2.0 SITE CHARACTERISTICS

2.5 Geology, Seismology, and Geotechnical Engineering

Section 2.5 of the Site Safety Analysis Report (SSAR), Revision 1 (TVA, 2017 – Agencywide Documents Access and Management System (ADAMS) Accession No. ML18003A374), prepared by the Tennessee Valley Authority (TVA) for the Clinch River Nuclear (CRN) Site Early Site Permit (ESP) Application, contains information on geologic, seismic, and geotechnical engineering characteristics of the proposed CRN site. The applicant (TVA) followed guidance in Regulatory Guide (RG) 1.206, "Combined License Applications for Nuclear Power Plants (LWR Edition)," (NRC, 2007 - ADAMS Accession No. ML070720184) to develop the information presented in Section 2.5 of the SSAR. The applicant also followed guidance in RG 1.208, "A Performance-Based Approach to Define Site-Specific Earthquake Ground Motion," (NRC, 2007 - ADAMS Accession No. ML070310619) to define the following four zones around the site in which site characterization investigations conducted by the applicant proceeded in progressively greater detail passing from the larger site region to the smaller site location:

Site region – Area within a 320-kilometer (km) (200-mile (mi)) radius of the site location.
Site vicinity – Area within a 40-km (25-mi) radius of the site location.
Site area – Area within an 8-km (5-mi) radius of the site location.
Site location – Area within a 1-km (0.6-mi) radius of the proposed plant.

To prepare the SSAR, the applicant incorporated regional and site-specific geologic, geophysical, seismic, and geotechnical engineering information derived from reviews of previous reports prepared for the proposed Clinch River Breeder Reactor Project (CRBRP), Oak Ridge National Laboratory (ORNL) reports related to the Oak Ridge Reservation (ORR), and published literature. The applicant also used data obtained from surface and subsurface field investigations specifically conducted to characterize the CRN Site for the ESP application.

Section 2.5 of this safety evaluation report (SER) prepared by the U.S. Nuclear Regulatory Commission (NRC) staff comprises five main parts, Sections 2.5.1 through 2.5.5, which parallel the five SSAR sections prepared by the applicant for the CRN Site ESP application. These five SER sections are as follows: Section 2.5.1, "Geologic Characterization Information," Section 2.5.2, "Vibratory Ground Motion," Section 2.5.3, "Surface Deformation," Section 2.5.4, "Stability of Subsurface Materials and Foundations," and Section 2.5.5, "Stability of Slopes." These SER sections address the geologic, seismic, and geotechnical engineering characteristics of the proposed CRN Site. Each of the five main sections consists of two parts: (a) the staff's summary of materials presented by the applicant in the SSAR, including associated analyses, explanations, and conclusions made by the applicant as documented in the SSAR; and (b) the staff's detailed technical evaluation of information presented by the applicant in the SSAR. The technical evaluation section presents results of the staff's detailed safety review, including information obtained through NRC site visits and audits, applicant responses to requests for additional information (RAI), evaluation of those RAI responses, and findings and conclusions made by staff based on their detailed safety review.

2.5.1 Geologic Characterization Information

2.5.1.1 Introduction

In Section 2.5.1 of the CRN Site SSAR, the applicant describes geologic characterization information, including regional and site-specific geologic, geophysical, and seismic data derived from reviews of previous reports for the proposed CRBRP, ORNL reports related to the ORR, and published literature, as well as data obtained from surface and subsurface field investigations specifically conducted to characterize the CRN Site. The applicant conducted the field investigations at progressively greater levels of detail nearer to the site within each of the four circumscribed areas corresponding to site region, site vicinity, site area, and site location as defined above in Section 2.5. These investigations made it possible for the applicant to assess geologic and seismic suitability of the site; determine whether new geologic or seismic data existed that could significantly impact seismic design based on results of probabilistic seismic hazard analysis; and provide geologic and seismic data appropriate for plant design. The applicant indicated that, by following guidance in RG 1.206 and RG 1.208 for developing the geologic site characterization information, the content of SSAR Section 2.5.1 demonstrates compliance with the regulatory requirements in Title 10 of the *Code of Federal Regulations* (10 CFR), 100.23(c), "Geological, seismological, and engineering characteristics." The requirements in 10 CFR 100.23(c) specifically state that geologic, seismic, and engineering characteristics of a site and its environs must be investigated in sufficient scope and detail to permit an adequate evaluation of the proposed site; provide sufficient information for estimating the Safe Shutdown Earthquake (SSE) ground motion; and permit adequate engineering solutions for actual or potential geologic and seismic effects at the proposed site. The applicant also considered guidance in NUREG–0800, "Standard Review Plan for Review of Safety Analysis Reports for Nuclear Power Plants (LWR Edition)," (NRC, 2013 - ADAMS Accession No. ML13311A639) for development of SSAR Section 2.5.1.

2.5.1.2 Summary of Application

The two main sections comprising SSAR Section 2.5.1 are SSAR Section 2.5.1.1, "Regional Geology," and SSAR Section 2.5.1.2, "Local Geology." SSAR Section 2.5.1.1 includes information for the area within a 320-km (200-mi) radius of the CRN Site location (i.e., the site region). SSAR Section 2.5.1.2 contains information for the areas within 40-km (25-mi) and 8-km (5-mi) radii of the CRN Site location (i.e., the site vicinity and site area, respectively) and the 1-km (0.6-mi) radius of the proposed plant (i.e., the site location). The following SER Sections 2.5.1.2.1 and 2.5.1.2.2 summarize the geologic and seismic information presented by the applicant in SSAR Section 2.5.1.

2.5.1.2.1 Regional Geology

SSAR Section 2.5.1.1 provides information on physiography, topography, and geomorphic processes; fluvial processes; karst processes and occurrence; geologic history and tectonic evolution; stratigraphy; tectonic setting; geophysical data; distribution of stress and seismicity; and non-seismic geologic hazards for the CRN Site region. The following subsections under SER Section 2.5.1.2.1 summarize the information provided by the applicant in SSAR Section 2.5.1.1.

2.5.1.2.1.1 *Regional Physiography, Topography, and Geomorphic Processes*

SSAR Subsection 2.5.1.1.1 describes the six physiographic provinces that lie within a 320-km (200-mi) radius of the CRN Site location (i.e., within the site region), regional geomorphic processes, and regional topography. From west to east, the physiographic provinces are the Central Lowlands; the Interior Low Plateaus; the Appalachian Plateaus, which include the Cumberland Plateau at the latitude of the site region; the Valley and Ridge; the Blue Ridge; and the Piedmont. SER Figure 2.5.1-1, reproduced from SSAR Figure 2.5.1-1, shows these physiographic provinces relative to the location of the CRN Site, which lies in the Valley and Ridge province.

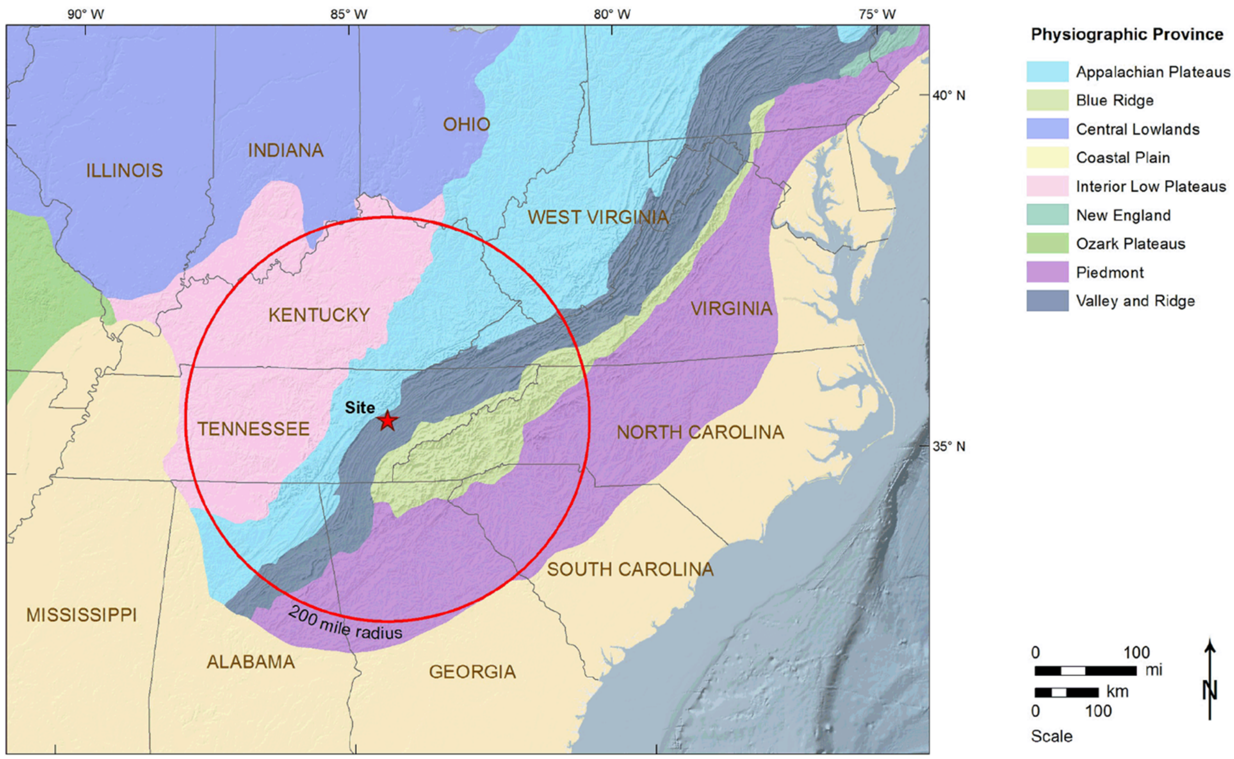

Figure 2.5.1-1: Map showing physiographic provinces in the CRN Site region, (Reproduced from SSAR Figure 2.5.1-1)

SSAR Subsection 2.5.1.1.1 discusses the Valley and Ridge physiographic province in which the site lies. The applicant stated that this province extends about 1,931 km (1,200 mi) southwest from the Saint Lawrence Lowlands and eastern New York to central Alabama and ranges in width from 22.5 to 129 km (14 to 80 mi). The applicant reported that parallel ridges and valleys trending northeast-southwest characterize the province, with geomorphology related directly to differential weathering and erosion of the folded and faulted Paleozoic sedimentary strata found in the province. The Paleozoic covered the time frame between 541 and 252 million years (Ma) ago. The applicant explained that approximately 16 major thrust faults cut stratigraphic units at the latitude of the CRN Site. The applicant noted that most of the site vicinity lies within the Tennessee River drainage basin, and the Clinch River meanders westerly in an entrenched channel which cuts across regional topography in the site area.

SSAR Subsection 2.5.1.1.1.2 briefly describes fluvial processes in the site region. The applicant cross-referenced SSAR Subsection 2.5.1.2.1, which contains a discussion of fluvial processes in relation to the CRN Site, including those operative during Pleistocene time (between 2.58 Ma to 11,700 years ago) associated with formation of entrenched meanders and fluvial terraces of the Tennessee and Clinch Rivers.

SSAR Subsection 2.5.1.1.1.3 describes karst processes and the occurrence of soluble carbonate strata (i.e., limestone and dolomite) in the site region. The applicant discussed geologic hazards that can potentially occur in karst landscapes, including ground subsidence or collapse, rapid underground drainage, irregular soil-bedrock contacts, and deep weathering along bedding planes, joints, fractures, and faults. The applicant explained that development of a karst landscape and associated potential geologic hazards are the result of the karstification process, which involves chemical dissolution of soluble rock due to circulation of weakly acidic groundwater through the rock units. The applicant noted that, in humid temperate to subtropical regions such as Tennessee, abundant vegetation, high rainfall, and high atmospheric carbon dioxide also favor dissolution of soluble rock units. The applicant reported that distinct karst terrains in the Valley and Ridge and Interior Low Plateaus physiographic provinces dominate the site region. Karst terrains in both provinces form in similar Paleozoic carbonate rock units under similar climatic conditions.

SSAR Subsection 2.5.1.1.1.3.1 describes karst features in the folded and faulted Paleozoic carbonate rocks of the Valley and Ridge province in which the CRN Site lies. These features include sinkholes, caves, springs, seeps, and sinking streams. The applicant stated that cover-collapse sinkholes, which form from collapse of unconsolidated deposits or residual soils into cavities produced by dissolution of soluble bedrock, are the most common type of sinkholes in the province. The applicant reported that caves in the Valley and Ridge tend to be less than a few kilometers in length because folded carbonate units and interbedded clastic strata strongly control cave development. The applicant indicated that most cave passages parallel the strike of bedding, with the passages oriented along joints or joint-bedding plane intersections. The applicant stated that 9,839 known caves exist in Tennessee, with about 15 percent located in the Valley and Ridge province.

2.5.1.2.1.2 Regional Geologic History and Tectonic Evolution

SSAR Subsection 2.5.1.1.2 describes geologic history and tectonic evolution of the site region. The applicant stated that the CRN Site lies immediately west of the main northeast-southwest-trending axis of the Appalachian orogenic belt. The applicant explained that at least three regional Paleozoic contractional events affecting the eastern margin of ancestral North America (i.e., Laurentia), and associated with opening and closing of several proto-Atlantic Ocean basins, formed the Appalachian orogenic belt. The applicant noted that these three orogenies, which directly influenced geology and structural features of the CRN Site region, included the Middle Ordovician (about 470-458 Ma) Taconic orogeny, the Early Devonian to Mississippian (about 419-358 Ma) Acadian/Neoacadian orogeny, and the Pennsylvanian to Permian (about 320-280 Ma) Alleghanian orogeny. The applicant stated that the latest stages of the Alleghanian orogeny resulted in folding and faulting of stratigraphic units in the Valley and Ridge and accommodated more than 400 km (250 mi) of crustal shortening.

2.5.1.2.1.3 Regional Stratigraphy

SSAR Subsection 2.5.1.1.3 describes stratigraphy of the site region. Because the CRN Site lies in the Valley and Ridge physiographic province, the applicant focused on stratigraphic units found in that province. The applicant stated that the CRN Site, which lies in the southwestern portion of the Valley and Ridge province, consists predominantly of a sequence of Paleozoic sedimentary rocks ranging in age from Lower Cambrian to Pennsylvanian (i.e., about 541 to 323 Ma). The applicant noted that the following four major subdivisions deposited atop ancient continental crust (greater than 980 Ma in age) make up this sedimentary sequence: (1) the Lower Cambrian Rome Formation, a basal, mainly clastic transgressive unit with a western source; (2) a thick, extensive Cambrian to Ordovician carbonate shelf sequence that includes formations of the Middle Cambrian Conasauga, Upper Cambrian to Lower Ordovician Knox, and Middle Ordovician Chickamauga Groups; (3) a thin, laterally variable shelf sequence of Upper Ordovician to Lower Mississippian carbonate rocks and thin clastic units; and (4) a Middle Mississippian to Pennsylvanian synorogenic (i.e., synchronous with the orogenic event) clastic wedge.

2.5.1.2.1.4 Regional Tectonic Setting

SSAR Subsection 2.5.1.1.4 describes the tectonic setting of the CRN Site region, including subdivision of tectonic terranes and physiographic provinces, regional geophysical data, and the distribution of seismicity and stress in the Eastern United States. SSAR Subsection 2.5.1.1.4.1 discusses the Valley and Ridge province in which the CRN Site lies in relation to structural style and deformation history. The applicant stated that the Valley and Ridge province exhibits a unique structural style compared to adjacent terranes and physiographic provinces, noting that the linear northeast-southwest-trending ridges and valleys characteristic of the province are the direct result of differential erosion of Paleozoic strata deformed into an imbricate stack of southeast-dipping thrust sheets. The applicant indicated that $^{40}Ar/^{39}Ar$ age dates on clay fault gouge from several major faults in the Valley and Ridge province indicate emplacement of the thrust sheets occurred at 276-280 Ma.

SSAR Subsection 2.5.1.1.4.2 describes geophysical data sets, including information derived from seismic reflection and aeromagnetic and gravity surveys used to delineate distribution of tectonic elements in the southern Appalachians. The applicant noted seismic reflection data collected by the Consortium for Continental Reflection Profiling showed that major Valley and Ridge faults propagate from a basal detachment near the basement-cover interface, but major structures in the Valley and Ridge are generally not visible on gravity and aeromagnetic maps.

SSAR Subsection 2.5.1.1.4.3 presents information related to current orientation of maximum horizontal compressive stress in the CRN Site region (i.e., generally northeast-southwest) based on Hurd and Zoback (2012) and briefly addresses vertical stresses derived from upper mantle buoyancy forces based on Biryol et al, (2016). The applicant stated that the combination of local upper mantle buoyancy forces proposed by Biryol et al. (2016) and far-field ridge-push forces from the Mid-Atlantic Ridge proposed by Zoback and Zoback (1989) provide a viable explanation for the combined mechanisms that generate the current regional stress field in the Southeastern U.S., including the site region and, consequently, the current state of stress at the CRN Site.

SSAR Subsection 2.5.1.1.4.3 also describes the broad zone of elevated seismic activity from low-magnitude earthquakes (i.e., a maximum magnitude of M 4.6 from historical records) that occurred in the Eastern Tennessee seismic zone (ETSZ). The applicant noted that this zone is approximately 300 km (186 mi) long and 50 km (31 mi) wide and trends northeasterly beneath eastern Tennessee and parts of North Carolina, Georgia, and Alabama. The applicant pointed out that the CRN Site lies within this seismic zone. The applicant stated that instrumentally-located epicenters in the ETSZ indicate most of the earthquakes have a source beneath the 5-km (3-mi) thick Appalachian foreland fold-thrust belt in ca. 1 Ga (billion-year-old) Precambrian basement rocks at a mean focal depth of approximately 15 km (9 mi).

2.5.1.2.1.5 Regional Non-Seismic Geologic Hazards

SSAR Subsection 2.5.1.1.5.1 states that carbonate rock dissolution and karst formation is the dominant non-seismic geologic hazard in the CRN Site region. The applicant explained that the folded and faulted Paleozoic limestones and dolomites in the Valley and Ridge province contain fractures, which provide conduits for fluid flow and enhanced carbonate dissolution, and that cave development and geometry show structural control of karst features.

In SSAR Subsection 2.5.1.1.5.2, the applicant stated that the site lies in an area of moderate susceptibility for and low incidence of landslides, whereas surrounding areas in the site region range from high to moderate susceptibility. The applicant stated that erosion has produced steep slopes, and persistent rainfall followed by more intense precipitation resulted in damaging debris slides and avalanches. The applicant indicated that 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.

2.5.1.2.2 Local Geology

SSAR Section 2.5.1.2 provides information on local physiography and geomorphologic processes; geologic history; stratigraphy and lithology; structural geology, including folds, faults, and shear-fracture zones; geologic hazards, including a detailed discussion of karst; and site engineering geology. The applicant indicated that the geologic investigations conducted to characterize the CRN Site covered the site vicinity, site area, and site location and specifically included field reconnaissance, karst mapping, river terrace mapping, and geomorphic analyses complemented by high-resolution LiDAR digital elevation data acquired for the site area. The following subsections under SER Section 2.5.1.2.2 summarize the information provided by the applicant in SSAR Section 2.5.1.2.

2.5.1.2.2.1 Local Physiography and Geomorphic Processes

SSAR Subsection 2.5.1.2.1 describes local physiography and geomorphic processes. In SSAR Subsection 2.5.1.2.1.1, the applicant stated that the CRN Site lies in the northwestern Valley and Ridge physiographic province, which is the topographic expression of structures in the southern Appalachian foreland fold-thrust belt that formed during the Alleghanian orogeny. The applicant noted that the CRN Site vicinity contains parallel ridges and intervening valleys, oriented northeast-southwest, which are typical of the regional physiographic setting of the Valley and Ridge. The applicant stated that the southeastern third of the CRN Site area contains low hills and exhibits a dendritic drainage pattern, and that Knox Group carbonate rock units containing karst features underlie this area.

SSAR Subsection 2.5.1.2.1.2 describes surficial Quaternary (2.6 Ma to the present in age) deposits at the site. The applicant stated that these surficial deposits include both colluvium (as weathered residuum deposited at the toe of hillslopes and in hollows on hillsides) and alluvium (as weathered residuum deposited in hillside gullies and principal tributary valleys across the site area). The applicant also noted the occurrence of fluvial terraces along the Clinch River.

SSAR Subsection 2.5.1.2.1.3 describes geomorphic features in the site vicinity. The applicant discussed late Tertiary (about 5.3 to 2.6 Ma) and early Pleistocene (about 2.6 to 1.8 Ma) geomorphic processes; Pleistocene geomorphic processes; and the modern Holocene (11,700 yrs to present) geomorphic period. In SSAR Subsection 2.5.1.2.1.3.1, the applicant noted that, although the Late Paleozoic Alleghanian orogeny was the last orogenic event to affect the Valley and Ridge province, there exists a growing body of evidence that the southern Appalachians might have experienced uplift in the late Tertiary, specifically during Miocene time (23 - 5.3 Ma). The applicant remarked that this uplift might have affected development of karst in the site area. The applicant also stated that glacial periods during the Pleistocene (2.6 Ma to 11,700 yrs) had a strong influence on geomorphic development of the CRN Site vicinity because each glacial period produced changes in base level that resulted in isolation and erosion of stream terraces. The applicant reported that recent studies identified Pleistocene terraces in the site vicinity, which the applicant used to evaluate the presence or absence of surface deformation using terraces along the Clinch River.

2.5.1.2.2.2 Local Geologic History

SSAR Subsection 2.5.1.2.2 describes the geologic history of the CRN Site vicinity in relation to the three primary Paleozoic orogenic events that affected the Appalachian orogenic belt (i.e., the Middle Ordovician Taconic orogeny, the Early Devonian to Mississippian Acadian/Neoacadian orogeny, and the Pennsylvanian to Permian Alleghanian orogeny). The applicant explained that the Alleghanian orogeny, which drove deformation in the Valley and Ridge, was mainly responsible for the physiographic and geomorphic expression of the foreland fold-and-thrust belt as observed in the CRN Site vicinity. The applicant stated that the west-directed thrust sheets propagated from the Rome Formation at the basement-cover interface, which is about 3 km (1.9 mi) deep at the CRN Site. The applicant reported that geochronologic analyses of fault gouge from several Valley and Ridge thrust faults indicates emplacement of the thrust sheets around 276-280 Ma ago.

The applicant identified the Lower Cambrian Rome Formation as the basal stratigraphic unit in the CRN Site vicinity that nonconformably overlies ca. 1 Ga Grenvillian basement rocks. A nonconformity is an unconformity between sedimentary rocks and older plutonic or metamorphic rocks that were eroded prior to deposition of the overlying sedimentary units. The applicant stated that sedimentary rocks of the Middle to Late Cambrian Conasauga Group conformably overlie the Rome Formation and consist of fine-grained siliciclastic rocks that become progressively more dolomitic up-section, grading into carbonate rocks of the Late Cambrian to Early Ordovician Knox Group. The applicant indicated that deposition of the dolomite and limestone units, which mainly comprise the Knox Group, coincided with a eustatic (i.e., global) sea level high that was possibly 180 m (590 ft) above present-day mean sea level. The applicant noted that a sea level drop and subsequent erosion produced the Middle Ordovician Knox unconformity, after which a sea level rise resulted in continued carbonate deposition of the Middle Ordovician Chickamauga Group atop the Knox Group. The applicant pointed out that the Chickamauga Group, composed predominantly of limestone in the northwest but becoming increasingly clastic to the southeast in the CRN Site vicinity, dominates the stratigraphic sequence in the CRN Site area.

2.5.1.2.2.3 Local Stratigraphy and Lithology

SSAR Subsection 2.5.1.2.3 discusses stratigraphy and lithology of the CRN Site. After discussing the basis for stratigraphic nomenclature in SSAR Subsection 2.5.1.2.3.1, in SSAR Subsection 2.5.1.2.3.2, the applicant stated that stratigraphy at the CRN Site comprises rock units of the Lower Cambrian Rome Formation, the Middle Cambrian to Lower Ordovician Knox Group, and the Middle Ordovician Chickamauga Group. The applicant reported that the Rome Formation does not crop out at the CRN Site. The applicant indicated that 76 boreholes drilled at the CRN Site encountered the following stratigraphic units, ranging in age 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. SER Figure 2.5.1-2, reproduced from SSAR Figure 2.5.1-30, presents a northwest-southeast geologic cross-section showing the specific stratigraphic units that underlie the CRN Site.

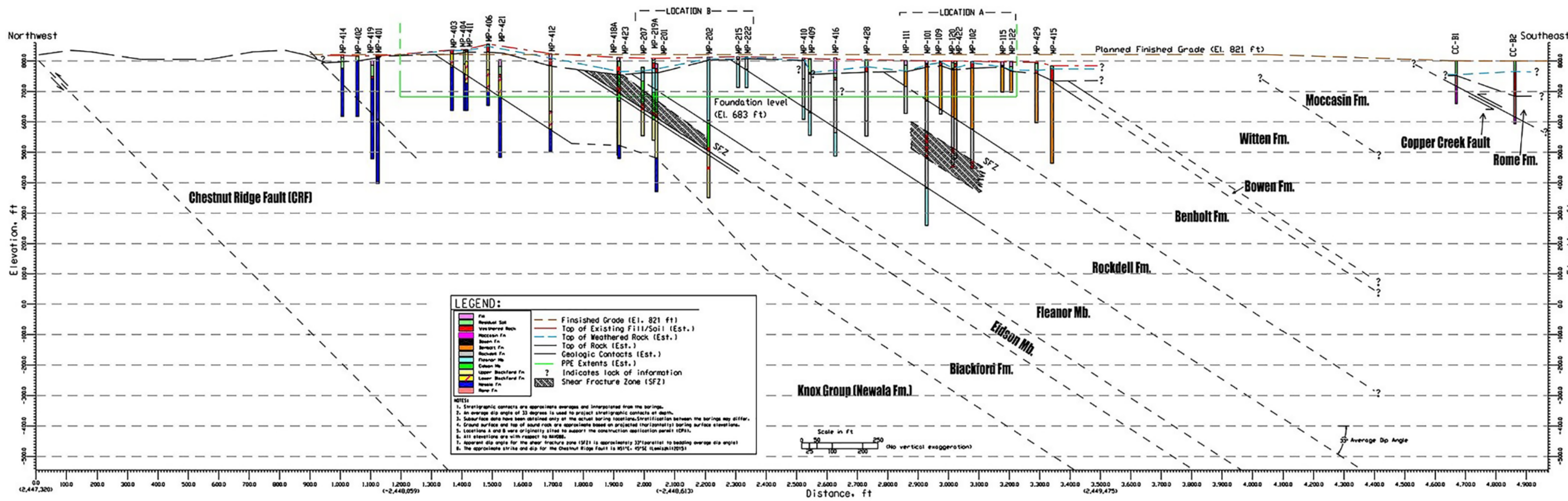

Figure 2.5.1-2: Northwest-southeast geologic cross-section across the CRN Site showing stratigraphic units underlying the site at Locations A and B; shear-fracture zones penetrated in the Eidson Member of the Lincolnshire Formation under Location B and in the Rockdell Formation under Location A; location of the Chestnut Ridge fault in the subsurface northwest of Location B; location of the Copper Creek fault and boreholes CC-B1 and CC-B2 that penetrate the fault to the southeast of Location A. (Figure reproduced from SSAR Figure 2.5.1-30)

In SSAR Subsection 2.5.1.2.3.3, the applicant described rock units encountered at the CRN Site in the Rome Formation and the Knox and Chickamauga Groups based on borings and geologic mapping conducted for the CRN Site ESP and previous investigations. The applicant supplemented lithologic descriptions with laboratory, downhole geophysical, and petrographic data collected during subsurface investigations at the CRN Site.

The applicant stated that the Rome Formation comprises mainly shale and siltstone with lesser amounts of sandstone, dolostone, limestone, and evaporite deposits. The applicant indicated that two boreholes placed to locate and characterize the Copper Creek thrust fault on the southern end of the CRN Site penetrated the Rome Formation, which does not crop out at the CRN Site. The applicant reported that approximately 1.3 to 2.3 m (4.3 to 7.4 ft) of fault gouge related to the Copper Creek thrust occurs between the base of the Rome Formation and the top of the stratigraphically younger Chickamauga Group Moccasin Formation, which underlies the Rome Formation due to thrusting of the Rome Formation over the Moccasin Formation. The applicant stated that the Newala Formation stratigraphically overlies the Rome Formation and represents the Knox Group at the CRN Site. The applicant described the Newala Formation as a fine- to medium-grained, variegated (i.e., gray, pink, and green in color) dolomite that commonly contains nodular, bedded jasperoidal chert. The applicant indicated that the formation also contains several 1.5 to 4.6 m (5 to 15 ft) thick limestone and dolomitic limestone interbeds. The applicant reported that stratigraphic units of the Chickamauga Group are lithologically variable and consist mainly of interbedded limestone and siltstone.

Karst Evaluation

In SSAR Subsection 2.5.1.2.3.4, the applicant reviewed existing dissolution cavity data and discussed the shape of conduits. The applicant stated that, based on compiled borehole data, the largest and highest frequency of dissolution cavities at the CRN Site occur in the Rockdell Formation and the Eidson Member of the Lincolnshire Formation of the Chickamauga Group. The applicant reported that these two stratigraphic units also contain the greatest thicknesses of pure limestone compared to other Chickamauga Group strata at the site. The applicant also stated that environment of formation, hydrologic setting, and rock characteristics control the shape of dissolution cavities. The applicant indicated that variation in rock solubility, bed thickness, structural discontinuities, geometry of fracture pathways, and the degree to which initial fractures have been enlarged governs the shape of conduits.

2.5.1.2.2.4 Local Structural Geology

SSAR Subsection 2.5.1.2.4 describes the structural geology of the site vicinity and site area. The applicant stated that structural geology at the CRN Site is directly related to its position in the foreland fold-and-thrust belt (i.e., the Valley and Ridge province) of the Appalachian orogenic system. The applicant explained that thrust faults in a foreland fold-and-thrust belt propagate through mechanically weak layers at lower angles rather than through mechanically stronger units, which results in the characteristic ramp-flat geometry of the faults observed in the Valley and Ridge.

Macroscopic Structures in the Site Vicinity

In SSAR Subsection 2.5.1.2.4.1, the applicant discussed macroscopic structures (i.e., folds and faults) that occur in the site vicinity. The applicant stated that macroscopic scale folds in the CRN Site vicinity are open, upright to overturned synclines and anticlines with axes trending parallel to major faults and strike of lithologic units. The applicant reported that these macroscopic scale folds extend for distances of 0.8 km (0.5 mi) to more than 11.3 km (7 mi) throughout the site vicinity, with fold axes normal to the inferred regional shortening direction, which supports their development as coincident with Alleghanian emplacement of Valley and Ridge thrust sheets.

The applicant explained that most faults in the CRN Site vicinity are bedding-parallel, northeast-striking, southeast-dipping thrust faults, which formed during late stages of the Alleghanian orogeny and represent a cumulative shortening greater than 120 km (75 mi). The applicant reported that radiometric age dates on features associated with deformation in the Valley and Ridge agree with this timing and range from 265 to 290 Ma. The applicant noted that recent $^{39}Ar/^{40}Ar$ analyses of fault gouge from several Valley and Ridge faults suggest emplacement occurred 276 to 280 Ma. The applicant discussed individual faults that occur in the site vicinity in regard to fault geometry and amount and timing of displacement. These faults, illustrated in SER Figure 2.5.1-3, reproduced from SSAR Figure 2.5.1-27, are as follows, with genetically-related subordinate faults grouped together.

- Emory River and Bitter Creek Faults (Faults 7 and 2 in SER Figure 2.5.1-3)
- Rockwood, Harriman, and Chattanooga Faults (Faults 11, 8, and 3 in SER Figure 2.5.1 3)
- Kingston Fault (Fault 9 in SER Figure 2.5.1-3)
- Beaver Valley Fault (Fault 1 in SER Figure 2.5.1-3)
- Saltville Fault (Fault 12 in SER Figure 2.5.1-3)
- Knoxville Fault (Fault 10 in SER Figure 2.5.1-3)
- Dumplin Valley, Chestuee, and Wildwood Faults (Faults 6, 4, and 14 in SER Figure 2.5.1-3)

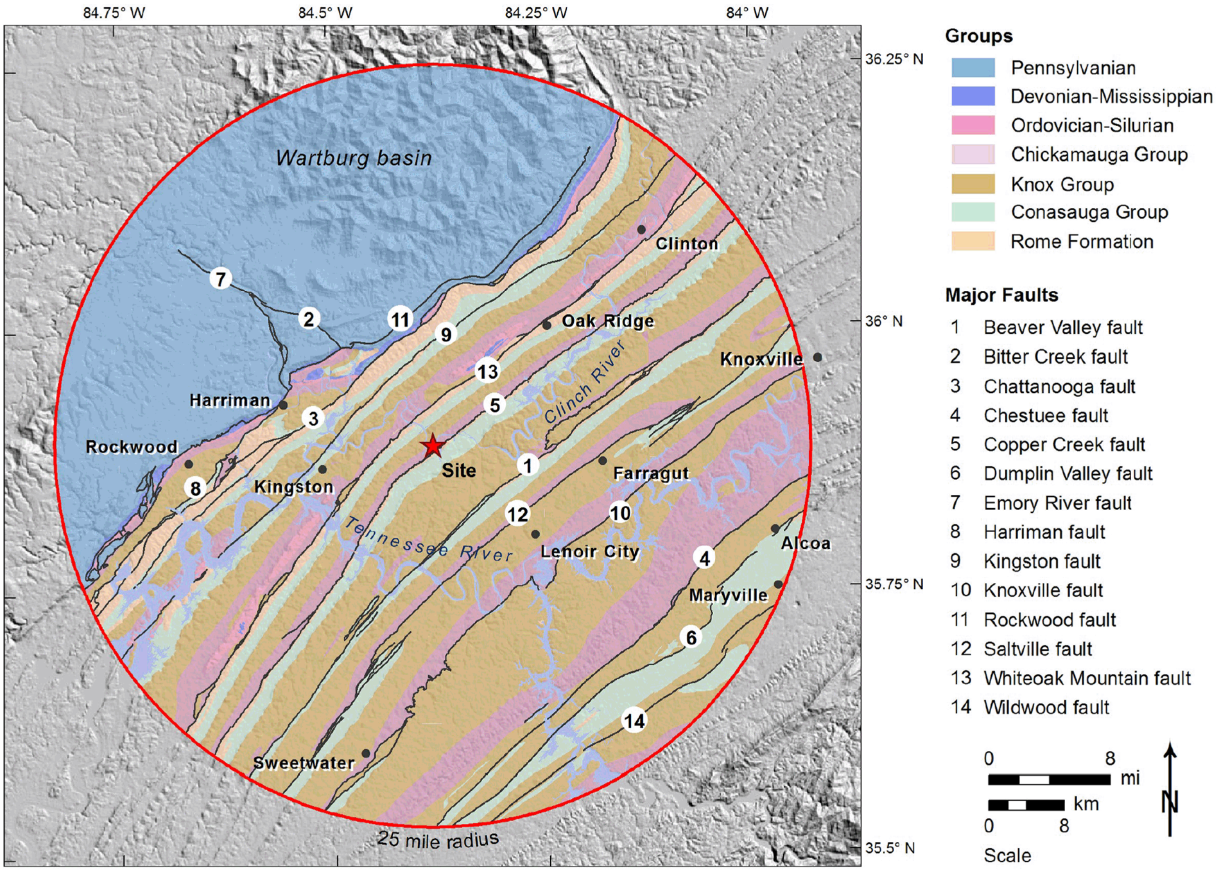

Figure 2.5.1-3: Simplified site vicinity geologic map

Macroscopic Structures in the Site Area

In SSAR Subsection 2.5.1.2.4.2, the applicant discussed three faults which lie within the CRN Site area: Whiteoak Mountain fault, Copper Creek fault, and Chestnut Ridge fault. The applicant included a discussion of the use of both seismic reflection and refraction data for subsurface investigations in this subsection.

In SSAR Subsection 2.5.1.2.4.2.1, the applicant stated that the primary objectives of the seismic reflection surveys conducted for the CRN Site were to interpret the contact between the Knox and Chickamauga Group rocks, interpret the dip of bedding between borehole locations, and identify possible subsurface structures beneath survey lines. The applicant also stated that the primary objective of the seismic refraction surveys was to map depth to bedrock, and that the objectives for both types of surveys were accomplished.

In SSAR Subsection 2.5.1.2.4.2.2, the applicant stated that the Whiteoak Mountain fault, located 3.2 km (2 mi) northwest of the CRN Site as shown in SER Figure 2.5.1-3 (i.e., Fault 13), is a major regional thrust that places Cambrian Rome Formation above Cambrian to Mississippian footwall strata with a minimum displacement of 10 to 12 km (6.2 to 7.5 mi). The applicant stated that the Whiteoak Mountain fault is a late Paleozoic thrust related to development of the foreland fold-and-thrust belt.

In SSAR Subsection 2.5.1.2.4.2.3, the applicant described the Copper Creek fault, located 1 km (0.6 mi) southeast of the CRN Site as shown in SER Figure 2.5.1-3 (Fault 5), as a major thrust in the Valley and Ridge fold-and-thrust belt. (SER Figure 2.5.1-2 also shows the location of the Copper Creek fault in a northwest-southeast geologic cross-section, as well as boreholes CC-B1 and CC-B2 that penetrated the fault.) The applicant noted that this fault places Cambrian Rome Formation rocks above the Ordovician Moccasin Formation with an estimated displacement of 12 to 50 km (7.4 to 31 mi). The applicant stated that materials indicative of fault displacement (i.e., fault gouge, breccia, and cataclasite) occur in association with this fault at the CRN Site and in the site area, and that $^{40}Ar/^{39}Ar$ age dates on gouge samples collected from the fault in northeastern Tennessee gave an age of 279.5 +/-11.3 Ma.

In SSAR Subsection 2.5.1.2.4.2.4, the applicant stated that the Chestnut Ridge fault is a subordinate thrust no greater than 4.5 km (2.8 mi) in length, located about 1 km (0.6 mi) northwest of the CRN Site as shown in the cross-section of SER Figure 2.5.1-2. The applicant noted that the fault is similar in strike orientation to major thrust faults of the Valley and Ridge, although displacement along the fault is likely to be relatively small because it does not juxtapose rock units with significant stratigraphic or temporal differences, which would be indicative of a larger displacement. The applicant explained that the interpreted relatively steep dip of the Chestnut Ridge fault, which is not exposed at the surface, could have resulted from rotation of the fault in the hanging wall block of the Whiteoak Mountain fault as the hanging wall of the Whiteoak Mountain fault climbed over a footwall ramp during Alleghanian deformation of the Valley and Ridge. The applicant stated that this rotation suggests displacement along the Chestnut Ridge fault pre-dated at least some of the movement along the Whiteoak Mountain fault.

Mesoscopic Structures in the Site Vicinity

SSAR Subsection 2.5.1.2.4.3 describes folds, bedding, fractures, and shear-fracture zones at the CRN Site and in the site vicinity. The applicant stated that the data include information derived for the CRN Site from geologic field investigations, boreholes, and seismic reflection and refraction surveys.

In SSAR Subsection 2.5.1.2.4.3.1, the applicant explained that mesoscopic scale folds in the site vicinity are primarily buckle folds with wavelengths of 0.3 m (1 ft) or less, which formed during compression and shortening that drove deformation in the Valley and Ridge fold-and-thrust belt. The applicant noted that several tight, asymmetric, overturned meter-scale folds with wavelengths of about 1 m (3.3 ft) also occurred in the CRBRP excavation.

In SSAR Subsection 2.5.1.2.4.3.2, the applicant stated that geologic mapping, acoustic televiewer borehole log data, and geometric solutions derived from three elevation points measured on key stratigraphic horizons in boreholes (i.e., standard 3-point problem solutions) indicates that bedding at the site primarily strikes 050 to 070 (N50°E to N70°E) and dips between 20 to 50 degrees southeast. The applicant noted that seismic reflection data support consistent dips of stratigraphic units between boreholes at the CRN Site.

In SSAR Subsection 2.5.1.2.4.3.3, the applicant discussed information from Hatcher et al. (1992) suggesting that fracture sets developed before Alleghanian Valley and Ridge thrust faulting. The applicant noted that orientation of fracture sets consistently rotates with orientation of bedding, which provides evidence for development of the fracture sets prior to deformation related to thrust faulting. The applicant stated that two orthogonal fracture sets occur throughout the CRN Site area, with one set parallel to strike of bedding but perpendicular to bedding dip, and the other perpendicular to both strike and dip of bedding.

In SSAR Subsection 2.5.1.2.4.3.4, the applicant discussed shear-fracture zones identified within the site vicinity and described four attributes used to classify a feature as a “shear-fracture zone” based on borehole data. The geologic cross-section of SER Figure 2.5.1-2 shows the subsurface positions of two separate shear-fracture zones penetrated in boreholes beneath potential CRN Site Locations A and B. The applicant interpreted bedding-parallel stylolites that truncate the shear-fracture zones and calcite veins in the zones to demonstrate a pre- to syn-diagenetic, non-tectonic origin for the zones due to pressure solution caused by lithostatic loading during burial. In addition, the applicant interpreted the truncation of calcite veins in the shear-fracture zones by steeply-dipping stylolites, folding and deformation of calcite veins, and slickensides on veins and bedding surfaces to demonstrate a post-diagenetic, tectonic overprint on the zones related to Alleghanian emplacement of Valley and Ridge thrust faults, including the Whiteoak Mountain and Copper Ridge faults known to occur in the site area. Therefore, the applicant determined that both diagenetic and tectonic stylolites occur in the shear-fracture zones. The applicant considered a “shear zone” previously described in the excavation for the CRBRP site (Drakulich, 1984 - ADAMS Accession No. ML17286A618), no longer visible for a direct comparative examination, and the shear-fracture zones penetrated by boreholes at the CRN Site to most likely have a similar origin. The applicant made this interpretation because the description of the “shear zone” provided by Drakulich (1984) appears similar to the shear-fracture zones observed in rock core samples from the CRN Site based on the four attributes used by the applicant to classify those zones.

In SSAR Subsection 2.5.1.2.4.4, the applicant stated that attributes of the Valley and Ridge thrust faults within the site area are a function of lithology and mechanical and chemical responses to stress during deformation. The applicant reported that two borings at the CRN Site penetrated the Copper Creek fault (i.e., CC-B1 and CC-B2, located on the geologic cross-section of SER Figure 2.5.1-2). The applicant noted that materials collected from the fault zone over a 1.2 to 2.1 m (4 to 7 ft) interval in the borings comprised angular carbonate and siliciclastic fragments in a clayey gouge matrix, which represent mechanical grain-size reduction due to cataclasis (i.e., fracturing, milling, crushing, and grinding) resulting from displacement along the fault.

2.5.1.2.2.5 Local Geologic Hazards

In SSAR Subsection 2.5.1.2.5, the applicant assessed potential geologic hazards in the site vicinity and site area and at the site location. The applicant explained that karst features and active karst processes are common throughout the site vicinity and include sinkholes, caves, springs, underground drainage, and irregular soil-bedrock contacts. The applicant stated that karst dissolution of carbonate bedrock, which underlies all plant facilities, is the primary potential geologic hazard at the CRN Site.

2.5.1.2.2.5.1 Karst Hazards

In SSAR Subsection 2.5.1.2.5.1, the applicant discussed karst processes and features in the site vicinity and site area and at the site location. The applicant reviewed conceptual karst models to provide a context for discussion of hazards at the CRN Site due to karst. The applicant presented discussions of previous karst studies in the site area, a detailed inventory of karst features in the site area, and a summary of local karst development. The applicant also discussed karst processes and features at the CRN Site, including karst susceptibility of stratigraphic units at the site, and karst-related surface and subsurface features at the site.

The applicant classified conceptual karst models based on whether karst evolved by epigenic or hypogenic dissolution, or both, of carbonate bedrock by water. The applicant explained that epigenic dissolution occurs by water moving downward from the ground surface into soluble rock formations, then through those formations along the hydraulic gradient. The applicant noted that permeability of the rock formations controls the depth to which the water can penetrate for development of epigenic karst. The applicant explained further that hypogene dissolution occurs when groundwater moves upward from below, with movement of water independent of recharge from the ground surface. The applicant indicated that hypogenic karst systems require a setting in which waters descend to great depth and then move upward through overlying soluble rocks. The applicant noted that the rising water can aggressively dissolve soluble rock units because of water chemistry or increased water temperature.

The applicant reported that studies of karst aquifers by Wolfe et al. (1997) resulted in development of a karst model for the Valley and Ridge of Tennessee showing epigenic karst dissolution throughout the vadose (i.e., above the water table) and shallow and deep phreatic (i.e., below the water table) zones. Based on this model, the applicant stated that dissolution is most intense near the surface, but also proceeds downward along bedding planes and joints. The applicant noted that dissolution can extend to depths greater than 180 m (600 ft).

Karst in the Site Vicinity and Site Area

Because karst development in the site vicinity is similar to that in the site area due to consistency of stratigraphy and geologic structure, the applicant focused the detailed discussions of karst in SSAR Subsection 2.5.1.2.5.1.1 on the site area. The applicant explained that, although all carbonate units contain some dissolution features, karst development varies strongly in relation to stratigraphic unit such that the thickest and purest carbonate rocks generally have the largest and most abundant karst features. The applicant stated that dissolution rates are variable and depend on multiple factors, including bedrock geochemistry, location of rock units relative to the water table, fracture density, and localized anthropogenic effects such as acid mine drainage. The applicant reported that the dissolution rate of carbonate bedrock in the Appalachians is in the range of 30 mm (1.2 in) per thousand years.

In SSAR Subsection 2.5.1.2.5.1.1, the applicant stated that previous studies to characterize karst development at the ORR, which comprises most of the northern half of the CRN Site area, significantly advanced the understanding of karst in the CRN Site area. To extend the information derived about karst at the ORR to the CRN Site area, the applicant conducted detailed mapping and prepared an inventory of karst features in the site area based on interpretation of high-resolution LiDAR data obtained in 2013 for characterization of the CRN Site.

SSAR Subsection 2.5.1.2.5.1.1 provides an explanation of the karst features inventory of the site area, completed for the CRN Site application, to assist with understanding the nature and extent of karst development as a function of bedrock lithology, structure, and topography. The information presented included a discussion of the mapping of karst features, distribution of karst depressions, and cave development.

Regarding distribution of karst depressions, the applicant identified a total of 2797 karst depressions in the karst inventory, 1210 of which were sinkholes at least 0.6 m (2 ft) deep and

9.2 m^2 (100 ft^2) in area. The applicant calculated depression density for the CRN Site area within an 8-km (5-mi) radius of the site. The applicant reported that the analysis showed stratigraphic units characterized by thick and relatively pure carbonate have the highest depression density (i.e., number of depressions per unit area examined). The applicant noted that these stratigraphic units included the Knox Group dolomites and the purer limestones of the Chickamauga and the Conasauga Groups. The applicant stated that the Witten and Rockdell formations, stratigraphic units of the Chickamauga Group underlying the CRN Site footprint, averaged 8 to 9 depressions per square kilometer (0.39 mi^2), while other units of the Chickamauga Group contained less than three depressions per square kilometer (0.39 mi^2) based on mapping by the applicant within a 9-km (5-mi) radius of the site. The applicant noted that stratigraphic units containing interbedded carbonate and clastic lithologies (e.g., the Benbolt formation of the Chickamauga Group) have a moderate number to few depressions, and units dominated by clastic material (i.e., sandstone, siltstone, shale) have few to no depressions.

Regarding cave development, the applicant described two categories of cave passages based on groundwater setting. The applicant explained that vadose zone cave passages form above the water table by water moving down from the surface toward the water table, and the passages tend to follow the steepest available openings such as vertical joints and dipping bedding planes. The applicant further explained that phreatic cave passages form at or just beneath the water table where groundwater flows laterally in the direction of the hydraulic gradient. The applicant stated that the ideal phreatic passage is a tube-shaped conduit reflecting dissolution on all sides of the water-filled passage, although shape of the conduit can be modified by joints and bedding planes and the presence of less soluble strata. The applicant explained that, during the late Tertiary and Quaternary, stream incision and landscape lowering resulted in abandonment of former phreatic passages, which consequently became dry. The applicant also explained that, after abandonment, passages can divide into segments due to surface erosion and be partially filled with sediments, cave formations, and collapsed rock from the dry conduit ceiling.

The applicant identified 24 caves within the 8-km (5-mi) site radius, all of which formed in the Copper Ridge Dolomite, Chapultepec Dolomite, or Maynardville Limestone. The applicant reported that the largest cave in the CRN Site area, the Copper Ridge Cave, has a stream-carved entrance passage which carries water from the hillside that then flows underground in a down-dip direction for about 213 m (700 ft). The applicant noted that a 122 m (400 ft) length segment of the entrance passage follows a prominent northwest-oriented joint set, and the passage eventually intersects a 12.2-m (40-ft) diameter tube-shaped passage. The applicant interpreted the passage, now more than 30.5 m (100 ft) above the present-day level of the Clinch River, as a relict phreatic feature formed when base level was higher. The applicant reported that most of the caves represent relict abandoned phreatic passages.

Summary of Local Karst Development

In the summary regarding local karst development, the applicant reiterated that field inspections and descriptions of local caves in the CRN Site area support the concept of geologic structure, stratigraphy, and lithology strongly controlling cave development. The applicant stated that the extent to which deep phreatic conditions existed, including hypogenic conditions, is currently unknown, and cave passage geometry is consistent with either phreatic or vadose dissolution. However, the applicant indicated that the presence of deep cavities in water wells suggests that deep phreatic dissolution is occurring, although no clear evidence of hypogene dissolution (e.g., secondary minerals characteristic of hypogene processes, such as travertine springs, or exotic minerals deposited in caves) has been documented in the site area. The applicant noted that most springs in the ORR have water chemistry typical of meteoric water.

Karst Processes and Features at the CRN Site

In SSAR Subsection 2.5.1.2.5.1.2, the applicant discussed karst susceptibility of site-specific stratigraphic units, karst-related surface and subsurface features at the site, and the site-specific karst model. The applicant explained that karst features at the CRN Site consist primarily of karst depressions (i.e., sinkholes) observed at the ground surface and cavities encountered in boreholes. The applicant stated that information derived from geologic mapping, field reconnaissance, and geotechnical investigations conducted for the CRBRP and the CRN Site provided the basis for the discussion.

The applicant stated that susceptibility of a stratigraphic unit to karst development depends strongly on composition, bedding, and jointing characteristics of the unit. Regarding rock composition, the applicant indicated that stratigraphic units of the Chickamauga Group, which underlie the CRN Site, comprise varying proportions of calcite, sand, silt, clay, and chert. The applicant noted that the Eidson member of the Blackford Formation and the Rockdell and Benbolt Formations have the highest carbonate content, while the Fleanor Shale, the rest of the Blackford Formation, and the Bowen Formation have a relatively lower carbonate content. The applicant also noted that variability in carbonate content within any given stratigraphic unit reflected the presence of alternating interbeds of carbonate and clastic strata as observed in core of the Chickamauga Group. Regarding bedding and jointing, the applicant stated that bedding planes, joints, and fracture zones constituted the initial pathways for water to penetrate the stratigraphic units and start the dissolution process.

The applicant stated that the primary documentation of subsurface dissolution features at the CRN Site comes from boreholes. However, the applicant also stated that borings show only a fraction of the dissolution features present in the subsurface. In addition, the borings do not clearly define the extent and geometry of the features due to spacing between borings and the small diameter of the borings. The applicant indicated that two seismic reflection lines completed during the CRN Site investigations showed planar beds of uniformly dipping strata, which provides evidence against the presence of large-scale subsurface karst collapse features along the survey lines.

The applicant reported that rock core borings drilled in the CRN Site area revealed both open and clay-filled cavities. The applicant observed that, of the 180 borings completed at the CRBRP (104) and the CRN Site (76), 75 borings encountered one or more cavities and frequency and size of cavities, which were greater in stratigraphic units having a higher carbonate content, generally decreased with depth. The applicant stated that borings in the Rockdell Formation of the Chickamauga Group encountered the greatest number of, and largest, cavities (i.e., more than 100 cavities up to 5 m (16.5 ft) in the vertical dimension), while borings in the Fleanor Shale, with the lowest carbonate content of the Chickamauga Group, encountered 19 cavities up to 0.4 m (1.4 ft) in the vertical dimension. The applicant pointed out that the shear-fracture zones, penetrated in 15 boreholes during subsurface investigations, did not appear to be the loci for accelerated dissolution.

In SSAR Subsection 2.5.1.2.5.1.2, the applicant presented the features of a conceptual model for karst development at the CRN Site based on concepts, observations, and data derived from regional, local, and site-specific investigations. The applicant also stated that a geologic mapping and subsurface exploration program will be implemented during site excavation to delineate karst features below the floor of the excavation.

Potential Karst Hazard at the CRN Site

In SSAR Subsection 2.5.1.2.5.1.3, the applicant stated that overburden and cavities formed by dissolution near the top of rock will be removed during the excavation process and there will be little hazard due to cover-collapse sinkholes at plant facilities sited on these excavations. The applicant acknowledged that this type of sinkhole is the most common type in the CRN Site area. The applicant stated that dissolution cavities have been observed in boreholes down to an elevation of 201 m (660 ft), and data collected for the CRN Site provides a comprehensive understanding of karst within approximately 91 m (300 ft) of the ground surface.

The applicant discussed three types of potential karst hazards posed by dissolution cavities at the CRN Site. The first potential hazard relates to the presence of cavities below the water table in the walls of the excavation, which might result in discharge of groundwater from the cavities that could make it difficult to maintain a dry excavation. The applicant stated that information from the CRBRP excavation into the Fleanor Shale showed the excavation to have been relatively dry. The second potential hazard involves the presence of dissolution cavities below the base of the foundation that might require mitigation to ensure foundation stability. The applicant stated that small cavities can be mitigated by grouting, and geophysical tests or boreholes in the finished excavation can be used to detect deeper cavities, with the information derived used to determine the appropriate mitigation strategy for the cavities. The applicant indicated that final conclusions regarding karst hazard will be based on detailed geologic mapping of the excavations and geophysical surveys which penetrate below the foundation level. The third potential hazard relates to the presence of cavities that might enable rapid movement of an accidental release.

2.5.1.2.2.5.2 Other Local Geologic Hazards

In SSAR Subsection 2.5.1.2.5.2, the applicant addressed local geologic hazards related to slope failure, unrelieved residual stresses, and effects of human activities. For a discussion of slope failure, the applicant cross-referenced SSAR Subsection 2.5.3. Regarding unrelieved residual stresses, the applicant characterized the local stress regime as an unloading condition within the consistent stress field of the Eastern United States. The applicant commented that stress release due to weathering and erosion might be expressed in closely-spaced joints that occur near the ground surface, but there are no conditions conducive to high residual stresses in the rock units. The applicant noted that underground mining and hydrocarbon extraction have not taken place at the site, and the site has not experienced significant groundwater withdrawal. Therefore, the applicant stated that subsidence due to mining, hydrocarbon or mineral extraction, or groundwater withdrawal are not potential hazards at the CRN Site.

In a summary evaluation of local geologic hazards in SSAR Section 2.5.1.2.5.3, the applicant indicated that the primary geologic hazard at the CRN Site is the potential for karst dissolution features, which could compromise safety or stability of the excavation or enable rapid movement of groundwater. The applicant stated that such hazards related to karst, if present, can be mitigated during construction. The applicant reiterated that the planned geologic mapping of the walls and floor of excavations for safety-related structures will be conducted to fully describe karst features and enable planning of an appropriate mitigation approach.

2.5.1.2.2.6 Site Engineering Geology

In SSAR Subsection 2.5.1.2.6, the applicant summarized conditions related to engineering geology beneath the power block area at the CRN Site based on information derived from review of existing site-specific reports and geologic literature, as well as geologic and geotechnical investigations. The applicant stated that bedrock belonging to the Knox and Chickamauga Groups underlies the CRN Site, and that the discussions in SSAR Subsection 2.5.1.2.6 focus on geologic features and characteristics that might affect the bedrock units.

In SSAR Section 2.5.1.2.6.1, the applicant reported that the subsurface investigation program for the CRN Site involved drilling and sampling a total of 82 geotechnical borings, including six soil borings (Borehole location map: SER Figure 2.5.4-2). The applicant noted that ground surface elevations within the potential power block area range from about 260.6 m (855 ft) to 237.7 m (780 ft) NAVD88 (i.e., North American Vertical Datum of 1988). The applicant stated that the stratigraphic units underlying the power block area include the Newala Formation of the Knox Group overlain up-section by the Blackford, Lincolnshire (Eidson and Fleanor Members), Rockdell, and Benbolt Formations of the Chickamauga Group. The applicant stated that the estimated final grade elevation at the CRN Site is 250 m (821 ft) NAVD88.

In SSAR Subsection 2.5.1.2.6.2, the applicant briefly discussed ranges of the Geologic Strength Index (GSI) for each of the stratigraphic units that underlie the CRN Site.

In SSAR Subsection 2.5.1.2.6.3, the applicant reported that borings drilled at the CRN Site indicate the occurrence of fracture zones or zones of weathering within the stratigraphic units which likely represent early dissolution of limestone. The applicant stated that most of the fracture zones occurred between elevations of approximately 243.8 to 22.6 m (800 to 750 ft NAVD88). The applicant noted that rock mass discontinuities became tighter and less frequent with depth, although fracture zones occur between depths ranging between about 1.8 to 122 m (6 to 400 ft) below the ground surface, and few fractures below the power block foundation level exhibit weathering.

In SSAR Subsection 2.5.1.2.6.4, the applicant indicated that the average GSI rating for each of the stratigraphic units in which the zones occur incorporate the shear-fracture zones, so bearing capacity based on GSI considered these zones. The applicant stated that further evaluation of the shear-fracture zones might be required for a future combined license application. The applicant also stated that detailed geologic mapping of the excavations for safety-related engineered structures will provide additional characterization of the shear-fracture zones if they occur in the excavations.

In SSAR Subsection 2.5.1.2.6.8, the applicant stated that no permitted natural gas wells, coal mines, or quarries occur within 8 km (5 mi) of the CRN Site. SSAR Subsection 2.5.1.2.6.9 states that groundwater levels at the site are likely to require temporary dewatering of foundation excavations and noted that solution cavities, bedding planes, and open fractures might require grouting to reduce groundwater flow into the excavation and to reduce the amount of dewatering. In SSAR Subsection 2.5.1.2.6.10, the applicant stated that future excavations for safety-related engineered structures will be geologically mapped in detail and any unforeseen geologic features that are encountered will be evaluated. The applicant indicated that the detailed geologic mapping will document dissolution features; determine whether dissolution cavities decrease in size and abundance with depth; provide the opportunity to collect in situ data to refine rock mass characterization; confirm or refine interpretations of subsurface geology derived from borehole data; and verify the absence of active tectonic faults.

2.5.1.2.2.7 Relational Analysis

In SSAR Subsection 2.5.1.2.9, the applicant discussed the relationships between stratigraphic units, structural geology, and karst features for the proposed CRN Site and the previous CRBRP site. The applicant considered this analysis important because the two sites are co-located on the peninsular landform defined by the incised Clinch River arm of the Watts Bar Reservoir and results of the investigations for each can be compared.

Regarding karst features, the applicant indicated that borehole data revealed 216 subsurface dissolution cavities at the CRBRP site and 23 at the CRN Site, with the fewer number of cavities encountered in the CRN Site borings, which overlapped those for the CRBRP site, being consistent with removal of the cavity-rich near-surface strata during excavation at the CRBRP site. The applicant also indicated that the distribution of cavity size with elevation at the CRN Site is consistent with data collected at the CRBRP site. Based on the quality and compatibility of both boring programs, the applicant determined that the two data sets could be combined and used for analysis of subsurface cavities at the CRN Site. The applicant stated that results of the CRBRP site investigations (i.e., geologic mapping and subsurface investigations) can be used to enhance understanding of the geology and engineering suitability of foundation rock units at the CRN Site.

2.5.1.3 Regulatory Basis

The applicable regulatory requirements for basic geologic and seismic information that must be considered in an ESP application are as follows:

- 10 CFR 52.17(a)(1)(vi) as related to identifying geologic and seismic characteristics of a proposed site with appropriate consideration of the most severe natural phenomena that have been historically reported for the site and surrounding area, and with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated.

- 10 CFR 100.23 as related to evaluating the suitability of a proposed site based on consideration of geologic, geotechnical engineering, geophysical, and seismic characteristics of the proposed site. Geologic and seismic siting information must be sufficient to support estimates of the SSE for the site and identify the potential for surface tectonic and non-tectonic deformation.

The related acceptance criteria from Section 2.5.1 of NUREG‑0800 are as follows:

- Regional Geology (SSAR Section 2.5.1.1): Requirements of 10 CFR 52.17 and 10 CFR 100.23(c) are met and guidance in RGs 1.206, 1.208, and 4.7 followed for this area of review if a complete and documented discussion is presented for geologic setting, tectonic framework, and conditions caused by human activities that have the potential to affect safe siting and design of the proposed facility. This SSAR subsection should contain a review of regional stratigraphy, lithology, structural geology, geologic and tectonic history, tectonic features (with an emphasis on the Quaternary period), seismology, geomorphology, paleoseismology, and physiography within the 320 km (200 mi) site region, or beyond as necessary, to provide a framework within which significance to safety can be evaluated in regard to geology, seismology, and conditions caused by human activities. Geologic maps and cross-sections constructed at scales adequate to illustrate relevant regional features should be included in the application.

- Site Geology (SSAR Section 2.5.1.2): Requirements of 10 CFR 52.17 and 10 CFR 100.23(c) are met and guidance in RGs 1.206, 1.208 and 4.7 followed for this area of review if the SSAR contains a description and an evaluation of geologic features, tectonic features, and conditions caused by human activities at appropriate levels of detail for determining any potential natural hazards that might affect the design and operation of the proposed facility. This subsection should contain the following information within the 40 km (25 mi) site vicinity, the 8 km (5 mi) site area, and the 1 km (0.6 mi) site location:

    a. Structural geology, including identification and characterization of faults, joints, and other tectonic deformation features and discussion of the relationships between these features and regional tectonic structures.

    b. Geologic maps and cross-sections constructed at scales adequate to clearly illustrate pertinent features.

    c. Stratigraphy and lithology of rock units and discussion of their relationships to the regional lithostratigraphic framework.

    d. Geomorphologic features as tectonic strain markers or indicators of other potentially hazardous natural phenomena (e.g., landslides, karst development and dissolution collapse, growth faults).

    e. Geologic and tectonic history, particularly for the Quaternary Period, and discussion of the relationship to regional geologic and tectonic history.

    f. Tectonic framework description, including identification of historical and instrumentally-recorded earthquakes; identification and characterization of any local tectonic features that might be related to seismicity; discussion of the relationships between local and regional tectonic structures and any relationships to seismicity.

    g. Evidence for paleoseismic features, including a description of investigations performed by the applicant to verify the presence or absence of the features.

    h. Geologic features that have significance for geotechnical engineering, including (1) zones of mineralization, alteration, irregular or deep weathering, or structural weakness in surface or subsurface materials; and (2) surface and subsurface dissolution features in soluble rocks such as limestone, gypsum, or salt.

2.5.1.4 Technical Evaluation

The NRC staff reviewed SSAR Section 2.5.1 of the CRN Site ESP application (Revision 1) to ensure that the materials provided by the applicant present the information required for geologic characterization of the CRN Site. The information presented in SSAR Section 2.5.1 includes geologic, geophysical, and seismic data for the site region, site vicinity, site area, and site location derived from the applicant's reviews of previous CRBRP reports, ORNL reports, and published literature as well as from surface and subsurface field investigations specifically conducted by the applicant to characterize the geology of the CRN Site for the ESP application.

SSAR Section 2.5.1 contains information related to assessment of the potential for tectonic and non-tectonic surface deformation at the CRN Site, including faulting and limestone dissolution, which the applicant addressed in detail in SSAR Section 2.5.3, as well as geologic and seismic data to support the analysis of vibratory ground motion and development of the site-specific GMRS in SSAR Section 2.5.2. In addition, SSAR Section 2.5.1 includes site-specific geotechnical information related to suitability of subsurface materials and foundations, which the applicant discussed in detail in SSAR Section 2.5.4.

The staff's review of SSAR Section 2.5.1 confirmed that materials included in the application addressed the types of information required for geologic characterization of the CRN Site. By performing the review, staff determined that the applicant had collected sufficient information for geologic characterization of the site to comply with applicable regulatory requirements in 10 CFR 52.17(a)(1)(vi) and 10 CFR 100.23(c), and conducted the site characterization investigations at the appropriate levels of detail in accordance with guidance in RG 1.208. RG 1.208 recommends that an applicant evaluate any significant new geologic, seismic, and geophysical data to determine whether revisions to existing seismic source models and ground motion attenuation relationships are necessary. RG 1.208 also recommends that an applicant evaluate faults encountered at a site to determine whether they are seismogenic or might cause tectonic surface deformation.

To further confirm that the applicant provided the information necessary for adequate geologic characterization of the CRN Site, the NRC staff participated in two site audits and a site visit. The staff conducted the first audit for the CRN Site on July 17-18, 2013, to observe field activities being undertaken by the applicant to collect subsurface geotechnical and geologic data prior to submitting the ESP application for the site. An audit report of this first audit (NRC, 2013 - ADAMS Accession No. ML13210A307) documents the information discussed during this first site audit.

The second site audit, conducted on May 8-9, 2017, and the site visit, held on January 30-31, 2018, occurred after the applicant had submitted the ESP application for the CRN Site. During the May 2017 audit, staff interacted with the applicant to discuss the geologic, seismic, geophysical, and geotechnical investigations conducted by the applicant to characterize the proposed site. The staff held these discussions while examining select core samples to observe subsurface characteristics of the Copper Creek fault, a shear-fracture zone, karst-related cavities, and the Knox unconformity; rock outcrops; and geomorphic features. The staff visited field locations where three subsurface geologic features (i.e., the Copper Creek fault, a shear-fracture zone, and the Chestnut Ridge fault) would likely intersect the ground surface based on the interpreted subsurface orientations of these features. The interpreted subsurface orientations are derived from rock core samples, previous geologic mapping, and the analysis of subsurface stratigraphy. The staff's visit confirmed there is no evidence that these three features are presently visible at the ground surface. The applicant marked the location of the surface projection of the Copper Creek fault on a Quaternary river terrace to enable staff to confirm that the terrace surface did not exhibit any evidence of Quaternary offset. The staff also visited and examined sinkholes, the Melton Hill and Copper Ridge Caves, and exposures of pinnacle and cutter type karst in the site area to increase understanding of the overall characteristics of karst at and around the CRN Site. A thorough understanding of the karst activity at and near the CRN Site is necessary because limestone dissolution, which creates karst, can produce subsurface cavities that might impact site suitability. An audit report in

ADAMS (Accession No. ML17223A428) summarizes the features observed and the information discussed during the May 2017 site audit.

The January 2018 site visit allowed staff to re-examine and analyze some of the geologic features observed during the May 2017 site audit and get further clarification from the applicant related to the applicant's descriptions and interpretations of those features. The primary focus for the site visit was on field characteristics of the shear-fracture zones and karst features. During the January 2018 site visit, the staff confirmed the applicant's descriptions and interpretations of karst features provided in SSAR Section 2.5.1 based on direct field examination of outcrops and features, as well as rock core samples. These confirmatory activities, along with discussions with the applicant during these activities, supported the applicant's conclusion that karst is the primary geologic hazard at the CRN Site. Confirmation of the applicant's characterization of karst at the site was important for staff's findings regarding this potential hazard. The staff also clarified the basis for the applicant's interpretation of the distinction between thrust faults and shear-fracture zones based on direct examination and analysis of those two features in core samples and discussions with the applicant. It was clear that the thrust faults are tectonic in origin and formed during the Late Paleozoic Alleghanian orogeny with no indication of Quaternary deformation, and that the shear-fracture zones likely reflect both diagenetic effects and a Late Paleozoic tectonic overprint, but without major displacement along the zones as the thrust faults exhibit. Confirmation of the applicant's characterization of the shear-fracture zones and thrust faults was important for the staff's findings regarding these features to ensure that neither feature reflected Quaternary deformation. A trip report in ADAMS (Accession No. ML18220A749) describes the features observed and the information discussed during the January 2018 site visit.

The following SER sections present the staff's evaluation of information provided by the applicant in SSAR Section 2.5.1 and in the applicant's responses to RAIs related to SSAR Section 2.5.1. The RAIs issued by the staff and discussed in the following sections of this SER ensure the applicant's compliance with 10 CFR 52.17(a)(1)(vi) and 10 CFR 100.23(c), as well as conformance with Section 2.5.1 of NUREG‑0800. In addition to RAIs addressing specific technical issues for the CRN Site, discussed in detail below, the staff also prepared a few editorial RAIs asking the applicant to more clearly define the locations of certain geologic features shown in SSAR figures. This technical evaluation does not include a discussion of the editorial RAIs, but staff examined the pertinent figures to ensure that the applicant had made the requested changes.

2.5.1.4.1 Regional Geology

The staff reviewed SSAR Subsection 2.5.1.1 which included information provided by the applicant related to the following topics within 320 km (200 mi) of the CRN Site (i.e., the site region): physiography, topography, and geomorphic processes; fluvial processes; karst processes and occurrence; geologic history and tectonic evolution; stratigraphy; tectonic setting; and non-seismic geologic hazards. The staff focused its review on the applicant's descriptions of Valley and Ridge thrust faults that developed during the Late Paleozoic Alleghenian orogeny; potential Quaternary tectonic features, specifically possible faults and paleoliquefaction features that could be associated with the ETSZ, which falls within the CRN Site region; and karst processes and features resulting from limestone dissolution of carbonate rocks that the applicant qualified as the dominant non-seismic geologic hazard in the CRN Site region.

2.5.1.4.1.1 Regional Physiography, Topography, and Geomorphic Processes

In SSAR Subsection 2.5.1.1.1, the applicant described physiography, topography, and geomorphic processes of the site region, specifically including regional karst processes and occurrence in SSAR Subsection 2.5.1.1.1.3. The staff focused its review of SSAR Subsections 2.5.1.1.1 on the Valley and Ridge physiographic province because the CRN Site lies in that province.

Based on its review of information presented in SSAR Subsection 2.5.1.1.1 and literature cited by the applicant in the SSAR related to regional physiography, topography, and geomorphic processes in the Valley and Ridge; examination of regional topographic maps; and direct observation of physiographic, topographic, and geomorphic features at and around the CRN Site during the second site audit in May 2017, and the site visit in January 2018, the staff concludes that the underlying geology and tectonic structures characteristic of the site region strongly control morphology of the surrounding landscape. The staff makes this conclusion because all existing data clearly support the concept of lithologic and structural control on landscape morphology.

In addition, based on its review of information presented in SSAR Subsection 2.5.1.1.1.1.3 and literature cited by the applicant in the SSAR specifically related to regional karst processes and occurrence in the Valley and Ridge, as well as direct observation of karst features in the folded and faulted Paleozoic carbonate rocks at and around the CRN Site during the second site audit in May 2017, and the site visit in January 2018, the staff also concludes that sinkholes occur in carbonate strata of the Valley and Ridge province and caves are relatively short due to the deformation characteristics (i.e., folding and faulting) and compositional variations of rock units in the province. The staff makes these conclusions because all existing data support the existence of sinkholes and relatively short caves in the Valley and Ridge Province.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.1.1 as outlined in the above paragraphs, the staff finds that the applicant provided a thorough and accurate description of regional physiography, topography, and geomorphic processes, including regional karst processes and occurrence, in support of the CRN Site ESP application.

2.5.1.4.1.2 Regional Geologic History and Tectonic Evolution

In SSAR Section 2.5.1.1.2, the applicant discussed geologic history and tectonic evolution of the site region, which covered the three Paleozoic orogenies (i.e., the Taconic, Acadian/Neoacadian, and Alleghanian orogenies) that directly influenced geology and structural features of the CRN Site region and, consequently, the CRN Site; Mesozoic extension associated with continental rifting in the CRN Site region that formed the present-day Atlantic Ocean Basin; and potential Miocene uplift of the southern and central Appalachians. The applicant noted that the Alleghanian orogeny resulted in folding and faulting of stratigraphic units in the Valley and Ridge physiographic province.

The staff focused the review of SSAR Subsection 2.5.1.1.2 on the discussion of the thrust faults and folds that developed during the Alleghanian orogeny because these structural features occur in the site region, site vicinity, site area, and at the CRN Site location. Based on the review of information presented in SSAR Subsection 2.5.1.1.2 and literature cited by the applicant in Section 2.5 of the SSAR, as well as examination of the Copper Ridge thrust fault in core samples from the site location, the staff concludes that geologic history and tectonic evolution in the site region are appropriately characterized by the applicant. The staff makes this conclusion because all existing data strongly support the descriptions of geologic history and tectonic evolution of the site region provided by the applicant in SSAR Subsection 2.5.1.1.2.

Based on the actions performed by the staff associated with its review of SSAR Subsection 2.5.1.1.2 as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of regional geologic history and tectonic evolution in support of the CRN Site ESP application.

2.5.1.4.1.3 Regional Stratigraphy

In SSAR Section 2.5.1.1.3, the applicant discussed stratigraphy of the site region with a primary focus on rock units found in the Valley and Ridge physiographic province in which the site lies. The applicant stated that the site consists predominantly of a sequence of Paleozoic sedimentary rocks ranging in age from Lower Cambrian to Pennsylvanian comprising the Lower Cambrian Rome Formation; a thick, extensive Cambrian to Ordovician carbonate shelf sequence; a thin, laterally variable shelf sequence of Upper Ordovician to Lower Mississippian carbonate rocks and thin clastic units; and a Middle Mississippian to Pennsylvanian synorogenic clastic wedge.

The staff focused the review of SSAR Subsection 2.5.1.1.3 on the discussion of stratigraphic units in the Valley and Ridge physiographic province because the CRN Site lies in that province. Based on its review of information presented in SSAR Section 2.5.1.1.3 and literature cited by the applicant in Section 2.5 of the SSAR, as well as examination of core and outcrops of parts of the stratigraphic sequence at and around the CRN Site during the second site audit and the site visit, the staff concludes that the site is underlain predominately by a sequence of Paleozoic rocks containing both carbonate (i.e., limestone and dolomite) and clastic lithologies. The staff makes this conclusion because all existing data, including field observations of outcrops and core samples, strongly support the interpretation that the site is underlain by Paleozoic carbonate and clastic rock units.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.1.3, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of regional stratigraphy in support of the CRN Site ESP application.

2.5.1.4.1.4 Regional Tectonic Setting

In SSAR Subsection 2.5.1.1.4, the applicant discussed the tectonic setting of the site region, presenting information regarding subdivision of principal tectonic terranes and physiographic provinces; regional geophysical data; and distribution of seismicity and stress in the Eastern United States. Under SSAR Subsection 2.5.1.1.4.3, the applicant included discussions of the current stress regime in the Eastern United States and the distribution of seismicity in the ETSZ.

The staff focused its review of SSAR Subsection 2.5.1.1.4 on information related to the age of thrust faults in the Valley and Ridge province and the discussion of the ETSZ. The staff maintained this focus because the age of major thrust faults in the Valley and Ridge also reveal the age of faulting at the CRN Site. In addition, the site lies within the ETSZ, which makes understanding the occurrence of seismicity in the zone important in regard to potential seismic hazard for the site. Based on its review of information presented in SSAR Subsection 2.5.1.1.4 and literature cited by the applicant, the staff concludes that the age of major thrust faults in the site region and at the site is well-constrained to be Late Paleozoic (i.e., much older than Quaternary). The staff also concludes that seismicity in the ETSZ has been reasonably assessed in light of existing data with due consideration for different potential interpretations of pre-historic earthquake magnitudes in the ETSZ. The staff makes these conclusions because the age of the major thrust faults is clearly documented to be late Paleozoic, which indicates that the potential for these faults to pose a hazard for the CRN Site is negligible, and the applicant has considered all different potential interpretations related to characterization of seismicity in the ETSZ.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.1.4, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of regional tectonic setting in support of the CRN Site ESP application.

2.5.1.4.1.5 Regional Non-Seismic Geologic Hazards

In SSAR Section 2.5.1.1.5, the applicant discussed non-seismic geologic hazards in the site region, noting that carbonate rock dissolution and karst formation is the dominant non-seismic geologic hazard in the region. The applicant also noted that the CRN Site lies in an area of moderate susceptibility for and low incidence of landslides, while susceptibility for landslides in the surrounding site region ranges from high to moderate.

The NRC staff focused its review of SSAR Section 2.5.1.1.5 on information related to carbonate rock dissolution and karst formation because the applicant considers karst to be the primary non-seismic geologic hazard in the site region. Based on its review of information presented in SSAR Section 2.5.1.1.5 and literature cited by the applicant in Section 2.5 of the SSAR, and examination of karst features in outcrops and core samples during the second site audit and the site visit, the staff concludes that karst resulting from dissolution of carbonate rock units is the dominant non-seismic geologic hazard in the site region as well as at the site. The staff makes this conclusion because all existing data support the interpretation that karst is the primary hazard.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.1.5, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of regional non-seismic geologic hazards in support of the CRN Site ESP application.

2.5.1.4.2 Local Geology

The staff reviewed SSAR Section 2.5.1.2 which included information provided by the applicant on the following topics within 40 km (25 mi), 8 km (5 mi), and 1 km (0.6 mi) of the CRN Site (i.e., the site vicinity, site area, and site location respectively): physiography and geomorphic processes; geologic history; stratigraphy and lithology; structural geology; geologic hazards; site engineering geology; site groundwater conditions; tsunami and seiche hazards; and relational analysis. The staff particularly concentrated on discussions provided by the applicant related to shear-fracture zones and their association with Paleozoic thrust faults; hypogene karst; detection of voids using seismic reflection; field reconnaissance studies to assess the presence or absence of paleoliquefaction features related to earthquakes in the ETSZ; and current tectonic stresses that affect the state of stress in bedrock at the CRN Site.

2.5.1.4.2.1 Local Physiography and Geomorphic Processes

In SSAR Section 2.5.1.2.1, the applicant discussed physiography and geomorphic processes in the site vicinity and site area and at the site location. The staff focused its review of SSAR Subsection 2.5.1.2.1 on information related to Late Tertiary and Pleistocene geomorphic processes because they have the highest likelihood of affecting karst development in the site area and controlling the erosional dissection of terraces, which the applicant used to assess the presence or absence of surface deformation at the site and discussed in SSAR Subsection 2.5.3.2.5. Based on its review of information presented in SSAR Section 2.5.1.2.1 and literature cited by the applicant in the SSAR, the staff concludes that the applicant appropriately considered the potential effects of Late Tertiary and Pleistocene geomorphic processes on karst development and terrace dissection. The staff makes this conclusion because all data discussed by the applicant enabled the initial assessment of the potential effects of these processes.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.2.1, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of local physiography and geomorphic processes in support of the CRN Site ESP application.

2.5.1.4.2.2 Local Geologic History

In SSAR Subsection 2.5.1.2.2, the applicant described geologic history of the CRN Site vicinity in relation to the three primary Paleozoic orogenic events that affected the Appalachian orogenic belt (i.e., the Middle Ordovician Taconic orogeny, the Early Devonian to Mississippian Acadian/Neoacadian orogeny, and the Pennsylvanian to Permian Alleghanian orogeny). The applicant noted that the Alleghanian orogeny resulted in the physiographic and geomorphic expression of the Valley and Ridge foreland fold-and-thrust belt observed in the CRN Site vicinity. The applicant identified the Rome Formation as the basal stratigraphic unit overlying basement in the site vicinity, noting that sedimentary rocks of the Middle to Late Cambrian Conasauga Group overlie the Rome Formation and grade into predominantly carbonate rocks of the Late Cambrian to Early Ordovician Knox Group. The applicant stated that, following development of the Knox unconformity in the Middle Ordovician due to a sea level drop and subsequent erosion, a sea level rise resulted in continued carbonate deposition of the Middle Ordovician Chickamauga Group atop the Knox Group. The applicant noted that the Chickamauga Group dominates the stratigraphic sequence in the site area.

The staff focused its review of SSAR Subsection 2.5.1.2.2 on descriptions of the Alleghanian thrust faults, in particular the Copper Ridge thrust fault, and stratigraphic units that occur in the site vicinity because certain thrust faults and all of the stratigraphic units also occur at the CRN Site. Based on its review of the information presented in SSAR Section 2.5.1.2.2 and literature cited by the applicant in the SSAR, as well as examination of stratigraphic units in core samples and outcrops and a thrust fault in core samples during the second site audit and the site visit, the staff concludes that the Copper Ridge thrust lies immediately south of the CRN Site and the stratigraphic units described for the site vicinity exist in the subsurface at the CRN Site. The staff makes this conclusion because all existing data document the existence of thrust faults and verify the stratigraphic sequence in the site vicinity and site area and at the site location.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.2.2, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of local geologic history in support of the CRN Site ESP application.

2.5.1.4.2.3 Local Stratigraphy and Lithology

In SSAR Subsection 2.5.1.2.3, the applicant discussed stratigraphy and lithology of the CRN Site, including information on stratigraphic nomenclature and the evaluation of karst. The applicant cross-referenced SSAR Sections 2.5.3 and 2.5.4, respectively, regarding details for Quaternary terrace deposits and unconsolidated soils and fill. Regarding stratigraphic units, the applicant stated that 76 geotechnical boreholes drilled at the CRN Site encountered the following sedimentary sequence: 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. SER Figure 2.5.1-2 shows the stratigraphic units that underlie the CRN Site, and the applicant described these units in SSAR Subsection 2.5.1.2.3.3.

Regarding the evaluation of karst, in SSAR Subsection 2.5.1.2.3.4, the applicant stated that the largest and highest frequency of dissolution cavities at the CRN Site occur in the Rockdell Formation and the Eidson Member of the Lincolnshire Formation of the Chickamauga Group. The applicant noted that these two stratigraphic units also contain the greatest thickness of pure limestone compared to other Chickamauga Group strata at the site.

The staff focused its review of SSAR Subsection 2.5.1.2.3 on the applicant's description of stratigraphic units in the Chickamauga Group and the evaluation of karst in the Chickamauga Group because Chickamauga formations underlie the CRN Site and will comprise the foundation material for the proposed CRN Site facility. Based on its review of information presented in SSAR Section 2.5.1.2.3 and literature cited by the applicant in the SSAR, as well as examination of stratigraphic units in core samples and outcrops during the second site audit and the site visit, the staff concludes that the applicant appropriately described stratigraphic units and karst in the formations comprising the Chickamauga Group. The staff makes this conclusion because all existing data confirm the applicant's descriptions of the stratigraphic units and karst features that occur in the Chickamauga Group.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.2.3, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of local stratigraphy and lithology in support of the CRN Site ESP application.

2.5.1.4.2.4 Local Structural Geology

In SSAR Subsection 2.5.1.2.4, the applicant discussed structural geology of the CRN Site vicinity, site area, and site, including macroscopic scale folds and 12 individual faults in the site vicinity; macroscopic scale faults in the site area (i.e., the Whiteoak Mountain, Copper Ridge, and Chestnut Ridge faults) and seismic reflection and refraction data; mesoscopic scale structures in the site vicinity and at the site location (i.e., folds, fractures, and shear-fracture zones); and Alleghanian foreland fold-and-thrust structures in the site area. The applicant stated that geologic structures in the site vicinity and site area and at the site location resulted from the position of the site in the foreland fold-and-thrust belt comprising the Valley and Ridge province.

Regarding the macroscopic scale folds and faults in the site vicinity discussed in SSAR Section 2.5.1.2.4.1, the applicant provided information documenting that they are Late Paleozoic in age. Concerning the macroscopic scale faults in the site area discussed in SSAR

Section 2.5.1.2.4.2, the applicant noted that the Whiteoak Mountain, Copper Ridge, and Chestnut Ridge faults are also Late Paleozoic in age. The applicant stated that materials indicative of fault displacement (i.e., fault gouge, breccia, and cataclasite) occur in association with the Copper Creek fault at the CRN Site and in the site area, and that $^{40}Ar/^{39}Ar$ age dates on gouge samples collected from the fault in northeastern Tennessee gave an age of 279.5 +/-11.3 Ma.

In SSAR Subsection 2.5.1.2.4.3, the applicant described mesoscopic scale structures in the site vicinity and at the site, including folds, bedding, fractures, and shear-fracture zones. The applicant stated that the descriptions of mesoscopic structures include information derived for the CRN Site from geologic field investigations, boreholes, and seismic reflection and refraction surveys. The applicant noted that the shear-fracture zones contain both non-tectonic diagenetic and tectonic stylolites indicative of a complex strain history.

The staff focused its review of SSAR Subsection 2.5.1.2.4 on the applicant's discussion of shear-fracture zones and the relationship between these zones and the Late Paleozoic (i.e., Alleghanian) Whiteoak Mountain and Copper Creek faults. The staff maintained this focus because it is important to understand the origin of shear-fracture zones to clarify the relationship between Alleghanian thrust faults and the zones and to ensure that the zones do not represent Quaternary tectonic deformation features. In eRAI-8991 (RAI No. 5) (NRC, 2017 – ADAMS Accession No. ML17213A971), Questions 02.05.01-04(a) and (b), staff asked the applicant to clarify the relationship between diagenetic and tectonic stylolites in the shear-fracture zones in regard to timing of development of the stylolites. In Question 02.05.01-04(d), staff asked the applicant to explain the relationship between the shear-fracture zones, the Whiteoak Mountain and Copper Ridge faults, and the site tectonic setting, to specify the timing of formation of the faults and the shear-fracture zones. In Question 02.05.01-04(c), staff asked the applicant to provide a justification for why the applicant considered a "shear zone" in the excavation for the CRBRP, previously mapped and described by Drakulich (1984), to be equivalent to the "shear-fracture zones" found in the subsurface at the CRN Site location.

The applicant provided responses to eRAI-8991 (RAI No. 5), Questions 02.05.01-04(a) through (d), in Response Letter CNL-17-114 dated October 19, 2017 (TVA, 2017 – ADAMS Accession No. ML17295A001). In Revision 1 of the SSAR, the applicant incorporated information cited in the responses to eRAI-8991 (RAI No. 5), Questions 02.05.01-04(a), (b), and (d), into SSAR Subsection 2.5.1.2.4.3.4 to clarify that the shear-fracture zones contain both non-tectonic diagenetic stylolites oriented subparallel to bedding and tectonic stylolites oriented at higher angles to bedding, neither of which reflect pressure solution effects or deformation younger than Late Paleozoic. The applicant explained that the tectonic stylolites resulted from pressure solution related to Late Paleozoic Alleghanian thrust faulting, and that the non-tectonic stylolites formed earlier due to diagenetic pressure solution. The applicant stated that the tectonic and non-tectonic stylolites developed at distinctly different times in two different strain regimes. The applicant pointed out that the abundance of pressure solution features and the paucity of evidence for mechanical grain size reduction suggest that the shear-fracture zones mainly accommodated strain by pressure solution resulting from both non-tectonic and tectonic effects, but with limited cataclastic deformation during the tectonic event (i.e., Alleghanian thrust faulting). This tectonic event included emplacement of the Whiteoak Mountain and Copper Ridge thrust faults in the site area. The applicant also incorporated information cited in the response to eRAI-8991 (RAI No. 5), Questions 02.05.01-04(c), into SSAR Subsection 2.5.1.2.4.3.4 to clarify that the "shear zone" previously mapped and described by Drakulich (1984) in the CRBRP excavation, which has been filled such that the "shear zone" is no longer visible, likely has an origin similar to shear-fracture zones observed in boreholes at the CRN

Site. The applicant stated that the description of the "shear zone" clearly reflects certain attributes of the shear-fracture zones found at the CRN Site.

Based on its review of information presented in SSAR Section 2.5.1.2.4, literature cited by the applicant in the SSAR, and the applicant's responses to eRAI-8991 (RAI No. 5), Questions 02.05.01-04(a) through (d), as well as examination of a shear-fracture zone and gouge related to the Copper Ridge fault in core during the second site audit and the site visit, the staff concludes that the applicant adequately described local structural geology, including the development of shear-fracture zones and the timing of development of the zones in relation to Late Paleozoic thrust faulting. The staff makes this conclusion because information provided by the applicant supports the interpretation that the shear-fracture zones contain both diagenetic, bedding-parallel stylolites resulting from pressure solution due to lithostatic loading during burial and tectonic stylolites oriented at high angles to bedding resulting from pressure solution due to Alleghanian thrust faulting. This interpretation suggests the bedding-parallel diagenetic stylolites formed under a vertical maximum compressive stress that did not result in cataclasis and the stylolties oriented at high angles to bedding developed under a horizontal maximum principal compressive stress, which possibly resulted in localized minor cataclasis. The information provided by the applicant reinforced the concept that the stylolites formed at two different times and in two distinctly different strain regimes. The staff's direct examination of a shear-fracture zone and the Copper Ridge fault in core samples during the second site audit and the site visit enabled staff to confirm the applicant's interpretations of these structures and make the conclusion as stated. Accordingly, the staff considers eRAI-8991 (RAI No. 5), Questions 02.05.01-04(a) through (d), to be resolved.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.2.4, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of local structural geology in support of the CRN Site ESP application.

2.5.1.4.2.5 Local Geologic Hazards

In SSAR Subsection 2.5.1.2.5, the applicant discussed geologic hazards for the CRN Site vicinity, site area, and site location, including karst hazards, other local geologic hazards, and evaluation of local geologic hazards. The applicant stated that karst features and active karst processes are common throughout the site vicinity and karst dissolution of carbonate bedrock, which underlies all proposed plant facilities, is the primary geologic hazard of concern for the CRN Site.

The staff focused its review of SSAR Subsection 2.5.1.2.5 on the potential for hypogene karst systems at the CRN Site and understanding the applicant's technical basis for not using seismic reflection data to determine the presence or absence of dissolution voids at the site. The staff maintained the focus on hypogene karst because Nativ (1996) and Nativ et al. (1997) documented evidence of deep groundwater flow at the ORR based on the presence of brines with geochemical signatures indicative of partial recharge by recent waters at depths of more than 91 m (300 ft), as well as the occurrence of contaminants at a depth of approximately 268 m (880 ft). In eRAI-8991 (RAI No. 5), Question 02.05.01-05(b), staff asked the applicant to discuss the potential for the occurrence of hypogene karst systems at the CRN Site. In addition, staff sought to understand why seismic reflection data were generally not successful at detecting voids, as reported by the applicant based on Doll et al. (2005), who evaluated seismic reflection data at the ORR. In eRAI-8991 (RAI No. 5), Question 02.05.01-03, staff asked the applicant to explain why seismic reflection data could not be used to determine the presence or absence of subsurface dissolution voids at the CRN Site.

The applicant provided a response to eRAI-8991 (RAI No. 5), Question 02.05.01-05(b), in Response Letter CNL-77-100 dated September 29, 2017 (TVA, 2017 – ADAMS Accession No. ML17275A215). In Revision 1 of the SSAR, the applicant incorporated information cited in the response to eRAI-8991 (RAI No. 5), Question 02.05.01-05b into SSAR Subsection 2.5.1.2.5.1 to clarify that direct evidence of hypogene dissolution is not documented at the CRN Site or within the ORR. The applicant noted that most evidence is consistent with dissolution by epigenetic processes in the vadose and phreatic zones. The applicant stated that this evidence includes a decrease in frequency of fractures and dissolution cavities with depth in boreholes; phreatic passage geometry and morphology of known caves and solution conduits within the ORR; and a lack of secondary minerals characteristic of hypogene processes. The applicant noted further that a lack of definitive evidence for present-day active hypogene karst development does not indicate hypogene processes were inactive in the past or could not occur in the future.

The applicant provided a response to eRAI-8991 (RAI No. 5), Question 02.05.01-03, in Response Letter CNL-17-100 dated September 29, 2017. In Revision 1 of the SSAR, the applicant incorporated information cited in the response to eRAI-8991 (RAI No. 5), Question 02.05.01-03 into SSAR Subsection 2.5.1.2.5.1 to clarify that seismic reflection data, used successfully to detect geologic structures, did not readily detect voids because characteristics of the karst features (i.e., steeply-dipping boundary surfaces and rough and laterally discontinuous interfaces) directly affected quality of the stacked reflection profiles. In addition, in SSAR Subsection 2.5.1.2.4.2.1, "Geophysical Data," the applicant stated that the primary objectives of the seismic reflection surveys, which were achieved, were to interpret the contact between the Knox Group and the overlying stratigraphic units of Chickamauga Group; interpret dip of bedding between boreholes; and identify potential subsurface faults beneath the survey lines. The applicant stated that, for a future COL application, detailed geologic mapping and a subsurface exploration program will be implemented to characterize the excavations for safety-related structures at the CRN Site in regard to the presence or absence of karst features in and below the floor of those excavations. These activities are captured by Permit Condition 1 as discussed in SER Section 2.5.3.5.

Based on its review of information presented in SSAR Section 2.5.1.2.5, literature cited by the applicant in the SSAR, and the applicant's responses to eRAI-8991 (RAI No. 5), Questions 02.05.01-05(b) and 02.05.01-03, the staff concludes that the applicant clarified the lack of evidence for hypogene dissolution at the CRN Site and on the ORR, as well as clearly explained why seismic reflection investigations likely cannot be used to detect the presence of dissolution voids at the CRN Site. The staff makes the conclusion regarding hypogene dissolution because, based on existing data, no unequivocal evidence exists for the presence of hypogene karst (i.e., frequency of subsurface fractures and dissolution cavities decrease with depth based on borehole data; passage morphology of caves and solution conduits within the ORR exhibit characteristics of phreatic dissolution; and secondary minerals characteristic of hypogene processes are not found). Likewise, staff makes the conclusion regarding applicability of seismic reflection surveys to detect subsurface voids because the results of studies conducted at the ORR indicate physical characteristics of dissolution voids unavoidably affect quality of the survey results. Accordingly, the staff considers eRAI-8991 (RAI No. 5), Questions 02.05.01-05(b) and 02.05.01-03, to be resolved.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.2.5, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of local geologic hazards in support of the CRN Site ESP application.

2.5.1.4.2.6 Site Engineering Geology

In SSAR Subsection 2.5.1.2.6, the applicant discussed geologic features of bedrock units beneath the power block area at the CRN Site, noting that the Knox and Chickamauga Groups comprise the bedrock units beneath the site. The applicant presented a summary of subsurface conditions and then discussed rock mass characterization for each stratigraphic unit beneath the site, fracture zones, deformational zones (i.e., shear-fracture zones), karst features, prior earthquake effects, residual stresses in bedrock, effects of human activities, construction groundwater control, and unforeseen geologic conditions.

The staff focused its review of SSAR Subsection 2.5.1.2.6 on the applicant's investigation of potential paleoliquefaction features within the CRN Site vicinity and the discussion of current tectonic forces that might affect the site. The staff maintained the focus on potential paleoliquefaction features because the applicant initially reported primarily on reconnaissance investigations for such features conducted within 80.5 km (50 mi) of the CRN Site and did not include details regarding investigations performed within the 40-km (25-mi) radius of the CRN Site (i.e., the site vicinity). In eRAI-8991 (RAI No. 5), Question 02.05.01-01, staff asked the applicant to discuss the evaluation of potential paleoliquefaction features within the site vicinity. The staff particularly focused on the need for any additional information collected by the applicant during field reconnaissance studies conducted for the CRN Site along the Clinch River arm of the Watts Bar and Tellico Reservoirs. The applicant examined Pleistocene and Holocene (i.e., Quaternary) fluvial terrace deposits in those locations for definitive evidence of paleoliquefaction related to Quaternary seismic events in the ETSZ. In addition, staff sought to better understand the applicant's interpretation of current tectonic forces in the area because the applicant initially discussed only previous tectonic forces and weight of the rock (i.e., overburden) for assessing the natural state of stress at the site. In RAI No. 5, Question 02.05.01-02, staff asked the applicant to discuss current tectonic forces and how these forces might affect residual stress in bedrock at the site.

The applicant provided a response to eRAI-8991 (RAI No. 5), Question 02.05.01-01, in Response Letter CNL-17-099 dated September 15, 2017 (TVA, 2017 – ADAMS Accession No. ML17261A062). In Revision 1 of the SSAR, the applicant incorporated information cited in the response to eRAI-8991 (RAI No. 5), Question 02.05.01-01, into SSAR Subsection 2.5.1.2.6.6. In the response, the applicant explained its conclusions derived from the paleoseismic reconnaissance investigations performed for studying Pleistocene and Holocene fluvial terrace deposits along the shorelines of the Watts Bar and Tellico Reservoirs. The applicant stated that the reconnaissance did not reveal any evidence for paleoseismic features around these two reservoirs and cross-referenced SSAR Subsections 2.5.3.1.2 and 2.5.3.2 for details supporting this statement.

The applicant also provided a response to eRAI-8991 (RAI No. 5), Question 02.05.01-02, in Response Letter CNL-17-099 dated September 15, 2017. In Revision 1 of the SSAR, the applicant incorporated information cited in the response to eRAI-8991 (RAI No. 5), Question 02.05.01-02, into SSAR Subsection 2.5.1.2.6.7. In its response, the applicant discussed the current tectonic forces that likely influence the state of stress in rock units at the CRN Site in addition to previous tectonic forces and weight of the rock. The applicant explained that upper mantle buoyancy forces combined with ridge-push forces from the Mid-Atlantic Ridge provide a viable explanation for the orientation of the current regional stress field in the site region and, consequently, the current tectonic forces that influence state of stress in bedrock at the CRN Site. The applicant cited Biryol et al. (2016) for an explanation of upper mantle buoyance forces, which generate vertical forces, and Zoback and Zoback (1989) for an explanation of ridge-push forces, which produce horizontal forces.

Based on its review of information presented in SSAR Section 2.5.1.2.6, cross-referenced SSAR Subsections 2.5.3.1.2 and 2.5.3.2, literature cited by the applicant in the SSAR, and the applicant's responses to eRAI-8991 (RAI No. 5), Questions 02.05.01-01 and 02.05.01-02, the staff makes the following two conclusions: (a) the applicant provided an adequate discussion of the results of the field reconnaissance studies conducted for the CRN Site along the Clinch River arm of the Watts Bar and Tellico Reservoirs to search for paleoliquefaction features, and (b) the applicant provided an adequate discussion regarding interpretations related to current tectonic forces that might affect residual stress in bedrock at the site. The staff makes the conclusion regarding the field reconnaissance studies because, in cross-referenced SSAR Subsections 2.5.3.1.2 and 2.5.3.2, the applicant documented the logic for concluding that no field data clearly indicate the presence of paleoseismic features related to earthquakes in the ETSZ. The staff makes the conclusion regarding current tectonic forces because the applicant presented information to explain the interpretation that both vertical and horizontal forces influence the state of stress in rock units at the CRN Site. Accordingly, the staff considers eRAI-8991 (RAI No. 5), Questions 02.05.01-01 and 02.05.01-02, to be resolved.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.2.5, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of local geologic hazards in support of the CRN Site ESP application.

2.5.1.4.2.7 Site Groundwater Conditions and Tsunami and Seiche Hazards

In SSAR Subsection 2.5.1.2.7, the applicant cross-referenced SSAR Section 2.4.12 for a detailed discussion of groundwater at the CRN Site. In SSAR Subsection 2.5.1.2.8, the applicant cross-referenced SSAR Section 2.4.6 for a detailed discussion of potential tsunami and seiche hazards. The staff evaluation of SSAR Sections 2.4.6 and 2.4.12 are covered in Section 2.4 of the SER.

2.5.1.4.2.8 Relational Analysis

In SSAR Subsection 2.5.1.2.9, the applicant discussed the relationships between the proposed CRN Site and the CRBRP site regarding stratigraphic units, structural geology, and karst features. The applicant noted that the stratigraphic units in the CRBRP excavation and the northernmost part of the proposed CRN Site power block area (i.e., Location B as shown in the cross-section of SER Figure 2.5.1-2) are identical. In addition, regarding karst features based on quality and compatibility of data derived from both boring programs, the applicant determined that the two data sets can be combined for analysis of subsurface cavities at the CRN Site. The applicant stated that results of the geologic mapping and subsurface investigations performed for the CRBRP site can be used to enhance understanding of the geologic characteristics of foundation rock units at the CRN Site and cross-referenced SSAR Subsection 2.5.1.2.4 for details about local structural geology.

The staff focused its review of SSAR Subsection 2.5.1.2.9 on the applicant's comparison of data from the CRN Site with that from the CRBRP site because the applicant used the data from the CRBRP site to enhance the understanding of geologic characteristics at the CRN Site. Based on its review of information presented in SSAR Section 2.5.1.2.9 and literature cited by the applicant in the SSAR, particularly the report prepared by Drakulich (1984) presenting data and conclusions derived from his geologic mapping of foundation units, geologic structures, and karst features in the CRBRP excavation, the staff concludes that the applicant's statement regarding similarities between the two sites is appropriate and the data derived for the CRBRP site can be used to enhance understanding of the geologic characteristics of foundation rock units at the CRN Site. The staff makes this conclusion because the detailed descriptions provided for both sites clearly illustrate the similarities.

Based on the actions performed by staff associated with its review of SSAR Subsection 2.5.1.2.9, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of the similarities between the proposed CRN Site and the CRBRP site in support of the CRN ESP application.

2.5.1.5 Permit Conditions

There are no Permit Conditions related to SSAR Section 2.5.1. However, in SER Section 2.5.3.5, the staff identified a Permit Condition related to detailed geologic mapping of excavations for safety-related engineered structures at the CRN Site as the responsibility of the COL applicant. This Permit Condition relates to the assessment of both tectonic and non-tectonic (i.e., karst-induced collapse and subsidence) surface deformation features at the site.

2.5.1.6 Conclusions

As documented in Sections 2.5.1.1 through 2.5.1.4 of this SER, the NRC staff reviewed and evaluated the detailed geologic characterization information submitted by the applicant in SSAR Section 2.5.1 of the CRN Site ESP application. The review and evaluation process, which included direct examination by staff of geologic characteristics in core and outcrops during site audits and a field visit, provided a sound basis for staff to confirm that no tectonic features occur in the site region, site vicinity, site area, or at the site location with a potential for adversely affecting suitability and safety of the CRN Site (i.e., no data suggest the presence of tectonic features of Quaternary age). These activities also enabled staff to confirm that the potential for development of non-tectonic karst features resulting from dissolution of subsurface carbonate rocks is the primary geologic hazard at the site. The staff consider the applicant's plan to geologically map future excavations for safety-related engineered structures in detail to be necessary for documenting the presence or absence of undetected dissolution features; confirming or refining interpretations of subsurface geology initially determined from borehole data; and verifying the absence of active tectonic faults. The mapping is identified as a Permit Condition in SER Section 2.5.3.5, as stated above.

The staff concludes that the applicant identified and appropriately characterized all seismic sources of potential significance for determining the SSE for the CRN Site in accordance with regulatory requirements stated in 10 CFR 100.23(c) and guidance provided in RG 1.208 and Section 2.5.1 of NUREG–0800. In addition, based on results of the investigations discussed in SSAR Section 2.5.1, the staff concludes that the applicant appropriately characterized the geology of the site region (including physiography, topography, and geomorphic processes; fluvial processes; karst processes and occurrence; geologic history and tectonic evolution; stratigraphy; tectonic setting; geophysical data; distribution of seismicity and stress in the Eastern United States; and non-seismic geologic hazards) as well as the local geology of the site vicinity, site area and site location (including physiography and geomorphic processes, geologic history, stratigraphy and lithology, karst evaluation, structural geology, geologic hazards, and site engineering geology).

The staff further concludes that the applicant appropriately assessed the potential for detrimental effects of human activity, including natural gas wells, coal mines, and quarries within 8 km (5 mi) of the CRN Site. The applicant documented a lack of any of these activities in the site area, and the staff concludes that negligible potential exists for detrimental effects at the site location as a result of human activity.

Based on results of the review and evaluation of the detailed information presented in SSAR Section 2.5.1, supplemented by knowledge gained through direct examination of geologic characteristics in core and outcrops during site audits and a site visit, staff concludes that the applicant provided a thorough and accurate description of the geologic characteristics of the CRN Site region, site vicinity, site area and site location in full compliance with regulatory requirements stated in 10 CFR 52.17(a)(1)(vi) and 10 CFR 100.23(c) and in accordance with guidance in RG 1.208.