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2.5.3 Surface Deformation

This section evaluates the potential for tectonic and non-tectonic surface deformation at the Clinch River Nuclear (CRN) Site. Information presented within this section has been developed in accordance with Regulatory Guide (RG) 1.208 and is intended to demonstrate compliance with 10 CFR 100.23, *Geologic and Seismic Siting Criteria*. Specifically, this subsection addresses the following issues:

- Potential surface deformation associated with active tectonism, including any significant neotectonic features (faults).
- Potential surface deformation associated with non-tectonic processes such as collapse structures (karst collapse), slope failures, and anthropogenic deformation (e.g., mine collapse).

RG 1.208 states, "Comprehensive geological, seismological, geophysical, and geotechnical engineering investigations should be performed." It also states that these investigations should be performed at four levels with the degree of detail based on distance from the site. This is consistent with guidance provided in RG 1.206 Section C.I.2.5 with the site region being defined as within a radius of 320 kilometer (km) (200 mile [mi]) and documented in Subsection 2.5.1.1.

In addition, according to NUREG-0800, *Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition*, Section 2.5.3:

> "The applicant reports this information [geologic, seismic, geophysical, and geotechnical information with respect to surface deformation] in its application in each of three areas defined by radii of 40 km (25 mi), 8 km (5 mi), and 1 km (0.6 mi) around the site...However, applicants need to report any significant neotectonic features found beyond these distance ranges, which have a potential to impact the site safety."

The term "significant neotectonic feature" is not clearly defined in NUREG-0800, nor is it defined in RG 1.208. NUREG-0800 does, however, state that:

> "Emphasis is placed on Quaternary-age features because evidence of surface deformation during the last approximately 2.6 million years generally indicates a potential for future surface deformation to occur."

Consistent with earlier NRC guidance, the term "a significant tectonic feature" is defined in this Site Safety Analysis Report by the following criteria:

(1) Movement at or near the ground surface at least once within the Quaternary Period (within the past 2.6 million years);

(2) Macro-seismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the feature;

(3) A structural relationship to a seismogenic fault according to characteristics (1) or (2) above such that movement on one could be reasonably expected to be accompanied by movement on the other.

This section summarizes the evaluation of the site to the above criteria and will establish that there are no significant neotectonic features within the 200-mi CRN site region that have a potential to impact the site. Several features within the site region have been proposed to exhibit evidence for Quaternary deformation and are discussed in more detail in Subsection 2.5.3.7.

Likewise, there is negligible potential for tectonic surface rupture within the site vicinity (25-mi radius). The CRN Site is located in the Valley and Ridge province, which is characterized by sub-parallel northeast-trending ridges and valleys, with generally 100 to 300 feet (ft) of relief throughout eastern Tennessee. This characteristic physiography is directly related to the structural geology of the region (Figure 2.5.3-1); the Valley and Ridge consists of numerous northeast-striking southeast-dipping imbricate thrust faults that were emplaced during the late Paleozoic assembly of the supercontinent Pangea (described in more detail in Subsection 2.5.1.1.2). This thin-skinned deformation is associated with the Alleghenian orogeny (see Subsection 2.5.1.1.2).

The site lies within the Eastern Tennessee Seismic Zone (ETSZ), which is the second-most active seismic zone in eastern North America (see Subsection 2.5.2; Reference 2.5.3-1, Section 7.3.4.1.2). The majority of earthquake hypocenters occur at depths of 5 to 26 km (3 to 16 mi) and are below the basal Paleozoic detachment surface that underlies the Valley and Ridge province (Reference 2.5.3-2). No unequivocal evidence for historic surface rupture has ever been reported (Reference 2.5.3-4). Intraplate earthquakes are not well understood, and as such, the nature of the seismicity remains ambiguous and debated. No **M**>5 earthquakes have been recorded in the ETSZ since instrumental seismicity recordings began in 1973 (see Subsection 2.5.2.1).

Karst dissolution is the primary non-tectonic surface deformation hazard at the CRN Site. The site is underlain by moderately east-dipping sedimentary strata that are variably susceptible to karst dissolution; this variability is primarily a function of carbonate content and bed thickness (see Subsection 2.5.1.2.5). All stratigraphic units at the site are to some degree calcareous and contain karst features. The thicker and more pure carbonate units contain the larger and more abundant karst features. Cavities encountered in boreholes are most frequent at higher elevations near the ground surface and steadily decrease in frequency with decreasing elevation (Reference 2.5.3-3). The primary karst hazard at the site is cavities that may be encountered in the wall or floor of excavations for safety-related structures in the power block area (Figure 2.5.1-52). The dimensions and extent of cavities cannot be predicted from the borehole data; however, their presence is indicated by the scatter of cavities encountered (see Subsection 2.5.1.2.5). Borehole data combined with a site karst model and an understanding of the origin and nature of these cavities suggests that cavities might be encountered in carbonate beds projected downdip toward the excavations, and some may occur below the base of the planned excavations. More thorough discussions of karst features and processes at the CRN Site are presented in Subsection 2.5.1.2.5; these are summarized below where relevant to the issue of surface deformation. A discussion of detailed geologic excavation mapping is presented in Subsection 2.5.1.2.6.

2.5.3.1 Geological, Seismological, and Geophysical Investigations

Available information regarding the potential for surface deformation at the CRN Site was compiled from several primary sources:

- Geologic mapping published by the Tennessee Division of Geology
- Previous geologic studies of the site and site vicinity (e.g., Reference 2.5.3-5, 2.5.3-6, and 2.5.3-7)
- Unpublished geologic mapping (Reference 2.5.3-8)

In addition to incorporating these existing data, the following investigations were performed to assess the potential for tectonic and non-tectonic deformation within the 5-mi CRN Site radius:

- Interpretation of aerial photography
- Geologic field reconnaissance mapping
- Detailed geomorphic analysis of high-resolution LiDAR digital elevation data (0.5-ft pixel resolution that covers 168 square mi) acquired during this investigation; LiDAR data were also used to map karst features
- Subsurface borehole and downhole shear wave velocity investigation
- Analysis and interpretation of seismic reflection data
- Review of the EPRI et al. CEUS Seismic Source Characterization (Reference 2.5.3-1), which includes a seismicity catalog that covers the period from 1568 through 2008, and post-2008 seismicity derived from available catalogs (see Subsection 2.5.2.1.1)

2.5.3.1.1 Previous Site Investigations

The CRN Site was previously investigated as part of the Clinch River Breeder Reactor Project (CRBRP). A preliminary safety analysis report (PSAR) for the site was completed before the CRBRP was terminated in 1983 (Reference 2.5.3-5 and 2.5.3-6). Data from previous site investigations relevant to ground deformation, seismic, and non-seismic hazard data from regional studies have been incorporated as part of this early site permit application (ESPA) investigation and are discussed in Subsection 2.5.1.

2.5.3.1.2 Regional and Local Geologic Studies

In addition to the extensive site investigation related to the CRBRP, the CRN Site and vicinity have also been the focus of several other detailed geologic and hydrogeologic investigations because of its proximity to the Oak Ridge Reservation (ORR) (e.g., Reference 2.5.3-7) and the Melton Hill Dam (Reference 2.5.3-9).

An integrated study of the geology of the ORR is provided by Hatcher et al. (Reference 2.5.3-7). This study combines detailed mapping of the ORR area with exploratory boreholes and geophysical data (both seismic reflection and refraction); provides a very detailed report on the soils, bedrock stratigraphy, and structural geology of the region; and proposes a hydrogeologic model based on data collected for that report. Rubin and Lemiszki (Reference 2.5.3-10) built on the hydrogeologic model proposed in that study and demonstrated that lithology and structural geology of the Valley and Ridge province in the ORR area strongly controls the spatial development of karst features through the region. They suggested that cave systems tend to develop extensive along-strike networks that are the result of restricted groundwater flow in siliciclastic lithologies adjacent to carbonate units. The geologic map that was produced during the Hatcher et al. (Reference 2.5.3-7) investigation was updated by Lemiszki et al. (Reference 2.5.3-8) and is included in the compiled geologic map (Plate 1) in Part 8 of this Application.

Several recent studies in eastern Tennessee have focused on evaluating evidence of Quaternary surface deformation and its possible association with the ETSZ (Reference 2.5.3-12, 2.5.3-13, 2.5.3-14, and 2.5.3-15). The primary focus of these studies has been on Quaternary terrace deposits that surround Douglas Reservoir (approximately 50 mi from the CRN Site), as this area may contain conditions conducive for finding evidence for paleoliquefaction features. Vaughn et al. (Reference 2.5.3-11) reported evidence of minor surface faulting, fracturing, and disrupted features in terrace alluvium, along with minor paleoliquefaction, northeast of Knoxville, Tennessee. Similarly, studies along Douglas Reservoir document bleached fracture systems and possible sandy intrusions in terrace deposits that they interpret as paleoseismic in origin, although the origin of these features is unclear. Howard et al. (Reference 2.5.3-15) and Warrell et al. (Reference 2.5.3-13) reported fractures, small faults, and displacements in Quaternary alluvium along Douglas Reservoir that they suggest resulted from earthquakes with magnitudes greater than 6.0 and 6.5 (magnitude scale unspecified). While a seismic origin for many of the observed features in these studies cannot be definitively confirmed or ruled out, there are multiple alternative hypotheses that can explain their origin (e.g., pedogenic processes, karst collapse, slope failure). See Subsection 2.5.2.2.6.1.3 for a discussion of ETSZ Maximum Magnitude (Mmax) sensitivity studies.

2.5.3.2 Geological Evidence, or Absence of Evidence, for Surface Deformation

2.5.3.2.1 Bedrock Faults

The CRN Site is located between two major late Paleozoic thrust faults: the Whiteoak Mountain fault approximately 2 mi to the northwest, and the Copper Creek fault approximately 0.25 mi to the south (Figure 2.5.1-35) (see Subsection 2.5.1.2.4). Both faults juxtapose lower Cambrian Rome Formation above Middle Ordovician Chickamauga Group rocks and sole into the basal Appalachian detachment at 3.5 to 4 km below the ground surface (Figure 2.5.1-35). Additionally, Lemiszki et al. (Reference 2.5.3-8) traced out a relatively small-displacement thrust fault (Chestnut Ridge fault) 0.6 mi to the west that juxtaposes Ordovician units of the Knox Group (Figure 2.5.1-35) (see Subsection 2.5.1.2.4). This fault is interpreted as a thrust fault that propagated from bedding-parallel slip within the Knox Group and likely does not sole into the basal Appalachian detachment. Seismic reflection surveys conducted at the site revealed no evidence for blind faults (see Subsection 2.5.1.2.4; Reference 2.5.3-3). A blind fault might be indicated by reflectors that are offset or truncated by a more steeply dipping reflector that propagates through the Paleozoic section but either (1) does not penetrate the ground surface or (2) is overlain by sediments to the extent that the surface trace is not mappable. This would differ from the expression of faults identified in nearby seismic reflection profiles that include fault traces that are mapped at the ground surface.

Several lines of evidence strongly support late Paleozoic emplacement of Valley and Ridge thrust faults:

- The youngest strata that Valley and Ridge faults offset are Carboniferous (Pennsylvanian) in age (e.g., Reference 2.5.3-16).
- $^{40}K/^{40}Ar$ and $^{40}Ar/^{39}Ar$ geochronologic analyses of fault gouge from the Copper Creek fault yielded ages of 280 to 290 and 279.5 ± 11.3 *mega annum* (Ma), respectively (Reference 2.5.3-6; Reference 2.5.3-17).
- In the central Pennsylvania Valley and Ridge, undeformed Mesozoic diabase dikes have been mapped that clearly crosscut Valley and Ridge structures (Reference 2.5.3-18).

Additionally, undeformed Quaternary river terraces in the CRN site vicinity overlie the traces of Valley and Ridge thrust faults (Subsection 2.5.3.2.5; Figures 2.5.3-2 and 2.5.3-3), which further supports the conclusion that they are inactive structures.

2.5.3.2.2 Shear Fracture Zones

As discussed in Subsections 2.5.1.2.4 and 2.5.1.2.6, a structure loosely described as a shear zone was identified in the Eidson Member of the Lincolnshire Formation in the CRBRP PSAR (References 2.5.3-5 and 2.5.3-6). The shear zone was penetrated in 37 boreholes during the CRBRP investigation, and a surface exposure in the northeastern portion of the site was described in the CRBRP PSAR (Reference 2.5.3-6). This zone ranges from 19 to 46 ft thick and is, on average, approximately 35 ft thick (Reference 2.5.3-6). The zone, including slickensides, is roughly parallel to bedding and occurs in the same stratigraphic position where encountered (Reference 2.5.3-5). It is characterized as "a zone of interbed slippage characterized by a combination of slickensides, calcite veins, and 1-inch to 1-foot segments that are either severely warped or brecciated" (Reference 2.5.3-5). Interbed slippage in the zone is estimated to be on the order of inches (Reference 2.5.3-6), as no stratigraphic offset is demonstrable.

Similar structures identified in the Lincolnshire (Eidson Member), Rockdell, and Benbolt Formations are defined as shear fracture zones in the current subsurface investigation (see Subsections 2.5.1.2.4 and 2.5.1.2.6). These shear fracture zones are located and characterized in 15 of the 100- and 200-series boreholes (Table 2.5.1-17; Figure 2.5.1-60). Shear fracture zones consist of intensely fractured, calcite-healed zones that form parallel to bedding, with thicknesses that range from 1 to 18 ft (see Subsections 2.5.1.2.4 and 2.5.1.2.6). These shear fracture zones are interpreted to be the same structures that were encountered and described as shear zones in the CRBRP PSAR (References 2.5.3-5 and 2.5.3-6).

Fifteen boreholes penetrated shear-fracture zones during the subsurface investigation (Reference 2.5.3-3; see Table 2.5.1-17). Core recovered from 100- and 200-series borings in shear-fracture zones is commonly described as calcite-healed, with rock quality generally described as high with moderate to high core recovery (Reference 2.5.3-3; see Subsection 2.5.1.2.6.4). Shear fracture zones do not appear to be loci for accelerated dissolution relative to adjacent rock.

Foreman and Dunne (Reference 2.5.3-19) describe the occurrence of bed-parallel slickensided veins in a detailed fracture analysis in eastern Tennessee. These veins are calcite-filled and appear to be similar structures as those identified as shear zones in the CRBR investigation.

Elsewhere in the site vicinity, Lemiszki (Reference 2.5.3-20) reported mesoscopic shear zones that offset extensional fractures. These are described as both left- and right-lateral shears based on offset of chert marker beds and mineral-filling geometries (Reference 2.5.3-20). Lemiszki (Reference 2.5.3-20) indicates the development of these shear zones is closely related to faulting and folding in the area, although the report provides no technical basis for that conclusion.

2.5.3.2.3 Karst

Carbonate dissolution features that occur at the CRN Site and within the site area (5-mi radius) were identified using new data acquired for this ESPA, including (1) detailed analysis of high-resolution LiDAR-based digital elevation data and aerial photography; (2) field reconnaissance mapping; (3) seismic refraction surveys at the site; and (4) analysis of soil and rock-core borings drilled at the site. New data were compiled with existing site-specific data developed for the CRBRP, local investigations, and reports (e.g., References 2.5.3-21, 2.5.3-5 and 2.5.3-6; 2.5.3-10; 2.5.3-7; and 2.5.3-3). A comprehensive evaluation of karst features is provided in Subsection 2.5.1.2.5.

Within the site area, a total of 2797 karst depressions were identified (Figure 2.5.1-47). Of these, 1210 were classified as sinkholes at least 2 ft deep with an area of 100 ft^2 (see Subsection 2.5.1.2.5). The occurrence of karst depressions is strongly controlled by lithology; geologic units that comprise the highest depression densities consist of thick, relatively pure carbonates. These include the Knox Group dolomites and more pure limestones of the Chickamauga and Conasauga Groups. Stratigraphic units that contain interbedded carbonate and siliciclastic lithologies (e.g., Benbolt and the upper Blackford formations of the Chickamauga Group) have a moderate to few number of depressions, and those dominated by siliciclastics (sandstone, siltstone, shale) have very few to no depressions. Additionally, geologic structures (e.g., fractures, folds) can exert a strong influence in the development of karst features (Reference 2.5.3-10).

Bedrock at the CRN Site location primarily consists of the Chickamauga Group, with Knox Group rocks in the northwest portion of the 0.6-mi radius (Figure 2.5.1-37). Rubin and Lemiszki (Reference 2.5.3-10) reported that, in this structural position within the Valley and Ridge (hanging wall of the Whiteoak Mountain thrust sheet), the Rockdell, Benbolt, and Witten formations are the purest and thickest carbonate units, and the Fleanor Shale is a major potential barrier to down-dip conduit development. Bedding dip, faults, and fractures in the carbonates act as infiltration pathways and sites for potential dissolution, while groundwater flow is constrained by the presence of siliciclastic units. This results in the development of laterally extensive strike-parallel cave systems (Reference 2.5.3-10). Twenty-four caves were identified in the karst inventory of the site area (see Subsection 2.5.1.2.5), all of which formed in the Copper Ridge Dolomite, Chepultepec Dolomite, or Maynardville Limestone (see Subsection 2.5.1.2.5).

Karst-related surface features at the site, identified during the CRBRP and during the current investigation, include large funnel- and dish-shaped sinkholes and small holes in the ground. Two major sinkhole clusters occur within the 0.6-mi site radius: one in the Knox Group (at the contact between the Kingsport Formation and Mascot Dolomite) and the other in the Chickamauga Group (Witten Formation) (see Subsection 2.5.1.2.5).

In addition to analysis of the ground surface, seismic refraction tomography surveys were conducted to identify features related to carbonate dissolution in the shallow subsurface (Reference 2.5.3-3). These surveys were conducted primarily in areas that had been graded as part of CRBRP construction activities. The deep excavation of the site had been filled to create a planar ground surface following the termination of the project. The resulting tomography models primarily delineate the margins of the fill, and no features in these data can clearly be attributed to karst phenomena.

A total of 180 exploratory rock core borings have been collected at the site (104 for the CRBRP and 76 for the current investigation), 42 percent of which encountered one or more cavities. Cavities were encountered in every stratigraphic unit that was drilled underlying or adjacent to the power block area, including the Blackford Formation, Eidson Member, Fleanor Shale, Rockdell Formation, and Benbolt Formation. The frequency and size of cavities are observed to be greater in units with higher carbonate content and, generally, decrease with depth (see Subsection 2.5.1.2.5).

2.5.3.2.4 Slope failure

Reconnaissance geologic mapping, aerial photograph analysis, and slope analysis using high-resolution digital elevation data revealed no existing landslides or other slump-related hazards in the site location. Additionally, landslide hazard maps (Reference 2.5.3-22) and landslide incidence and susceptibility maps (Figures 2.4.9-5 and 2.5.1-22) indicate the site is located in an area of moderate susceptibility and low incidence (see Subsection 2.5.1.1.5).

2.5.3.2.5 Longitudinal Terrace Profiles along the Clinch River

The acquisition of LiDAR across the CRN site area offered the opportunity to reevaluate the evidence for surface faulting or the absence of surface faulting at the site. Evidence for surface faulting in the Quaternary is often expressed by subtle deformation of geomorphic landforms, including river terraces, and can be delineated using anomalies in longitudinal stream and terrace profiles. The high-resolution LiDAR data (0.5 ft pixel resolution) allowed for detailed mapping of Clinch River terraces across the 5-mi radius site area (Figures 2.5.3-2 and 2.5.3-3) and evaluation of the relative ages of terrace levels using morphological correlation and longitudinal profiling (Figure 2.5.3-4). Analysis of longitudinal profiles of terrace elevations can provide a means to assess irregularities that could be associated with reactivation of faults and possible surface deformation. As such, an investigation of terraces along the Clinch River in the site area was undertaken to evaluate any potential evidence for Quaternary surface deformation (Figure 2.5.3-4).

2.5.3.2.5.1 Quaternary Deposits

Holocene through Pleistocene alluvial terrace deposits are mapped along larger tributary valleys in the site area (Figure 2.5.3-2). Terraces along the Clinch River were delineated using high-resolution LiDAR digital elevation data and were checked during field reconnaissance. In these drainages Holocene terrace levels are assigned based on geomorphology and relative topographic positions, with Qht0 representing the historical flood plain (now flooded and not shown on maps). Tributary terraces of probable Pleistocene age were not assigned a relative terrace level.

Colluvial (Qc) deposits consist of weathered residuum transported by hillslope processes including slopewash and creep. No landslides were mapped within the site area. Colluvium is deposited at the toe of hillslopes and in hollows on the hillsides. Colluvium mapped in the site area is predominantly Holocene, although Pleistocene deposits are likely present. The thickness and areal extent of colluvial deposits varies significantly dependent on the subsurface bedrock unit. The Rome Formation, which erodes primarily by mechanical weathering, produces abundant colluvial deposits which blanket the lower angle slopes underlain by stratigraphically adjacent units. Alternatively, carbonate deposits, which erode primarily by chemical processes, tend to only produce areally extensive colluvial deposits if they contain a significant percentage of chert, such as the Longview Dolomite. Colluvium was mapped primarily on the basis of topographic expression, and only larger bodies are included in Figure 2.5.3-2.

Holocene alluvium (Qha) deposits occur in hillside gullies and in the principle tributary valleys across the site area (Figure 2.5.3-2). Unit Qha includes channel bottom alluvium and low terrace deposits that are undivided at the scale of mapping. The unit is composed largely of silt, with sand and gravel present in varying amounts dependent on the local bedrock parent material. Holocene alluvial fan (Qhaf) deposits are present primarily at the mouths of the larger gullies incised into ridges underlain by the Rome Formation.

2.5.3.2.5.2 Clinch River Terraces

Clinch River terraces are extensively preserved within the site area and record a history of incision likely dating back to the early Pleistocene and possibly into the Tertiary, indicative of a broad, stable landscape. Terrace surfaces were delineated primarily based on topographic expression in the LiDAR digital elevation model and field observations from surfaces accessed during the field reconnaissance (Figure 2.5.3-2). A soil survey of Oak Ridge National Laboratory described in Hatcher et al. (Reference 2.5.3-7) identified Pleistocene age terrace remnants associated with the Clinch River, including a number of terraces between 840 and 850 ft in elevation (Reference 2.5.3-7). This terrace level is interpreted to record a short period of landscape instability during the Wisconsin glaciation, during which the Clinch River basin received a large influx of sediment (References 2.5.3-7 and 2.5.3-23). These terraces were delineated as part of the reconnaissance mapping and have been grouped into terrace levels Qpt5 and Qpt6 in Figure 2.5.3-2. The only known absolute age control of Clinch River terrace deposits was obtained from archaeological excavations during the CRN Site investigation. The oldest material dated was obtained from organic materials in the alluvium that underlies the Clinch River floodplain and yielded an age of about 2500 years old (Reference 2.5.3-5).

Longitudinal profiles of the modern Clinch River baseline and terraces Qht1 through Qpt6 are shown in Figure 2.5.3-4. The baseline longitudinal profile was developed to represent the modern Clinch River prior to the construction of the Watts Bar Dam using the map view baseline stream course shown in Figure 2.5.3-2 and elevation points extracted or inferred from historic USGS topographic maps that were created prior to impoundment of Watts Bar Dam. The slope of the modern Clinch River baseline was used to determine permissible gradients of the paleo-Clinch River. Terrace elevations were extracted from the LiDAR digital elevation data and projected onto the baseline shown in Figure 2.5.3-2. Relative terrace levels were initially assigned using the terrace elevation and position relative to neighboring surfaces and morphology of terrace surfaces. These preliminary terrace levels were then refined by fitting the elevation data from each terrace level with a linear regression and comparing the slope of each regression to the slope of the modern Clinch River baseline. With some analytical refinement, the terrace elevations clustered into groups with regression slopes within a permissible range (Figure 2.5.3-4).

Regional terrace studies include an investigation by Delcourt (Reference 2.5.3-24) along the Little Tennessee River which found nine topographically unique terrace levels based on elevation profiles and field reconnaissance. The terraces range in elevation above the main channel from less than 4 to 26 m (13 to 85 ft). Age control was largely qualitative and based on weathering characteristics; however, several radiocarbon dates were obtained from the lowest terrace levels, T1 and T2, at 3.5 to 15 and 28 thousand years, respectively. The T1 age is consistent with the age of a Tennessee River T1 terrace described in an archaeological study near the Tellico Dam. It stands 6 m (20 ft) higher than the adjacent river and contains charcoal samples with calibrated radiocarbon ages of 9270 to 9475 calendar years before present (BP) and 9545 to 9745 calendar years BP (Reference 2.5.3-25). The Delcourt (Reference 2.5.3-24) T2 age is broadly consistent with radiocarbon dates of approximately 29 to 31 thousand years reported for a T2 terrace deposit beneath the Watts Bar Nuclear Plant adjacent to the Tennessee River (Reference 2.5.3-26). Although detailed mapping of this set of terraces is not available, this deposit is estimated to be 2 to 6 m (6 to 20 ft) above the modern river level.

The distinction between Holocene (Qht) and Pleistocene (Qpt) terraces in Figure 2.5.3-4 is qualitative based on terrace morphology and elevation above the modern Clinch River baseline. In order to better constrain the relative ages of terraces along the Clinch River, morphological correlation and longitudinal profiling of terrace elevations was completed along the Clinch River in the site area, downstream of the Melton Hill Dam (Figure 2.5.3-4). The oldest terrace assigned a Holocene age (Qht3) is only slightly dissected by gully erosion and typically has an intact, continuous terrace riser separating it from Qht2, which suggest a relatively young Holocene age.

2.5.3.2.5.3 Evaluation of Terrace Profiles and Quaternary Surface Deformation

Evidence for Quaternary surface faulting in the site area was evaluated in two ways: (1) examination of Pleistocene terrace surfaces which directly overlie the mapped trace of faults (Figure 2.5.3-3); and (2) evaluation of longitudinal terrace profiles for systematic, along-profile irregularities suggestive of repeated fault displacements (Figure 2.5.3-4). Both methods used high-resolution LiDAR digital elevation data with pixel resolution of 0.5 ft.

Clinch River terrace surfaces overlie a portion of the concealed trace of each of the three faults within the site area (Figure 2.5.3-3). A fault surface rupture that post-dates the formation and deposition of the overlying terrace would produce deformation on the terrace surface in the form of a fault scarp or lineation. These deformation features would be evident on the LiDAR hillshades, slope maps, and on longitudinal terrace profiles. The Whiteoak Mountain fault is directly overlain by Qht2 and Qpt2 terraces; the Copper Creek fault by Qht1, Qht2 and Qht3 terraces; and the northeast projection of the Chestnut Ridge fault is overlain by Qht2. While each of these terrace surfaces have some amount of topographic erosion and anthropogenic alteration, none of them display topographic linear features or irregularities suggestive of surface deformation (Figures 2.5.3-2 and 2.5.3-3). The Copper Creek fault is overlain by a suite of undeformed Holocene terraces adjacent to the site (Figure 2.5.3-3) and at an abandoned meander northeast of the site (Figure 2.5.3-2, Sheet 2 of 4).

Repeated thrust faulting and relative uplift would result in increased incision and terrace formation in the hanging wall of the fault. The consistent number of terraces levels with similar longitudinal profile slopes that can be correlated across the site area suggest that there has not been discernible displacement such as hanging wall uplift, nor differential incision resulting from Quaternary movement along the faults (see Figures 2.5.3-3 and 2.5.3-4).

2.5.3.3 Correlation of Earthquakes with Capable Tectonic Sources

The CRN Site is located within the ETSZ, an approximately 300-km-long (186 mi) and less than 50-km-wide (31 mi) northeasterly trending, elongate band of seismicity within the Valley and Ridge and westernmost Blue Ridge physiographic provinces; it underlies parts of eastern Tennessee, North Carolina, Georgia, and Alabama (e.g., References 2.5.3-27, 2.5.3-28, 2.5.3-2, and 2.5.3-29). After the New Madrid seismic zone, the ETSZ has the second highest rate of small (i.e., moment magnitude **(M)**<5) earthquakes in the eastern United States (Reference 2.5.3-1, Section 7.3.4.1.2). Within the CRN site vicinity, two **M**>4 have been recorded in recent history (4.01, 3 November 1973, and 4.03, 27 March 1987; Reference 2.5.3-1). Twenty-eight earthquakes between **M**2.9 and 4.0 have been recorded within the site vicinity; of these 28, four have occurred within the site area (Figure 2.5.3-5).

Instrumentally located epicenters within the ETSZ indicate that the overwhelming majority of earthquake hypocenters are located in Neoproterozoic (approximately 1.1 Ga) basement rocks beneath the 5-km (3 mi) thick Paleozoic foreland fold-thrust belt (Reference 2.5.3-2). The mean focal depth of earthquakes within the ETSZ is approximately 15 km (9 mi) (Reference 2.5.3-2). These earthquakes have been correlated with potential aeromagnetic anomalies (mostly the NY-AL lineament) and associated with alternative tectonic models (References 2.5.3-30; 2.5.3-27; 2.5.3-28; 2.5.3-2; 2.5.3-31; 2.5.3-32; 2.5.3-29; and 2.5.3-33). The vast majority of ETSZ earthquakes with instrumental hypocenters have depths below the detachment (approximately 3 km [2 mi] below the site), and, of the few known to have more shallow depths, none have been correlated with known faults exposed near the ground surface.

2.5.3.4 Ages of Most Recent Deformation

2.5.3.4.1 Bedrock Faults

Multiple lines of evidence suggest bedrock thrust faults in the Valley and Ridge were active during the late Paleozoic Alleghanian orogeny (discussed in Subsections 2.5.1.1.2, 2.5.1.1.4, 2.5.1.2.4, and 2.5.3.2.1). ^{40}K/^{40}Ar and ^{40}Ar/^{39}Ar geochronologic analyses of fault gouge from the Copper Creek fault yielded ages of 280 to 290 and 279.5 ± 11.3 Ma, respectively, which support this timing (Reference 2.5.3-6; Reference 2.5.3-17). In the site vicinity, there is no evidence for later reactivation of these structures. Mesozoic faults, basin fill, and volcanic intrusions associated with the breakup of Pangea are generally restricted to areas more proximal to the Atlantic coast at the latitude of the site, which prohibits the direct observation of any crosscutting relationship near the site. However, several undeformed diabase dikes crosscut Valley and Ridge structures in the central Appalachians (central Virginia and Pennsylvania), which supports thrusting along those faults and associated folding occurred prior to approximately 200 Ma (see Subsection 2.5.1.1.4.1.3). Additionally, high-resolution LiDAR data yielded no evidence of deformation where Pleistocene and Holocene river terraces overlie major bedrock thrust faults in the site area, lending further support to the hypothesis that these faults are not active. Based on the available data, the most recent deformation of Valley and Ridge thrust faults within the site region occurred during the late Paleozoic.

The CRBRP PSAR also evaluated the potential for surface faulting along these structures, and, based on similar evidence presented herein (fault gouge geochronology, crosscutting relationships with surficial material), determined that they were not capable tectonic sources and likely last active during the Alleghanian orogeny (Reference 2.5.3-6). The safety evaluation report issued by the NRC in response to the licensing application for the CRBRP agreed with this conclusion (Reference 2.5.3-34).

2.5.3.4.2 Shear Fracture Zones

The formation of the shear fracture zones encountered in the Lincolnshire (Eidson Member), Benbolt, and Rockdell Formations likely coincides with deformation associated with the Alleghanian orogeny, based on the truncation of calcite-filled fractures by stylolites (Reference 2.5.3-6). Stylolites in the Valley and Ridge province can be diagenetic or tectonic in origin (Reference 2.5.3-35), although the nature of the stylolites that truncate shear fracture zone fabric is not discussed in the CRBRP PSAR (Reference 2.5.3-6). While it is permissible that tectonic stylolites in Valley and Ridge carbonate rocks in eastern Tennessee developed during the Mesozoic breakup of Pangea, it is more likely that they developed during intense shortening related to the Alleghanian orogeny. Evidence for compressional deformation associated with Pangea breakup (related to the rift-to-drift transition) is mostly confined to Mesozoic rift basins in the southern Appalachians (Reference 2.5.3-37, 2.5.3-39, and 2.5.3-41), whereas evidence for compressional deformation related to the Alleghanian orogeny extends well into the continental interior (Reference 2.5.3-43).

Bed-parallel slickensided veins described by Foreman and Dunne (Reference 2.5.3-19) also were noted to almost ubiquitously cut bed-normal fractures that demonstrably formed prior to the Alleghanian orogeny (see Subsection 2.5.1.2.4.3.3). Reference 2.5.3-19 concludes bed-parallel slickensided veins formed during the Alleghanian orogeny based on (1) slickensides parallel slip-directions of Alleghanian thrust faults, and (2) pervasive twinning of calcite vein fill (see Subsection 2.5.1.2.4.3.4).

2.5.3.4.3 Karst Collapse

Carbonate dissolution and the development of karst features are ongoing processes. Subsidence of Quaternary terrace material within the site area that overlies carbonate units indicates these processes have locally been active through the Holocene (see Subsection 2.5.1.2.5 for more detailed discussion of karst features).

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

Alleghanian bedrock faults that occur within the CRN site area (Copper Creek and Whiteoak Mountain faults, Figure 2.5.1-35) are part of the more regional Valley and Ridge foreland fold-thrust belt system. Faults of this nature (northeast-striking, southeast-dipping thrust faults) occur along orogenic strike from northeastern Alabama to eastern Pennsylvania (see Subsection 2.5.1.1.4). These faults are demonstrably late Paleozoic in age, and the evidence for this timing is discussed thoroughly in Subsection 2.5.1 and Subsections 2.5.3.2.1 and 2.5.3.4.1. Valley and Ridge thrust faults exposed at the ground surface generally have a listric geometry (shallow with depth) and sole into the master Appalachian detachment at the base of the Paleozoic passive margin sedimentary section (see Subsections 2.5.1.1.4 and 2.5.1.2.4 for more detailed discussion). Earthquakes associated with the ETSZ occur in crystalline basement rocks below the Appalachian detachment, 5 to 26 km (3 to 16 mi) deep (Reference 2.5.3-38).

Therefore, Alleghanian bedrock thrust faults exposed in the site area are not related to seismicity associated with the ETSZ.

2.5.3.6 Characterization of Capable Tectonic Sources

Based on the analysis and results presented in Subsections 2.5.1, 2.5.3.2, and 2.5.3.5, there is no evidence for significant neotectonic features within the 200-mi CRN site region radius that have a potential to impact site safety. Alleghanian bedrock faults in the valley and ridge are demonstrably late Paleozoic in age, and the evidence for this timing is discussed thoroughly in Subsection 2.5.1 and Subsections 2.5.3.2.1 and 2.5.3.4.1. Regional geologic mapping and longitudinal profiles along the Clinch River using high-resolution LiDAR data (described in Subsection 2.5.3.2.5) indicate that there has not been discernible displacement resulting from Quaternary movement along faults in the site area. Additionally, there is no evidence that ETSZ earthquakes are related to faults at the ground surface.

Seismicity in the site region is elevated near the CRN Site and is associated with the ETSZ. Seismicity within the ETSZ is included in a larger seismic source area described in Subsection 2.5.2.2. Four earthquakes with **M** ≥ 2.9 and < 3.6 have been recorded within the CRN site area (Figure 2.5.3-5), three of which have occurred since 1982.

Earthquakes associated with the ETSZ are likely related to present-day compressive stresses present throughout eastern North America (Reference 2.5.3-36). Chapman et al. (Reference 2.5.3-38) found ETSZ focal mechanism solutions to be bimodal based on statistical analyses. One group includes right-lateral motion on north-trending nodal planes and left-lateral motion on east-trending nodal planes. The second group includes right-lateral motion on northeasterly trending nodal planes and left-lateral motion on southeasterly trending nodal planes. Chapman et al. (Reference 2.5.3-38) proposed: (1) that the earthquakes have occurred primarily through left-lateral motion on east-west trending faults that are east of and adjacent to the NY-AL lineament, and (2) that the preferred orientation of focal mechanism nodal planes and epicenter alignments suggest seismicity is distributed over a series of northeast-trending, en-echelon segments and is structurally controlled by basement faults. Chapman et al. (Reference 2.5.3-29) suggested that these linear segments and the locations of their terminations may reflect basement fault structure that is being reactivated in the modern stress regime by the presence of a weak lower crust and/or increased fluid pressures within the upper to middle crust, as indicated by the anomalously low velocities within the seismic zone. Chapman et al. (Reference 2.5.3-29) suggested a slight correlation may exist between the seismicity, the major drainage pattern, and the general topography of the region, which could result from a hydrological element linkage (Reference 2.5.3-40).

Steltenpohl et al. (Reference 2.5.3-33) attributed seismicity in the ETSZ to the N15°E magnetic grain of hypothesized metasedimentary gneisses of the buried Ocoee block correlative with the Amish anomaly. Additionally, Steltenpohl et al. (Reference 2.5.3-33) proposed that the stress that initiated dextral motion along the NY-AL lineament and the modern stress field are compatible. Long and Zelt (Reference 2.5.3-42), Long and Kaufmann (Reference 2.5.3-44), and Kaufmann and Long (Reference 2.5.3-31) proposed an alternative interpretation of seismicity and velocity structures in the ETSZ, in which the majority of seismicity is concentrated in areas of low velocity at midcrustal depths and is not associated with major crustal features, such as distinct crustal blocks defined by the NY-AL lineament. This alternative model suggests intraplate earthquakes occur in midcrustal zones of weakness that may result from increased fluid content in the crust (Reference 2.5.3-42).

Investigations and subsequent evaluation of potential tectonic features associated with the ETSZ described by Hatcher et al. (Reference 2.5.3-12) and Warrell (References 2.5.3-13 and 2.5.3-14) are thoroughly discussed and evaluated in Subsections 2.5.2.2.5.1 and 2.5.2.2.6.1.3. Based on field inspection and review, nearly all the features interpreted as paleoseismic in origin can also be explained by other plausible, non-seismic processes.

2.5.3.7 Designation of Zones of Quaternary Deformation in the Site Region

There are no zones of Quaternary deformation associated with tectonic faults that require detailed investigation within the CRN site vicinity or site area (see Subsection 2.5.3.2). However, three possible Quaternary fault systems occur within the CRN site region (Kentucky River fault system, Rough Creek-Shawneetown fault system, and several unnamed Quaternary faults in western North Carolina; References 2.5.3-45 and 2.5.3-46). Van Arsdale (Reference 2.5.3-47) correlates the Kentucky River and Rough Creek-Shawneetown fault systems.

The Kentucky River fault system is an east-northeast-trending system in northeastern Kentucky (see Figure 2.5.1-18, Sheet 1); at its closest extent, the Kentucky River fault system is approximately 125 mi from the CRN Site. Zeng et. al. (Reference 2.5.3-48) demonstrated the Kentucky River fault system was active as a growth fault during the Carboniferous based on thickening sequences of carbonate strata buttressed against the fault zone. Van Arsdale (Reference 2.5.3-47) indicated that faults appear to offset Pliocene-Pleistocene terrace deposits in a reverse sense, based on evidence from exploratory trenches at several sites in north-central Kentucky (Reference 2.5.3-47). Crone and Wheeler (Reference 2.5.3-45) suggest evidence of Quaternary deformation from exploratory trenches on the Kentucky River fault system could also be related to karst collapse of underlying carbonate bedrock. Crone and Wheeler (Reference 2.5.3-45) classified the Kentucky River fault system as a Class B feature, which is defined as follows:

> “Geologic evidence demonstrates the existence of a fault or suggests Quaternary deformation, but either (1) the fault might not extend deeply enough to be a potential source of significant earthquakes, or (2) the currently available geologic evidence is too strong to confidently assign the feature to Class C but not strong enough to assign it to Class A.”

The Rough Creek-Shawneetown fault system occurs in west-central Kentucky, approximately 125 mi northwest of the CRN Site (see Figure 2.5.1-18, Sheet 1). Bedrock steps beneath Pliocene(?)-Holocene alluvium have been suggested to represent Holocene reactivation of Neoproterozoic-early Paleozoic Rough Creek graben normal faults (see Reference 2.5.3-45 and references therein). However, no evidence of Quaternary faulting has been reported in the Rough Creek-Shawneetown fault system, and Krausse and Treworgy (Reference 2.5.3-49) and Thomas (Reference 2.5.3-50) suggest a late Paleozoic age (see Subsection 2.5.1.1.4.1.1). The Rough Creek-Shawneetown fault system is therefore classified by Crone and Wheeler (Reference 2.5.3-45) as Class C, meaning:

> “Geologic evidence is insufficient to demonstrate (1) the existence of tectonic fault, or (2) Quaternary slip or deformation associated with the feature.”

Prowell (Reference 2.5.3-46) reported three localities small faults near Saluda, North Carolina, that appear to offset alluvial and colluvial deposits interpreted as Quaternary (Figure 2.5.1-18). These faults are described as reverse, strike-slip, tear and normal faults, with apparent vertical offsets of 4 m (reverse) and 5 m (normal) (Reference 2.5.3-46). These faults were originally identified by Conley and Drummond (Reference 2.5.3-51) and later revisited by York and Oliver (Reference 2.5.3-52). Although these are identified as Quaternary features, they were not evaluated by Crone and Wheeler (Reference 2.5.3-45) or Wheeler (Reference 2.5.3-53). The closest of this group of faults is approximately 118 mi southeast of the CRN Site (Figure 2.5.1-18).

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

2.5.3.8.1 Potential for Tectonic Deformation

The potential for tectonic surface deformation at the CRN Site is negligible based on evidence presented herein. Although the site lies within the boundary of the ETSZ, earthquakes occur below the Paleozoic foreland-fold thrust belt, and no Quaternary tectonic faults are exposed within the site area or site vicinity. Detailed mapping of the excavation(s), as called for in Subsection 2.5.1.2.6, will help to confirm the negligible potential for tectonic deformation of the CRN Site.

2.5.3.8.2 Potential for Non-Tectonic Deformation

2.5.3.8.2.1 Karst-Related Deformation

The potential for non-tectonic surface deformation as a result of karst features represents the most significant geologic hazard to the CRN Site. A more comprehensive assessment of karst hazards at the CRN Site is addressed separately in Subsection 2.5.1.2.5.

The site consists of thick residual soils that cover an irregular bedrock surface of slots and pinnacles. Fifteen stratigraphic units, most of which are calcareous, comprise the bedrock geology at the site (see Figure 2.5.1-28). The planned site construction will bear on the middle Chickamauga to upper Knox Group bedrock units. Overburden soils and cavities associated with dissolution near the top of rock will be removed during the excavation process, thereby mitigating hazard of a cover-collapse or subsidence sinkhole. However, cavities have been observed in boreholes as deep as 660 ft elevation (see Subsection 2.5.1.2.5; Figure 2.5.1-52); these cavities and karst conditions pose four types of hazards to the proposed construction:

- The ground surface may experience collapse or subsidence from sinkholes. Cover-collapse and cover-subsidence sinkholes are present in the landscape (see Subsection 2.5.1.2.5), and additional sinkholes may develop during the lifetime of the plant. Construction activities such as grading, which thins the soil overburden; loading from buildings, roads, and waste ponds, or changes in groundwater levels, can trigger new sinkholes. The site area karst features inventory shows that several of the lithologic units are especially prone to sinkhole development (see Subsection 2.5.1.2.5).

- The potential presence of cavities in the excavation walls below the groundwater table may pose a hazard to the safety of the excavation. Groundwater may discharge from the cavities, making it difficult to maintain a dry excavation, and the water may affect slope stability. The CRBRP PSAR (References 2.5.3-5 and 2.5.3-6) anticipated this problem, although records indicate that excavation had been relatively dry (Reference 2.5.3-54). Subsections 2.5.1.2.5.1.3, 2.5.1.2.6.10, and 2.5.4.12 discuss mitigation strategies that will be employed prior to and during the excavation.

- The presence of cavities below the base of the foundation would compromise the structural stability of the foundation. As discussed in Subsection 2.5.1.2.5, slightly deeper cavities that cannot be seen may be detected using geophysical methods or boreholes in the finished excavation. Final conclusions regarding karst hazard should be based on detailed geologic mapping of the excavations and geophysical surveys at foundation level (see Subsection 2.5.1.2.6.10).

- The presence of cavities may enable rapid movement of groundwater through the underground karst drainage system.

2.5.3.8.2.2 Slope Failure

Reconnaissance geologic mapping, aerial photograph analysis, and slope analysis using high-resolution LiDAR digital elevation data revealed no existing landslides or other slump-related hazards at the CRN Site.

2.5.3.8.2.3 Anthropogenic Features

The CRN Site has never been commercially mined; there is no potential hazard from mine collapse (see Subsection 2.5.1.2.6.8). The previous grading/excavation of the CRBRP may contain unengineered fill and will be evaluated for any future development.

2.5.3.9 References

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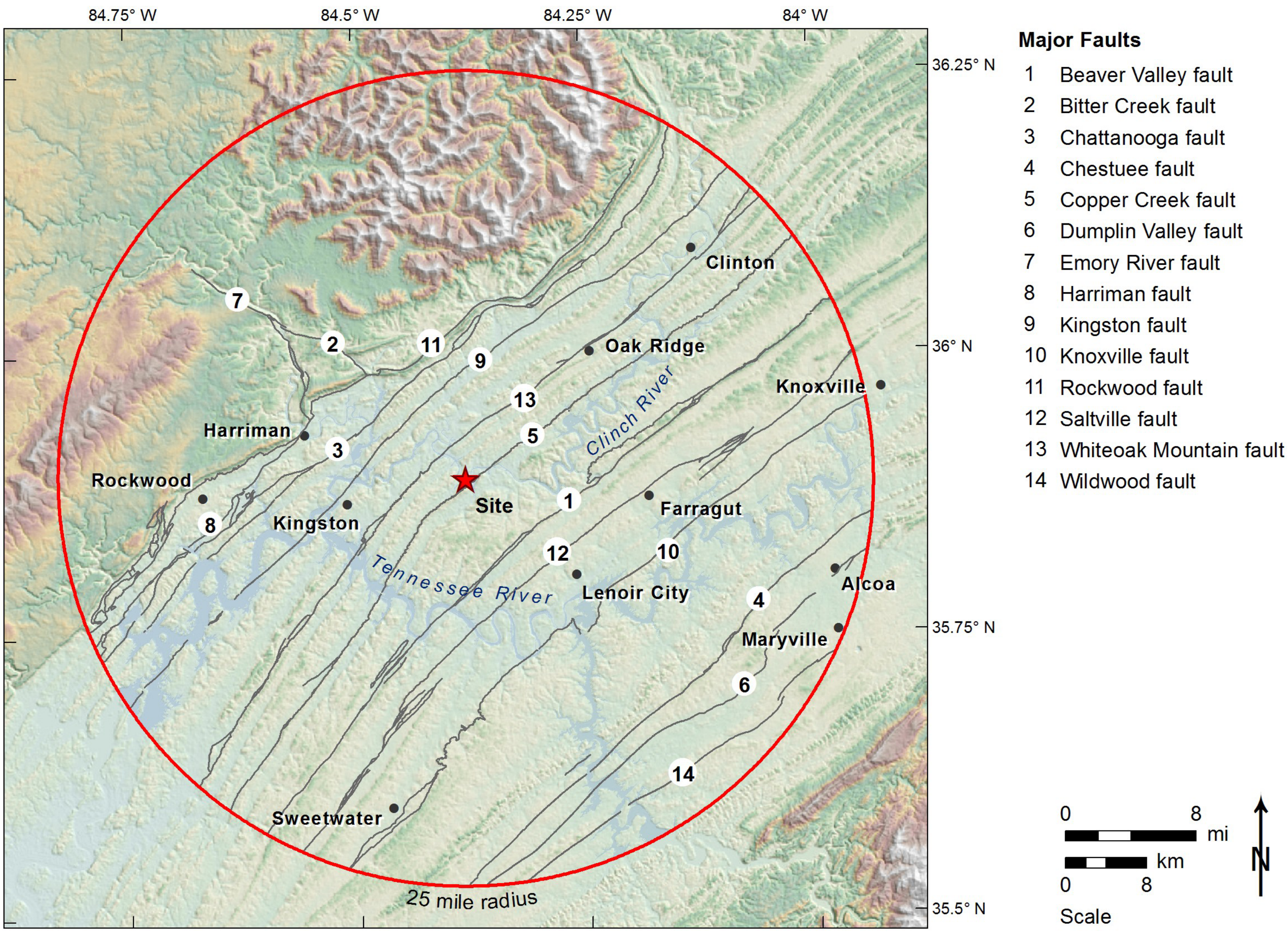

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Figure 2.5.3-1. Shaded Relief Map of the Site Vicinity Illustrating the Relationship Between Physiography and Major Thrust Faults of the Pennsylvanian to Permian Alleghanian Orogeny

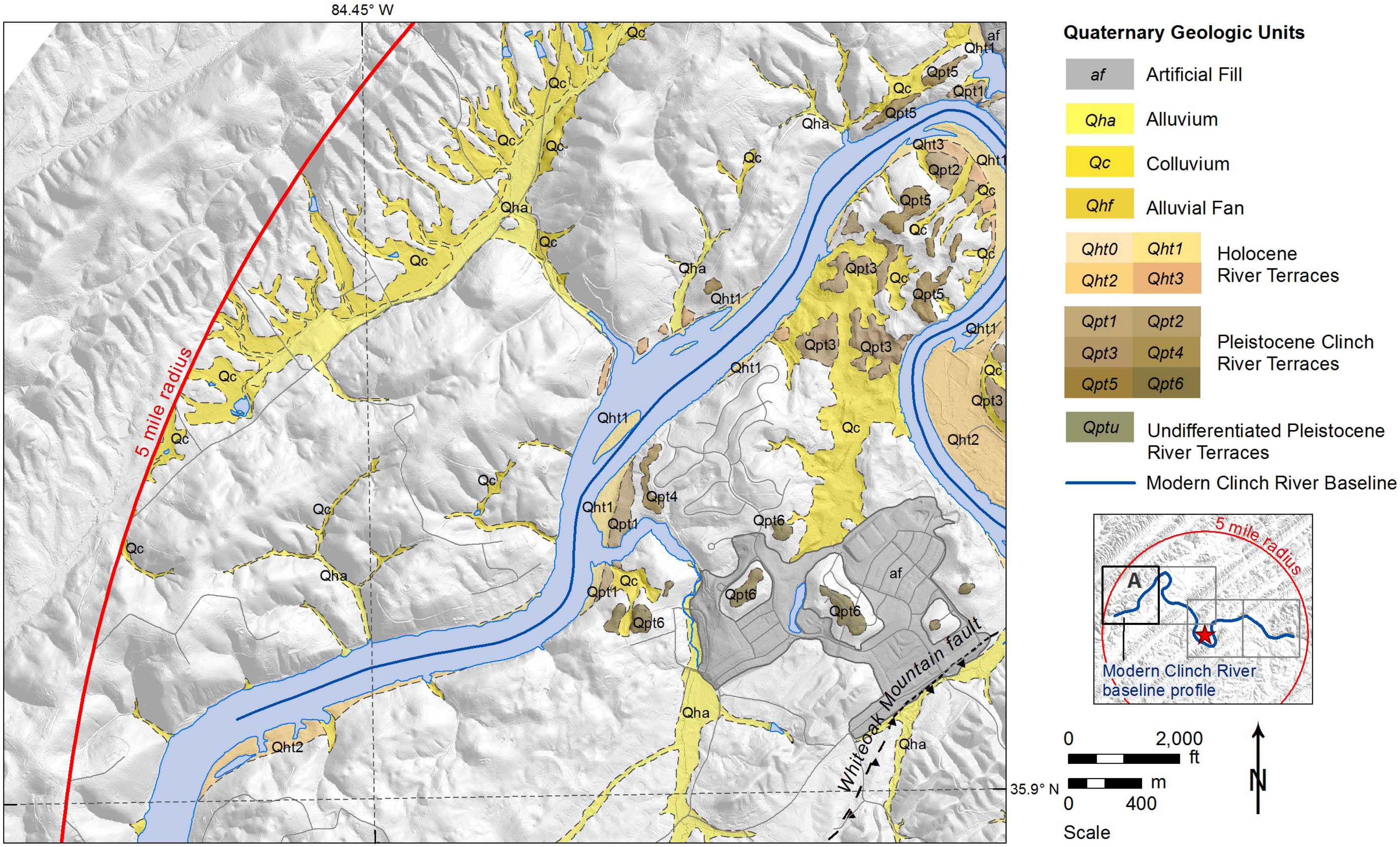


Figure 2.5.3-2. (Sheet 1 of 4) Quaternary Terrace Map Adjacent to the Clinch River Arm of the Watts Bar Reservoir Within the Clinch River Nuclear Site Area, Location A

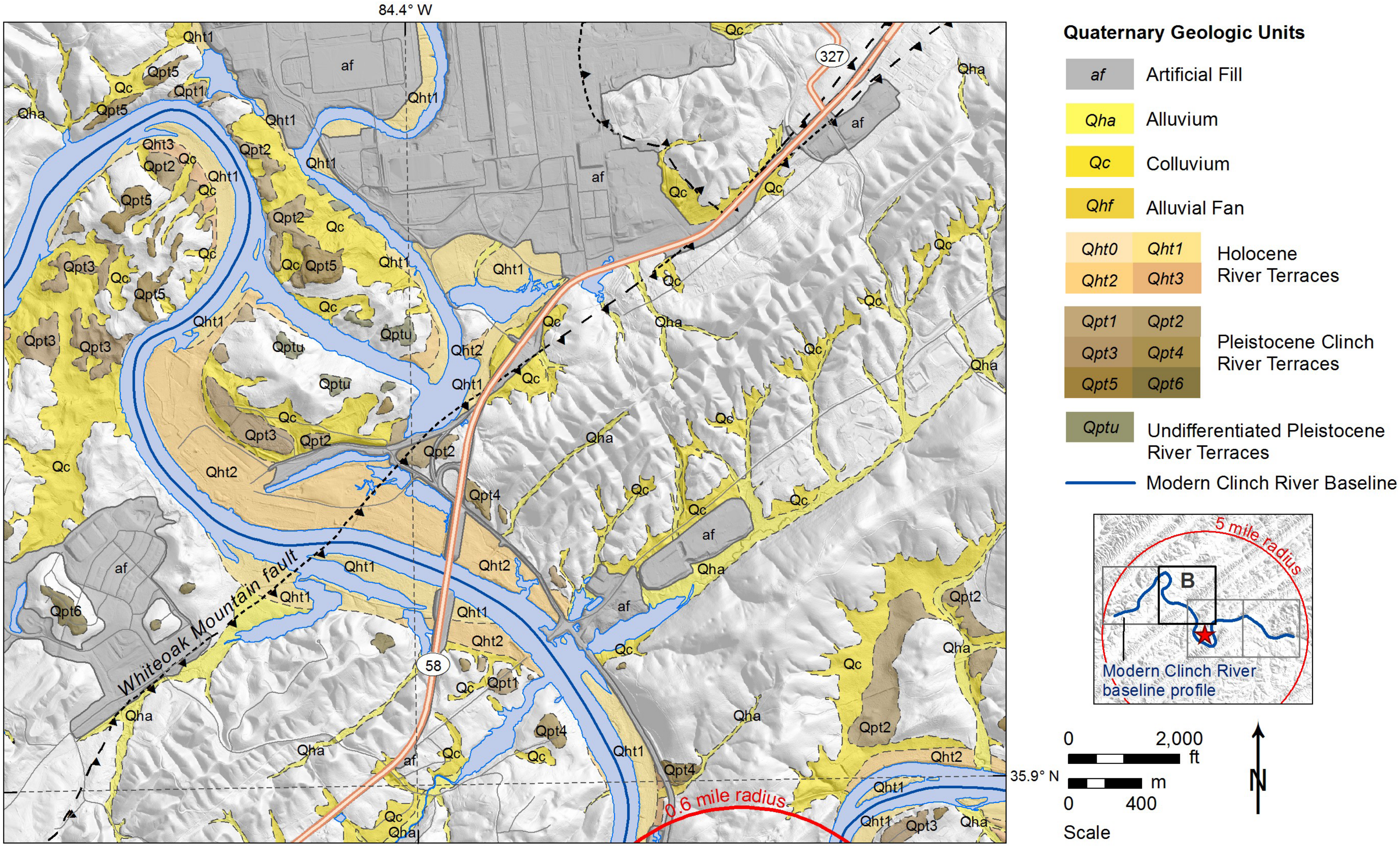


Figure 2.5.3-2. (Sheet 2 of 4) Quaternary Terrace Map Adjacent to the Clinch River Arm of the Watts Bar Reservoir Within the Clinch River Nuclear Site Area, Location B

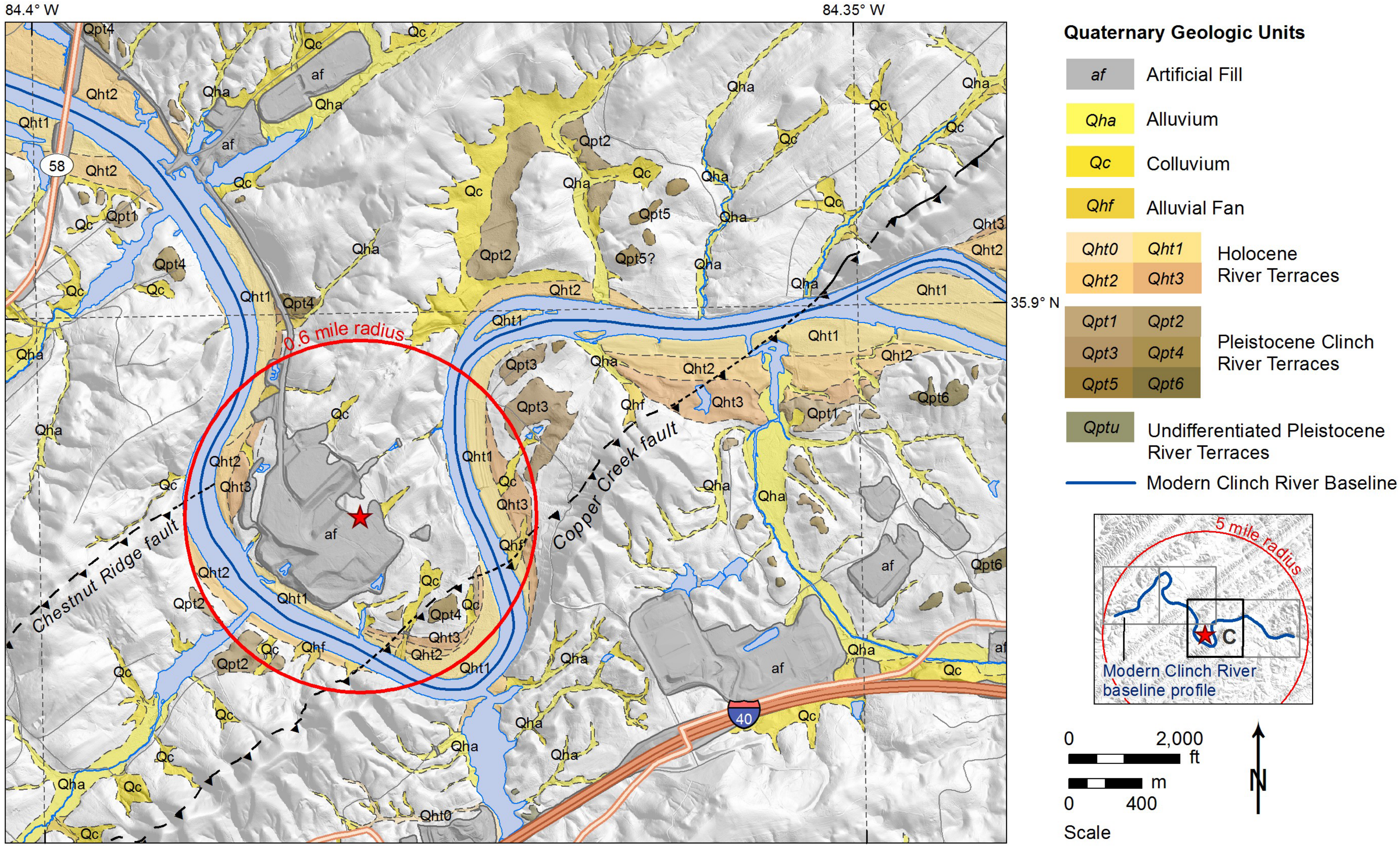


Figure 2.5.3-2. (Sheet 3 of 4) Quaternary Terrace Map Adjacent to the Clinch River Arm of the Watts Bar Reservoir Within the Clinch River Nuclear Site Area, Location C

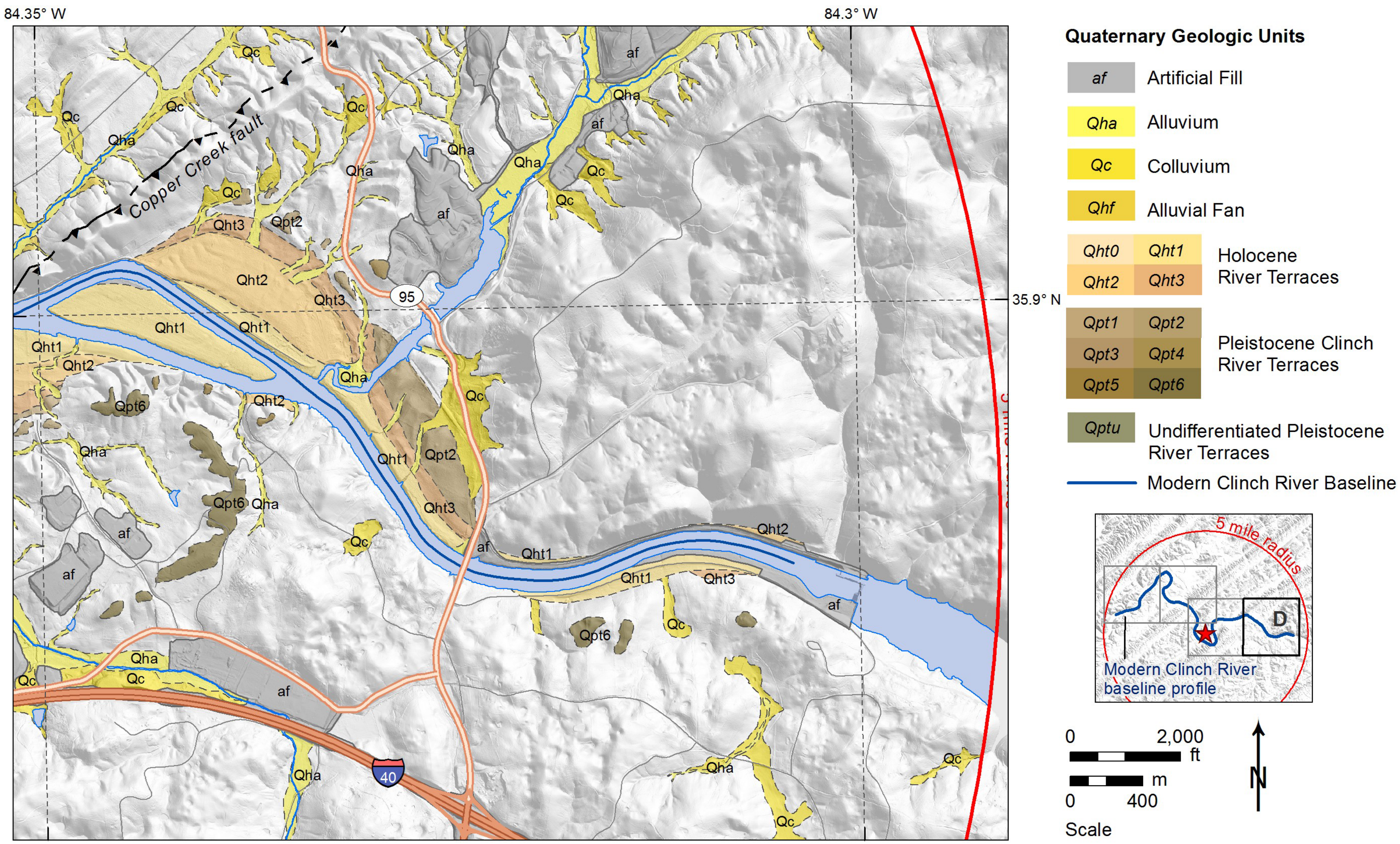
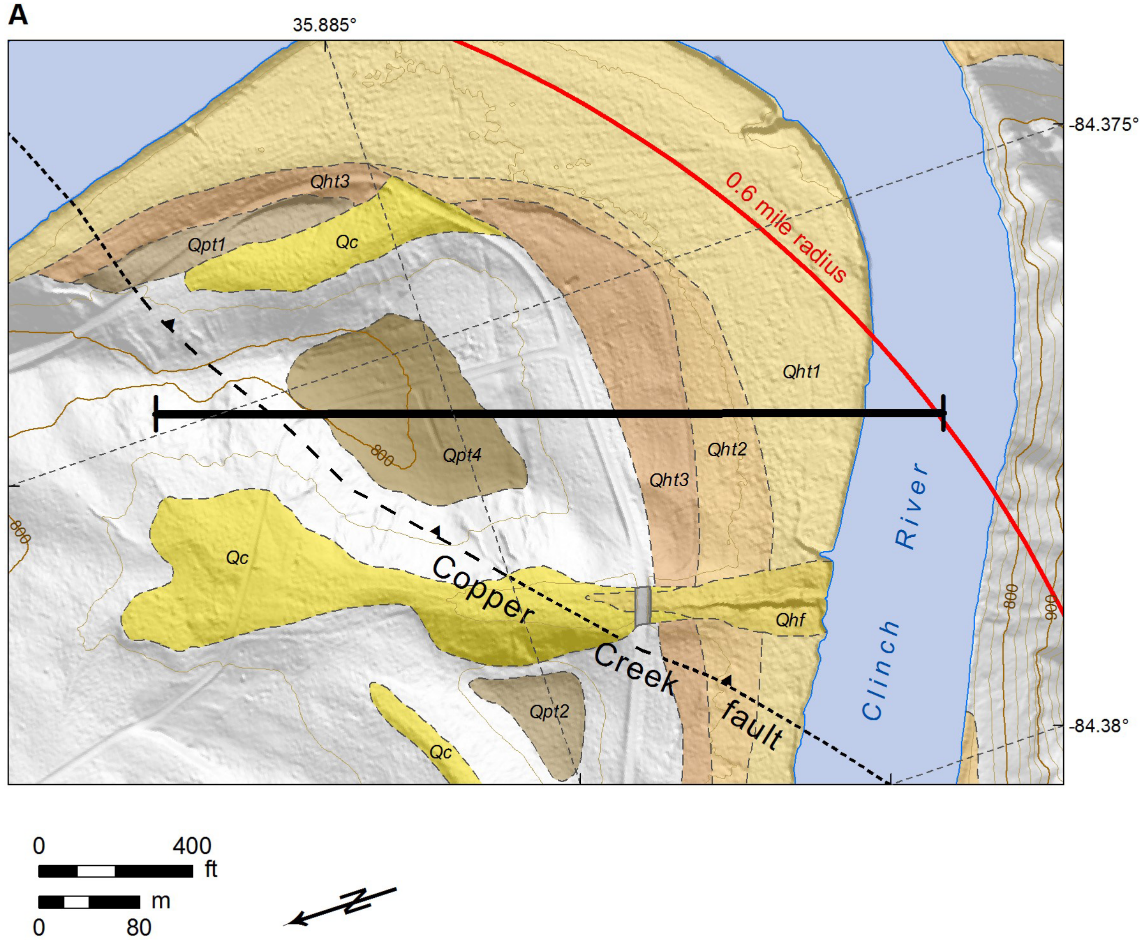
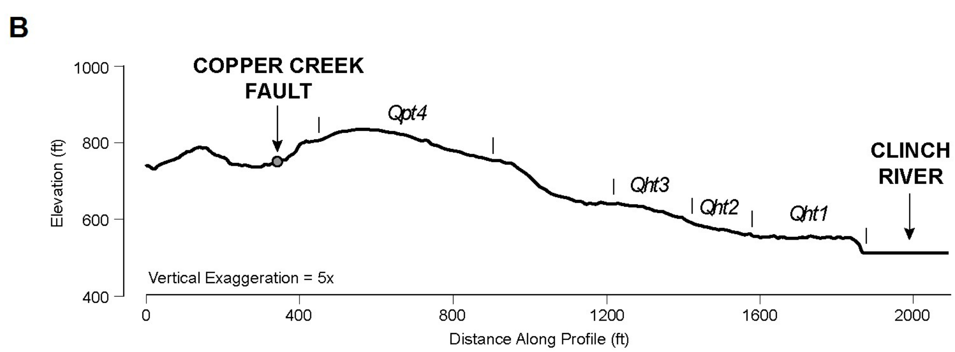


Figure 2.5.3-2. (Sheet 4 of 4) Quaternary Terrace Map Adjacent to the Clinch River Arm of the Watts Bar Reservoir Within the Clinch River Nuclear Site Area, Location D



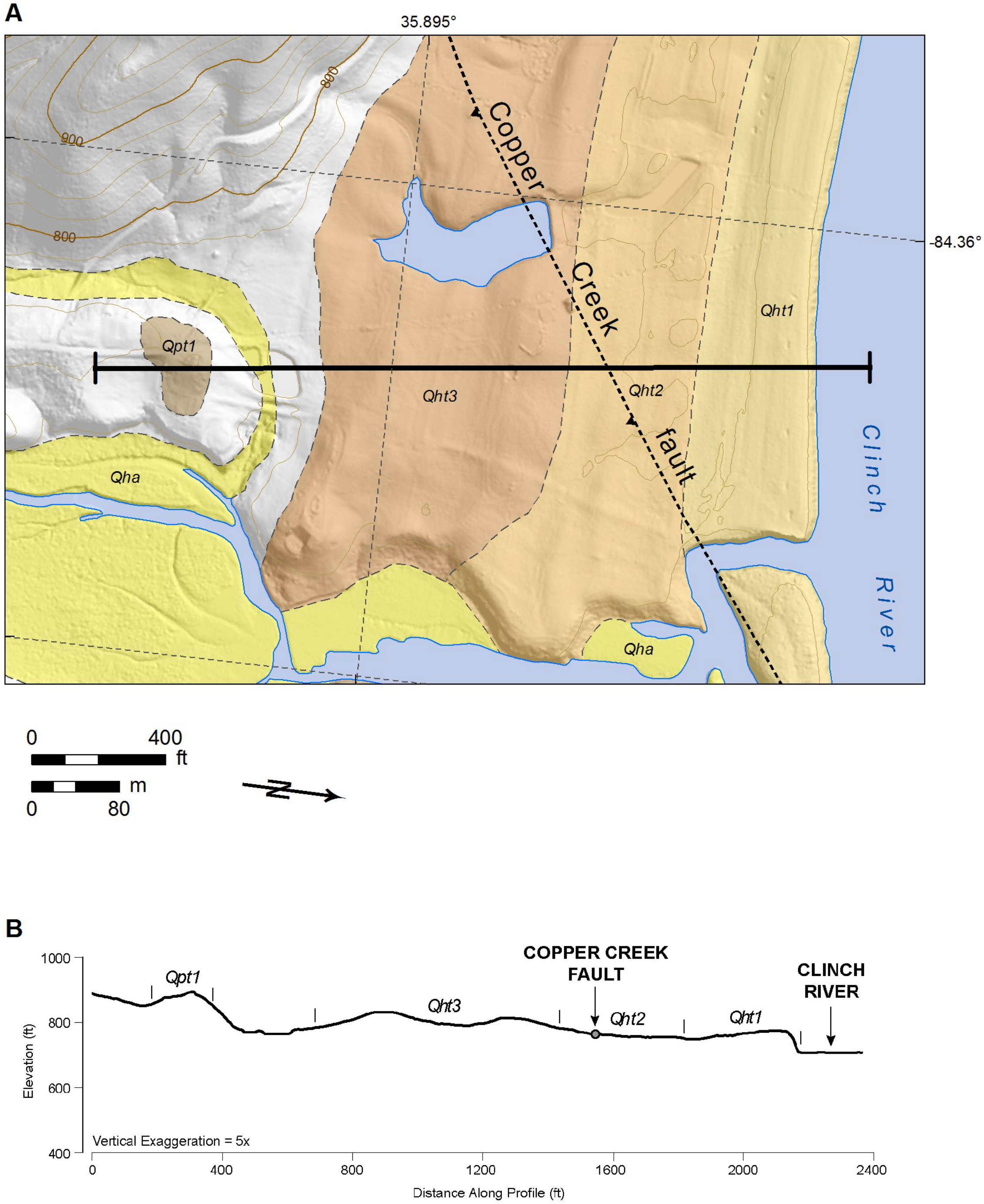


Notes:

A = Map of Clinch River terraces that overlie the Copper Creek fault

B = Topographic profile across terraces and Copper Creek fault

Figure 2.5.3-3. (Sheet 1 of 2) Clinch River Terraces that Overlie the Copper Creek Fault



Notes:

A = Map of Clinch River terraces that overlie the Copper Creek fault

B = Topographic profile across terraces and Copper Creek fault

Figure 2.5.3-3. (Sheet 2 of 2) Clinch River Terraces that Overlie the Copper Creek Fault

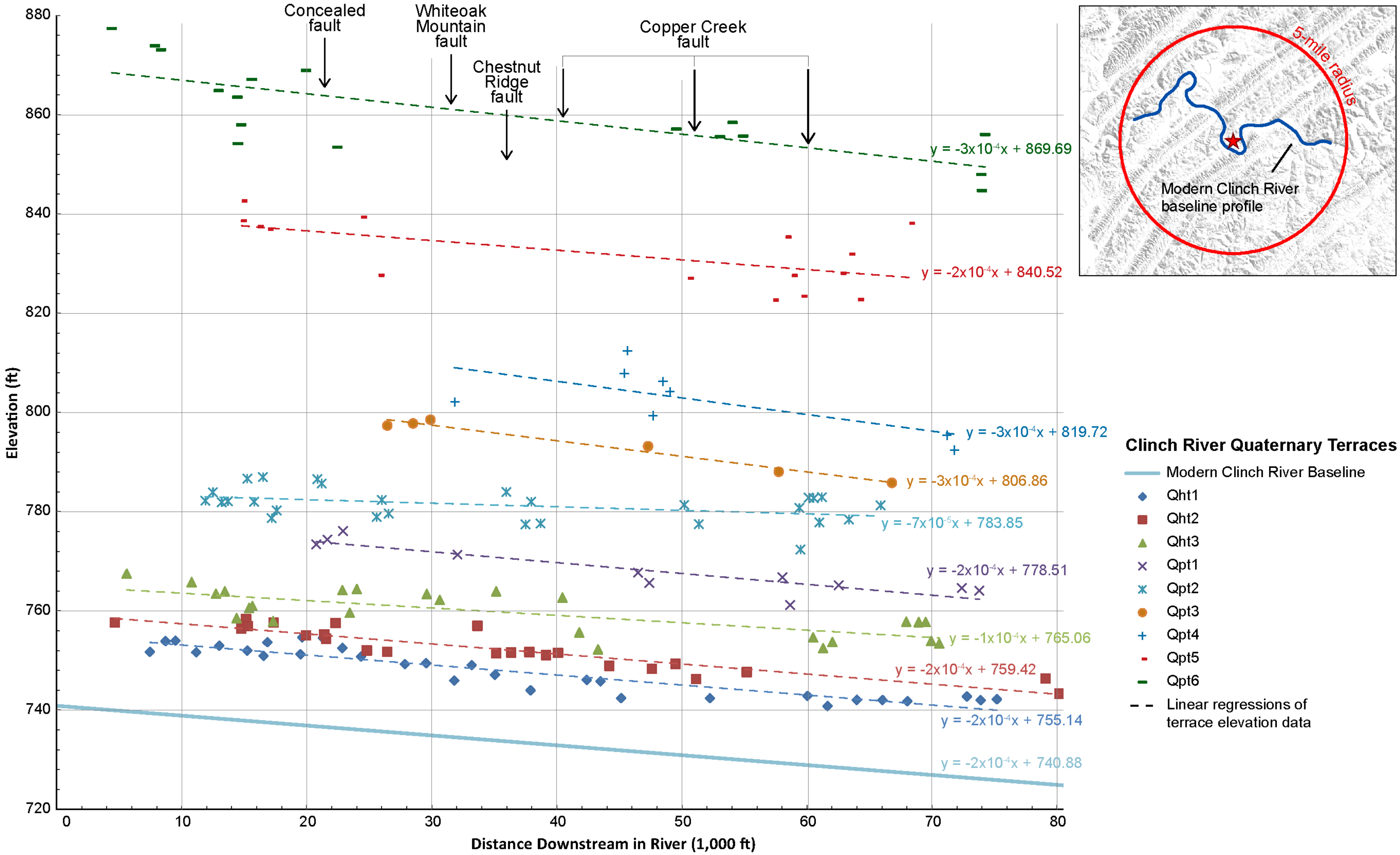
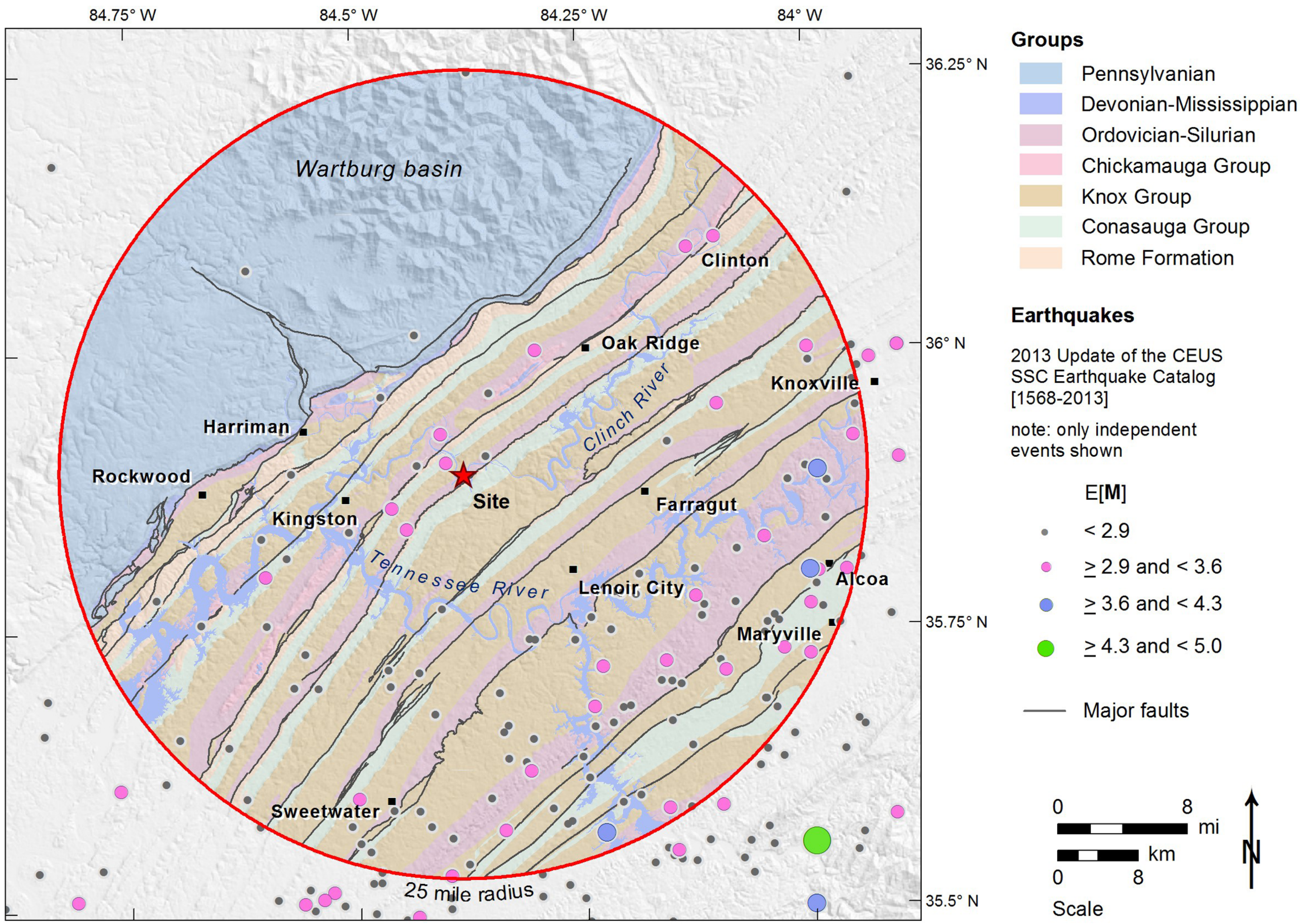


Figure 2.5.3-4. Longitudinal Profiles of Quaternary Terraces Along the Clinch River



Source: Reference 2.5.3-55

Figure 2.5.3-5. Seismicity within the Clinch River Nuclear Site Vicinity