Members), and Rockdell and Benbolt Formations belonging to the Chickamauga Group (Appendix B.1 Reference 2.5.1-214). The stratigraphic units encountered at the site are shown on a cross-section on Figure 2.5.1-30.

The bedrock structure at the CRN Site is presented in Subsection 2.5.1.2.4. Information on the orientation of the bedding planes and fractures is from downhole ATV logging performed at the site in 27 borings. The results of the ATV logging are presented in Reference 2.5.1-214, Appendix C. In addition to the ATV logging, discontinuities are also characterized from geologic field mapping performed at the site. Fracture zones and shear-fracture zones present at the site are described in Subsections 2.5.1.2.6.3 and 2.5.1.2.6.4.

The footprint of the power block area is shown on Figure 2.5.1-31. Final grade elevation at the site is estimated to be 821 ft NAVD88. The shallowest foundation level within the power block area is estimated to be approximately 80 ft below the final grade (El. 741 ft NAVD88) and the deepest foundation level is not expected to exceed a depth of approximately 138 ft below final grade (El. 683 ft NAVD88).

2.5.1.2.6.2 Rock Mass Characterization

The Geological Strength Index (GSI) classification system is used to characterize the bedrock stratigraphic units at the CRN Site. The GSI is used to develop rock mass strength properties using the Hoek-Brown failure criterion and deformation properties for each of the stratigraphic units for foundation design purposes as described in Subsection 2.5.4.

Subsequent to the well-known Rock Mass Rating (RMR) and Q classification systems (References 2.5.1-258, 2.5.1-259, and 2.5.1-260) developed for the estimation of underground excavation and support, the GSI classification system has been developed for the estimation of rock mass properties and is a key input parameter in the Hoek-Brown failure criterion. Originally developed by Hoek et al. (Reference 2.5.1-261) as a hard rock system, the system expanded to include poor quality rock masses (References 2.5.1-262, 2.5.1-263, and 2.5.1-264) and the development of the GSI chart which is based on the blockiness of the rock mass and the condition of the discontinuity surfaces in the rock mass. An essentially qualitative classification system, the original GSI system (Reference 2.5.1-261) relied upon visual and qualitative assessment of rock mass quality in outcrops and surface excavations. Attempts over the years to quantify the system have resulted in revisions of the GSI system and the one that is used here is by Hoek at al. (Reference 2.5.1-265). This recent revision allows an estimation of GSI based on quantitative assessment of rock mass quality in rock cores, and incorporates elements of the RMR and Q systems. As seen in Figure 2.5.1-58, the horizontal axis represents the Joint Condition rating ($JCond_{89}$) (Reference 2.5.1-259) and is defined by 1.5 $JCond_{89}$ and the vertical axis (represents the blockiness of the rock mass using the Rock Quality Designation (RQD) (Reference 2.5.1-266) defined by RQD/2. The GSI is given by the sum of these two scales.

The application of the GSI classification and Hoek-Brown failure criterion assumes that the rock mass contains several sets of discontinuities that are closely spaced relative to the proposed structure, such that it behaves as a homogeneous and isotropic mass. In other words, while the behavior of the rock mass is controlled by the movement and rotation of the rock blocks separated by intersecting discontinuities, there are no preferred failure directions (Reference 2.5.1-267). The size of the power block excavation is expected to be much larger than the blocks that make up the rock mass at the site (Figure 2.5.1-31).

The subset of borings at the CRN Site selected to apply the GSI classification are the 100-series and 200- series borings in which ATV logging was performed and a select number of 400-series borings, also in which ATV logging was performed. These include MP-101, -102, -111, -112, -113, -120, -201, -202, -212, -213, -219A, -412, -416, -421, and -424. The ATV data are used to support the borehole log information. These borings are selected as they include some of the inclined borings and some of the deepest borings drilled at the site. The open and clay-filled cavities encountered in MP-424 are included to assist in characterizing the most unfavorable zones within the bedrock. The GSI classification is applied to bedrock stratigraphic units below a

depth of approximately 60 ft below the ground surface (El.741 ft NAVD88). The depth of influence of the foundations is not expected to exceed 440 ft below the deepest foundation level (El. 243 ft NAVD88). Based on this information, bedrock units exposed at and underlying the foundation level in the power block area are predominantly the Newala, Blackford, Lincolnshire (Eidson and Fleanor Members), Rockdell, and Benbolt Formations.

The GSI classification system takes into account weathered and fractured zones associated with dissolution plus shear-fracture zones, but not open- and clay-filled cavities. Such dissolution features are relatively insignificant to the GSI classification because, based on the karst investigation performed at the CRN Site and the boring logs drilled for the CRN Site (Appendix B.1 Reference 2.5.1-214), open- and clay-filled cavities compose less than 1 percent of the total length of the stratigraphic units drilled at the CRN Site. However, open- and clay-filled cavities encountered in boring MP-424 close to or below the deepest foundation level (El. 683 ft NAVD88) are included in the GSI classification to assist in characterizing the most unfavorable zones within the stratigraphic units. The clay-filled cavities are characterized in the rock mass as thick clay zones.

Assigning Joint Condition Ratings ($JCond_{89}$)

The quantified GSI chart developed by Hoek et al. (Reference 2.5.1-265) uses a joint condition rating ($JCond_{89}$) (Reference 2.5.1-259) which is defined by 1.5 $JCond_{89.}$ This joint condition rating, $JCond_{89}$, is calculated using the quotient Jr/Ja (originally from Barton’s Q tunneling index, (Reference 2.5.1-260) to represent the roughness (Jr) and frictional/alteration (Ja) characteristics of the discontinuities (Reference 2.5.1-268).

$JCond_{89} = 35\ Jr/Ja/(1 + Jr/Ja)$ Equation 2.5.1-1 (Reference 2.5.1-265)

Using bedding plane and joint descriptions from the selected boring logs, Jr and Ja ratings are assigned and the $JCond_{89}$ is calculated using Equation 2.5.1-1 above. Average joint conditions are calculated for each 5-ft of core run. Core runs without discontinuity descriptions are not included. Definitions of the $JCond_{89}$ after Bieniawski (Reference 2.5.1-259) are provided in Table 2.5.1-12.

The average joint condition ratings (Av. $JCond_{89}$) calculated from the boring logs are summarized in Table 2.5.1-13. The average joint condition ratings are estimated to range from about 3 to 28 with average ratings of between 17 and 19 with standard deviations of between 4 and 5.

In addition to characterizing the condition of the discontinuities on the boring logs, discontinuities at three of the geological field mapping locations (located northeast of the power block area) are assigned Jr and Ja ratings and the joint condition rating, $JCond_{89,}$ is calculated using Equation 2.5.1-1 above. The $JCond_{89}$ at each location are summarized in Table 2.5.1-14. The average joint condition ratings at the three locations are estimated to range from approximately 19 to 25 with an overall average rating of approximately 22 with a standard deviation of approximately 3.

GSI Calculation

Using the quantified GSI chart developed by Hoek et al. (Reference 2.5.1-265), the GSI value is given by the following equation:

$GSI = 1.5\ JCond_{89} + RQD/2$ Equation 2.5.1-2 (Reference 2.5.1-265)

Using the average joint condition ratings (Av. $JCond_{89}$) and the Rock Quality Designation (RQD) from the boring logs, the GSI is calculated for each 5-ft of core run using Equation 2.5.1-2 above.

The GSI results for each of the stratigraphic units are summarized in Table 2.5.1-15 with a recommended GSI range of approximately ±1 standard deviation from the average, and rounded up or down to nearest 5 GSI. Scatter plots of GSI against depth for each of the rock units are shown on Figure 2.5.1-56. Figure 2.5.1-57 shows scatter plots of 1.5 $JCond_{89}$ against RQD/2 and the GSI for each of the formations on a portion of Hoek et al.'s (Reference 2.5.1-265) GSI chart (Figure 2.5.1-58) that has been modified to include RQD/2 > 40, representative of intact or massive rock mass with few widely-spaced discontinuities.

At the three geologic field outcrop mapping locations (#2, 8, and 9) the RQD is estimated based on the visible blockiness of the outcrops using best judgment. Using this and the estimated joint condition ratings, the GSI is calculated using Equation 2.5.1-2 above. The GSI for each of the outcrops are shown on Figure 2.5.1-58.

Following are brief discussions on the ranges of GSI estimated for each of the stratigraphic units.

Benbolt Formation

The GSI for the Benbolt Formation is estimated to range from about 70 to 80. Figure 2.5.1-57 shows that with the exception of one of the data points in the 1.5 $JCond_{89}$ against RQD/2 plot, the data have RQD/2 > 40 corresponding to intact or massive rock with few widely-spaced discontinuities.

Rockdell Formation

The GSI for the Rockdell Formation is estimated to range from about 55 to 80. Figure 2.5.1-57 shows that the majority of data points in the 1.5 $JCond_{89}$ against RQD/2 plot have RQD/2 > 40, corresponding to massive or intact rock and RQD/2 of 30 to 40 corresponding to blocky rock. A small number of the data points have RQD/2 of 10 to 30 corresponding to very blocky and blocky, disturbed/seamy rock and RQD/2 of less than 10 corresponding to disintegrated rock.

The plots of the GSI (Figures 2.5.1-56 and 2.5.1-57) show a wide scatter of GSI, reflecting slickensided fractures and bedding surfaces, discrete fracture zones, and voids / clay-filled cavities. The low GSI (≤ approximately 10) between depths of about 120 and 150 ft below the ground surface corresponds with the open- and clay-filled cavities encountered in MP-424. Decreases in the GSI below this depth correspond with the depth of shear-fracture and fracture zones in this formation.

The GSI for the bedrock exposure of the Rockdell Formation (Figure 2.5.1-58) is calculated at about 60. Marinos et al. (Reference 2.5.1-269) recommend that the GSI from observations in outcrops shift to the left or to the left and upwards to obtain projected conditions at depth. This gives a GSI of about 70 which is close to the mid-point of the range of the GSI estimated from the borings logs.

Fleanor Member

The GSI for the Fleanor Member is estimated to range from about 65 to 85. Figure 2.5.1-57 shows that with the exception of a number of data points in the 1.5 $JCond_{89}$ against RQD/2 plot the data have RQD/2 > 40, corresponding to intact or massive rock with few widely-spaced discontinuities.

Eidson Member

The GSI for the Eidson Member is estimated to range from about 50 to 80. Figure 2.5.1-57 shows the majority of data points in the 1.5 $JCond_{89}$ against RQD/2 plot have RQD/2 > 40, corresponding to massive or intact rock, but a number of data points have RQD/2 of 20 to 30 corresponding to very blocky and RQD/2 of 10 to 20 corresponding to blocky, disturbed/seamy rock. A couple of the data points have RQD/2 = 0 corresponding to zero rock recovery.

The plots of GSI (Figures 2.5.1-56 and 2.5.1-57) for this formation, like the Rockdell Formation, show a wide range of scatter reflecting slickensided fractures and bedding surfaces, and discrete fracture zones. Decreases in the GSI correspond with the depths of the shear-fracture and fracture zones in this formation.

Blackford Formation

The GSI for the Blackford Formation is estimated to range from about 60 to 80. Figure 2.5.1-57 shows that the majority of data points in the 1.5 $JCond_{89}$ against RQD/2 plot have RQD/2 > 40, corresponding to massive or intact rock and RQD/2 of 30 to 40 corresponding to blocky rock. A small number of the data points have RQD/2 of 10 to 30 corresponding to very blocky and blocky, disturbed/seamy rock. One of the data points has an RQD/2 < 10 corresponding to low quality rock during core recovery.

The GSI for the bedrock exposure of the Blackford Formation (Figure 2.5.1-58) is estimated to range from about 50 to 70. Using Marinos et al.'s (Reference 2.5.1-269) recommendation to obtain projected conditions at depth gives a GSI in the range of 60 to 80, which is similar to the GSI estimated from the boring logs.

Newala Formation

The GSI for the Newala Formation is estimated to range from about 70 to 80. Figure 2.5.1-57 shows that with the exception of a couple of the data points in the 1.5 $JCond_{89}$ against RQD/2 plot, the data have RQD/2 > 40 corresponding to intact or massive rock.

The GSI for the bedrock exposure of the Newala Formation (Figure 2.5.1-58) is estimated to range from about 55 to 70. Using Marinos et al.'s (Reference 2.5.1-269) recommendation to obtain projected conditions at depth gives a GSI in the range of about 65 and 80 which is similar to the GSI estimated from the boring logs.

The GSI classification of the stratigraphic units characterizes the rock mass as predominantly intact or massive to moderately jointed or blocky with surface conditions of the discontinuities predominantly fair to good. The GSI for each stratigraphic unit is appropriately represented as a range rather than single value to take into account the inherent variability (uncertainties) about the mean (Table 2.5.1-15). The range in GSI is used to estimate the rock mass strength and deformation properties of each of the stratigraphic units for calculation of foundation bearing capacity and settlement (Subsection 2.5.4).

The GSI classifications of the stratigraphic units are based on a select number of 100-, 200- and 400-series borings drilled at the CRN Site. Depending on the technology selected for the Combined License Application (COLA), further interpretation of the subsurface investigation data within the power block area may be required.

2.5.1.2.6.3 Fracture Zones

Borings drilled at the CRN Site (Appendix B.1 Reference 2.5.1-214) indicate the presence of weathered or fracture zones within the stratigraphic units. The weathered or fracture zones typically occur along bedding planes or fractures and likely represent early dissolution of the limestone. These zones typically represent poor to fair quality rock consisting of multiple, healed to open, slightly to highly weathered fractures or bedding planes, some calcite or dolomite filled, with occasional core loss and loss of drilling fluid reported. Below the uppermost weathered zone (depth of 100 ft or less), rock mass discontinuities (including bedding joints) become tighter, less frequent, and shorter as depth increases (References 2.5.1-303 and 2.5.1-315). The site investigation data indicate that few bedding fractures have weathering or weakening below the power block foundation level.

A summary of the weathered or fracture zones (greater than or equal to approximately 0.9 ft thick (apparent thickness along boring axis)) encountered in the 100- and 200-series borings drilled at the CRN Site are contained in Table 2.5.1-16 and shown on Figure 2.5.1-59. Fracture zones are encountered between depths ranging from approximately 6 to 400 ft below the ground surface. The apparent thickness of the fracture zones ranges from about 1 to 12 ft with an average thickness of approximately 3 ft. The majority of the fracture zones are encountered between elevations of approximately 800 and 750 ft NAVD88.

Weathered and fracture zones are incorporated in the average GSI rating for each of the stratigraphic units, so bearing capacity based on GSI considers these zones in the foundation rock mass. During excavation for the safety-related structures in the power block area, detailed geologic mapping of the foundations provides further characterization of the weathered or fracture zones if found present in those foundations.

Characterization of the weathered or fracture zones is based on the 100- and 200-series borings drilled at the CRN Site. Further evaluation of these zones may be required in support of the COLA, when a reactor technology has been selected.

2.5.1.2.6.4 Deformational Zones

Borings drilled at the CRN Site encountered what is termed shear-fracture zones, which represent localized zones of strain accommodated via pressure solution with limited cataclasis (see Subsection 2.5.1.2.4.3.4). The zones are characterized by a relative increase in calcite vein fill, subvertical and bedding-parallel stylolites, and slickenlined bedding and vein surfaces. The development of these shear-fracture zones at the site is considered to be closely related to folding and faulting in the area reflecting a long and varied stress history (Subsection 2.5.1.2.4) and are often associated with fracture zones (SZ/FZ) or occur as single shear fractures (SH) (noted as joints on the boring logs).

A summary of the shear-fracture zones (greater than or equal to approximately 0.9 ft thick (apparent thickness along boring axis)) encountered in the 100-, 200-, and 400-series borings drilled at the CRN Site are contained in Table 2.5.1-17 and shown on Figure 2.5.1-60 (see Subsection 2.5.1.2.4). Shear-fracture zones are encountered in the Rockdell and Benbolt Formations (in the 100-series borings) between depths of about 50 and 350 ft below the ground surface. The shear-fracture zones range in thickness from about 1 to 7 ft with an average apparent thickness of about 3 ft. Shear-fracture zones are encountered in the Eidson Member (200- and 400-series borings) between depths of about 115 and 280 ft below the ground surface. These zones range in thickness up to 22 ft with an average apparent thickness of approximately 4 ft. Descriptions from the 100-, 200-, and 400-series borings logs indicate that the shear-fracture zones are typically zones that contain closely spaced, tightly healed, calcite filled fractures with occasional, primarily discrete, fracture zones and the fractures commonly form orthogonal to

bedding. The quality of the rock within these zones is generally high, unless associated with fracture zones (Reference 2.5.1-214).

A shear zone is reported to have been encountered during the subsurface investigation for the CRBRP. Thirty-nine borings drilled as part of the CRBRP investigation encountered the “shear zone” in the lower portion of the Eidson Member, which is reported to range in thickness from 19 to 46 ft. The “shear zone” outcrops to the northeast of the CRBRP along the right bank of the Clinch River arm of the Watts Bar Reservoir and strikes parallel to the strike of the bedding planes. The “shear zone” is described as a hard, re-healed, cemented zone characterized by continuous, thin to medium bedded gray limestone with 1 to 6 inch layers of maroon and gray calcareous siltstone and gray-white chert. The results of the subsurface investigation on the “shear zone” for the CRBRP reveal that it is not a fault breccia or fault zone (Reference 2.5.1-238).

Shear-fracture zones are incorporated in the average GSI rating for each of the stratigraphic units, so bearing capacity based on GSI considers these zones in the foundation rock mass. During excavation for the power block area, detailed geologic mapping of the foundations for the safety-related structures provides further characterization of shear-fracture zones, if found present in those foundations.

Characterization of the shear-fracture zones is based on the 100-, 200-, and 400-series borings drilled at the CRN Site. Further evaluation of these zones may be required in support of the COLA, when a reactor technology has been selected.

2.5.1.2.6.5 Karst Features

As described in Subsection 2.5.1.2.5 karst-related ground failure or subsidence is a geologic hazard at the CRN Site. The results of the karst investigation performed for the CRN site area (5-mile radius) reveal the presence of karst-related surface features in the form of sinkholes and subsurface features in the form of cavities, both open and clay-filled. Primary dissolution pathways are strike-parallel consistent with the strike-parallel drainage system at the site. Secondary dissolution pathways occur both down-dip following bedding planes and along lithologic contacts and along fractures.

The results of the karst investigation performed for the CRN site area reveal cavities to be present in each of the stratigraphic units at the site. These cavities (equal to or greater than 0.1-ft in height) include open- and clay-filled cavities and range in height from less than 1 ft to about 17 ft. These cavities are encountered predominantly in the Rockdell Formation and Eidson Member with fewer cavities encountered in the Benbolt and Blackford Formations and the Fleanor Member. The frequency with which these cavities occurs decreases with increasing depth and the majority of the cavities occur within approximately 100 ft of the ground surface. This concentration of cavities is consistent with karst dissolution taking place at and above the water table level (or above the water level elevation of the Watts Bar Reservoir of 740 ft NAVD88.

During the subsurface investigation for the CRBRP, weathering and solutioning along fractures and bedding planes is reported to have been observed and in some cases this weathering is reported to have advanced into sound rock to produce clay seams and cavities. However, the size and frequency of these features are reported to have decreased with depth (Reference 2.5.1-257).

Borings drilled for the CRN Site reveal open and clay-filled cavities present in borings MP-102, MP-104, MP-406, MP-410, MP-412, MP-418, MP-420, MP-423, MP-424, and MP-428. The cavity bottom elevations range from 807 to 661 ft NAVD88 and the cavities range in height from less than 0.5 ft to 11 ft, with an average height of approximately 3 ft. A number of the cavities are

encountered close to and just below the shallowest expected foundation level (El. 741 ft NAVD88). These include two cavities encountered in boring MP-418 in the Eidson Member with cavity bottom elevations of 741.1 ft NAVD88 and 730.6 ft NAVD88 and cavity heights of 0.8 ft and 9.5 ft, respectively. A number of cavities encountered in MP-424 in the Rockdell Formation are close to and below the deepest expected foundation level (El. 683 ft NAVD88). Four of the five cavities are encountered approximately 5 to 20 ft below the deepest expected foundation level. These four cavities range in height from 0.7 to 4.3 ft with cavity bottom elevations ranging from approximately 661 to 676 ft NAVD88.

Mitigation of potential karst features is discussed in Subsection 2.5.1.2.6.10.

2.5.1.2.6.6 Prior Earthquake Effects

As described in Subsections 2.5.2 and 2.5.3, the CRN Site is located within a broad zone of elevated activity of historically low-magnitude seismicity that comprises the ETSZ, which is the second most active seismic zone in the eastern United States after the New Madrid seismic zone described in Subsection 2.5.2.2.5). Instrumentally located epicenters in the ETSZ indicate that the majority of earthquake hypocenters are located in the basement rocks beneath the Appalachian fold-thrust belt. Because it is within a zone of elevated seismicity, the CRN site vicinity (25 mile radius) has been extensively evaluated for the presence of paleoseismic features, such as those resulting from paleoliquefaction (see Subsection 2.5.3.2).

An investigation into the presence of paleoliquefaction features within the CRN Site and site vicinity included literature review, geologic field reconnaissance, geologic and geomorphologic mapping, and trench logging of Quaternary terrace deposits along the Douglas Reservoir, Tellico Reservoir and Watts Bar Reservoir. The results of the investigation reveal that while several researchers have identified potential paleoseismic features around the Douglas Reservoir, the origin and interpretation of these features is unclear (as described in Subsection 2.5.3.1.2). Geologic field reconnaissance along the Clinch River arm of the Watts Bar Reservoir and along Tellico Reservoir did not identify evidence for paleoseismic features (see Subsection 2.5.3.2).

In addition to paleoseimic features, landslides or unstable hillsides or mountain sides can be indicators of past earthquake activity. As described in Subsection 2.5.3 an evaluation of landslide incidence and susceptibility maps indicate that the CRN Site is located in an area of moderate susceptibility and low incidence (Figure 2.4.9-5). Geologic field reconnaissance, aerial photograph analysis, and slope analysis using high-resolution digital elevation data revealed one small, shallow landslide within the site location, along the northeastern edge of the site peninsula (Subsection 2.5.3.2.4).

2.5.1.2.6.7 Residual Stresses in Bedrock

The natural state of stress in a rock is caused by three main factors (Reference 2.5.1-270):

- Previous tectonic forces
- Current tectonic forces
- The weight of the rock

All three of these factors can influence the state of stress in a rock mass in addition to factors such as weathering and erosion and discontinuities. Residual stresses in a rock mass are stresses that remain in the rock mass after their causes have been removed (Reference 2.5.1-278). Upon sudden unloading, high residual stresses in a rock mass can result

in rock bursts, rock spalling, sudden fracturing, pop-ups, borehole break-outs, rock core micro-cracking and discing etc.

High residual stress is not expected in the rock mass at the CRN Site. As described in Subsection 2.5.1.2.4, bedrock at the site has been subject to previous tectonic stresses as characterized by the parallel valleys and ridges formed by differential erosion of folded and faulted Paleozoic age sedimentary strata. The deformational event responsible for the development of this Appalachian fold-thrust belt is the Alleghanian orogeny that occurred during the late Paleozoic Era. Since this time, the bedrock has undergone gradual relaxation through weathering and erosion and there is no evidence to suggest recent (during the Quaternary Period) tectonic activity has occurred at the site (see Subsections 2.5.1.2.2, 2.5.1.2.4, and 2.5.3.2). Unlike much of the northeastern United States, the southeastern United States including Tennessee has not been subject to stresses induced through glacial loading. Stress-relief features such as those described above have not been observed or reported at the CRN Site.

Bedrock at the CRN Site has been subject to normal overburden stress and so removal of this stress will result in an adjustment in the rock mass in terms of loosening along discontinuities and possibly the development of additional discontinuities. Site development for the power block area at the CRN Site will involve the removal of overburden by blasting techniques. As a result of blasting and stress unloading, a disturbed zone of rock adjacent to the foundation will occur. As described in Subsection 2.5.4 rock mass strength properties and deformation moduli are estimated for this disturbed zone, in addition to the rock below this zone, to ensure adequate bearing capacity of the foundation rock mass.

Current tectonic forces in the site region and the associated broad stress regime of the Eastern U.S. (see Subsection 2.5.1.1.4.3.1), as well as residual stresses, are not expected in the rock mass at shallow depths (hundreds of feet) at the CRN Site and are not considered to be a hazard during construction or for bearing capacity of the foundation rock mass.

2.5.1.2.6.8 Effects of Human Activities

Fossil fuels such as oil and natural gas, coal, oil shales and radioactive minerals are found in Tennessee. Only oil and natural gas and coal are currently being recovered (Reference 2.5.1-271).

The Tennessee Department of Environment and Conservation (TDEC) (Reference 2.5.1-272) allows access to its databases through Dataviewer, which reflects overnight updates to the agency’s consolidated state databases. Accessing the Water Resources Permits Dataviewer for oil and gas wells reveals four permit applications for Roane County, TN, dating from June, 1981 to July, 2006, as listed in Table 2.5.1-18. None of these wells for which a permit application was submitted are within 5 mi of the CRN Site. The closest permit-application well to the site is the Edwards-Fowler Unit #1 well (Permit No. 10766) located approximately 5.5 mi to the northwest. According to information obtained from the TDEC (Reference 2.5.1-272) this well currently produces gas. The other three wells listed in Table 2.5.1-18 either produced gas for a period of time (Eula Butler Etal #1 well; Permit No. 10574) or were never permitted for gas production.

Areas of Tennessee mined for coal, past and present, and with potential reserves of coal are located along the Roane-Morgan and Roane-Cumberland county lines. There are no coal mines within 5 miles of the CRN Site. Accessing the TDEC Water Resources Permits Mapviewer (Reference 2.5.1-273) indicates that the closest coal mines to the CRN Site are in Morgan County, owned and operated by Clear Energy Corporation (formerly Dalco of Tennessee, LLC.) and are producers of bituminous coal and lignite (Figure 2.5.1-61).

Construction materials mined or quarried in Tennessee include dimension stone (sandstone and marble), crushed stone, limestone and clay and sand and gravel (Reference 2.5.1-271). Accessing the TDEC Water Resources Permits Mapviewer (Reference 2.5.1-273) Figure 2.5.1-61 shows the water resource permit applications that currently exist within approximately 10 miles of the CRN Site. As shown on this figure several of these water permits are for mining purposes, however, none of these are within 5 mi of the CRN Site. The two mines closest to the site are quarries and are located approximately 8 mi northwest and east of the site and are Roane County Quarry and Dixie Lee Quarry, respectively. Both of these quarries produce crushed and broken limestone.

Injection of radioactive waste at the ORNL, located about 4 mi east of the CRN Site, is well documented (References 2.5.1-100 and 2.5.1-238). All experimental and operational injections are reported to have been made within the Conasauga shale which underlies the Rome Formation at the CRN Site (See Figure 2.5.1-37). The radioactive waste was mixed with a cement grout slurry and injected into the shale. Hydrofracturing techniques were used to create cracks in the rock to accommodate the radioactive waste solutions. Several experimental well injection sites and an operational well injection site were established between 1959 and 1972 and during this time, periodic injections of radioactive waste solutions were made between depths of approximately 300 and 1000 ft below the ground surface. Ground behavior monitoring techniques implemented within the vicinity of the operation well site indicated minimal uplift of the ground surface, approximately 0.06 ft within a 1700-ft (0.3-mi) radius. A fourth operational injection well site was planned for future injections at the site (References 2.5.1-100 and 2.5.1-238).

Anthropogenic activities at the CRN Site included large-scale grading and excavation for the CRBRP. These graded areas contain fill (see Subsection 2.5.4).

2.5.1.2.6.9 Construction Groundwater Control

Groundwater flow at the CRN Site occurs primarily through secondary openings in the form of bedding planes, fractures and solution openings or cavities in the bedrock rather than through primary porosity openings such as pores or voids. The weathered bedrock, which ranges in thickness from less than 1 ft to approximately 20 ft in the power block area, acts as a water table aquifer and most of the groundwater flow occurs within this zone parallel to the strike of the bedding planes. Significant groundwater flow is also assumed to occur through discontinuities and openings in the bedrock below this weathered zone predominantly within the upper 100 ft of bedrock where the highest frequency of open discontinuities is reported to occur.

Groundwater levels at the site are likely to result in the need for temporary dewatering of the foundation excavations extending below the water table. Solution openings or cavities, and open bedding planes and fractures may be filled with cement grout to reduce groundwater inflow to the excavation and reduce the extent of dewatering.

2.5.1.2.6.10 Unforeseen Geologic Conditions

Future excavations (following issuance of the combined license) for safety-related structures would be geologically mapped. Unforeseen geologic features that are encountered would be evaluated. The NRC would be notified when any excavations for safety-related structures are open for their examination and evaluation.

Detailed geologic mapping of excavation walls during construction will permit TVA to document the characteristics of dissolution features in the near-surface carbonate rock units and verify whether cavities decrease in size and abundance with depth, as predicted by the subsurface investigation and geological mapping. The mapping would provide the means to locate and

remediate or seal any dissolution features that might serve as groundwater flow paths into the excavation. This mapping would also provide information on whether fractures, along which dissolution and weathering might occur are confined to specific depths or lithologies, persist to foundation depths or close up and cease to serve as groundwater pathways and potential dissolution surfaces. The mapping would also provide the opportunity to collect additional *in situ* data on the rock and fractures and refine the rock mass characterization. Excavation wall mapping would also provide the opportunity to confirm or refine interpretations of subsurface geology from the borehole data and verify the absence of active tectonic faults.

The presence of cavities at and below the level of the foundations within the power block area may affect the bearing capacity of the foundation rock mass and groundwater flow. A mitigation plan, including detailed geologic mapping of the excavation floor, a potential grouting program and geophysical surveys to address possible cavities at and below the foundation levels of safety-related structures would be developed based on the technology chosen, described in the COLA, and executed during construction. The geophysical surveys would be designed to detect cavities below the foundation elevation that could adversely affect foundation performance and are dependent on the technology chosen for the CRN Site. A Plaxis or similar analysis would provide the information on potential critical subsurface cavity size. Additional drilling may be required to characterize geophysical anomalies. It is anticipated that the NRC staff would be notified when the excavation(s) are open for inspection.

2.5.1.2.7 Site Groundwater Conditions

A detailed discussion of the groundwater is presented in Subsection 2.4.12.

2.5.1.2.8 Tsunami and Seiche Hazards

As indicated in Subsection 2.4.6, the CRN Site is located more than 300 mi from the nearest seacoast. In addition, the plant finish grade elevation is at 821 ft NAVD88, which is much higher than the sea level at the coast. Thus, the site is not subject to any tsunami events originating from submarine earthquakes or submarine slope failures.

Surface water in the Clinch River arm of the Watts Bar Reservoir can be disturbed by tsunami-like or seiche-like waves resulting from massive slope failures into the reservoir. Reconnaissance geologic mapping, aerial photograph analysis and slope analysis using high-resolution digital elevation data revealed one small, shallow landslide within the site location, along the northeastern edge of the site peninsula (Subsection 2.5.3.2.4). Because the landslide is defined as small and shallow, there is no credible seiche hazard. Additionally, landslide hazard maps (Reference 2.5.1-202) and landslide incidence and susceptibility maps (Figures 2.4.9-5 and 2.5.1-22 indicate that the site is located in an area of moderate susceptibility and low incidence, compared with surrounding areas. Potential flooding of the site by a tsunami event originating in the adjacent water bodies is addressed in Subsection 2.4.6.

2.5.1.2.9 Relational Analysis

General

The proposed sites for the CRBRP and the CRN are co-located on the peninsula landform nearly surrounded by the incised Clinch River arm of the Watts Bar Reservoir and are located in the Valley and Ridge physiographic province of eastern Tennessee. The general site area is underlain by a sequence of Cambrian to lower Ordovician carbonate and clastic rocks that strike northeast and dip at an angle of about 33 degrees to the southeast.

The geology as mapped for the CRBRP is shown on Figure 2.5.1-80. The geology, as mapped for the CRN Site is shown on Figure 2.5.1-37. The relationship between the stratigraphic units defined for each project is summarized on Table 2.5.1-1. The lithologic characteristics of the CRBRP excavation and anticipated for the CRN power block area are described in more detail below.

Geology

Local Stratigraphy

The site-specific stratigraphies defined for the CRBRP and the CRN Sites are shown on Table 2.5.1-1. As documented in the references associated with Table 2.5.1-1, the stratigraphic interpretations shown in the table indicate that the Middle Ordovician-age Chickamauga Group is separated from the underlying Cambrian to Lower Ordovician Knox Group by an erosional surface. The CRBRP Unit A Lower Siltstone corresponds with the Blackford Formation. The Unit A Limestone corresponds with the Eidson Member of the Lincolnshire Formation. The Unit A Upper Siltstone corresponds with the Fleanor member of the Lincolnshire Formation. The Unit B Limestone corresponds with the Rockdell Formation. Stratigraphic units overlying Unit B were not anticipated for, nor did they occur in, the excavation for the CRBRP and were mapped as undifferentiated Chickamauga. As shown on Figures 2.5.1-80 and 2.5.1-81, the foundations for the CRBRP were located primarily in the Unit A Upper Siltstone to the northwest and the Chickamauga Unit B Limestone to the southeast. This corresponds with the Fleanor member and the lower Rockdell Limestone as currently mapped for the CRN Site. Descriptions of these stratigraphic units are provided in Subsection 2.5.1.2.3.3.

As shown on Figure 2.5.1-30, the CRN Site power block area has a foundation elevation of approximately 683 ft NAVD88. The stratigraphic units that occur at this elevation in the power block area include the upper Knox Group (Newala Formation) through the overlying Blackford Formation, Eidson and Fleanor members, Rockdell Formation and the Benbolt Formation. Descriptions of these stratigraphic units are also provided in Subsection 2.5.1.2.3.3.

Local Structural Geology

Geologic field mapping and acoustic televiewer (ATV) log data indicate bedding at the site overwhelmingly strikes 050–070 with southeast dips that range between 20 and 50 degrees (References 2.5.1-97 and 2.5.1-106). Mean orientations reported during the CRBRP PSAR Project ranged from 052/31 (derived using 3-point problems) to 052/37 from surface mapping (Reference 2.5.1-100). A recent estimate based on surface mapping and 3-point problems from key horizons in boreholes yielded a similar 052/33. ATV log data of total borehole measurements (n=4733) yielded a mean bedding attitude of 063/33 (Figures 2.5.1-38, Sheets 1 and 2); orientation between different stratigraphic units was consistent down-hole. Additionally, seismic reflection data supports consistent dip of strata between borehole locations (Figure 2.5.1-36). Geologic cross-sections that were constructed using subsurface contacts observed in boreholes also indicate bedding dips are consistent throughout the site (Figure 2.5.1-30). The similarities between the CRBRP Site and the CRN Site are shown on Figures 2.5.1-30, 2.5.1-37, 2.5.1-80, and 2.5.1-81. These figures show that the stratigraphic units in the CRBRP excavation and in CRN location B are identical. The differences in stratigraphic nomenclature are discussed above and shown in Table 2.5.1-1. Subsection 2.5.1.2.4 contains additional detail on local structural geology.

Dissolution and Karst

Karst hazards at the CRN Site are described in Subsection 2.5.1.2.5.1.

The data clearly show concentrations of depressions in certain geologic units (Table 2.5.1-7 and Figure 2.5.1-47). Depression density, DD, was greatest in members of the Knox Group. Between twenty and thirty depressions per square kilometer were observed in the Mascot Dolomite, Longview Dolomite, Chapultepec Dolomite, and Copper Ridge Dolomite. Ten to twenty depressions per square kilometer were observed in four formations of the Stones River Group and in the Kingsport Formation of the Knox Group. The Witten and Rockdell Formation, members of the Chickamauga Group, average eight to nine depressions per square kilometer. The Rockdell underlies the southern portion of the power block area, while the Witten Formation crops out south of the power block area and dips to the southeast. Other members of the Chickamauga Group contained less than three depressions per square kilometer.

Data for area ratio, RD, or the area of all closed depressions per area of bedrock unit, show similar patterns, with a few significant differences (Table 2.5.1-7). Again, members of the Knox Group and Stones River Group have the highest area ratios, typically 1 to 3 percent. The Witten Formation of the Chickamauga Group, also shows an area ratio in this range. Several wide depressions likely account for this relatively high area ratio. The Longview Dolomite, which has a very high depression density, forms a steep-sided topographic ridge due to the presence of significant chert beds. Due to the steep slopes, depressions are typically of the two-sided and three-sided type that do not count toward the area ratio, thus the Longview Dolomite has a relatively low RD area ratio. Area ratio data more closely correlate with the density of closed depressions, type D on Table 2.5.1-7.

The above analysis shows that geologic units having the highest depression density and area ratios are those characterized by thick and relatively pure carbonate lithology. These include the Knox Group dolomites, and the more pure limestones of the Chickamauga Group, Stones River Group, and the Conasauga Group. Units that contain interbedded carbonate and clastic lithologies, such as the Benbolt and Blackford formations of the Chickamauga Group have a moderate number to few depressions, and those dominated by clastic material (sandstone, siltstone, shale), have very few to no depressions. The presence of chert in the carbonate does not appear to influence the number of depressions, but may influence the type of depressions present.

Figures 2.5.1-30, 2.5.1-51, and 2.5.1-81 are geologic cross sections drawn parallel to dip. Figure 2.5.1-81 indicates the extent of the CRBR Site excavation. Figure 2.5.1-30 is based on borings drilled in support of the CRN Site subsurface investigation and indicates the extent of the power block area. Figure 2.5.1-51 incorporates data from both the CRBRP and the CRN Site subsurface investigations. This figure shows the locations of cavities based on the combined project data. Figure 2.5.1-81 shows that the excavation for the CRBRP was planned primarily in the Unit A Upper Siltstone (current Fleanor member) and to a lesser extent in the Unit B Limestone (current lower Rockdell Formation). The stratigraphy and structure of the CRBRP Site is similar to Location B within the CRN power block area (Figures 2.5.1-30 and 2.5.1-81). These figures show that the stratigraphic units in the CRBRP excavation and in CRN location B are identical. The differences in stratigraphic nomenclature are discussed above and shown in Table 2.5.1-1. Except for the Mascot Formation, the karst depression densities and area ratios for the other stratigraphic units within the power block area are all less than those in the stratigraphic units noted above as occurring to the northwest and southeast of the power block area.

Voids/Cavities Encountered at and Below the Depth of Foundation

The results of the CRBRP Site investigation can be used to enhance and further inform the understanding of the geology and engineering suitability of the CRN Site. The CRBRP Site investigation began in 1972, and site drilling was completed in 1980 (References 2.5.1-100 and 2.5.1-303), whereas the CRN Site investigation was conducted in 2013 (Reference 2.5.1-214).

As these investigations were conducted at the same site with overlapping borehole coverage and comparable drilling and logging methods, geologic observations and interpretations can be correlated and compared from one dataset to the other. The deep excavation for the CRBRP nuclear island in 1983 was primarily in the Fleanor member (calcareous siltstone), and foundation conditions on this rock type were found to be excellent (Reference 2.5.1-303).

Geotechnical Site Investigations

The boundary of the 2013 CRN Site geotechnical site investigation overlaps to a large extent with that of the 1972-1980 CRBRP Site geotechnical site investigation (Figure 2.5.1-74). A total of 104 borings were drilled during the CRBRP Site investigation (Reference 2.5.1-100), and 74 were drilled for the CRN Site investigation (Reference 2.5.1-214). Both site investigations included widely distributed borings to fully characterize the site stratigraphy and concentrated most borings in the areas of safety-related facilities. The northern cluster of CRN Site borings, which corresponds to proposed Location B, is centered northeast of the greatest concentration of borings related to the CRBRP Site investigation and occurs within the same geologic unit (Figure 2.5.1-74). The southern cluster of CRN Site borings, which corresponds to proposed Location A, is centered within the Benbolt formation, a slightly younger geologic unit with similar lithologic characteristics. These three concentrations of borings fall within the Chickamauga Group, a middle Ordovician sequence of limestones, silty and cherty limestones, and calcareous siltstones.

Although the CRBRP and CRN Site boring investigations utilized a different stratigraphic nomenclature, the unit designations are directly correlative. The positions of formation contacts correlate well between CRN and CRBRP borings, which demonstrates consistency in topographic survey and geologic logging. Both programs began rock coring at the top of rock and cored continuously to boring termination.

Cavities encountered in both site investigations were logged to the nearest tenth of a foot, with bottom and top elevations of the cavity recorded. A total of 216 cavities were logged during the CRBRP Site investigation, whereas the CRN Site program logged a total of 23 cavities. The fewer number of cavities encountered in the CRN Site borings is consistent with removal of the cavity-rich near-surface strata during the deep CRBRP excavation and associated grading activities prior to 2013 (Figure 2.5.1-74). This combined cavities dataset is illustrated on the distribution of cavities cross section (Figure 2.5.1-51) and on the plot of cavity size versus elevation (Figure 2.5.1-52). Additionally, the distribution of cavity size vs. elevation of the CRN Site data is consistent with that of the CRBRP Site data. Based on the quality and compatibility of both boring investigations, the combined dataset was used for CRN Site analysis of cavities in boreholes.

CRBRP Excavation Records

Excavations for the CRBRP Site were virtually complete before the project was cancelled in November 1983. The excavations were mapped and described in detail prior to backfilling to provide documentation of the geology and structure exposed during the excavation (Reference 2.5.1-303). Two excavations were made, a large excavation (480 ft long x 360 ft wide, and 100 ft deep) for the nuclear island and a smaller excavation (180 ft x 180 ft shallow depth) for the Equalization Basin.

The nuclear island excavation exposed the Fleanor member, primarily a shaly calcareous siltstone at the site, over most of the walls and floor. The Fleanor member exhibited deep chemical weathering of siltstone strata, with minor dissolution of its thin limestone interbeds. The siltstone was fresh at the base of the excavation, but found prone to slaking and disintegration upon subaerial exposure.

The base of the overlying Rockdell Formation, primarily limestone at the site, was exposed on the southeast wall of the nuclear island excavation and contained a concentration of solution cavities at an elevation of approximately 780 ft. The cavities had a maximum radius of a few feet, with lengths ranging “from a few feet to several tens of feet” along discontinuities (Reference 2.5.1-303). Most cavities were partially filled with lateritic clay and silt. Cavities exposed during the excavation were cleaned and plugged with concrete.

The excavation mapping report concluded that the site was suitable for development of the proposed facility or other industrial facilities based on the character of the rock exposed (Reference 2.5.1-303). The planned foundation level of the CRBRP, 714 ft, was below the zone of weathered siltstone observed in the excavation, and the limestone at that elevation was found to be hard and sound. No cavities were described on the floor of the excavation. Any weathered siltstone found to be softer and prone to disintegration and slaking would be mitigated by the planned concrete base mat.

Conclusions

The aforementioned relational analysis provides a comparison of the CRN Site with the CRBRP Site with respect to geologic formation, rock type, geologic structure and occurrence and character of karst and voids/cavities encountered at and below the depth of foundations. The geologic units mapped in the CRBRP Site excavation (Fleanor member and Rockdell Formation) are the same as those occurring in Location B of the CRN Site power block area. Except for the Mascot Formation, the karst depression densities and area ratios for the other stratigraphic units within the power block area are all less than those in the stratigraphic units noted above as occurring to the northwest and southeast of the power block area; indicating that the power block area carbonates appear to have similar dissolution characteristics to the Rockdell Formation.

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Table 2.5.1-1
Stratigraphic Units Encountered at the Clinch River Nuclear Site

<table>
<tr><th colspan="2">CRBR PSAR
Reference 2.5.1-100</th><th colspan="2">Lee & Ketelle (1988)
Reference 2.5.1-110
Stockdale (1951)
Reference 2.5.1-109</th><th colspan="3">Hatcher et. al (1992)
Reference 2.5.1-9
(Current Investigation)</th></tr>
<tr><td colspan="2" rowspan="4">Undifferentiated Chickamauga</td><td rowspan="8">Chickamauga Group</td><td>H</td><td rowspan="8">Chickamauga Group</td><td colspan="2">Moccasin Formation</td></tr>
<tr><td>G</td><td colspan="2">Witten Formation</td></tr>
<tr><td>F</td><td colspan="2">Bowen Formation</td></tr>
<tr><td>E</td><td colspan="2">Benbolt Formation</td></tr>
<tr><td rowspan="4">Chickamauga Group</td><td>Unit B</td><td>C/D</td><td colspan="2">Rockdell Formation</td></tr>
<tr><td>Unit A USS</td><td>B</td><td rowspan="2">Lincolnshire Formation</td><td>Fleanor Member</td></tr>
<tr><td>Unit A LS</td><td>A2</td><td>Eidson Member</td></tr>
<tr><td>Unit A LSS</td><td>A1</td><td colspan="2">Blackford Formation</td></tr>
<tr><td colspan="2" rowspan="2">Knox Group</td><td colspan="2" rowspan="2">Knox Group</td><td colspan="2" rowspan="2">Knox Group (Newala Fm)</td><td>Mascot Dolomite</td></tr>
<tr><td>Kingsport Formation</td></tr>
</table>

Table 2.5.1-2 (Sheet 1 of 4)
Clinch River Nuclear Stratigraphic Boundaries

GEOTECHNICAL BORINGS STRATIGRAPHIC SUMMARY TABLE CLINCH RIVER SMR PROJECT (AMEC NO. 6468-13-1072								Rome Formation		CHICKAMAUGA GROUP																			KNOX GROUP	
										Moccasin Formation		Witten Formation	Bowen Formation		Benbolt Formation		Rockdell Formation				Lincolnshire Formation				Blackford Formation		Five Oaks Formation			
																					Fleanor Member		Eidson Member							
Boring Number	As-Drilled Coordinates/Elevations/Depths				Fill	Residual Soil	Weathered Rock			Unit H		Unit G	Unit F		Unit E		Unit D		Unit C		Unit B		Unit A						Newala Formation	
	Northing (US ft)	Easting (US ft)	Ground Surface Elevation (ft)	Total Drilled Depth (ft)	Depth (ft)	Depth (ft)	Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Not Encount-ered	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)
CC-B1	569036.1	2449632.4	800.3	140.6		45.0	48.8	48.8	83.3	83.3	140.6 (TD)																			
CC-B2	568891.0	2449759.9	799.8	206.0		34.8	115.7	115.7	183.9	183.9	206.0 (TD)																			
MP-101	570249.6	2448355.2	800.5	540.6	9.1	13.0	17.3								17.3	134.0	134.0	319.8	319.8	419.8	419.8	540.6 (TD)								
MP-102	570097.9	2448404.3	797.9	350.6	4.5		5.8								5.8	221.2	221.2	350.6 (TD)												
MP-103	570287.2	2448367.5	800.6	174.5	12.0	17.0	20.2								20.2	119.0	119.0	174.5 (TD)												
MP-104	570093.9	2448449.1	797.7	177.2	7.0	11.2	12.8								12.8	177.2 (TD)														
MP-105	570210.2	2448343.5	800.2	190.2	5.0	9.5	10.8								10.8	148.3	148.3	195.2 (TD)												
MP-106	570136.4	2448377.2	798.7	174.2	5.0	6.7									6.7	174.2 (TD)														
MP-107	570291.6	2448284.8	801.6	174.6	6.0	39.0	40.0								40.0	85.5	85.5	174.6 (TD)												
MP-108	570051.7	2448376.3	798.5	174.3	2.5	8.1									8.1	174.3 (TD)														
MP-109	570144.6	2448295.8	799.9	174.0	2.5	5.0	6.4								6.4	160.7	160.7	174.0 (TD)												
MP-110	570190.7	2448403.3	798.7	174.0	3.0	14.3	20.9								20.9	174.0 (TD)														
MP-111	570328.7	2448345.0	801.1	173.9	16.0	34.7									34.7	85.7	85.7	173.9 (TD)												
MP-112[a]	570261.9	2448472.1	799.2	177.5	18.5	26.2									26.2	177.5 (TD)														
MP-113[b]	570184.9	2448486.5	797.5	178.0	13.0	26.3									26.3	178.0 (TD)														
MP-114	570052.5	2448464.6	797.2	175.2	2.0	11.9									11.9	175.2 (TD)														
MP-115	570094.9	2448562.0	796.9	99.1	13.0	17.0	17.5								17.5	99.1 (TD)														
MP-116	570202.4	2448560.2	797.6	100.4	21.0	28.0	32.7								32.7	100.4 (TD)														
MP-117	570296.0	2448520.2	800.0	99.7	18.0	26.0	26.5								26.5	99.7 (TD)														

Table 2.5.1-2 (Sheet 2 of 4)
Clinch River Nuclear Stratigraphic Boundaries

GEOTECHNICAL BORINGS STRATIGRAPHIC SUMMARY TABLE CLINCH RIVER SMR PROJECT (AMEC NO. 6468-13-1072								Rome Formation		CHICKAMAUGA GROUP																			KNOX GROUP	
										Moccasin Formation		Witten Formation	Bowen Formation		Benbolt Formation		Rockdell Formation				Lincolnshire Formation				Blackford Formation		Five Oaks Formation			
																					Fleanor Member		Eidson Member							
	As-Drilled Coordinates/Elevations/Depths				Fill	Residual Soil	Weathered Rock			Unit H		Unit G	Unit F		Unit E		Unit D		Unit C		Unit B		Unit A						Newala Formation	
Boring Number	Northing (US ft)	Easting (US ft)	Ground Surface Elevation (ft)	Total Drilled Depth (ft)	Depth (ft)	Depth (ft)	Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Not Encount-ered	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)
MP-118	570370.9	2448445.5	799.8	99.1	13.0	18.6	19.1								19.1	99.1 (TD)														
MP-119	570414.6	2448544.7	802.1	100.8	4.0		11.0								11.0	100.9 (TD)														
MP-120	570319.1	2448584.2	800.1	350.0	7.0	25.0	27.0								27.0	183.9	183.9	350.0 (TD)												
MP-121	570227.9	2448623.1	797.6	100.9	16.0	23.3	23.7								23.7	100.9 (TD)														
MP-122	570130.4	2448654.4	796.7	99.3	16.0	27.0	30.9								30.9	99.3 (TD)														
MP-201	571083.7	2447980.8	790.9	420.6	16.5		20.6														20.6	85.9	85.9	175.3	175.3	309.9			309.9	420.6 (TD)
MP-202	570922.1	2448050.0	811.8	461.0	5.0		9.0														9.0	207.8	207.8	304.5	304.5	461.0 (TD)				
MP-203	571118.2	2448014.3	791.5	225.6	19.2		19.8														19.8	84.9	84.9	171.6	171.6	225.6 (TD)				
MP-204	570921.7	2448097.0	812.0	176.9	3.0		3.4														3.4	176.9 (TD)								
MP-205	571025.3	2448006.8	810.9	225.5	5.5	11.5	23.5														23.5	140.2	140.2	225.5 (TD)						
MP-206	570964.0	2448025.6	811.8	176.4	2.5	5.0	13.8														13.8	175.4	175.4	176.4 (TD)						
MP-207	571101.6	2447930.3	779.7	225.7	3.0	12.5	19.0														19.0	46.7	46.7	141.3	141.3	225.7 (TD)				
MP-208	570880.5	2448024.1	811.9	174.6	3.1		6.0														6.0	174.6 (TD)								
MP-209	570972.7	2447945.1	807.7	225.7			3.9														3.9	143.2	143.2	225.7 (TD)						
MP-210	571019.3	2448051.2	809.9	174.4	20.5		21.7														21.7	160.5	160.5	174.4 (TD)						
MP-211	571162.0	2447986.6	779.8	176.0	8.5	9.5	10.4														10.4	42.2	42.2	134.8	134.8	176.0 (TD)				
MP-212[c]	571093.5	2448107.3	810.7	177.8	40.0		46.3														46.3	168.5	168.5	177.8 (TD)						
MP-213[d]	571009.3	2448148.5	813.0	177.3	5.0	7.0	15.6														15.6	174.5	174.5	177.3 (TD)						
MP-214	570881.2	2448110.8	812.5	175.8	4.0		4.8												4.8	5.0	5.0	175.8 (TD)								
MP-215	570924.5	2448210.7	813.4	100.6	8.0		8.9												8.9	23.2	23.2	100.6 (TD)								
MP-216	571031.0	2448209.1	813.4	101.5			5.9														5.9	101.5 (TD)								
MP-217	571125.2	2448169.2	811.6	99.3	23.0	38.0	39.3														39.3	99.3 (TD)								

Table 2.5.1-2 (Sheet 3 of 4)
Clinch River Nuclear Stratigraphic Boundaries

GEOTECHNICAL BORINGS STRATIGRAPHIC SUMMARY TABLE CLINCH RIVER SMR PROJECT (AMEC NO. 6468-13-1072								Rome Formation		CHICKAMAUGA GROUP																			KNOX GROUP	
										Moccasin Formation		Witten Formation	Bowen Formation		Benbolt Formation		Rockdell Formation				Lincolnshire Formation: Fleanor Member		Lincolnshire Formation: Eidson Member		Blackford Formation		Five Oaks Formation			
	As-Drilled Coordinates/Elevations/Depths				Fill	Residual Soil	Weathered Rock			Unit H		Unit G	Unit F		Unit E		Unit D		Unit C		Unit B		Unit A						Newala Formation	
Boring Number	Northing (US ft)	Easting (US ft)	Ground Surface Elevation (ft)	Total Drilled Depth (ft)	Depth (ft)	Depth (ft)	Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Not Encount-ered	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)
MP-218	571176.5	2448147.4	810.9	99.6	35.0	38.4	41.3														41.3	99.6 (TD)								
MP-219	571223.7	2448195.7	812.9	96.5	2.0	3.9	24.5														24.5	96.5 (TD)								
MP-219A	571254.2	2448184.6	808.6	269.1	7.0	15.7	18.0														18.0	112.3	112.3	202.2	202.2	269.1 (TD)				
MP-220	571146.9	2448232.2	813.2	101.3	3.0	8.0	28.7														28.7	101.3 (TD)								
MP-221	571056.6	2448270.6	813.1	101.2	0.4	3.0	8.3														8.3	101.2 (TD)								
MP-222	570965.5	2448308.6	812.9	101.0	3.0		6.0												6.0	40.6	40.6	101.0 (TD)								
MP-401	571954.2	2447605.1	817.7	419.6	4.9		5.2																						5.2	419.6 (TD)
MP-402	571941.4	2447479.8	816.5	199.3	2.0	16.8																							16.8	199.3 (TD)
MP-403	571646.0	2447607.5	836.2	199.2	2.0		9.0																				9.0	56.5	56.5	199.2 (TD)
MP-404	571709.4	2447758.1	837.1	199.8	4.0	47.0	49.0																				49.0	80.7	80.7	199.8 (TD)
MP-405	571979.1	2447644.2	816.9	20.4	2.0	5.3	5.6																						5.6	20.4 (TD)
MP-405A	571975.7	2447647.3	817.1	199.4	1.8																								1.8	199.4 (TD)
MP-406	571775.0	2447965.9	855.1	201.3	2.0	8.0	15.3																		15.3	84.7	84.7	154.6	154.6	201.3 (TD)
MP-407	569888.8	2447094.2	761.5	200.2	12.0	19.0	25.6												25.6	87.6	87.6	200.2 (TD)								
MP-409	570584.3	2448158.9	807.0	251.5	2.5	46.0	51.1										51.1	79.5	79.5	177.4	177.4	251.5 (TD)								
MP-410	570774.2	2448368.8	809.4	201.0	6.2		8.1										8.1	69.7	69.7	159.6	159.6	201.0 (TD)								
MP-411	571500.5	2447500.3	836.8	199.6	2.5		8.0																		8.0	39.7	39.7	110.4	110.4	199.6 (TD)
MP-412	571424.0	2447850.6	823.7	321.0	14.6																		14.6	18.3	18.3	189.4	189.4	247.4	247.4	321.0 (TD)
MP-413	571645.7	2446938.7	809.0	199.2	22.0	52.2																							52.2	199.2 (TD)
MP-414	572070.0	2447564.7	817.5	199.4	7.0	42.3																							42.3	199.4 (TD)
MP-415	569577.1	2448164.8	784.3	320.1	2.5	11.0	11.4						11.4	45.3	45.3	320.1 (TD)														
MP-416	569978.3	2447520.0	809.6	321.7	51.0	65.0	65.8										65.8	138.0	138.0	245.5	245.5	321.7 (TD)								

Table 2.5.1-2 (Sheet 4 of 4) Clinch River Nuclear Stratigraphic Boundaries

GEOTECHNICAL BORINGS STRATIGRAPHIC SUMMARY TABLE CLINCH RIVER SMR PROJECT (AMEC NO. 6468-13-1072								Rome Formation		CHICKAMAUGA GROUP																					KNOX GROUP	
										Moccasin Formation		Witten Formation	Bowen Formation		Benbolt Formation		Rockdell Formation				Lincolnshire Formation: Fleanor Member		Lincolnshire Formation: Eidson Member		Blackford Formation		Five Oaks Formation					
	As-Drilled Coordinates/Elevations/Depths				Fill	Residual Soil	Weathered Rock			Unit H		Unit G	Unit F		Unit E		Unit D		Unit C		Unit B		Unit A						Newala Formation	
Boring Number	Northing (US ft)	Easting (US ft)	Ground Surface Elevation (ft)	Total Drilled Depth (ft)	Depth (ft)	Depth (ft)	Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Not Encount-ered	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)	Start Depth (ft)	End Depth (ft)		
MP-417	569915.4	2446630.3	772.7	320.0	16.5	37.0	43.0														43.0	148.2	148.2	252.8	252.8	320.1 (TD)						
MP-418	570500.3	2447030.2	811.6	87.8	27.0	43.0	46.8																46.8	87.8 (TD)								
MP-418A	570514.7	2447049.6	811.1	320.0	27.0	78.0	78.6																78.6	118.1	118.1	305.6	305.6	320.6 (TD)				
MP-419	571269.8	2446700.6	799.6	321.1	14.0	51.4	51.8																						51.8	321.1 (TD)		
MP-420	572033.0	2446918.3	803.1	319.4	2.0	19.2																							19.2	319.4 (TD)		
MP-421	570532.3	2446439.6	803.6	320.3	22.0	48.9	50.2																		22.0*	42.0*	42.0*	119.5	119.5	320.3 (TD)		
MP-422	570423.7	2448732.0	799.9	320.0	2.0	9.0	10.7								10.7	191.0	191.0	320.0 (TD)														
MP-423	571470.3	2448276.4	799.0	319.3	2.0	34.0	37.3																37.3	131.6	131.6	276.7			276.7	319.3 (TD)		
MP-424(e)	570450.2	2448361.2	800.6	273.2	24.0	36.5											36.5	187.1	187.1	273.2 (TD)												
MP-425(f)	570814.6	2448199.5	811.9	272.9	3.8		6.2												6.2	81.8	81.8	272.9 (TD)										
MP-426(g)	571764.5	2447811.0	842.2	272.3	2.5	19.0	21.9																				21.9	49.1	49.1	272.3 (TD)		
MP-428	570755.5	2448681.6	803.8	250.7		23.0	30.8										30.8	201.7	201.7	250.7 (TD)												
MP-429	569975.5	2448591.1	796.0	199.2	4.5	27.0	31.0						31.0	37.6	37.6	199.2 (TD)																

(a) Angle Boring, Inclination= 28 degrees, Azimuth= N47°E
(b) Angle Boring, Inclination= 28 degrees, Azimuth= N37°W
(c) Angle Boring, Inclination= 27 degrees, Azimuth= N47°E
(d) Angle Boring, Inclination= 28 degrees, Azimuth= N34°W
(e) Angle Boring, Inclination= 25 degrees (± 5 degrees), Azimuth= N38°W (± 5 degrees)
(f) Angle Boring, Inclination= 29 degrees, Azimuth= N49°E
(g) Angle Boring, Inclination= 28 degrees, Azimuth= N40°W

Notes:
* = Inferred contact in residual soils (Blackford/Five Oaks Formations) MP-421

(TD) = Total Depth Drilled For Boring
Blank cells indicate formations not encountered for a specific boring.

Horizontal/Vertical Datum: Tennessee State Plane Coordinates (East Zone) NAD83/NAVD88

True unit thickness calculated as follows: Assuming a uniform dip of 33 degrees, true thickness = cos 33 x observed thickness

Depths shown for angle borings are lengths below ground surface measured along the inclination (from vertical) and azimuth of the borings as stated below, and are not corrected to represent true vertical depth.

Source: Reference 2.5.1-214

Table 2.5.1-3
Average Thickness and Variability of Each Stratigraphic Unit

Rock Unit Thicknesses Across Site		
	Average Thickness (ft)	
Strata	True	Vertical
Rome Formation[(a)]	–	–
Moccasin Formation[(a)]	–	–
Witten Formation[(b)]	–	–
Bowen Formation[(a)]	–	–
Benbolt Formation	277	330
Rockdell Formation	241	287
Fleanor Member	216	257
Eidson Member	86	102
Blackford Formation	213	254
Newala Formation[(a)]	–	–

(a) Unit not fully penetrated during the subsurface investigation drilling program
(b) Unit not encountered during the subsurface investigation drilling program

Table 2.5.1-4
Lithologic Adjectives and Modifiers

KEY TO CLASSIFICATION OF SOILS

Soils to be classified under the Unified Soil Classification System (USCS) and in accordance with ASTM D 2488-09a

CORRELATION OF SPT RESISTANCE WITH RELATIVE DENSITY-CONSISTENCY				MOISTURE CONTENT	MODIFIERS	
GRANULAR MATERIAL		**SILTS AND CLAYS**		**DRY**-Absence of moisture	**Approximate %**	**Modifiers**
RELATIVE DENSITY	SPT N Value (blows/ft)	CONSISTENCY	SPT N Value (blows/ft)	**MOIST**-Damp/no visible H2O	<5%	TRACE
VERY LOOSE	0 - 4	**VERY SOFT**	0 - 2	**WET**-Visible free water	5 to 10%	FEW
LOOSE	5 - 10	**SOFT**	3 - 4		15 to 25%	LITTLE
MEDIUM DENSE	11 - 30	**MEDIUM STIFF**	5 - 8	**HCl Reaction**	30 to 45%	SOME
DENSE	31 - 50	**STIFF**	9 - 15	**NONE** - No visible reaction	50 to 100%	MOSTLY
VERY DENSE	> 50	**VERY STIFF**	16 - 30	**WEAK** - Some reaction/slow	**Modifiers provide an estimate of the percentages of gravel, sand, and fines (silt or clay size particles) or other material such as organics, shells, etc.**	
		HARD	> 30	**STRONG** - Violent reaction		

COLOR of Soil/Rock: see Munsell Soil Color Charts	**SPT Sample Numbering:** SS-1, SS-2, SS-3, etc.
Particle Size Range for Sand: Fine, Medium, Coarse	**Undisturbed/Shelby Tube Sample Numbering:** ST-1, ST-2, ST-3, etc.
Particle Size Range for Gravel: Fine or Coarse	**Measurements:** Horizontal measurements are rounded to nearest foot. Vertical measurements, such as SPT sample recovery or penetration, sample depths, core run depth, core run length, core recovery, core RQD, etc. are rounded to nearest tenth of a foot (0.1 ft).
Plasticity: Nonplastic (NP), Low (LP), Medium/Moderate (MP), High (HP)	

KEY TO CLASSIFICATION OF ROCK

Rock to be described and classified in general accordance with Dunham, 1962 Classification of Carbonate Rocks and Bechtel Guidelines

CRYSTALLINE LIMESTONE	MUDSTONE	WACKESTONE	PACKSTONE	GRAINSTONE	BOUNDSTONE
Depositional texture not recognizable (MICRITE)	*<10% Grains*	*>10% Grains, mud supported*	*>10% Mud, grain supported*	*<10% Mud, grain supported*	*Original components bound together*

WEATHERING	STRENGTH-HARDNESS DESCRIPTION		STRATIFICATION-LAMINATION	
Residual Soil (Rock material converted to soil, fabric destroyed)	**Extremely Weak**	Indented by thumbnail.	**Massive**	**>10 Feet**
Completely Weathered (Rock material decomposed to soil, fabric preserved; Saprolite)	**Very Weak**	Crumbles under firm blows with hammer, can be peeled with knife.	**Very Thickly**	**3-10 Feet**
Highly Weathered (More than half the rock material decomposed to soil, rock present as discontinuous framework)	**Weak**	Can be peeled by knife with difficulty, indentions show with firm blow with hammer.	**Thickly**	**1-3 Feet**
Moderately Weathered (Less than half the rock material decomposed to soil, rock present as a continuous framework)	**Medium Strong**	Cannot be scraped or peeled with knife, can be fractured with single firm, blow with hammer.	**Moderately**	**0.3-1.0 Feet**
Slightly Weathered (Discoloration inwards from fractures, all rock material may be discolored)	**Strong**	Sample requires more than one blow of hammer to fracture it.	**Thinly**	**0.1-0.3 Feet**
Fresh (No sign of weathering, slight discoloration on major discontinuity surfaces)	**Very Strong**	Sample requires many blows of hammer to fracture it.	**Very Thinly**	**0.03-0.1 Feet**
	Extremely Strong	Sample can only be chipped with hammer blows.	**Laminated**	**<0.03 Feet**

Vug Types	**Pit (pitted)** - Pinhole to 0.03 feet opening	**Vug (vuggy)** - Small openings 0.03 ft to 0.33 ft
	Cavity - Openings > 0.33 ft	**Honeycombed** - Cell like form, thin walls separate individual openings
	Molds - Vugs of various sizes formed by dissolution of fossils; note as separate or touching	

Sample Identification - Laboratory Tested Rock Core Samples: LX-X. (Where LX indicates the laboratory assignment number and -X indicates the sample number from that assignment; L1-5 would be the the fifth sample from laborotary assignment one, L3-10 would be the tenth sample from assignment three)

Core Terms-Abbreviations	EXPLANATION
DRILL RATE	Time in minutes it takes to core one foot, for each foot or partial foot of a core run. (1:32; 0:54/0.7 ft)
CORE RUN; RUN LENGTH	Cored Interval; Total distance of core run measured to nearest 0.1 ft. Core runs are not to exceed 5 feet.
CORE RECOVERY (REC.)	Total length of recovered core, divided by the core run length, and expressed as a percentage.
RQD (Rock Quality Designation)	Sum of intact core pieces greater than 4 inches in length, divided by the core run length, and expressed as a percentage.

Source: Reference 2.5.1-214

Table 2.5.1-5 (Sheet 1 of 5) Summary of Petrographic Examination

Upper Blackford Formation			
Color	Top 6.5 in: Dark reddish brown to dark brownish gray. Bottom 4.5 in: Dark greenish gray.	**Rock Name**	Fine-grained, siliceous limestone.95
Structure	Top 6.5 in: Thinly layered or laminated. Bottom 4.5 in.: Structureless to thinly layered. The core readily splits along the observed thin layering and lamination when hit with a hammer.	**Carbonate Constituents**	Clay and silt-sized calcite. Presence of rhombohedral carbonate minerals indicates possible occurrence of some dolomite.
Hardness	Moderately hard; when scratched by a metal probe, the probe creates shallow grooves.	**Non-Carbonate Constituents**	Quartz, fine mica flakes or sericite, and iron oxides/hydroxides with minor to trace amounts of feldspar and greenish mineral (likely chlorite). Overall abundance of non-carbonate materials is somewhat higher in the top 6.5 in. portion compared to the bottom 4.5 in. portion.
Water Absorbency	Moderately low; water droplets applied to fresh fractures are slowly absorbed by the rock.	**Grain Size**	Carbonate constituents: Top 6.5 in. – silt to clay-sized calcite. Bottom 4.5 in. – mainly clay sized calcite with a lesser amount of silt-sized calcite. Non-carbonate constituents: Mostly silt and clay-sized particles; less than 55 µm.
Voids and Porosity	No visible voids or porosity observed.	**Texture**	Consists almost entirely of silt to clay-sized calcite and other non-carbonate constituents. In layered or laminated top 6.5 in. portion, the dark reddish brown layers are more abundant in non-carbonate materials while the gray layers are more abundant in carbonate mineral (calcite). In bottom 4.5 in. portion, the non-carbonate materials are more uniformly distributed, and both carbonate and non-carbonate constituents are finer in grain size compared to the top portion.
Microcracking	Microcracks oriented parallel to the layering and lamination are frequently observed; many of these microcracks likely occurred during coring or subsequent handling.	**Microporosity**	No visible microporosity.

Table 2.5.1-5 (Sheet 2 of 5)
Summary of Petrographic Examination

Eidson Member of the Lincolnshire Formation			
Color	Light medium gray; locally appears dark gray where cherty nodules are observed.	**Rock Name**	Micritic limestone.
Structure	Overall massive. Thin dark gray seams of less than 0.04 in. thick, likely dissolution seams, are observed throughout the core body; the core splits along these seams when hit with a hammer. Small cherty nodules, up to 1.5 in. long and 1.0 in. wide, are locally observed.	**Carbonate Constituents**	Predominantly clay to silt-sized calcite.
Hardness	Moderately hard to hard; when scratched by a metal probe, the probe does not create grooves. The materials along the seams are softer.	**Non-Carbonate Constituents**	Patches of microcrystalline silica (chert) are observed in the nodules. Clayey materials and iron oxides/hydroxides are observed in the thin seams. A minor amount of small metallic particles (likely pyrite) is observed.
Water Absorbency	Low; water droplets applied to fresh fractures are very slowly absorbed by the rock.	**Grain Size**	Predominantly clay to silt-size grains of calcite and other non-carbonate materials.
Voids and Porosity	The rock is dense without visible voids or porosity.	**Texture**	Consists almost entirely of clay to silt-sized calcite without significant amounts of crystalline calcite or fossil fragments.
Microcracking	Several microcracks are observed along the thin seams; many of these microcracks likely occurred during coring or subsequent handling.	**Microporosity**	No visible microporosity.

Table 2.5.1-5 (Sheet 3 of 5)
Summary of Petrographic Examination

Fleanor Member of the Lincolnshire Formation			
Color	Dark reddish brown to gray.	**Rock Name**	Highly calcareous siltstone.
Structure	Exhibits thin layering or lamination; lamination planes are oriented obliquely to the core axis (parallel to the core end surfaces). The dark reddish brown layers are more abundant in non-carbonate materials while the gray layers are more abundant in carbonate mineral (calcite). The core readily splits along the laminae.	**Carbonate Constituents**	Fine, silt to clay-sized (less than 60 µm) calcite grains. Presence of rhombohedral carbonate minerals indicates possible occurrence of some dolomite.
Hardness	Moderately soft; when scratched by a metal probe, the probe creates relatively deep grooves, and the rock locally fractures into thin flakes.	**Non-Carbonate Constituents**	Quartz, fine mica flakes or sericite, and iron oxides/hydroxides with minor to trace amounts of feldspar and greenish minerals (likely chlorite).
Water Absorbency	Low to moderate; water droplets applied to fresh fractures are slowly to locally somewhat readily absorbed by the rock.	**Grain Size**	Carbonate constituents: Mostly silt and clay-sized calcite, less than 60 µm across. Non-carbonate constituents: Mostly silt and clay sized particles, less than 45 µm across.
Voids and Porosity	No visible voids or porosity observed.	**Texture**	Consists almost entirely of silt to clay-sized particles of calcite and other non-carbonate constituents The dark reddish brown layers are more abundant in non- carbonate materials while the gray layers are more abundant in carbonate mineral (calcite). Many of the mica flakes are oriented parallel to lamination.
Microcracking	Microcracks oriented parallel to lamination are frequently observed; many of these microcracks likely occurred during coring or subsequent handling.	**Microporosity**	No visible microporosity.

Table 2.5.1-5 (Sheet 4 of 5)
Summary of Petrographic Examination

Rockdell Formation Unit D			
Color	Light to light medium gray.	**Rock Name**	Micritic limestone.
Structure	Overall massive. Thin seams (likely dissolutions seams and/or stylolites) are observed in 6.5 to 10.5 in. zone below top end, and oriented obliquely to the core axis; the rock locally splits along these seams when hit with a hammer. A few stylolites oriented obliquely to these seams are observed in remaining portion of core. Several fine cracks and microcracks are observed in the core body and completely filled with crystalline calcite.	**Carbonate Constituents**	Predominantly clay-sized calcite and a small amount of crystalline calcite.
Hardness	Moderately hard to hard; when scratched by a metal probe, the probe does not create grooves. The materials along the dark gray seams and/or stylolites are softer.	**Non-Carbonate Constituents**	Clayey materials, iron oxides/hydroxides, and occasional quartz in the seams.
Water Absorbency	Low; water droplets applied to fresh fractures are slowly absorbed by the rock.	**Grain Size**	Carbonate constituents: Predominantly clay-sized calcite grains with a small amount of crystalline calcite. Non-carbonate constituents: Mostly clay to silt-sized particles.
Voids and Porosity	The rock is dense without visible voids or porosity.	**Texture**	Small blebs or fragments of crystalline calcite and fossils are scattered in the clay-sized calcite matrix.
Microcracking	Rare; a few microcracks are locally observed along the thin seams.	**Microporosity**	No visible microporosity.

Table 2.5.1-5 (Sheet 5 of 5)
Summary of Petrographic Examination

Benbolt Formation			
Color	Light medium to dark gray.	**Rock Name**	Fine grained limestone.
Structure	Exhibits lighter and darker areas. The darker areas often occur as narrow bands or zones oriented obliquely to the core axis. Thin seams (likely dissolution seams) are locally observed, mostly in the darker areas; the core splits along these seams when hit with a hammer.	**Carbonate Constituents**	Clay to silt-sized calcite and a lesser amount of crystalline calcite and fossil fragments. A small amount of rhombohedral carbonate minerals, possibly dolomite, are locally observed.
Hardness	Moderately hard; when scratched by a metal probe, the probe creates shallow grooves.	**Non-Carbonate Constituents**	Small localized patches of microcrystalline silica as partial replacement of fossils. Clayey materials, iron oxides/hydroxides, and minor amounts of fine mica flakes and quartz grains locally occur in the thin seams. Small amounts of clay-sized material locally present in the darker areas. Small patches and streaks of pyrite at localized areas.
Water Absorbency	Low; water droplets applied to fresh fractures are slowly absorbed by the rock.	**Grain Size**	Carbonate constituents: Crystalline calcite and fossil fragments up to 0.3 in. wide and 0.7 in. long are scattered in clay and silt-sized calcite matrix. Non-carbonate constituents: Mostly clay and silt-sized particles.
Voids and Porosity	The rock is dense without visible voids or porosity.	**Texture**	Small blebs or fragments of crystalline calcite and fossils are observed in the clay to silt-sized calcite. In general, the darker areas consist of finer calcite (mostly clay-sized calcite), and contains higher amounts of non-carbonate materials compared to the lighter areas.
Microcracking	Several microcracks are observed along the thin seams and in the darker areas.	**Microporosity**	No visible microporosity.

Table 2.5.1-6
Description of Mapped Karst Features

Karst Depression. A broad term that includes all features that show evidence of loss of surface material into an underground drainage system. Karst depressions are classified into the four types below based on topographic expression.
Sinkhole. (D) Karst depression that can be outlined by a closed contour at least 100 ft^2 in area, and is 2 ft or greater in depth. Sinkholes are shown with a red dot placed at the deepest place within the sink, and a green polygon that fills depression to the highest closed contour. In the case of a compound sinkhole, where smaller depressions occur within a larger closed depression, a red dot is place in the center of each smaller depression.
Shallow depression. (SD) Karst depression that can be outlined by a closed contour at least 100 ft^2 in area, and is less than 2 ft in depth. Shown with an orange dot placed in the center of the depression.
Three-sided depression. (A) Karst depression that is closed on three sides and open on the fourth side such that it cannot be outlined by a closed contour. Contour lines on the first and third sides are parallel to almost enclosed. The floor is level to gently sloping, especially if on a hillslope, and the slope may steepen markedly at the point beyond the margin of the depression. Shown with a yellow dot placed in the most level part of the floor.
Two-sided depression. (B) Karst depression characterized by an open arcuate headwall above a gentle to almost level slope, which then steepens downhill. These appear as “dimples” on the LiDAR slope map, and are common on hillslopes. Shown with a blue dot placed in the most level part of the floor.
Cave. Entrances of known caves. These data were obtained from the Oak Ridge Reservation Karst Inventory map (Reference 2.5.1-239), and from the word “cave” shown on U.S. Geological Survey 7.5-minute topographic maps.
Spring. Locations where water is known to come up out of the ground or exit a cave or other karst conduit. Springs were marked based on the word “Spring” on USGS topographic maps, and interpretation of LiDAR–based topographic data. Field-based spring data of Lemiszki et al. (Reference 2.5.1-239) for the Oak Ridge Reservation are not included, but suggest many additional springs exist.

Notes:

See Figure 2.5.1-37 for mapping of karst features.

Table 2.5.1-7 (Sheet 1 of 2)
Occurrence of Karst Depressions by Geologic Unit in the 5-Mile Site Radius

Geologic Unit			Area (sq km)	Karst Depressions (count per type[a])					Depr. Density (total/sq km)	Depr. Area (sq m)	Area Ratio (%)[b]
Group	Symbol	Name		D	SD	A	B	Total			
	Sr	Rockwood Formation	0.17	0	0	0	0	0	0.00	0	0.00
	Os	Sequatchie Formation	0.19	0	0	0	0	0	0.00	0	0.00
	Or	Reedsville Shale	0.17	0	0	0	0	0	0.00	0	0.00
Nashville	Ocncy	Cannon, Leipers, Catheys, undiff.	4.13	1	0	0	1	2	0.48	307	0.01
	Ocyl	Catheys and Leipers Formations	0.40	1	0	0	0	1	2.52	16	0.00
	Ocn	Cannon Limestone	0.11	0	0	0	0	0	0.00	0	0.00
	Oh	Hermitage Formation	1.12	1	0	1	0	2	1.79	3,589	0.32
Chickamauga	Och	Chickamauga Gp., undiff.	0.03	0	0	0	0	0	0.00	0	0.00
	Omc	Moccasin Formation	3.47	3	0	1	2	6	1.73	6,486	0.19
	Owi	Witten Formation	1.97	10	0	1	7	18	9.12	24,423	1.24
	Obw	Bowen Formation	0.58	0	0	0	0	0	0.00	251	0.04
	Obe	Benbolt Formation	2.64	2	1	0	0	3	1.14	1,860	0.07
	Ork	Rockdell Formation	2.19	5	3	2	8	18	8.23	2,553	0.12
	Ofl	Fleanor Shale	2.28	0	0	0	0	0	0.00	0	0.00
	Ofo	Five Oaks Formation	1.31	0	0	1	2	3	2.29	0	0.00
Stones River	Osr	Stones River Gp., undiff.	3.21	19	0	4	2	25	7.79	54,436	1.70
	Oca	Carters Limestone	2.66	23	0	1	2	26	9.76	50,603	1.90
	Olb	Lebanon Limestone	0.89	9	0	0	5	14	15.73	7,091	0.80
	Ord	Ridley Limestone	2.39	18	3	3	8	32	13.38	16,858	0.71
	Omp	Pierce and Murfreesboro Limestone	1.28	14	4	4	2	24	18.68	36,980	2.89
	Ops	Pond Spring Formation	3.36	42	3	5	8	58	17.27	152,115	4.53
Knox	Oma	Mascot Dolomite	16.85	185	19	23	156	383	22.73	410,868	2.44
	Ok	Kingsport Formation	20.14	141	9	43	128	321	15.94	302,987	1.50
	Olv	Longview Dolomite	6.05	47	4	16	76	143	23.65	58,640	0.97
	Oc	Chepultepec Dolomite	32.96	337	26	63	384	810	24.57	857,883	2.60
	Ccr	Copper Ridge Dolomite	29.44	309	13	62	413	797	27.07	803,479	2.73

Table 2.5.1-7 (Sheet 2 of 2)
Occurrence of Karst Depressions by Geologic Unit in the 5-Mile Site Radius

Geologic Unit			Area (sq km)	Karst Depressions (count per type[a])					Depr. Density (total/sq km)	Depr. Area (sq m)	Area Ratio (%)[b]
Group	Symbol	Name		D	SD	A	B	Total			
Conasauga	Cc	Conasauga Gp., undiff.	12.79	0	0	0	0	0	0.00	0	0.00
	Cmn	Maynardville Limestone	10.81	42	1	13	50	106	9.80	51,853	0.48
	Cn	Nolichucky Shale	9.23	0	0	0	2	2	0.22	0	0.00
	Cdg	Dismal Gap Formation	5.92	0	0	0	2	2	0.34	0	0.00
	Crg	Rogersville Shale	1.84	0	0	0	0	0	0.00	0	0.00
	Cf	Friendship Formation	1.17	0	0	0	0	0	0.00	0	0.00
	Cpv	Pumpkin Valley Shale	4.02	0	0	0	0	0	0.00	0	0.00
Rome	Cr	Rome Formation	17.65	1	0	0	0	1	0.06	3,200	0.02
TOTALS			203.42	1,210	86	243	1,258	2,797	13.75	2,846,478	1.40

(a) Depression types: D–Depression, closed, greater than or equal to 100 ft^2 in area and 2 ft deep; SD–Shallow depression, closed, less than 2 ft deep; A–Three-sided depression, open; B–Two-sided depression, open.

(b) Area Ratio (%) = (Area of closed depressions/Area of bedrock unit) x 100

Notes:

The Five Oaks Formation consists of undifferentiated Blackford Formation and Eidson Member.

Table 2.5.1-8
Occurrence of Cave Entrances by Geologic Unit in the 5-Mile Site Radius

Geologic Unit			
Group	**Symbol**	**Name**	**Cave Entrances**
Knox	Oma	Mascot Dolomite	2
	Ok	Kingsport formation	1
	Olv	Longview Dolomite	1
	Oc	Chapultepec Dolomite	2
	Ccr	Copper Ridge Dolomite	12
Conasauga	Cmn	Maynardville Limestone	6
		TOTAL	24

Table 2.5.1-9 (Sheet 1 of 2)
Chemistry, Mineralogy, and Petrography of Rock Core

Sample no	Boring	Depth (ft. bgs)	Geologic Unit	Field Description	Percent calcite *	Test **	Percent insoluble	Non-carbonate minerals: X-ray difraction	Non-carbonate minerals: Petrography	Petrographic classification	Petrographic Features
L6-01	MP-202	50.1-50.7	Fleanor	Reddish brown calc. siltstone w/ burrows	42	A	50	Quartz with minor muscovite	Quartz, mica,iron oxide, fsp, chlorite	Calcareous siltstone	Reddish brown and gray laminated
L6-02	MP-202	78.5-79.1	Fleanor	Reddish brown calcareous siltstone	28	B	—	—	—	—	—
L6-03	MP-202	113.1-113.7	Fleanor	Dark & light gray banded silty lms.	40	B	—	—	—	—	—
L1-22	MP-202	148.7-149.6	Fleanor	—	28	B	—	—	—	—	—
L6-04	MP-202	195.8-197.9	Fleanor	Brown and gray laminated calc. lms.	28	B	—	—	—	—	—
L6-05	MP-202	241.0-242.4	Eidson	Med gray silty limestone	51	B	—	—	—	—	—
L6-06	MP-202	247.8-249.0	Eidson	Light & dark gray fossiliferous lms.	54	B	—	—	—	—	—
L6-07	MP-202	261.0-261.6	Eidson	Gray limestone with chert, bioturbated	67	A	28	Quartz	Quartz, chert, clay, iron oxide	Micritic to fine-grained limestone	Light medium gray, massive, cherty
L6-08 top	MP-202	329.9-330.4	Blackford	Gray calcareous siltstone, banded	67	A	26	Quartz with minor muscovite, albite	Quartz, mica, iron oxide, fsp, chlorite	Fine-grained siliceous limestone	Dark reddish brown to gray laminated
L6-08 btm	MP-202	330.4-330.8	Blackford	Gray calcareous siltstone, banded	62	A	31	Quartz with minor muscovite	Quartz, mica, iron oxide, fsp, chlorite	Fine-grained siliceous limestone	Dark greenish gray massive to layered
L6-09	MP-202	385.2-385.9	Blackford	Reddish brown calc. siltstone, massive	39	B	—	—	—	—	
L6-10	MP-101	39.1-40-0	Benbolt	Gray, nodular imestone	80	A	16	Quartz with minor muscovite, pyrite	Quartz, clay, iron oxide, mica, pyrite	Fine-grained limestone	Light medium to dark gray, fossiliferous
L6-11	MP-101	90.0-91.5	Benbolt	Dk-gy laminated silty limestone	27	B	—	—	—	—	—
L6-12	MP-101	144.6-145.1	Rockdell D	Gray limestone, micritic, crystalline	75	B	—	—	—	—	—
L1-05	MP-101	148.7-149.7	Rockdell	—	62	B	—	—	—	—	—
L6-13	MP-101	184.6-185.2	Rockdell D	Gy /dk-gy wavy banded silty limestone	45	B	—	—	—	—	—
L6-14	MP-101	275.6-276.6	Rockdell	Gray lms. with stylolites, fine grained	94	A	3	Quartz with minor muscovite	Quartz, clay, iron oxide	Micritic to fine-grained limestone	Light to medium gray, massive, stylolitic
L6-15	MP-101	378.9-379.6	Rockdell C	Gray silty limestone	48	B	—	—	—	—	—

Table 2.5.1-9 (Sheet 2 of 2)
Chemistry, Mineralogy, and Petrography of Rock Core

Sample no	Boring	Depth (ft. bgs)	Geologic Unit	Field Description	Percent calcite *	Test **	Percent insoluble	Non-carbonate minerals: X-ray difraction	Non-carbonate minerals: Petrography	Petrographic classification	Petrographic Features
L1-13	MP-101	451.4-452.4	Fleanor	—	45	B	—	—	—	—	—
L6-16	MP-415	28.5-28.9	Bowen	Light gray wackestone, weathered face	88	B	—	—	—	—	—
L6-17	MP-415	25.1-25.7	Bowen	Laminated red/gy silty limestone	57	B	—	—	—	—	—
L6-18	MP-415	38.6-39.1	Bowen	Red calcareous siltstone	26	B	—	—	—	—	—
L6-19	MP-401	79.0-79.6	Mascot	Red micrite, dissolution cavities	77	B	—	—	—	—	—
L6-20	MP-401	216.4-216.9	Mascot	Light reddish gray dolomitic grain stone	90	B	—	—	—	—	—

* Includes dolomite as calcite equivalent
** Method used to determine percent calcite: A = Thermogravimetry, B = Rapid method, ASTM-D-4373
__ = Not tested   lms. = limestone

Table 2.5.1-10 (Sheet 1 of 2)
Mineralogy of Rock Core from Clinch River Breeder Reactor Project

CR SMR Project	CRBRP	Sample Location	Rock Type	Percent Composition							
				Calcite	Dolomite	Chert and Quartz	Feldspar	Illite	Other Clay Materials	Hematite	Pyrite
Rome	Rome Formation	B-43 at 51 ft	Dolomite	TR	60	20	15	5	TR	–	TR
		B-43 at 77 ft	Sandstone	–	TR	50	45	–	1	4	–
		B-43 at 66 ft	Shale	5	20	20	10	40	1	4	–
		I-40 Roadcut	Dolomite	–	94	5	–	–	1	–	–
	Copper Creek Fault	I-40 Roadcut	Mylonite	60	10	15	–	10	5	–	–
Moccasin, Witten, Bowen, Benbolt	Undifferentiated Chickamauga	I-40 Roadcut	Limestone	92	TR	5	–	1	2	–	–
		B-43 at 274 ft	Limestone	85	–	8	1	4	2	–	–
		B-43 at 284 ft	Limestone	60	20	10	3	5	2	–	–
		B-24 at 133 ft	Limestone	70	5	12	–	6	7	–	–
Rockdell	Chickamauga Unit B	B-25 at 23 ft	Limestone	80	–	10	2	8	TR	–	–
		B-37 at 94 ft	Limestone	70	10	10	–	6	4	–	TR
		B-38 at 106 ft	Limestone	86	2	–	–	–	12	–	–
		B-41 at 42 ft	Limestone	40	12	18	–	13	17	–	–
		B-38 at 106 ft	Limestone	42	20	15	–	10	13	–	–
Fleanor	Chickamauga Unit A Upper Siltstone	B-38 at 110 ft	Siltstone	15	25	35	–	15	9	1	–
		B-41 at 195 ft	Siltstone	35	15	25	–	12	12	1	–
		B-25 at 100 ft	Siltstone	20	15	25	10	15	12	3	–
		B-28 at 94 ft	Siltstone	35	10	30	3	15	5	2	–
		B-25 at 101 ft	Limestone	40	15	20	TR	15	10	–	–
		B-80 at 198 ft	Limestone	26	32	26	7	4	5	–	–

Table 2.5.1-10 (Sheet 2 of 2)
Mineralogy of Rock Core from Clinch River Breeder Reactor Project

CR SMR Project	CRBRP	Sample Location	Rock Type	Percent Composition							
				Calcite	Dolomite	Chert and Quartz	Feldspar	Illite	Other Clay Materials	Hematite	Pyrite
Eidson	Chickamauga Unit A Limestone	B-39 at 257 ft	Limestone	50	10	20	5	10	5	–	–
		B-28 at 146 ft	Limestone	60	5	15	5	10	5	–	–
		B-26 at 173 ft	Limestone	80	–	10	–	4	6	–	–
		B-26 at 178 ft	Limestone	92	–	8	–	–	–	–	–
		B-26 at 194 ft	Limestone	88	–	10	–	–	2	–	–
		B-32 at 148 ft	Limestone	90	–	8	–	–	2	–	–
		B-26 at 175 ft	Limestone	90	2	5	TR	3	TR	–	–
		B-32 at 149 ft	Limestone	50	5	35	–	8	2	–	–
		B-28 at 200 ft	Limestone	60	–	40	–	–	TR	–	–
		B-39 at 291 ft	Limestone	85	5	5	TR	3	2	–	–
		B-26 at 194 ft	Chert	–	–	100	–	–	–	–	–
		B-32 at 148 ft	Chert	5	0	95	–	–	–	–	–
Blackford	Chickamauga Unit A Lower Siltstone	B-32 at 222 ft	Siltstone	18	18	50	–	6	6	2	–
		B-38 at 202 ft	Siltstone	20	12	44	–	12	12	–	–
		B-39 at 212 ft	Siltstone	20	25	30	TR	20	5	–	–
		B-28 at 252 ft	Limestone	70	10	10	3	7	TR	TR	–
		B-32 at 284 ft	Limestone	93	5	2	–	–	–	–	–
		B-28 at 270 ft	Siltstone	25	15	30	5	20	2	3	–
Mascot	Knox	B-5 at 159 ft	Dolomite	TR	92	–	–	6	2	–	–
		B-5 at 224 ft	Dolomite	TR	96	–	–	4	–	–	–

Notes:
Reproduced from Reference 2.5.1-100, Table 2.5-5
TR = Trace
Dash (–) = Not present
Refer to Table 2.5.1-1 for more details.

Table 2.5.1-11 (Sheet 1 of 7)
Cavities in Boreholes Drilled at Clinch River Nuclear Site, 1973–1978 and 2013

Borehole	CRBRP Strat Unit	SMR Strat Unit	Cavity Top Elev'n (ft)	Cavity Bottom Elev'n (ft)	Cavity Average Elev'n (ft)	Cavity Height (ft)	Water Table Elev'n (ft)	Top of Rock Elev'n (ft)	Bottom of Hole Elev'n (ft)
2	A	Blackford	838.3	838	838.15	0.3	822	841.2	626
2	A	Blackford	837.2	837	837.1	0.2			
2	A	Blackford	833	831.5	832.25	1.5			
3	A	Eidson	861.8	861.7	861.75	0.1	ND	862.2	661.8
3	A	Eidson	860.5	860.3	860.4	0.2			
3	A	Eidson	859.5	859.1	859.3	0.4			
3	A	Eidson	857.4	856.8	857.1	0.6			
3	A	Eidson	855	854.5	854.75	0.5			
3	A	Eidson	854	852.2	853.1	1.8			
3	A	Eidson	851.8	851	851.4	0.8			
3	A	Eidson	850.5	847	848.75	3.5			
3	A	Blackford	840.2	840	840.1	0.2			
3	A	Blackford	838	837.4	837.7	0.6			
3	A	Blackford	835.2	835	835.1	0.2			
3	A	Blackford	829.7	829.4	829.55	0.3			
3	A	Blackford	828.7	828	828.35	0.7			
3	A	Blackford	827.9	827.7	827.8	0.2			
3	A	Blackford	796.1	796	796.05	0.1			
3	A	Blackford	792	791.8	791.9	0.2			
4	A	Eidson	730	729.3	729.65	0.7	739	769.7	619.4
5	A	Blackford	868	867.2	867.6	0.8	812	871	665.4
5	A	Blackford	863.5	861	862.25	2.5			
5	A	Blackford	855.3	855	855.15	0.3			
5	A	Blackford	854.5	853.5	854	1			
5	A	Blackford	848	847.7	847.85	0.3			
5	A	Blackford	843.6	842.2	842.9	1.4			
5	A	Blackford	815	813.8	814.4	1.2			
6	A	Eidson	824	822.1	823.05	1.9	818	833.3	682.7
6	A	Eidson	821.3	820.5	820.9	0.8			
6	A	Eidson	820	819.7	819.85	0.3			
6	A	Eidson	816.1	815.7	815.9	0.4			
6	A	Blackford	806	805.8	805.9	0.2			
6	A	Blackford	805.1	803.7	804.4	1.4			
6	A	Blackford	796.3	796	796.15	0.3			

Table 2.5.1-11 (Sheet 2 of 7)
Cavities in Boreholes Drilled at Clinch River Nuclear Site, 1973–1978 and 2013

Borehole	CRBRP Strat Unit	SMR Strat Unit	Cavity Top Elev'n (ft)	Cavity Bottom Elev'n (ft)	Cavity Average Elev'n (ft)	Cavity Height (ft)	Water Table Elev'n (ft)	Top of Rock Elev'n (ft)	Bottom of Hole Elev'n (ft)
7	A	Eidson	778.5	777.6	778.05	0.9	761	779.8	629.4
7	A	Eidson	777.2	777	777.1	0.2			
7	A	Eidson	776.7	776	776.35	0.7			
7	A	Eidson	775.2	774.2	774.7	1			
7	A	Eidson	774	772.5	773.25	1.5			
7	A	Eidson	771.4	771.2	771.3	0.2			
7	A	Eidson	771	767.6	769.3	3.4			
7	A	Eidson	766.1	764.5	765.3	1.6			
7	A	Eidson	748.4	748	748.2	0.4			
8	A	Fleanor	827.6	827.5	827.55	0.1	802	829.1	679
8	A	Fleanor	824.5	824	824.25	0.5			
9	A	Eidson	787.2	784.3	785.75	2.9	773	797.5	648.3
9	A	Blackford	766.1	765.8	765.95	0.3			
9	A	Blackford	760	758.9	759.45	1.1			
9	A	Blackford	758.2	757.2	757.7	1			
9	A	Blackford	756.7	755.8	756.25	0.9			
10	A	Eidson	791.2	790.5	790.85	0.7	ND	791.7	656.9
10	A	Eidson	786.2	785.6	785.9	0.6			
10	A	Eidson	776.4	775	775.7	1.4			
10	A	Eidson	774.8	773	773.9	1.8			
10	A	Eidson	771.6	771	771.3	0.6			
10	A	Eidson	768.7	766	767.35	2.7			
10	A	Eidson	764	759.1	761.55	4.9			
11	A	Fleanor	771.1	770.2	770.65	0.9	772	772.3	678.7
11	A	Fleanor	769.4	768	768.7	1.4			
11	A	Fleanor	765.9	765.4	765.65	0.5			
11	A	Fleanor	762.8	761.9	762.35	0.9			
11	A	Eidson	748	747.2	747.6	0.8			
12	A	Rockdell?	846.4	846	846.2	0.4	827	848.1	696
12	A	Rockdell?	845.6	845	845.3	0.6			
12	A	Rockdell?	844.6	844	844.3	0.6			
12	A	Rockdell?	843.5	842	842.75	1.5			
12	A	Rockdell?	840.9	840	840.45	0.9			
12	A	Fleanor?	835.7	835	835.35	0.7			
12	A	Fleanor?	827.8	827.5	827.65	0.3			

**Table 2.5.1-11 (Sheet 3 of 7)
Cavities in Boreholes Drilled at Clinch River Nuclear Site,
1973–1978 and 2013**

Borehole	CRBRP Strat Unit	SMR Strat Unit	Cavity Top Elev'n (ft)	Cavity Bottom Elev'n (ft)	Cavity Average Elev'n (ft)	Cavity Height (ft)	Water Table Elev'n (ft)	Top of Rock Elev'n (ft)	Bottom of Hole Elev'n (ft)
13	B	Rockdell	816.4	816.2	816.3	0.2	795	817.7	678.5
13	B	Rockdell	814.4	814	814.2	0.4			
13	B	Rockdell	813.5	813	813.25	0.5			
13	B	Rockdell	810.5	807.6	809.05	2.9			
13	B	Rockdell	806.6	806.2	806.4	0.4			
13	B	Rockdell	806	804.2	805.1	1.8			
13	B	Rockdell	803.5	803.1	803.3	0.4			
13	B	Rockdell	802.6	802.1	802.35	0.5			
13	B	Rockdell	800.5	796.2	798.35	4.3			
15	A	Fleanor	755.8	755	755.4	0.8	765	756.8	641.3
15	A	Fleanor	754.2	753	753.6	1.2			
15	A	Fleanor	752.5	752	752.25	0.5			
15	A	Fleanor	746	745.7	745.85	0.3			
16	B	Rockdell	812	811	811.5	1	789	815.1	694.3
16	B	Rockdell	805.8	805.5	805.65	0.3			
16	B	Rockdell	801	798.1	799.55	2.9			
16	B	Rockdell	797.8	797	797.4	0.8			
17	B	Rockdell	824.2	810.2	817.2	14	ND	834.1	581.3
17	B	Rockdell	804.4	804.3	804.35	0.1			
18	B	Rockdell	818.7	815.4	817.05	3.3	805	819	698.5
18	B	Rockdell	815	814.2	814.6	0.8			
18	B	Rockdell	814	813.5	813.75	0.5			
18	B	Rockdell	812.6	812.3	812.45	0.3			
18	B	Rockdell	811.4	810	810.7	1.4			
18	B	Rockdell	809.8	807	808.4	2.8			
18	B	Rockdell	806.5	805.8	806.15	0.7			
18	B	Rockdell	805.3	805	805.15	0.3			
18	B	Rockdell	804.2	804	804.1	0.2			
18	B	Rockdell	803.6	803	803.3	0.6			
18	B	Rockdell	802.8	802.4	802.6	0.4			
18	B	Rockdell	802.3	801.7	802	0.6			
18	B	Rockdell	801.6	801.4	801.5	0.2			
18	B	Rockdell	800.4	799.5	799.95	0.9			
18	B	Rockdell	798	797.2	797.6	0.8			
18	B	Rockdell	796.3	795.7	796	0.6			
18	B	Rockdell	795.2	794.9	795.05	0.3			

Table 2.5.1-11 (Sheet 4 of 7)
Cavities in Boreholes Drilled at Clinch River Nuclear Site, 1973–1978 and 2013

Borehole	CRBRP Strat Unit	SMR Strat Unit	Cavity Top Elev'n (ft)	Cavity Bottom Elev'n (ft)	Cavity Average Elev'n (ft)	Cavity Height (ft)	Water Table Elev'n (ft)	Top of Rock Elev'n (ft)	Bottom of Hole Elev'n (ft)
18	B	Rockdell	793.8	793.1	793.45	0.7			
18	B	Rockdell	791.1	790.3	790.7	0.8			
18	B	Rockdell	784	781.4	782.7	2.6			
19	Undif Chk	Benbolt	777.4	777	777.2	0.4	785	781.6	630.6
19	Undif Chk	Benbolt	772.1	772	772.05	0.1			
19	Undif Chk	Benbolt	766.4	764.4	765.4	2			
20	B	Rockdell	771.5	766.8	769.15	4.7	ND	772.6	595
20	B	Rockdell	763.6	760	761.8	3.6			
20	B	Rockdell	720.8	720.4	720.6	0.4			
20	B	Rockdell	713.8	711	712.4	2.8			
20	B	Rockdell	708	705	706.5	3			
20	B	Rockdell	700	699.3	699.65	0.7			
21	B	Rockdell	782.8	782	782.4	0.8	761	787.9	687.9
21	B	Rockdell	761.7	761.5	761.6	0.2			
22	B	Rockdell	758	757.8	757.9	0.2	740	758.7	647
22	B	Rockdell	757	755.8	756.4	1.2			
22	B	Rockdell	755.6	753.8	754.7	1.8			
22	B	Rockdell	753	748	750.5	5			
22	B	Rockdell	747.8	745.6	746.7	2.2			
22	B	Rockdell	745.4	745.1	745.25	0.3			
22	B	Rockdell	745	743.9	744.45	1.1			
22	B	Rockdell	743.3	743	743.15	0.3			
22	B	Rockdell	741.7	741	741.35	0.7			
22	B	Rockdell	740.3	740	740.15	0.3			
22	B	Rockdell	738.5	738	738.25	0.5			
22	B	Rockdell	737.7	737	737.35	0.7			
22	B	Rockdell	736.5	736.4	736.45	0.1			
22	B	Rockdell	736	735.8	735.9	0.2			
22	B	Rockdell	734.2	733.8	734	0.4			
22	B	Rockdell	733	732.5	732.75	0.5			
22	B	Rockdell	729.6	722	725.8	7.6			
22	B	Rockdell	711.3	711	711.15	0.3			
23	Undif Chk	Benbolt	770.3	769.4	769.85	0.9	779	777	638.4
24	Undif Chk	Benbolt	776	773.3	774.65	2.7	777	777.2	572.9
24	Undif Chk	Benbolt	772.5	772.2	772.35	0.3			
24	Undif Chk	Benbolt	769	768.9	768.95	0.1			

**Table 2.5.1-11 (Sheet 5 of 7)
Cavities in Boreholes Drilled at Clinch River Nuclear Site,
1973–1978 and 2013**

Borehole	CRBRP Strat Unit	SMR Strat Unit	Cavity Top Elev'n (ft)	Cavity Bottom Elev'n (ft)	Cavity Average Elev'n (ft)	Cavity Height (ft)	Water Table Elev'n (ft)	Top of Rock Elev'n (ft)	Bottom of Hole Elev'n (ft)
25	B	Rockdell	840.4	840	840.2	0.4	774	840.4	552.3
26	A	Fleanor	786.4	785.3	785.85	1.1	776	797	509.6
30	A	Fleanor	720	719.5	719.75	0.5	774	805.6	555.6
31	A	Eidson	750	749.5	749.75	0.5	743	780.4	552.1
31	A	Eidson	710.5	710	710.25	0.5			
34	A	Eidson	760	755.5	757.75	4.5	742	763	545.1
34	A	Eidson	753.9	753	753.45	0.9			
34	A	Eidson	730	729.1	729.55	0.9			
34	A	Eidson	713.6	711.8	712.7	1.8			
35	A	Eidson	789.1	788.6	788.85	0.5	775	801.8	529.8
35	A	Eidson	788.2	787.3	787.75	0.9			
35	A	Eidson	784.6	784.1	784.35	0.5			
35	A	Eidson	775.9	773	774.45	2.9			
35	A	Blackford	730	728.2	729.1	1.8			
38	B	Rockdell	832.7	833.6	833.15	0.9	ND	842.6	500.1
40	A	Fleanor	761.3	761	761.15	0.3	762	818.1	524.1
41	B	Rockdell	767.3	767.1	767.2	0.2	771	791.5	458.6
48	B	Rockdell	797.1	794.4	795.75	2.7	ND	799.8	709.8
49	B	Rockdell	777.3	776	776.65	1.3	ND	812.9	687.9
50	B	Rockdell	773.6	767.9	770.75	5.7	747	774.5	566.5
50	B	Rockdell	766.8	760.2	763.5	6.6			
50	B	Rockdell	760	757.5	758.75	2.5			
50	B	Rockdell	755.5	749.5	752.5	6			
50	B	Rockdell	748.7	746.4	747.55	2.3			
50	B	Rockdell	745.5	737	741.25	8.5			
51	A	Eidson	733.6	728	730.8	5.6	746	780.5	466.5
52	A	Blackford	767.8	767.6	767.7	0.2	ND	817.2	602.2
52	A	Blackford	736.4	735.3	735.85	1.1			
54	A	Fleanor	759.1	758.7	758.9	0.4	ND	789.1	579.5
54	A	Fleanor	728.2	727.8	728	0.4			
56	A	Eidson	755.6	755.2	755.4	0.4	ND	773.6	560.6
56	A	Eidson	723.6	723.2	723.4	0.4			
56	A	Eidson	722.7	715.9	719.3	6.8			
58	Undif Chk	Benbolt?	751.8	751.4	751.6	0.4	757	757.1	548.1
59	Undif Chk	Witten?	744.5	744.3	744.4	0.2	750	758.1	509.6

Table 2.5.1-11 (Sheet 6 of 7) Cavities in Boreholes Drilled at Clinch River Nuclear Site, 1973–1978 and 2013

Borehole	CRBRP Strat Unit	SMR Strat Unit	Cavity Top Elev'n (ft)	Cavity Bottom Elev'n (ft)	Cavity Average Elev'n (ft)	Cavity Height (ft)	Water Table Elev'n (ft)	Top of Rock Elev'n (ft)	Bottom of Hole Elev'n (ft)
61	Knox	Ok/Oma	749	748.2	748.6	0.8	808	795.3	710.3
61	Knox	Ok/Oma	743.6	742	742.8	1.6			
65	Knox	Ok/Oma	870	869.4	869.7	0.6	803	873.9	774.3
66	Knox	Ok/Oma	841.8	837.7	839.75	4.1	807	843.9	749.3
66	Knox	Ok/Oma	826.4	825.4	825.9	1			
66	Knox	Ok/Oma	823.6	823.1	823.35	0.5			
66	Knox	Ok/Oma	821.8	819.3	820.55	2.5			
66	Knox	Ok/Oma	817.3	817	817.15	0.3			
66	Knox	Ok/Oma	776.3	776.1	776.2	0.2			
70	A	Eidson	757.3	757.05	757.175	0.25	ND	794.1	658.1
70	A	Eidson	756.4	755.9	756.15	0.5			
70	A	Eidson	753.7	753.2	753.45	0.5			
70	A	Eidson	751.3	750	750.65	1.3			
80	B	Rockdell	800	799	799.5	1	ND	804.7	402.7
94	A	Eidson	735.5	735.2	735.35	0.3	ND	782.9	620.9
100	B	Rockdell	807.3	804.6	805.95	2.7	ND	845.3	604.4
100	B	Rockdell	802.7	802	802.35	0.7			
102	A	Fleanor	772.7	772.4	772.55	0.3	ND	786	642.2
102	A	Fleanor	764.5	764.2	764.35	0.3			
103	B	Rockdell	847.2	846.4	846.8	0.8	ND	864.5	752.5
127	B	Rockdell	826.3	824.3	825.3	2	ND	827.9	715.9
128	B	Rockdell	799.1	796.6	797.85	2.5	ND	831.8	712.8
129	B	Rockdell	804.5	798.5	801.5	6	783	836.2	716.2
130	B	Rockdell	831	830	830.5	1	777	841	717
130	B	Rockdell	807.2	806.2	806.7	1			
131	B	Rockdell	776.3	775.3	775.8	1	ND	813	696.4
133	B	Rockdell	810	809	809.5	1	803	817.3	700.3
140	B	Rockdell	797.2	780.7	788.95	16.5	770	804	655
140	B	Rockdell	698.1	697.1	697.6	1			
142	B	Rockdell	799	792.8	795.9	6.2	771	809.5	656
142	B	Rockdell	719.1	719	719.05	0.1			
143	B	Rockdell	790.5	790	790.25	0.5	785	820	758.4
144	B	Rockdell	782.7	782.6	782.65	0.1	785	819.3	759.3
144	B	Rockdell	781.8	781.7	781.75	0.1			
144	B	Rockdell	780.9	780.1	780.5	0.8			
145	B	Rockdell	781.8	780.5	781.15	1.3	787	822.6	758.8

Table 2.5.1-11 (Sheet 7 of 7) Cavities in Boreholes Drilled at Clinch River Nuclear Site, 1973–1978 and 2013

Borehole	CRBRP Strat Unit	SMR Strat Unit	Cavity Top Elev'n (ft)	Cavity Bottom Elev'n (ft)	Cavity Average Elev'n (ft)	Cavity Height (ft)	Water Table Elev'n (ft)	Top of Rock Elev'n (ft)	Bottom of Hole Elev'n (ft)
147	B	Rockdell	850.1	850	850.05	0.1	805	852.1	759.3
147	B	Rockdell	832.7	832.6	832.65	0.1			
147	B	Rockdell	811.8	811.7	811.75	0.1			
149	B	Rockdell	819.1	803.8	811.45	15.3	803	825	759.2
MP-102	NA	Benbolt	790.1	789.9	790	0.2	791	792.1	447.3
MP-102	NA	Benbolt	788.1	787.9	788	1.2			
MP-102	NA	Benbolt	785.1	783.6	784.35	1.5			
MP-104	NA	Benbolt	769.7	769.1	769.4	0.6	809–788	785.6	620.5
MP-406	NA	Blackford	800.8	799.7	800.25	1.1	792	839.8	653.8
MP-410	NA	Rockdell D	797.2	796.2	796.7	1	796	801.3	608.4
MP-410	NA	Rockdell D	795.1	793.4	794.25	1.7			
MP-410	NA	Rockdell D	793.1	791.7	792.4	1.4			
MP-410	NA	Rockdell D	788.2	778.1	783.15	10.1			
MP-412	NA	Blackford	808.1	807.4	807.75	0.7	783	809.1	502.7
MP-418	NA	Eidson	762.2	751.4	756.8	10.8	760	764.8	723.8
MP-418	NA	Eidson	750.2	748.1	749.15	2.1			
MP-418	NA	Eidson	746.4	743.9	745.15	2.5			
MP-418	NA	Eidson	741.9	741.1	741.5	0.8			
MP-418	NA	Eidson	740.1	730.6	735.35	9.5			
MP-420	NA	Ok/Oma	762.5	756.2	759.35	6.3	744–767	782.4	483.7
MP-423	NA	Eidson	756	754.2	755.1	1.8	755	761.7	479.7
MP-424	NA	Rockdell D	687.7	683.5	685.6	4.2	742	767.5	553.0
MP-424	NA	Rockdell D	679.9	675.6	677.7	4.3			
MP-424	NA	Rockdell D	675.3	674.1	674.7	1.3			
MP-424	NA	Rockdell D	665.7	661.8	663.7	3.9			
MP-424	NA	Rockdell D	661.2	660.5	660.8	0.7			
MP-428	NA	Rockdell D	768.6	764	766.3	4.6	775	773	553.1

Notes:
ND = no data
NA = not applicable
Ok/Oma = Ordovician Knox Group/Ordovician Mascot
Undif Chk = Undifferentiated Chickamauga

CRBRP borings were drilled from 1973 to 1978 and reported in Reference 2.5.1-100.

Boreholes MP-102 through MP-428 were drilled in 2013 for the CR SMR Project and reported in Reference 2.5.1-214.

Refer to Table 2.5.1-1 for more details.

Table 2.5.1-12
Definition of Joint Condition Ratings

Condition of Discontinuities	Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation < 1mm Slightly weathered walls	Slightly rough surfaces Separation < 1mm Highly weathered walls	Slickensided surfaces or Gouge < 5mm thick or separation 1-5 mm continuous.	Soft gouge > 5mm thick or separation > 5mm continuous
Rating	30	25	20	10	0

Source: Reference 2.5.1-259

Table 2.5.1-13
Summary of Average Joint Condition Ratings at 5-ft Intervals

	100-series borings	200-series borings	400-series borings
Minimum	7.00	6.50	3.18
Maximum	28.00	28.00	26.25
Average	17.17	18.52	16.52

Table 2.5.1-14
Summary of Joint Condition Ratings at Outcrop Location Numbers 2, 8, and 9

Outcrop Location Number	Joint Condition Ratings
2	21
8	24.5
9	19.4
Average	21.6

Table 2.5.1-15
Summary of Geological Strength Index per Stratigraphic Unit

Description of GSI	Formation					
			Lincolnshire			
	Benbolt	**Rockdell**	**Fleanor Mb**	**Eidson Mb**	**Blackford**	**Newala**
No. of values	94	188	77	53	113	75
Minimum	61	5	56	13	31	65
Maximum	89	92	92	89	89	86
Median	76	69	76	68	73	76
Average	76	67	75	65	70	75.8
Standard Deviation	6	14	8	15	12	4.5
Actual average plus/minus one standard deviation	70 to 82	53 to 81	67 to 83	50 to 80	58 to 82	71 to 80
Typical GSI range (recommended for design).	**70 to 80**	**55 to 80**	**65 to 85**	**50 to 80**	**60 to 80**	**70 to 80**

Notes:

Use of average values is not suggested for characterization; the use of ranges is recommended.

"Typical Geological Strength Index (GSI) Range" is defined here as the GSI mean ± one standard deviation, then rounded to the nearest 5 GSI.

Statistics exclude data above the depth of 60 feet.

Table 2.5.1-16 (Sheet 1 of 3)
Summary of Fracture Zones (≥ Approximately 0.9 ft thick) using 100- and 200-Series Borings

Boring Number	Ground Surface El. (ft)	Drilled Depth From (ft)	Drilled Depth To (ft)	Elevation (NAVD88) From (ft)	Elevation (NAVD88) To (ft)	Apparent Thickness (ft)	Run No.	RQD (%)	Boring Log Description[d]
MP-101	800.5	31.9	33.7	768.6	766.8	1.8	4	66	FZ, 45°, PR, PO-T, B, II
		134.3	136.3	666.2	664.2	2.0	25	94	FZ, 60°, PR, VT, A, I, with calcite
MP-102	797.9	5.8	7.0	792.1	790.9	1.2	1	54	FZ, UR, O,C, III, highly weathered, loss of recovery
		15.6	21.7	782.3	776.2	6.1	4	10	FZ, PR-UR, PO-O, C, III, BJ at 30°, J 65-90°, spaced at 0.2'; FZ, 25-30°, SR-PR, PO-O, C-D, III
MP-105	800.2	12.1	20.7	788.1	779.5	8.6	1, 2, 3	22, 32, 52	FZ, 0-30°, PO-O, C-H, III, with clay; FZ, no recovery - 3.5' core loss; FZ, 0-30°, PO-O, C-H, IIII, with clay
		32.3	33.4	767.9	766.8	1.1	5	47	FZ, 30°, PR, PO-O, B, II, 0.2' core loss
MP-106	798.7	6.7	18.6	792.0	780.1	11.9	1, 2, 3	0, 0, 10	FZ, 5-45°, O, K, V; FZ, 5-45°, O-PO, K, V; FZ, 5-45°, PS-SS, O, F-G, IV; FZ, 30°, PS, PO, B-F, III-IV
MP-107	801.6	42.8	43.8	758.8	757.8	1.0	1	78	FZ, 30-90°, PS-PR, O-PO, B-F, II-III, mechanically abraded from 43.4 - 43.7'
MP-108	798.5	11.6	12.9	786.9	785.6	1.3	2	52	FZ, 30°, PS-PR, O, K IV, highly to moderately weathered with 0.9' core loss
		27.9	29.4	770.6	769.1	1.5	5	36	FZ, highly to moderately weathered with 1.5' core loss
MP-109	799.9	7.3	16.3	792.6	783.6	9.0	1, 2, 3	27, 0, 38	FZ, 30°, PR, PO-O, G, IV; FZ, 5-90°, SS-PS, W-PO, C, V; FZ, 5-55°, PS-SR, W-PO, B-H, III; FZ, 30-55°, PS-SR, O, F, V
		157.9	159.0	642.0	640.9	1.1	31	100	FZ, 80-90°, SR, VT, A, I, with calcite
MP-110	798.7	20.9	23.7	777.8	775.0	2.8	1, 2	0, 54	FZ, 10-45°, PR-SR, O-PO, B-C, IV; FZ, 10-35°, PO, C, IV
		28.3	33.9	770.4	764.8	5.6	2, 3	54, 34	FZ, 5-45°, PR-SR, B-C, T-PO, IV; FZ, 10-45°, SR-PR, O, B, III; FZ, 30°, PS, T-PO, B, III; FZ, 30-45°, T-PO, B-C, III-IV, spaced at about 0.1-0.2'
		90.2	91.4	708.5	707.3	1.2	15	50	FZ, 30° and 90°, PR-UR, PO-O, B,II
MP-113*	797.5	28.2	35.7	772.6	766.0	7.5	2, 3	0, 24	FZ, 0-10°, PR, T-O, C-D, II-IV; FZ, 0-10°, PR, T-PO, B, II-III
		39.7	45.4	762.4	757.4	5.7	4, 5	26, 56	FZ, 0-10°, PR-PS, T-O, B, II-III; FZ, 0-10°, PR-PS, PO-O, B, II
MP-114	797.2	18.5	20.2	778.7	777.0	1.7	2	44	FZ, 30°, PS-PR, T-PO, B-C, III
MP-117	800.0	29.4	36.4	770.6	763.6	7.0	2, 3	31, 59	FZ, 5-45°/30°/30-60°, PS-US, T-PO, F/B/G, IV; FZ, 15-30°, PS, PO-T, F-B, IV
		68.7	69.8	731.3	730.2	1.1	9	88	FZ, 20-30°, PS, T-O, G, IV

Table 2.5.1-16 (Sheet 2 of 3)
Summary of Fracture Zones (≥ Approximately 0.9 ft thick) using 100- and 200-Series Borings

Boring Number	Ground Surface El. (ft)	Drilled Depth From (ft)	Drilled Depth To (ft)	Elevation (NAVD88) From (ft)	Elevation (NAVD88) To (ft)	Apparent Thickness (ft)	Run No.	RQD (%)	Boring Log Description[d]
MP-118	799.8	19.1	25.4	780.7	774.4	6.3	1, 2	40, 74	FZ, 5-45°, PS-SS, W-O, B-F, IV; FZ, 30-60°, PR, T-PO, A-B, IV; FZ, 30-75°, US-SR, PO-O, F-H, IV; FZ, 30-60°, PS-US, PO-O, B-F, IV
		67.8	69.1	732.0	730.7	1.3	10	94	FZ, 30-75°, SS, T-PO, B, II
MP-119	802.1	17.2	20.9	784.9	781.2	3.7	5	22	FZ, 30°, PR, T-PO, C, II, spaced 0.1', slightly weathered
		27.0	28.5	775.1	773.6	1.5	7	48	FZ, 30°, PR, K, IV, mod. weathered; 1.2' core loss
MP-120	800.1	48.1	49.8	752.0	750.3	1.7	5	63	FZ, 30°, PS, T, F, II
		230.0	231.9	570.1	568.2	1.9	42	30	FZ (8 BJs) 30°, US, T, B, II; FZ (6 BJs), 30°, US, T, B, II
MP-121	797.6	24.0	25.8	773.6	771.8	1.8	2	30	FZ, 25-45°, SS, O, D, IV, mod. weathered
		28.2	31.0	769.4	766.6	2.8	2, 3	30, 38	FZ, 30°, SR, O, D-B, II-III, mod. weathered
		38.3	40.7	759.3	756.9	2.4	4, 5	56, 64	FZ, 10-35°, PS/SR/US, O, C, III; FZ, 30-45°, PS, T-O, A-B, III
MP-122	796.7	29.4	30.9	767.3	765.8	1.5	1	69	FZ, 10-30°, PR-SR, O, F, III
MP-201	790.9	29.0	30.6	761.9	760.3	1.6	3	42	FZ, mod. to highly weathered - 0.8' loss of core
		42.7	44.1	748.2	746.8	1.4	6	66	FZ, 30°, PR-SR, PO, K, III, mod. to highly weathered, 0.2' loss of core
		237.7	239.7	553.2	551.2	2.0	45	68	FZ (10 BJs), 20-30°, PR-UR, T-PO, A-B, I-II; FZ (5 BJs), 30°, PR, T-PO, B-C, II
		293.7	299.9	497.2	491.0	6.2	56, 57	60, 34	FZ (7 BJs), 30°, PR-SR, A-C, I-II; FZ (8 BJs), 30°, PR, T-PO, B, II / J, 60°, PR, O, B, II; 0.3' loss of core; FZ, 30°, PR, PO-O, D-K, II-IV; FZ, 20-40°, PR, PO, C-G, II-III; FZ, 30°, PR, PO-O, II-IV; mechanically broken rock with loss of recovery
		400.6	403.2	390.3	387.7	2.6	78	82	FZ, 20-80°, VT, A, I, intact, healed with dolomite and trace indurated siltstone/clay; FZ, 0-20°, PR, O, B, I, 0.3' loss of core (mechanically broken)
MP-202	811.8	279.1	280.1	532.7	531.7	1.0	57	46	FZ, BJ(6), 30°, and J, 0°
MP-203	791.5	22.5	23.6	769.0	767.9	1.1	2	62	FZ, 30-40°, PS-PR, O-W, C-D, III-IV
		26.4	29.6	765.1	761.9	3.2	3	62	FZ, 30-40°, PS-PR, O-W, C-D, III-IV; FZ/BJ/J, 35° and 40°, PS-PR, T-PO, B, II-III; FZ, 30-40° and 60°, PS-PR, O-MO, C, III
		130.8	132.3	660.7	659.2	1.5	25	66	FZ, 30°, PR-PS, O, B, II

Table 2.5.1-16 (Sheet 3 of 3)
Summary of Fracture Zones (≥ Approximately 0.9 ft thick) using 100- and 200-Series Borings

Boring Number	Ground Surface El. (ft)	Drilled Depth From (ft)	Drilled Depth To (ft)	Elevation (NAVD88) From (ft)	Elevation (NAVD88) To (ft)	Apparent Thickness (ft)	Run No.	RQD (%)	Boring Log Description[d]
MP-205	810.9	27.4	29.3	783.5	781.6	1.9	2	58	FZ, moderately to highly weathered, core loss of 1.3'
		36.9	38.7	774.0	772.2	1.8	4	48	FZ, moderately to highly weathered, core loss of 1.6'
		46.2	49.5	764.7	761.4	3.3	6	16	FZ, core loss of 2.8'
		181.5	183.4	629.4	627.5	1.9	34	46	FZ, core loss of 1.3'
MP-206	811.8	103.4	104.3	708.4	707.5	0.9	19	84	FZ, PR, PO, K, II
MP-208	811.9	6.2	7.5	805.7	804.4	1.3	1	36	FZ, moderately weathered
MP-209	807.7	17.6	18.9	790.1	788.8	1.3	4	52	FZ, EW, K, IV, moderately to highly weathered with 0.3' loss of core
		45.7	47.8	762.0	759.9	2.1	10	42	FZ/BJ, 30°, O, F, III; FZ/BJ, 30°, PR-SR, K, IV
		198.5	199.5	609.2	608.2	1.0	40	32	FZ, 60°, SR, O, C, III, core loss (mechanical) from 199.2 to 199.5'
MP-213*	813.0	39.6	40.7	778.0	777.1	1.1	6	84	FZ, moderately weathered, 0.5' core loss
		48.9	49.8	769.8	769.0	0.9	8	80	FZ/J, 80-90°, PR-SR, T-PO, B, II, 0.3 core loss (mechanical)
MP-219	812.9	38.0	39.0	774.9	773.9	1.0	4	50	FZ, 30-40°, PS-SR, O-MO, K, IV, mod. weathered
MP-222	812.9	9.8	11.2	803.1	801.7	1.4	1, 2	64, 96	FZ, 30°, PR-SR, PO-O, B-C, II-III; FZ, 30/90°, likely mechanical
Minimum	791	6	7	390	388	0.9			
Maximum	813	401	403	806	804	11.9			
Average	802	NA	NA	NA	NA	2.8			

(a) * indicates inclined borings. Depths have not been corrected for inclination.
(b) Fracture zones (FZ) include one or a combination of FZs (with the exception of SHs/SZs) ≥ 0.9 ft thick and >50% of total depth interval; FZs with separation of ≤ 2 ft are combined into one zone (provided FZs still constitute >50% of apparent thickness). Mechanical FZs are not included; fluid loss zones are not included unless associated with a natural FZ.
(c) Thickness of the fracture zones is apparent as not measured perpendicular to the bounding discontinuity.
(d) Explanation of abbreviations is contained in Table B.1.1 in Appendix B in Reference 2.5.1-214 (included in Part 8 of the ESPA).

Notes:

NA = Not applicable

Source: Reference 2.5.1-214

Table 2.5.1-17 (Sheet 1 of 4)
Summary of Shear-Fracture Zones (≥ Approximately 0.9 ft thick) using 100-, 200-, and 400-Series Borings

Boring Number	Strati-graphic Unit	Ground Surface El.	Drilled Depth		Elevation (NAVD88)		Apparent Thickness	Run No.	RQD	Boring Log Description[d]
			From	To	From	To				
		(ft)	(ft)	(ft)	(ft)	(ft)	(ft)		(%)	
MP-101	Rockdell Formation	800.5	246.6	253.4	553.9	547.1	6.8	47, 48	100	SZ/FZ, multiple shears at 45˚ and parallel to bedding, intensely fractured and healed with calcite (intact), some folding/rotation of bedding observed; SZ/FZ, several healed fractures at 80°, VT, A, I, with calcite
			259.2	263.3	541.3	537.2	4.1	49, 50	96, 94	SZ/FZ intensely fractured, 60-80°, PL-PR, VT, A, I-Intact and healed with calcite.
			280.6	282.0	519.9	518.5	1.4	54	100	SH, 40-50°, PL, VT, A, I, with calcite (intact)
			287.1	290.1	513.4	510.4	3	55	92	BJ/SH, 30-40°, PL-PR, PO-T, C, III, with calcite
			291.0	294.9	509.5	505.6	3.9	56	70	BJ/SH, 30-35°, SL, VT, A, III, with calcite
			311.7	315.0	488.8	485.5	3.3	60	82	BJ/SH, 30-40°, PL, VT-T, C, II
MP-102	Rockdell Formation	797.9	322.8	324.5	475.1	473.4	1.7	65	90	SH, 30-35°, VT, A, I, with calcite
			326.9	332.6	471.0	465.3	5.7	66, 67	84, 94	SH, 20-30°, VT, A, I, with calcite; BJ/SH, 30°, PL, T-PO, C, III, with calcite; SH, 60°, PL, PO, C, III, with calcite; SH, 30°, VT, A, I, with calcite; SZ, 15-25°, PL, T-PO, C, II, with calcite containing brecciated siltstone
			346.8	350.3	451.1	447.6	3.5	70	84	SH, 35-20°, PL, T-PO, C, II-III, with calcite; SH, 30-70°, VT, A, I, with calcite (intact)
MP-103	Rockdell Formation	800.6	125.3	129.0	675.3	671.6	3.7	22	60	SH/BJ, 40°, PL-SL, VT-T, C, II, with calcite; SH/BJ, 40°, PL-SL, VT-T, C, II, with calcite
			146.8	149.5	653.8	651.1	2.7	26	46	SH/BJ, 30°, PL-PR, T, C, II with calcite
			160.0	162.4	640.6	638.2	2.4	29	92	SH/BJ, 30-35°, PL-PR, VT-T, B, II with trace calcite
			164.6	168.8	636.0	631.8	4.2	30, 31	50, 98	SH/BJ, 25-30°, SL-SR, VT-PO, C, II with calcite; SH/BJ, 25-35°, SL-SR, VT-PO, C, II with calcite
MP-107	Rockdell Formation	801.6	171.9	173.0	629.7	628.6	1.1	27	90	SH, 20-30°, PL, T-PO, B-C, II, with calcite
MP-108	Benbolt Formation	798.5	131.9	133.5	666.6	665.0	1.6	26	92	SH, 30°, PL, T-PO, C, II, with calcite; SH, 30-50°, PL-UL, VT-T, A-B, I-II, with calcite; SZ, 30-50°, PL-UL, VT-T, A-B, C, I-II, with calcite

Table 2.5.1-17 (Sheet 2 of 4)
Summary of Shear-Fracture Zones (≥ Approximately 0.9 ft thick) using 100-, 200-, and 400-Series Borings

Boring Number	Strati-graphic Unit	Ground Surface El. (ft)	Drilled Depth From (ft)	Drilled Depth To (ft)	Elevation (NAVD88) From (ft)	Elevation (NAVD88) To (ft)	Apparent Thickness (ft)	Run No.	RQD (%)	Boring Log Description[d]
MP-114	Benbolt Formation	797.2	164.0	165.9	633.2	631.3	1.9	31, 32	100, 94	SH, 30-35°, PL, T, B, II with calcite; SZ, 35-55°, PL-UL, VT, A, I with calcite; SH, 35°, PL, T, B, II with calcite
MP-120	Rockdell Formation	800.1	281.8	283.2	518.3	516.9	1.4	52	62	SH, 30°, PL, T, B, II; SH, 30°, PL, VT, A, I, intact with calcite
			287.3	290.7	512.8	509.4	3.4	53, 54	64, 68	SH, 30-35°, PL, T-PO, B, II, most with calcite; SH, 25-30°, PL, T, B, II
			293.3	299.0	506.8	501.1	5.7	54, 55	68, 98	SH, 25-30°, PL, T, B, II; SZ, 30°, PL, O, C, II, with calcite, 0.1' loss of core; SZ, 30-50°, PL, VT/T/O, A-C, I-II, mostly intact with calcite and irregular healed fractures around chert nodules; SH, 30°, PL, T, B, II, most with calcite; SZ, 0°, US, VT, A, I-II, mostly intact-tensional shears; SH, 30°, PL, VT, A, I, intact with calcite
			341.7	342.7	458.4	457.4	1	64	82	SH, 30°, PL, T, B, II with calcite; SZ, 10-80°, UL, VT-T, A-B, I-II, mostly intact, intense calcite mineralization along multiple cross-cutting shears
MP-121	Benbolt Formation	797.6	47.0	48.8	750.6	748.8	1.8	6	66	SZ/FZ, 30°, PL, T, B, II; SZ/FZ, 45-60° and 90°, VT, A, I, with calcite and spaced at about 0.1'; SH, 40-45°, PL, T-PO, B, II
			51.6	53.6	746.0	744.0	2	7	62	SZ/FZ, 30-40°, PL, T, B, II, with calcite
			56.1	58.0	741.5	739.6	1.9	8	92	SH, 30-45°, PL, T, B-C, II-III, with calcite
MP-201	Eidson Member	790.9	146.7	164.3	644.2	626.6	17.6	27, 28, 29, 30	70, 22, 74, 72	SZ, 30°, PL, PO-MO, A-C, I-II, with calcite healed gouge; SH, 20-30°, PL, T-PO, A-C, I-II, with calcite; SZ, 30°, PL, T-PO, B, I, with calcite; BJ/SH (10), 35-40°, PL, T-PO, A-D, I-III; SZ, 20-30°, PL, PO, C-D, II-III, with calcite; SZ, 35°, PL, T-PO, A-D, II-III, with calcite; SZ, 30°, PL, PO-O, C, III, with calcite; SH, 30°, PL, T-PO, A-C, I-II, with calcite; SZ, 30°, PL, T-PO, A-C, I-II; SH, 30°, PL, T-PO, C, I; SZ, 30°, PL, T-PO, A-C, I-II, with calcite
MP-202	Eidson Member	811.8	276.9	282.2	534.9	529.6	5.3	57, 58	46, 72	SHEAR ZONE, intense shearing with calcite mineralization
	Blackford Formation		366.3	367.2	445.5	444.6	0.9	75	94	SH, 80°, VT, A, I with calcite

Table 2.5.1-17 (Sheet 3 of 4)
Summary of Shear-Fracture Zones (≥ Approximately 0.9 ft thick) using 100-, 200-, and 400-Series Borings

Boring Number	Strati-graphic Unit	Ground Surface El. (ft)	Drilled Depth From (ft)	Drilled Depth To (ft)	Elevation (NAVD88) From (ft)	Elevation (NAVD88) To (ft)	Apparent Thickness (ft)	Run No.	RQD (%)	Boring Log Description[d]
MP-205	Eidson Member	810.9	202.6	203.5	608.3	607.4	0.9	38	78	SZ, 30°, US-UL-PL
			206.3	212.1	604.6	598.8	5.8	39, 40	52, 67	SZ, core loss 1.2'; SZ, PR, MO, C, II, core loss of 0.4'; FZ/SZ, core loss of 1.0'
MP-207	Eidson Member	779.7	116.8	119.5	662.9	660.2	2.7	21	60	SZ, 70-80°, PL-PR, C-K, II with calcite
			123.2	124.4	656.5	655.3	1.2	22	82	SZ, 30°, PL, PO-O, C, II with calcite
MP-209	Eidson Member	807.7	207.7	208.7	600.0	599.0	1	42	72	SZ, 30°, SL, VT-T
MP-211	Eidson Member	779.8	112.8	113.9	667.0	665.9	1.1	22	96	SZ, 30-80°, US-UL, VT, I
MP-219A	Eidson Member	808.6	175.8	177.2	632.8	631.4	1.4	35	88	SZ, 30-40°, VT-T, C, I, with calcite
MP-417	Eidson Member	772.7	228.9	233.5	543.8	539.2	4.6	38, 39	60, 88	SHEAR ZONE, multiple calcite healed shears at 40-65° to core axis; BJ/SH, 35°, PL, T, C, II; SHEAR ZONE, multiple calcite healed shears at 20-30° to core axis
MP-418A	Eidson Member	811.1	88.9	90.8	722.2	720.3	1.9	4	48	SZ, 45-50°, PR-PL, T-PO, C, III; SZ, 45-50°, UR-PR/PL, O-PO, B, III, with calcite
			94.4	95.9	716.7	715.2	1.5	5	80	BJ/SH, 40-50°, PR-PL, T-PO, B-C, II-III; SZ, 50°, PL, PO, H-C, III, calcite

Table 2.5.1-17 (Sheet 4 of 4)
Summary of Shear-Fracture Zones (≥ Approximately 0.9 ft thick) using 100-, 200-, and 400-Series Borings

Boring Number	Strati-graphic Unit	Ground Surface El.	Drilled Depth		Elevation (NAVD88)		Apparent Thickness	Run No.	RQD	Boring Log Description[d]
			From	To	From	To				
		(ft)	(ft)	(ft)	(ft)	(ft)	(ft)		(%)	
MP-423	Eidson Member	799.0	80.1	101.9	718.9	697.1	21.8	13, 14, 15, 16, 17, 18, 19	89, 74, 33, 0, 70, 60, 84	FZ/SZ, 40-75°, PR, VT-T, A, I, with calcite; FZ-SZ, 50-80°, calcite-healed fractures; SZ-FZ, 50-90°, VT-PO, A-B, I; SH/BJ, 30°, PL-SL, T, C, II; FZ/SZ, 35-85°; SH, 35-40°, SL/PL, T-PO, B, II; SZ, 30-85°, with calcite-healed limestone breccia
			109.8	118.2	689.2	680.8	8.4	21, 22	80, 85	SH, 30°, PL-SL, T-PO, B, II; SZ, 30-35°, VT, A, I, calcite-healed shears closely spaced; SH, 30°, PL-SL, T-PO, B II; SH, 30-35°, PL/UR/PR, TP-O, D-B, II; FZ/SZ, 40-60° and 30°, VT, A, I, with calcite; BJ/SH, 35°, PL, PO, B, II

(a) Shear-fracture zones include one or a cluster of SZs or SHs ≥ 0.9 ft (and/or BJ/SH) with average frequencies per cluster of ≤ 0.5 ft.
(b) Thickness of the shear-fracture zones is apparent as not measured perpendicular to the bounding discontinuity.
(c) “Thick shear zones” are defined as consisting of multiple shear-fracture zones (as described in Note a) with separations of ≤ 2 ft.
(d) Explanation of abbreviations is contained in Table B.1.1 in Appendix B in Reference 2.5.1-214 (included in Part 8 of the ESPA).

Source: Reference 2.5.1-214

Table 2.5.1-18
List of Oil and Gas Well Permits in Roane County, Tennessee

County	EFO Name	Permit Date	Permit No.	API No.	Operator Name	Well Name and No.	Latitude	Longitude	Elevation	Formation and Total Depth
Roane	Knoxville	Jul-26-2006	0011096	145-20142	Miller Energy Resources, Inc.	Edwards-Gann #1	35.962944	-84.432972	885	Knox Group
Roane	Knoxville	Jun-04-1981	0004034	145-20001	United American Energy Inc.	ROANE CO INDUSTRIAL PARK RCIP #1	35.875222	-84.645028	848.8	Knox Group
Roane	Knoxville	Apr-13-2005	0010574	145-20002	Miller Energy Resources, Inc.	Eula Butler Etal #1	35.979111	-84.40775	855.7	Knox Group
Roane	Knoxville	Nov-01-2005	0010766	145-20141	Miller Energy Resources, Inc.	Edwards-Fowler Unit #1	35.959694	-84.428611	815	Knox Group

Notes:

Search based upon county field containing “Roane.”

Last data refresh on November 15, 2014.

Source: Reference 2.5.1-272.

Table 2.5.1-19
Largest Cavities Encountered in Boreholes, Listed by Height

Borehole	Formation	Cavity Average Elevation (ft)	Cavity Top Elevation (ft)	Cavity Bottom Elevation (ft)	Cavity Height (ft)
B-140	Rockdell	789.0	797.2	780.7	16.5
B-149	Rockdell	811.5	819.1	803.8	15.3
B-17	Rockdell	817.2	824.2	810.2	14.0
MP-418	Eidson	756.8	762.2	751.4	10.8
MP-410	Rockdell	783.2	788.2	778.1	10.1
MP-418	Eidson	735.4	740.1	730.6	9.5
B-50	Rockdell	741.3	745.5	737.0	8.5
B-22	Rockdell	725.8	729.6	722.0	7.6
B-56	Eidson	719.3	722.7	715.9	6.8
B-50	Rockdell	763.5	766.8	760.2	6.6