2.0 SITE CHARACTERISTICS

2.5.3 Surface Deformation

2.5.3.1 Introduction

The applicant's Site Safety Analyis Report (SSAR), Revision 1 (TVA, 2017 – ADAMS Accession No. ML18003A374), Section 2.5.3, "Surface Deformation," evaluates the potential for tectonic and non-tectonic surface deformation at the Clinch River Nuclear (CRN) Site. The applicant stated that SSAR Section 2.5.3 demonstrates compliance with regulatory requirements in Title 10 of the *Code of Federal Regulations* (10 CFR) 100.23, "Geologic and seismic siting criteria," by providing information on the following topics: geological, seismological, and geophysical investigations; geologic evidence, or absence of evidence, for surface deformation; correlation of earthquakes with capable tectonic sources; ages of most recent deformation; relationship of tectonic structures in the site area to regional tectonic sources; characterization of capable tectonic sources; designation of zones of Quaternary deformation in the site region; and the potential for tectonic or non-tectonic deformation at the site. Based on this information, the applicant concluded that there are no faults within the site vicinity that can generate both tectonic surface deformation and vibratory ground motion, which the applicant indicated would represent a capable fault (i.e., a capable tectonic source) in accordance with the definition in Regulatory Guide (RG) 1.208, Appendix A, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion", (NRC, 2007 - ADAMS Accession No. ML070310619). The applicant reported that the primary non-tectonic surface deformation hazard at the CRN Site is karst dissolution.

2.5.3.2 Summary of Application

The applicant developed SSAR Section 2.5.3 based on the review of existing information in the following primary sources related to the potential for tectonic and non-tectonic surface deformation at the CRN Site: geologic maps published by the United States Geological Survey (USGS), state geological surveys, and other researchers; literature published in journals and field trip guidebooks, with emphasis on materials published since the 1986 studies conducted by Electric Power Research Institute, including instrumental and historical seismicity data; reports on previous site investigations for the Clinch River Breeder Reactor Project (CRBRP); and the Central and Eastern United States Seismic Source Characterization (CEUS SSC) model presented in NUREG-2115, "Central and Eastern United States Seismic Source Characterization for Nuclear Facilities", (NRC, 2012 - ADAMS Accession No. ML12048A776). In addition to the review of this existing information, the applicant also performed the following activities to further assess the potential for tectonic and non-tectonic surface deformation within the site area: examination and interpretation of aerial photographs, LiDAR (Light Detection and Ranging), and remote sensing imagery; geologic field reconnaissance; analysis of terraces to assess the Eastern Tennessee Seismic Zone (ETSZ); and collection of subsurface and geophysical data from boreholes. Sections 2.5.3.2.1 through 2.5.3.2.8 of this safety evaluation report (SER) summarize the information described by the applicant in SSAR Section 2.5.3.

2.5.3.2.1 Geological, Seismological and Geophysical Investigations

In SSAR Section 2.5.3.1, the applicant describes the available information compiled to address the potential for tectonic and non-tectonic surface deformation at the CRN Site. Primary sources include: geologic mapping published by the Tennessee Division of Geology; previous geologic studies of the site and site vicinity; and unpublished geologic mapping studies. Several other detailed geologic and hydrogeologic investigations from the Oak Ridge Reservation (ORR) and the Melton Hill Dam included the CRN Site and vicinity within the scope. The applicant incorporated data from the previous CRBRP investigations relevant to ground deformation, including seismic and non-seismic hazard data from regional studies, into the CRN Site Early Site Permit (ESP) Application.

Recent studies of Quaternary terrace deposits surrounding the Douglas Reservoir in eastern Tennessee, approximately 80 km (50 mi) from the CRN Site, evaluated potential evidence of Quaternary surface deformation and paleoliquefaction features associated with the ETSZ (Hatcher, Vaughn and Obermeier, 2012; Warrell et al., 2012; Warrell, 2013; Howard et al., 2011). The applicant stated that it could not definitively confirm or rule out a seismic origin for many of the observed features in these studies and that alternate hypotheses, such as pedogenic processes, karst collapse, and slope failure, could also explain their origin. The applicant referred to SSAR Subsection 2.5.2.2.6.1.3 for a discussion of the ETSZ maximum magnitude (Mmax) sensitivity studies.

In addition to existing data, the applicant conducted the following investigations to assess the potential for tectonic and non-tectonic surface deformation in the 8-km (5-mi) site area:

- Interpretation of aerial photography
- Geologic field reconnaissance mapping
- Detailed geomorphic analysis of high-resolution LiDAR digital elevation data acquired during this investigation
- Subsurface borehole and downhole shear wave velocity investigation
- Analysis and interpretation of seismic reflection data
- Review of the CEUS SSC (NUREG−2115)

2.5.3.2.2 Geologic Evidence, or Absence of Evidence, for Surface Deformation

SSAR Section 2.5.3.2 addresses the presence or absence of evidence for tectonic and non-tectonic surface deformation in the site vicinity and site area. The SSAR and the following sections in this SER specifically address late Paleozoic (360 to 252 Ma) bedrock faults, shear-fracture zones at the CRN Site, carbonate dissolution features (karst), slope failure, longitudinal terrace profiles along the Clinch River, and proposed Quaternary (2.6 Ma to present) deformation features along the Douglas Reservoir.

2.5.3.2.2.1 Bedrock Faults

In SSAR Subsection 2.5.3.2.1, the applicant stated that the CRN Site is between the Whiteoak Mountain and Copper Creek thrust faults. SSAR Subsections 2.5.1.1 and 2.5.1.2 discuss the evidence suggesting that bedrock thrust faults in the Valley and Ridge were active during the late Paleozoic Alleghanian orogeny. The applicant summarized the geochronologic analyses performed on fault gouge from the Copper Creek fault that estimated ages of 290 to 279 Ma. The applicant also noted that Carboniferous (359 to 299 Ma) strata are the youngest offset by the Valley and Ridge faults and that Mesozoic (252 to 66 Ma) diabase dikes cross-cut Valley and Ridge structures without offset suggesting that offset by the Valley and Ridge structures is not younger than the late Paleozoic.

2.5.3.2.2.2 Shear-Fracture Zones

SSAR Subsection 2.5.3.2.2 refers to previous discussions in SSAR Section 2.5.1.2 related to the shear-fracture zones at the CRN Site. The applicant observed the shear-fracture zone in 39 boreholes from the CRBRP investigations and 18 boreholes from the CRN Site investigations. The applicant identified several zones in rock core samples from the current subsurface investigation and the CRBRP investigation and noted that the average thickness of the shear-fracture zone is about 10.7 m (35 ft). The CRBRP investigation reported a surface exposure of the shear-fracture zone in the northeastern portion of the site. As observed in rock core samples, the applicant characterized the shear-fracture zones as a zone of interbed slippage on the order of inches with no demonstrable stratigraphic offset and notable for the combination of slickensides, calcite veins, and segments no greater than 0.3 m (1 ft) that are either severely warped or brecciated (PMC, 1982). SSAR Subsection 2.5.1.2.4.3.4 provides additional description of the shear-fracture zones, including the attributes used to classify the shear-fracture zones.

2.5.3.2.2.3 Karst

SSAR Subsection 2.5.3.2.3 discusses carbonate dissolution features at the CRN Site from the perspective of surface deformation. The applicant evaluated newly acquired LiDAR data for karst features within the site area and observed that all stratigraphic units underlying the site are to some degree calcareous and contain karst features. However, the applicant also noted that cavities are most frequent near the ground surface and decrease in frequency with increasing depth in the boreholes. Based on borehole data, a site karst model, and an understanding of the origin and nature of these cavities, the applicant suggested that cavities might be present in carbonate beds projected downdip toward the excavations and below the base of the planned excavations. SSAR Subsection 2.5.1.2.5.1 provides a more detailed evaluation of karst.

The local lithology of relatively pure carbonate rocks, such as the Knox Group dolomites, and the more pure limestones of the Chickamauga and Conasauga Groups, controls the occurrence of karst depressions. The applicant identified a total of 2,797 karst-related surface features within the 8-km (5-mi) site area during the CRBRP and CRN Site ESP investigations, including large funnel- and dish-shaped sinkholes and small holes in the ground. SER Figure 2.5.3-1 (SSAR Figure 2.5.1-47) shows the locations of the karst features in the site area. The applicant identified 24 caves in the karst inventory of the site area, all of which formed in the Copper Ridge Dolomite, Chepultepec Dolomite, or Maynardville Limestone. Within the 0.6-mi (1 km) site radius, the applicant identified two major sinkhole clusters, one between the Kingsport Formation and Mascot Dolomite in the Knox Group, and the other in the Witten Formation of the Chickamauga Group. SSAR Section 2.5.1.2.5.1 provides additional information on karst hazards in the site area.

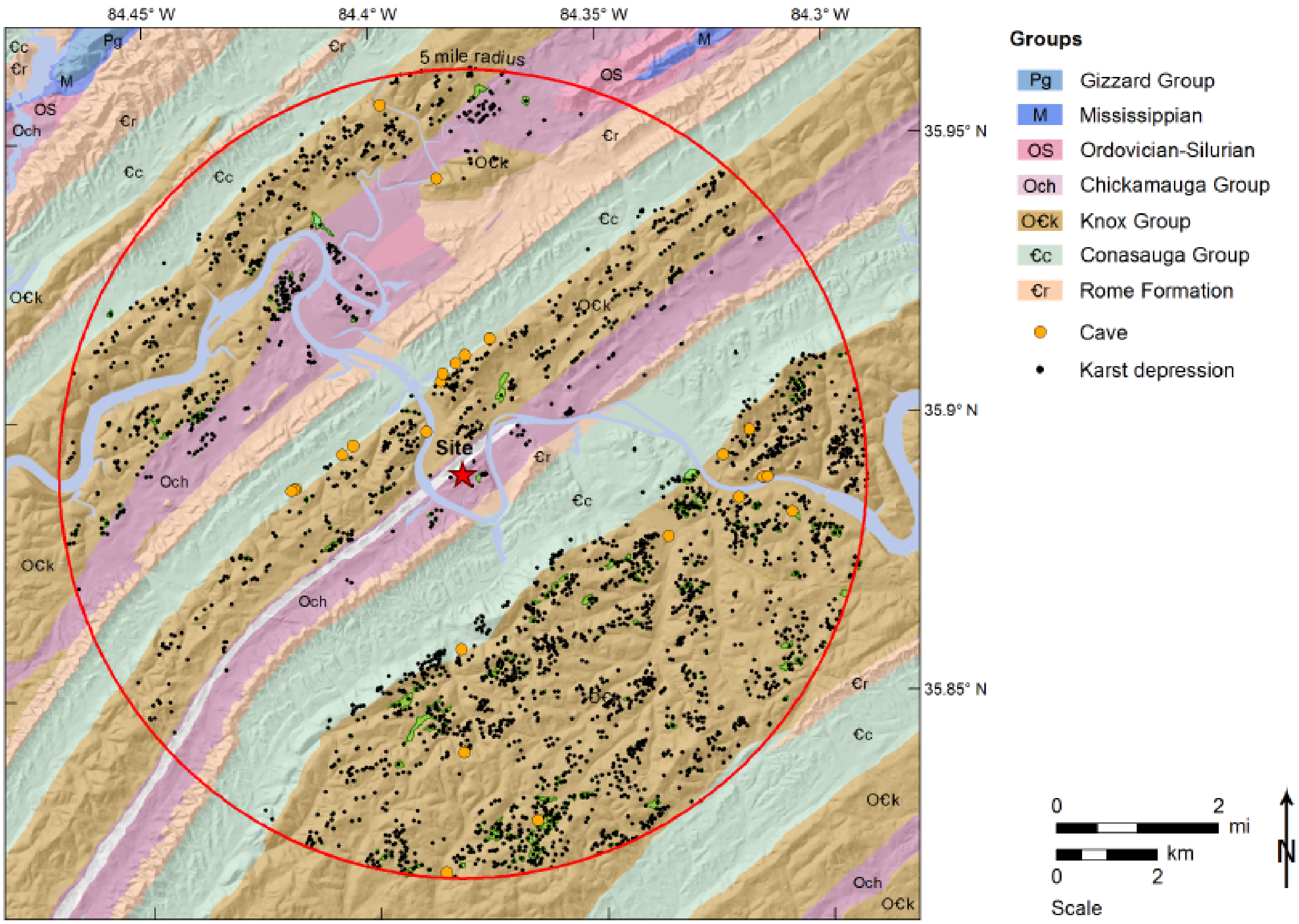

Figure 2.5.3-1: Distribution of Mapped Karst Features in the CRN Site Area (Reproduced from SSAR Figure 2.5.1-47)

2.5.3.2.2.4 Slope Failure

In SSAR Subsection 2.5.3.2.4 the applicant summarized the site investigations for slope failure and reported that there are no existing landslides or other slump-related hazards in the site location.

2.5.3.2.2.5 Evaluation of the Presence or Absence of Surface Deformation along the Clinch River Arm of the Watts Bar Reservoir

SSAR Subsection 2.5.3.2.5 evaluates potential surface deformation features through a detailed geomorphic investigation supplemented by geologic field reconnaissance along fluvial terraces. The applicant used longitudinal stream and terrace profiles to identify any potential irregularities that could be associated with reactivation of faults and possible surface deformation. The applicant characterized the youngest geologic units found in the site vicinity, Quaternary deposits, and discussed the delineation of the river terraces.

In SSAR Subsection 2.5.3.2.5.1, the applicant mapped Holocene (11,700 yrs to present) through Pleistocene (2.6 Ma to 11,700 yrs) alluvial terrace deposits along larger tributary valleys in the site area and delineated terraces along the Clinch River using high-resolution LiDAR digital elevation data. The applicant summarized the observations made during field reconnaissance, noting differences in soil development between the Holocene and Pleistocene terraces. The applicant used geomorphology and relative topographic position to assign levels to Holocene terraces representing the historical floodplain to the highest and oldest terrace level.

In SSAR Subsection 2.5.3.2.5.2 the applicant reported that the history of incision recorded in the Clinch River terraces dates back to the early Pleistocene (2.6 Ma) and possibly into the Tertiary (5.3 to 2.6 Ma). The applicant developed baseline longitudinal profiles to represent the modern Clinch River prior to the construction of the Watts Bar Dam and determined terrace elevations from LiDAR digital elevation data projected onto the baseline. There is limited absolute age control available; therefore, the applicant used regional terrace studies and terrace ages from analogous rivers to estimate the Clinch River terrace ages. The applicant used morphological correlation and longitudinal profiling to determine the oldest Holocene-age terrace (Qht3) and noted that the oldest and highest terraces in the site area, Qpt5 and Qpt6, are at least 200 thousand years old. SSAR Figure 2.5.3-4 shows the longitudinal profiles of the modern Clinch River baseline and terraces Qht1 through Qpt6. The applicant evaluated longitudinal profiles of terrace levels for irregularities that could be associated with repeated fault surface rupture, noting that repeated thrust faulting and relative uplift would result in increased incision and terrace formation in the hanging wall of the faults. The applicant concluded that the consistent number of terraces levels with similar longitudinal profile slopes correlated across the site area indicate the absence of discernible Quaternary displacement on the Alleghanian thrust faults in the site area.

SSAR Subsection 2.5.3.2.5.3 discusses evidence for Quaternary surface faulting in the site area. The applicant examined Pleistocene terrace surfaces which directly overlie the mapped trace of faults and longitudinal terrace profiles for irregularities suggestive of repeated fault displacements. The applicant reported that fluvial terraces overlie the five mapped Alleghanian thrust faults and the projected trace of the shear-fracture zone at the CRN Site. The applicant concluded that there are no linear topographic features or warping of the terrace profile suggestive of surface deformation as a result of faulting.

2.5.3.2.2.6 Proposed Quaternary Deformation Features along Douglas Reservoir, TN

SSAR Subsection 2.5.3.2.6 discusses the ETSZ and the recent field investigations in the area reporting possible surface faults and paleoliquefaction features associated with one or more late Quaternary earthquakes. The applicant indicated that the CEUS SSC discussed the ETSZ in general terms as a zone of elevated seismicity but modeled the ETSZ as part of the Paleozoic Extended Zone areal source rather than as a unique seismic source. The applicant also discussed the established criteria for evaluating evidence for paleoliquefaction and other paleoseismic features, and recent terrace mapping and field reconnaissance studies around Douglas Reservoir.

In SSAR Subsection 2.5.3.2.6.1, the applicant discussed the criteria used to determine whether a feature should be included in the CEUS SSC paleoliquefaction database as an earthquake-induced liquefaction feature. In SSAR Subsection 2.5.3.2.6.2, the applicant described the morphological correlation and longitudinal profiling of terrace elevations completed along approximately 95 km (59 mi) of the French Broad River as part of the CRN Site investigation to better constrain the relative ages of terraces along Douglas Reservoir. SSAR Figures 2.5.3-10 and 2.5.3-11 show the terrace maps and longitudinal profiles, respectively. The applicant correlated location and elevation data for the eight identified terraces, performed a linear regression and compared the results to a baseline longitudinal profile developed to represent the incised French Broad River prior to the construction of Douglas Dam. The applicant noted that the linear regressions for the modern French Broad River and terraces have similar slopes, the number of terrace levels are consistent, and longitudinal profiles are similar. As such, there was no Quaternary displacement along Douglas Reservoir.

In SSAR Subsection 2.5.3.2.6.3, the applicant described a recent pilot study to locate paleoseismic features in the ETSZ (Hatcher, Vaughn and Obermeier, 2012). These potential paleoseismic features include possible faults, fissures, bleached clay fractures, evidence of paleoliquefaction, shale "boils," and disturbed sediments at six different sites within fluvial terraces of the French Broad River at Douglas Reservoir. Warrell et al. (2012) studied potential paleoliquefaction features at the six sites presented in Hatcher, Vaughn and Obermeier (2012) and one additional site.

The applicant implemented a Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 study, as described in SSAR Section 2.5.2.2.5 and discussed in SER Section 2.5.2.4.2.3. As part of the SSHAC process, the applicant considered potential paleoseismic features associated with the ETSZ. The Technical Integration (TI) team, accompanied by the principal researchers, observed the potential paleoseismic features in the field and summarized the interpretations and conclusions for the features observed at each of the seven sites in SSAR Section 2.5.3.2.6.3. Based on the observations, interpretations and evaluations made by the TI team during field reconnaissance, the applicant noted that there is not sufficient evidence to support a seismic origin of any of the features examined in the field. The TI team further noted that the features observed at each site could be the result of commonly occurring non-seismic geomorphic and pedogenic processes.

2.5.3.2.2.7 Evaluation of the Presence of Absence of Surface Deformation along the Tellico Reservoir

SSAR Section 2.5.3.2.7 summarizes the terrace surfaces mapped along the Tellico Reservoir on the Little Tennessee River. The applicant developed longitudinal topographic profiles for these terraces but noted that the construction of the Tellico Dam flooded many of the terrace surfaces. Based on available pre-impoundment topographic data and observation of exposed terraces, the applicant concluded that there is no Quaternary displacement or evidence of potential paleoseismic features in the terrace deposits observed along the Tellico Reservoir.

2.5.3.2.3 Correlation of Earthquakes with Capable Tectonic Sources

SSAR Section 2.5.3.3 addresses the possible correlation of earthquakes with capable tectonic sources. The applicant noted that the ETSZ has the second highest rate of small magnitude earthquakes in the eastern United States; twenty-eight earthquakes between M2.9 and 4.0 were recorded in the site vicinity, of which four occurred in the site area. The majority of earthquake hypocenters occur at depths of 5 to 26 km (3 to 16 mi), with a mean focal depth of approximately 15 km (9 mi) in Neoproterozoic (approximately 1.1 Ga) basement rocks overlain by the 5-km (3 mi) thick Paleozoic foreland fold-thrust belt, which is below the basal detachment surface that underlies the Valley and Ridge province. The applicant noted that there is no unequivocal evidence for historic surface rupture reported (Powell and Beavers, 2009). The applicant reported that ETSZ earthquakes have been correleated with potential aeromagnetic anomalies, like the New York-Alabama lineament, but observed that none of these earthquakes correlate with known faults exposed near the ground surface. SSAR Subsections 2.5.1.1.4.3.2, 2.5.3.2.6 and 2.5.2 provide more details regarding the ETSZ.

2.5.3.2.4 Ages of Most Recent Deformation

SSAR Section 2.5.3.4 evaluates the ages of most recent deformations within the site area including bedrock faults, shear-fracture zones, and karst collapse. In regard to bedrock faults, the applicant stated that evidence suggests bedrock thrust faults in the Valley and Ridge were active during the late Paleozoic Alleghanian orogeny and referred to previous discussions in SSAR Subsections 2.5.3.2.1, 2.5.1.1.2, 2.5.1.1.4, and 2.5.1.2.4. The applicant constrained the timing of the formation of the shear-fracture zone using the orientation and crosscutting relationships of stylolites within the shear-fracture zones. The applicant concluded that the truncation of the shear-fracture zones and calcite veins within the zones by bedding-parallel stylolites suggests pre- to syn-diagenetic formation of the shear-fracture zones while truncation by steeply dipping and subvertical stylolites suggests a tectonic overprint, most likely due to Alleghanian shortening associated with the emplacement of Valley and Ridge thrust faults. Finally, the applicant stated that carbonate dissolution and the development of karst features are ongoing processes and subsidence of Quaternary terrace material overlying carbonate units indicates these processes have been locally active through the Holocene.

2.5.3.2.5 Relationship of Tectonic Structures in the Site Area to Regional Tectonic Sources

In SSAR Section 2.5.3.5, the applicant stated that the Copper Creek and Whiteoak Mountain bedrock faults that occur within the CRN Site area are part of the regional Valley and Ridge foreland fold-thrust belt system. These bedrock faults are late Paleozoic in age, whereas the earthquakes associated with the ETSZ occur in crystalline basement rocks below the Appalachian detachment, 5 to 26 km (3 to 16 mi) deep. Therefore, the applicant concluded that there is no evidence to definitively relate the Alleghanian bedrock thrust faults exposed in the CRN Site area to seismicity in the ETSZ.

2.5.3.2.6 Characterization of Capable Tectonic Sources

In SSAR Section 2.5.3.6, the applicant stated that based on material presented in SSAR Sections 2.5.1, 2.5.3.2, and 2.5.3.5, there is no evidence for significant neotectonic features within the 320-km (200-mi) radius CRN Site region that have the potential to impact site safety. The applicant noted that the Alleghanian Valley and Ridge bedrock faults are late Paleozoic in age. The applicant also observed that regional geologic mapping and development of longitudinal profiles along the Clinch River, based on high-resolution LiDAR data presented in SSAR Subsection 2.5.3.2.5, indicate no observable Quaternary displacement along faults in the site area. Furthermore, the applicant concluded that there is no evidence relating ETSZ earthquakes to faults at the ground surface.

The applicant also reported that recent investigations of potential tectonic features associated with the ETSZ and the applicant's field inspection support the conclusion that nearly all the features interpreted as paleoseismic in origin can be plausibly explained by other non-seismic processes (Hatcher, Vaughn and Obermeier, 2012; Warrell, 2013; Warrell et al., 2012).

2.5.3.2.7 Designation of Zones of Quaternary Deformation in the Site Region

In SSAR Section 2.5.3.7, the applicant stated that, although there are no zones of Quaternary deformation associated with tectonic faults that require detailed investigation within the CRN Site vicinity or site area, there are three possible Quaternary fault systems within the CRN Site region. These fault systems are the Kentucky River fault system in northeastern Kentucky approximately 201 km (125 mi) north of the CRN Site; the Rough Creek-Shawneetown fault system in west-central Kentucky about 201 km (125 mi) northwest of the CRN Site; and several unnamed Quaternary faults in western North Carolina approximately 190 km (118 mi) southeast of the CRN Site.

The applicant noted that the Kentucky River fault system was possibly active during the Carboniferous (360 to 300 Ma; Zeng et al., 2013) and the faults appear to offset Pliocene-Pleistocene (5.3 Ma to 11,700 yrs) terrace deposits based on several exploratory trenches in north-central Kentucky (Van Arsdale, 1986). Crone and Wheeler (2000) suggest evidence of Quaternary deformation from the exploratory trenches could be related to karst collapse of underlying carbonate bedrock and classified the Kentucky River fault system as a Class B feature, suggesting that there is either not enough evidence to be classified as A or C, or the fault is too shallow to produce significant earthquakes.

The applicant reported that the Rough Creek-Shawneetown fault system is likely Paleozoic (541 to 252 Ma) in age, but Crone and Wheeler (2000) interpreted the bedrock steps beneath Pliocene to Holocene (5.3 Ma to present) alluvium as Holocene reactivation of Neoproterozoic to early Paleozoic Rough Creek graben normal faults. Crone and Wheeler (2000) classified this fault system as Class C, suggesting there is insufficient evidence to conclude this is a tectonic fault or a feature associated with Quaternary slip or deformation.

Prowell (1983) identified three small faults near Saluda, North Carolina, described as reverse, strike-slip, tear and normal faults, with vertical offsets of 4 m (reverse) and 5 m (normal). Although Prowell (1983) reported that the faults appear to offset Quaternary alluvial and colluvial deposits, Crone and Wheeler (2000) did not evaluate these features in their assessment of Quaternary faults.

2.5.3.2.8 Potential for Tectonic Deformation or Non-Tectonic Deformation at the Site

SSAR Subsection 2.5.3.8 assesses the potential for tectonic and non-tectonic surface deformation at the CRN Site. The applicant stated that the potential for tectonic surface deformation at the CRN Site is negligible. Although the CRN Site lies within the ETSZ, the applicant concluded that earthquakes occur below the Paleozoic foreland fold-thrust belt and there are no Quaternary tectonic faults exposed within the site area or site vicinity.

The applicant stated that the potential for non-tectonic surface deformation as a result of karst activity represents the most significant geologic hazard to the CRN Site. The applicant identified four specific types of hazards to the proposed construction: collapse or subsidence from sinkholes; cavities in the excavation walls below the groundwater table; cavities below the base of the foundation; and cavities enabling the movement of groundwater through underground karst drainage systems. The applicant stated that detailed geologic mapping of the excavations and geophysical surveys at foundation level will form the basis of the final conclusions regarding karst hazard at the CRN Site.

The applicant stated that there is no evidence of existing landslides or other slump-related hazards at the CRN Site. The applicant also considered anthropogenic activities (e.g., mining) that may cause non-tectonic surface deformation but concluded that there is no potential hazard from mine collapse. The applicant stated that it will evaluate the previous grading/excavation of the CRBRP for any future development.

2.5.3.3   Regulatory Basis

The applicable regulatory requirements for tectonic and non-tectonic surface deformation that must be considered in an ESP application are as follows:

- 10 CFR 52.17(a)(1)(vi), as it relates to the requirement for an ESP applicant to prepare an SSAR that contains information on geologic and seismic characteristics of the proposed site with appropriate consideration of the most severe of the 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(c), as it relates to the requirement for an ESP applicant to investigate geologic, seismic, and engineering characteristics of a site and its environs in sufficient scope and detail to permit an adequate evaluation of the proposed site; and to permit adequate engineering solutions for actual or potential geologic and seismic effects at the proposed site.

- 10 CFR 100.23(d), as it relates to the requirement for an ESP applicant to consider geologic and seismic siting factors for the "determination of the potential for surface tectonic and nontectonic deformations. Sufficient geological, seismological, and geophysical data must be provided to clearly establish whether there is a potential for surface deformation."

The information on tectonic and non-tectonic surface deformation provided by the applicant in compliance with the above regulatory requirements should also be sufficient to allow a determination in the combined license (COL) application regarding whether the proposed facility complies with the following requirements in 10 CFR Part 50, Appendix A, "General Design Criteria for Nuclear Power Plants," and 10 CFR Part 50, Appendix S, Section IV, "Application to Engineering Design":

- General Design Criterion 2 of 10 CFR Part 50, Appendix A, requires that SSCs important to safety be designed to withstand effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami, and seiche without loss of capability to perform their safety functions.

- 10 CFR Part 50, Appendix S, Section IV, requires that the potential for surface deformation be taken into account in the design of the nuclear power plant.

The staff applied methods and approaches specified in NUREG–0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants (LWR Edition)," Section 2.5.3, "Surface Faulting." As recommended in RG 1.208, the applicant provided information characterizing tectonic and non-tectonic surface deformation at the proposed site in SSAR Section 2.5.3. NUREG–0800, Section 2.5.3, defines the acceptance criteria for the tectonic and non-tectonic surface deformation information presented in SSAR Section 2.5.3, as follows. In addition, information provided by the applicant in SSAR Section 2.5.3 should be consistent with appropriate sections from RG 1.208. As applicable to an ESP, Section 2.5.3 of NUREG-0800

(Revision 5, July 2014) defines the acceptance criteria for information on tectonic and non-tectonic surface deformation presented in SSAR Section 2.5.3 as follows.

- Geologic, Seismic, and Geophysical Investigations: Requirements of 10 CFR 52.17(a)(1)(vi), 10 CFR 100.23(c) and 10 CFR 100.23(d)(2) are met and guidance in RG 1.208 and 4.7 followed for this area of review if discussions of Quaternary tectonics, structural geology, stratigraphy, geochronologic methods used for age dating, paleoseismology, and geologic history of the site vicinity, site area, and site location are complete, compare reasonably with studies conducted by others in the same area, and are supported by detailed investigations performed by the applicant. Site vicinity, site area, and site location-specific geologic maps and cross-sections constructured at scales adequate to clearly illustrate surficial and bedrock geology, structural geology, topography, and the relationship of power plant foundation and site boundaries to these features should be included in the application. For sites located near bodies of water, the application should address how investigations have been conducted to detect possible surface deformation features that might be located beneath the water.

- Geologic Evidence for Surface Tectonic Deformation: Requirements of 10 CFR 52.17(a)(1)(vi), 10 CFR 100.23(c) and 10 CFR 100.23(d)(2), are met and guidance in RG 1.208 and 4.7 followed for this area of review if the applicant provides sufficient surface and subsurface information for the site vicinity, area, and location to confirm and characterize the presence or absence of surface deformation (e.g., faulting, growth faulting, subsidence or collapse related to dissolution of limestone, salt or gypsum deposits, or salt diapirism and paleoliquefaction) features. The applicant should also take into account the potential for blind faults.

- Timing of Deformation: Requirements of 10 CFR 52.17(a)(1)(vi), 10 CFR 100.23(c) and 10 CFR 100.23(d)(2), are met for this area of review if recognized surface deformation features (e.g., tectonic faults and non-tectonic features including growth faults) and features associated with a blind fault, are investigated in sufficient detail to constrain the age of the most recent deformation event, and, if applicable, the ages of preceding deformation events. The application shall also provide an acceptable evaluation of sensitivity and resolution of the exploratory geologic and geophysical techniques used to determine whether or not appropriate techniques were applied to assess the age of the most recent displacement.

- Correlation of Earthquakes with Tectonic Features: Requirements of 10 CFR 52.17(a)(1)(vi), 10 CFR 100.23(c) and 10 CFR 100.23(d)(2) are met for this area of review if the applicant evaluates all reported historical earthquakes within the site vicinity with respect to accuracy of hypocenter location and source of origin, and with respect to correlation to tectonic features. The applicant shall evaluate the potential for historical activity on tectonic features in the site vicinity. The application should include a plot of earthquake epicenters superimposed on a map showing tectonic features in the site vicinity.

- Relationship of Geologic Features in the Site Vicinity to Regional Geologic Features: Requirements of 10 CFR 52.17(a)(1)(vi), 10 CFR 100.23(c) and 10 CFR 100.23(d)(2), are satisfied for this area of review if the applicant evaluates the relationships between faults or other deformation features in the site vicinity and the regional framework. The application should provide an acceptable evaluation of the relationships between the regional (tectonic and non-tectonic) framework and deformation features in the site vicinity, including growth faults and growth fault systems. The applicant should show how this information is used in the evaluation of potential for future surface deformation at the site.

- Potential for Surface Tectonic Deformation at the Site Location: To meet requirements of 10 CFR 52.17(a)(1)(vi), 10 CFR 100.23(c) and 10 CFR 100.23(d)(2), for this area of review, the applicant should assess the potential future tectonic and nontectonic surface deformation at the site. The applicant should provide sufficient geological, seismological, and geophysical information to clearly establish whether there is a potential for future surface deformation at the site.

2.5.3.4 Technical Evaluation

The NRC staff reviewed SSAR Section 2.5.3 of the CRN Site ESP application (Revision 1) to ensure that the materials provided by the applicant present the information required to assess the potential for tectonic and non-tectonic surface and near-surface deformation. The staff's review of SSAR Section 2.5.3 confirmed that the applicant provided the data and analysis required for topics in Section 2.5.3.

The technical information presented in SSAR Section 2.5.3 resulted from the applicant's review of geologic maps published by the USGS, state geological surveys, and other research workers; literature published in journals and data included in field guides; geophysical data and reports on previous site investigations for the CRBRP; current site investigations for the CRN Site; and the CEUS SSC model presented in NUREG–2115. The applicant also collected information by performing the following activities to assess the potential for tectonic and non-tectonic surface deformation within the site area: examination and interpretation of aerial photographs, LiDAR, and remote sensing imagery; aerial and geologic field reconnaissance, including terrace studies related to the assessment of the ETSZ; subsurface borehole and downhole shear wave velocity investigation; and interpretation of seismic reflection data. Through the review of SSAR Section 2.5.3, the staff determined whether the applicant complied with applicable regulatory requirements in 10 CFR 52.17(a)(1)(vi), 10 CFR 100.23(c), and 10 CFR 100.23(d) 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. In SSAR Section 2.5.3, the applicant included geologic and seismic information to support the analysis of vibratory ground motion and development of the site-specific GMRS, as discussed in SSAR Section 2.5.2. RG 1.208 also recommends that an applicant evaluate faults encountered at a site to determine whether they are seismogenic or may cause surface deformation. SSAR Section 2.5.3 specifically includes information related to the applicant's assessment of the potential for future tectonic and non-tectonic surface deformation at the site location.

The staff visited the CRN Site on June 17-18, 2013, to observe pre-application subsurface investigation activities (NRC, 2013 - ADAMS Accession No. ML13210A307). After the applicant submitted the ESP application, the staff conducted a site audit on May 8-9, 2017, to examine selected portions of borehole rock core samples, observe karst features and geomorphic land forms relative to known mapped thrust faults resulting from the Alleghanian orogeny, and to discuss various aspects of the geologic, seismic, geophysical, and geotechnical investigations conducted to characterize the CRN Site (NRC, 2017 - ADAMS Accession No. ML17223A428).

Within the CRN Site area, the NRC staff visited several sinkholes, Melton Hill water cave, Copper Ridge Cave, and a large exposure of pinnacle and cutter type karst. The staff also visited the CRN Site on January 30-31, 2018, to examine karst features, shear-fracture zones, thrust faults and other geomorphic features in the site area and vicinity. During the January 2018 site visit, the staff examined selected rock core samples to view the characteristics of the Copper Creek fault, the shear-fracture zone, karst-related cavities from subsurface locations, and the stratigraphic boundary at the Knox unconformity. This examination of rock core allowed the staff to better understand and characterize the shear-fracture zones and how these zones compare to the deformation associated with the thrust faults at the CRN Site. The staff also viewed the surface projections of the Copper Creek fault, shear-fracture zone, and Chestnut Ridge fault but noted that there are no observable surface exposures of these structures at the CRN Site. Based on direct examination and evaluation of these geologic features in rock core samples and in the field during the May 2017 site audit and the January 2018 site visit, the staff concludes that there is no evidence of recent deformation or surface offset at the CRN Site location.

The following SER Sections present the staff's evaluation of information provided by the applicant in SSAR Section 2.5.3 and the applicant's responses to RAIs for that SSAR section. The information provided by the applicant and discussed in the following sections of this report provide reasonable assurance of the applicant's compliance with 10 CFR 52.17(a)(1)(vi), 10 CFR 100.23(c), and 10 CFR 100.23(d), as well as conformance to NUREG‑0800, Section 2.5.3.

2.5.3.4.1 Geological, Seismological and Geophysical Investigations

The staff focused its review of SSAR Section 2.5.3.1 on information presented by the applicant related to published geologic maps, regional geologic studies, seismicity data, previous site investigations, aerial imagery analysis, field reconnaissance, and current and past site subsurface investigations. The staff focused on the description of site vicinity geologic studies, previous site investigations, current site investigations, and field reconnaissance for evaluating the potential for surface tectonic and non-tectonic deformation in the site vicinity and site area, and at the site location.

The staff noted that primary sources of information in the CRN Site ESP application include: geologic maps previously published by the Tennessee Geological Survey; previous geologic studies of the site and site vicinity; and geomorphic analysis of high-resolution LiDAR digital elevation data acquired during the CRN Site investigation. The applicant provided several other detailed geologic and hydrogeologic investigations from the ORR and the Melton Hill Dam for staff's review. The applicant also incorporated data from the CRBRP investigations relevant to surface deformation and seismic and non-seismic hazard data from regional studies into the ESP application. The applicant performed a detailed assessment of Quaternary terrace deposits around Douglas Reservoir to evaluate the potential for Quaternary surface deformation near the CRN Site.

The staff considered the applicant's assessment of recent studies in eastern Tennessee conducted on Quaternary terrace deposits surrounding Douglas Reservoir, approximately 80 km (50 mi) from the CRN Site. These studies evaluated evidence for potential Quaternary surface deformation and paleoliquefaction interpreted to be associated with earthquakes and seismicity in the ETSZ. The staff also observed some of these potential Quaternary surface deformation features in the field, including potential evidence of faulting and paleoliquefaction. Based on field observations, staff considered the features unrelated to surficial primary faults associated with earthquakes and seismicity in the ETSZ. The staff noted that the observed surficial features are most likely secondary and not primary, even if related to earthquakes and resultant seismicity in the ETSZ. The staff noted that the CEUS SSC quantifies a reasonable Mmax for the ETSZ by including the ETSZ in the Paleozoic Extended Zone areal source. The staff considers the existing data in which multiple alternative hypotheses can explain the origin of these features as the result of either seismic or non-seismic mechanisms or processes that could result in the potential Quaternary surface deformation and possible paleoliquefaction features observed around Douglas Reservoir. Therefore, staff could not definitively confirm or rule out a seismic origin for many of the observed features given the present state of knowledge and available information.

Based on actions performed by staff associated with the review of SSAR Section 2.5.3.1, as outlined in the above paragraphs, the staff finds that the applicant provided a thorough and accurate description of geological, seismological, and geophysical investigations in support of the CRN ESP application.

*2.5.3.4.2 Geologic Evidence, or Absence of Evidence, for Surface Deformatio*n

In the evaluation of geologic evidence for surface deformation, staff considered the information provided in SSAR Section 2.5.3.2 to characterize the geological evidence for surface deformation near the CRN Site. The applicant assessed the bedrock thrust faults and shear-fracture zones and the projected surface exposures of the bedrock thrust faults and shear-fracture zones on the river terraces along the Clinch River; surface and subsurface karst features at the CRN Site and in the site vicinity; slope failure; and potential surface deformation on the Clinch River Arm of the Watts Bar Reservoir and along Douglas Reservoir, TN.

2.5.3.4.2.1 Bedrock Faults and Shear-Fracture Zones

In SSAR Subsections 2.5.3.2.1 and 2.5.3.2.2 the applicant discussed the bedrock thrust faults and shear-fracture zones that occur at the CRN Site with an emphasis on evidence of surface deformation. The staff considered information the applicant provided regarding the Whiteoak Mountain, Copper Creek and Chestnut Ridge faults, and the shear-fracture zones. The staff focused its review on information regarding fault traces that the applicant mapped at the ground surface or at the surface of bedrock but overlain by Quaternary sediments or landforms. The staff particularly focused on borehole data related to faults and the shear-fracture zone.

The staff considered information presented in the SSAR and, based on observations in the field, identified the Copper Creek fault in two rock core samples from the CRBRP program (CC-B1 and CC-B2). The staff examined these rock core samples during the 2017 site audit and 2018 site visit observing that the fault zone is up to 2 m thick in the core. The staff further noted that the core is composed of highly weathered siltstone and shale derived from hanging wall Rome Formation strata with minor footwall Moccasin Formation limestone. Based on high-resolution LiDAR data, undisturbed or undeformed Quaternary river terrace deposits overlie the Copper Creek fault.

The applicant stated that the Chestnut Ridge fault is a minor fault associated with Alleghanian deformation. During its site visits, the staff did not observe the Chestnut Ridge fault exposed at the surface at the CRN Site. The staff viewed a surface projection that the applicant determined from thickened or repeated stratigraphic units in the Knox Group and from surface float of chert from the Kingsport Formation.

The CRBRP program identified shear-fracture zones in plant excavations, in borehole core, and at one outcrop in the northeast corner of the CRN Site. The applicant did not find this surface evidence of the shear-fracture zone during more recent field work at the CRN Site. During the May 2017 site audit, and the subsequent January 2018 site visit, the staff observed two distinct orientations of stylolites in the shear-fracture zones in core but did not see features associated with shear-fracture zones in outcrop. The staff examined shear-fracture zones in core, and noted that the cataclastic character of the fault gouge, produced by mechanical grinding and crushing (i.e., cataclasis) during displacement along the Copper Creek fault, contrasts with material properties of rock units in the shear-fracture zones that show evidence of pressure solution without extensive crushing and grinding. The staff observed that both non-tectonic diagenetic (bedding-parallel) and post-diagenetic (tectonic overprinting – high angles to bedding) stylolites occur to paint a complex picture of developmental history for the shear-fracture zones, but without intense cataclasis, suggesting there is no evidence for post-Alleghanian tectonic deformation or pressure solution. The staff also noted that stylolites at high angles to bedding were likely produced during fault displacement due to pressure solution resulting from near-horizontal maximum principal compressive stress. The staff also noted that the overall fabric of rock units in the shear-fracture zones suggests that little bedding-parallel shearing displacement occurred in the zones during post-diagenetic tectonic overprinting.

In Request for Additional Information eRAI-8991 (RAI No. 5), Question 02.05.01-4(c) (NRC, 2017 – ADAMS Accession No. ML17213A971), the staff asked the applicant to clarify the logic for equating the shear-fracture zone observed in the CRBRP excavation and mapped by Drakulich (1984) with the shear-fracture zone observed in the subsurface. The applicant provided a response to eRAI-8991 (RAI No. 5), Question 02.05.01-04(c), in Response Letter CNL-17-114 dated October 19, 2017 (TVA, 2017 – ADAMS Accession No. ML17295A001). The applicant revised SSAR Subsections 2.5.3.2.2 and 2.5.3.4.2 to provide additional description of the shear-fracture zones including the relationship of stylolites within the shear-fracture zone. The applicant also clarified that the shear-fracture zone is not a fault breccia or fault zone but represents the accommodation of localized strain during the Alleghanian orogeny. The staff reviewed the applicant's response, which states that the correlation of the shear-fracture zone is warranted due to the similar descriptions of the surficial and subsurface observations of the shear-fracture zones. The staff concluded the response to eRAI-8991 (RAI No. 5), Question 02.05.01-4(c) is acceptable, as discussed in SER Section 2.5.1.4.2.4.

Based on the review of the information provided by the applicant regarding bedrock thrust faults and shear-fracture zones, and the staff's examination of those features in core, the staff concludes that there is no evidence of Quaternary deformation due to the thrust faults or shear-fracture zones. Accordingly, the staff concludes that there is no evidence to support potential site hazard from these features at the CRN Site.

2.5.3.4.2.2 Karst

SSAR Subsection 2.5.3.2.3 discusses carbonate dissolution features at the CRN Site and site area from the perspective of evidence for surface deformation. The applicant stated that while there is some evidence of phreatic dissolution in the CRN Site area there is no clear evidence of hypogene dissolution documented in the site area.

The staff focused the review of this subsection on the applicant's use of the available data to characterize karst at the site. The staff noted that although the applicant used seismic refraction surveys to characterize carbonate dissolution features, the original SSAR did not include the data used for this characterization. Therefore, staff asked the applicant in eRAI-8991 (RAI No.

5), Question 02.05.01-05(a) to discuss the evaluation of seismic refraction surveys as used to identify carbonate dissolution features.

The applicant provided a response to eRAI-8991 (RAI No. 5), Question 02.05.01-05(a), in Response Letter CNL-17-100 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 02.05.01-05(a), to clarify that the primary objective of the seismic refraction surveys was to identify the surface of bedrock beneath the site. The applicant also used the data to identify potential karst features in the subsurface. However, the applicant also noted that seismic refraction data are not the most effective for assessing karst features in the CRN Site area because of the presence and thickness of fill. The applicant provided the seismic refraction tomography profiles and a mark-up of the SSAR to include additional information related to the use of seismic refraction surveys to characterize karst.

The staff reviewed the tomography profiles and the updated SSAR sections, which the applicant incorporated into Revision 1 of the SSAR. The staff concludes that although the primary objective of the seismic refraction surveys was to map the bedrock surface at depth, it is appropriate for the applicant to use any available data to identify anomalies that could potentially indicate the presence of large dissolution features in the subsurface. For the CRN Site, the staff reviewed the seismic refraction tomography profiles but did not identify any features clearly attributable to karst. Accordingly, the staff considers eRAI-8991 (RAI No. 5), Question 02.05.01-05(a), to be resolved. The staff concludes that, due to the presence of carbonate rocks in the subsurface, direct observation of karst features in core as indicated by missing segments, and the ongoing dissolution processes, karst has the potential to cause surface deformation at the CRN Site.

2.5.3.4.2.3 Slope Failure

SSAR Subsection 2.5.3.2.4 summarizes the applicant's assessment of potential surface deformation due to slope failure at the CRN Site. The applicant concluded that there are no existing landslides or slump-related hazards at the CRN Site. The staff reviewed the information provided, including landslide incidence and susceptibility maps, and noted that the landslide susceptibility is moderate and the incidence is low. Accordingly, the staff concludes that potential surface deformation due to slope failure is unlikely to occur at the CRN Site.

2.5.3.4.2.4 Evaluation of the Presence or Absence of Surface Deformation along the Clinch River Arm of the Watts Bar Reservoir

SSAR Subsection 2.5.3.2.5 describes a detailed geomorphic investigation of exposed Quaternary fluvial terraces. The applicant considered Quaternary deposits and Clinch River terraces in the assessment of surface deformation along the Clinch River Arm of the Watts Bar Reservoir. The staff reviewed the information in the SSAR and directly observed the Quaternary deposits and Clinch River terraces during the May 2017 site audit and January 2018 site visit. Based on field reconnaissance and the observation of no notable offset or deformation of Quaternary deposits or terraces, the staff concludes that there is no evidence of Quaternary surface deformation along the Clinch River Arm of the Watts Bar Reservoir.

2.5.3.4.2.5 Proposed Quaternary Deformation Features Along Douglas Reservoir, TN

In SSAR Subsection 2.5.3.2.6, the applicant summarized the potential evidence for paleoliquefaction or other paleoseismic features near the CRN Site. The applicant also summarized the criteria for including features in the paleoliquefaction database of the CEUS SSC. SSAR Subsection 2.5.3.2.6.3 summarizes the field reconnaissance and terrace mapping completed for proposed Quaternary deformation features along Douglas Reservoir on the French Broad River east of the CRN Site.

The staff notes that Quaternary deformation or faulting can be expressed by subtle deformation of geomorphic landforms (i.e., river terraces), and can be identified in anomalies in longitudinal stream and terrace profiles. The applicant reviewed the various criteria currently used to interpret paleoliquefaction and other paleoseismic features and completed a morphological correlation and longitudinal profile of the French Broad River and the associated terraces based on extracted digital elevation model elevation points. The applicant concluded that the re-constructed terrace profiles have similar slopes to the baseline longitudinal profile, which implies no deformation of these terraces since the latest Pleistocene. The staff noted that this method of linear regressed profile slopes would not show small amounts of uplift or localized deformation and that erroneous inclusion of unrelated terrace surfaces under a single profile might impact the slope of the line. Therefore, in eRAI-8991 (RAI No. 5), Question 02.05.01-06, the staff asked the applicant to describe possible tectonic uplift and displacement rates that could be detected with the terrace deformation method described in the SSAR; provide a minimum deformation rate that could be present but undetected by this method; and discuss how uncertainties for projection and grouping errors are evaluated and propagated in the analysis and how these uncertainties affect the minimum deformation rate in the analysis.

In response to eRAI-8991 (RAI No. 5), Question 02.05.01-06, the applicant explained that the longitudinal river terrace profiles can constrain deformation rates (TVA, 2017 – ADAMS Accession No. ML17295A001). The applicant used the Qpt6 terrace level, the oldest and highest of the Clinch River terraces, because it provides the longest temporal baseline. The applicant noted that movement along the site area faults would increase the gradient, thereby allowing for the calculation of the vertical separation rate along the site area faults. The applicant determined that the steepest terrace gradient was 0.00014 m/m (0.00048 ft/ft), which corresponds to a relative separation of ± 1.9 m (6.1 ft) and a maximum vertical separation rate of less than 0.02 millimeters per year (mm/yr; 0.0008 in./yr). The applicant stated that a vertical separation rate of 0.02 mm/yr (0.0008 in./yr) or greater would result in an observable steepening of the terrace while a rate less than 0.02 mm/yr (0.0008 in./yr) would be undetectable. Due to the low gradient of the modern Clinch River baseline of 0.00014 m/m (0.0002 ft/ft), the applicant noted that the vertical error for a terrace projected 3,048 m (10,000 ft) too far upstream or downstream would result in a vertical error of 0.6 m (2 ft); therefore, the applicant concluded that vertical errors are minimal. However, the applicant also noted that horizontal uncertainties may occur where terraces overlap but did not quantify these uncertainties. The applicant noted that horizontal uncertainties where terraces overlap are likely due to differential erosion of terrace surfaces and other factors that may result in minor changes to the local gradients. The applicant also updated the SSAR to include additional discussions of terrace mapping, grouping, and ages. The applicant incorporated these changes into Revision 1 of the SSAR.

Based on the review of information provided in response to eRAI-8991 (RAI No. 5), Question 02.05.01-06 and Revision 1 of the SSAR, the staff concludes that the applicant adequately described the deformation rate of possible tectonic uplift or displacements and appropriately identified the errors and uncertainties associated with the deformation rate. The staff makes this conclusion because the applicant determined the rate based on measured changes in the terrace gradient and described the error and uncertainty associated with these measurements.

The staff further agrees with the applicant's conclusion that horizontal errors are more likely due to the spatial orientation of the terraces used to estimate the vertical separation rate.

Based on actions performed by the staff associated with the review of SSAR Section 2.5.3.2, as outlined in the above subsections, the staff finds that the applicant provided a thorough and accurate description of geologic evidence, or absence of evidence, for surface deformation, in support of the CRN Site ESP application.

2.5.3.4.3 Correlation of Earthquakes with Capable Tectonic Sources

SSAR Section 2.5.3.3 addresses the possible correlation of earthquakes with capable tectonic sources. The applicant explained that the CRN Site is located within the ETSZ. The applicant correlated the earthquakes occurring in the ETSZ with potential aeromagnetic anomalies, like the New York-Alabama lineament, but the applicant did not correlate any earthquakes with known faults exposed at the ground surface.

The staff reviewed the information provided by the applicant, including regional geologic maps, LiDAR data, longitudinal terrace profiles, and potential tectonic features observed in the field. The staff also reviewed the work of Hatcher, Vaughn and Obermeier (2012) and the applicant's evaluation for potential paleoseismic features in the ETSZ in SER Subsection 2.5.3.4.2 ("Geologic Evidence for Surface Deformation"). The staff considered the discussion of the ETSZ in the CEUS SSC and SSAR Subsection 2.5.2.2.5 ("Post-CEUS SSC Studies"). The staff notes that the ETSZ earthquakes are located below the Alleghanian décollement, and Paleozoic thrust faults mapped in the site vicinity do not penetrate through the regional décollement. Because the ETSZ earthquakes are located below the Paleozoic thrust faults and based on the discussion and characterization of the seismicity of the ETSZ in SSAR Subsection 2.5.2.2.5, the staff agrees with the applicant's conclusion that there is no evidence linking seismicity in the ETSZ to faults at the ground surface.

Based on actions performed by staff associated with the review of SSAR Section 2.5.3.3, as outlined in the above section, the staff finds that the applicant provided a thorough and accurate description of the correlation of earthquakes with capable tectonic sources in support of the CRN Site ESP application.

2.5.3.4.4 Ages of Most Recent Deformation

In SSAR Subsection 2.5.3.4, the applicant discussed the timing of deformation due to the bedrock thrust faults, the formation of the shear-fracture zone, and karst collapse. SSAR Subsections 2.5.1.1.2, 2.5.1.1.4, 2.5.1.2.4, and 2.5.3.2.1 summarize multiple lines of evidence suggesting bedrock thrust faults in the Valley and Ridge were active during the late Paleozoic Alleghanian orogeny. The applicant also cited the geochronologic analyses of fault gouge (ages of 280 to 290 and 279.5 ± 11.3 Ma) from the Copper Creek fault and the lack of evidence for later reactivation and concluded that the bedrock thrust faults were not active more recently than the late Paleozoic. In addition, the applicant observed that several undeformed Mesozoic diabase dikes cross-cut Valley and Ridge structures in the central Appalachians in central Virginia and Pennsylvania suggesting that thrusting and folding on these structures occurred prior to approximately 200 Ma.

The staff examined the figures the applicant developed from high-resolution LiDAR and noted that there is no apparent deformation of Pleistocene and Holocene river terraces that overlie the projected surface trace of the shear-fracture zone, indicating that deformation within the shear-fracture zone was not active since at least the deposition of the terraces. The staff also viewed the shear-fracture zone in rock core during the 2017 site audit and 2018 site visit. The staff observed that stylolites show two distinct orientations, one subparallel to bedding and the other at higher angles. In SER Section 2.5.3.4.2.1 the staff interpreted the subparallel stylolites as non-tectonic diagenetic pressure solution features related to overburden pressures while the higher angle stylolites are likely the result of tectonic overprinting associated with late Paleozoic thrust faulting. The staff concluded that the field relationships support this interpretation of pressure solution resulting from both non-tectonic diagenetic effects and tectonic effects during the Alleghanian thrust faulting.

Based on the available data, staff concludes that the most recent deformation of Valley and Ridge thrust faults within the site region occurred during the late Paleozoic. Accordingly, based on all available data derived from field examination of the shear-fracture zones, the staff agrees with the applicant that the shear-fracture zones have a history defined by both diagenetic non-tectonic pressure solution features and post-diagenetic tectonic overprint pressure solution features and are not characterized by the extensive cataclasis exhibited by the thrust faults. The staff further concludes that the formation of the shear-fracture zones likely coincided with deformation associated with the Alleghanian orogeny.

The staff based this conclusion on observations of stylolites in rock core that show two orientations interpreted as non-tectonic subparallel stylolites with a tectonic overprint of high-angle stylolites. The staff's field observations also support the applicant's conclusion that the abundance of pressure solution features and paucity of evidence for mechanical grain size reduction (i.e., cataclasis) in the shear-fracture zones suggest the zones accommodated strain mainly by pressure solution resulting from both non-tectonic diagenetic and later tectonic effects, but with limited cataclastic deformation of the shear-fracture zones during the tectonic event (i.e., Alleghanian thrust faulting).

Regarding the timing or age of limestone dissolution and karst collapse, SSAR Subsection 2.5.3.4.3 states that carbonate dissolution and the development of karst features is ongoing. During the May 2017 site audit and January 2018 site visit, the staff observed karst features, such as sinkholes, caves, and pinnacle and cutter exposures, at the CRN Site location and in the CRN Site area. Based on field observations, the staff agrees with the applicant that it is likely that limestone dissolution was active through the Holocene and is still active. Therefore, the staff concludes that the development of karst features in the CRN Site area remains an ongoing process with the potential for future surface deformation. The staff's review and evaluation of the potential for surface deformation at the site is in SER Subsection 2.5.3.4.8. Furthermore, because carbonate dissolution and the development of karst are ongoing processes in the CRN Site area, in SER Section 2.5.3.5 the staff propose a geologic mapping permit condition to assess this potential hazard during excavation and construction activities.

Based on actions performed by staff associated with the review of SSAR Section 2.5.3.4, as outlined in the above section, the staff finds that the applicant provided a thorough and accurate description of the ages of the most recent deformation in support of the CRN Site ESP application.

2.5.3.4.5 Relationship of Geologic Features in the Site Area to Regional Geologic Features

In SSAR Section 2.5.3.5, the applicant reported that Alleghanian Copper Creek and Whiteoak Mountain bedrock faults that occur within the CRN Site area are part of the regional Valley and Ridge foreland fold-thrust belt system. The applicant mapped the northeast-striking, southeast-dipping thrust faults along orogenic strike from northeastern Alabama to eastern Pennsylvania in the Valley and Ridge province distinct from the adjacent terrane/province subdivisions.

The staff reviewed the information provided by the applicant, including regional maps and aerial photography and agrees with the applicant that the strike and dip of the Copper Creek and Whiteoak Mountain bedrock faults are consistent with the thrust faults of the Valley and Ridge province. The staff concludes that the applicant adequately described the relationship of the Whiteoak Mountain and the Copper Creek faults with respect to the regional geologic features of the Valley and Ridge thrust faults formed during the Alleghanian orogeny.

The staff noted that, in addition to the Whiteoak Mountain and Copper Creek faults, there are also the Chestnut Ridge fault and shear-fracture zones within the CRN Site area. The staff noted that the applicant did not discuss these faults with respect to the relationship to regional tectonic structures. The need to address the interrelationship between these structures and the tectonic setting of the CRN Site are included in eRAI-8991 (RAI No. 5), Question 02.05.01-04(d). The applicant provided a response to eRAI-8991 (RAI No. 5), Question 02.05.01-04(d) in Response Letter CNL-17-114 dated October 19, 2017 (TVA, 2017 – ADAMS Accession No. ML17295A001), which included revisions to SSAR Subsections 2.5.1.2.4.4, 2.5.3.2.2 and 2.5.3.4.2. The applicant discussed the Valley and Ridge thrust faults and shear-fracture zones in terms of the three primary deformation mechanisms: brittle cataclasis, diffusive mass transfer and intracrystalline plasticity. The applicant concluded that the thrust faults and shear-fracture zones accommodated strain during the Alleghanian orogeny with varying contributions from the primary deformation mechanisms. The staff determined that the applicant adequately discussed the relationship of the Chestnut Ridge fault and shear-fracture zones. The staff makes this conclusion based on the applicant's discussion of the relationship between the deformation mechanisms and how the Chestnut Ridge fault and shear-fracture zone accommodated strain during the Alleghanian orogeny. SER Subsection 2.5.1.4.2.4 also documents the staff's evaluation of the information provided in response to this RAI. The staff concluded that the response is sufficient and the RAI is resolved.

Based on actions performed by staff associated with the review of SSAR Section 2.5.3.5, as outlined in the above section, the staff finds that the applicant provided a thorough and accurate description of the relationship of tectonic structures in the site area to regional tectonic sources in support of the CRN Site ESP application.

2.5.3.4.6 Characterization of Capable Tectonic Sources

In SSAR Section 2.5.3.6, the applicant stated that there are no significant neotectonic features within the 200-mi CRN Site region but noted the elevated seismicity in the site region that is associated with the ETSZ. Vaughn et al. (2010) provided the basis for their conclusions regarding Quaternary tectonic structures and paleoliquefaction features. Subsequent field work and associated publications, theses and abstracts provide further support to the original hypothesis (e.g., Hatcher, Vaughn and Obermeier, 2012; Warrell et al., 2012). The applicant provided additional characterization and analysis to demonstrate that the ETSZ does not represent a potentially significant seismic hazard for the site. The work completed and in progress in the ETSZ will clarify if there is possible secondary faulting at the surface associated with true paleoliquefaction features that are ‘off fault’, which could potentially refine the current understanding of earthquake magnitude, frequency and distribution. The applicant also provided alternative non-tectonic interpretations based on field observations and concluded that pedogenic processes can also explain the origin of these potential paleoliquefaction features.

The staff considered the published evidence and interpretations, as well as field observations and new research presented at the annual meeting of the Southeastern Section of the Geological Society of America in April 2018 (Cox et al., 2018). The staff reviewed the results of the field work, including trenches that the applicant re-excavated in the ETSZ; alternate hypotheses regarding Quaternary tectonic deformation in the ETSZ; and documentation provided by the SSHAC Level 2 study and sensitivity analysis, as described in SSAR Section 2.5.2.2.2 (“Post-CEUS SSC Studies”) and discussed in SER Subsections 2.5.2.2.6, 2.5.2.4.2.3, and 2.5.2.4.5.2. In SER Section 2.5.2.4.2.3, the staff reviewed the sensitivity studies and determined that no modifications are needed to the CEUS SSC model to account for seismicity in the ETSZ. The staff also observed potential tectonic features in the field and notes that although interpreted to be paleoseismic in origin, alternate interpretation of these features could suggest a non-seismic origin. The staff concluded that although the interpretations and hypotheses regarding Quaternary surface deformation continue to evolve, there is no new information that would alter the current characterization of geologic hazards and surface deformation in the CRN Site area related to the ETSZ.

The staff reviewed the information provided in the SSAR including the alternate interpretation that paleoseismic features observed in the CRN Site area could be the result of non-tectonic processes. Based on its review of currently-available information, the staff identified no evidence that the ETSZ earthquakes are structurally linked to the Alleghanian thrust faults. Therefore, the staff concludes there is no evidence that recent seismicity in the ETSZ is due to the reactivation of Paleozoic thrust faults. SER Section 2.5.2 discusses the sensitivity calculations, including the possibility that the paleoseismic features are tectonic in origin. Based on available information, the staff concludes that there is no known correlation of a tectonic feature with earthquakes associated with the ETSZ.

Based on actions performed by staff associated with the review of SSAR Section 2.5.3.6, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of the characterization of capable tectonic sources in support of the CRN Site ESP application.

2.5.3.4.7 Designation of Zones of Quaternary Deformation in the Site Region

In SSAR Section 2.5.3.7, the applicant stated that there are no zones of Quaternary deformation in the site vicinity or site area. However the applicant identified three possible fault systems showing potential evidence of Quaternary deformation within the site region, the Kentucky River fault system, Rough Creek-Shawneetown fault system, and the unnamed Quaternary faults in western North Carolina. The applicant also noted that there are alternate, non-seismic interpretations that could explain the potential Quaternary deformation observed within the Kentucky River fault system (Crone and Wheeler, 2000). The staff reviewed the information provided by the applicant in the SSAR and noted that the three possible zones of Quaternary deformation are each over 177 km (110 mi) from the CRN Site. The staff further noted that Crone and Wheeler (2000) concluded that there is insufficient research to definitively conclude whether the observed Quaternary deformation is seismic in origin.

Based on actions performed by staff associated with the review of SSAR Section 2.5.3.7, as outlined in the above paragraph, the staff finds that the applicant provided a thorough and accurate description of the designation of zones of Quaternary deformation in the site region in support of the CRN Site ESP application.

2.5.3.4.8 Potential for Tectonic and Non-Tectonic Deformation at the Site

SSAR Subsection 2.5.3.8.1 states that, although the CRN Site lies within the boundary of the ETSZ, earthquakes within the ETSZ occur below the Paleozoic foreland fold-thrust belt. The applicant noted that there are no Quaternary tectonic faults exposed within the CRN Site area or site vicinity. Therefore, the applicant stated that the potential for tectonic surface deformation at the CRN Site is negligible. The applicant also stated that the potential for non-tectonic surface deformation as a result of karst features is possible and represents the most significant geologic hazard to the CRN Site.

SSAR Subsection 2.5.3.8.2.1 states that the planned site construction will bear on carbonate rocks of the middle Chickamauga to upper Knox Group bedrock units in which both the staff and applicant observed cavities and karst conditions in boreholes. The staff noted that although the applicant will remove overburden soils and cavities associated with limestone dissolution near the top of rock during the excavation process, thereby mitigating the hazard of a cover-collapse or subsidence sinkhole, the remaining cavities and karst conditions might compromise the structural stability of the foundation. However, SSAR Subsection 2.5.4.13 states that the anticipated foundation rocks are the Fleanor Member of the Lincolnshire Formation and the Benbolt and Rockdell formations, all of which the applicant characterized as intact or massive rock in SSAR Subsection 2.5.1.2.6.2. The staff also noted that the applicant will perform detailed geologic mapping of the excavation to confirm the staff's conclusions with respect to the potential for tectonic and non-tectonic deformation at the CRN Site.

For tectonic surface deformation, the staff observed that there is no known or defined Quaternary age surface faulting in the CRN Site vicinity. The staff considered the impact of the ETSZ seismicity and evaluated that zone using sensitivity studies in SER Section 2.5.2. The staff also noted that earthquakes in the ETSZ generally occur beneath the décollement in crystalline basement rocks. Furthermore, the staff noted that thrust faults in the site area are overlain by undeformed Quaternary river terraces in multiple locations. Accordingly, the staff concludes that the potential for tectonic surface deformation in the CRN Site vicinity is negligible because all existing data strongly support that interpretation.

For non-tectonic surface deformation related to karst, staff noted that although the potential for non-tectonic surface deformation as a result of karst features represents the most significant geologic hazard to the CRN Site, the CRN Site plant structures will likely be placed in deep excavations that will decrease the likelihood of a cover-collapse or subsidence sinkholes. The staff also noted that the presence of cavities below the base of the foundation might compromise the structural stability of the foundation. SER Subsection 2.5.4.4.13 describes the staff's evaluation of the foundation assessment model to analyze the impact of subsurface cavities on foundation stability, which refers to COL Action Item 2.5-2 in SER Section 2.5.4.4.1. Accordingly, the staff concludes that the final evaluation for potential surface deformation associated with karst at the CRN Site should be based on detailed geologic mapping of the excavations for safety-related engineered structures and geophysical surveys at foundation level to determine the presence or absence of voids beneath the sub-foundation elevation. Therefore, in SER Section 2.5.3.5, the staff proposes a permit condition requiring detailed geologic mapping of the excavations.

Based on actions performed by staff associated with the review of SSAR Section 2.5.3.8, as outlined in the above section, the staff finds that the applicant provided a thorough and accurate description of the potential for tectonic and non-tectonic deformation at the site in support of the CRN Site ESP application.

2.5.3.5 Geologic Mapping Permit Condition

For evaluation of suitability of a proposed site, requirements in 10 CFR 100.23, specifically 100.23(c), provide that geologic data on tectonic and non-tectonic surface deformation must be obtained through review of pertinent literature and field investigations. The regulation in 10 CFR 100.23(d)(2) explicitly states that geologic and seismic siting factors considered for design must include determination of the potential for tectonic and non-tectonic surface deformation at the proposed site. RG 1.208 specifically states that faults exposed in site excavations should be mapped and assessed in regard to rupture potential while walls and floors of the excavations are exposed, to include assessment of non-tectonic surface deformation. In SSAR Section 2.5.1.2.6.10, the applicant acknowledged the need to perform geologic mapping for documenting the presence or absence of karst features, faults, or shear-fracture zones in plant foundation materials. In supplemental information letter CNL-16-184, submitted on December 15, 2016 (TVA, 2016 - ADAMS Accession No. ML16350A420), as incorporated in SSAR Section 2.5.1.2.6.10, Revision 1, the applicant described plans to perform detailed geologic mapping of excavation walls during excavation and construction; document characteristics of dissolution features in the near-surface carbonate rock units; and verify a decrease in cavity size and abundance with depth. The applicant also stated that it would design and conduct surface geophysical surveys, develop a grouting program, and perform confirmatory drilling, among other activities, during the excavation and construction phase at the CRN Site. These confirmatory activities, and the development of a grouting program and associated ITAAC are included as part of COL Action 2.5-3, as discussed in SER Section 2.5.4.4.1. Therefore, the staff considers it the responsibility of the COL or CP applicant who will reference the ESP application to perform geologic mapping of future excavations for safety-related engineered structures at the CRN Site. This activity is Permit Condition 1, the required actions for which are as follows:

> Permit Condition 1: The applicant for a combined license (COL) or a construction permit (CP) that references this early site permit (ESP) shall perform detailed geologic mapping of excavations for safety-related engineered structures; examine and evaluate geologic features discovered in those excavations; and notify the Director of the Office of New Reactors, or the Director's designee, once excavations for safety-related structures are open for examination by NRC staff.

2.5.3.6 Conclusions

As documented in SER Sections 2.5.3.1 through 2.5.3.4 presented above, the NRC staff reviewed and evaluated information related to surface tectonic and non-tectonic deformation submitted by the applicant in SSAR Section 2.5.3 of the CRN Site ESP application. The review and evaluation allowed the staff to confirm that this information provides an adequate basis for concluding that there is negligible potential for tectonic surface deformation in the site vicinity, area or location that could adversely affect the suitability of the CRN Site. Based on the review and evaluation, the staff recognize karst as a potential hazard and cause of non-tectonic surface deformation at the CRN Site. Completion of geologic mapping and geophysical testing and boring programs as outlined in Permit Condition 1 and COL Action Item 2.5.3 will allow the staff to verify, and the applicant to confirm, ESP determinations related to surface deformation and, if necessary, mitigate this hazard through appropriate means.

The staff also concludes there is no potential for the effects of anthropogenic activities, such as surface or subsurface mining, to cause surface deformation that would compromise the safety of the CRN Site.

Finally, based on results of the review and evaluation of SSAR Section 2.5.3, the staff concludes that the applicant provided a thorough and accurate description of the potential for tectonic and non-tectonic surface deformation in the site vicinity and site area and at the site location in full compliance with applicable regulatory requirements in 10 CFR 52.17(a)(1)(vi), 10 CFR 100.23(c), and 10 CFR 100.23(d) and in accordance with guidance in RG 1.208 and Section 2.5.3 of NUREG–0800.