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2.5 Geology, Seismology, and Geotechnical Engineering

This section of the SAR presents information on the geological, seismological, and geophysical characteristics of the Site Region (200-mile radius), Site Vicinity (25-mile radius), Site Area (5-mile radius), and Site Location (0.6-mile radius) (Figure 2.5-1). This information was used to evaluate geologic and seismic hazards at the location of the proposed new unit at the Grand Gulf Nuclear Station and to develop the Safe Shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE) ground motions. These analyses were performed in accordance with the applicable federal regulations and regulatory guidelines described in Section 1.3 of this report, and which are summarized below.

- Federal regulation 10CFR52 - "Early Site Permits, Standard Design Certifications, and Combined Licenses for Nuclear Power Plants" requires that the ESP application contain a description and safety assessment of the site on which the facility is to be located, including seismic, hydrologic, and geologic characteristics (Reference 1).
- 10CFR52 references Appendix S of 10CFR50 - "Earthquake Engineering Criteria for Nuclear Power Plants", which provides requirements for development of the Safe Shutdown Earthquake ground motions (Reference 2).
- 10CFR100 "Reactor Site Criteria", Part 23 - "Geologic and Seismic Siting Factors", sets forth the principal geologic and seismic considerations required to demonstrate the suitability of a proposed site and adequacy of the design basis in consideration of the geologic and seismic characteristics of the proposed site for the new facility (Reference 3).

The ground motion analysis was performed in compliance with Regulatory Guide (RG) 1.165 – "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion" (Reference 4). This guide provides detailed methodology and guidance to satisfy the requirements of 10CFR52, Appendix S of 10CFR50, and 10CFR100 Part 23 for the assessment of ground motions at the site.

Detailed site investigations and laboratory analyses completed to evaluate site conditions in accordance with RG-1.165 were performed following the methodology provided in:

- Draft Regulatory Guide, DG-1101 (the proposed revision to RG-1.132), Site Investigations for Foundations of Nuclear Power Plants (Reference 5); and,
- Draft Regulatory Guide, DG-1109 (the proposed revision to RG-1.138), Laboratory Investigations of Soils and Rocks for Engineering Analysis and Design of Nuclear Power Plants (Reference 6).

These investigations and analyses were performed to support evaluation of ground motion site response and to provide a preliminary assessment of geotechnical parameters (i.e. modulus reduction) at the site. A detailed geotechnical evaluation of the site as required for full compliance of DG-1101 (RG-1.132) will be performed following selection of the final site design and footprint of the facility.

Ground motion site response was evaluated following the methodology provided in NUREG/CR-6728 (Reference 7).

Regulatory Guide 1.165 recommends that a probabilistic seismic hazard assessment (PSHA) be performed to define the median rock ground motion at the site that has an annual probability of exceedance of not greater than 10^{-5}, and for soil sites, that a site response analysis be performed to develop the SSE ground motion. RG-1.165 further recommends that the applicant may use either the Lawrence Livermore National Laboratory (LLNL) or Electric Power Research Institute (EPRI) PSHA methodology to develop the median 10^{-5} rock ground motion at the site. Either of these methodologies may be used provided that a thorough review of geological, seismological, and geophysical data and information published since the LLNL, 1993 (Reference 10) or EPRI 1986 (Reference 9) studies does not show significant change in either the seismic source model or ground motion model. If changes have occurred then an updated LLNL or EPRI model should be used to perform the PSHA.

For this ESP application, the EPRI methodology (Reference 11) was adopted for developing the 10^{-5} median rock ground motion at the site. Because most of the seismic source characterization for the EPRI study occurred in 1985, data and information published since 1985 was compiled and reviewed to evaluate the current status of scientific knowledge regarding seismic sources in the Grand Gulf Site Region (including the New Madrid Seismic Zone). This review is presented below in Section 2.5.1.

Review of data published since 1985 show that the EPRI seismic source model should be updated to include an improved understanding of the New Madrid source zone and a recently identified potential seismic source, the Saline River source zone, within the Site Region. These sources are described in Section 2.5.1 and the updated EPRI PSHA is summarized in Section 2.5.2.

In parallel with this review of the seismic source model, EPRI (Reference 13) performed a review of the 1986 EPRI SOG ground motion attenuation model. This review showed a significant change in the ground motion model for the central and eastern United States, including the Gulf Coast region. This updated model was used for the PSHA for the Grand Gulf site (Reference 14). Based on the PSHA, a site response analysis was performed to develop the SSE ground motion at the site as desired in section 2.5.2.

As recommended by RG-1.165, a site geotechnical investigation was performed to develop information on soil properties to support the ground motion Site Response analysis. These geotechnical investigations were performed following the methodologies provided in RG-1.132 and 1.138, although a full geotechnical evaluation of the site in compliance with these guides will be deferred until selection of the final plant design and footprint of the facility during the Construction and Operating License (COL) phase of the project. Results of the site geotechnical investigations are presented in Sections 2.5.1.2.5, 2.5.4, and 2.5.5.

Other geological hazards, including surface faulting, stability of subsurface materials, liquefaction, stability of slopes, and safety of embankments and dams are described in Sections 2.5.3 through 2.5.6, respectively. References of literature and data sources used in this assessment are presented in Section 2.5.7.

2.5.1 Basic Data

This section provides basic data and information on the geology, seismology, geophysics and tectonic setting of the Site Region. A detailed description of the existing site and Site Region is provided in the updated Final Safety Evaluation Report (UFSAR) for the Grand Gulf Nuclear Station (Reference 16). This information has been reviewed and approved by the NRC staff, and forms the basis for understanding the site geology.

Information contained in the UFSAR has been updated based on review of data and information published since the 1986 EPRI study (Reference 9) and discussions with current researchers familiar with the regional geology. References reviewed are listed in Section 2.7. In addition, new geologic maps showing the distribution of surficial deposits in the Site Vicinity, Site Area, and Site Location have been prepared, and new geologic cross-sections and subsurface contour maps have been prepared incorporating data from the geotechnical exploration program.

The proposed location of the new facility at the Grand Gulf Nuclear Station (Grand Gulf Site) is in west-central Mississippi adjacent to the Mississippi River floodplain (Figure 2.5-1). The Site Region is divided into both physiographic and geologic provinces and subprovinces, which are shown on Figures 2.5-2 and 2.5-3 respectively, and are summarized in Table 2.5-1.

2.5.1.1 Regional Geology

The Gulf Coastal Plain consists of two primary geological provinces, the Gulf Coast Basin and Mississippi Embayment (Figure 2.5-3). These geologic provinces encompass a variety of geologic features including localized uplifts, zones of salt migration, growth faults, pre-Quaternary tectonic faults, and basins. These provinces and geologic features are described in Section 2.5.1.1.2 and 2.5.1.1.5.

The Gulf Coastal Plain has been dominated by marine and fluvial processes along the Gulf of Mexico continental margin for several hundred million years (Reference 17). Thick sedimentary sequences deposited by the Mississippi River within the Gulf Coastal Plain played an important role in the geologic processes of the region since post-Miocene time. The distribution of major geologic features and sedimentary units in the Gulf Coastal Plain and Site Region is shown on Figures 2.5-3 and 2.5-4.

The Gulf Coast Basin contains marine sediments deposited during episodic sea-level transgressions and regressions, and terrestrial sediments deposited on river floodplains and deltas along the continental margin. The sediments are composed of sand, silt, gravel, clay, marl, limestone, salt, and chalk that range in age from Jurassic to Holocene, and form a seaward thickening wedge greater than 50,000-feet-thick near the present Gulf of Mexico coastline. Development of the thick sedimentary wedge resulted in depression of the crust within the Gulf Coast Basin to depths of up to 7 miles (Reference 18).

Global climatic changes and tectonic events played important roles in the geologic history of the Gulf Coastal Plain. Tectonic and climatic events from the eastern coast of North America to as far west as the Rocky Mountains influenced the formation of sedimentary rocks, emplacement of igneous bodies, and deformation of the crust and overlying sedimentary section in the Site Region. The principal tectonic events include: the Taconic, Acadian, and Allegheny orogenies that formed the Appalachian Mountains and the Ouachita Orogenic Belt; continental rifting that formed the Gulf of Mexico; and changes in regional stress that deformed the crust along the Reelfoot Rift and formed the Mississippi Embayment. Secondary processes such as igneous intrusion, basin settlement, and salt diapirism also played important roles in the geological development of the Site Region.

The Site Region is characterized by extremely low rates of earthquake activity (Figure 2.5-5). Previous seismic hazard investigations, such as the original licensing studies for the Grand Gulf Nuclear Station (Reference 16), the 1986 EPRI study (Reference 9), and the 2002 USGS National Seismic Hazard maps (Reference 19) all indicate that the rate of earthquake activity in the Gulf Coastal Plain is among the lowest in the United States. The geologic setting and modern tectonic framework suggest that the earthquake hazard for the Site Region will remain low for the foreseeable future. A detailed discussion of the seismological setting is presented in Section 2.5.1.1.6.

2.5.1.1.1 Regional Physiography

The Grand Gulf Site is located within the Gulf Coastal Plain physiographic province (Figure 2.5-2). The Site Region also includes the Ouachita Mountains province and a buried continuation of the Southern Appalachian province (Figure 2.5.2). The Gulf Coastal Plain province is divided into subprovinces including the Mississippi Alluvial Valley, Chenier/Delta Plain, Loess Hills, Prairie Coastwise Terrace, Southern Hills, Eastern Hills, and Western Hills.

2.5.1.1.1.1 Loess Hills Subprovince

The Grand Gulf Site straddles the margin of the Loess Hills subprovince and the Mississippi Alluvial Valley subprovince (described below; Figure 2.5-2). The Loess Hills subprovince extends along the eastern bank of the Mississippi River from Kentucky to southwestern Mississippi (Figure 2.5-2). The Loess Hills consists of an eastward thinning loess (silt) deposit that is zero to 100-feet-thick and extends 10- to 30-miles east of the Mississippi River (References 17, 21).

The topography of the Loess Hills is characterized by flat-topped ridgelines and fluvial terraces separated by deeply incised dendritic drainage systems. In the Site Vicinity, the Loess Hills vary in elevation from 100- to 300-feet above mean sea level (amsl). Erosion along the eastern edge of the Mississippi River flood plain has formed a steep escarpment along the western edge of the Loess Hills. At the Grand Gulf Nuclear Station the bluff is approximately 65- to 80-feet high.

The Loess Hills were formed through deposition of successive sheets of silt during late Quaternary time. Up to five distinct periods of loess deposition are documented. Each of these deposits are separated by leached buried soils that represent significant periods of landscape stability (Reference 20; 21). Loess deposits up to 82-feet-thick are present in the Site Vicinity. These deposits are described in Section 2.5.1.2, below.

2.5.1.1.1.2 Mississippi Alluvial Valley Subprovince

The Mississippi Alluvial Valley subprovince extends up to 80 miles west and 200 miles north and south of the proposed new facility at the Grand Gulf Nuclear Station (Figure 2.5-2). In the Site Region, the Mississippi Alluvial Valley subprovince also includes a number of interdistributary lowlands, basins and ridges. Elevations generally range from 50 to 250 feet. Higher elevations occur in tributary valleys with highs of 300 feet in the Ouachita River valley and 500 feet in the upper Red River valley near the Ouachita Mountains. The topographic highs along the Mississippi River are remnants of older alluvial deposits that mostly were eroded and removed from the valley. The valley topography is relatively flat with a gentle southward gradient and is characterized by fluvial geomorphic features typical of a braided stream and meandering river system (e.g. valley train, oxbow lakes, meander belts, and floodplains). Deposits in the Mississippi Alluvial Valley consist primarily of Pleistocene to Holocene sediments derived from the Mississippi River and its tributaries.

2.5.1.1.1.3 Eastern Hills Subprovince

The Eastern Hills subprovince lies north of the Southern Hills and east of the Loess Hills (Figure 2.5-2). The subprovince covers the area from central Mississippi and central Alabama to western Tennessee, and extends to the eastern margin of the Gulf Coastal Plain. The topography is characterized by gently rolling hills that range in elevation from 100 to 600 feet (amsl) and which gradually decrease in elevation southward. The Eastern Hills are underlain by Miocene to Paleocene sedimentary rocks and drained by tributaries of the Mississippi River.

2.5.1.1.1.4 Western Hills Subprovince

The Western Hills subprovince lies north of the Southern Hills and west of the Mississippi Alluvial Valley (Figure 2.5-2). The subprovince covers the area from central Louisiana to central Arkansas, and extends westward into eastern Texas. The topography is characterized by gently rolling hills that range in elevation from 200 to 700 feet (amsl) and gradually decrease in elevation southward. The Western Hills are underlain by Miocene to Paleocene sedimentary rocks and drained by the Arkansas River and Red River, two major tributaries of the Mississippi River.

2.5.1.1.1.5 Southern Hills Subprovince

The Southern Hills subprovince occupies the area between the Prairie Coastwise Terrace (described below) and the Eastern and Western Hills subprovinces (Figure 2.5-2). The Southern Hills cover portions of southern Mississippi, southern Louisiana, and southeastern Texas. The topography of this subprovince is characterized by gently rolling hills and flat-topped ridges that range in elevation from 50 to 500 feet, and generally decrease toward the Gulf Coast. The Southern Hills are underlain by the Miocene Catahoula Formation, and the Pliocene and Pleistocene Upland Complex.

2.5.1.1.1.6 Prairie Coastwise Terrace Subprovince

The Prairie Coastwise Terrace subprovince occupies the area south of the Southern Hills, and north of the Chenier and Delta Plain subprovinces (described below) along the Gulf Coast (Figure 2.5-2). The subprovince extends across southern Mississippi, southern Louisiana and southeastern Texas. The topography of the Prairie Coastwise Terrace is characterized by gently rolling hills and remnants of dissected terrace surfaces that range in elevation from 25 to 150 feet and gradually decrease in elevation coastward. This subprovince is underlain by terrace deposits of the late Pleistocene Prairie Complex.

2.5.1.1.1.7 Chenier Plain Subprovince

The Chenier Plain subprovince occupies the area between the Prairie Coastwise Terrace and the Gulf of Mexico (Figure 2.5-2). The subprovince extends along the Louisiana and eastern Texas coastline. “Cheniers” are abandoned beaches of the Gulf of Mexico, with large expanses of Holocene marshes that developed on prograding mudflats (Reference 17). A typical chenier ridge is less than 10-feet high, but may extend for miles or tens of miles. The topography of the Chenier Plain is characterized by low lying coastal ridges and marshes. The most prominent features are abandoned beach ridges at elevations of between sea level and 25-feet amsl. Subtle variations in elevations, on the order of inches, have a pronounced effect on vegetation and habitat in the Chenier Plain (Reference 17). The only preserved pre-Holocene features are remnants of the Prairie Coastwise Terrace and emergent landforms developed above salt dome piercement structures (Reference 17).

2.5.1.1.1.8 Delta Plain Subprovince

The Delta Plain subprovince occurs in southeastern Louisiana where the Mississippi River meets the Gulf of Mexico (Figure 2.5-2). The topography of the Delta Plain is characterized by abandoned distributary channels, distributary levee ridges, and coalescing delta complexes near the mouth of the Mississippi River. The distributary levee ridges form the most prominent topographic features, but do not exceed 10 feet elevation. Distributary channels radiate in a fan shape and form apices of delta complexes (Reference 17). The morphologic expression of the channel and distributary features become markedly less pronounced with increasing age, and eventually become buried due to coastal subsidence

2.5.1.1.2 Regional Geological Provinces

The Gulf Coastal Plain province is divided into two primary geological provinces, the Gulf Coast Basin and the Mississippi Embayment (Figure 2.5-3). Both the Gulf Coast Basin and Mississippi Embayment have distinct geological histories.

2.5.1.1.2.1 Mississippi Embayment

The Mississippi Embayment extends from the buried Ouachita Orogenic belt to the northern margin of the Gulf Coastal Plain and lies between the Appalachian Mountains in west-central Alabama and the Ouachita Mountains in southern Arkansas (Figure 2.5-3). The Mississippi Embayment formed in response to crustal downwarping associated with extension of the Reelfoot Rift (described in Section 2.5.1.1.5.4) within the North American craton during the Late Cretaceous. The Mississippi Embayment is underlain by Paleozoic strata, and igneous and metamorphic basement rocks. The structure of the embayment is characterized by a south-southwest plunging syncline that continues southward across the Gulf Coast Basin (Figure 2.5-3). The top of the Paleozoic section in the Mississippi Embayment defines a slightly asymmetric syncline: the western limb dips 0.59 degrees and the eastern limb dips 0.34 degrees. The southern portion of the Mississippi Embayment and the seismically active Reelfoot Rift lie within the northern part of the Site Region.

2.5.1.1.2.2 Gulf Coast Basin

The Gulf Coast Basin extends from the Gulf of Mexico to the buried Ouachita Orogenic Belt (Figure 2.5-3; described in Section 2.5.1.1.4.2). The Gulf Coast Basin formed during initial rifting of the Gulf of Mexico in the Triassic. As a result of continental rifting and formation of new oceanic crust, the properties of basement materials within the Gulf Coast Basin are transitional between continental and oceanic materials. In the northern part of the basin, the basement is defined as thick transitional crust reflecting continental affinity. In areas closer to the Gulf of Mexico oceanic plate the crust is defined as thin transitional crust reflecting oceanic affinity (Reference 18). The basin has been affected by a long series of tectonic, volcanic, depositional, isostatic and climatic processes, which are described in greater detail below.

The southward plunging syncline that characterizes the Mississippi Embayment projects across the Gulf Coast Basin and forms a structural downwarp that affects the depth to basement and thickness of the overlying sedimentary column. The limbs of the syncline in the Gulf Coast Basin typically dip less than 1-degree towards the synclinal axis (Figure 2.5-6).

2.5.1.1.3 Regional Geologic History

Crystalline basement of the North American craton in the central United States is wholly Precambrian in age, with the possible exception of basement rocks underlying the Gulf Coast Basin (Reference 18, 22, 23). The central United States basement complex is divided into eight major cratonic elements (Figure 2.5-7). These are the products of major Precambrian orogenic events, ranging in age from Archean (3.8 billion years) to middle Proterozoic (750 million years [Ma]; Reference 22). The North American craton is inferred to have progressively enlarged to the south and east due to lateral accretion during successively younger Precambrian orogenies (Reference 23).

Primary tectonic elements within the south-central part of the North American craton include the Reelfoot Rift complex, Paleozoic Ouachita Orogenic belt, and Appalachian Mountains (Figure

2.5-3). The Reelfoot Rift, and possibly other rift systems within the North American craton, were reactivated and experienced additional extension and intrusion during early Mesozoic time (Reference 24; 25). The similarity in ages of rift systems within the craton suggests that they initially formed as failed arms of triple junctions during an episode of late Precambrian continental fragmentation that predated the Paleozoic Ouachita and Appalachian orogenies (Reference 26). The sequence of major geological events is summarized on Figure 2.5-8.

Cratonic rocks of south-central North America extend to the southern margin of the Ouachita Orogenic Belt (Figure 2.5-7). The exact nature of the basement materials beneath the Paleozoic sediments south of the Ouachita Orogenic Belt is equivocal. However, the basement materials likely are related to formation of oceanic crust during rifting and evolution of the Gulf of Mexico (Reference 27). The Gulf of Mexico began forming in Triassic time by tensional rifting of the supercontinent Pangea and the divergent motion of the North American and Afro-South American plates (Reference 28).

As separation of Pangea continued through mid-Jurassic time, the Gulf Coastal Plain began to develop north of the Gulf of Mexico by the slow deposition of sediment on top of the Paleozoic sedimentary rocks. During the Triassic, sediments accumulated in grabens formed during rifting and block faulting, and by the mid-Jurassic, the region became a restricted seaway with evaporitic condition that accumulated more than 9,900 feet of salt deposits (Reference 28). By the late Jurassic, conditions changed to an open marine environment and resulted in the first major marine transgression into the Gulf Coast Basin and Mississippi Embayment (Reference 29). During the Cretaceous, a series of transgressive and regressive episodes, and coincident crustal subsidence caused widespread deposition of carbonates over the Jurassic sediments and salt deposits throughout the Gulf Coast basin (Reference 30).

In the Mississippi Embayment, crustal subsidence continued into the Early Cretaceous allowing marine deposition to extend further north and west towards the Ouachita Mountains (Reference 17; 32). During the mid-Cretaceous, the area was uplifted and partially eroded, although minor deposition locally occurred. During the Late Cretaceous, marine sediments lapped onto Early Cretaceous and older coastal plain sediments in response to the advance of the Gulfian Sea (Reference 17). The weight of these sediments accelerated subsidence of the Mississippi Embayment in the early part of the Upper Cretaceous. Minor transgressions and regressions of the Cretaceous Gulfian Sea caused deposition of alternating shallow and moderately deep water lithologies that are separated by unconformities. Near the end of the Cretaceous, volcanic activity and igneous intrusion formed the Sabine and Monroe Uplifts, and the Jackson Dome (Figures 2.5-3 and 2.5-4; Reference 34). These features continued to uplift into the Oligocene (Reference 34). Formation of these volcanogenic structural highs, oriented across the axis of the Mississippi Embayment, isolated the northern part of the embayment from the Gulf Coast Basin to the south (Reference 17).

During the latest Cretaceous and early Tertiary, the Laramide orogeny in western North America supplied voluminous quantities of terrigenous siliciclastic sediment to the Mississippi Embayment and Gulf Coastal Basin (Reference 35). Paleocene marine sediments of the Midway group were deposited unconformably on top of the Cretaceous sediments in the northernmost Mississippi Embayment (Reference 36). Subsidence of the Mississippi Embayment ceased in the Eocene due to a tectonic change from crustal extension to crustal shortening with development of folds and faults along the Reelfoot Rift. In Oligocene time, the locus of deposition shifted southward in response to progradation of sediments within the Mississippi Embayment. In the southern part of the basin, where the Cretaceous deposits are thickest, the weight of overlying sediments initiated the intermittent upward diapiric movement of salt plugs and folds, which eventually formed salt domes during the Tertiary (References 30; 37). Localized tensional faults are associated with the salt domes. Growth of salt domes in the Mississippi and Northern Louisiana salt basins ceased in the Oligocene (Reference 30). South of the Mississippi Embayment, in the Gulf Coast Basin, minor sea level fluctuations resulted in partial erosion of sediments.

During the Cenozoic, the rate of deposition into the Gulf Coast Basin exceeded the rate of regional subsidence, resulting in gulfward progradation of the Gulf Coastal Plain by as much as 250 miles. The rates of sedimentation, basin subsidence, and eustatic changes were not synchronous, so that transgressive and regressive cyclic deposits characterize the late Tertiary stratigraphic section. The basin depocenter, located along successive shelf edges, migrated across the Gulf Coast Basin throughout Tertiary time reflecting changing sediment sources and volumes (Reference 17; 29; 38).

Sea level retreat in the late Tertiary (Reference 39) allowed deposition of the littoral and non-marine Catahoula Formation (Miocene) and the alluvial Citronelle Formation (Pliocene) on the exposed Gulf Coastal Plain (Reference 17). The Catahoula Formation, which underlies the Site Vicinity, was deeply eroded in the Late Miocene and Pliocene (Reference 16).

During the Pleistocene, massive volumes of sediment were transported to the Gulf Coast Basin by the Mississippi River, partly in response to advances and retreats of continental glaciers (References 17; 31; 32; 40). The thickest accumulations of Pleistocene deposits occur along the present Louisiana shelf edge (Reference 41). The entire sedimentary wedge in the vicinity of the Louisiana shelf edge is on the order of 50,000-feet thick (Reference 17). Late Wisconsin sea level rise submerged the late Pleistocene continental shelf and reached its present position approximately 3,000 to 4,000 years ago, defining the current configuration of the Gulf Coast margin (Reference 17). Throughout the Quaternary, alluvial material was deposited in the Mississippi Alluvial Valley and extensive blankets of loess mantled the former ground surface (Reference 32; 21).

The prograding clastic wedge of the Mississippi delta has been affected by gravity-failure structures, such as the syndepositional growth faults observed in southern Louisiana and eastern Texas (Figures 2.5-3 and 2.5-5). The growth faults typically are oriented parallel or subparallel to the depositional strike (east-west orientation), and are characterized by (1) down-to-the-south displacement; (2) notable thickening of displaced strata on the downthrown side; (3) an increase in stratigraphic throw with depth; and (4) lack of significant seismic activity. Post-depositional gravity failures, or growth faults, also are common intra-basin structures. No surficial growth faults have been mapped at the surface closer than about 90 miles from the Grand Gulf site.

The Site Region is characterized by very low rates of historical seismicity (Figure 2.5-5). Only one earthquake of m_b 3.3 to 3.9 has been recorded within 90 miles of the site since 1777 and only 39 earthquakes $>m_b$ 3.3 have been recorded in the entire 200 mile radius area around the site since 1777. Most earthquakes in the Site Region occur in areas underlain by crystalline basement rock of the North American Craton.

2.5.1.1.4 Regional Stratigraphy

Regional stratigraphic units within the Gulf Coastal Basin are described from youngest to oldest in the following sections. Geologic maps of the Site Region (200 miles), Site Vicinity (25 miles), and Site Area (5 miles) are shown on Figures 2.5-4, 2.5-9 and 2.5-10, respectively. Cross-sections through the Site Region and Site Vicinity are shown on Figures 2.5-6, 2.5-11, and 2.5-

12. The major stratigraphic units are summarized on Figure 2.5-13. A detailed description of the Site Location stratigraphy is presented in Section 2.5.1.2.

2.5.1.1.4.1 Cenozoic Era

2.5.1.1.4.2 Quaternary System

Quaternary deposits within the Site Region occur along the Mississippi Alluvial Valley and its tributaries, the Southern Hills subprovince of the Gulf Coastal Plain, and the Loess Hills subprovince (Figure 2.5-4). Quaternary deposits predominantly include alluvial sediments related to the Mississippi River, lacustrine sediments, and eolian silt derived from sediment sources in the Mississippi Alluvial Valley (Reference 17; 32). The composition, texture and morphology of Quaternary sediments in the Site Region are strongly influenced by climatic changes and glacial cycles. The response of regional marine, alluvial, and terrestrial systems to these changes is summarized in Table 2.5-2.

In the Pleistocene, episodes of continental glaciation produced massive volumes of sediment that were transported through the Mississippi Alluvial Valley to the Gulf of Mexico (References 17; 31; 32). These sediments were deposited at various elevations due to climatic changes, local depositional environments (e.g. lakes formed behind glacial outwash deposits) and the isostatic effects of continental glaciations, sea level fluctuations, and regional epirogenic uplift. The major Holocene and Pleistocene units are described below.

2.5.1.1.4.2.1 Holocene Series

Within the Site Region, Holocene deposits include alluvium and loess that occur within the Mississippi River valley and its tributary valleys, and deltaic and beach facies within the Chenier Plain and Delta Plain (Reference 17). Holocene sediments within the Site Vicinity and Site Area include alluvium (Hal), backswamp (Hb), and a series of Mississippi meander belt (Hmm_1 to Hmm_3) deposits (Figures 2.5-9 and 2.5-10).

Holocene alluvial and deltaic deposits thicken from a few tens of feet in the northern portion of the Site Region to greater than 600 feet in the southern portion of the Site Region (Reference 16). In the Site Vicinity, the thickness of Holocene deposits in the Mississippi Alluvial Valley is on the order of 0 to 400 feet thick (Reference 17). Holocene sediments in the two main tributary valleys within the Site Vicinity, Bayou Pierre and Big Black River (Figure 2.5-9), range in thickness from 70 to 100 feet (Reference 16).

The composition of Holocene alluvial deposits varies depending on the specific type of depositional environment. The meander belt deposits commonly form an upward fining sequence that grades from a basal gravel and coarse sand into a sand facies capped by silt and clay facies (Reference 17). Backswamp deposits consist of overbank sediments (silt and fine sand) along with a large component of organic material. Lacustrine deposits are also fine grained with significant organic materials. The Chenier Plain consists of Mississippi deltaic sediments that were deposited episodically in beach environments by longshore transport (Reference 17). The thickness and areal distribution of Holocene alluvial deposits are variable and occur as interfingering lenses of sand, silt, and clay.

2.5.1.1.4.2.2 Pleistocene Series

2.5.1.1.4.2.2.1 Loess Deposits

Regionally extensive sheets of Pleistocene loess occur along the eastern edge of the Mississippi Alluvial Valley and the surrounding areas (Figure 2.5-2). The deposits also occur within the Site Vicinity and Site Area (Figures 2.5-9 and 2.5-10). Erosion along the eastern side of the Mississippi flood plain forms a prominent erosional escarpment in the loess.

Loess deposits mantle the former landscape and consist predominantly of silt with minor sand and clay fractions (Reference 44). The loess has internal stratigraphy with distinct silty layers separated by buried soils. In the Site Region, loess deposits occur in a belt up to 30 miles wide on the east side of the Mississippi River (Figure 2.5-2). These deposits unconformably overlie Pleistocene to Pliocene alluvial deposits, and Tertiary deposits in the Site Vicinity and Site Area (Figures 2.5-8 and 2.5-9).

During near-maximum to early-waning stages of glaciation, strong seasonally prevailing, north-to-northwest winds carried large quantities of silt from unvegetated areas of glacial outwash in the central United States for tens to hundreds of miles throughout the Site Region (Table 2.5-2; Reference 17). In the Vicksburg area, depositional rates for the Peoria loess (late Wisconsin age) exceeded 2 mm/yr between about 15,500 and 17,000 years ago (Reference 42). Individual loess sheets are well-sorted, massive to subtly banded, unconsolidated, tan to brown silt. The maximum thickness (75 feet) and most prominent outcrops of the loess occur east of the Mississippi Alluvial Valley in a 10 to 30 -mile-wide zone across the Site Region (Reference 17). Loess deposits thin considerably eastward and form only localized deposits outside of the Loess Hills subprovince. Four discrete loess deposits are identified in the region, including from youngest to oldest, the Peoria, Ferndale, Roxana, and Loveland loess sheets (Reference 21, 32; 43). In the Site Vicinity, only the Peoria, Roxanne and Loveland loess sheets are present.

2.5.1.1.4.2.2.2 Terrace Deposits

Pleistocene terrace deposits occur along most of the Mississippi Alluvial Valley and extend across the Site Region (Reference 17). The terraces are assigned different names in different parts of the Site Region (Figure 2.5-13). Terrace deposits that occur in eastern Texas and southwestern Louisiana include the Beaumont and Lissie terraces. Terrace deposits in southern Louisiana include the Prairie, Montgomery, Bentley, and Williana terraces. Terrace deposits in southern Arkansas, Northern Louisiana, and west-central Mississippi include valley trains, Deweyville Complex, Prairie Complex, and Intermediate Complex. In the Site Vicinity, these include undifferentiated terraces in Bayou Pierre (probable Prairie Complex) and the Pliocene to Pleistocene Upland Complex.

Investigations of the Quaternary geology of the Mississippi Alluvial Valley (Reference 17; 32; 44) resulted in major updates and refinements of the seminal work of Fisk (Reference 31). Figure 2.5-14 and Table 2.5-3 present comparisons of the proposed terrace relationships (References 31; 32). The model of Fisk (Reference 31) was revised because the sequence of continental glaciations leading to terrace formation along the Mississippi River is far more complex than thought in 1944, and the processes leading to terrace formation are better understood. Fisk's postulated model (Reference 31) involves progressive narrowing and downcutting of the Mississippi Alluvial Valley (Figure 2.5-14). However, during the Pleistocene the Mississippi Alluvial Valley progressively widened during downcutting, rather than narrowing (Reference 32). This observation indicates that the Pleistocene terraces of Fisk are now interpreted to be Pliocene to early Pleistocene age (i.e. Upland Complex). Saucier also observed that Quaternary erosional surfaces, or "strath" terraces are present in the Site Region and likely formed in response to base-level changes (Reference 17).

Early to Late Wisconsin valley train terraces occur in the northern portion of the Site Region, but not within the Site Vicinity. Five distinct levels of Early Wisconsin terraces and two distinct levels of Late Wisconsin terraces are mapped (Reference 44). The deposits consist of thin, 5- to 10-

feet thick, very silty and sandy clays, silts, and silty sands that overlie much thicker coarse grained sediments (Reference 17). The fine-grained surface and near surface deposits are slightly organic, horizontally bedded, slack-water accumulations of clays, silts, sands, loess, and local lacustrine deposits. These sediments directly overlie massive, clean sands that may be 75 to 100 feet in thickness and are indicative of high energy fluvial channel deposition. The clean sands locally overlie coarse sand and gravel, forming an upward-fining sequence.

Terrace deposits of the Deweyville Complex occur in the northwestern portion of the Site Region (Figure 2.5-4) along the Ouachita and Saline Rivers, but are not present in the Site Vicinity. The Deweyville Complex is similar in age to the Wisconsin valley train deposits, and is characterized by unique meander scars that are considerably larger than observed along the present river courses (Reference 45). There is little direct information regarding this complex (Reference 17). Based on analogy with other terrace complexes, the Deweyville Complex most likely includes multiple fluvial environments, such as point bar, backswamp, and abandoned channel. The deposits consist of a fining upward sequence approximately 100-feet thick. The coarser grained deposits of the Deweyville Complex, relative to other terrace complexes, may reflect higher stream discharges and energy levels than along the current fluvial system (Reference 32).

Terrace deposits of the Prairie Complex occur within the Site Region along the Gulf Coast from Texas to Alabama (included in unit Qp on Figure 2.5-4). The Prairie Complex includes a wide range of sediments including fluvial terrace deposits, colluvium, estuarine, deltaic and marine deposits. The Prairie Complex deposits range in age from pre-Wisconsin to late-Wisconsin. Undifferentiated terrace deposits in the Site Vicinity occur along tributary stream valleys (shown as Ptu on Figures 2.5-9 and Pt1 to Pt3 on 2.5-10), including Big Black River and Bayou Pierre, and may be related to the Prairie Complex (Reference 44). In the Site Area, terrace deposits equivalent to the Prairie Complex occur between elevations of 140 +/- 10 feet and 180 +/- 20 feet.

Terrace deposits of the Intermediate Complex occur in the western and southern portions of the Site Region, but are not mapped in the Site Vicinity. The deposits occur in tributary valleys west of the Mississippi River and in a 10- to 20-mile-wide, coast-parallel belt that extends from Texas to Alabama. Very little information is available regarding the Intermediate Complex, but the available data suggest that much of the complex consists of sediments deposited as a broad alluvial apron by small streams draining the adjacent higher terraces and uplands (Reference 17). The Intermediate Complex represents a transitional unit between the younger Prairie Complex and the Pliocene-Pleistocene Upland Complex described below.

Deposits of the Upland Complex occur extensively along the Mississippi Alluvial Valley and Gulf Coast margin in the Site Region, Site Vicinity, Site Area, and Site Location (Figures 2.5-9, 2.5-10, and 2.5-27). The deposits range in age from Pliocene to Pleistocene (approximately 1 to 4 million years) reflecting uncertainty in the time of deposition; we describe the Upland Complex in greater detail in the Pliocene-Pleistocene discussion, below. In general, the Upland Complex includes the Lafayette and Citronelle gravels and consists of sandy gravels, clayey sandy gravels, silty sands, and clayey gravelly sands (Reference 46). The deposits may be more than 100 feet thick and individual beds typically are lenticular and laterally discontinuous. Beds of clay and silt are rare.

Pleistocene terraces extend continuously along the length of the Mississippi Valley (Reference 44). The continuity and absence of vertical deformation of the terraces serves to demonstrate the tectonic stability of the Gulf Coastal Plain through the Pliocene and Pleistocene.

2.5.1.1.4.2.3 Tertiary System

Tertiary deposits are more than 6,000-feet thick in the Site Vicinity (Figure 2.5-9). These deposits thicken from north to south across the region with a maximum thickness greater than 50,000 feet in the Gulf of Mexico. The Tertiary deposits consist of terrigenous sediment eroded from the interior of North America and marine sediment deposited during marine transgressions and regressions. These deposits are divided into a number of formations in the Site Region and Site Vicinity and are described below (Figure 2.5-13).

2.5.1.1.4.2.3.1 Pliocene-Pleistocene Series

Pliocene deposits occur in the southern part of the Site Region, but are not present in the Site Vicinity (Figure 2.5-4). South of the Site Vicinity, the Pliocene section consists of interbedded marginal marine sediments that reach a maximum thickness of about 6,000 feet offshore. These deposits are overlain unconformably by the Upland Complex deposits (Figure 2.5-13).

The Pliocene-Pleistocene Upland Complex, also referred to as the Citronelle and Lafayette formations, is one of the most regionally extensive deposits in the Gulf Coastal Plain (Reference 32). Remnants of Upland Complex are identified in a 10- to 50-mile wide band east of the Mississippi River and extend from the head of the Mississippi Embayment to the Gulf of Mexico (Reference 17). This formation covers the majority of southern Mississippi, south of Jackson, and also crops out west of the Mississippi Alluvial Valley in south-central and southwestern Louisiana (Reference 17). The Upland Complex represents a widespread sand and gravel sheet deposited prior to regional stream entrenchment (Reference 44). Other Pliocene units in the Site Region include the Willis formation in southeastern Texas, and Graham Ferry in southeastern Mississippi, eastern Alabama, and offshore (Figure 2.5-13)

Deposits of the Upland Complex generally consist of a basal gravel and coarse sand facies, overlain by a finer sand facies that grades into an upper silt-and-clay facies. Gravels are predominantly chert and quartz and are reddish in color, while the silt-and-clay facies vary in color from reddish to light gray and tan (Reference 47). Silicified wood is common near the base of higher terraces. Individual terraces range in thickness from tens to hundreds of feet and commonly are buried by loess. The basal contact of the terrace deposits, as identified in test wells, ranges from 85 feet to over 300 feet below ground surface (Reference 47).

The Upland Complex is considered to be a combination of glacial outwash and non-glacial fluvial deposits of both central United States and Appalachian Mountains provenance (References 17; 48). However, the age and origin of the deposits are controversial. Fluvial gravels were inferred to have been deposited in the Mississippi Valley during the Pliocene to Early Pleistocene (Reference 49). The source of the Upland Complex terrace material was attributed to glacial outwash along the Mississippi River (Reference 31), and to erosion of the eastern Appalachian Mountains (References 46; 48). The deposits most likely formed from a combination of both sources (Reference 17).

A prolonged period of low sea level in the early Pleistocene led to entrenchment of upland areas, and erosion and partial redistribution of Pliocene glacial outwash and alluvial fan deposits (Reference 17). Inset terraces formed due to reworking of Upland Complex deposits and grading of streams to sequentially lower base levels during the Early Pleistocene. These reworked terrace deposits occur at progressively lower elevations and are generally finer grained than the source materials. These Early Pleistocene terraces commonly are described as being a part of the Upland Complex. At some localities, the deposits clearly originated from glacial outwash processes (Reference 17). Thus, the younger terrace deposits may represent a combination of alluvial fan and glacial outwash deposits that merged or interfingered at the mouth of tributary valleys.

Deposits of the Upland Complex are present in the Site Location, and are described in greater detail in Section 2.5.1.2, Site Geology

2.5.1.1.4.2.3.2 Miocene Series

Miocene Series deposits (Tm) occur in the Site Region and Site Vicinity (Figures 2.5-4 and 2.5-9. Miocene Series formations include the Catahoula, Pascagoula, Hattiesburg, Amphist shale, and Flemming formations (Figure 2.5-12). The locus of deposition for the Catahoula formation shifted through time as a result of eustatic sea level fluctuations. In the eastern and southern part of the Site Region, the Catahoula Formation was deposited in the upper Oligocene and lower Miocene. In the Site Vicinity, the Catahoula formations is of Miocene age.

Miocene deposits occur beneath the Grand Gulf Nuclear Station at depths of between approximately 140 and 260 feet (Figure 2.5-11). The Miocene deposits reflect a regressional sequence of nonmarine clays, sandy clays, and sands that grade upward to deltaic and occasional lignitic non-marine sand and clay (Reference 16). The Miocene deposits consist of hard, gray, green or blue, freshwater to brackish-water clay and sandy clay interbedded with irregular fine sand, cemented sandstone, and lenses of black chert gravel (Reference 17). The thickness of Miocene deposits ranges from 750 feet to more than 44,000 feet from north to south across the Gulf Coastal Plain and offshore northern Gulf of Mexico (References 17; 16; 50; 51).

In the Site Vicinity, the Miocene Series has an unconformable lower contact with Oligocene and Upper Eocene marine deposits and an unconformable upper contact with the Pliocene-Pleistocene Upland Complex (Reference 16). The unconformable lower contact projects to the surface in the northern portion of the Site Vicinity near Vicksburg, and the unconformable upper contact with the Upland Complex occurs in the southeastern portion of the Site Vicinity (Figure 2.5-9). In the Site Vicinity, the Miocene deposits are covered by loess, Upland Complex deposits, alluvium, and colluvium (Figure 2.5-9).

The Miocene Series deposits dip gently southward across the Site Region. There are no surficial faults or structures that deform these deposits in the Site Vicinity (References 52; 53).

The Miocene Catahoula Formation is one of the most prominent and widespread deposits in the Site Vicinity (Figure 2.5-9). The formation underlies the Site Area and is identified as the load-bearing stratum for the existing Grand Gulf Nuclear Station. These deposits are described in greater detail in Section 2.5.1.2, Site Geology.

2.5.1.1.4.2.3.3 Oligocene Series

The Oligocene Series is exposed in the Site Vicinity and consists of the Vicksburg Group, including the Bucatunna, Byram, Mint Springs, Forest Hill, Red Bluff formations, and the Glendon, Bump Nose, and Marianna limestone formations (Figures 2.5-9 and 2.5-13). Other Oligocene formations in the Site Region include the Paynes Hammock, Chickasawhay, Hackberry, Frio, Anahuac, and Catahoula formations (Figure 2.5-13). As shown on Figure 2.5-4, Oligocene Series deposits are exposed in the banks of the Mississippi River bluffs for approximately 20 miles in the vicinity of Vicksburg (Reference 17). Additionally, Oligocene deposits crop out in the uplands northwest of Sicily Island and the uplands of southwestern Mississippi (Reference 17). Oligocene Series deposits increase in thickness southward and dip into the subsurface south of Vicksburg.

Deposits of the Vicksburg Group consist of estuarine to marine, limestone and marl with lesser amounts of bentonite, clay, and sand (Reference 52). These deposits unconformably overlie freshwater, interbedded, clayey, lignitic silts and fine cross-bedded sands of the Forest Hill Formation. The Forest Hill Formation is in unconformable contact with the underlying Eocene Jackson Group (described below). Oligocene deposits range in thickness from about 300 feet in the Site Vicinity (Figure 2.5-10) to a maximum thickness of approximately 12,000 feet in the southern portion of the Site Region (Reference 17; 54). The Oligocene Series deposits occur at a depth of about 350 feet beneath the Grand Gulf Site (Figure 2.5-11), and are described in greater detail in Section 2.5.1.2, Site Geology.

A structure contour map of the top of the Glendon Limestone Formation of the Vicksburg Group shows no evidence for faults or structures that deform these deposits in the Site Vicinity (Figure 2.5-15). The structure contours project smoothly through the Site Area documenting the absence of faulting or other forms of tectonic or non-tectonic (i.e. salt piercement structures) deformation in the Site Area. As shown by the structure contour map, salt diapirs have formed domes in the Oligocene deposits approximately 8-miles to the northeast and southwest, respectively. However, the salt diapirs have not pierced the Oligocene horizon at these locations.

2.5.1.1.4.2.3.4 Eocene Series

The Eocene Series is exposed in the Site Region (Figure 2.5-4) and includes the Jackson (Te3), Claiborne (Te2), and the Wilcox (Te1) Groups (Figure 2.5-13). As shown on Figure 2.5-6, these stratigraphic groups occur beneath the Site Area at depths of between approximately 1,000 to 7,000 feet. Deposits of the Eocene Series in the Site Region range in thickness from 2,900 to 6,900 feet (Reference 17; 33). The Eocene Series deposits are composed of carbonaceous and calcareous shales, sandy clays, marls, sands, silts, and beds of lignite (Reference 52).The Eocene Series is interpreted to have an unconformable upper contact with the Oligocene deposits and a transitional or conformable contact with underlying Paleocene deposits (Reference 50). The lower contact with the Paleocene was later reinterpreted to be locally unconformable (Reference 52).

Deposits of the upper Eocene Jackson Group are exposed in a continuous 50- to 75-mile-wide band that extends from the uplands of southeastern Arkansas northeastward into the uplands of western Tennessee and southwestern Kentucky (Reference 17; Figure 2.5-4). The deposits also are exposed in the bluffs west of the Ouachita River in central Louisiana and in the bluffs east of the Yazoo Basin in western Mississippi. The maximum thickness of the Jackson Group is 540 feet (Reference 17). In the Site Region, the Jackson Group includes the Whitsett, Manning, Wellborn, Cadell, Yazoo Clay and Moodys Branch Formations (Figure 2.5-13). In the Site Vicinity, the Yazoo Clay Formation consists of dark gray to brown, massive fossiliferous clay with irregular zones of fine sand and silty clay. The Yazoo Clay overlies the Moodys Branch Formation, which consists of fossiliferous, sandy and clayey marls with occasional limestone nodules.

Deposits of the Claiborne Group are exposed in the Site Region (Figure 2.5-4). Subdivisions are shown on Figure 2.5-13 and vary by region. The Claiborne Group has a total thickness of up to 1,450 feet (Reference 56). In the Site Vicinity, the formations include thinly interbedded gray to gray-brown clays, silt and silty sands, thick brown clays, massive fine to medium grained sands, and fossiliferous, calcareous, clays, marls, and sands. Faults deform Claiborne Group deposits in the eastern portion of the Site Region, approximately 135 miles east of the site (Figure 2.5-4)

Deposits of the lower Eocene-upper Paleocene Wilcox Group occur beneath the site at depths between approximately 3,500 feet and 7,000 feet (Figure 2.5-6), but are not exposed at the surface within the Site Region (Figure 2.5-4). Subdivisions of the Wilcox Group are shown on Figure 2.5-13. In the Site Region, the Wilcox Group ranges in thickness from 100 to 3,500 feet and consists of fine- to medium-grained sands and sandy clays interbedded with massive coarse grained and gravelly sands (References 17, 56). The Wilcox Group has unconformable contacts with both the overlying Claiborne Group and the underlying Paleocene Midway Group.

2.5.1.1.4.2.3.5 Paleocene Series

The Paleocene Series (Tx, Figure 2.5-4) includes the Porters Creek Clay, Clayton, Wills Point, Kincaid, and Naheola formations of the Midway Group (Figure 2.5-13). These deposits are exposed in the eastern and northern portions of the Site Region (Figure 2.5-4), but are not exposed within the Site Vicinity (References 17; 44). The Porters Creek Clay Formation consists of massive, dark gray to black fissile shales, clay shales, and clays with sandy clay beds. The underlying Clayton Formation consists of gray, calcareous, glauconitic, fossiliferous, shales with lenses of white limestone. Deposits of the Midway Group occur beneath the Grand Gulf site at depths of 5,000 to 6,000 feet (Reference 16), and unconformably overlie Upper Cretaceous rocks (Figure 2.5-12). The maximum thickness of Paleocene deposits in the Site Region ranges from 730 to 1,200 feet (References 17, 33, 56).

2.5.1.1.4.3 Mesozoic Era

Mesozoic deposits in the Site Region consist of buried Triassic and Jurassic rocks, and locally exposed Cretaceous marine and terrestrial sediments that accumulated in response to active rifting and marine transgressions and regressions (Figures 2.5-4, 2.5-8). Non-marine, Triassic and Jurassic deposits in the Site Region were originally termed the Eagle Mills Formation or “Red Beds” (References 57, 58). Later, the “Red Bed” sequence was further subdivided into the Late Triassic Eagle Mills Formation and the Middle Jurassic Werner, Luann, and Norphlet Formations (Figure 2.5-13). Accumulation of sediment accelerated crustal subsidence and formation of the Mississippi Embayment in the northern Gulf Coast Plain. Each of the major stratigraphic systems of the Mesozoic Era is described below.

2.5.1.1.4.3.1 Cretaceous System

Deposits of the Cretaceous System are exposed in the eastern and northern portions of the Site Region (Figure 2.5-4). The subdivisions of the Cretaceous System are shown on Figure 2.5-13. In the Site Vicinity, deposits of the Cretaceous System occur at depths of between 3,000 and 10,000 feet (Figure 2.5-12). The Cretaceous System is also referred to as the Gulfian Series, which is subdivided into the Arkadelphia Marl and Nacatoch Sand formations (Figure 2.5-13; Reference 17). Previous mapping of Cretaceous System deposits includes a greater number of subdivisions including the Tuscaloosa Formation, Eutaw Formation, and Selma Group (Reference 52). Current stratigraphic nomenclature is summarized on Figure 2.5-13 (Reference 56).

Deposits of the Cretaceous Selma Group (Arkadelphia Marl Formation of Reference 17), include chalk and calcareous clay, glauconitic sand and sandy limestone and marl (Reference 52). Deposits of the underlying Eutaw Formation consist of massive, cross bedded, glaucanitic, fine sand, and deposits of the Tuscaloosa Formation consist of irregularly bedded sand, clay and gravel (Reference 52). Each of the above formations is separated by erosional unconformities. The Cretaceous System deposits have a maximum combined thickness of more than 5,000 feet beneath the site (Reference 16).

2.5.1.1.4.3.2 Jurassic System

Deposits of the Jurassic System in the Site Region include the Cotton Valley Group (Upper Jurassic), the Louark Group (Upper Jurassic), Louann Salt Group (Middle Jurassic), and unnamed Lower Jurassic deposits of anhydrite, sandstone, and conglomerate (Figure 2.5-13; Reference 56). These deposits are not exposed, but occur in the subsurface in the Site Region and Site Vicinity. The Cotton Valley Group includes the Knowles Limestone, Schuler, and Bossier formations and consist of marine and terrestrial sandstone, shale, and limestone. The Louark Group includes the Haynesville, Buckner, Smackover, and Norphlet formations and consist of basal red clay overlain by oolitic limestone, shale, and sandstone. The Louann Salt consists of thick evaporite deposits. Plastic flow of the Louann Salt related to sediment loading effects caused widespread diapirism and associated folding and faulting in the Interior Salt Basin and Coastal Salt Basin (Figure 2.5-3). The Louann Salt overlies the Werner Formation, which is also part of the evaporite sequence. Cumulatively, the Jurassic deposits in the southern portion of the Site Region have a thickness of nearly 10,000 feet (References 33, 59).

2.5.1.1.4.3.3 Triassic Deposits

The Eagle Mills Formation is the only Late Triassic deposit identified in the Site Region. This depositional sequence is not exposed at the surface, but has been penetrated by wells in southern Arkansas, eastern Texas, west-central Mississippi, northern Louisiana, south-eastern Mississippi, and southern Alabama at depths ranging from 984 feet to 9,840 feet (Reference 60). Deposits of the Eagle Mills Formation consist of non-marine, clastic, varicolored (red, purplish, greenish-gray, or mottled) shales, mudstones, and siltstones with less abundant fine- to very fine-grained sandstone (Reference 60). Basal units of the Eagle Mills Formation contain pebbles and cobbles of Paleozoic limestone. The Eagle Mills Formation represents the deposits that filled grabens, half grabens, and rift basins in prograding alluvial fan, fluvial, deltaic plain, and freshwater lake environments. The lower contact of the Eagle Mills formation is unconformable with Paleozoic rocks and the upper contact is unconformable with the Jurassic Werner Formation. The Eagle Mills Formation changes thickness over short distances from less than 10 feet to over 7,200 feet due to contemporaneous deposition in an active rift system (Reference 60).

2.5.1.1.4.4 Paleozoic Era

Paleozoic rocks are exposed in the northwestern portion of the Site Region, but do not occur in the Site Vicinity Figure 2.5-4. In the subsurface, deposits of the Paleozoic Era consist of seven major stratigraphic series and 19 individual formations (References 17, 56). The maximum combined thickness of Paleozoic deposits in the northwestern portion of the Site Region is in excess of 5,600 feet (Reference 17) and the maximum thickness south of the site is unknown. South of the Ouachita and Appalachian Mountains, Paleozoic and older deposits are not exposed. The depth to these deposits in the subsurface beneath the Site Vicinity is greater than 13,000 feet (Figure 2.5-6). Deposits of the Mississippian and Pennsylvanian Systems consist of interbedded shale, fine-grained sandstone, and minor limestone. Deposits of the Ordovician System consist of dolomite interbedded with thin beds of limestone, shale, and sandstone. Paleozoic rocks have an unconformable contact with the overlying Mesozoic rocks. The nature of the lower contact is unknown, but most likely is a nonconformity separating the Paleozoic deposits from crystalline basement rocks.

2.5.1.1.4.5 Precambrian

Precambrian basement rocks are not exposed in the Site Region (Figures 2.5-4 and 2.5-16a). The depth to basement in the Site Vicinity is estimated to be between 6 and 8 miles (Figure 2.5-16b; Reference 18).

Samples obtained from deep oil and gas exploration wells in the Site Region indicate the presence of Precambrian age North American continental crust beneath the Paleozoic stratigraphic section along the buried Ouachita Orogenic Belt (Reference 61). The basement rocks consist of sialic hornblende syenite dated approximately 785 +/- 34 Ma. The location of this subcrop, association with other samples collected from deep exploration borings, and similarity in age and composition to samples from the Blue Ridge Terrane of the southern Appalachian Mountains (described below) suggests that the Precambrian rocks encountered in the Site Region are related to the North American craton.

South of the buried Ouachita Orogenic Belt, Precambrian crystalline basement consists of highly attenuated continental crust or transitional crust related to formation of the Gulf of Mexico (Figure 2.5-5; Reference 18). Due to the depth of the crust in the Gulf Coast Basin actual rock samples have not been obtained. However, based on seismic velocity surveys the crust is thought to be transitional between continental and oceanic materials (Reference 18).

2.5.1.1.5 Regional Tectonic Setting

In 1986, EPRI developed a seismic source model for the Central and Eastern United States (CEUS) including the Site Region (Reference 9). The seismic source model included the independent interpretations of six earth science teams and reflected the general state of knowledge of the geoscience community as of 1986. The seismic source models developed by each of the six teams for the EPRI model were based on the tectonic setting and the occurrence, rates, and distribution of historical seismicity.

Since 1986, additional geological, seismological, and geophysical research has been completed in the Site Region. This more recent research has identified a potentially active seismic source, the Saline River source zone within the Site Region that includes the trends of the Arkansas, Saline, and Ouachita river lineaments in southeastern Arkansas (Figure 2.5-5). Recent research also has improved the characterization of seismic source parameters associated with the New Madrid seismic zone, the source of the 1811-1812 earthquake sequence.

In the following sections, we describe each of the major tectonic features in the Site Region, and the tectonic basis for their identification. The original seismic sources identified by EPRI (Reference 9) are thoroughly described in the EPRI report. The discussion below provides a summary of each tectonic feature modeled by EPRI in the Site Region and focuses on new information acquired since 1986 that is relevant to the assessment of seismic parameters for each source zone. A description of the Saline River source zone and new information on the New Madrid seismic zone is provided.

The EPRI Earth Science teams independently defined the geometry and source parameters of seismic sources in the CEUS. This independent assessment led to a range of interpretations that captured the variability and uncertainty in each seismic source. Each team modeled the major tectonic elements of the CEUS to develop their seismic source models. Figure 2.5-5 illustrates the distribution of tectonic features and historical seismicity in the Site Region from which the six EPRI team source models are based. The tectonic features shown on Figure 2.5-5 reflect the cumulative deformation of tectonic events throughout the Paleozoic, Mesozoic, and

Cenozoic Eras. A chronology of events that influenced the development and distribution of tectonic features in the Site Region is described below and presented in Figure 2.5-8.

The south central United States is a passive continental margin with no relative differential motion between the Gulf of Mexico oceanic plate and the North American continental plate (Reference 63). The region is one of low earthquake activity and low stress, and is cited as an example of a stable continental region (References 62; 64, 65, 66, 67). The orientation of the maximum horizontal stress is northeast to east-northeast within the craton. The orientation of maximum extension is south-southeast near the Gulf Coast (Figure 2.5-5; Reference 68; 69). The southward oriented extension along the Gulf Coast reflects crustal loading and deformation within the Mississippi River deltaic complex in the Gulf of Mexico and may be distinct from the regional east-northeastward directed regional compressive stress in the underlying basement.

The primary tectonic elements of the region are fossil rift systems such as the Reelfoot Rift, or former collision zones such as the Paleozoic Ouachita Orogenic Belt and Appalachian Mountains (Figures 2.5-5). Each of these structures are regional in scale, and geologically and geophysically recognizable. Quaternary active structures, if present, appear to be entirely related to reactivation of these older bedrock rift or collisional structures. Nearly all earthquakes with well-located hypocenters occur within the Precambrian basement complex, and a majority of events >M4.5 appear related to regional scale structures such as the Reelfoot Rift, or Ouachita Orogenic Belt (Figure 2.5-5; Reference 70).

2.5.1.1.5.1 Tectonic Stress in the Mid-Continent Region

Expert teams that participated in the 1986 EPRI evaluation of intra-plate stress found that tectonic stress in the CEUS primarily is characterized by NE-SW-directed horizontal compression. In general, the expert teams concluded that the most likely source of tectonic stress in the mid-continent region was ridge-push force associated with the Mid-Atlantic ridge, transmitted to the interior of the North American plate by the elastic strength of the lithosphere. Other potential forces acting on the North American plate were judged to be less significant in contributing to the magnitude and orientation of the maximum compressive principal stress ($\sigma 1$). Some of the expert teams noted that deviations from the regional NE-SW trend of $\sigma 1$ may be present along the east coast and in the New Madrid region. They assessed the quality of stress indicator data, and discussed various hypotheses to account for what were interpreted as variations in the regional stress trajectories.

Since 1986, an international effort to collate and evaluate stress indicator data resulted in publication of a new World Stress Map (References 68; 71). Data for the map were ranked in terms of quality, and plate-scale trends in the orientations of principal stresses were assessed qualitatively (Reference 72). Subsequent statistical analyses of stress indicators confirmed that the trajectory of the maximum compressive principal stress ($\sigma 1$) is uniform across broad continental regions at a high level of statistical confidence (Reference 73). In particular, the NE-SW orientation of $\sigma 1$in the central and eastern United States inferred by the EPRI experts is statistically robust, and is consistent with the theoretical trend of compressive forces acting on the North American plate from the mid-Atlantic ridge (Reference 73).

The more recent assessments of lithospheric stress have not confirmed inferences of some EPRI expert teams that the orientation of $\sigma 1$ may be locally perturbed in the New England area, along the east coast of the United States, or in the New Madrid region. Zoback and Zoback summarized a variety of data, including well-bore breakouts, results of hydraulic fracturing studies, and newly calculated focal mechanisms, which indicate that the New England and eastern seaboard regions of the U.S. are characterized by horizontal NE-SW to E-W compression (Reference 68). Similar trends are present in the expanded set of stress indicators for the New Madrid region. All of these regions, were grouped with a large area of eastern Canada, and the central and eastern U.S. in an expanded "Mid-Plate" stress province (Reference 68).

In addition to better documenting the orientation of stress, research conducted since 1986 has addressed quantitatively the relative contributions of various forces that may be acting on the North American plate to the total stress within the plate. Richardson and Reding (Reference 74) performed numerical modeling of stress in the continental U.S. interior, and considered the contribution to total tectonic stress from three classes of forces:

1) Horizontal stresses arising from gravitational body forces acting on lateral variations in lithospheric density. These forces are commonly called "buoyancy forces". Richardson and Reding emphasize that what is commonly called "ridge-push force" is an example of this class of force (Reference 74). Rather than a "line-force" that acts outwardly from the axis of a spreading ridge, "ridge push" arises from the pressure exerted by positively buoyant, young oceanic lithosphere near the ridge against older, cooler, denser and less buoyant lithosphere in the deeper ocean basins (Reference 75). The force is an integrated effect over oceanic lithosphere ranging in age from about 0 to 100 million years (Reference 76). The "ridge push" force is transmitted as stress to the interior of continents by the elastic strength of the lithosphere.
2) Shear and compressive stresses transmitted across major plate boundaries (i.e., strike-slip faults and subduction zones).
3) Shear tractions acting on the base of the lithosphere from relative flow of the underlying asthenospheric mantle.

The observed NE-SW trend of σ_1 in the central and eastern United States dominantly reflects "ridge-push" body forces (Reference 74). They estimated the magnitude of these forces to be about 2 to 3 x 10^{12} N/m (i.e., the total vertically integrated force acting on a column of lithosphere 1 meter wide), which corresponds to average equivalent stresses of about 40 to 60 MPa distributed across a 50-km-thick elastic plate. The fit of the model stress trajectories to data is improved by addition of modest compressive stress (about 5 to 10 MPa) acting on the San Andreas fault and Caribbean plate boundary structures (Reference 74). The fit of the model stresses to data further indicated that shear stresses acting on these plate boundary structures must also be in the range of 5 to 10 MPa.

The general NE-SW orientation of σ_1 in the central and eastern United States also can be reproduced by numerical models that assume a shear stress, or "drag", is acting on base on the North American plate (Reference 74). This model is not favored (Reference 74; 68) as a significant contributor to total stress in the mid-continent region, however, because it predicts or requires that the horizontal compressive stress in the lithosphere increase by an order of magnitude moving from east to west across the central United States. The state of stress in the southern Great Plains is characterized by north-south extension, which is contrary to this prediction (Reference 68). They further observed that seismic activity generally increases from west to east across the central and eastern U.S., which is not consistent with the prediction of the basal drag model that compressive stresses (and presumably rates of seismic activity) should be higher in the west central U.S. than in the eastern U.S.

2.5.1.1.5.2 Appalachian Mountains

The Appalachian Mountains extend from Newfoundland, Canada to central Alabama. The Appalachian Mountains consists of a southwest-trending complex of folded, thrusted, and metamorphosed terranes that evolved over a period of approximately 800 million year.

The Appalachian Mountains are up to 400 miles wide and 2,000 miles long and include the Valley and Ridge, Piedmont, and Blue Ridge terranes. Each terrane is bounded by a zone of major thrust faults. These terranes include Proterozoic and younger age rocks of both oceanic and continental affinity that were accreted to the North American craton during three episodes (or orogenies) of plate collision and northwest-directed crustal shortening. The episodes of plate collision include the Allegheny orogeny (270 to 350 Ma), Acadian orogeny (350 to 400 Ma), and Taconic orogeny (400 to 500 Ma; Reference 77). The Taconic orogeny produced the Blue Ridge terrane which consists of highly metamorphosed, folded and thrust faulted Proterozoic and Cambrian crystalline rocks. The Acadian orogeny produced the Piedmont terrane and deformed the eastern Blue Ridge. The Piedmont terrane consists of metamorphosed Precambrian and Paleozoic sediments and volcanic rocks that were intruded by granitic plutons. The Allegheny orogeny produced the Valley and Ridge terrane and deformed the Blue Ridge and Piedmont terranes. The Valley and Ridge terrane consists of a thick sequence of folded and thrust faulted Paleozoic sediments (Reference 77). Each subsequent orogeny deformed the pre-existing rocks from earlier orogenies resulting in a complex sequence of poly-deformed and metamorphosed rocks.

The surface expression of the Appalachian Mountains terminates outside of the 200-mile Study Region. However, the northeast-trending geological structures associated with the Appalachian Mountains extend in the subsurface into the northeastern portion of the Site Region where they merge with the northwest-trending Ouachita Mountains in southeastern Mississippi and southwestern Alabama (Figure 2.5-4). The southern end of the Appalachian Mountains structures approximately coincides with the Pickens-Gilberttown fault zone (Figure 2.5-5). The Appalachian and Ouachita Mountains define the eastern and southeastern edges, respectively, of the current North American craton (Reference 78).

Many Paleozoic thrust faults of regional extent are mapped within the Appalachian Mountains. However, in the Site Region none of these faults have geological or seismological evidence of Quaternary activity and only the southernmost portion of the Appalachian Mountains extends in the subsurface into the Site Region. There are no distinct faults identified as individual seismic sources within the Appalachian Mountains in the Site Region. Historical seismicity generally aligns along the northeastern trend of the Appalachian Mountains, but within the Site Region, only nine earthquakes m_b 3.3 to 3.9 (lower bound threshold used by Reference 9) were recorded between 1777 and 1986. Since the EPRI 1986 study, only one earthquake (m_b<3.9) occurred within the subsurface extent of the Appalachian Mountains in the Site Region during the period 1986 and 2002 (Reference 11; Figure 2.5-5). The seismicity that occurs at the southern end of the buried Appalachian Mountains also coincides with the location of the Pickens-Gilberttown fault zone. These earthquakes are spatially related to an area of high petroleum withdrawal and may be triggered events caused by fluid recovery.

The April 2003 M_w 4.9 Alabama earthquake occurred within the Appalachian Mountains province, outside of the Site Region (Figure 2.5-17). This event is within the normal range of earthquake magnitudes expected for this region. The event occurred at a depth of about 3 miles (5 km) and had a strike-slip focal mechanism. The event was not felt at the Grand Gulf Nuclear Station and did not trigger any monitoring instruments at the site.

The six EPRI teams developed estimates of maximum earthquake magnitudes for the Appalachian Mountains province that range from m_b 5.4 to 7.2 (M_w 5.1 to 7.6). Since the EPRI study, the USGS developed a new seismic source model that estimates a maximum earthquake magnitude of M_w 7.5 for the Appalachian Mountains in the Site Region. No new information was identified during our data review that provides estimates of the maximum earthquake magnitudes for the Appalachian Mountains that are outside of the range of values developed by the six EPRI teams (Reference 9).

2.5.1.1.5.3 Ouachita Orogenic Belt

The Ouachita Orogenic Belt is the eroded core of a mountain belt that formed during continental collision and formation of the supercontinent Pangea, in the Paleozoic (Figure 2.5-8; Reference 79). The Ouachita Orogenic Belt extends from western Alabama through northern Mississippi, central Arkansas, southeastern Oklahoma, and eastern Texas (Figure 2.5-5). The Ouachita Orogenic Belt consists of an arcuate salient of complexly folded, thrust-faulted, and metamorphosed rocks that, like the Appalachian Mountains, includes accreted oceanic crust of Proterozoic age (Reference 79).

The Ouachita Orogenic Belt is up to 50 miles wide and 1,260 miles long, although about 80 percent of its length is buried beneath Mesozoic and Tertiary sediments of the Gulf Coast Basin. The Ouachita Orogenic Belt defines the northern edge of the Gulf Coastal Basin, the southern margin of the Mississippi Embayment, and the southern edge of the North American craton (Figures 2.5-3 and 2.5-7). The belt includes three regional subdivisions including the Southeastern Ouachitas, the Ouachita Mountains, and the Subsurface Ouachitas of Texas.

The topography of the Ouachita Orogenic Belt is expressed by a low relief erosional surface that was buried by Jurassic sediments in the Gulf Coastal Plain. Across the Gulf Coastal Plain from Alabama to southern Texas this erosional unconformity dips toward the Gulf of Mexico at an angle of less than 1 degree (References 79; 80).

Repeated episodes of deformation formed asymmetrical folds, and low- and high-angle thrust faults that involve Middle to Upper Paleozoic rocks along the edge of the North American craton (Reference 81). Middle to Upper Paleozoic rocks are unconformably overlain by late Paleozoic rocks that were not involved in the Ouachita orogeny. Thus, deformation along the Ouachita Orogenic Belt ceased in late Paleozoic time.

Throughout the entire length of the Ouachita Orogenic Belt, the base of the orogen is defined by a major decollement, along which allochthonous marine sedimentary rocks are thrust northward over North American cratonic rocks. The northern side the Ouachita Orogenic Belt overlies 21- to 24-miles of North American continental crust (Reference 82). On the southern, or Gulf Coast side, the Ouachita Orogenic Belt overlies transitional continental crust (Reference 18; 82).

Two major stratigraphic units collectively known as the Ouachita facies compose the majority of rocks in the Ouachita Orogenic Belt. The lower stratigraphic unit, referred to as the pre-orogenic off-shelf facies, ranges from Late Cambrian to Early Mississippian in age, and is approximately 9,500 to 11,000 feet thick. This lower stratigraphic unit consists of shale, sandstone and micrite that grade upward to chert, siliceous shale, and novaculite.

The upper stratigraphic unit is referred to as the synorogenic facies. This unit ranges from Late Mississippian (Meramecian) to Early Permian (Wolfcampian) in age, and represents over 50,000 feet of shelf-delta clastic deposits that originated in foreland basins, and outboard deep water clastic wedge deposits. The shelf-delta deposits of the foreland basin were deformed by folding and faulting during the Ouachita orogeny (Reference 79).

The Southeastern Ouachitas, in the Site Region, lie entirely in the subsurface of northern Mississippi and southwestern Alabama (Reference 81), within the Gulf Coastal Plain (Figure 2.5-2). On the northern side of the Ouachita Orogenic Belt, Carboniferous age shelf-delta deposits (upper stratigraphic unit) occur in the subsurface foreland basin and extend southward into the frontal thrusts in Mississippi. Southwest of the Orogenic Belt undifferentiated pre-orogenic and synorogenic rocks are present.

In Mississippi, the decollement beneath the Southeastern Ouachitas ramps downward into the shelf strata of the Appalachian Mountains and interleaves with the decollement beneath the southern part of the Appalachian Mountains (Reference 79). The intersection of the Ouachita Orogenic Belt and the thrust faults of the Appalachian Mountains leads to a cross-cutting fault pattern (Figure 2.5-5).

Although many large Paleozoic thrust faults of regional extent are mapped through the Ouachita Orogenic Belt, none display geological evidence of Quaternary activity. As shown on Figure 2.5-5, historical seismicity occurs along the trend of the Ouachita Orogenic Belt, but within the Site Region, only 18 earthquakes of m_b 3.3 to 3.9 (lower threshold used by EPRI (Reference 9) were recorded between 1777 and 1986. Since the EPRI study, only three earthquake of m_b<3.9 occurred during the period 1986 and 2002, within the Ouachita Orogenic Belt in the Site Region (Figure 2.5-5; Reference 83).

The six EPRI teams developed estimates of maximum earthquake magnitudes for the area encompassing the Ouachita Orogenic Belt that range from m_b 5.5 to 7.2 (M_w 5.1 to 7.5). Since the EPRI study, the USGS developed a new seismic source model that estimates a maximum earthquake magnitude of M_w 7.5 for the Ouachita Orogenic Belt in the Site Region (Reference 84). This new information is within the range of estimates of maximum earthquake magnitude for the Ouachita Orogenic Belt provided by the EPRI teams (Reference 9). The USGS estimate of M_w 7.5 is defined for an areal source zone that includes the entire area of the Gulf and East Coasts that extends from the edge of the North American cratonic rocks to the coastline (Reference 84).

Several potential Quaternary active fault zones within the Ouachita Orogenic Belt have been identified primarily by geomorphic evidence of basin asymmetry, and localized evidence of faulting in road-cuts and trenches, weak clustering of earthquake epicenters, and liquefaction features (Reference 85). The potential faults are identified along the Arkansas River, Saline River, and Ouachita rivers in northern Louisiana and Arkansas. Detailed descriptions of these features are provided in Section 2.5.1.1.5.7.

2.5.1.1.5.4 Arkoma Basin and Black Warrior Basins

The Arkoma and Black Warrior basins are located directly north of the Ouachita Orogenic Belt (Figure 2.5-3). Both basins straddle the margin of the Site Region. The Arkoma and Black Warrior basins are foreland basins containing synorogenic sedimentary deposits associated with the Ouachita Orogenic Belt. The sedimentary deposits overlie North American cratonic rocks. The major period of deposition and basin deformation ceased in Late Paleozoic to early Mesozoic time (Figure 2.5-8). There are no active tectonic features identified within the Arkoma Basin and Black Warrior basins (Reference 86, 90).

Paleozoic thrust faults in the Arkoma and Black Warrior basins show no evidence of Quaternary activity. Historical seismicity within the parts of the Arkoma and Black Warrior basins that are within the Site Region is sparse Figure 2.5-5. Only two earthquakes of m_b 3.3 to 3.9 (lower threshold used by Reference 9) were recorded between 1777 and 1986. Since the EPRI study, no additional earthquakes greater than m_b 3.3 have been recorded (Figure 2.5-5) in the Site Region. A swarm of small magnitude earthquakes m_b<4.5 occurred in central Arkansas, within the Arkoma Basin, outside of the Site Region. This event, referred to as the Enola earthquake swarm, occurred within a small volume of crust (approximately 25 km^3; Reference 159). The earthquake swarm is interpreted to be associated with a short, 2.6-km long, west-northwest-trending fault segment, that is related to a basement listric fault within a Paleozoic graben (Reference 160). This fault may have a favorable orientation with respect to the east-northeast maximum compressive stress (Reference 69) to produce left-lateral strike slip deformation (Reference 159). Based on the cross-cutting fault patterns within this area (Reference 160) larger earthquakes are not expected to occur in the Enola, Arkansas area.

The six EPRI teams developed estimates of maximum earthquake magnitudes for the area encompassing the Arkoma and Black Warrior basins that range from m_b 5.4 to 7.2 (M_w 5.1 to 7.5). Since the EPRI study, the USGS developed a new seismic source model that estimates a maximum earthquake magnitude of Mw 7.5 for the area encompassing the Arkoma and Black Warrior Basins. The estimate of maximum earthquake magnitude for the area encompassing the Arkoma and Black Warrior basins is within the range of values developed by the six EPRI teams (Reference 9).

2.5.1.1.5.5 Reelfoot Rift

The Reelfoot Rift represents a northeast-trending fault system that originated in Precambrian or Early Cambrian time during extension of the North American continent (Figure 2.5-8; References 81; 87). The Reelfoot Rift extends from southern Illinois at the northern end of the Mississippi Embayment, to east-central Arkansas and northern Mississippi beneath the Ouachita Orogenic Belt (Reference 27). As shown on Figures 2.5-3 and 2.5-5, the closest approach of faults within the Reelfoot Rift to the site is approximately 175-miles. The Reelfoot Rift now accommodates crustal shortening due to northeast-southwest directed regional compressive stress (References 68, 69).

The Reelfoot Rift is approximately 45 miles wide and 180 miles long with as much as 25,000 feet of structural relief (Reference 88). An alignment of magnetic intrusive rocks defines the rift boundaries (References 24, 87; 91). Within the Reelfoot Rift, Upper Paleozoic through Middle Cretaceous strata are absent and a major unconformity exists between Late Cretaceous and Early Paleozoic strata (Reference 92). The Reelfoot Rift comprises a number of distinct structural features, including the Commerce Geophysical Lineament, Western Margin of Reelfoot Rift, Crowleys Ridge, Sikeston Ridge, New Madrid Seismic Zone, and Eastern Margin of Reelfoot Rift (Reference 93). The New Madrid Seismic Zone is the primary seismically active tectonic feature within the Reelfoot Rift, and is described in Section 2.5.1.1.5.6, below.

The geologic history of the Reelfoot Rift includes numerous episodes of uplift, subsidence, intrusion, and sedimentation (Figure 2.5-8). During Precambrian to Cambrian time, the Reelfoot Rift formed as a result of continental rifting and crustal extension of the North American continent (Reference 27). In Late Cambrian time, rifting ceased and the Reelfoot Rift was filled with Paleozoic marine clastic and carbonate rocks (Reference 92). During Middle Cretaceous time, the Reelfoot Rift was reactivated forming an arch that resulted in erosion and removal of Late Paleozoic to Middle Cretaceous rocks of the Late Cambrian Reelfoot Rift (Reference 27; 85).

Reactivation of the Reelfoot Rift in Middle Cretaceous time was accompanied by emplacement of igneous rocks along the rift margins (Reference 85; 94). The emplacement of plutons and crustal arching in the Middle Cretaceous may have been related to the North American continent passing over the Bermuda Hot Spot (Reference 85). Cox and Van Arsdale (Reference 85) also suggest that reactivation of the Reelfoot Rift occurred in Middle Cretaceous time rather than Jurassic time, and therefore could not have been related to opening of the Gulf of Mexico (Reference 92). Reactivation of rift structures in the Late Cretaceous to Eocene caused crustal subsidence and formation of the Mississippi Embayment subprovince of the Gulf Coastal Plain, and initial deposition of alluvial sediment from the Mississippi River over Jurassic age carbonates in the northern Gulf of Mexico.

Regional stress again changed from extension to compression in Late Eocene time causing minor folding and faulting (e.g. Crittenden County fault) within the Reelfoot Rift (References 92; 95). Oligocene and Miocene strata are absent in the Mississippi Embayment and deposits in the Gulf Coast Basin indicate that the embayment was subaerially exposed and subjected to erosional processes during this time. Pliocene to Pleistocene glacial outwash deposits of the Upland Complex unconformably overlie Eocene deposits in the Mississippi Embayment (as well as Miocene deposits in the Site Vicinity). The Mississippi Embayment was entrenched during the Pleistocene and Holocene resulting in progressive flights of terraces incised into Upland Complex deposits along the Mississippi River and its tributaries (Reference 17).

Potentially active faults within the Mississippi Embayment may be associated with the Precambrian, Middle Cretaceous, Late Cretaceous, or Early Tertiary faults of the Reelfoot Rift (Reference 87). The potentially active faults may have been reactivated in Late Eocene time when the regional stress field changed from extension to NE-SW compression. Extensive geophysical investigations of the Reelfoot Rift have been completed for a variety of purposes including deep crustal dynamics, oil exploration, active tectonics, and geotechnical projects (Reference 92). These geophysical investigations indicate that many faults in the Reelfoot Rift do not offset post-Cretaceous deposits (Reference 88). However, Tertiary and Quaternary age faults are identified beneath the margins of Crowley's Ridge (References 97; 98), Sikeston Ridge (References 99, 100), Blytheville Arch (References 89, 101, 102, 104), Benton Hills (Reference 103), Reelfoot fault (Reference 105, 106, 108, 109), Bootheel Lineament (Reference 100, 107), Crittenden County fault (Reference 95; 96), Commerce Geophysical Lineament (Reference 110) and one of the west-bounding faults of the Reelfoot Rift (Reference 98).

With the exception of seismicity associated with the New Madrid seismic zone (described below), seismicity within the Reelfoot Rift is diffuse (Figure 2.5-5). A visual assessment of seismicity patterns indicates that pre-1985 and post-1985 earthquake occurrence has been relatively constant.

The six EPRI teams developed estimates of maximum earthquake magnitudes for the area encompassing the Reelfoot Rift (exclusive of the New Madrid Seismic Zone) that range from m_b 5.4 to 7.2 (Mw 5.0 to 7.5). Since the EPRI study, the USGS developed a new seismic source model that estimates a maximum earthquake magnitude of Mw 7.5 for the Reelfoot Rift (Reference 84). The USGS estimate of maximum earthquake magnitude for the area encompassing the Reelfoot Rift is within the range of values developed by the six EPRI teams (Reference 9). The USGS estimate of Mw 7.5 is defined for an areal source zone that includes the entire area along the southern and eastern edge of the North American craton to the Gulf and Atlantic coasts.

2.5.1.1.5.6 New Madrid Seismic Zone

The New Madrid Seismic Zone (NMSZ) lies within the Reelfoot Rift and is defined by post-Eocene to Quaternary faulting, and historical seismicity. The NMSZ extends from southeastern Missouri to northeastern Arkansas and northwestern Tennessee (Figure 2.5-18). The NMSZ lies outside of the Site Region, but remains a significant contributor to the seismic hazard at the site of the proposed new facility at GGNS.

EPRI (Reference 9) defined the NMSZ as an aerial source zone that is approximately 124-miles long and 25-miles wide. Additional information published since 1986 shows that a distinct fault system is embedded within this source zone. The fault system consists of three distinct segments (Figure 2.5-18). These three segments include a southern northeast-trending dextral slip fault referred to as the Cottonwood Grove fault and Blytheville Arch, a middle northwest-trending reverse fault referred to as the Reelfoot fault, and a northern northeast-trending dextral strike-slip fault referred to as the East Prairie fault (References 92; 102; 111; 112; 113). In the current east-northeast to west-southwest directed regional stress field, Precambrian and Late Cretaceous age extensional structures of the Reelfoot Rift have been reactivated as right-lateral strike-slip and reverse faults (Reference 114).

The NMSZ produced three large magnitude earthquakes (estimates range from M_w 7.1 to 8.4) between December, 1811 and February, 1812 (Reference 115; 116; 117; 114; 118; 119; 120). The actual size of these pre-instrumental events is not known with certainty and is based primarily on various estimates of damage intensity and amount and pattern of liquefaction. Magnitude estimates using these approaches range from Mw 7.1 to 8.4.

The December 16, 1811 earthquake is inferred to be associated with strike-slip displacement along the southern portion of the NMSZ, either on the Blytheville Arch-Cottonwood Grove fault, or Blytheville Arch-Bootheel Lineament (Figure 2.5-18; References 118; 114). The southern portion of the NMSZ extends for approximately 70 miles from northeastern Arkansas through the eastern corner of the Missouri "Bootheel" (References 92; 113). This southwestern part of the NMSZ follows the pre-middle Ordovician subsurface Blytheville Arch and coincides with the axis of the Reelfoot Rift. Johnston estimated the December event to have a magnitude of M_w 8.1 ± 0.31 (Reference 118). Hough, later re-evaluated the intensity data for the region and concluded that the event had a magnitude of M_w 7.2 to 7.3 (Reference 117). Bakun and Hopper also re-evaluated the intensity data and derive a magnitude of M_w 7.2 for the December,1811 event (Reference 115).

The February 7, 1812 New Madrid earthquake is associated with reverse displacement along the middle part of the NMSZ (Figure 2.5-18; Reference 108; 109; 114; 115; 118). This earthquake most likely occurred along the northwest-trending Reelfoot fault that extends approximately 43 miles from northwestern Tennessee to southeastern Missouri (Reference 121; 122). The Reelfoot fault is a northwest-trending southwest-vergent reverse fault (Reference 109; 123). The Reelfoot fault forms a topographic scarp developed as a result of fault-propagation (References 109; 122; 124). Kelson et al. (Reference 109) investigated near-surface deformation along the trace of the scarp and found evidence for three events within the past 2,400 years. The most recent event was associated with the 1811-1812 earthquake sequence. The penultimate event is estimated to have occurred between A.D. 1260 and 1650. The pre-penultimate event occurred prior to about A.D. 780-1000 (Reference 108). A range of recurrence intervals for the Reelfoot fault are estimated between 150 to 900 years, with a preferred range of about 400 to 500 years (Reference 109). The geometry and reverse sense of motion of the Reelfoot fault implies that the fault serves as a step-over segment between the southern and northern portions of the fault (Reference 92; 113). Johnston estimated a magnitude of M_w 8.0 ± 0.33 for the February, 1812 event (Reference 118). Hough (Reference 117) later re-evaluated the intensity data for the region and concluded that the February event had a magnitude of M_w 7.4 to 7.5. Bakun and Hopper (Reference 115) also re-evaluated the intensity data from 1811-1812 sequence and derive a magnitude of Mw 7.2 to 7.6 for the event.

The January 23, 1812 earthquake is inferred to be associated with strike-slip displacement on the East Prairie fault along the northern portion of the NMSZ (Figure 2.5-30; Reference 114). The northern portion of the NMSZ extends 45 miles in a northeast direction through southeastern Missouri, and approximately coincides with the northwestern boundary of the Reelfoot Rift (Reference 114). The interpretation that the January, 1812 earthquake occurred along the East Prairie fault of the NMSZ is based on fault mechanics and limited historical data, and is more poorly constrained than interpretations of the December 16, 1811 and February 7, 1812 earthquakes. Baldwin et al. conducted paleoseismic investigations along this segment of the fault (Reference 99). Although they have identified liquefaction evidence for the 1811/1812 earthquake sequence, their data do not support the presence of a major throughgoing fault with repeated late Holocene events.

Johnston estimated a magnitude of Mw 7.8±0.33 for the January, 1812 event (Reference 118). Hough et al. later re-evaluated the intensity data for the region and concluded that the January event had a magnitude of Mw 7.1 (Reference 117). Bakun and Hopper also re-evaluated the intensity data from 1811-1812 sequence and derive a magnitude of M_w 7.1 for the January 23, 1812 event (Reference 115).

2.5.1.1.5.6.1 Earthquake Recurrence

Because there is very little surface expression of faults within the NMSZ, earthquake recurrence estimates are based largely on dates of paleo-liquefaction and offset geological features (References 125; 126;109). These data suggest that strong earthquakes occurred around A.D. 900 +/- 100, A.D. 1450 +/- 150, and A.D. 1810 +/- 130 (References 125; 127; 128; 129). Kelson dated the penultimate event that deformed the scarp of the Reelfoot fault between A.D. 1260 and 1650, and an older event between A.D. 780 and 1000 (References 109).

Conclusions from paleoseismic investigations suggest that the recurrence interval for surface deforming earthquakes in the NMSZ is about 200 to 800 years (Reference 125; 130; 131; 132; 133; 109; 127; 129). The 200 to 800 year recurrence estimate, with a preferred estimate of 500 years is significantly shorter than the 5,000 year earthquake recurrence interval used in the 1986 EPRI study based on extrapolation of historical seismicity (Reference 9).

2.5.1.1.5.6.2 Slip Rate

A wide range of slip rates are reported for the NMSZ. Slip rate estimates include data from geodetic measurements that range from 5 to 7 mm/yr (Reference 134) to no detectable deformation (Reference 135), and geologic rates that range from 1.8 to 6.2 mm/yr for the Holocene, and 0.0003 to 0.002 mm/yr for the late Cretaceous to late Eocene (References 122; 136). Mueller and Pujol (Reference 123) report a slip rate along the northern and southern portions of the NMSZ of 1.8-2.0 mm/yr based on the geometric relationships (fault strike and slip vectors) with the Reelfoot fault.

2.5.1.1.5.6.3 Maximum Earthquake Magnitude

The six EPRI teams developed estimates of maximum earthquake magnitudes for the NMSZ that range from m_b 7.1 to 7.9 (Mw 7.3 to 8.7). Since the EPRI study, several independent estimates of maximum earthquake magnitudes for the NMSZ have been developed (Reference 84; 118; 117; 115). The estimates of maximum earthquake magnitude of Frankel et al. (Reference 84) and Johnston (Reference 118) are within the range of values developed by the six EPRI teams (Reference 9). The estimates presented by Hough et al. (Reference 117), Bakun and Hopper (Reference 115), and Mueller and Pujol (Reference 123) are lower than the EPRI range of maximum magnitudes for the NMSZ.

2.5.1.1.5.7 Gulf Coast Basin

The Grand Gulf Nuclear Station is located in the Gulf Coast Basin (Figure 2.5-3), a broad, low relief geomorphic province extending from eastern Texas to western Alabama and Florida, and from southern Arkansas to the Gulf Coast. The Gulf Coast Basin is a north-south trending syncline approximately 280 miles long and 400 miles wide. The basin is structurally bounded by the buried Ouachita Orogenic Belt on the north, and southern Appalachian Mountains on the east. These structures define the boundaries of a deep crustal depression that contains more than 50,000 feet of Mesozoic and Cenozoic sediment (Reference 17). Sediments within the Gulf Coast Basin accumulated since post-Jurassic continental rifting and formation of the Gulf of Mexico (Reference 27). The amount of sediment transported to the Gulf Coast Basin exceeded the volume that could be accommodated through basin subsidence and infilling, and as a result, fluvial depocenters have migrated through time, and the sedimentary complex has prograded gulfward over 250 miles. Each shift in the depocenter was marked by development of a series of growth faults (e.g. Pickens-Gilberttown, Southern Arkansas, Gulf Margin Normal faults) that defined the margins of unstable shelves. The growth faults are interpreted as aseismic gravitational collapse features that slip basinward under sedimentary load. Currently active growth faults are located along the Cretaceous shelf edge in the vicinity of the modern Gulf Coast, 90 miles south of the site (Figure 2.5-5; Reference 29).

2.5.1.1.5.8 Pickens-Gilberttown and Southern Arkansas Fault Zones

The Pickens-Gilberttown and Southern Arkansas fault zones are a system of faults that extend from southwestern Alabama through west-central Mississippi (Figure 2.5-5, Reference 137) to southern Arkansas and eastern Texas. The Pickens-Gilberttown and Southern Arkansas fault zones consist of a series of grabens developed in Paleozoic to Middle Tertiary deposits, on the gulfward side of the Ouachita Orogenic Belt (Reference 16).

The Pickens-Gilberttown and Southern Arkansas fault zones together are more than 500 miles long in a zone typically less than 25-miles wide (Figures 2.5-3 and 2.5-5). The Pickens-Gilberttown and Southern Arkansas fault zones offset Mesozoic and Cenozoic deposits. Mesozoic and Cenozoic deposits thicken gulfward across the fault zones indicating syndepositional down-to-the-south movement. Movement along the Pickens-Gilberttown and Southern Arkansas fault zones displaces Miocene age sediments as much as 200 feet, but Pliocene and Pleistocene age deposits are not offset. Pre-Miocene deposits are offset up to 1,000 feet at depth, and similar age deposits on opposite sides of the fault zones are as much as 10-fold thicker on the down-dropped, gulfward side of the structure (Reference 16). The Pickens-Gilberttown and Southern Arkansas fault zones formed by gravitational collapse related to large sedimentary loads in the Tertiary age Gulf Coastal Plain, or continental shelf. The Pickens-Gilberttown and Southern Arkansas fault zones are Tertiary age analogues to the currently active Gulf Margin Normal faults.

Unfaulted Pliocene and Pleistocene Upland Complex terrace deposits overlie the Pickens-Gilberttown fault zone in the vicinity of the Alabama River (Reference 138). The continuity of Pliocene and Pleistocene deposits across the fault zone indicates that the Pickens-Gilberttown fault zone is not active. Seismic data and continuity of stratigraphy documented from deep exploration wells also indicate that the Southern Arkansas fault zone has not been active since Miocene time (Reference 139).

Very little historical seismicity has occurred along the Pickens-Gilberttown and Southern Arkansas fault zones (Figure 2.5-5). Six earthquakes of m_b 3.3 to 3.9 occurred along the southeastern portion of the Pickens-Gilberttown fault zone near the Mississippi-Alabama border within the Site Region, and three additional earthquakes (m_b<4.4) occurred along the trend of the fault zone in southern Alabama, outside of the Site Region. These earthquakes occurred at the 1.8- to 3.6-mile depth of fluid recovery in active well fields, suggesting that they are most likely triggered earthquakes related to hydrocarbon recovery (Reference 140). No earthquakes > m_b 3.3, the lower threshold used by EPRI (Reference 9), have been recorded along the Southern Arkansas fault zone in the Site Region.

EPRI defined a- and b-values to characterize earthquake occurrence for major tectonic features within the Site Region (Reference 9). However, because the geologic data indicate that these fault zones have been inactive since post-Miocene time, none of the six EPRI Teams specifically characterized the Pickens-Gilberttown or Southern Arkansas fault zones in their seismic source models. The Pickens-Gilberttown and Southern Arkansas fault zones were incorporated within background seismic source zones across the Gulf Coastal Plain gulfward of the Ouachita Orogenic Belt. Therefore, no specific seismicity parameters were developed for the Pickens-Gilberttown or Southern Arkansas fault zones for the EPRI study. Since the EPRI study, only one new earthquake of m_b 3.3 to 3.9 has occurred along the entire 500 mile long Pickens-Gilberttown Southern Arkansas fault zone. The addition of this one earthquake does not significantly modify the earthquake rate parameters within the Site Region used by the six EPRI Teams in their seismic source model for the southern portion of the Gulf Coastal Plain.

The six EPRI teams developed estimates of maximum earthquake magnitudes for the area encompassing the Pickens-Gilberttown and Southern Arkansas fault zones (Gulf Coastal Plain south of Ouachita Orogenic Belt) that range from m_b 4.6 to 7.2 (Mw 4.2 to 7.5). Since the EPRI study, maximum earthquake magnitudes for this area have been estimated to be Mw 7.5 (Reference 19) and m_b 5.0 (Reference 70). These estimates of maximum earthquake magnitude are within the range of values developed by the six EPRI teams (Reference 9).

2.5.1.1.5.9 Saline River Source Zone

The Saline River source zone lies within the Ouachita Orogenic Belt and structurally overlies the southwestward subsurface extension of the Proterozoic Reelfoot Rift. The Saline River source zone is located primarily in southeastern Arkansas and northwestern Mississippi, with a minor extension into northern Louisiana (Figure 2.5-19). The source zone was not identified by any EPRI earth science team, and is defined based on more recent geomorphic, geologic and seismologic data that is suggestive of Holocene and late Pleistocene deformation and paleoseismicity (Reference 150; 151; 152; 153). Although suggestive of late-Pleistocene deformation, the evidence is not conclusive and may alternatively be explained by activity along the Reelfoot Rift and/or through non-tectonic processes such as isostatic adjustments from glacial loading to the north, or sediment loading within the Mississippi Embayment and/or Mississippi delta fan complex.

2.5.1.1.5.9.1 Geomorphic Evidence

Basin analysis techniques were used to assess possible tectonic influences on the location and orientation of the Ouachita, Saline, and Arkansas Rivers (Reference 150). Based on the distribution and ages of river terraces, the progressive southwestward migration of each river channel producing drainage basins with distinct asymmetries was documented. The southwestward river migration and drainage basin asymmetry was interpreted to reflect southwestward tilting of a series of northwest-trending structural blocks (Reference 154). These northwest-trending, tilted structural blocks are bordered by assumed northwest-trending normal or oblique slip faults and are interpreted to control the patterns, position, and orientation of these major drainages.

Quaternary geological mapping (References 44; 154) identified a sequence of Quaternary fluvial terraces within the Mississippi River and tributary valleys. In the vicinity of the Arkansas, Saline, and Ouachita rivers these terraces include from oldest to youngest the Intermediate Complex, Prairie Complex and Deweyville Complex (Figures 2.5-20, 2.5-21 and 2.5-22). Each of these individual terrace complexes contains several discrete terrace treads.

The amount of stream incision into terraces of known age can be used as a proxy to estimate the total amount and rate of block uplift and thus, the amount and rate of vertical separation on the assumed bordering faults (Reference 161). This approach was used to evaluate the possible rate of deformation within the Saline River source zone. Cross-sections used to estimate slip rates on the Saline River source zone are shown on Figure 2.5-23. The incision rates provide an order of magnitude estimate of long-term incision and slip rate. Figure 2.5-23 provides estimates of incision rates, used as a proxy for vertical slip-rates, for various terrace surfaces. The rates range from 0.05 to 1.7 mm/yr.

The location and vertical position of terraces within the Arkansas, Saline, and Ouachita rivers indicate basin asymmetry. The oldest and highest terraces (e.g. Intermediate Complex) typically are preserved on the northeast side of the basin. The lowest and youngest terraces (Deweyville Complex), as well as the active stream channels, are located on the southwest sides of the basins (Figures 2.5-29, 10 and 11). Although there is a general pattern of basin asymmetry, the positions of Holocene to recent stream patterns do not always follow this pattern as streams have migrated locally due to channel avulsion (Reference 17). Furthermore, geomorphic mapping (References 17; 154;150) is preliminary and regional in nature, and therefore the mapped locations and correlations of some terraces are uncertain.

2.5.1.1.5.9.2 Geological Evidence – Surface faulting

Geological field investigations in the vicinity of Saline River were conducted to evaluate faults initially identified in road-cuts (Reference 151). Trenches were excavated at several of the road-cuts to evaluate the recency of fault activity. The locations of the field investigation areas are shown on Figure 2.5-20. Investigations have not yet been conducted along the Arkansas or Ouachita Rivers. Observations made in the trench and road-cut exposures indicate post-Eocene faulting and are suggestive of Quaternary faulting, but are not conclusive.

Surface expression of the Saline River source zone includes topographic lineaments and linear drainage patterns. Six small-displacement fault splays have been identified in trenches and road-cuts near Monticello, Arkansas (References 85; 151). Two of these faults trend in a northwest direction parallel to the Saline River. Four subsidiary faults strike east-northeast. The chronology of deformation for each of the sites is summarized in Table 2.5-4.

Five trench and road-cut locations expose faults with Eocene or younger deformation (Reference 151). All faults deform Eocene Jackson Group deposits (Figure 2.5-24). Three trenches exposed faults that deform Pliocene to Pleistocene Upland Complex (Lafayette Gravel). One fault may displace the late Pleistocene Peoria Loess. Holocene silt deposits may be deformed in two trenches, although these relationships are equivocal and could be explained by erosional processes (Reference 151). Relationships observed in the fault exposures indicate strike-slip, normal and reverse senses of displacement. One fault splay underlies a gentle anticline that deforms alluvium with an age of 640 cal. yr B.P. (Figure 2.5-25; note: all ages are reported as 2-sigma calibrated radiocarbon years before A.D. 1950 (present)). This fold is interpreted to be a fault-propagation fold related to Holocene activity along the Saline River fault zone (Figure 2.5-25; Reference 155).

2.5.1.1.5.9.3 Geological Evidence – Liquefaction

Liquefaction-related features have been identified locally within the Saline River source zone in Ashley County and Desha County, Arkansas (Reference 152). The liquefaction features are recognized on the surface as sand blows (Figure 2.5-26). These surficial sand blows were trenched (Reference 152) at three locations to document their stratigraphic relationships and provide estimates of event ages. The three liquefaction sites include Portland and Montrose in Ashley County, and Kelso in Desha County. The liquefaction data from the three sites are summarized in Tables 2.5-5, and 2.5-6.

One or two liquefaction events are stratigraphically discernable at the Portland site in Ashley County ((Reference 152; Table 2.5-5). The oldest event at this site is identified as a series of sand dikes that feed a sand layer. Sand dikes are cross-cut by a krotavina dated 150 to 500 cal. yr B.P. and therefore are older than the age of the krotavina. Charcoal from within the sand blow yielded ages of 0 to 430 cal. yr B.P. Charcoal from the substrate alluvium yielded an age of 910 to 990 cal. yr B.P., which provides a maximum possible age for this liquefaction event. The youngest event is constrained by stratigraphic relationships where a sand vent cross-cuts the older sand blow and is therefore younger than 150 to 500 cal. yr B.P. This younger event could be a separate liquefaction event, or could be related to the initial liquefaction event.

Three liquefaction events are stratigraphically discernable at the Montrose site in Ashley County including an upper sand blow crater and sand dikes (Event III), a middle vented sand layer and sand-dikes (Event II), and a lower vented sand layer and sand dikes (Event I; Table 2.5-5). The youngest liquefaction event is preserved as a sand blow crater filled with organic material dated between 320 and 740 cal. yr B.P., which represents a minimum limiting age for Event III. The middle sand layer (Event II at Montrose) overlies and cross-cuts the lower sand (Event I); no soil development is observed between the two sand units representing Events I and II. The maximum limiting age for Event III and minimum limiting age of Events II and I is constrained by a radiocarbon date on the organic soil that is developed within the middle sand layer (1,300 to 1,550 cal. yr B.P.). The maximum limiting age of Events I and II is constrained by the radiocarbon age of the underlying substrate (5,055 to 5,320 cal. yr B.P.). Event I could have occurred anytime after deposition of the alluvial substrate. We infer that the minimum age of liquefaction events I and II must be a minimum of several hundred years older than the age of the soil dated (1300 to 1550 cal. yr B.P.), as development of the soil horizon on the sand blow would require a period of time. Thus, we infer a minimum age for Events I and II of about 1700 ybp. The exact ages of these events are equivocal. Because there is an absence of soil development between these two events, it is possible that the two sand layers may represent the same event.

Three possible liquefaction events are recognized at the Kelso site in Desha County (Reference 152). The youngest event (Event III) is based on an anecdotal report that describes ground cracking and bank failures, possibly associated with liquefaction during the 1812 New Madrid earthquakes at this location (Reference 152). The older events (Events I and II) are recognized based on stratigraphic relationships observed in the trench where sand vents feed a sand horizon. Charcoal from organic fill in these sand vents yield ages of 740 to 1,000, 960 to 1,310, 1,030 to 1,040, 2,010 to 2,190, and 2,230 to 2,310 cal. yr B.P. Cox (Reference 152) interprets these dates to represent two events. Event II is inferred to have occurred prior to 740 and 1,310 cal. yr B.P., and Event I is inferred to have occurred prior to 2,010 and 2,310 cal. yr B.P. An alluvial horizon at the base of the trench was dated using infrared spectral luminescence (IRSL) at 5740+/-560 ybp and represents the maximum limiting age for Events I and II.

The available data support the interpretation of three to five liquefaction events. The three event interpretation involves:

- Event III – Liquefaction at Portland (prior to 150 to 990 cal. yr B.P.), Kelso (prior to 740 to 1310 cal. yr B.P.), and Montrose (prior to 320 to 1550 cal. yr B.P.);
- Event II – Liquefaction at Kelso (prior to 2010 to 2310) and Montrose (prior to 1700 ybp inferred based on repose time necessary to produce an organic soil (dated 1300 to 1550 cal. yr B.P.) on vented sand layer);
- Event I – Older event at Montrose some time between 1700 ybp (inferred as above), and 5320 cal. yr B.P.

The four event interpretation involves:

- Event IV – Liquefaction at Portland (prior to 150 to 990 cal. yr B.P.) and Montrose (prior to 320 to 1550 cal. yr B.P.);
- Event III – Liquefaction at Kelso (prior to 740 to 1310 cal. yr B.P.);
- Event II - Liquefaction at Kelso (prior to 2010 to 2310) and Montrose (prior to 1700 ybp inferred based on repose time necessary to produce an organic soil (dated 1300 to 1550 cal. yr B.P.) on vented sand layer);
- Event I – Older event at Montrose some time between 1700 ybp (inferred as above), and 5320 cal. yr B.P.

The five event interpretation involves:

- Event V - Liquefaction at Portland post 150 to 560 cal. yr B.P.
- Event IV – Liquefaction at Portland (prior to 150 to 990 cal. yr B.P.) and Montrose (prior to 320 to 1550 cal. yr B.P.);
- Event III – Liquefaction at Kelso (prior to 740 to 1310 cal. yr B.P.);
- Event II - Liquefaction at Kelso (prior to 2010 to 2310) and Montrose (prior to 1700 ybp inferred based on repose time necessary to produce an organic soil (dated 1300 to 1550 cal. yr B.P.) on vented sand layer);
- Event I – Older event at Montrose some time between 1700 ybp (inferred as above), and 5320 cal. yr B.P.

The observed liquefaction features can be interpreted in three ways. First, the liquefaction events record local moderate magnitude earthquakes that produced small liquefaction fields. These events may have been associated with earthquake activity within the Saline River source zone. Second, the observed liquefaction features record far-field ground shaking related to events along the New Madrid Seismic Zone. This is supported by the historical observation of ground cracking and bank failures near the Kelso site during the 1811-1812 New Madrid earthquake sequence (Reference 156), although this also may be a local 1812 triggered aftershock within the Saline River source zone. Third, the observed liquefaction fields record a combination of these processes.

2.5.1.1.5.9.4 Seismological Evidence

Very little historical seismicity has occurred within the Saline River seismic zone (Figures 2.5-5 and 2.5-20). Nine earthquakes of m_b 3.3 (lower bound used by EPRI, 1985) to 4.9 occurred within the source zone during the period 1777 to 1985. These events were not temporally or spatially sufficient for the EPRI earth science teams to identify a unique source zone in the Saline River area. Three additional earthquakes of m_b 3.3 to 3.9 occurred in the source zone during the period 1985 to 2002. Based on the locations of events smaller than m_b 3.3, Cox et al. (Reference 151) suggest that these earthquakes form a weak alignment in a northwest-southeast direction along the trends of the Ouachita, Saline and Arkansas rivers (Figure 2.5-20).

2.5.1.1.5.9.4.1 Earthquake Recurrence Interval

To evaluate earthquake recurrence using these paleoliquefaction features, we calculate average recurrence intervals assuming that three to five events occurred between 5320 and 150 ybp (assumes events post-A.D. 1800 would have been reported). The recurrence times are shown on Table 2.5-6. The calculated average recurrence times are 2,585, 1,725, and 1,295 years. We also calculate the average recurrence assuming that three to five events occurred between 1700 (inferred based on repose time necessary to produce an organic soil (dated 1300 to 1550 cal. yr B.P.) on vented sand layer) and 150 ybp (A.D. 1800), the minimum allowable time period. These calculated recurrence intervals are 775, 517, 388 years. Geological data from the Montrose site, where three events are recognized, support a maximum inter-event recurrence interval of approximately 3,500 to 4,000 years. Based on these estimates, we have selected the following recurrence times to represent the uncertainty in earthquake recurrence within the Saline River source zone: a low value of 390 years (minimum recurrence for minimum time period); and a middle value of 1,725 years (middle recurrence for maximum time period); and a high value of 3,500 years (lower estimate of maximum recurrence interval from the geological record at the Montrose site).

2.5.1.1.5.9.4.2 Slip Rate

The amount of stream incision into terraces of known age can be used as a proxy to estimate the total amount and rate of block uplift and thus, the amount and rate of vertical separation on the assumed bordering faults (Reference 157). This approach was used to evaluate the possible rate of deformation within the Saline River source zone. Cross-sections used to estimate slip rates on the Saline River source zone are shown on Figure 2.5-23. Although not as precise as displacement data from paleoseismic trenches, the incision rates provide an order of magnitude estimate of long-term incision and slip rate. Figure 2.5-23 provides estimates of incision rates, used as a proxy for vertical slip-rates, for various terrace surfaces. The rates range from 0.05 to 1.7 mm/yr.

We use the geologic relationships in trenches near Monticello (Sites 3 and 4 of Reference 151) to estimate fault slip-rate. As shown on the enlargement on Figure 2.5-20, a subsidiary northeast-trending fault is offset approximately 30 meters by a northwest-trending fault that possibly deforms Upland Complex deposits. The base of the Upland Complex is offset by the northwest trending fault; this fault terminates within the Upland Complex. Based on the 30-meter offset of the secondary fault and a 1 to 4 million year age range of the Upland Complex, the fault slip rate is estimated to be 0.008 to 0.03 mm/yr. Because this fault is likely a subsidiary fault within a larger fault zone, we infer that this slip-rate is a minimum bounding estimate for the rate of deformation within the Saline River source zone.

2.5.1.1.5.9.4.3 Maximum Earthquake Magnitude

Potential magnitudes of M 5.5 to 6.0 for the events that produced the liquefaction fields in Ashley and Desha counties have been estimated (Reference 152). If the events reflect localized seismicity, this magnitude range is a reasonable lower bound estimate for the maximum magnitude within the Saline River source zone. However, if each of the liquefaction fields corresponds to a prior New Madrid seismic zone event, the observed liquefaction features would not support the presence of a distinct seismic source along the Saline River in southeastern Arkansas.

2.5.1.1.5.10 Non-Tectonic Structural Features

In addition to the tectonic features described above, non-tectonic (non-seismogenic; Reference 141) processes also produced structural and topographic features in the Site Region. These features locally deformed Gulf Coastal Basin sediments and include volcanic domes, salt diapirs, and growth faults. The timing and processes controlling these features are described in the following sections.

2.5.1.1.5.10.1 Volcanic Domes

The Jackson Dome is a circular, 16-mile-diameter volcanic plug located at the southern margin of the Mississippi Embayment near the city of Jackson in west-central Mississippi (Figure 2.5-3). The dome was formed by the arching of strata above a deep-seated igneous intrusion. The dome became active in the Early Cretaceous, continued to rise through post Oligocene time, and has a total structural relief of about 10,000 feet. Outcrops of the Oligocene Vicksburg Group, including the Glendon Limestone are preserved on the dome's northwestern flank (Reference 142). Although the dome appears to be dormant, radiometric dates in the State #2 Fee well show a 26-million-year gap in activity between 101- and 75-million year old igneous rocks suggesting long intervals between periods of activity (Reference 142). Interpreted seismic lines along the flanks of the Jackson Dome have identified several faults in the Jackson area, including an east-west-trending fault south of Florence, Mississippi, and six additional northwest-southeast trending faults that extend from the dome's eastern flank (Reference 34). The youngest strata offset by these faults is the Upper Cretaceous Eutaw Formation. Bograd speculated that a 1927 earthquake that shook houses as far away as Meridian, Mississippi occurred on a fault in the Jackson area (Reference 143). However, there is no clear association of earthquake activity with faults associated with the Jackson Dome.

The Monroe Uplift is a volcanic dome that straddles southern Arkansas, northern Louisiana, and west central Mississippi (Figure 2.5-3). The northern margin of the Gulf Coast Basin and southwestern extent of the Mississippi Embayment coincides with the Monroe Uplift. The circular area of the dome is approximately 93 miles in diameter and is characterized by the arching of strata above a deep-seated igneous intrusion. The Monroe Uplift initially became active in the Jurassic and experienced continued movement into post-Miocene time. There is no topographic expression of the Monroe Uplift at the surface. However, Burnett and Schumm (Reference 144) evaluated fluvial geomorphic features distributed across the uplift and concluded that the rivers were adjusting to modern deformation. Upstream of the uplift the river had less bank erosion, a reduced sinuosity, lower channel and valley gradient, and lower channel depth than downstream (Reference 144). Additionally, they found that the river terraces showed a convex pattern across the Monroe Uplift and inferred active uplift in the Pleistocene and Holocene.

The Sabine Uplift is a volcanic dome located in east Texas and western Louisiana (Figure 2.5-3). The dome has a roughly oval shape, approximately 124-miles long in the north-south direction and 93-miles wide in the east-west direction. The uplift is a flat-topped structural high that was active in post-Middle Eocene time. No active faulting or seismicity has been associated with the Sabine Uplift.

2.5.1.1.5.10.2 Salt Diapirs

Salt migration structures or salt domes occur in two subprovinces within the Gulf Coastal Plain, the Interior Salt Basin and the Coastal Salt Basin (Figure 2.5-3). Salt migration produced anticlinal structures, ridge-like diapiric folds, and piercement domes in these subprovinces. Salt originated from the Middle Jurassic Louann Salt and salt migration structures are concentrated in an approximately 100-mile-wide zone extending from southwestern Alabama to eastern Texas (Figure 2.5-3). The source depth for the Louann Salt is around 15,000 feet and becomes progressively deeper to the south (Reference 30). Salt Domes in the Interior Salt Basin were active from Late Cretaceous to Oligocene and have not been active since (Reference 30).

Salt Domes in the Coastal Salt Basin began to form in the Miocene and have been active through the Quaternary. The source depth for the Louann Salt in the Coastal Salt Basin is around 35,000 feet and approaches 65,000 feet in the vicinity of the southernmost offshore salt domes.

Salt migration in the Coastal Salt Basin deforms the ground surface. The Five Islands structural uplift is a northwest-southeast trending line of salt domes in south central Louisiana. These domes are expressed at the surface and deform a subsurface Quaternary gravel suggesting Pleistocene activity (Reference 17).

2.5.1.1.5.10.3 Growth Faults

East-west-trending growth faults along the southern margin of the Gulf Coastal Basin are referred to as the Gulf Margin Normal faults. These faults include the Tepetate-Baton Rouge, Denham Springs-Scotlandville, Lake Hatch, Golden Meadow, Lake Sand, Grand Chenier, Lake Arthur and Mamou faults, as well as many other un-named faults. Seismicity within the zone is sparse, with only nine felt earthquakes in historic time (Reference 145).

The opening of the Gulf of Mexico formed a south–facing, rifted margin during the Triassic. Along this margin, a thick package of Jurassic and younger sediment was deposited including the Louann Salt, and overlying carbonate and clastic marine sediments. This sedimentary sequence is in excess of seven miles thick in the vicinity of the Gulf Margin Normal faults. The Louann Salt is inferred to form a sliding layer on which the overlying sedimentary section has mobilized forming a series of Tertiary and Quaternary growth faults. Because the faults are located in poorly lithified rocks and sediments, they may not be able to support the stresses required for the propagation of significant seismic ruptures that could cause damaging ground motions (Reference 113).

Faults generally dip between 50 and 70 degrees at the surface and shallow to less than 50 degrees at depth (Reference 29). Additionally, strata increase in thickness on the downthrown side of faults and displacements increase with depth. Periods of movement on the faults range in age from late Eocene to Holocene depending on the location of the Mississippi River depo-center. The current Gulf Margin Normal faults are localized along the subsurface Cretaceous shelf edge and experience high rates of aseismic slip.

Slip rate estimates for the Baton Rouge fault vary from a Pleistocene rate of 0.05-0.08 mm/yr (References 113; 146) to a Holocene rate of 9 mm/yr determined by leveling surveys conducted by the Louisiana Water Research Institute (Reference 16). Rates as high as 4 cm/yr have been measured from Global Positioning System (GPS) data (Reference 147). The largest earthquakes recorded in Louisiana were two M 4.4 events that occurred on the same day in April, 1964, however, the majority of the recorded earthquakes in Louisiana range in magnitude from 2.5 to 3.5 (Reference 148). The most recent and best located event occurred on October

16, 1983. The depth determination for this event shows that it occurred at approximately 8.5 miles (Reference 148; 149), possibly in basement materials beneath the sedimentary prism.

2.5.1.1.6 Regional Seismicity

Much of the central and eastern U.S. seismicity appears to occur due to reactivation of older Rift bounding faults and sutures between exotic terranes (References 164, 165). Historical seismicity in the region is most strongly concentrated in the Reelfoot Rift and New Madrid Seismic Zone north of the Gulf Coastal Plain. Small magnitude earthquakes also occur along the general trend of the Ouachita Orogenic Belt and Appalachian Mountains. In the areas south of the Ouachita Orogenic Belt and Appalachian Mountains there is a very low rate and a random spatial distribution of epicenters.

Due to the regions tectonic stability, there have been relatively few recorded earthquakes. Reference 78 compared the seismicity of the central U.S. to that of the southern California. The activity rate of magnitude 4 earthquakes in the 3,000,000 km^2 area of the central U.S. is more than a factor of 10 lower than that of a 200,000 km^2 area of southern California. The rate of magnitude 6 earthquakes is about a factor of 30 lower. This low rate of activity has characterized the seismicity of the Gulf Coastal Plain for over 150 years, and most likely throughout the Quaternary.

Because the south central United States is a passive continental margin, there are *no plate boundary fault systems* that accommodate relative plate motion, focus earthquake activity, and produce repeated large magnitude events. Earthquake activity appears to be concentrated along reactivated older tectonic elements such as the Reelfoot Rift. Furthermore, no faults have been mapped within approximately 90 miles of the proposed location of the new facility at the Grand Gulf Nuclear Station.

2.5.1.1.6.1 Location and Distribution

The location of seismicity is shown on Figure 2.5-5. The seismicity shown on this figure is for the period 1777 to 1984, which covers the period used in the 1986 EPRI analysis, and 1985 to 2002, which covers the period since the EPRI study. The updated EPRI Seismicity catalog is described in section 2.5.2.1.4. As can be seen on Figure 2.5-5, the current seismicity trends are very similar to the location and distribution of seismicity for the period considered in the EPRI study (Reference 9). The events are concentrated along the Reelfoot Rift, Ouachita Orogenic Belt, and Appalachian Mountains, primarily in regions underlain by continental crust. Few earthquakes have occurred within the Gulf Coast Basin, and no earthquakes have been recorded within the Site Vicinity or Site Location.

2.5.1.1.6.2 Historical Events in Site Region

The Site Region is characterized by very low rates of seismic activity. Only one earthquake of $3.3<m_b<3.9$ has been recorded within 90 miles of the site since 1777 and only 39 earthquakes of $m_b>3.3$ have been recorded in the entire 200 mile radius area around the site since 1777. Most earthquakes in the site region occur in areas underlain by crystalline basement rock of the North American craton, and within the buried Ouachita Orogenic Belt, or Appalachian Mountains.

Since the 1986 EPRI study, only four earthquakes of $m_b>3.3$, the lower limit used in the EPRI study, have been recorded in the Site Region.

2.5.1.1.6.3 Historical Events in Site Vicinity

Historical seismicity records for the Site Region extend back to A.D. 1777. Based on our review and analysis of these historical seismicity records there have been no earthquakes recorded within the Site Vicinity. The nearest earthquake to the site occurred approximately 90 miles to the west in central Louisiana.

2.5.1.2 Site Geology

This section presents information on the physical setting, geological history and subsurface conditions within the Site Area (5-mile radius) and Site Location (0.6-mile or 1-km radius) of the proposed new facility at the Grand Gulf Nuclear Station.

2.5.1.2.1 Site Physiography and Geomorphology

The Site Area and Site Location straddle the western boundary of the Loess Hills physiographic subprovince (Figure 2.5-2). The proposed location of the new facility is approximately 1.1 miles east of the Mississippi River and adjacent to the Mississippi River flood plain (Figures 2.5-9 and 2.5-27). The boundary between the Mississippi Alluvial Valley and Loess Hills physiographic subprovinces crosses the Site Location and is defined by the approximately 65- to 80-foot-high north-trending erosional escarpment at the edge of the Mississippi River flood plain.

As shown on Figure 2.5-27, the topography of the Loess Hills in the Site Area is characterized by steep-walled stream valleys, flat-topped ridgelines, and dendritic drainage systems. Large river terraces occur along river floodplains and valley bottoms. Older terraces are present between elevations of about 140 and 200 feet along the tributary valleys of Bayou Pierre and Big Black River, and along the eastern margin of the Mississippi Valley (Figures 2.5-9 and 2.5-27). The topography of the Mississippi Alluvial Valley in the Site Area is relatively flat and characterized by flood plain, cut-banks, point bars, and oxbow lakes. The 0.6-mile radius of the Site Location does not extend to the active channel of the Mississippi River.

The proposed location of the new facility encompasses approximately 30 acres (Figure 2.5-27). The location does not represent the footprint of the proposed power block, but a larger area for overall construction purposes that envelops all potential facility footprints being considered. The proposed location straddles two previously graded surfaces at elevations of 132 feet and 155 feet, separated by a 23-foot high engineered cut-slope (Figure 2.5-28). The graded surfaces were former parking lots and lay-down areas used during construction of the existing Grand Gulf Nuclear Station.

The proposed facility location is bounded on the east by existing internal plant roads and parking lots (Figure 2.5-28). The location is bounded on the west by the erosional escarpment at the edge of the Mississippi River flood plain and on the north and south by two ravines that drain the Site Location.

2.5.1.2.2 Site Geologic History

The geological formations underlying the Site Area and Site Location record a long history of tectonic stability and deposition. The formations include both marine and terrestrial sediments that reflect distinct changes in depositional environments, climatic conditions, and glacial-eustatic cycles over the past 36 Ma. Deposits of at least Oligocene and younger age dip very gently southward and are laterally continuous across the Site Region (Figures 2.5-6, 2.5-11 and 2.5-12). These deposits are not deformed and thus document long term tectonic stability. The geological history of the Site Area and Site Location from the Oligocene period to the present is discussed below; regional geological history and descriptions of events that are older than Oligocene are presented in Section 2.5.1.1.

The Oligocene depositional environment in the Site Area was dominated by shallow marine seas, in which the Glendon Limestone and Byram Marl formations of the Vicksburg Group were deposited (Reference 16). These deposits primarily consist of limestone and marl with interbedded calcareous sands and clays. The Byram Marl was overlain by the late Oligocene Bucatunna Clay Formation, possibly representing a transition to a deep water or estuarine environment. The Glendon Limestone occurs at a depth of approximately 300 feet beneath the Site Area (Figure 2.5-15; Reference 16). These deposits are overlain unconformably by the Miocene Catahoula Formation.

In the Miocene, the depositional environment at the site changed from a marine to a marginal shoreline environment, in which the Catahoula Formation was deposited (Reference 16). These deposits consist of silty to sandy clays, clayey silts, and sands. The surface of the Catahoula Formation was deeply eroded at the site prior to deposition of the Pliocene to Pleistocene age Upland Complex based on the structural contour map shown on Figure 2.5-29.

In the Pliocene and Pleistocene, the depositional environment again changed from a marginal shoreline to an alluvial environment, in which alluvial deposits correlative with the Upland Complex were deposited. These deposits consist of coarse sand and gravel derived from both glacial and non-glacial sources (Reference 17). Pliocene-Pleistocene Upland Complex deposits unconformably overlie the eroded surface of the Catahoula Formation (Figures 2.5-30, and 2.5-31).

Late Pleistocene terraces were deposited in response to Wisconsin-age glacial cycles that supplied large volumes of sediment to the Mississippi Alluvial Valley (References 17; 31; 32). Subsequent stream incision eroded the terraces along north-northeast trending valleys that cross the Site Location (Figure 2.5-32).

At various periods in the late Pleistocene, strong seasonally prevailing winds transported silt from unvegetated glacial outwash in the central United States (Reference 17). As a result, the Peoria, Ferndale, Roxanna, and Lovelend loess sheets were deposited in the Site Vicinity and Site Area, between Vicksburg and Natchez (Figure 2.5-8). The youngest loess sheet, the Peoria Loess, is late Wisconsin in age (Reference 21). The average thickness of loess in the Site Location is about 65 feet; however, individual loess sheets have not been differentiated in the Site Location. Throughout the Holocene, loess deposits were deeply eroded by tributary streams to the Mississippi River. During this time alluvial sediment also was deposited on the Mississippi River flood plain in the western part of the Site Area and Site Location, and in tributary stream valleys along the northern and southern portions of the Site Area and Site Location (Figures 2.5-9 and 2.5-27). Deposition of alluvial deposits during peak glacial outwash may have changed local base-levels, blocking stream outlets and leading to the ponding or deposition of silt and alluvium in tributary valleys. The subsequent drop in river-level in the current interglacial period is inferred to have caused incision and formation of the terraces remnants along Bayou Pierre and Big Black River.

The Oligocene and younger deposits demonstrate a long period of tectonic stability and the absence of tectonic deformation in the Site Area and Site Location. As shown on Figures 2.5-9, there are no faults or folds in the Site Area. A structure contour map on the surface of the Oligocene Glendon Limestone (Figure 2.5-15) also documents the absence of post-Miocene age deformation. Figure 2.5-12, a cross-section through the Site Area, documents the lateral continuity of strata, and therefore the absence of faulting within the Site Area.

2.5.1.2.3 Site Geologic Conditions

The characteristics of the individual deposits that occur in the Site Area and Site Location are described below in Section 2.5.1.2.4.1. Geologic maps of the Site Area and Site Location are shown on Figures 2.5-9 and 2.5-27, respectively. Geologic cross-sections are shown on Figures 2.5-11 for the Site Vicinity, and Figures 2.5-30 and 2.5-31 for the Site Location.

2.5.1.2.3.1 Site Stratigraphy

Extensive geological and geotechnical data for the Site Area and Site Location are available as a result of the investigations completed for the existing Grand Gulf Nuclear Station (Reference 16). During this investigation, 275 borings were drilled within the Site Area to a maximum depth of 447 feet. The borings were completed to document geological and geotechnical conditions of the Site Area. In addition, 22 seismic refraction surveys were completed. The seismic refraction surveys were completed to document the lateral continuity and seismic velocity characteristics of the subsurface stratigraphy.

In addition to the existing database for the Grand Gulf Nuclear Station, three new soil borings, four Cone Penetrometer Tests (CPT), two down-hole geophysical surveys, and geological field observations were completed during this study to evaluate subsurface conditions at the proposed location of the new facility and to provide input parameters to assess dynamic response of subsurface materials (Sections 2.5.2 and 2.5.4). The new soil borings were advanced to depths ranging from 141 to 238 feet and penetrated strata ranging in age from the Holocene to the Miocene. The CPTs were advanced to depths of 60 to 80 feet terminating in sands and gravels of the terrace deposits of probable Pleistocene age.

2.5.1.2.3.1.1 Quaternary Deposits

Holocene and Pleistocene age gravels, sands, silts, and clays occur within the Site Area and Site Location (Figures 2.5-9 and 2.5-27). These deposits are related to fluvial processes along the Mississippi River and its tributaries, and eolian processes that formed the Loess Hills along the eastern margin of the Mississippi Alluvial Valley. The Quaternary deposits described in this section typically have an unconformable depositional relationship with the underlying Pliocene to Pleistocene Upland Complex, or Tertiary Catahoula deposits, described below.

2.5.1.2.3.1.1.1 Holocene Series

Holocene sediments consist of fluvial deposits on the flood plain of the Mississippi River, alluvium and terrace deposits in tributary valleys, and colluvium along hill slopes in the Loess Hills. Holocene fluvial deposits of the Mississippi River flood plain occur between the Mississippi River and the Loess Hills bluff, and represent the filling of at least two abandoned river channels (Reference 16). Hamilton and Gin lakes, which lie within or adjacent to the Site Location, are oxbow lakes that represent abandoned Mississippi River meander scars. The area between Hamilton Lake and the Loess Hills bluff is underlain by backswamp deposits (Hb) shown on Figure 2.5-9.

Holocene alluvium and terrace deposits in the Site Area occur along Bayou Pierre and small tributary streams (Figure 2.5-9). Terrace deposits along Bayou Pierre lie at elevations of approximately 120 feet and form well-defined planar surfaces above the modern flood plain. Remnants of Holocene terraces also occur along the Loess Hills bluff and along the tributary valley that crosses the Site Location (Figure 2.5-27). Holocene alluvial deposits in the Site Area range in thickness from 22 to 182 feet and unconformably overlie the Miocene Catahoula Formation (Reference 16).

Holocene colluvial deposits in the Loess Hills drape the base of the bluffs and valley walls along the flood plain and tributary valleys of the Mississippi River. The colluvial deposits consist of brown silt, clayey silt, or silty clay derived from erosion of the loess materials and are up to 47 feet thick (Reference 16).

2.5.1.2.3.1.1.2 Pleistocene Series

The distribution of Pleistocene sediments within the Site Area and Site Location is shown on Figures 2.5-9 and 2.5-27, respectively.

<u>Terrace Deposits</u>

Pleistocene terrace deposits occur in the Site Area along the Loess Hills bluff, Bayou Pierre, and small tributary streams (Figures 2.5-9, 2.5-33). Although not within the Site Area, Pleistocene terraces also occur along the Big Black River. The Pleistocene terraces in the Site Area were mapped in a generalized manner (undifferentiated), as shown on Figure 2.5-8 (Reference 44). Figures 2.5-9 and 2.5-27 present more detailed mapping of the Pleistocene terraces. The terraces shown on Figures 2.5-9 and 2.5-27 were identified based on aerial photograph interpretation, topographic analysis, and field observations.

Terraces are recognized as broad very low relief surfaces up to 0.75-miles across that are dissected by dendritic surface drainage systems (Figure 2.5-33). The back-edges of the terraces are defined by topographic breaks in hillslopes. In the Site Area, terraces occur at elevations of approximately 140, 160, and 180 feet. The elevations of the terrace treads vary by plus or minus 10 feet. Additional discontinuous remnants of terraces may occur at elevations in excess of 200 feet, though distinguishing these from older pediment surfaces is difficult.

The location of the proposed new facility lies on an inferred latest Pleistocene terrace surface at an elevation of approximately 150 feet. Based on subsurface data from borings completed at the site (Figures 2.5-34 through 2.5-37), the Pleistocene terrace surface is underlain by up to 75 feet of loess. The loess is underlain by coarse-grained alluvial sand and gravel deposits of the Upland Complex (described below).

The Pleistocene terraces appear to be formed on the loess deposits or have incorporated reworked loess within the alluvial systems. Therefore, these surfaces are inferred to be of late Pleistocene (late-Wisconsin) age, the age of the loess sheets in the Site Area (Reference 21).

The Pleistocene terraces are inferred to have formed through a combination of processes. During the late-Wisconsin the Mississippi River was a much higher energy river and as such would have a higher base level to tributary drainages (Reference 17). The model involves either erosion of loess deposits within the tributary valleys, or ponding of loess within tributary valleys, as a result of the higher base level in the Mississippi River. Transport of course-grained valley train deposits during the late-Wisconsin also could have dammed or bridged the mouths of tributary streams causing formation of fill terraces or lakes. The late-Wisconsin Lake Monroe is an example of a lake formed by natural damming of an alluvial valley by the valley train deposits (Reference 17).

Incision of alluvial systems within tributary valleys where fluvial terraces are preserved is related to a lowering of base level along the Mississippi River. This change in base-level may be partly related to the fall in river base-level following de-glaciation. Elevation differences between Pleistocene valley train deposits and the Holocene meander belts indicates a minimum base-level change of 16 to 32 feet. Flexural bending of the crust due to large sediment loads in the Mississippi River delta also may have caused uplift and subsequent stream incision. Land leveling data indicate that uplift is occurring with rates of 0.039 in/yr (1 mm/yr) to 0.078 in/yr (2 mm/yr) extending as far north as Jackson, Mississippi (Reference 158), which encompasses the Site Area. A rate of 0.039 in/yr (1 mm/yr) extrapolated over the past 18 thousand years would result in approximately 60-feet (18-meters) of uplift. The combination of base-level change following deglaciation and uplift due to flexural bending provides a sufficient change in relative base-levels (i.e. 76 to 92 feet) to have caused incision and preservation of the fluvial terraces observed in Bayou Pierre and the smaller tributary valleys in the Site Area. The formation and preservation of Pleistocene terraces in the Site Area is interpreted to have occurred due to the combination of these non-tectonic processes.

Loess

Three distinct Pleistocene age loess sheets occur between Vicksburg and Natchez in the Site Vicinity. These include the Peoria, Roxanne, and Loveland loess sheets (Reference 21). Within the Site Area, the loess deposits are undifferentiated. Loess deposits are up to 100 feet thick and consist of well sorted, yellowish brown, damp, medium stiff sandy to clayey silt with weak blocky structure. Below depths of about 12 to 15 feet, the loess has a slightly darker color, becomes more calcareous and massive with depth, and contains zones of gastropods and shell fragments. Zones with shell fragments are interpreted to represent either reworked surficial deposits or small ponds and depressions in the loess surface that supported gastropods. The loess unconformably overlies Upland Complex deposits.

2.5.1.2.3.1.2 Tertiary Deposits

2.5.1.2.3.1.2.1 Pliocene – Pleistocene Series

Upland Complex deposits occur beneath the loess deposits in the Site Area (Figure 2.5-9; Reference 17, 32, 33). This complex consists of interbedded alluvial gravel, sand, and clay (Reference 17). Individual depositional units and unit ages within the Upland Complex are not differentiated.

Borings advanced in the Site Location encountered two alluvial units (Figures 2.5-30 and 2.5-31); these alluvial deposits are mapped as part of the Upland Complex (Reference 44). At the proposed location of the new facility, the upper alluvial deposit is first encountered between 68 to 71 feet elevation and ranges from 46 to 85 feet thick. The upper alluvial deposit consists of light gray to brownish yellow sand to silty sand. The silty sand consists of fine- to medium-grained well-sorted quartz grains with silt, and is massive, dense, and friable to very friable.

The lower alluvial deposit is first encountered between elevations of 24 to –14 feet and ranges from 11 feet to 89 feet thick across the proposed facility location. The variation in the thickness of the lower alluvial deposit is due to the amount of relief on the underlying and eroded Catahoula Formation surface (Figure 2.5-29). The lower alluvial deposit consists of stratified thinly bedded sands, silty clays, and gravels. The silty clay beds range in thickness from a few inches to feet, and are yellowish brown to brown. Sand beds are similar to the upper alluvial deposit described above, but generally are better sorted, finer grained, and have a greater degree of oxidation. Gravel layers range in thickness from one foot to tens of feet, and are composed of fine- to medium-grained, sub-rounded gravel with localized cobbles.

2.5.1.2.3.1.2.2 Miocene Series

Miocene deposits are not mapped at the surface in the Site Area or Site Location, but underlie terrace and loess deposits at shallow depth (Figures 2.5-29, 2.5-30, and 2.5-31). In the subsurface, Miocene deposits include the shallow marine sediments of the Catahoula

Formation. These deposits consist of hard to very hard, gray to gray-green, silty to sandy clay, and clayey silt and sand, with some locally indurated or cemented clay, sand, and silt seams (Reference 22). The Catahoula Formation occurs about 125- to 175-feet below the Site Location (-20 to -30 feet elevation) and has a maximum thickness of 320 feet in the Site Area (Reference 16). The Catahoula Formation unconformably underlies the Upland Complex and loess, and overlies the Oligocene Vicksburg Group. The Catahoula Formation is identified as the load-bearing stratum for the existing major plant structures at the Grand Gulf Nuclear Station (Reference 16).

2.5.1.2.3.1.2.3 Oligocene Series

Oligocene deposits do not occur at the ground surface in either the Site Area or Site Location. The Oligocene deposits in the subsurface include sediments of the Vicksburg Group and the Forest Hill Formation (Figures 2.5-5 and 2.5-11). The Vicksburg Group consists of four formations, which from youngest to oldest include the Bucatunna, Byram Marl, Glendon Limestone, and Mint Spring formations. These deposits were encountered in two previous borings in the Site Location (B-4 and B-84; Reference 16) and two previous borings in the Site Area (G-3 and G-4; Reference 16). Lithologic descriptions of the Vicksburg Group formations are presented below.

The Bucatunna Formation consists of stiff to hard greenish-black to black clay with thin, gray, fine sand seams. This formation occurs at an elevation of -250 feet and unconformably overlies the Byram Marl. The Byram Marl Formation consists of hard to very hard, green to gray, fine sandy, calcareous clay, is discontinuous, and conformably overlies the Glendon Limestone. The Glendon Limestone consists of interbedded, light gray, fossiliferous limestones, and hard to partly indurated, grayish-green, fine sandy, calcareous clays. This formation occurs between elevations of –260 and –340 feet, and unconformably overlies the Mint Springs Marl. The Glendon Limestone Formation is laterally continuous beneath the Site Area and provides an excellent marker horizon to construct a structure contour map from which to evaluate the presence or absence of tectonic deformation (Figure 2.5-15). The Mint Springs Marl consists of hard, grayish green fossiliferous, glauconitic sand and clay and is at least 45 feet thick beneath the Site Location. The Mint Springs Formation unconformably overlies the Forest Hill Formation.

2.5.1.2.4 Site Structure

2.5.1.2.4.1 Faults and Folds

Laterally continuous deposits of Oligocene and younger age extend in the subsurface across the Site Area (Reference 16). These deposits have a gentle southward depositional gradient and are undeformed (Figures 2.5-10, 2.5-30 and 2.5-31). No faults are mapped within the 5-mile radius of the Site Area (Figure 2.5-9; References 52; 53).

The continuity of subsurface deposits demonstrates the tectonic stability of the Site Area and Site Vicinity from at least Oligocene time, approximately 30 Ma, to present. For example, the top of the Glendon Limestone surface shows no morphology indicative of tectonic deformation (Reference 16). The top of the Glendon Limestone Formation within the Vicksburg Group slopes to the southeast from elevations of approximately -140-feet in the northwestern part of the Site Area to -440-feet in the southeastern part of the Site Area (Figure 2.5-15). The surface appears to have been eroded, forming a buried drainage basin morphology. The lateral continuity of the formation and the absence of faults or folds documents the absence of post-Oligocene deformation in the Site Area and Site Location. No new information has been developed since the original investigations for the Grand Gulf Nuclear Station (Reference 16) that would suggest the presence of faulting within the Site Area.

The Oligocene Vicksburg Group was eroded and unconformably overlain by deposits of the Miocene Catahoula Formation. The top of the Catahoula Formation in the Site Location forms a gentle southwestward sloping surface (Figure 2.5-29). The Catahoula surface morphology preserves a Pliocene to Pleistocene erosion surface of the ancestral Mississippi Alluvial Valley, as well as a former tributary valley that extended across the Site Location; variations in elevations across the surface of the Catahoula Formation reflects former stream erosion. The top of the Catahoula Formation shows no morphology indicative of tectonic deformation, and no new information is available since the original investigations for the Grand Gulf Nuclear Station (Reference 16) that would suggest the presence of faulting within the Site Area.

Upland Complex deposits in the Site Location are eroded and two west-trending drainages cross the Site Location (Figure 2.5-32). These drainages are the current active channels in the Site Location. As discussed above, the Upland Complex is unconformably overlain by loess. The surface of the Upland Complex shows no morphology indicative of tectonic deformation, and no new information is available since the original investigations for the Grand Gulf Nuclear Station (Reference 16) that would suggest the presence of faulting within the Site Area.

2.5.1.2.4.2 Unconformities

With the exception of the conformable contact between the Oligocene Glendon Limestone and Byram Marl formations of the Vicksburg Group, all of the subsurface deposits in the Site Area and Site Location are separated by erosional unconformities. The unconformities indicate that erosion rather than tectonic deformation is responsible for elevation differences across the surfaces of the Upland Complex alluvial deposits, Catahoula Formation, and the Glendon Limestone Formation (Figures 2.5-15, 2.5-29, and 2.5-32).

2.5.1.2.4.3 Other Structures

2.5.1.2.4.3.1 Salt Domes

The proposed location of the new facility at the Grand Gulf Nuclear Station is located along the northern margin of the Mississippi Salt Basin (Figure 2.5-3). However, no salt domes occur in the Site Area or Site Location. The nearest salt domes are the Bruinsburg Dome located 6.5 miles southwest of the site, and the Galloway Dome located 8 miles northeast of the site (Figure 2.5-8). The depth to salt of the Bruinsburg Dome is 2020 feet, and the depth to salt of the Galloway Dome is 4196 feet (Reference 16). The Bruinsburg and Galloway domes have upwarped the Glendon Limestone strata in the Site Vicinity (Figure 2.5-15), but do not affect the Miocene Catahoula Formation.

2.5.1.2.5 Geotechnical Properties of Subsurface Materials

On the basis of review of existing UFSAR and site investigation data, the proposed ESP location appears to be suitable for support and good performance of the new facility. Plant foundations should be supported on dense alluvium, old alluvium, or Catahoula Formation below the surficial loess soils. Because the Catahoula Formation claystone was encountered at a significant depth below the ESP Site (greater than 170 feet deep), unreasonably deep excavations extending well below the water table would be required to place foundations in this material. It is more likely that dense layers within the alluvium or old alluvium will be considered for foundation support of the new plant. The alluvium primarily consists of medium dense to dense sands that should be suitable for foundation support provided that future quantitative analyses confirm that liquefaction or cyclic pore pressure increases will not adversely affect foundations. The old alluvium consists of sandy and clayey strata that appear to be in a dense to very dense (very stiff to hard) condition, and are similar to the materials described as supporting the existing GGNS foundations. According to the UFSAR, the operating GGNS has performed well without adverse foundation movements (Reference 16).

As discussed previously, a plant design has not been selected, and the footprint and embedment depth of the plant have not been determined. It is anticipated that any new facility will maintain the existing plant grade of approximately Elevation 132, but that the plant will be founded in alluvium, at or below the bottom of the loess deposits, at approximately Elevation 80, or lower, where the average shear wave velocity exceeds 1,000 feet per second. If the bottom of the plant is located above this elevation, then the natural soils should be excavated to below the loess and replaced with engineered fill that has a minimum shear wave velocity of 1,000 feet per second. Any excavation outside the structural walls of the plant would also be backfilled with engineered fill. All engineered fill would be compacted to a density that would preclude settlement or, should it be below the water table, liquefaction under dynamic loading conditions. The ESP site envelopes all potential plant layouts and embedment depths. Additional site exploration, laboratory testing, and geotechnical analyses will be performed specifically to characterize site conditions for geotechnical analyses and foundation design for the Construction and Operating License (COL) phase of the project after a plant design has been selected. These additional studies should include the following:

- Additional conventional SPT and mud rotary borings on a pattern throughout the plant footprint area;
- Additional CPT and geophysical surveys;
- Additional laboratory index, strength and consolidation testing;
- Quantitative liquefaction, bearing, and settlement analyses;
- Dynamic soil-structure interaction;
- Stability analyses for planned cuts and foundation excavations;
- Groundwater and potential excavation seepage studies;
- Confirmatory site-response analysis.

2.5.1.2.5.1 Static Properties

Static soil properties are described in Section 2.5.4.1, and are summarized on Table 2.5-7. These properties include: moisture content, dry density, Atterberg Indices, mechanical sieve and hydrometer grain size analyses, and consolidated undrained (CU) triaxial shear testing.

No swelling or consolidation tests were conducted for the ESP study, but the UFSAR for the existing plant (Reference 16) states that: *"Tests were performed to evaluate the swell potential of the Catahoula Formation. Swell tests and X-ray diffraction indicate the Catahoula Formation is nonexpansive and the swell deformation potential is negligible. The natural moisture content is near the plastic limit, which indicates preconsolidation. The Catahoula Formation is a granular-cohesive material which is insensitive, the compressibility is low, and the overconsolidation ratio is in excess of 2."*

An overconsolidation ratio of 2 referenced in the UFSAR (Reference 16) appears to actually be a lower bound value based on both the geologic history of the site and the material properties.

As described in Section 2.5.1.2.5.2, generally good agreement was obtained between the field and laboratory shear wave velocity measurements of the Upland Complex upper and lower alluvial deposits. Laboratory measurements were made when specimens were reconsolidated assuming a Ko value of 1.0, consistent with an overconsolidation ratio of 4 to 8 (Reference 162). Additionally, as described in Section 2.5.4.1.5, the CPT results suggests that the alluvium and loess are overconsolidated. Quantitative determination of the overconsolidation ratio for materials underlying the proposed site location should be performed during the COL phase on the basis of additional field and laboratory testing.

In summary, from a geotechnical and foundation engineering point of view, the loess is a clayey silt which exhibits moderately high strengths and stands vertically in cuts because of weak cementation when dry. However, the loess is potentially susceptible to gully erosion and collapse when saturated, and is not suitable for support of heavy or safety-related structures. The Upland Complex alluvium is a fairly clean coarse to fine sand, and the old alluvium is a clayey sand and silt with claystone clasts derived from the underlying Catahoula Formation. Both are relatively old and stiff and could serve as the foundation support layer for the facility designs being considered.

2.5.1.2.5.2 Dynamic Properties

Dynamic properties for “equivalent linear” site response analysis are: (1) shear wave velocity or low strain shear modulus; and (2) relationships that define the “equivalent linear” or secant shear modulus and the damping ratio as a function of cyclic shear strain. For convenience, the secant shear modulus is usually normalized to the low strain shear modulus. The required relationships are usually referred to as shear modulus reduction and damping curves. These curves are needed for each material type and, since these properties may vary with confining pressure, for as many depth ranges as is necessary. Shear wave velocity profiles for the ESP site are shown in Figures 2.5-34 through 2.5-37. Shear modulus reduction and damping curves are presented and discussed in Section 2.5.4.1.4.

2.5.2 Vibratory Ground Motion

This section describes the data and methodology used to develop the Safe Shut-down Earthquake (SSE) ground motion for the proposed new unit at the existing Grand Gulf Nuclear Station (GGNS) in Grand Gulf, Mississippi (hereafter referred to as the “Site”). Regulatory Guide 1.165 (Reference 4) “Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion” states that the SSE ground motion can be developed using either the Electric Power Research Institute (EPRI) Seismicity Owners Group (SOG) project or Lawrence Livermore National Laboratory (LLNL) Probabilistic Seismic Hazard Analyses (PSHA) methodologies (References 8 and 9), updated through a comprehensive review of the geology, seismology and geophysics of the Site Region (200-mile radius around the site). If review of existing data shows a significant change to either the seismic source model or ground motion model (i.e., attenuation relationships), then Regulatory Guide 1.165 recommends that an updated PSHA be performed to develop the SSE ground motion.

Regulatory Guide 1.165 (Reference 4), therefore, provides the following four-step process to develop the SSE ground motion:

1. Review and update the EPRI or LLNL seismic source model with new information, as appropriate.
2. Review and update the EPRI or LLNL ground motion model with new information, as appropriate.

3. Perform an updated PSHA utilizing the updated seismic source model and/or ground motion model, if appropriate.
4. Develop the SSE ground motion using the original or updated EPRI or LLNL PSHA results corrected for site-specific soil properties, as required.

This process has been completed and documented for the GGNS ESP site. Section 2.5.2.1 describes the seismic source model used in the analysis. Section 2.5.2.2 describes the ground motion model and development of the vibratory rock ground motion from the PSHA. Sections 2.5.2.3 and 2.5.2.4 describe the site-response analysis and development of the SSE ground motion for the GGNS ESP site.

For the GGNS ESP application, the EPRI SOG methodology was adopted to develop the SSE ground motion, including use of the 1986 EPRI SOG seismic source model developed by six Earth Science Teams (EST's), an updated EPRI ground motion model (Reference 13), and the EPRI EQHAZARD software (Reference 14). Following review of the data and information developed since publication of the EPRI SOG results in 1986, significant new information regarding seismic sources and earthquake ground motion attenuation in the Site Region was identified. To address new information and approaches for ground motion attenuation modeling, EPRI (Reference 13) developed a new ground motion attenuation model for the central and eastern United States, including the Gulf Coast region. These new relationships were used in the PSHA and are described in Section 2.5.2.2

The seismic source model used to develop the SSE ground motions for the Site was developed following a comprehensive review of geological, seismological and geophysical data related to active tectonic features in the Site Region (Section 2.5.1). In particular, data were reviewed to identify any significant changes in: (1) source geometry – primarily in terms of changes of source to site distance; (2) maximum earthquake magnitude; and (3) earthquake recurrence. Based on the review of literature and syntheses of regional data (e.g. Reference 86), there are no newly identified features of tectonic origin with convincing evidence of Quaternary activity in the Site Region. Wheeler and Crone (Reference 86) identify four features, the Wiggins Arch, Gulf Margin Normal faults, Monroe Uplift, and Saline River source zone that display evidence of Quaternary activity, but which appear to have originated from non-tectonic processes or lack convincing evidence to conclude that they are seismogenic.

With two exceptions, our review and analysis of existing data shows that all tectonic features in the GGNS Site Region, and northern extension including the Reelfoot Rift Complex, are adequately characterized by the EPRI SOG seismic source model. The two exceptions identified in our review of existing data are (1) identification of the Saline River source zone within the Site Region, and (2) revision of source parameters for the New Madrid Seismic Zone (NMSZ), which lies within the Reelfoot Rift Complex north of the Site Region. Revisions to the NMSZ source parameters include changes in source geometry, maximum magnitude, and earthquake recurrence since publication of the 1986 EPRI SOG source model.

Based on the new information on seismic sources and new ground motion attenuation modeling that have been published since the 1986 EPRI SOG study, the EPRI PSHA has been updated for use in this ESP application. The EPRI PSHA was updated by revising the seismic source model, adding the ground motion attenuation model developed by EPRI (Reference 13), and updating the EPRI EQHAZARD software that was published in 1986 (Reference 14).

The seismic source model developed for input to the PSHA for the Site adopts the 1986 EPRI SOG source model, updated through addition of the Saline River source zone and a characteristic earthquake model for the NMSZ. The new information for the Saline River source zone and NMSZ do not replace any of the existing EPRI SOG source zones, but are added, or “layered”, onto the EPRI SOG seismic source model. The details of this model are described in Section 2.5.2.1.

Regulatory Guide 1.165 recommends that a PSHA be performed to define the median rock ground motion at the site that has an annual probability of exceedance of 10^{-5}, and for soil sites, that a site-response analysis be performed to develop the SSE ground motion. The PSHA used to develop the 10^{-5} median rock ground motions is described in Section 2.5.2.2. Because the Site is underlain by soils rather than rock, a site-specific site-response analysis was conducted following the methodology described in NUREG/CR-6728 (Reference 7). The site-specific site-response analysis is described in Sections 2.5.2.3 and 2.5.2.4. The site investigations and laboratory analyses that were completed to provide the soil parameters for the site-response analysis are described in Section 2.5.4.

2.5.2.1 Seismic Source Characterization

As described in Section 2.5.1, a comprehensive review of available geological, seismological, and geophysical data was performed for the GGNS ESP site and region. This review generally shows that the existing EPRI 1986 seismic source model adequately captures the source information and uncertainty associated with new data and knowledge developed since the mid-1980’s. No new information was found that would suggest significant modification to the EPRI 1986 seismic source model, with two exceptions:

1. The average recurrence interval for large magnitude earthquakes in the New Madrid source zone is approximately 300 to 800 years based on new paleoseismic and paleoliquefaction information, as opposed to several thousand years in the EPRI seismic source model, and the geometry of the source zone has been modified to include three distinct fault segments imbedded within the source zone. New maximum magnitude information also has been developed for the source zone and a characteristic earthquake model is used to estimate recurrence for the fault segments.
2. The Saline River source zone represents a new postulated seismic source in southern Arkansas. The closest approach of this new source zone is approximately 90 miles to the GGNS ESP site.

These two revisions to the EPRI source model are described in Sections 2.5.2.1.2 and 2.5.2.1.3, respectively.

Conducting a PSHA requires information on the location of seismic source zones, maximum earthquake magnitudes, and earthquake recurrence intervals for each seismic source zone included in the model area. The estimated value for each of these parameters is presented in a seismic source model. Seismic source zones are characterized using a logic tree approach to explicitly document the range of estimated parameter values considered and to assign weights to each parameter estimate to indicate the degree of certainty that a given estimate is the correct alternative (Reference 166 and 167). The seismic source parameters for the EPRI SOG model are presented in Table 2.5-8, and are described in detail in EPRI (Reference 9). In addition to the EPRI seismic source model, we provide new logic tree characterizations for the Saline River source zone and the revised NMSZ.

Logic trees are composed of a series of nodes and branches. Each node represents an assessment of an input parameter value necessary to perform the analysis. Each branch leading from the node represents one possible alternative for the state of nature or parameter value being assessed. In practice, a sufficient number of branches are placed at a given node to adequately express the range of uncertainty in the parameter characterization. Each branch of the logic tree, therefore, represents a credible model of the behavior of a seismic source that has a certain probability that it is the correct representation of that seismic source.

Weights are assigned to each branch of the logic tree and represent a probability that the branch is the correct estimate of the input parameter. Because the available data are typically too limited to allow for objective statistical analyses, weights are assigned subjectively on the basis of scientific judgment. The logic tree approach simplifies the subjective assessments because the uncertainty of a single parameter is considered individually assuming that all other parameters leading up to that parameter assessment are known with certainty. Thus, the nodes of the logic tree are sequenced to provide for the conditional dependencies among the parameters and to provide a logical progression from general to specific in defining the input parameters for an evaluation.

In order to compute the SSE ground motion for the Site, we have developed a seismic source model that describes the seismic source zones and related parameters for the Site Region, and includes the NMSZ that extends approximately 300-miles farther northward (Figure 2.5-38). As described in greater detail below, we have not modified the original EPRI SOG seismic source model, but have added the Saline River source zone and the NMSZ characteristic earthquake model as new sources to the 1986 EPRI SOG source model. This is a conservative approach that preserves the integrity of the seismic source model developed by the six EPRI EST's, while incorporating the new geological, seismological, and geophysical data of the Site Region.

The remainder of this section provides descriptions of the seismic source model used to compute ground motions at the proposed location of the new facility at the Grand Gulf site and includes a general description of the EPRI SOG seismic source model, and detailed descriptions of the Saline River source zone, and revised NMSZ.

2.5.2.1.1 Summary of EPRI Seismic Source Model

This section summarizes the seismic sources and parameters used in the 1986 EPRI SOG project (Reference 9) and subsequent PSHA completed by EPRI in 1989 (Reference 10). The descriptions of seismic sources is limited to those within 200 miles of the ESP Site (the "Site Region") and those at distances greater than 200 miles that may significantly contribute to the ground motion hazard at the Grand Gulf ESP Site.

For the EPRI SOG project, six ESTs evaluated geologic, geophysical, and seismological data to develop seismic source zones in the Central and Eastern United States (CEUS). These source zones were used to model the occurrence of future earthquakes and evaluate earthquake hazards at nuclear power plant sites across the CEUS. The six ESTs involved in the EPRI project were the Bechtel Group, Dames & Moore, Law Engineering, Rondout Associates, Weston Geophysical Corporation, and Woodward-Clyde Consultants. Each team produced a report (Volumes 5 through 10 of Reference 9) providing detailed descriptions of how they identified and defined the seismic source zones in the CEUS. For the computation of hazard in the 1989 study, a few of the seismic source parameters were modified or simplified from the original parameters developed by the six ESTs during the 1986 EPRI SOG study. The parameters used in 1989 PSHA calculations are the primary source for the seismicity parameters used in this study.

The seismic source models developed for each of the six EPRI teams are shown on Figures 2.5-39 through 2.5-44. The spatial relationship between seismicity and regional tectonic features is illustrated on Figure 2.5.5. The earthquake epicenters shown on this figure includes events from the EPRI SOG earthquake catalog for the period between 1777 and 1984, updated with seismicity for the period between 1985 and 2001, as described in Section 2.5.1.1.6. The plot shows events greater than body-wave magnitude (m_b) > 3.3, the lower magnitude cut-off used in the EPRI SOG (Reference 9) study used to estimate a- and b-values.

The maximum magnitude, closest distance, and probability of activity of each ESTs seismic sources are summarized in Tables 2.5-8a through 2.5-8f. These tables list the parameters assigned to each source and specify whether or not the source was included in the site hazard in the original EPRI 1989 seismic hazard analyses. The tables also indicate whether new information has been identified that would lead to a revision of the source's geometry, maximum earthquake magnitude, or recurrence parameters. The seismicity recurrence parameters (a- and b-values) used in the EPRI seismic hazard study were computed for each 1-degree latitude and longitude cell that intersects any portion of a seismic source.

The EPRI SOG seismic hazard study expressed maximum magnitude (Mmax) values in terms of m_b, whereas most modern seismic hazard analyses describe Mmax in terms of moment magnitude (M_w). To provide a consistent comparison between magnitude scales, the average of three individual magnitude conversion relations is used (References 168, 169, and 170) to convert m_b to M_w and vice-versa. Throughout this section, the largest assigned values of Mmax distributions assigned by the ESTs to seismic sources are presented for both magnitude scales, to give perspective on the maximum earthquakes that were considered possible in each source. As shown on Tables 2.5-8a through 8f, the estimate of Mmax established by the ESTs for sources in the Site Region often are less than m_b 5.0 or in the range from m_b 5.1 to 5.3. in the conversion from m_b to M_w, these values would convert to M_w of less than 5.0. In the conversion from m_b to M_w, therefore, for the purpose of hazard calculations, we do not allow M_w to be less than 5.0.

The following sections describe the most significant EPRI sources for each of the six ESTs, with respect to the ESP Site. The nomenclature used by each EST to describe the various seismic sources in the CEUS varies from team to team. Therefore, a number of different names may be used by the EPRI EST to describe similar tectonic features, or one team may describe seismic sources that another team does not. For example, the Dames & Moore team describes the source of the 1811-1812 New Madrid earthquake sequence as the New Madrid Compression Zone while the Rondout team describes this source as the New Madrid Seismic Zone, and the Bechtel team describes this source as the New Madrid fault zone. The reader is referred to the original 1986 EPRI report for the data and rational used by each EST to define each seismic source zone.

2.5.2.1.1.1 Bechtel Team

The Bechtel team identified five seismic source zones within the Site Region (Table 2.5-8a and Figure 2.5-39). Although outside of the 200-mile Site Region, they also identified the New Madrid fault zone, which contributes to the hazard at the Site.

The site is located within Bechtel's Gulf Coast Region background source zone "BZ1". This source zone was defined based on geopotential and seismic data, and magnetic and gravity anomaly data. The Bechtel team assigned a maximum earthquake magnitude of m_b 5.4-6.6 (M_w 5.0-6.5) to this source.

The Northern Plains Region, background source zone “BZ3” is located 30 miles northeast of the Grand Gulf Site. The Bechtel team assigned a maximum earthquake magnitude of m_b 5.4-6.6 (M_w 5.0-6.5) to this source.

The Ouachita source zone is located 70 northwest of the Grand Gulf Site. This source was defined based on geopotential data outlining the crystalline core of the fold belt, historical seismicity above the background level, and the surface exposure of the Ouachita Mountains in Arkansas and Oklahoma. The western boundary of the source zone was defined as the intersection of the Ouachita Mountains with the rocks of the Wichita-Arbuckle system. The Bechtel team assigned a maximum earthquake magnitude of m_b 5.4-6.6 (M_w 5.0-6.5) for this source zone and determined that known faults of the Ouachita feature were not favorably oriented in the contemporary stress field for reactivation.

The New Madrid region background source zone “BZ0” is located 140 miles north of the Grand Gulf Site. This source zone was defined based on the possibility of moderate-to-large earthquakes occurring outside of recognized source zones contained within the background zone. The Bechtel team assigned a maximum earthquake magnitude of m_b 5.7-6.6 (M_w 5.3-6.5) to this source.

The Reelfoot Rift source zone is located 190 miles north of the Grand Gulf Site. This source was defined based on geophysical and geopotential data (magnetic and gravity anomalies), which identified ancient structures that parallel local seismicity trends. The Bechtel team assigned a maximum earthquake magnitude of m_b 5.7-6.6 (M_w 5.3-6.5) to this source zone. Association of the Reelfoot Rift with moderate-to-large earthquakes was based on spatial association and a favorable orientation for reactivation in an east-west compressive stress field.

The New Madrid fault zone is located 235 miles north of the Grand Gulf Site. This source was defined based on distinct microseismicity patterns, seismic reflection profiles, and the occurrence of the 1811 and 1812 earthquake sequence. The Bechtel team assigned a maximum earthquake magnitude of m_b 7.4-7.5 (M_w 7.9-8.0) to this source.

New information on seismic sources in the Site Region, published since the 1986 EPRI SOG study, was compiled and reviewed to evaluate whether the source geometry, Mmax, or source recurrence parameters should be updated. The reviewed information identifies a potential seismic source in southeastern Arkansas, the Saline River source zone. The characteristics of this potential seismic source are discussed in Section 2.5.2.1.3. New information also is available regarding the magnitude estimates and earthquake recurrence intervals for 1811-1812 “type” earthquakes on the NMSZ, discussed in Section 2.5.2.1.2. This new information has been accounted for by adding new seismic source zones over the existing EPRI SOG seismic source model. The EPRI SOG source zones for each of the six ESTs that are overlain by the new source zones are indicated by a “yes” in the right-hand columns of Table 2.5-8a through 2.5-8f.

2.5.2.1.1.2 Dames & Moore Team

The Dames & Moore team identified six seismic source zones within the Site Region (Table 2.5-8b and Figure 2.5-40). Although outside of the 200-mile Site Region, they also identified the New Madrid Compression Zone, which makes a significant contribution to the hazard at the Site.

The site is located within Dames & Moore's Southern Coastal Margin source zone. This source zone was defined based on its fairly low, diffuse seismicity and represents the down warping miogeosynclinal wedge of sediment that accumulated within the Gulf Coast Basin since the Cretaceous. The Dames & Moore team assigned a maximum earthquake magnitude of m_b 5.3-

7.2 (M_w 4.9-7.5) to this source zone. The team did not provide a tectonic basis to explain the occurrence of seismicity in this source zone. The Saline River source zone partially overlies the northern part of the Southern Coastal Margin zone.

The Ouachita fold belt source zone is located about 60 miles northwest of the Grand Gulf Site. This source zone was defined based on historical and instrumental patterns of recent microseismicity. The Dames and Moore team considered the historical and instrumental seismicity rates to be indicative of future activity. Kinks or bends in the source zone geometry were defined based on the margin of failed arms of former continental rifts. The Dames & Moore team assigned a maximum earthquake magnitude of m_b 5.5-7.2 (M_w 5.1-7.5) to this source zone. The Saline River source zone partially overlies the southeastern part of the Ouachita fold belt.

The Indiana-Illinois Block source zone is located about 165 miles north of the Grand Gulf Site. This source zone was defined based on geophysical anomalies, basement structural boundaries, and diffuse seismicity. However, the team lacked confidence in identifying a tectonic basis to explain the diffuse seismicity. The block is bound on the north and east by basement warps including the Kankakee Arch, Cincinnati Arch, and Nashville Dome, on the northwest by the Illinois Basin/Lasalle Anticlinal Belt, and on the west by the trend of the Mississippi Embayment/Reelfoot Rift-Southern Indiana Arm Eocambrian rifts. The Dames & Moore team assigned a maximum earthquake magnitude of m_b 5.7-7.2 (M_w 5.3-7.5) to this source zone.

The Reelfoot Rift source zone is located about 165 miles north of the Grand Gulf Site. This source zone was defined based on the pattern of linear, segmented seismicity, and earthquake structure within the zone. The Dames & Moore team assigned a maximum earthquake magnitude of m_b 6.9-7.2 (M_w 7.0 to 7.5) to this source zone.

The Appalachian fold belt source zone is located about 170 miles northeast of the Grand Gulf Site. This source zone was defined based on historical and instrumental seismicity. The Dames & Moore team assigned a maximum earthquake magnitude of m_b 6.0-7.2 (M_w 5.7-7.5) to this source zone.

The Eastern Marginal Basin source zone is located about 175 miles northeast of the Grand Gulf Site. This source zone was defined based on the occurrence of several moderate-sized earthquakes and diffuse background seismicity. The Dames & Moore team assigned a maximum earthquake magnitude of m_b 5.6-7.2 (M_w 5.2-7.5) to this source zone.

The New Madrid compression zone is located about 250 miles from the Grand Gulf Site. This source was defined as an independent source within the Reelfoot Rift source zone based on the long, linear zone of microseismicity between Marked Tree, Arkansas and the area north of New Madrid, Missouri. The Dames & Moore team assigned a maximum earthquake magnitude of m_b 7.2-7.5 (M_w 7.5-8.0) to the New Madrid compression zone. The Dames & Moore team also considered the New Madrid compression zone combined with the Reelfoot Rift as an optional source geometry. A new source characterization for the NMSZ has been overlain on the New Madrid compression zone source of Dames & Moore.

2.5.2.1.1.3 Law Engineering Team

The Law Engineering team identified four seismic source zones within the Site Region (Table 2.5-8c and Figure 2.5-41). Although outside of the 200-mile Site Region, they also identified the Postulated Faults in Reelfoot Rift source zone, which makes a significant contribution to the ground motion hazard at the Site.

The Grand Gulf Site is located within Law Engineering's Southern Coastal Block source zone. The southern boundary of this source zone was defined based on broad wavelength magnetic anomalies that extend from the southeast Texas-Mexico border to the continental shelf offshore Florida. The northern boundary of this source zone was defined by the Paleozoic edge of the North American craton (Reference 171). The Law Engineering team assigned a maximum earthquake magnitude of m_b 4.6-4.9 (M_w 4.2-4.5) to this source zone. The Saline River source zone partially overlies Law Engineering's Southern Coastal Block.

The Mississippi Embayment source zone is located about 80 miles northeast of the Grand Gulf Site. This source was defined based an anomalously broad gravity high that extends into the central United States up the Mississippi Valley (Reference 171). The Law Engineering team assigned a maximum earthquake magnitude of m_b 5.2-5.7 (M_w 4.8-5.3) to this source zone.

The Eastern Basement source zone is located about 140 miles east of the Grand Gulf Site. This source was defined based on an area of buried Precambrian-Cambrian normal faults developed in the North American craton and includes the Giles County-Eastern Tennessee seismic zone, the Pennsylvania Aulacogen, and the Scranton Gravity High. The Law Engineering team assigned a maximum earthquake magnitude of m_b 5.7-6.8 (M_w 5.3-6.8) to this zone.

The Reelfoot Rift source zone is located about 170 miles north of the Grand Gulf Site. This source zone was defined based on gravity and magnetic anomalies. The Law Engineering team assigned a maximum earthquake magnitude of m_b 6.2-6.8 (M_w 5.9-6.8) to this zone.

The Postulated Faults in Reelfoot Rift source zone is located about 230 miles north of the Grand Gulf Site. This source zone was defined based on the occurrence of the 1811-1812 earthquakes. The Law Engineering team assigned a maximum earthquake magnitude of m_b 7.4 (M_w 7.9) to this source zone. A new source characterization for the NMSZ has been overlain on the Postulated Faults in Reelfoot Rift source zone of Law Engineering.

2.5.2.1.1.4 Rondout Team

The Rondout team identified six seismic source zones within the Site Region (Table 2.5-8d and Figure 2.5-42). Although outside of the 200-mile Site Region, they also identified the New Madrid seismic zone, which makes a significant contribution to the ground motion hazard at the Site.

The Grand Gulf Site is located within Rondout's Gulf Coast/Bahamas source zone. This source zone was defined based on the unique, rapid accumulation of sediments in the Gulf Coastal basin and differences in the orientation of the stress regime between the Paleozoic crust within the zone and the Appalachian crust of roughly the same age to the east and northeast. The Rondout team assigned a maximum earthquake magnitude of m_b 4.8-5.8 (M_w 4.4-5.4) to this source zone. The new Saline River source zone partially overlies Rondout's Gulf Coast/Bahamas source zone.

The Southern Oklahoma Aulacogen-Ouachita source zone is located about 100 miles northwest of the Grand Gulf Site. This source was defined based on an association with complex disturbed crust related to the Eocambrian Southern Oklahoma Aulacogen (Reference 172; Reference 173), Ouachita and Arbuckle Mountains, and Arkoma and Anadarko Basins. The zone also was defined based on seismicity; however, the Rondout team did not present a correlation between specific tectonic features and observed seismicity. The Rondout team assigned a maximum earthquake magnitude of m_b 5.8-6.8 (M_w 5.4-6.8) to this zone. The new Saline River source zone partially overlies Rondout's Southern Oklahoma Aulacogen-Ouachita source zone.

The Pre-Grenville PreCambrian Craton source zone is located about 110 miles northeast of the Grand Gulf Site. This source was defined as all “older-than-Grenville crust” that was not previously included in a seismic source zone. The Rondout team assigned a maximum earthquake magnitude of m_b 4.8-5.8 (M_w 4.4-5.4) to this background source zone.

The Grenville Crust source zone is located about 125 miles east of the Grand Gulf Site. This source zone was defined based on a level of background seismicity higher than other Grenville Crust areas and all areas of Grenville crust not previously captured in other source zones. The Rondout team assigned a maximum earthquake magnitude of m_b 4.8-5.8 (M_w 4.4-5.4) to this source zone.

The New Madrid Rift Complex (Reelfoot Rift) source zone is located about 170 miles north of the Grand Gulf Site. This source was defined based on geological, geophysical, and seismicity data (Reference 174) that divide the Reelfoot Rift into three arms. These arms include the Rough Creek Graben, Southern Indiana Arm, and Saint Louis Arm. An earthquake density contour map (Reference 175) was used to define the margins of the Southern Indiana and Saint Louis Arms. The Rough Creek Graben was excluded from the source zone because it is not favorably oriented for reactivation by the prevailing east-west horizontal stress field. The Rondout team assigned a maximum earthquake magnitude of m_b 6.6-7.0 (M_w 6.5-7.2) to this source zone.

The Southern New York-Alabama Lineament source zone is located about 180 miles northeast of the Grand Gulf Site. This source was defined based on a major discontinuity in the basement rocks underlying the western part of the Appalachians fold belt (Reference 176). The discontinuity corresponds to a change in strike of the magnetic anomaly pattern and intensity of seismicity. The Rondout team assigned a maximum earthquake magnitude of m_b 5.2-6.5 (M_w 4.8-6.3) to this source zone.

The is located about 255 miles north of the Grand Gulf Site. This source was defined based on the location of the 1811-1812 earthquake sequence, and the boundary of intense seismicity presented in Stauder (Reference 177). The zone was divided into three elements roughly coincident with the 1811-1812 earthquakes. The Rondout team assigned a maximum earthquake magnitude of m_b 7.1-7.4 (M_w 7.3-7.9) to this source zone. A new source characterization for the NMSZ has been overlain on the New Madrid seismic zone of Law Engineering.

2.5.2.1.1.5 Weston Geophysical Corporation Team

The Weston Geophysical Corp. team identified five seismic source zones within the Site Region (Table 2.5-8e and Figure 2.5-43). Although outside of the 200-mile Site Region, they also identified the New Madrid fault zone, which makes a significant contribution to the ground motion hazard at the Site.

The Grand Gulf site is located within their Gulf Coast background source zone. This source zone was defined as an independent background source that does not contain any other seismic source regions. The Weston Geophysical Corp. team assigned a maximum earthquake magnitude of m_b 5.4-6.0 (M_w 5.0-5.7) to this background source zone. The new Saline River source zone partially overlies Weston’s Gulf Coast background source zone.

The South Central background source zone is located about 60 miles northeast of the Grand Gulf Site. This source was defined based on boundaries with other source zones including the Reelfoot Rift on the west, Southern Appalachian background to the east, Pickens-Gilberttown fault zone to the south, and Rough Creek Graben-Kentucky River fault zone to the north. The

Weston Geophysical Corp. team assigned a maximum earthquake magnitude of m_b 5.4-6.6 (M_w 5.0-6.5) to this background source zone. The new Saline River source zone partially overlies the South Central background source zone.

The Ancestral Rockies source zone is located 100 miles northwest of the Grand Gulf Site. This source was defined based on a region of seismicity coincident with the Wichita-Ouachita Uplifts and the Anadarko-Arkoma Basins. The Weston Geophysical Corp. team assigned a maximum earthquake magnitude of m_b 5.4-6.6 (M_w 5.0-6.5) to this source zone. The new Saline River source zone partially overlies the Ancestral Rockies source zone.

The Southern Appalachian background source zone is located about 160 miles northeast of the Grand Gulf Site. This source zone was defined based on physiographic province boundaries that include the western terminus of the Valley and Ridge thrust belt and the eastern margin of the Towaliga, Lowdenville, and Kings Mountain fault trends. The Weston Geophysical Corp. team assigned a maximum earthquake magnitude of m_b 5.4-6.6 (M_w 5.0-6.5) to this source zone.

The Reelfoot Rift source zone is located about 185 miles north of the Grand Gulf Site. This source was defined based on interpretation of geophysical and seismicity data. The Weston Geophysical Corp. team assigned a maximum earthquake magnitude (M_{max}) of m_b 7.2 (M_w 7.5).

The New Madrid fault zone is located about 235 miles north of the Grand Gulf Site. This source was defined based on a dense pattern of microseismicity. The Weston Geophysical Corp. team assigned a maximum earthquake magnitude (M_{max}) of m_b 7.2 (M_w 7.5) to this source zone. The team also considered the New Madrid fault combined with the Reelfoot Rift as an optional source geometry. A new source characterization for the NMSZ has been overlain on the New Madrid fault zone of Weston Geophysical Corporation.

2.5.2.1.1.6 Woodward Clyde Consultants Team

The Woodward Clyde Consultants team identified three seismic source zones within the Site Region (Table 2.5-8f and Figure 2.5-44). Although outside of the 200-mile Site Region, they also identified the Saint Louis Arm and "None of the Above" (NOTA), Southern Indiana Arm and NOTA, and Disturbed Zone of Reelfoot Rift, which make a significant contribution to the ground motion hazard at the Site. The NOTA incorporates the alternative "*that none of the identified seismic sources were associated in a genetic manner"* with observed earthquakes.

The Grand Gulf Site is located within Woodward Clyde Consultants' River Bend regional background source zone. This source zone was defined as an independent background source that does not contain any other seismic source regions. The Woodward Clyde Consultants team assigned a maximum earthquake magnitude of m_b 5.0 (M_w 4.6) to this source zone. The new Saline River source zone partially overlies the River Bend regional background source zone.

The Reelfoot Rift -New Madrid Rift Complex source zone is located about 130 miles north of the Grand Gulf Site. This source zone was defined as the portion of the New Madrid rift system that extends to the southwest from the Cottage Grove-Rough Creek fault zone, and was based on aligned gravity and magnetic anomalies along its edges (Braile et al., 1982). The Woodward Clyde Consultants team assigned a maximum earthquake magnitude of m_b 5.4-7.2 (M_w 5.0-7.5) to this source zone. The team also considered the Reelfoot Rift-New Madrid Rift Complex combined with the Disturbed Zone of Reelfoot Rift (described below) as an optional source geometry.

The New Madrid Rift Loading Volume source zone is located about 135 miles north of the Grand Gulf Site. This source zone was defined based on scattered seismicity outside of the concentrated seismicity associated with the Disturbed zone of Reelfoot Rift. The Woodward Clyde Consultants team assigned a maximum earthquake magnitude of m_b 5.6-6.9 (M_w 5.2-7.0) to this source zone.

The Disturbed Zone of Reelfoot Rift source zone is located about 225 miles north of the Grand Gulf Site. This source zone was defined based on the occurrence of the 1811-1812 earthquake sequence, strong localization of microseismicity, seismic reflection data (Reference 178), and distribution of abundant liquefaction sand blows. The Woodward Clyde Consultants team assigned a maximum earthquake magnitude of m_b 7.2-7.9 (M_w 7.5-8.7) to this source zone. A new source characterization for the NMSZ has been overlain on the New Madrid fault zone of Woodward Clyde Consultants.

The Southern Indiana Arm and NOTA source zone is located about 310 miles north of the Grand Gulf Site. This source zone was defined as the northeast-trending arm of the New Madrid rift system that extends from New Madrid into south-central Indiana, and was based on gravity and magnetic anomalies and scattered seismicity. The Wabash Valley fault zone defines the northwestern border of the southwestern half of the Southern Indiana Arm. The Woodward Clyde Consultants team assigned a maximum earthquake magnitude of m_b 5.8-7.4 (M_w 5.4-7.9) to this source zone.

The Saint Louis Arm and NOTA source zone is located about 325 miles north of the Grand Gulf Site. This source zone was defined as the rift arm that extends northwesterly from New Madrid to Saint Louis, and was based on magnetic and gravity anomalies and scattered seismicity centered on the rift arm. The Woodward Clyde Consultants team assigned a maximum earthquake magnitude of m_b 6.2-7.2 (M_w 6.1-7.6) to this source zone.

2.5.2.1.2 Characterization of the New Madrid Seismic Zone

A characteristic earthquake model for the NMSZ has been added to the existing EPRI SOG seismic source model. The characteristic earthquake model is added to incorporate new data on source geometry, estimated maximum earthquake magnitude, and earthquake recurrence interval. The NMSZ characteristic earthquake model identifies specific fault segments within the NMSZ, maximum earthquake magnitudes, and earthquake recurrence intervals rather than treating the NMSZ as a single areal source zone with an exponential earthquake recurrence model. The logic tree for the NMSZ (Figure 2.5-45) describes the range of values considered for the following parameters: (1) Source geometry; (2) Maximum magnitude; and (3) Recurrence (note: numbers refer to nodes shown on the logic tree).

2.5.2.1.2.1 Source Geometry

Node 1 considers the source geometry used in the hazard calculation. The source geometry for the NMSZ is defined by the closest approach (modeled as a point source) of the three fault segments that approximate the locations of the 1811-1812 earthquake events (Reference 123; Reference 179; Reference 180). From closest to furthest from the Site, the three fault segments include: (1) the Blytheville Arch fault (BAF); (2) the Reelfoot fault (RF); and (3) the East Prairie fault (EPF) (Figure 2.5-18). Because the maximum magnitude earthquakes for each of the three fault sources are conservatively modeled as occurring at the closest approach to the Site, additional alternative fault geometries are not considered. The points of closest approach were identified using the fault geometries of Johnston (Reference 179), Crone (Reference 102), Van Arsdale et al. (Reference 121), and Champion et al. (Reference 181) and are summarized in

Table 2.5-9 and Figure 2.5-18. The three fault segments are modeled as point sources at the southernmost end of each fault due to the large source to site distances and the subparallel northward trend of the NMSZ with respect to the directional bearing to the Site.

2.5.2.1.2.2 Characteristic Earthquake Magnitude

As summarized in Table 2.5-10, significant differences exist in the estimated magnitudes of the largest historical events in the NMSZ. Hough et al. (2000, Reference 180) and Bakun and Hopper (Reference 115) discuss factors that may contribute to the uncertainty in magnitude estimates. These factors include: (1) the lack of instrumental data on large magnitude events from the NMSZ; (2) the paucity of intensity data, especially west of the Mississippi River, and the sparse, and sometimes inconsistent intensity data east of the Mississippi River; (3) the subjective nature of interpretation of felt reports and contouring of damage intensity data, especially with sparse and or old reports; (4) the lack of large recent earthquakes in the eastern United States to calibrate the intensity attenuation relation; and (5) the potential bias introduced by site response in the intensity assignments. In addition, magnitude estimates based on liquefaction features have considerable uncertainty due to the variability of local soil conditions, site-response effects, and the broad uncertainties associated with empirical relations based on world-wide databases (e.g. Reference 126; Reference 182; Reference 183).

For this study, maximum magnitudes assigned to each of the major faults within the NMSZ are considered on Node 2 of the logic tree (Figure 2.5-45). The southern segment is alternatively considered in the literature as either the Blytheville Arch/Bootheel Lineament or Blytheville Arch/Cotton Grove fault. For our purposes, the southern termination of both alternatives is the same (Figure 2.5-45). The characteristic maximum earthquake magnitudes for the southern segment are assigned the following values: M_w 7.3 (0.4), M_w 7.7 (0.5), and M_w 8.1 (0.1). The highest value of M_w 8.1 represents the preferred value of Johnston (Reference 118 and 114) for the December 1811 event based on isoseismal areas and a common attenuation relationship developed for a worldwide database of all stable continental regions. The lowest value of M_w 7.3 reflects the magnitude estimate of Hough et al. (Reference 180) after adjusting intensities for site amplification. The M_w 7.3 estimate also corresponds to the magnitude derived using the empirical relationship for magnitude vs. area of Wells and Coppersmith (Reference 184) as cited in Cramer (Reference 130), assuming a 117-km rupture length and 15-km rupture width. This value also agrees with the preferred magnitude estimated by Bakun and Hopper (Reference 115) for this event. The intermediate value of M_w 7.7 reflects the current magnitude estimate for the largest events of the 1811-1812 sequence used by the U.S. Geological Survey in their recent PSHA for the United States (Reference 19). The M_w 7.7 estimate also corresponds to the magnitude derived using the empirical relationship for magnitude vs. area of Sommerville and Sakia (Reference 185) as cited in Cramer (Reference 130), assuming a 117-km rupture length and 19-km rupture width. Frankel et al. (Reference19) also note the general similarity in the isoseismals with distance between the 2001 Bhuj India earthquake (M_w 7.6-7.7) and those of the December 1811 New Madrid event, although they caution that there may be differing rates of attenuation of intensities for the eastern U.S. and India.

The characteristic maximum magnitudes assigned to the Reelfoot fault encompass the range of published estimates for the February 1812 event. In addition, consideration is given to estimates based on the constraints for the geometry and extent of the Reelfoot fault (e.g., Reference 123; Reference 130). The following magnitude distribution is assigned to this fault: M_w 7.2 (0.2), M_w 7.4(0.4), M_w 7.6 (0.3) and M_w 8.0 (0.1). The lowest value is based on the estimated moment and magnitude presented by Mueller and Pujol (Reference 123) that uses fault geometry, slip rate, and displacement data from seismicity, geomorphic, and trench data. The M_w 7.4 and M_w 8.0

values reflect the estimated magnitudes from isoseismal contours of this event as given by Hough et al. (Reference 180) and Johnston (Reference 118), respectively. The M_w 7.4 value also represents the preferred value of Bakun and Hopper (Reference 115). The M_w 7.6 value captures the weighted average value assigned to the February 1812 Reelfoot fault event by experts in the general research community for the US Geological Survey model (Reference 19).

The characteristic maximum magnitudes assigned to the East Prairie fault encompass the range of published estimates for the January 1812 event. The following magnitude distribution is assigned to this source: M_w 7.0 (0.4), M_w 7.4 (0.5), and M_w 7.8 (0.1). The high and low values reflect estimates of Johnston (Reference 118) and Hough et al. (Reference 180), respectively. The intermediate value captures the upper range of values estimated by Bakun and Hopper (Reference 115). The M_w 7.4 estimate also corresponds to the magnitude derived using the empirical relationship for magnitude vs. area of Somerville and Sakia (Reference 185) as cited in Cramer (Reference 130), assuming a 59-km rupture length and 19-km rupture width. The lower and middle magnitude values are judged to be more consistent with the preferred fault length and downdip width (~15 km based on microseismicity) and, therefore, are given higher weight than the highest value estimated from intensity data.

In addition to the intensity based magnitude estimates described above, we have also considered in our assignment of magnitude weights the physical process of strain accumulation and release, and the relationship between earthquake magnitude and recurrence interval. Given the relatively short 200-800 year earthquake recurrence interval for 1811-1812 earthquake sequences, we consider it more likely that the correct estimate of earthquake magnitude is represented by the lower or middle values in the distribution (Figure 2.5-45). This interpretation is supported by geologic slip rate and coseismic displacement data. These data do not support the occurrence of earthquakes of magnitude greater than M_w 7.7 with recurrence intervals of 200 to 800 years. A discussion of the dependency of earthquake recurrence on magnitude is presented in Section 2.5.2.1.2.4.

As discussed in the next section, the present interpretation of the paleo-earthquake data is that the penultimate and pre-penultimate events prior to the 1811-1812 sequence also consisted of multiple large-magnitude earthquakes within the NMSZ. Therefore, for this assessment, the "characteristic" event is considered to be a clustered rupture of all three faults in the NMSZ within a short period of time. Therefore, a set of five alternative magnitude sets, or clusters of characteristic ruptures were developed from the distributions for each fault. These magnitude clusters are shown in the logic tree on Figure 2.5-45.

2.5.2.1.2.3 Recurrence

For this study, characteristic earthquakes for the NMSZ are considered on Node 3 of the logic tree (Figure 2.5-45). The best constraints on recurrence of characteristic NMSZ events are direct paleoseismic data from studies of the Reelfoot fault (Reference 109) and the New Madrid North (East Prairie) fault (Reference 99), and are supported by paleoliquefaction studies throughout the entire New Madrid region (Reference 125). Paleoseismic data are considered the most reliable data source because paleoseismic investigations document and date discrete displacements of geologic features. The paleoseismic data from the Reelfoot fault indicate that there have been three events within the past 2,400 years. The most recent event was associated with the 1811-1812 earthquake sequence. The penultimate event is estimated to have occurred between A.D. 1260 and 1650. The pre-penultimate event is estimated to have occurred prior to about A.D. 780-1000 (Reference

108). Kelson et al. (Reference 109) estimated a preferred recurrence interval of about 400 to 500 years for the Reelfoot fault.

Baldwin et al. (Reference 99) conducted paleoseismic investigations to identify possible evidence of surface deformation related to the January 1812 earthquake. The available information is currently insufficient to determine whether the observed features represent the primary trace of the New Madrid North fault, secondary deformation, or solely liquefaction-related features. However, the available data do not support the presence of a major fault with repeated M>7.8 earthquakes occurring with an average recurrence interval of 500 years.

Investigations in the NMSZ also have identified paleoliquefaction features associated with the 1811-1812 earthquake sequence, as well as two prior events at approximately A.D. 1450 and A.D. 900 (Reference 125; Reference 126). Based on the liquefaction data, Tuttle et al. (Reference 125) estimate recurrence intervals for 1811-1812 type events to be 200 to 800 years with a best estimate of 500 years. In addition, the composite characteristics of sand blow features are interpreted by Tuttle et al. (Reference 125) to indicate that the previous earthquake cycles involved multiple earthquake events similar to the 1811-1812 earthquake sequence. Similarity in the size of the liquefaction fields (Reference 125) and amount of displacements observed from paleoseismic trench investigations (Reference 109) indicate that the previous events were of similar size to the 1811-1812 earthquake sequence.

The composite characteristics of the sand blows suggests that rupture of the NMSZ occurs as an event sequence, and therefore all three fault segments are modeled as rupturing within a short period of time in a cluster of events. Based on the paleoseismic and paleoliquefaction data we have assigned recurrence times and probabilities for these event clusters of 200 years (0.1), 500 years (0.6), and 800 years (0.3). The minimum and maximum values are assigned based on the paleoliquefaction data, and the middle value is assigned based on consideration of both the paleoseismic and paleoliquefaction data.

2.5.2.1.2.4 Dependency of Magnitude on Earthquake Recurrence

Maximum earthquake magnitudes for each of the 1811-1812 fault ruptures were selected from published intensity-based magnitude estimates (Reference 114; Reference 115; and Reference 117), paleo-liquefaction-based magnitude estimates (Reference 123; Reference 126; and Reference 185), estimates of seismic moment from the Reelfoot fault (Reference 123; Reference 181), and empirical relationships between magnitude and rupture area (Reference 130). Published magnitude estimates for the 1811-1812 earthquake sequence are summarized in Table 2.5-10.

The range of magnitudes are M_w 6.7 to 7.8 for the East Prairie fault, M_w 7.0 to 8.0 for the Reelfoot fault, and M_w 6.8 to 8.1 for the Blytheville Arch fault. As discussed in Section 2.5.2.1.2, magnitude estimates were weighted after considering the most recent published analyses, physical constraints on potential rupture areas and displacements, and dependency on earthquake recurrence intervals.

The dependency of maximum earthquake magnitude on earthquake recurrence interval was considered in assigning weights to the magnitude estimates because the relationship

Seismic Moment Rate = Area * Displacement * Shear Modulus/Slip Rate requires that, assuming constant slip rate, larger magnitude earthquakes have longer earthquake recurrence intervals (Reference 186; Reference 187). Therefore, the weights assigned for each magnitude estimate in the hazard calculation for the NMSZ reflect a preference for lower published magnitude values given the 200 to 800 year range of earthquake recurrence intervals from paleoseismic and paleoliquefaction studies, and fault displacement data.

Data from the Reelfoot fault are used to estimate seismic moment and moment magnitude for the February 1812 earthquake (Table 2.5-11). This earthquake is inferred to be the largest event by Bakun and Hopper (Reference 115) and Hough et al. (Reference 180) and, therefore, provides an estimate of seismic moment and earthquake recurrence for the largest event in the New Madrid earthquake sequence. Seismic moment (M_o) is the product of fault rupture area, average coseismic displacement, and an assumed shear modulus of 3.5 x 10^{11} dyne cm^2.

The moment magnitude (M_w) is computed from seismic moment using the relationship:

$$M_w = 2/3 * \log M_o – 10.7$$(Reference 187).

Earthquake magnitudes estimated from geological data shown in Table 2.5-11 are within the range of intensity-based values estimated for the February 1812 earthquake on the Reelfoot fault by Hough et al. (Reference 180) and Bakun and Hopper (Reference 115). However, the magnitude estimates are inconsistent with the M_w 8.1 +/- 0.3 magnitude estimates of Johnston (Reference 118) for the February 1812 earthquake on the Reelfoot fault. The physical parameters required to produce an M_w 8.1 earthquake on the Reelfoot fault (i.e. area and displacement) are inconsistent with the geological observations. To illustrate this point we have included two hypothetical earthquakes in the calculations shown in Table 2.5-11. The required rupture area to produce an M_w 8.1 earthquake is more than a factor of 3.3 larger than the documented fault area for the Reelfoot fault (Reference 123), and the required displacement is more than a factor of 2.6 larger than the observed fault displacements (Reference 109). Consequently, we give lower weight in the logic tree for a M_w 8.1 earthquake on the Reelfoot fault (or other segments of the NMSZ).

Seismic moment rate and earthquake recurrence intervals are computed for the range of potential earthquake magnitudes on the Reelfoot fault using the seismic moment (Table 2.5-12) and estimated fault slip rates for the Reelfoot fault (Reference 122; Reference 181).

Three estimates of fault slip rate are used in the recurrence calculation (Table 2.5-12). The low slip rate estimate (2 mm/yr) is based on seismic reflection data that show 16 m of displacement across the Reelfoot fault in the past 9000 years (Reference 122). The mid slip rate estimate (4 mm/yr) is based on a 29.5-foot (9-meter) displacement of 2290 +/-60 year old sediment across the Reelfoot fault at Tiptonville Dome (Reference 181), and the high slip rate estimate (6 mm/yr) is based on offset deposits observed in trenches across the Reelfoot scarp (Reference 109; Reference 122). For each slip rate, recurrence intervals are calculated for the range of magnitudes estimated by Mueller and Pujol (Reference 123).

The calculation of earthquake recurrence shown in Table 2.5-12, illustrates that for the mid- to high-slip rate estimates, the recurrence intervals for M_w 7.2 to 7.5 earthquakes is consistent with the 200 to 800 year estimate of recurrence that is based on the paleoliquefaction data of Tuttle et al. (Reference 125), and the paleoseismic data of Kelson et al. (Reference 109). The recurrence interval for a M_w 7.2 earthquake using the low slip rate estimate is also within the 200 to 800 year range based on the paleoliquefaction data of Tuttle et al. (Reference 125). Recurrence intervals for M_w 7.3 to 7.5 earthquakes using the low slip rate estimate are longer than and outside the 200 to 800 year range. Recurrence intervals for events greater than M_w 7.5 are outside the 200 to 800 year range for all slip rate estimates.

The recurrence calculations in Table 2.5-12 provide constraints on the likely size of earthquakes given the 2 mm/yr, 4 mm/yr, and 6 mm/yr slip rate estimates for the Reelfoot fault (Reference 109; Reference 122; and Reference 181), and the geological evidence of 200 to 800 year recurrence for characteristic earthquakes within the NMSZ (Reference 125). Based on these magnitude and moment rate recurrence calculations, greater weight is given to smaller intensity-based magnitude estimates of M_w 7.3 to 7.5 (Reference 180) and M_w 7.4 (Reference 115), over the larger intensity-based magnitude estimate of M_w 7.9 to 8.1 (Reference 179).

2.5.2.1.3 Saline River Source Zone Characterization

The logic tree for the Saline River source zone (Figure 2.5-46) describes the range of values considered for the following parameters: (1) Probability of Existence (also called Probability of Activity in the EPRI SOG methodology); (2) Source Geometry; (3) Maximum Magnitude; (4) Recurrence Model; (5) Geological Approach for Estimating Recurrence; and (6) Recurrence (note: numbers refer to nodes shown on the logic tree).

2.5.2.1.3.1 Probability of Existence

Node 1 considers the probability that the Saline River source zone is an independent seismic source or whether the features observed in the Saline River area can be explained by the seismic source models by the ESTs either as part of activity in background source zones, by earthquake activity in the NMSZ, or by other non-tectonic processes. We assign a 50% probability to this branch to express the large uncertainty in the existence of the source. The coincidence of liquefaction, sparse seismicity, late Tertiary and possibly Pleistocene fault rupture, and geomorphic asymmetry of drainage basins suggests that a local seismic source may be present (Section 2.5.1). However, it is equally likely that the liquefaction features observed in southeastern Arkansas were produced from: (1) infrequent moderate magnitude events in the background source zone; or (2) distant ground shaking related to events along the NMSZ.

Alternatively, the geomorphic drainage basin asymmetry may be caused by regional tectonic arching, glacio-eustatic rebound, or non-tectonic processes related to sediment loading in the Mississippi River delta. Geologic evidence of faulting is not sufficient to define with certainty that a distinct capable fault is present within the Saline River source zone. Only one fault shows conclusive evidence for repeated late Quaternary activity (Site 4; Table 2.5-13 and Figure 2.5-20). Deformation along other faults is inferred to be Pliocene to early Pleistocene age (Upland Complex time). Based on the information presented in Cox et al. (Reference 151), neither the type of fault or sense of displacement is well known. Furthermore, each of the observed faults appears to be short, with minimal displacement, and variable orientation. Based on the available data it is not possible to confirm the existence, with certainty, of a distinct throughgoing fault.

2.5.2.1.3.2 Source Geometry

Node 2 describes the geometry of the Saline River source zone (Figures 2.5-19 and 2.5-46). We define an areal source zone for the Saline River source zone that encompasses all of the geomorphic, liquefaction, seismicity, and geologic data that suggest the existence of a localized seismic source. The source zone is defined by the intersection of the southwestward extension of the Proterozoic Reelfoot Rift and the Paleozoic Ouachita Orogenic Belt. The source zone geometry is defined based on the interpretation that northeast-trending faults within the Reelfoot Rift in the continental basement may structurally interact with northwest-trending faults in the overlying Ouachita Orogenic Belt. As with the NMSZ, faults within this zone of intersection may be reactivated due to east-northeast directed regional compressive stress (Section 2.5.1.2.2.1).

The northwestern boundary of the zone is defined based on the Northern Boundary fault of the Reelfoot Rift (Reference 188). The southeastern boundary is defined based on the southward projection of recently identified Reelfoot Rift-related marginal faults (Reference 189). The southwestern boundary of the seismic zone is defined based on the southern rifted margin of the North American craton. The Reelfoot Rift is a Proterozoic structure within the continental basement of the North American craton and was truncated by southward-directed rifting of the Gulf of Mexico in Triassic time. Therefore, the southern continuation of the Reelfoot Rift system is constrained by the limit of the North American continental crust. The northeastern boundary of the seismic zone is defined by the northernmost occurrence of basin asymmetry along the Arkansas River.

2.5.2.1.3.3 Characteristic Earthquake Magnitude

Node 3 describes the characteristic maximum earthquake magnitude for the Saline River source zone (Figure 2.5-46). The characteristic earthquake magnitude is estimated taking into consideration the observations of faulting from trenches along the Saline River fault (Reference 151), and the extent of liquefaction features observed in Ashley and Desha counties (Reference 152).

The range of characteristic magnitudes and weightings are M_w 6.0 (0.3), M_w 6.5 (0.6), and M_w 7.0 (0.1). The M_w 6.0 and 6.5 estimates are based on the empirical relationship between size of a liquefaction field and earthquake magnitude (Reference 182) and encompass the upper bound estimate provided by Cox et al. (Reference 151). The liquefaction field observed in Ashley County is approximately 9-miles (15 kilometers) across. The Ambrayses (Reference 182) relationship predicts a M_w 5.5 for a liquefaction field of this size; to be conservative we assign a magnitude of M_w 6.0 for the lower bound maximum magnitude. If the liquefaction features observed at the Kelso (Desha County) and Montrose (Ashley County) sites occurred during a single event the liquefaction field would be approximately 30-miles (50-kilometers) across corresponding to a magnitude estimate of M_w 6.5 (Reference 182). The occurrence of M_w 6.5 earthquakes along the Saline River source zone also is consistent with the observation of minor surface fault rupture. The limited occurrence of liquefaction features and evidence for minor discontinuous surface fault ruptures are consistent with earthquake magnitudes in the M_w 6.0 to 6.5 range.

A M_w 7.0 characteristic earthquake also is considered in the magnitude assessment. Although the occurrence of a larger magnitude event is a possibility, the geological data do not support the occurrence of an earthquake of this size. The repeated occurrence of M_w 7.0 earthquakes in this region would have produced more pronounced geomorphic expression of tectonic deformation, and also would have produced much more pronounced and extensive surface manifestation of liquefaction in susceptible deposits along the Arkansas, Saline, Ouachita, and Mississippi Rivers. As a sensitivity analysis, we calculated the size of the 0.1g isoseismal contour for a M_w 7.0 event. This area represents the likely size of the area that would exhibit surface manifestation of liquefaction in susceptible deposits. The radius of the 0.1g isoseismal using the 2-sigma ground motion attenuation relations (Reference 13) is about 70 miles (120 kilometers). Therefore, if there had been repeated Holocene M_w 7.0 events, the distribution of liquefaction features would be far more extensive than the limited extent of features observed in Ashley and Desha counties. The lack of these extensive liquefaction features, and minor expression of evidence of surface faulting supports the higher weighting on the M_w 6.0 to 6.5 characteristic earthquake magnitude than the M_w 7.0 magnitude.

2.5.2.1.3.4 Earthquake Recurrence

Node 4 describes the models used to compute earthquake recurrence. We consider both the exponential earthquake recurrence model (Reference 186) and the characteristic earthquake recurrence model (Reference 190) and weight these 0.1 and 0.9, respectively.

The characteristic earthquake recurrence model is given a predominant weighting of 0.9 because there is a record of several earthquake cycles, and a sequence of geomorphic terraces that provide a geological basis to estimate rates of tectonic deformation. The exponential recurrence model is given a lower weighting of 0.1 because of the sparse seismicity in the area and incomplete historical record.

2.5.2.1.3.5 Characteristic Earthquake Recurrence Model

Node 5 describes the geological approach for estimating the characteristic earthquake recurrence. The characteristic earthquake recurrence is estimated using both paleoliquefaction data and fault slip-rate data. The recurrence of the characteristic earthquake using paleoliquefaction data is assigned a weight of 0.6. The recurrence of the characteristic earthquake using fault slip-rate data is assigned a weight of 0.4. We assign a higher weight of 0.6 to the recurrence model using paleoliquefaction data because these data are better constrained through paleoseismic investigations, and several earthquake cycles are recorded.

2.5.2.1.3.5.1 Paleoliquefaction

In Node 6, the recurrence times for characteristic earthquakes based on the paleoliquefaction data are estimated at 390, 1,725, and 3,500 years. We assign weights of 0.2, 0.4, and 0.4 respectively, to these recurrence estimates. The shortest recurrence time of 390 years represents the average recurrence time for five events during the period 150 ybp (A.D. 1800) to 1,700 ybp, the shortest allowable time period. The 1,725 year recurrence time represents the average recurrence time for five events occurring between 150 and 5,320 ybp (Table 2.5-14). The 3,500 year recurrence time represents the maximum recurrence based on the dated maximum interval between liquefaction events at the Montrose site in Ashley County.

2.5.2.1.3.5.2 Slip-Rate

The recurrence times for characteristic earthquakes based on slip-rate data are estimated for each characteristic earthquake magnitude (M_w 6.0, 6.5 and 7.0), also shown in Node 6. The recurrence time is estimated by dividing the characteristic displacement by the slip rate. The recurrence calculations are summarized in Table 2.5-15. Characteristic displacement is derived from the empirical relationship between earthquake magnitude and average displacement from Wells and Coppersmith (Reference 184). Slip-rates are estimated from the amount of stream incision recorded along the Saline River. The assigned weights for each recurrence calculation reflect a preference for slip-rate values of 0.01, 0.05 and 0.1 mm/yr.

The recurrence times vary for each of the M_w 6.0, 6.5 and 7.0 characteristic earthquake magnitudes because the amount of displacement required to produce these earthquakes varies; larger earthquakes require greater displacement than smaller earthquakes. For M_w 6.0 characteristic earthquakes the recurrence times and assigned weights are 1,000 years (0.3), 2,000 years (0.6), and 10,000 years (0.1), respectively. For M_w 6.5 characteristic earthquakes the recurrence times and assigned weights are 3,000 years (0.3), 6,000 years (0.6), and 30,000 years (0.1), respectively. For M_w 7.0 characteristic earthquakes the recurrence times and assigned weights are 12,500 years (0.3), 25,000 years (0.6), and 125,000 years (0.1), respectively.

2.5.2.1.4 Effect of Updating the Earthquake Catalog on the EPRI SOG Seismicity Parameters

The EPRI earthquake catalog, updated to include seismicity from 1985 to 2002, was examined to evaluate possible correlation of seismicity to geologic structures, possible changes to the EPRI source geometry or seismicity parameters (a and b values), and any possible new or previously unrecognized seismic source. The original EPRI catalog covers earthquakes in the CEUS for the time period up to 1984. This catalog was updated for the period 1985 to 2002 for the region within 200 miles of the site (within the latitude interval from 28.5 to 35.5 degrees North and longitude interval from 87.5 to 94.5 degrees West).

Table 2.5-14 identifies 23 earthquakes for magnitude 3.0 and greater (m_b) that have occurred since 1984 within 200 miles of the site. These events were added to the EPRI earthquake catalog. All of the events were assumed to be main events. Figure 2.5-38 shows the distribution of earthquake epicenters from both the EPRI (pre-1984) and updated (post-1984) earthquake catalogs in comparison to major tectonic features and geologic structures in the Site Region. Evaluation of the updated earthquake catalog yields the following conclusions:

1. No new earthquakes of magnitude greater than m_b 3.0 have occurred within approximately 110 miles of the ESP Site since 1985;
2. The updated catalog does not show any earthquakes within the site region that can be correlated with a known geologic structure. The majority of seismicity appears to be occurring in areas underlain by continental crust that coincide with either the Appalachian Mountains, Ouachita Orogenic Belt, or Reelfoot Rift/NMSZ;
3. The updated catalog does not show a unique cluster of seismicity that would suggest a new seismic source outside of the EPRI source model;
4. The updated catalog does not show a pattern of seismicity that would require significant revision to the EPRI seismic source geometry;
5. The updated catalog does not show any increase in M_{max} for any of the EPRI sources;
6. The updated catalog does not show any increase in the estimated rate of earthquake occurrences.

Seismicity parameters (a- and b-values) for the seismic sources defined by the Earth Science Teams were based on an analysis of the earthquake catalog developed as part of the EPRI SOG project. To evaluate the sensitivity of the updated EPRI earthquake catalog to estimated earthquake recurrence rates, the EPRI program EQPARAM was used. EQPARAM is part of the EPRI EQHAZARD software package. Calculations were performed for the Woodward Clyde background source around the GGNS site. The GGNS site is located at the center of this source which is defined as a square polygon, 6 degrees on a side. An evaluation of the change in seismicity parameters for this seismic source provides a measure of the effect of the updated earthquake catalog. The EQPARAM evaluation was performed using the same seismicity options specified by the Woodward Clyde team (Reference 10).

Figure 2.5-47 shows a comparison of the estimated frequency of earthquake occurrences for the Woodward Clyde background seismic source based on the original EPRI earthquake catalog and the catalog updated to 2002. The results indicate that the earthquake frequencies based on the updated catalog are slightly lower than the frequencies based on the original EPRI SOG seismic parameters. For this reason, it was concluded it was not necessary to update the EPRI SOG source seismicity parameters. Therefore, the original EPRI seismicity parameters (a- & b- values) were used to calculate seismic hazard at the ESP site with the EPRI seismic sources.

Possible changes in the seismicity parameters for the New Madrid seismic source zones were not evaluated. Because the New Madrid source zone for all EST's were updated to include a characteristic event and current estimates of the frequency of these events, an update of the seismicity parameters for events smaller than the characteristic earthquake (associated with the exponential part of the earthquake recurrence model) is not necessary.

2.5.2.2 GGNS Probabilistic Seismic Hazard Analysis

A probabilistic seismic hazard analysis (PSHA) was performed for the GGNS following the procedure provided in RG 1.165 (Reference 4). The results were deaggregated in terms of earthquake magnitude (M_w) and distance to determine the controlling earthquakes for the site. The PSHA calculations were performed for rock site conditions. The PSHA results were input to a site response analysis to determine the free-field surface ground motion and Safe Shutdown Earthquake (SSE).

2.5.2.2.1 Seismic Source Characterization

The GGNS PSHA was performed using the EPRI SOG seismic sources listed in Tables 2.5-8a through 2.5-8f, the New Saline River seismic source described in Section 2.5.2.1.3 and the revised New Madrid seismic source described in Section 2.5.2.1.2. As described in Section 2.5.2.1, the Saline River seismic source and revised New Madrid seismic source are added to the EPRI SOG seismic sources without revision to these sources. The potential double-counting of hazard using this approach is conservative. The parameters for these sources are presented in Figures 2.5-45 and 46.

2.5.2.2.2 Magnitude Conversion

In the EPRI SOG study earthquake occurrences were defined in terms of body-wave magnitude, m_b (Reference 9). Modern seismic hazard studies define seismicity with respect to moment magnitude (M_w). Similarly, the new EPRI recommended ground motion models (Section 2.5.2.2.3) are based on moment magnitude. For the new Saline River seismic source developed in this analysis and for the updated seismicity parameters for the New Madrid characteristic events, seismicity also is defined in terms of moment magnitude. To perform the PSHA calculations, the seismicity parameters specified for seismic sources in the EPRI SOG study were input as originally defined and converted to moment magnitude as part of the calculation. To account for the uncertainty in this conversion, three alternative m_b– M_w models were used: Atkinson and Boore (1995), EPRI (1993), and Johnston et al. (1996). These models were assigned equal weight in the analysis.

2.5.2.2.3 Ground Motion Attenuation Models

The ground motion attenuation models developed as part of an EPRI-sponsored project were used in the PSHA (Reference 13). The EPRI 2003 ground motion models estimate ground motions for rock sites and include, for a given ground motion frequency (e.g., spectral acceleration (S_a) 1 Hz), alternative estimates of the median and aleatory uncertainty in ground motion. The alternative models of the median and aleatory uncertainty and their probability weights represent the epistemic uncertainty in ground motions.

The EPRI 2003 ground motion model provides median ground motion models for the Mid-continent and the Gulf region of the central and eastern U.S. (Reference 13). In addition, the model is defined for different seismic source types, including General Area sources, and Fault sources or sources capable of generating large magnitude ($M_w > 7$) events. In addition, specific ground motion models were defined for fault sources in rifted and non-rifted regions (Reference 191).

For the New Madrid seismic source, the Mid-continent, rifted ground motion attenuation models were used. For this case there are 12 estimates of the median ground motion, and 4 estimates of the aleatory uncertainty. This produces 48 ground motion model estimates. For seismic sources located in proximity to the GGNS, the General Area ground motion models for the Gulf region were used. For this case there are 9 estimates of the median ground motion, which combine with 4 aleatory variability models to produce 36 ground motion model estimates.

As described in the EPRI (2003) ground motion report, when General Area sources and Fault sources (also sources capable of generating large magnitude events at large distances) are included in a seismic source combination (i.e., both seismic source types are simultaneously active), these models are correlated (Reference 13).

2.5.2.2.4 Lower-Bound Magnitude

The PSHA calculations were performed using a lower-bound magnitude of 5.0 M_w. This value is consistent with the findings in EPRI (Reference 11) which recommended a lower-bound magnitude for PSHA calculations performed for well-engineered facilities such as nuclear power plants. The study recommended a lower-bound magnitude of 5.0 M_w**.** At the time, a lower-bound magnitude of 5.0 M_w was estimated to correspond to a lower-bound magnitude of 5.3 in terms of m_b. Thus, the lower-bound of m_b 5.0 used in the EPRI SOG study was slightly conservative..

The deaggregation of the seismic hazard at the GGNS ESP site was performed for seven magnitude and seven distance bins. The magnitude-distance bins are:

Magnitude (M_w): 5.0-5.5, 5.5-6.0, 6.0-6.5, 6.5-7.0, 7.0-7.5, 7.5-8.0, 8.0, and greater,

Distance (km): 0.0-15, 15-25, 25-50, 50-100, 100-200, 200-300, 300, and greater.

The distance bins are defined in terms of epicentral distance.

2.5.2.2.5 PSHA Calculations

The seismic hazard calculations for the GGNS PSHA were performed using the EPRI EQHAZARD software which has been upgraded to include the characteristic earthquake model, the EPRI 2003 ground motion model, expanded logic tree modeling capabilities, and the calculations described in RG 1.165.

2.5.2.2.5.1 Results

The seismic hazard results for rock site conditions are shown in Figures 2.5-48 to 2.5-54 for each ground motion frequency (0.5 Hz, 1 Hz, 2.5 Hz, 5 Hz, 10 Hz, 25 Hz and PGA). The results are provided in terms of the 0.15, 0.50 and 0.85 fractiles and the mean. Table 2.5-15 shows the 10^{-5} median uniform hazard response spectra (UHS) for the GGNS for rock site conditions.

Following the procedure in RG 1.165 the median hazard results were deaggregated for low (1 and 2.5 Hz) and high frequencies (5 and 10 Hz). Figure 2.5-57 shows the low-frequency magnitude-distance deaggregation. The results show that the majority of the contribution for low frequency hazard is produced by characteristic earthquake events associated with the New Madrid seismic source zone. The high-frequency deaggregation results are shown in Figure 2.5-58. The results show that the majority of the contribution to high frequency hazard also is produced by events associated with the characteristic earthquakes on faults within the New Madrid seismic source zone.

To manage the execution time of these calculations one simplification was introduced. For seismic sources defined in the original EPRI SOG study that have multiple seismicity options (e.g., alternative models for the a- and b-values of the exponential recurrence relationship), the mean hazard for these options was calculated and used in the final hazard calculation. This simplification reduced the number of branches in the logic tree and significantly reduced the computation time. This simplification is reasonable due to the low sensitivity of the median hazard to alternative seismicity options defined by the ESTs (Reference 10). The sensitivity of the Grand Gulf median seismic hazard estimates was evaluated and determined to be small as shown in Figures 2.5-55 and 2.5-56 for spectral accelerations of 1 and 10 Hz, respectively

2.5.2.2.5.2 Controlling Earthquakes

Following the procedure recommended in RG 1.165, the controlling earthquakes for low and high-frequency ground motions were determined. The magnitudes and distances for the controlling earthquakes for 1-2.5 Hz and 5-10 Hz are listed in Table 2.5-16. For the GGNS, the contribution of large distant events (distances greater than 100 km) to low frequency ground motions was greater than 5 percent. Therefore, as recommended in RG 1.165, the controlling event for distances greater than 100 km and for 1-2.5 Hz was calculated. This event also is listed in Table 2.5-16. Deaggregation plots for the hazard analysis are shown on Figures 2.5-57 and 2.5-58. The response spectra for each of the controlling earthquakes are listed in Tables 2.5-17 through 2.5-19.

For each controlling earthquake, a median response spectrum shape was determined using the EPRI (Reference 13) ground motion models. These median response spectra are shown in Figure 2.5-59 with the median 10^{-5} UHS. As shown, the response spectra from the S_a (1-2.5 Hz) (including all distances) and the S_a (5-10 Hz) controlling earthquakes approximate well the shape and amplitude of the UHS for frequencies greater than 1 Hz. At frequencies greater than approximately 12 Hz, the high frequency spectrum under predicts the UHS amplitudes. This underprediction is greatest at 25 Hz.

The rock response spectra for the S_a(1-2.5Hz) (including all distances) and the S_a(5-10Hz) controlling earthquakes are used in the site response analysis to determine the site transfer function and the resulting soil ground motions. This analysis is described in Sections 2.5.2.3 and 2.5.2.4.

2.5.2.3 Seismic Wave Transmission Characteristics of The Site

The rock outcrop UHS as well as the associated 1 to 2.5 Hz and 5 to 10 Hz scaled spectra presented in Section 2.5.2.2 (Figure 2.5-59) are based on updated CEUS attenuation relations for hard rock site conditions (Reference 13). The hard rock site conditions reflect a mid-continent crustal structure (Reference 170, 191) with a defined shear-wave velocity of 2.83 km/sec. This high velocity is generally associated with very competent crystalline or metamorphic basement material, which occurs at the GGNS ESP site at depths exceeding 10,000 ft, where Paleozoic basement material is encountered (Section 2.5.1).

To develop the SSE at the surface, site response analyses must accommodate the effects of the local shallow soils as well as deeper soils and soft rock to a depth where the shear-wave velocity reaches about 2.8 km/sec. Since the UHS and consequently the SSE are defined to 0.5 Hz (2 seconds) as the lowest frequency, accommodation of the deeper materials is required to depths which results is capturing the amplification to the lowest frequency of interest (Reference 170, 192, 193, 194). For typical deep firm profiles, maximum amplification at 0.5 Hz is reached at depths of about 1,000 ft (305m), at low levels of loading (Reference 193). To conservatively accommodate potential low frequency amplification, the local soil profile is extended to a depth of 3,300 ft (1 km) and Approach 2A of McGuire et al. (Reference 194) is used to accommodate the effects of both the local soils and deeper materials as well as their variabilities on the design ground motions.

The shear-wave velocity profile at the site was based on three suspension log surveys, with the deepest extending to a depth of about 225 ft (Section 2.5.2.4). The base case profile as well as the suspension log profiles are shown in Figure 2.5-60. These shallow materials consist of about 75 ft of loess, 85 ft of young alluvium, with old alluvium to a depth of about 200 ft where claystones of the Catahoula formation were encountered. Both the old and young alluvium comprise the terrace deposits of the Uplands Complex. To extend the profile to a depth of about 3,000 ft, a generic Mississippi embayment shear-wave velocity profile was used. This generic profile was developed for ground shaking studies in the embayment by Professor Glenn Rix of the MAE Center (Reference 195). The profile is based on a large number of shallow and several deep velocity surveys and extends to a depth of 3,600 ft (1,100m). For the site base case profile, the shallow velocities to a depth of about 225 ft (Figure 2.5-60) replaced those of the generic Mississippi embayment upland profile, which had similar velocities (about 2,000 ft/sec) at these depths. The complete base case profile is shown in Figure 2.5-61 to a depth of 1 km, where shear-wave velocity is set to 2.8 km/sec, appropriate for hard rock conditions.

Nonlinear dynamic material properties, G/Gmax and hysteretic damping curves, are based on laboratory testing of undisturbed samples taken during the site exploration program (Section 2.5.4). Generally, the laboratory dynamic test results showed similarity with the EPRI (Reference 170) G/Gmax and hysteretic damping curves for cohesionless soils. Specifically, samples within the loess (approximately top 75 ft) were similar to the EPRI (Reference 170) curves for depths of 120 to 250 ft while the test results for the alluvium and old alluvium were similar to EPRI (Reference 170) curves for depths of 250 to 500 ft and 500 to 1,000 ft, respectively (Section 2.5.4). Due to the similarity between the laboratory dynamic testing results and those developed by EPRI (Reference 170), the EPRI (Reference 170) curves were adopted for use and are shown in Figure 2.5-62. The deeper EPRI (Reference 170) curves (500-to-1,000 ft) were used to a depth of 500 ft, below which linearity was assumed (Reference 194). To constrain the damping below 500 ft, the kappa value at the surface was assumed to be 0.04 sec, a conservative estimate for this region of the Mississippi embayment (Reference 196).

2.5.2.4 Site Response Analysis

The site response analyses followed Approach 2A recommended in McGuire et al., 2001 (Reference 194) in which the 1 to 2 Hz and 5 to 10 Hz controlling earthquake spectra (R.G. 1.165) scaled to the UHS are used as control motions (Figure 2.5-63). Transfer functions, soil surface-to-hard rock outcropping, are developed for each controlling earthquake, enveloped, and the envelop applied to the rock UHS. This process is intended to conservatively maintain the hazard level of the rock outcrop UHS while incorporating variability in site-specific dynamic material properties (Reference 194).

Variability in the base case shear-wave velocity profile is accommodated through development of 60 randomized profiles for each control motion. The profile randomization scheme is based on an analysis of variance of over 500 measured profiles (Reference 194; Reference 197), and randomly varies both shear-wave velocity as well as layer thickness. To provide for uncertainty in depth to hard rock, depth is randomized using a uniform distribution from 850m to 1,150m.

To accommodate variability in modulus reduction and hysteretic damping curves, the curves are independently randomized about the base case values. A log normal distribution is assumed with a σ_{ln} of 0.30 at a cyclic shear strain of 3 x 10^{-2}%. These values are based on an analysis of variance on a suite of laboratory test results. An upper and lower bound truncation of 2σ is used to prevent modulus reduction or damping models that are not physically possible. The random curves are generated by sampling the transformed normal distribution with a σ_{ln} of 0.30, computing the change in normalized modulus reduction or percent damping at 3 x 10^{-2}% shear strain, and applying this factor at all strains. The random perturbation factor is reduced or tapered near the ends of the strain range to preserve the general shape of the median curves (Reference 198).

The ensemble average, or mean transfer function, for each of two control motions (1 to 2 Hz and 5 to 10 Hz), then reflects the best estimate effect of the soil/soft rock column, accommodating site specific variability in dynamic material properties as well as depth to basement material. For the top of loess, the two mean transfer functions (5% damped response spectra), corresponding to the 1 to 2 Hz and 5 to 10 Hz control motions (Figure 2.5-63), are shown in Figure 2.5-64 along with their envelop. To accommodate the possibility of removing the surficial loess to a depth of about 50 ft for structure embedment, transfer functions were also estimated considering the top of 1,000 ft/sec material as surficial outcrop (Figure 2.5-60). The corresponding estimate of the mean transfer function is shown in Figure 2.5-65 and shows little impact of the top 50 ft (Figure 2.5-64).

2.5.2.5 Safe Shutdown Earthquake

Applying the envelop mean transfer function for the top of loess and top of 1,000 ft/sec material (Figure 2.5-64 and 2.5-65 respectively) to the rock UHS results in horizontal soil motions that are consistent with the median 10^{-5} APE hard rock UHS. These expected soil motions are shown in Figure 2.5-66 along with the hard rock UHS. Design horizontal ground motions are taken as the envelope of the two expected soil motions and are shown in Figure 2.5-67 (solid line). For comparison, the R.G. 1.60 spectrum scaled to 0.3g is shown also in the Figure.

As a preliminary estimate of vertical motions, the V/H ratio of R.G. 1.60 was applied to the horizontal design motions. This ratio is 2/3 at low frequency (0.1 Hz to 0.3 Hz) increasing with frequency to unity near 8 Hz. With the deaggregation suggesting little contribution for sources within about a 50 km distance (Section 2.5.2.2) use of the R.G. 1.60 V/H ratio is considered to conservatively reflect expected vertical soil motions (Reference 197) and is shown in Figure 2.5-68.

2.5.2.6 Operating Basis Earthquake

The Operating Basis Earthquake (OBE) ground motion spectrum is assumed to be one third of the SSE ground motion spectrum in accordance with Appendix S to locFR50.

2.5.3 Surface Faulting

There is no potential for surface fault rupture at the Grand Gulf Site Location, and there are no capable tectonic sources within a 5-mile radius of the site (Site Area). A capable tectonic source is a tectonic structure that can generate both vibratory ground motion and tectonic surface deformation such as faulting or folding at or near the Earth's surface in the present seismotectonic regime (U.S. NRC, 1997). The following sections provide the data, observations and reference citations to support this conclusion. The information contained in these sections was developed in accordance with Appendix D of Regulatory Guide 1.165 "Geological, Seismological, and Geophysical Investigations to Characterize Seismic Sources" (U.S. NRC, 1997) and is intended to satisfy 10CFR100.23 "Geologic and Seismic Siting Criteria" (U.S. NRC, 2002).

2.5.3.1 Geological, Seismological, and Geophysical Investigations

Investigations performed to assess the potential for surface fault rupture at the Grand Gulf Site and Site Area included: (1) compilation and review of existing data; (2) interpretation of aerial photography; (3) discussions with researchers familiar with the geology of the Site Area; (4) review of seismicity; and (5) field reconnaissance. In particular, an extensive body of existing information is available for the Grand Gulf Site and Site Area. This information derives from three principal sources: (1) work performed as part of the existing Grand Gulf Nuclear Station (GGNS) and reviewed and accepted previously by NRC staff; (2) published and unpublished geologic mapping performed primarily by the U.S. Geologic Survey, States of Mississippi and Louisiana, and researchers from the University of Memphis; and (3) seismicity data compiled from published journal articles and evaluated as part of this study.

This existing information was supplemented by field reconnaissance and air photo interpretation of the Site Area and Site Location. In particular, an updated map of surficial deposits and geomorphology was prepared for the Site Location (Figure 2.5-27). The new geologic map was used in combination with existing maps showing the surface of buried stratigraphic horizons to provide direct evidence documenting the absence of surface or subsurface faulting or other forms of tectonic and non-tectonic deformation at the site.

2.5.3.2 Previous Site Investigations

Previous site investigations performed for the existing Grand Gulf Nuclear Station are presented in the Updated Final Safety Analysis Report (UFSAR) (Reference 16). These previous studies provide extensive subsurface data illustrating the distribution of buried stratigraphic horizons across the site. In particular, structure contour maps of the top of the Oligocene age Glendon Limestone (Figure 2.5-15), Miocene Catahoula Formation (Figure 2.5-29), and Pliocene to Pleistocene Upland Complex (Figure 2.5-32) show that these stratigraphic horizons, although eroded, are not deformed by faulting, folding, or tilting across the Site Location and Site Area. In addition, these subsurface data document the absence of salt diapirs beneath the Site Location, collapse structures, volcanic intrusions, or other forms of non-tectonic deformation.

New information developed since the original Grand Gulf site investigation confirms that no active faults exist within the Site Area (5-mile radius). Significant revisions to our knowledge of active faulting and tectonic process have been made since the early investigations of the Mississippi Alluvial Valley (Reference 31; Reference 163). Models of faulting proposed by Fisk and Krinitzsky were initially addressed during the original Grand Gulf site investigations (Reference 16), and new additional data have been developed that further support the conclusions of the Grand Gulf investigations (Reference 17; Eversull, 1984).

Fisk was the first to address Quaternary faulting in the Mississippi Alluvial Valley (Reference 31). He postulated that the Mississippi Alluvial Valley was crossed by a dense rectilinear pattern of northeast-southwest- and northwest-southeast-trending fractures. This interpretation was heavily influenced by the prevailing belief by geologists of Fisk's era that the earth's crust contained a world-wide grid pattern of faults caused by planetary-scale influences (Krinitzsky, 1950). Fisk interpreted the association of photographic lineaments with geomorphic criteria including sharp river bends, linear lake margins, topographic breaks, and oriented drainages to infer the presence of faults in the region.

Krinitzsky (Reference 163) mapped the distribution of several hundred inferred faults in the Mississippi Alluvial Valley and Delta Plain regions. His mapping was primarily based on physiographic evidence. However, at three localities, he used closely spaced borings to verify the presence of faults in uppermost Tertiary deposits. The three localities include sites at Big Creek and Old Town Lake west of Friars Point, Mississippi, and a site west of Reelfoot Lake, south of New Madrid, Missouri.

The development of plate tectonic theory over the last several decades dramatically updated the tectonic models prevalent in Fisk's era. Since 1950, detailed Quaternary mapping and numerous site-specific engineering geologic investigations have disproved the presence of the majority of the faults and fault zones indicated by Fisk (Reference 31) and Krinitzsky (Reference 163), although high-resolution seismic surveys identified some faults in Tertiary and Cretaceous formations. In the Site Region, these older faults lack surface expression in Quaternary deposits, providing evidence that they have not been active during Quaternary time (Reference 17).

Fisk (Reference 31) suggested that two possible fault zones may intersect about 3 miles north of the site, near the mouth of the Big Black River. These potential fault zones were evaluated during the original Grand Gulf site investigation using borings, geologic mapping, literature review, and LANDSAT imagery (Reference 16). A cross section was constructed using Boring G-3 from the original site investigation and borings AH-5 and E-161 previously drilled by the Mississippi State Geological Survey. Differences in formation contact elevations across the inferred faults were attributed to the regional dip of stratigraphic units rather than fault offset along the Big Black River (Reference 16). The second lineament identified by Fisk in the Site Vicinity coincided with the alignment of Bayou Pierre; however, continuous stratigraphy documented from borings drilled north and south of Bayou Pierre demonstrates the continuity of subsurface deposits and the absence of faulting (Reference 16). These investigations disproved the existence of Fisk's previously inferred fault zones and verify that no faults exist within 5 miles of the site (Reference 16).

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

As previously discussed, there is no evidence of Quaternary fault offset in the Site Location or the Site Area. Furthermore, there is no evidence of non-tectonic deformation at the site or in the Site Area. The closest Holocene active fault to the site are growth faults in the Gulf Coast Basin province about 90 miles south-southwest of the site. The closest postulated Quaternary active tectonic fault is the Saline River Lineament approximately 90 miles north-northwest of the site (Figure 2.5-19) (referred to as the Saline River source zone, Section 2.5.1). Two salt diapers, the Bruinsburg salt dome and the Galloway salt dome, are within approximately 8.5 miles to the southwest and northeast of the site, respectively (Figure 2.5-9).

2.5.3.4 Correlation of Earthquakes with Capable Tectonic Sources

There are no reported earthquake epicenters that can be associated with any fault within 5 miles of the site. The closest earthquake of Mw 3.0 or larger is located 90 miles west of the site (Figure 2.5-5).

2.5.3.5 Characterization of Capable Tectonic Sources

There are no capable tectonic sources within 5 miles of the Grand Gulf Site. As described in Section 2.5.1, the Site Area is underlain by approximately 500 feet of Oligocene and younger sediments that were deposited within the Gulf Coastal Plain (Figure 2.5-9). These deposits are gently warped forming a broad synclinal structure, the limbs of which dip less than one degree and extend from western Alabama to western Louisiana (Figures 2.5-4 and 2.5-11). The axis of this syncline approximately follows the current position of the Mississippi Alluvial Valley, and also forms the axis of the Mississippi Embayment to the north. The downwarping of the Mississippi Alluvial Valley is a slow, ongoing process related to deposition of the thick sedimentary sequence. Although the axis of the syncline trends through the Site Area, this is not considered a seismogenic feature, but rather is related to slow isostatic adjustment of the crust due to sediment loading in the Mississippi Alluvial Valley and Gulf Coastal Plain (Reference 17).

Although pre-Quaternary faults are mapped in the Site Region, none are mapped within the Site Vicinity or Site Area. Tertiary faults of the Pickens-Gilbertton and Southern Arkansas fault zones are mapped approximately 80 miles northeast of the Site Area, and approximately 100 miles northwest from the Site (Figure 2.5-5). The Saline River lineament in northern Louisiana and southeastern Arkansas is approximately 90 miles from the Site, and the growth faults in southern Louisiana are also approximately 90 miles from the Site at their closest approach (Figure 2.5-5). The growth faults in southern Louisiana are related to gravitational collapse of the Mississippi delta complex. The faults in the eastern and western portions of the Site Region are exposed in Eocene or older deposits and do not affect Quaternary deposits. The Saline River lineament in northern Louisiana is the only potentially active Quaternary tectonic fault in the Site Region, but is not mapped across the Mississippi Alluvial Valley (References 17; 44). There are no faults mapped closer than 90 miles to the site, or within either the Site Vicinity or Site Area (References 52; 53).

Investigations by the Army Corps of Engineers (Reference 204) were conducted to document subsurface geological conditions along the Mississippi River. Based on a series of geotechnical borings, the Army Corp developed geologic cross sections of Quaternary and Holocene alluvium in the Mississippi River channel. The boring data support previous conclusions that Quaternary deposits in the Site Area are unfaulted. The Army Corp data also support the interpretation that the faults previously mapped by Fisk (Reference 31) along the Big Black River and Bayou Pierre are not present (Reference 204).

Subsurface borings completed for the existing Grand Gulf Nuclear Station document the absence of faulting in the Site Area (Reference 16). Oligocene and younger deposits decrease in elevation from north to south, are laterally continuous, and have a constant gradient across the Site Area. No faults are identified along this section (Figure 2.5-16; Reference 16).

Additional subsurface data from deep exploration borings across the Site Vicinity in eastern Louisiana also document lateral continuity of Tertiary and younger deposits (Reference 205).

The continuity of subsurface deposits demonstrates the tectonic stability of the Site Location, Site Area, and Site Vicinity from at least Oligocene time, approximately 30 Ma to the present. the top of the Oligocene Glendon Limestone Formation slopes to the southeast (Figure 2.5-15). The surface appears to have been eroded, forming a buried drainage basin morphology, but does not show morphology indicative of tectonic deformation (Reference 16).

The top of the Miocene Catahoula Formation in the Site Location forms a gentle westward sloping surface (Figures 2.5-29). The surface morphology preserves the Pliocene to Pleistocene age erosion surface of the ancestral Mississippi Alluvial Valley, and a former tributary valley across the Site Location. The morphology of the surface of the Catahoula Formation is related to former stream erosion. The top of the Catahoula surface shows no morphology indicative of tectonic deformation (Reference 16).

As shown on Figure 2.5-32, the surface of the Pliocene to Pleistocene Upland Complex deposits have been eroded during the Pleistocene and Holocene forming two west-trending drainages that cross the property. These drainages are the current active channels in the Site Location. The surface of the terrace deposits shows no morphology indicative of tectonic deformation (Reference 16).

2.5.3.6 Zones of Quaternary Deformation Requiring Detailed Fault Investigation

There are no zones of Quaternary deformation requiring detailed investigation within the Site Area.

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

As discussed above, geologic cross sections and structure contour maps of the Site Vicinity, Site Area, and Site Location demonstrate the continuity of deposits of Oligocene and younger age, and the long-term tectonic stability of the Site Area. Therefore, the potential for surface-fault rupture at the site is considered negligible. In addition, there is no evidence of non-tectonic deformation in the Site Location or Site Area such as collapse structures, salt diapirs, growth faults, volcanic intrusion, etc.

2.5.4 Stability of Subsurface Materials and Foundations

2.5.4.1 Detailed Site Investigation Program

An engineering geologic and geotechnical site investigation (geotechnical investigation) was performed for the proposed location of the new facility to: (1) characterize site conditions to develop site-specific seismic design criteria; and (2) evaluate potential seismically-induced ground failure and hazard. The information also was used for an initial screening assessment of foundation conditions. The locations of the site explorations are shown on Figure 2.5-69 and 2.5-70. At this time, a plant design has not been selected, and the footprint and embedment depth of the plant have not been determined. Additional site exploration, laboratory testing, and geotechnical analyses will be performed to develop final plant design criteria for the Construction and Operating License (COL) phase of the project after a plant design has been selected.

The exploration and testing activities were specifically developed to comply with:

- NRC Regulatory Guide 1.165 “Identification and characterization of seismic sources and determination of safe shutdown earthquake ground motion” (Reference 4).

The site investigation also is in partial compliance with:

- Draft Regulatory Guides DG-1011 “Site investigations for foundations of nuclear power plants” (proposed revision to Regulatory Guide 1.132; Reference 5); and,
- DG-1109 “Laboratory investigations of soils and rocks for engineering analysis and design of nuclear power plants” (proposed revision to Regulatory Guide 1.138; Reference 6).

The COL phase investigations and testing will include additional exploratory borings throughout the planned excavation and building footprint area to obtain information for foundation design and site grading in full compliance with Regulatory Guides 1.132 and 1.138 and Draft Regulatory Guides D-1101 and D-1109.

2.5.4.1.1 Borings and Sampling

Four exploratory borings (Borings WLA B-1, B-2, B-2A, and B-3) were drilled at the proposed site location to depths of between 141.5 and 238.0 feet to characterize subsurface geologic conditions, perform in-situ testing and borehole geophysical surveys, and to obtain laboratory geotechnical test samples. Figure 2.5-70 shows the locations of the exploratory borings, and Tables 2.5-20 and 2.5-21 summarize the characteristics of the exploratory borings and general site stratigraphy. Figures 2.5-34 through 2.5-74 are summary logs of encountered conditions. Geologists classified the rock and soil materials according to standard engineering classification, and also assigned geologic units, inferred ages, and made interpretations of genesis for each stratum.

2.5.4.1.2 Site Geotechnical Profile

Geologic cross sections in Figures 2.5-75 through 2.5-77 show the site stratigraphy and subsurface conditions. Subsurface materials were classified into four different geologic units: late Pleistocene loess, Pliocene to Pleistocene Upland Complex alluvium (Qa), Upland Complex old alluvium (Qoa), and Miocene Catahoula Formation claystone based on field examination of recovered samples. In addition to these geologic units, localized fill was placed in the former topographic swales that crossed the site (Figure 2.5-69) to develop the current level pads. This fill is variable in thickness, and appears to consist mainly of excavated on-site loess that was removed from cut parts of the pads. Boring WLA B-3 is located in the approximate axis of one of the infilled swales. The materials encountered in the boring consist of massive silt similar to natural loess deposits, and exhibit similar field SPT and CPT response and laboratory index values. Therefore, the fill could not be differentiated from the natural loess, and was grouped together with the loess for site ground motion response and hazard analysis. The fill encountered in Boring WLA B-3, therefore, is not broken out as a separate unit, and is not described separately. Based on topography and site use history the infilled swale near Boring WLA B-3 should contain approximately 30 feet of fill.

The classification of deposits is based on textural composition, degree of sorting, relative density, color, and structures according to standard geologic interpretive procedures described in Compton (Reference 200). Each geologic unit is separated by a laterally continuous, subhorizontal, erosional unconformity that represent a hiatus in the depositional phase of each unit, and/or intervening period of erosion. The unconformable contacts, therefore, represent the former land surface at different times during the late Pliocene, Pleistocene, and Holocene. Structural contour maps showing the elevation of the unconformable contacts between old alluvium and alluvium, and alluvium and loess, are included in Figures 2.5-78 and 2.5-79, respectively.

The stratigraphy encountered generally agrees with the stratigraphy shown on the UFSAR boring logs, with the exception that the UFSAR borings describe the alluvium as “terrace alluvium”, and old alluvium as “Catahoula Formation”. Accounting for the differences in unit nomenclature between this study and UFSAR borings, material descriptions and contacts generally are consistent between the two data sets.

2.5.4.1.3 Material Engineering Properties

Standard Penetration Tests (SPT) were obtained at various intervals in the borings to provide estimates of the in situ density/consistency of site materials, obtain disturbed samples for index testing, and to use as a screening tool to evaluate potential liquefaction susceptibility and foundation properties. All SPT blow counts reported for this study are uncorrected for equipment and confining stress. SPT blow counts are summarized and compared against the blow counts from the GGNS UFSAR data on the geologic cross sections in Figures 2.5-75 through 2.5-77. In general, the blow counts from this investigation are somewhat lower than reported in the UFSAR for GGNS borings. The differences may be related to different equipment and techniques used during this study and earlier studies, such as different hammer efficiencies. Automatic trip hammers were used for this investigation and may have higher impact force efficiency than hammer systems used for the UFSAR investigations.

Ranges and averages of SPT blow counts for different geologic layers underlying the proposed site are summarized in Table 2.5-22.

2.5.4.1.3.1 Loess

Loess was encountered in each of the borings, and forms the surface layer across the site. The loess ranges from about 55- to 85-feet thick, and consists of relatively uniform, yellow-brown, slightly- to moderately-plastic silt to clayey silt (ML) with some silty clay (CL) intervals, weak blocky structure and pervasive small root pores and voids. Small gastropod and clam(?) shells commonly occur in discrete beds or zones. The silt typically exhibited a silky feel, is micaceous, and has low to moderate plasticity. The loess exhibits coarse layering defined by differences in clay content, color, shell content, and consistency. However, the engineering properties of the different loess layers do not differ significantly, and the index engineering properties fall within a narrow range throughout the deposits. Regionally and locally, the loess exhibits a slight carbonate cementation, and soil structure that allows it to stand vertically in cuts and stream banks. In borehole samples, the loess characteristically exhibits a moderate reaction to hydrochloric acid, documenting the weak calcium carbonate cementation. Typically, loess deposits contain calcium carbonate cementation as precipitates in root pores and voids, and may gain additional cohesion from clay films on silt grain surfaces (Reference 203). Testing performed for the UFSAR (Reference 16) showed that the loess has a honeycomb structure. Some weakly-developed paleosol layers marked by slightly clayier zones may separate individual pulses of loess deposition. The CPT soundings show that the loess exhibits individual layers that are between about 6-inches and 40-feet thick. SPT data show that the loess is medium stiff to stiff, with estimated undrained shear strengths on the order of 750 to 1,500 pounds per square foot (fps). The CPT-determined undrained shear strength of loess ranged between 2000 and >8000 psf (maximum instrumental range), increasing with depth. Shear wave velocities in loess ranged between 590 and 1,450 fps.

2.5.4.1.3.2 Alluvium (Upland Complex)

The alluvium consists of light yellow brown and gray, interbedded sand and silty sand (SP, SM) with lesser clayey sand (SC), gravelly sand (SW), and sandy gravel (GW) lenses. Discontinous layers ranged between about 6-inches and 3-feet thick. Individual layers could not be traced between the borings and CPT soundings. Sand grains are subrounded to subangular, fine- to medium-grained, and consisted of quartz with lesser feldspar and mafic lithologies. The alluvium typically is well sorted with low fines content, and low plasticity. The alluvium was readily drilled with mud rotary equipment, but some sandy layers below the water table caused caving problems in Boring WLA B-2A. SPT blows in the alluvium indicate that it is in a medium dense to dense condition. CPT refusal was met in the alluvium in each sounding after penetration of between 5 and 30 feet into the alluvium (10-ton capacity CPT rig). CPT shear strength values ranged between 4,000 to >8,000. Shear wave velocities in the alluvium ranged between 740 and 1,750 fps.

2.5.4.1.3.3 Old Alluvium (Upland Complex)

The old alluvium consists of interbedded, green to dark gray (gleyed) clayey sand, sandy clay, silty sand, and clean to gravelly sand. The old alluvium was poorly to well sorted, typically exhibiting much poorer grading than the overlying alluvium. Layering in the old alluvium ranged between about 3-inches and 3- to 4-feet thick, and some layers contained dark manganese and carbon streaks and pods, with some relict plant remains. Gravel-size clasts included a large percentage of soft clay and claystone rip-up clasts. Finer-grained layers exhibited low to moderately high plasticity. Drilling was moderately easy to moderately hard (slow), and some sandier zones appeared to have locally ravelled into the holes. SPT blow counts in the old alluvium indicate that it is dense to very dense. Shear wave velocity ranged between 530 and 3,360 fps.

2.5.4.1.3.4 Catahoula Formation

The Catahoula Formation was only encountered in Boring WLA B-2A (the deepest boring for this investigation), and consists of gray-green, hard clay to claystone that exhibited a slight degree of induration and somewhat brittle behavior. The claystone has a partial blocky structure, and contains silica-coated fractures. Some of the broken surfaces in the recovered core exhibited randomly-oriented slickensides, and the core slaked in water after several tens of minutes of saturation. The claystone is highly plastic. Drilling was hard (slow, near-refusal), and the sole SPT sample had a blow count of 82. This SPT value correlates with a very hard (very dense) consistency, and is typical for soft rock-like material. Shear wave velocity in the Catahoula Formation ranged between 1,500 and 2,830 fps. The claystone Plasticity Index (PI) and clay content suggest that it may be expansive.

2.5.4.1.4 Borehole Geophysical Velocity Surveys (P-S)

Borehole geophysical surveys were performed in three borings (WLA B-1, B-2A, and B-3) upon completion of drilling between July 29 and August 17, 2002 by GEOVision Geophysical Services (GEOVision) and under observation by the WLA geologists. The surveys were performed with an OYO Model 170 Suspension Logging system that measures both compression wave (P) and horizontal shear wave (V_{SH}) velocity in formation materials comprising the borehole walls. The results of the surveys are summarized as velocity-depth plots on Figures 2.5-80. All P-S surveys were performed in uncased holes because this results in better resolution of stratigraphic velocity layers. A thick mud was used to maintain the holes during the P-S logging.

The P-S velocity survey obtains a vertical velocity profile of the stratigraphy along borehole walls using both compressive (Vp) and shear (Vs) waves. Ranges of compression and shear wave velocities for the site geologic materials are shown in Table 2.5-23.

No clear velocity differences were observed between the loess and Upland Complex alluvium, or the Upland Complex alluvium and old alluvium. Rather, velocities typical increased gradationally in the various geologic layers (Figure 2.5-80). A well-defined velocity increase was observed in the lower half of the old alluvium that is not marked by a significant stratigraphic change based on the borehole logging data. It is possible that the higher velocities occur in more-dense and indurated sublayers within the old alluvium that are not marked by a lithologic change. Velocities remained relatively high in the Catahoula Formation.

The P-S datalogger used for this study represents a marked improvement and advancement of technique over the cross-hole seismic velocity techniques and equipment that were used for the operating GGNS in the 1970's (Reference 16). Therefore, a direct comparison cannot be made between the two data sets. However, the velocities for the various geologic layers generally fall within similar ranges, if the UFSAR data for the Catahoula Formation are compared against the velocity data for the Upland Complex Old Alluvium. A comparison between the shear wave velocities is made below.

2.5.4.1.5 Cone Penetrometer Test (CPT) Surveys

Four cone penetrometer test (CPT) soundings were performed by Eustis Engineering Company, Inc. (Eustis) in the proposed site location (Figure 2.5-70) to depths of between 79.0 and 95.3 feet. Summary CPT logs are shown on Figure 2.5-81. Each sounding was advanced to practical refusal, which occurred in the upper part of the Upland Complex alluvium. Because of refusal within the Upland Complex alluvium, CPT data could only be obtained for the loess, and uppermost part of the alluvium. No CPT data was obtained in the Upland Complex old alluvium or Catahoula Formation. The first CPT sounding (CPT-1) was located adjacent to boring WLA B-1 for calibration purposes. Comparisons of subsurface materials and contacts between boring WLA B-1 and CPT-1 were very good.

Tip resistance values in the loess were relatively uniform and below 100 tons per square foot (tsf). Tip resistance increased markedly at or near the top of the Upland Complex alluvium below the base of the loess, and were greater than 200 to 400 tsf. The loess exhibited typical friction resistance values of between 300 and 1,600 pounds per square foot (psf). The Upland Complex alluvium exhibited typical frictional resistance values from 2,400 psf to greater than CPT rig refusal (10 tons), but some local finer-grained layers had frictional values similar to those for loess.

The published relationships of Robertson (Reference 199) were used by Eustis to classify materials based on the CPT data. The CPT material classification roughly matched field and laboratory classifications, but tended to be somewhat coarser (sandier) than the field classifications and laboratory testing results. The CPT classifications and tip results show that the grain size and consistency of the loess are relatively homogenous, and the loess exhibits a generally coarse layering with individual strata on the order of several feet to up to about 40-feet thick. This is in agreement with the field borehole and laboratory data. Finer layering and increasing variability in tip and friction resistance occurred in the lower parts of the loess near the contact with the underlying Upland Complex alluvium. The finer stratigraphy and variability appear to be the result of possible paleosols at the top of the alluvium, and/or different pulses of sedimentation and reworking of the alluvium during initiation of loess deposition. The Upland Complex alluvium exhibited fine to medium stratigraphic layering, but was predominantly classified as sand with some gravelly layers.

Undrained shear strength estimates from CPT data were made by Eustis according to Lunne et al. (Reference 201), and using a Cone Factor value of 15 which Eustis has found to be regionally applicable for projects in Mississippi and Alabama. The CPT-determined undrained shear strength of loess ranged between 2,000 and >8,000 psf, and increased with depth. CPT undrained shear strength values for Upland Complex alluvium ranged between 4,000 to >8,000 psf. Estimated SPT blow counts from CPT data were made by Eustis according to correlations by Lunde (Reference 201), and are in general agreement with the range of SPT blow counts obtained in the exploratory borings. Equivalent SPT N60 values were calculated from CPT data by Eustis according to Lunne et. al. (Reference 201), and ranged between about 10 and 20 for the loess, and typically were greater than 40 for the alluvium. Evaluation of CPT data according to methodology of Andresen et al. (Reference 202) suggests that the overconsolidation ratios of loess and Upland Complex alluvium are both considerable, possibly in the ranges of greater than 2 for loess, and about 1.5 to 5 for Upland Complex alluvium.

2.5.4.1.6 Static Laboratory Analysis

Sixty samples of loess, Upland Complex alluvium, and Catahoula Formation bedrock from site borings were tested by Eustis for basic geotechnical properties in their Metairie, Louisiana laboratory. Index properties also were measured for the six samples submitted to the University of Texas, Austin (UTEXAS) for dynamic testing. The samples were shipped to Eustis by Federal Express (FedEx), and were transported to UTEXAS in a passenger vehicle. Both sample sets were documented with a chain-of-custody form. The scope of the laboratory index testing program included the following:

- fifty nine moisture content (ASTM D 2166)
- twenty four dry density (ASTM D 2216)
- seventeen Atterberg Indices (ASTM D 4318)
- forty nine mechanical sieves (ASTM D 422)
- fifteen hydrometer (ASTM D 422)
- six consolidated, undrained triaxial test series (1 to 3-point series; ASTM D 4767)

Table 2.5-24 and 2.5-25 summarizes the laboratory test program and testing data. Figures 2.5-82 and 2.5-83 summarize the results from the moisture content and grain size testing, respectively.

2.5.4.1.6.1 Laboratory Results for Loess

Twenty six samples of loess were tested for static geotechnical properties. Water content in the loess samples varied between 15.7% and 29.5%, with an average of 22.8%. Dry densities of loess ranged between 85.8 pcf and 104.7 pcf, with an average of 94.8 pcf. These dry densities show that the loess is relatively stiff, with relative densities ranging on the order of greater than 50% to about 75% (Reference 203). The densities suggest that the loess has a moderately low to low potential for saturation-induced settlement from particle structure collapse and dissolution of cementation (Reference 203). The loess is subject to gully erosion and possible piping, as evidenced by steep-walled erosional gullies in loess.

Plasticity Indices (PIs) for loess samples ranged between 3% and 16%, with an average of 10.5%, with corresponding Liquid Limits (LL) of between zero and 32%. These values indicate that the loess classifies as a low plasticity silt (ML). The fines percentage (silt and clay; minus 200 sieve) of loess samples ranged between 73.2 and 99.8, with an average of 97%. The clay-size fraction determined from hydrometer testing ranged between 8.2% and 11.1%, and show that the loess primarily consists of silt-size grains. The grain size distribution of the loess samples was quite uniform (Figure 2.5-83), and typical for loess deposits.

Two triaxial CU test series performed on loess samples indicate total stress cohesion of zero and internal friction angles of between 32 and 33 degrees. Effective strength internal friction angles were between 33 and 34 degrees. The results of these strength tests are on the high end for published values for loess (e.g., Reference 203), and indicate a high degree of grain interlocking and cementation. Locally, steep and vertical road cuts in loess soils appear to be quite stable, suggesting that some cementation and apparent cohesion exists in the natural, undisturbed loess.

2.5.4.1.6.2 Laboratory Results for Upland Complex Alluvium

Twenty one samples of Upland Complex alluvium were tested for static geotechnical properties. Water content in the alluvium samples varied between 9.9% and 25.5%, with an average of 19.2%. Dry densities ranged between 93.2 and 129.4 pcf, and averaged 106.0 pcf. These densities are typical for medium dense to dense silty and clean sands (Reference 203). PIs for alluvium samples ranged between 0% and 4% and LLs ranged between zero and 21%. This indicates that Upland Complex alluvium is essentially non-plastic.

The Upland Complex alluvium consisted primarily of sand to silty sand (SM-SP). Sand percentages ranged between 2% and 95.3%, with an average of 68.6%. Two samples contained significant gravel content (24.3% and 41.6% gravel); other samples had either zero, or less than 5%, gravel. The fines content of Upland Complex alluvium ranged between 4.7% and 92.9%, with an average of12%, and the clay-size fraction determined by hydrometer analysis ranged between 2.8% and 10.6%. The hydrometer test results show that the fines in the Upland Complex alluvium consist primarily of silt-size material. The grain size distribution of the alluvium samples was relatively uniform, primarily poorly-graded to silty sands (Figure 2.5-83). The grain size and sorting is typical for moderate-energy alluvial deposition and point bar deposits typical along the modern Mississippi River.

Three triaxial CU test series performed on Upland Complex alluvium samples indicate total stress cohesions of between zero and 1.16 psf, and internal friction angles of between 36 and 40 degrees. Effective strength cohesion was zero, and friction angles varied between 36 and 41 degrees. These results are relatively high for alluvium with silty sand to poorly graded sand consistency (Reference 203), and suggest that the alluvium is quite dense with interlocking packed grains.

2.5.4.1.6.3 Laboratory Results for Upland Complex Old Alluvium

Fifteen samples of Upland Complex old alluvium were tested for static geotechnical properties. Water content in the old alluvium ranged between 5.6% and 36.1%, and averaged 23.4 %. Two dry density determinations were 89.3 (sand layer) and 94.9 pcf (clay layer). These densities are low for sandy alluvium, but in the typical range for clayey alluvium (Reference 203). PIs for the fines component of the old alluvium ranged from zero to 16%, and averaged 9%. The corresponding LLs were between 17 and 42%. These results indicate that the Upland Complex old alluvium is non-plastic to moderately plastic, and that the fines classify as ML-CL soils. The fines in the old alluvium generally exhibit a higher plasticity than the fines in the overlying alluvium, suggesting differing sediment sources and/or weathering histories.

The Upland Complex old alluvium samples classify as a range of soil types, including lean clay and silt (CL and ML), silty and clayey sand (SM and SC), and poorly graded sand (SP). The sand content of the old alluvium samples ranged between zero and 89.2%, with an average of

34.0%. In general, the Upland Complex old alluvium has a lower percentage of sand, and higher clay content, than the overlying alluvium unit. Two samples had significant gravel content: 8.5% gravel; and 22% gravel. Other samples had zero or less than 0.3% gravel. Fines content in old alluvium samples ranged between 3 and 99%, with and average of 54.4%. The clay content of hydrometer samples ranged between 6.2 and 12.2% with an average of 9.4%. The hydrometer analyses show that the fines fraction in the old alluvium is primarily silt-size. The grain size distribution of Upland Complex old alluvium samples is significantly more poorly-sorted than the overlying alluvium, and samples typically contain a wide range of grain sizes commonly associated with sediments that are not transported far from the source deposits.

No triaxial strength tests were performed on old alluvium samples.

2.5.4.1.6.4 Laboratory Results for Catahoula Formation

Only one acceptable sample of Catahoula Formation claystone was obtained from the exploratory borings for laboratory testing. This sample had a moisture content of 21.5%, PI of 35%, LL of 54%, and fines content of 80.6%. No hydrometer or triaxial strength tests were performed on samples of Catahoula Formation. The PI of the Catahoula Formation sample is significantly higher than any of the other tested materials, and plots in the zone of highly plastic clay in the UCSC classification. The PI and grain size of the Catahoula Formation claystone suggest that it is an expansive material, and classifies as a fat clay (CH).

2.5.4.1.6.5 Comparison of ESP and UFSAR Laboratory Test Results

Results from the ESP laboratory testing are in a similar range to the results from the UFSAR laboratory testing for layers with similar composition and texture. Figures 2.5-84 through 2.5-86 are comparison plots of some index properties between the ESP and UFSAR testing programs. Index values for the ESP samples generally fall within the ranges of those determined for the UFSAR samples. Loess, in particular, exhibits quite similar properties (Figure 2.5-84) for moisture content, liquidity index, and dry density. The laboratory data show that the loess is uniform across the proposed site location. The Upland Complex alluvium unit exhibits higher dry densities, and lower moisture contents, than the UFSAR terrace alluvium samples (Figure 2.5-85). This may be due, in part, to local variations in the sand content of the alluvium. The moisture content and liquidity index for the Upland Complex old alluvium and Catahoula Formation samples are generally within the ranges reported for the UFSAR samples, but depart from the UFSAR data for ESP samples in the elevation range of between about zero and 20 feet (Figure 2.5-86). The differences may be because of a thin coarser-grained zone that exhibits locally higher moisture contents.

2.5.4.1.7 Dynamic Soil Testing

Shear modulus reduction and damping curves for the upper part of the site soil column were obtained from torsional shear and resonant column (TSRC) testing of six relatively undisturbed samples at the UTEXAS laboratory under the direction of Professor K.H. Stokoe II. Dynamic testing was performed to obtain dynamic modulus reduction curves and damping data in site soils for site response analysis. Testing was constrained to materials that could be successfully sampled in a relatively undisturbed state with thin walled Shelby tubes, and included 2 tests of eolian silt, 2 tests of Upland Complex alluvium, and 2 tests of Upland Complex older alluvium. The Catahoula Formation claystone could not be successfully sampled for dynamic testing. Table 2.5-26 summarizes the properties of the samples, and Figure 2.5-80 shows the locations of the samples and comparisons between borehole and laboratory-measured shear wave velocities. The dynamic testing results are summarized in Figures 2.5-87 through 2.5-94.

All dynamic test samples were relatively undisturbed Shelby tube samples that were transported to the laboratory in a passenger vehicle. A chain-of-custody form was filled out and maintained to document sample transportation, and is retained in the project files.

Each test specimen was subjected to a suite of tests at varying confining pressures and cyclic strain levels. Specimens were driven in the torsion shear mode of the TSRC equipment at increasing cyclic strain levels up to the limit of the equipment and were then excited in the resonant column mode to obtain results at higher strain levels. In order to obtain resonance of these specimens the frequencies of excitation were somewhat higher than those used in the torsional shear mode. General properties of the specimens are shown in Table 2.5-26.

Table 2.5-26 shows the estimated in-situ confining pressure for each test specimen. A K_o value of 0.5 was used for the loess specimens, and a value of 1.0 used for the Upland Complex alluvium and older alluvium. The ratio of the shear wave velocity measured in the laboratory at small strains and the shear wave velocity measured in the field at the same depth are shown in the table. These data include tests conducted the portion of the tests conducted at the estimated in-situ confining pressures and tests conducted at four times the estimated in-situ confining pressure (4 specimens). Ideally this ratio should approach unity. It appears that the estimate of K_o that was used for the loess specimens may have been too low. A better approximation of the field conditions was obtained by testing these samples at four times the estimated in-situ confining pressure.

The results of the TSRC tests are shown in Figures 2.5-87 through 2.5-94 as: (1) a function of the cyclic shear strain as values of the modulus reduction ratio (G/Gmax), that is the shear modulus divided by the low strain shear modulus; and (2) the damping ratio. The ESP data are plotted on the family of depth dependent modulus reduction and damping ratios developed by EPRI (Reference 170). The pattern of the ESP data is generally similar to the shape of the EPRI curves, however the ESP data are generally more linear. This is likely because the EPRI curves were developed for normally consolidated Holocene silty and clayey sands, whereas the soils at the proposed site location are both older (Pliocene to Pleistocene) and overconsolidated. The dynamic test results were evaluated with respect to the geologic origin and index properties of each test specimen to identify logical groupings of results for assigning modulus reduction and damping parameters for site response analyses. As a result of this evaluation, the UTEXAS test results were partitioned onto two different graphs: one set of graphs for loess, and the other set of graphs for Upland Complex alluvium and old alluvium (Figures 2.5-87 to 2.5-90, and 2.5-91 to 2.5-94).

2.5.4.2 Site Groundwater Occurrence

Because water was continuously injected into the hole during drilling operations, elevation of the groundwater table could not be directly evaluated in the borings. However, borehole seismic velocity P-S surveys allowed estimation of the groundwater table location using prominent increases in compression wave velocity that are not matched by shear wave velocity increases. The P-S determined groundwater table ranged between 70 and 100 feet deep, and corresponded to elevations of between 55 and 63 feet. The groundwater table exhibits a southwestward flow towards the Mississippi River floodplain with a gradient on the order of a 1-foot drop over a 100 to 125 foot distance (gradients of between 0.008 and 0.009) (Section 2.4). The groundwater levels and gradient are shown on the cross sections in Figures 2.5-75 through 2.5-77. It is possible that shallow perched water could form in parts of the loess during periods of high rainfall, especially over finer-grained zones. Such perched zones likely would dissipate rapidly after cessation of heavy rainfall.

2.5.4.3 Response of Soil to Dynamic Loading

Based on results from the geotechnical site investigation, the geologic materials underlying the proposed site location are not prone to dynamically-induced failure or excessive strength loss or deformation. The susceptibility of the deposits to liquefaction is low, as specifically addressed in Section 2.5.4.4. The preliminary assessment of bearing capacity and settlement are discussed in Section 2.5.4.5.2. The dynamic shear modulus reduction and damping of site soils are discussed in Section 2.5.4.1.4.

2.5.4.4 Liquefaction Potential and Seismic Site Stability

Geologic deposits underlying the proposed site location range in age from Miocene (Catahoula Formation), late Pliocene to Pleistocene (Upland Complex old alluvium and alluvium), and late Pleistocene (loess). These deposits all appear to be overconsolidated, and have acquired a certain level of liquefaction resistance by aging effects. No unconsolidated Holocene, sandy or silty deposits that are susceptible to liquefaction were identified at the site location, or are expected to occur based on extensive existing subsurface data. Obermeier et al. (Reference 126) report that the vast majority of identified liquefaction occurrences during the New Madrid earthquakes in 1811-1812 were within Holocene floodplain sediments. No Holocene floodplain deposits underlie the proposed site, and no reported paleoliquefaction features have been found at the GGNS or within the Site Vicinity.

Although the grain size and density of loess are within the range of potentially liquefiable deposits (Figure 2.5-83), it is Pleistocene in age, cemented, and above the groundwater table at the proposed site. Additionally, future plant structures would be founded below the loess. The Upland Complex alluvium and old alluvium are saturated and contain silt and sand-size material within the grain size and sorting range of potentially liquefiable deposits (Figure 2.5-83). However, both the alluvium and old alluvium are overconsolidated, and are Pliocene to Pleistocene in age. The age and past loading history of these deposits makes them resistant to liquefaction. SPT blow counts (Table 2.5-22; Figures 2.5-75 through 2.5-77) also show that the alluvium is in a medium dense to dense condition, and the old alluvium is in a dense to very dense condition. The density of the Upland Complex alluvial deposits make them very resistant to liquefaction. The Catahoula Formation claystone is Miocene in age, and partially lithified, and is not susceptible to liquefaction.

The influence of aging reduces liquefaction susceptibility in the Upland Complex alluvium and old alluvium. This process is reflected by the modulus reduction and damping characteristics described in 2.5.4.1.4 that show that these materials are significantly overconsolidated.

2.5.4.5 Static Site Stability

The proposed site location is on a bluff overlooking the Mississippi River that has been stable since at least late Pleistocene time when the loess deposits were laid down over the Upland Complex alluvium. It is not anticipated that the plant construction would significantly affect the site's static stability. Long term monitoring of the bluff for the existing GGNS indicates that there has been no appreciable instability during the monitoring period.

2.5.4.5.1 Bearing Capacity and Settlement

Detailed calculations of bearing capacity and settlement will be made during the COL phase of the project. Based on the known site conditions, the bearing capacity and settlement properties of the Upland Complex alluvium are expected to be suitable for a new nuclear power plant, and are not anticipated to provide any obstacles to construction. As noted in Section 2.5.4.3, it is anticipated that any new facility will maintain the existing plant grade of approximately elevation 132 feet, but that the plant will be founded in the Upland Complex alluvium, at or below the bottom of the loess deposits, at approximately elevation 80 feet, or lower, where the average shear wave velocity exceeds 1000 feet per second, or if the bottom of the plant is located above this elevation, that the natural soils would be excavated to this elevation and replaced with engineered fill that has a minimum shear wave velocity of 1000 feet per second. Consolidation tests will be performed on relatively undisturbed samples, particularly of the more clayey materials, to more precisely define the material overconsolidation ratios for quantitative settlement analyses. Any localized clayey layers present in the upper portion of the Upland Complex alluvium will be excavated and replaced with engineered fill as necessary.

2.5.4.5.2 Foundation Rebound

Excavation though the loess deposits into the Upland Complex alluvium will result in the removal of a minimum of about 7 kips per square foot (ksf) overburden. Up to several inches of predominantly elastic rebound may occur as a result of the excavation. This is insufficient to threaten stability of the excavation. Construction of the plant structure and backfilling of the excavation will cause reversal of much of the rebound. Construction of the existing plant required removal of approximately 11 ksf of overburden to reach the bearing stratum identified in the UFSAR as the Catahoula Formation. The rebound was estimated to be about 4 inches and was observed to be approximately 2 inches.

2.5.4.5.3 Lateral Earth Pressures and Hydrostatic Loading

Design of the structure will take account of the fact that short-term lateral earth pressures will be increased by heavy compaction of the backfill. Should the plant be embedded below the water table, hydrostatic and dynamic loadings will be evaluated during the COL phase using currently accepted standards of practice.

2.5.4.6 Design Criteria

Design criteria for plant foundations and excavations will be developed during the COL phase of the project, and will be based on additional subsurface exploration, laboratory testing, and geotechnical analysis. Bearing capacity analysis will be performed during the COL project phase. Refer to Section 2.5.4.5.1 for a general discussion of bearing capacity.

2.5.5 Stability of Slopes

The site is relatively flat, and not subject to large-scale landsliding or slope failures (Figure 2.5-70). The location of the proposed new facility encompasses two flat graded surfaces that are separated by an approximately 22-foot high, 3:1 (20 degrees) cutslope in loess soils. The cutslope is inclined at an angle less than laboratory-determined internal friction angle of the loess (32 to 34 degrees), and is stable without evidence of instability since it was constructed in the early 1970's. Although the entire proposed location of the new facility lies within the graded flat areas and cut slope, the area is bounded on the west by the 65-foot high erosional escarpment (bluff) that descends to the Mississippi River floodplain. Portions of the bluff are subject to surficial slumps and creeping soils that are confined within the loess soils in the face of the bluff slope. A possible slump scar on the bluff extends approximately 100 feet into the southwest corner of the site (Figure 2.5-70). No evidence of active or incipient slope movements, such as ground cracks or distressed facilities, were observed above or around the possible slump scar. Because the surficial slumping and erosion in the bluff slope are restricted to the loess soils, future instability in the bluff slope should not affect the planned facilities. It is likely that the future plant footprint will be sited at least 100 feet from the top of this possible slump feature, and the plant foundations would extend through the loess soils into underlying Upland Complex alluvium or old alluvium well below the elevation of the possible slide planes or toe of the bluff slope.

Specific stability analyses will be performed during the COL phase to evaluate the stability of deep foundation excavations for future facilities at the proposed site. However, no unstable conditions or materials were found underlying the site that should cause unusual stability problems for excavations, and standard shoring techniques were successfully used to stabilize deep foundations through the loess and alluvial soils at the operating GGNS site. Because foundation levels for the proposed new facility likely will be over 80-feet below grade in the area near the river bluff to reach suitable foundation materials, and the height of nearby slopes are less than about 60 feet, it is unlikely that any future slope failures would undermine or encroach within the foundation zone of the facility. Engineering solutions can be developed for any potential slope instability at the proposed site location and the hazard due to slope instability at the proposed new facility location is considered to be low. Potential hazards due to encroachment of slope failures will be evaluated during the COL phase of the project. It is not anticipated that there will be any permanent excavated slopes that might adversely affect the stability of the plant. Design of excavated slopes and /or tieback walls or other forms of temporary construction support are not anticipated to pose any obstacles to construction. Specific stability analyses will be performed during the COL phase to evaluate the stability of deep foundation excavations for future facilities at the proposed site. However, no unstable conditions or materials were found underlying the proposed site that could cause unusual stability problems for excavations, and standard shoring techniques were successfully used to stabilize deep foundations through the loess and Upland Complex alluvial soils at the operating GGNS site.

2.5.6 Embankments and Dams

Within the Site Location, there are no earth, rock, or earth and rock fill embankments used for plant flood protection or for impounding cooling water that could affect the safety of the proposed new facility. Furthermore, there are no impoundment structures within the Site Area that could pose a hazard to the proposed new facility. Therefore, the hazard due to embankment failure and surface water inundation of the proposed location of the new facility at the Grand Gulf Nuclear Station is negligible.

2.5.7 References

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3.0 SITE SAFETY ASSESSMENT

As required by 10 CFR 52.17(a)(1), an application for an early site permit (ESP) must contain a description and safety assessment of the site on which a new facility would be located. The assessment must contain an analysis and evaluation of the major structures, systems, and components of the facility that bear significantly on the acceptability of the site under the radiological consequence evaluation factors identified in 10 CFR 50.34(a)(1). That site characteristics comply with 10 CFR 100 must also be demonstrated.

Preceding sections provide detailed descriptions, assessments, and analyses of the proposed ESP Site (i.e., the Grand Gulf Nuclear Station (GGNS) site), and the ESP Facility as defined in Chapters 1.0 and 2.0 of this report.

This section provides an assessment of conformance with 10 CFR 100 requirements, including applicable parts of 100.10, 100.11, 100.20, 100.21 and 100.23, with respect to evaluation of the ESP Site for an Early Site Permit under Part 52. Specifically, this section demonstrates that radiological doses from normal operation and postulated accidents will be acceptably low, that natural phenomena and potential man-made hazards important to the design of the plant have been identified, that adequate security measures to protect the plant can be developed, and that there are no physical characteristics unique to the proposed site that could pose a significant impediment to the development of emergency plans for the ESP Facility.

3.1 Non-Seismic Siting Criteria

3.1.1 Exclusion Area and Low Population Zone

The ESP Site exclusion area authority and control thereof is described in Section 2.1.2. The ESP Site exclusion area boundary (EAB) includes an area encompassed by a circle of about 841 meters radius. The boundary line for the proposed EAB is shown in Figure 2.2-1. The ESP Site exclusion area meets the definition for an exclusion area provided in 10 CFR 100.3.

The ESP Site low population zone (LPZ) is described in Section 2.1.3.4. The ESP Site LPZ includes an area encompassed by a circle of approximately 2-mile radius (3219-m). The approximate LPZ is shown in Figure 2.1-3. The ESP Site LPZ meets the definition for an LPZ provided in 10 CFR 100.3.

3.1.2 Population Center Distance

The ESP Site population center distance is described in Section 2.1.3.5. The closest population center for the ESP Site is Vicksburg, Mississippi, located approximately 25 miles north-northeast of the site, with a 2000 population of 26,407. The ESP Site nearest population center is in accordance with the definition of a population center (more than a population of about 25,000 residents) provided in 10 CFR 100.3. In addition, it satisfies the criteria provided in 10 CFR 100.21(b) as being at least one-and-one-third times the distance from the proposed reactor location to the outer boundary of the low population zone or, in this case, approximately 2.7 mi.

3.1.3 Site Atmospheric Dispersion Characteristics and Dispersion Parameters

The site atmospheric dispersion characteristics and dispersion parameters for the ESP Site are described in Section 2.3.4 for the short term diffusion estimates used in assessing the site suitability (radiological consequences) associated with postulated accidents and Section 2.3.5 for the long term diffusion estimates used in evaluating the normal radiological effluent release limits.

The potential consequences and acceptance criteria for the postulated accidents used in the evaluation of the ESP Site are provided in Section 3.3. As demonstrated therein, the dose limits at the EAB and LPZ meet the requirements of 10 CFR 50.34(a)(1)(ii)(D)(1) and 10 CFR 50.34(a)(1)(ii)(D)(2), respectively.

The potential consequences and acceptance criteria for the normal operations gaseous radiological effluent release limits are provided in Section 3.2, where it is shown that the applicable regulatory limits, provided in 10 CFR 20 and 10 CFR 50, Appendix I, are satisfied for the ESP Site.

3.1.4 Physical Site Characteristics – Meteorology, Geology, Seismology, and Hydrology

3.1.4.1 Meteorology

The meteorological characteristics of the ESP Site are described in detail in Sections 2.3.1 and 2.3.2. Regional, local and site data were used to establish average and extreme meteorological parameters for the site.

Section 2.3.1 describes the regional meteorological characteristics of the general site based on long-term historical observations from National Weather Service Stations located in Jackson, Mississippi, and in Vicksburg, Mississippi, both of which are within 55 mile of the ESP Site. Recent data from these weather stations and from the National Oceanographic and Atmosphere Administration (NOAA) National Climatic Data Center (NCDC) data systems are provided as appropriate. Regional historical information for the site area includes data for temperature, relative humidity, wind, and precipitation (rain and snowfall). Severe weather information for the area is also summarized in this section for hurricanes (frequency of occurrence and wind speeds), thunderstorms (frequency of occurrence), hail (frequency and distribution in the region), and lightning (predicted stroke density), all of which have been characterized for consideration in the design of site structures, systems and components as required. Tornadoes (predicted frequency and intensity) and severe winds (maximum speed) were characterized to provide the site parameters to be considered in association with these events (including maximum linear and rotational wind speeds, pressure drop, and rate of pressure drop). Heavy snow (frequency and intensity), and freezing rain / ice (frequency and intensity) were characterized to provide worst-case accumulations of snow and ice to be accounted for in the design of site structures.

Section 2.3.2 describes the local and site-specific meteorological characteristics of the ESP Site as obtained from the Vicksburg weather station, and from an on-site meteorological monitoring system operated continuously by Entergy since 1972. A detailed description of the on-site monitoring system is provided in Section 2.3.3. Data from the on-site monitoring system was used to establish normal and extreme values of wind speed and direction, temperature, atmospheric moisture (wet bulb temperature, relative humidity, and dew point temperature), precipitation, and atmospheric stability. Site-specific meteorological data were also used to supplement the regional and local data, as well as to facilitate the development of site-specific atmospheric dispersion characteristics and dispersion parameters for routine and accidental gaseous releases from the ESP Facility, as described in Sections 2.3.4 and 2.3.5.

The information contained in Sections 2.3.1 and 2.3.2, on regional and local meteorology were evaluated to provide representative average and extreme meteorological information characteristic of the ESP Site.

3.1.4.2 Geology

The geological, seismological and geophysical characteristics of the proposed location of the new facility at the existing GGNS are described in Section 2.5. The geology of the Site Region (200-mile-radius) and Site Vicinity (25-mile-radius) is described in Section 2.5.1.1. The geology of the Site Area (5-mile radius) and Site Location (0.6-mile radius) is described in Section 2.5.1.2. Descriptions of the geological characteristics of the ESP Site are based on a compilation, review and analysis of existing data, as well as the results of a geological and geotechnical site investigation and laboratory testing program. The evaluation of the site geology included a review of results of geotechnical explorations and laboratory analyses completed as part of the original site evaluations documented in the PSAR for GGNS Units 1 and 2. The previous subsurface exploration program included 275 borings drilled to a maximum depth of 447 feet. The field investigation completed during this ESP investigation is described in Section 2.5.4 and included:

- Drilling and sampling of four borings to depths between 141.5 and 238.0 feet;
- Four Cone Penetrometer (CPT) soundings to depths of between 75 and 98 feet; and,
- Three down-hole shear-wave velocity surveys.

The ESP Site is underlain by a sequence of Quaternary eolian and alluvial deposits overlying Miocene Catahoula Formation bedrock. Four units were differentiated at the site, including: (1) an upper layer of late Pleistocene silt and clayey silt ("loess") ranging from 55- to 70-feet thick; (2) an intermediate layer of stiff to very stiff Pleistocene alluvium ranging from 50- to 100-feet thick; (3) a deeper layer of very stiff to hard older alluvium ranging from 40- to 90-feet thick; and (4) Catahoula formation bedrock.

The results of the data review and site investigations indicate that the geological and geotechnical conditions of the ESP Site are consistent with the information presented in the GGNS UFSAR. The ESP Site soil profile is relatively consistent across the footprint of the existing GGNS Unit 1 facility and the location of the power block for the proposed new facility.

Section 2.5.3 discusses the potential for surface fault rupture in the Site Area. The ESP Site is located within the tectonically quiescent Gulf Coastal Plain province and is underlain by unfaulted deposits of at least Oligocene age. No faults are mapped within the 5-mile radius of the ESP Site. The closest mapped faults in the Study Region occur in southeastern Arkansas, located approximately 90 miles north-northwest from the ESP Site. Deformation associated with salt migration has occurred in the Site Region. However, no salt domes occur within either the 5-mile radius or 0.6-mile radius of the ESP Site.

Results of the geological and geotechnical investigations conclude that the physical characteristics of the site pose no undue risk to the siting of a new facility at the proposed location. No geological hazards from surface fault rupture (Section 2.5.3), slope instability, or ground subsidence from sinkholes or mine collapse were identified either during the original PSAR site evaluations for GGNS Units 1 and 2 or during this ESP Site investigation (Section 2.5.5). Due to the position of the site on topographically high ground, and lack of surface water impoundments, there is no risk to the site from flooding or inundation (Section 2.5.6). There have been no reports of unusual or unacceptable behavior of the existing GGNS facility relative to geologic or geotechnical conditions during its nearly 20 years of operation. Subsurface materials exist beneath the ESP Site that are suitable bearing layers for the foundation of a new facility at the proposed location.

3.1.4.3 Seismology

Section 2.5.1 describes the seismotectonic environment of the Site Region and Section 2.5.2 describes the data and methodology used to develop the Safe Shutdown Earthquake (SSE) ground motion for the proposed location of a new facility at the existing GGNS site.

The Site Region is characterized by extremely low rates of earthquake activity. Only 39 earthquakes of magnitude greater than m_b 3.3 have been recorded within the entire Site Region. No earthquakes of magnitude greater than m_b 3.3 have been recorded within approximately 90-miles of the ESP Site.

Because the ESP Site is underlain by soils, investigations were completed to establish the soil profile, e.g., seismic wave transmission effects, for the site-specific site-response analysis and development of the SSE. In addition to the four borings and four CPT probes, the site investigation included:

- Borehole P-S seismic velocity surveys in three of the exploratory borings;
- Laboratory engineering index testing of sixty ESP borehole samples; and,
- Dynamic resonant column testing of six boring samples.

The average shear wave velocity for the ESP site ground motion site-response analysis was developed by normalizing the three borehole surveys to a common elevation, and then averaging the receiver-to-receiver shear wave velocities. The resulting averaged velocity plot (Section 2.5.4) was visually examined to identify discrete interval velocities that correspond, in part, to the geologic unit layers, and that have relatively distinct average velocity increases or breaks. Four interval velocities were differentiated from the P-S velocity survey profile:

- Loess – 770 fps;
- Upland Complex Alluvium and Loess-Alluvium Interface – 1,004 fps;
- Upland Complex Old Alluvium – 1,378 fps; and,
- Catahoula Formation – 2,118 fps.

The average velocities are within typical ranges for similar materials reported in published literature (e.g., Hunt, 1984).

The P-S datalogger used for the ESP study represents a marked improvement and advancement of technique over the cross-hole seismic velocity techniques and equipment that were used for the initial site evaluation for GGNS in the 1970s. Therefore, a direct comparison cannot be made between the two data sets. However, the velocities for the various geologic layers generally fall within similar ranges, if the GGNS data for the upper Catahoula Formation are compared against the velocity data for the Upland Complex Old Alluvium. A comparison between the shear wave velocities is shown below.

MATERIAL	ESP Vs (fps)	UFSAR Vs (fps)
Loess	590 to 1,450	670
Upland Complex Alluvium	740 to 1,750	1,100 to 1,600
Upland Complex Old Alluvium	530 to 3,360	1,640 to 1,720
Catahoula Formation	1,500 to 2,830	1,640 to 1,720

3.1.4.4 Hydrology

The hydrologic conditions of the ESP Site and vicinity are described in detail in Section 2.4. The descriptions include hydrologic features and characteristics that should be accounted for in the design of the ESP Facility. These hydrologic engineering characteristics include floods, ice effects, cooling water supply, low-water considerations, accidental releases in surface water, and ground water.

Section 2.4.2 presents information on the flooding history, flood design considerations, and the effects of local intense precipitation. The probable maximum precipitation event was determined to control facility flood design. Therefore, safety-related structures of the ESP Facility will need to be above the flood elevation or be designed to withstand the effects of flooding. The effects of and development of the probable maximum precipitation are presented in Section 2.4.2.3 and 2.4.3.1.

Section 2.4.3 describes the probable maximum flood characteristics for local streams and for the Mississippi River, and Section 2.4.10 discusses the flooding protection requirements. As described in Section 2.4.3, the maximum flood elevation of the river is about 103 ft msl, based on the height of the flood control levees on the west side of the river. Floods in the river would not affect the ESP Facility, the location of which is proposed at a similar grade elevation as that of the existing GGNS Unit 1 facility, on the bluffs east of the river.

Section 2.4.7 describes the effects of ice formation in the river at the location of the ESP Site, and the probable maximum winter flood on the river level. In Section 2.4.8 of the NRC Safety Evaluation Report (NUREG-0831) for GGNS Unit 1, the NRC concluded that the occurrence of a major ice jam on the Mississippi River is very unlikely, and concurred that ice flooding was not a design basis consideration for the GGNS site. Therefore, ice flooding is similarly not a design basis consideration for the ESP site.

Section 2.4.11 describes low river water considerations for the site, including the evaluation of plant requirements and ultimate heat sink (UHS) dependability requirements. The ultimate heat sink for the ESP Facility would be provided from closed-loop cooling systems utilizing basin type reservoirs, and would not rely on the river intake for cooling capability. Therefore, the UHS would be unaffected by a low river stage.

Section 2.4.13 describes the potential effects on ground water from accidental radiological releases. The evaluation for GGNS Unit 1 in their UFSAR indicated that strontium and cesium isotopic concentrations for a design basis accidental spill would be below the maximum permissible concentration at a distance of 57 feet from the location of the spill. An estimated ground water travel time to the Mississippi River was determined as about 12.5 years. Since the proposed location of the ESP Facility, like the GGNS Unit 1 facility, is approximately 3,200 feet from the Mississippi River, the isotopic concentrations from a similar spill into the ground water should be well below the maximum permissible concentration before they reach the Mississippi River. Therefore, the potential for effluents to reach a surface water body and surface water users is minimal.

Section 2.4.12 describes the regional and local aquifers, their formation, sources and sinks. Section 2.4.12.1 describes plant requirements from the ground water system and describes ground water quality. Section 2.4.12.2 describes the site hydrogeologic systems including the aquifers present and their characteristics (depth, permeability, potentiometric levels and velocity), and present and projected future ground water users. The design basis for subsurface hydrostatic loading is presented in Section 2.4.12.4.

The information contained in Section 2.4 on surface water and ground water conditions was evaluated and was determined to be adequate in support of the ESP Facility. These data would be used as appropriate in the design of the ESP Facility to ensure that no hydrology related site parameters would pose an undue risk to the operation of the ESP Facility.

3.1.5 Potential Off-site Hazards

The potential offsite hazards for the ESP Facility are described in Section 2.2. The description includes nearby industrial, transportation and military facilities.

Sections 2.2.1 and 2.2.2.5 addresses area airports and associated air transportation routes, as they may affect the ESP Facility. No commercial airport facilities are located within 10 miles of the GGNS site. The nearest commercial airport is located in Jackson, MS, approximately 65 miles northeast of the site. There are 5 general/public aviation airports located within the vicinity of the site. These general/public aviation airports are used only for small planes.

As noted in Section 2.2.3, highway accidents are not a concern for the ESP Site. The ESP Site area is accessible by U. S. Highway 61 and State Highway 18 which connect Port Gibson (5 miles southeast of the site) with Natchez, Jackson, and Vicksburg. U. S. Highway 61 passes approximately 4.5 miles east-southeast of the GGNS site at its closest point. The distance beyond which an exploding truck will not have an adverse effect on plant operations, nor prevent safe shutdown, is calculated to be 1,658 feet (0.31 miles). Since the closest point of U. S. Highway 61 to the ESP Site is about 4.5 miles, there is no hazard to the plant due to an accident on U.S. Highway 61.

There are currently no active rail lines in the vicinity of the ESP Site. Therefore, potential accidents involving railway traffic are not evaluated.

The nearest bank of the river is approximately 1.1 miles from the proposed location for the ESP Facility on the GGNS ESP Site. In addition, a new facility would be located on the bluffs to the east of the river, which are approximately 65 feet above the normal river level. As noted above for the GGNS Unit 1 plant, this bluff would provide an earthen shield against possible explosions originating from river barge traffic. Based on the combination of distance from the river bank and the intervening bluff, this would preclude any damage to the structures of the ESP Facility at the proposed location, resulting from an explosion originating from a ship or barge on the river.

Section 2.2.3.1 discusses explosions due to pipelines and nearby industrial facilities. Evaluation of the existing pipelines, their proximity to the site and the materials passing through them resulted in the determination that they do not represent a design concern for facilities at the ESP Site. There are no existing industrial facilities potentially representing an explosive source which would constitute a design consideration for the ESP Site.

Section 2.2.3.1 discusses explosions due to onsite hydrogen storage, and due to liquid-hydrogen delivery truck accidents/explosions. Liquefied hydrogen is delivered to the GGNS site by United States Department of Transportation (USDOT) approved truck, with a maximum capacity of 17,000 gallons. There are no regulations specifying a minimum distance between a liquid-hydrogen delivery truck and a safety-related structure. The current truck route on the GGNS (ESP) Site results in about 400 ft separation from the outer boundary of the proposed location for the power block of the ESP Facility, which is less than the minimum separation distance of 1285 ft calculated per Regulatory Guide 1.91 (Reference 1). However, the probability of an accident resulting in a hydrogen explosion calculated per the Regulatory Guide 1.91 methodology is 4.1×10^{-7} per year. Therefore, according to the guidelines presented in Regulatory Guide 1.91 (criteria is less than 10^{-6} per year), a liquid-hydrogen truck explosion event need not be considered a design basis accident for the ESP Facility on the site.

The presence of the 20,000 gallon liquid-hydrogen storage tank located in the north end of the abandoned GGNS Unit 2 cooling tower basin (Figure 2.2-4) presents a potential hazard of an explosion. An analysis was performed to determine the safe separation distance between the liquid-hydrogen storage tank and any GGNS Unit 1 safety-related structure. These calculations are valid for the ESP Facility at the GGNS ESP Site, so long as the minimum separation distances stated in the report are maintained, or structures are appropriately designed for the expected blast pressure. The proposed area for construction of the ESP Facility is beyond the minimum separation distance requirements given in the calculation for both blast considerations and gaseous cloud considerations.

Toxic chemicals are discussed in Section 2.2.3.1.2. The closest point of U.S. Highway 61 to the GGNS site is 4.5 miles. Therefore, an accidental release of toxic chemicals transported on U. S. Highway 61 would not endanger the safe operation of the ESP Facility at its proposed location on the ESP Site. In the year 2000, the majority of the hazardous materials transported near the GGNS site were fuel products moving on the Mississippi River. The 6-year onsite wind frequency distribution data (1996-2001) reported in Section 2.3 shows that the winds that originated from compass sectors W-SW, W, W-NW and NW, that would carry the hot plume from a fire caused by explosion to the proposed location for a new facility, had speeds generally under 20 mph. An analyses presented in the GGNS Unit 1 UFSAR concluded that a wind speed greater than 70 mph would be required to direct a plume toward GGNS Unit 1. The proposed location for the ESP Facility is on the bluffs above the river and about 1.1 miles inland. Since the proposed location for the ESP Facility is very near to that of the existing GGNS Unit 1, no toxic hazard to the ESP Facility would be expected.

There are no military installations, chemical or munitions plants, stone quarries, or major gasoline-storage areas located within 5 miles of the ESP site. Therefore, they do not need to be considered as a hazard for the ESP Facility on the ESP Site.

Section 2.2.3.1.3 discusses the possible offsite fire hazards to an ESP Facility on the GGNS ESP Site. It was concluded that offsite fires do not pose a design basis threat to a new facility on the site.

A collision (by river traffic) with the proposed cooling system intake is not considered likely and not a design basis event for the ESP Facility as discussed in Section 2.2.3.1.4.

Liquid spills on the Mississippi River do not pose a threat to safe shutdown of the ESP Facility, as the river intake is utilized only for non-safety related water supply. Any potential intrusion of hazardous chemicals or liquids into the proposed embayment and makeup water system could be mitigated by orderly shutdown of the facility, if required.

3.1.6 Site Characteristics - Security Plans

The ESP Facility power block proposed location (approximate center of the power block area) is approximately 1200 ft west and 1000 ft north of the existing GGNS Unit 1 Facility. A site plot plan is provided in Figure 2.1-1.

3.1.6.1 Land Sufficient To Implement The Criteria Of 10 CFR 73.55

Based upon the general location at the GGNS site on which the nuclear unit or units would be located; e.g., in the general vicinity of the GGNS Unit 1, there is sufficient land and distance to the site boundary and appropriate topography to implement the criteria of 10 CFR 73.55 relating to the development of a security plan. This conclusion is based in part on the fact that GGNS Unit 1 has implemented a security plan meeting the requirements of 10 CFR 73.55 and the interim compensatory measures required by the NRC's Order of February 25, 2002. While GGNS Unit 1 is still in the process of implementing the requirements of the revised design basis threat (DBT) Order of April 25, 2003, preliminary evaluations would indicate that neither the amount of land, the particular location of the GGNS site in relation to the topography and site boundaries or the distances to the site boundary or other natural features, would preclude compliance with the revised DBT.

It should be noted that existing commercial nuclear power plants, such as GGNS Unit 1, were designed to meet evolving 10 CFR 73.55 requirements, including effective changes in the DBT and revised DBT, on an "add-on" basis after completion of the initial physical design. Even given these circumstances, plants such as GGNS Unit 1 are capable of meeting the evolving NRC security requirements. For a plant which would be built in the future, security considerations (e.g., barriers, access, fences) would be incorporated as initial design requirements and inputs and integrated into the overall design as an important element, making it reasonable to conclude that such a facility will be able to meet NRC security requirements.

Given the opportunity to design security into a new facility, the distance specified in Regulatory Guide 4.7 would be sufficient to satisfy the criteria of 10 CFR 73.55 although a larger distance could be used at the GGNS ESP site, and even a smaller distance could be accommodated.

3.1.6.2 Site Characteristics That May Require Mitigation

No site characteristics that require significant mitigation in order to control close approaches to the proposed location of a new facility have been identified. As indicated Figure 2.1-1, the nearest public road is about 3000 feet from the general area of the proposed power block building site. The Mississippi river is approximately 1 mile from the proposed power block building site. Safety-related structures necessary for the ultimate heat sink would not be located on an accessible, navigable waterway.

3.1.6.3 Identification of Potential Hazards in the Site Vicinity

Initially, given the successful implementation of a security plan by Entergy Operations for GGNS Unit 1, there are no potential hazards in the site vicinity which would preclude the development of a security plan for the new unit or units. The new reactor or reactors will be sited at some distance from the existing GGNS Unit 1, and provisions will be made such that construction activities at a new facility will not adversely affect the ability of GGNS Unit 1 or any new operating unit to meet NRC security requirements. Similarly, the design of the security plan and defensive strategy will be such that during operation or other activities on site, the security plans of the units on site positively reinforce each other, or will be independent with regard to their individual ability to meet NRC security requirements and the design basis threat, as revised.

3.1.6.4 Law Enforcement Agencies

Given the location of a new facility in relationship to GGNS Unit 1 which has, as part of its security plan, made provisions with relevant local law enforcement agencies, there is high assurance that similar provisions can be made with regard to any new facility, in that the jurisdictions and local law enforcement agencies are the same as for GGNS Unit 1.

In summary, given the proposed location of a new facility near GGNS Unit 1, and the ability to assure compliance with NRC provisions through design, there is a high assurance that NRC security requirements can be met for a new facility.

3.1.7 Site Characteristics - Emergency Plans

Information regarding emergency planning capability is provided in the ESP Application, Emergency Planning Information, Part 4. The GGNS Unit 1 evacuation time estimate (ETE) performed in 1986 was re-evaluated in support of this application. This re-evaluation included an assessment of updated population levels and distributions and transportation networks. As part of the effort, each major roadway was driven and traffic count data was obtained, as appropriate. Improvement in several key roadways was noted, and updated roadway capacities were estimated to support this evaluation. Local Mississippi and Louisiana emergency management agency officials, as well as state department of transportation representatives, were consulted and provided their concurrence regarding the findings. Based on this re-evacuation of the ETE, it was determined that there are no physical characteristics unique to the GGNS site that could pose a significant impediment to the development of the required emergency plans for the ESP Facility.

3.1.8 Population Density

As described in Section 2.1.1 and Section 2.1.3.6, the ESP Site is located in a mostly rural, low population density, area. The most densely populated area within 30 miles of the site is to the north-northeast with an average projected population density of about 238 people per square mile in the year 2030. This population density is projected to increase to only about 268 persons per square mile in the year 2070. The current and projected population density in this area is well below the NUREG-0800 guidance of 500 people per mi^2.

3.1.9 References

1. U.S. Nuclear Regulatory Commission (NRC), February 1978, Evaluations of Explosions Postulated To Occur on Transportation Routes Near Nuclear Power Plants, Regulatory Guide 1.91, Revision 1, Washington, DC.

3.4 Geologic and Seismic Siting Factors

3.4.1 Geologic and Seismic Engineering Characteristics

The geological, seismological, and geotechnical characteristics of the EPS Site and its surroundings have been investigated to evaluate the suitability of the site with respect to geological hazards, to assess whether general foundation conditions are appropriate for placement of a new facility, and to provide the necessary information for developing the SSE ground motions. As discussed in Section 2.5 and Sections 3.1.4.2 and 3.1.4.3, there are no geological hazards that would adversely affect the ESP Site, and suitable foundations materials are present to support a new facility at the proposed location. The geological and geotechnical conditions of the ESP Site are suitable for the development of a new facility. As discussed below and in Section 2.5.2, the SSE ground motions for the ESP Site are lower than the Regulatory Guide 1.60 spectrum anchored to a peak free-field ground motion of 0.3g. Therefore, the ESP Site is also suitable with respect to earthquake ground motions.

Regulatory Guide 1.165 "Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion" recommends that the SSE ground motion be developed using either the Electric Power Research Institute (EPRI) Seismicity Owners Group (SOG) project or Lawrence Livermore National Laboratory (LLNL) Probabilistic Seismic Hazard Analyses (PSHA) methodologies (EPRI, 1986; LLNL, 1993), updated through a comprehensive review of the geology, seismology and geophysics of the Site Region. If review of existing data shows a significant change to either the seismic source model or ground motion model (i.e., attenuation relationships), then Regulatory Guide 1.165 recommends that an updated PSHA be performed to develop the SSE ground motion.

For the GGNS ESP Site evaluation, the EPRI SOG methodology was adopted to develop the SSE ground motion. Following review of the data and information developed since publication of the EPRI SOG results in 1986, significant new information regarding seismic sources and earthquake ground motion attenuation in the Site Region was identified. To address new information and approaches for ground motion attenuation modeling, EPRI (2003) developed a new ground motion attenuation model for the central and eastern United States, including the Gulf Coast region. These new relationships were used in the PSHA and are described in Section 2.5.2.3. The seismic source model used to develop the SSE ground motions for the ESP Site was developed following review of data related to active tectonic features in the Site Region (Section 2.5.1).

With two exceptions, the review and analysis shows that all tectonic features in the GGNS Site Region, and the Reelfoot Rift Complex extending north of the Site Region, are adequately characterized by the EPRI SOG seismic source model. The two exceptions are (1) identification of the Saline River source zone as a new source zone, within the Site Region, and (2) revisions in source parameters to the New Madrid Seismic Zone (NMSZ), which lies within the Reelfoot Rift Complex outside of the Site Region. Revisions to the NMSZ include changes in source geometry, maximum magnitude and earthquake recurrence since publication of the 1986 EPRI SOG source model.

Based on the new information on seismic sources and new approaches for ground motion attenuation modeling that have been published since the 1986 EPRI SOG study, the EPRI PSHA methodology has been updated for use in this ESP Application. The EPRI PSHA was updated by revising the seismic source model, adding the ground motion attenuation model developed by EPRI (2003), and updating the PSHA computational code that was published by EPRI in 1986 (EPRI, 2004).

Regulatory Guide 1.165 recommends that a PSHA be performed to define the median rock ground motion at the site that has an annual probability of exceedance of not greater than 10^{-5}, and for soil sites, that a site-response analysis be performed to develop the SSE ground motion. The PSHA used to develop the 10^{-5} median rock ground motions is described in Section 2.5.2.2. Because the ESP Site is underlain by soils rather than rock, a site-specific site-response analysis was conducted following the guidelines described in NUREG/CR-6728 (McGuire et al., 2001). The site-specific site-response analysis is described in Section 2.5.2.3 and the data used to develop the soil profile for the site response analysis are presented in Section 2.5.4.

The results of the updated EPRI PSHA were used to obtain the bedrock ground motions for the ESP Site. The results of the PSHA were deaggregated to identify the controlling earthquakes and used to develop a response spectrum for bedrock conditions, scaled at 1 hertz and 10 hertz, that is compatible with the controlling earthquakes. The resulting response spectrum for rock conditions was used in the site response analysis to obtain the SSE response spectrum for free-field conditions at the ground surface. The SSE ground motions for the ESP Site are lower than and are compatible with the Regulatory Guide 1.60 spectrum at all spectral frequencies.

The ESP Site is considered a suitable location for a new facility. The site has negligible risk from surface fault rupture hazards, slope instability, liquefaction-related ground failure, collapse or inundation. The geological and geotechnical conditions are similar to those of the existing GGNS site (of which the ESP Site is a part), which has performed well over the past 20 years. The SSE ground motions for the ESP Site were developed in accordance with the U.S. NRC Regulatory Guide 1.165 methodology, taking into account the most up-to-date information on the locations and characteristics of potential earthquake sources and site-specific seismic wave transmission effects. The SSE ground motions for the Grand Gulf ESP Site are consistent with the U.S. NRC's recommended design spectrum for new nuclear power plants.

3.4.2 References

1. U.S. Nuclear Regulatory Commission (NRC), Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion, Regulatory Guide 1.165, March 1977, Washington, DC.
2. U.S. Atomic Energy Commissioin (USAEC), Design Response Spectra for Seismic Design of Nuclear Power Plants, Regulatory Guide 1.160, Revision 1, December 1973, Washington, DC.
3. Electric Power Research Institute (EPRI), Guidelines for Determining Design Basis Ground Motions – Volume 1: Method and Guidelines for Estimating Earthquake Ground Motion in Eastern North America, EPRI Report TR-102293, 1993a.
4. Electric Power Research Institute (EPRI), Analysis of High-Frequency Seismic Effects, EPRI Report TR-102470, 1993b.
5. U. S. Nuclear Regulatory Commission, McGuire, R. K., W. J. Silva, and C. J. Costantino, NUREG/CR-6728, 2001, Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines, Washington, DC.