PRELIMINARY SCOPING REPORT OF PREVIOUS GEOLOGIC, PALEOSEISMIC, SEISMIC, AND GEODETIC STUDIES AT YUCCA MOUNTAIN, NEVADA:

Implications for Understanding Seismic Hazards at the Proposed High-Level Nuclear Waste Repository

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EXECUTIVE SUMMARY

Yucca Mountain is a potential repository for nuclear waste in Nye County, Nevada, about 130 km (80 miles) northwest of Las Vegas. It lies in the eastern part of the Walker Lane, which is a system of active faults currently accommodating ~25% of the relative motion between the Pacific and North American plates. Numerous earthquakes have ruptured the ground in the past thousands to tens of thousands of years and have broken the landscape into multiple fault blocks. From the late 1970's to mid-1990's, the history and extent of deformation related to active faulting was extensively studied. This preliminary report reviews the geologic setting of the region and previous studies of recent earthquakes, seismic monitoring, and GPS measurement of current tectonic deformation, with the aim of identifying major data gaps in the context of recent technological and scientific developments.

A review of previous studies of the earthquake prone areas within 100 km (62 miles) of Yucca Mountain shows that most faults have been characterized from geologic mapping, paleoseismic trenching, and geochronology. Fault rupture parameters were determined, providing essential input data for probabilistic seismic hazard assessments. Eight faults in the immediate vicinity of Yucca Mountain have clear evidence of recent activity. Limitations related to the geochronologic methods and quality of imagery available at the time of the studies resulted in large uncertainties in both the ages of faulted deposits and location of some fault traces. These uncertainties compromised past earthquake recurrence estimates and the siting of trenches, which in some cases yielded inconclusive results. We recommend acquisition of modern high-resolution topographic imagery (lidar) and improved geochronologic data to reduce the uncertainties in previous analyses. This will result in a more robust seismic source characterization.

Since the 1960s, various levels of seismic monitoring have been conducted in the area. The USGS installed the first regional seismic network in 1978. The Nevada Seismological Laboratory (NSL) at UNR assumed its operation in 1992. By 1995 digital seismographs formed the basis of seismic monitoring. A formal Probabilistic Seismic Hazard Analysis by the DOE in the mid-1990s was based mainly on analog-network-era seismicity catalogs. Earthquakes capable of producing notable ground motions were compiled and weighted statistically. The more recent digital network, including strong motion sensors, has provided a robust database with real-time processing. Most digital seismic stations were removed in 2008, but eight stations maintained by the DOE remain. NSL now operates a digital, continuous high performance real-time seismic network in the region, but it does not include stations at Yucca Mountain. There have been 67,958 recorded seismic events in the region since 2000 with six notable M3.8 to M5.7 earthquakes since 1992. We recommend deploying the latest seismic monitoring technologies, including high-bandwidth wireless networks that will improve prediction of ground motion and provide earthquake early warning.

To record current ongoing deformation, a geodetic network of GPS instruments was installed during the repository evaluation and has since been complemented by other networks. The existing network provides crustal velocities to a precision of ~0.1 mm/yr, but does not provide complete coverage, with large gaps east and north of Yucca Mountain. The GPS data show that ~25% of the relative motion between the Pacific and North American plates is accommodated across the Walker Lane. These data indicate an increase in strain rate toward the Sierra Nevada and more modest gradients of ~1 mm/yr near Yucca Mountain. These data indicate an even greater amount of seismic potential than that derived from paleoseismic studies. Most GPS stations in the area became inactive in ~2010. We recommend reviving and updating the GPS network, as well as integrating the geodetic data with geologic, paleoseismic, seismic, and other geophysical data into models of active tectonic deformation and earthquake occurrence.

Development of a master geodatabase in an ArcGIS platform for all datasets would facilitate data integration, synthesis, and innovative modeling (e.g., 3D modeling). We also recommend enhancing the subsurface 3D geologic framework through acquisition and integration of additional geophysical datasets.

INTRODUCTION

Yucca Mountain, as designated by the Nuclear Waste Policy Act amendments of 1987, is a potential geological repository for spent nuclear fuel and other high-level radioactive waste in the U.S. The site is situated on federal land adjacent to the Nevada National Security Site (NNSS; formerly Nevada Test Site) in Nye County, Nevada, about 130 km (80 miles) northwest of Las Vegas Valley. The site lies in an active tectonic setting within a segment of the Pacific – North American plate boundary (Figure 1A). As such, active faults and recent volcanic activity characterize the Yucca Mountain area, as evidenced by many large historic earthquakes in the region (Figure 1B).

From the late 1970's to mid-1990's, the history and extent of deformation related to active faulting in the Yucca Mountain region was extensively studied by the U.S. Department of Energy (DOE), U.S. Geological Survey (USGS), both the Nevada Bureau of Mines and Geology (NBMG) and Nevada Seismological Laboratory (NSL) at the University of Nevada, Reno (UNR), and other institutions to assist in the evaluation and site characterization of the area for the proposed high-level radioactive waste repository. These studies identified multiple faults with demonstrable recent activity, significant current seismicity in the region, and ongoing crustal motion related to the Pacific-North American plate boundary and San Andreas fault system. Although these studies applied the most advanced techniques and methodologies available at the time, the ages of faulted deposits, essential for precise earthquake hazard estimates, were compromised by limitations of experimental techniques. Furthermore, significant advances in analysis and dating of faulted materials (i.e., paleoseismology), fault identification by remotely sensed methods, GPS geodetic data, and the scientific community's general understanding of the regional tectonic setting over the last two decades suggest that the previous studies may not completely describe the seismic hazards in the region.

In this preliminary report, we evaluate these preexisting studies in an effort to better understand the state of knowledge on the seismic hazards, as well as the adequacy of the methodologies and approach applied to characterize the hazard. We also briefly address potential information and data gaps that may not have been included in the original data collection and evaluation, although a detailed accounting of such data gaps will be covered in a subsequent report. We first provide an overview of the regional geologic and tectonic setting and then furnish reviews of the paleoseismic, seismic, and geodetic studies. The paleoseismic studies record deformation over the past tens to hundreds of thousands years; the seismic investigations reflect deformation over the past approximately ~150 years; and the geodetic studies account for ongoing crustal deformation in the region (i.e., past couple decades). Collectively, these datasets provide an excellent overview of recent and geologically relevant deformation in the region in the context of a rapidly evolving plate boundary responsible for that deformation. This perspective is important for estimating future seismic hazards in the vicinity of Yucca Mountain.

NEOTECTONIC SETTING (PAST ~20 MILLION YEARS): WALKER LANE AND CRUSTAL EXTENSION

The boundary between the North American and Pacific plates, which is marked by the San Andreas fault, began developing approximately 30 million years ago off the southern California coast and has been progressively lengthening to the north and south since that time (Atwater and Stock, 1998). The San Andreas is a right-lateral transform fault that accommodates the relative motion between the North American and Pacific plates. Growth of this plate boundary has been marked by periodic inland steps of the developing transform. Most of the plate boundary strain is currently focused on the San Andreas fault system in coastal regions of California and the related dextral fault system within the Gulf of California (Figure 1A). In the western Great Basin, however, a system of dextral faults, known as the Walker Lane (Stewart, 1988; Faulds and Henry, 2008), currently accommodates as much as ~20-25% of the Pacific–North America dextral motion, as evidenced by GPS geodetic data (Dixon et al., 2000, 2003; Bennett et al., 2003; Hammond and Thatcher, 2007; Blewitt et al., 2009; Hammond et al., 2009; Kreemer et al., 2009).

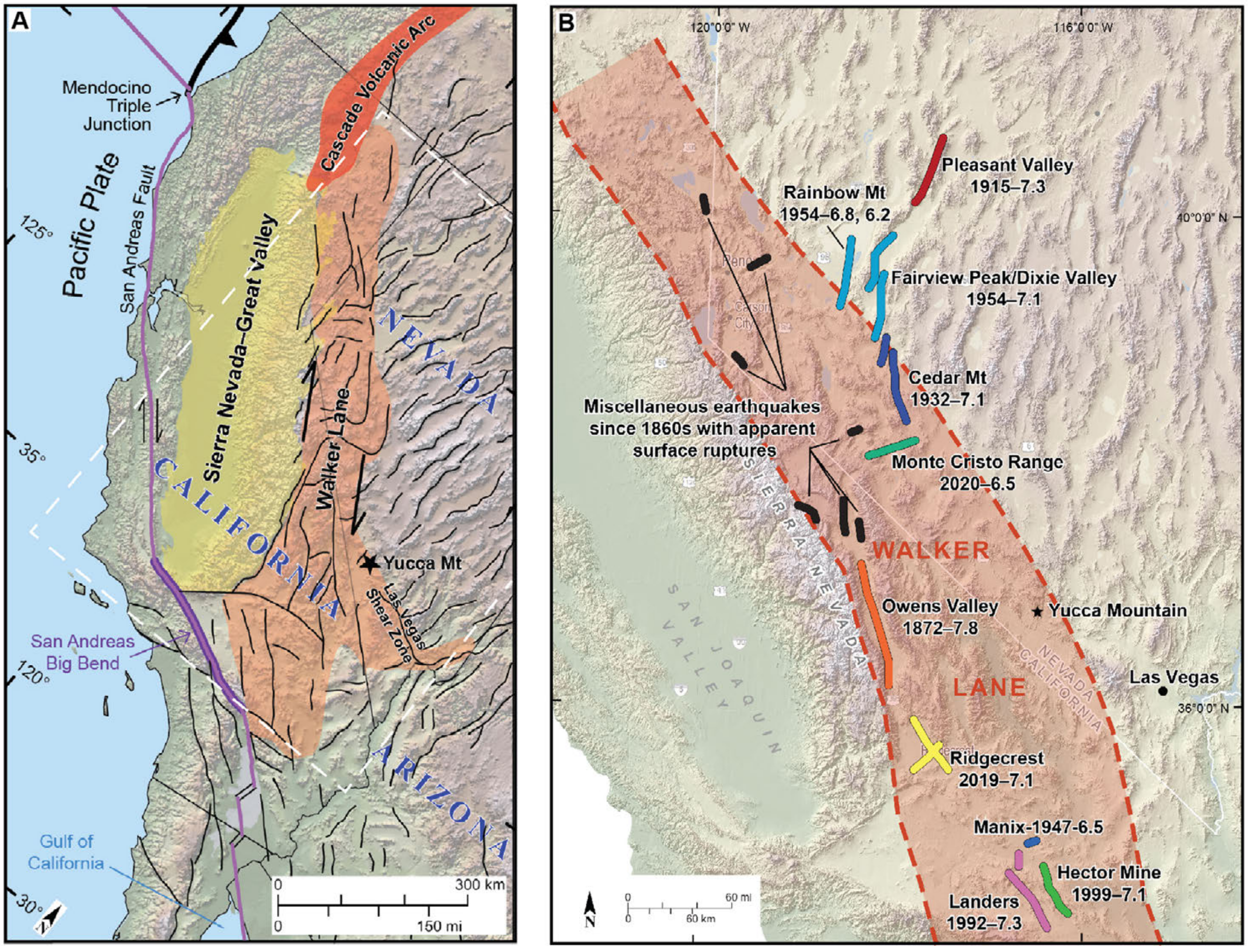

Figure 1. Regional perspective of Yucca Mountain in the context of the Walker Lane. **A.** Broad region showing Walker Lane (orange shading) and San Andreas fault. The San Andreas currently accommodates about 80% of the relative motion between the Pacific and North American plates, whereas the Walker Lane accommodates about 20-25% of that motion. Note the relative alignment of the Walker Lane with the Gulf of California, which contains the southern part of the Pacific – North America plate boundary. White dashed line outlines area shown in B. **B.** Major historic earthquakes (showing magnitudes) that produced ruptures of the Earth's surface within or proximal to the Walker Lane. Orange shading denotes the most active part of the Walker Lane at present.

The Walker Lane splays from the San Andreas fault in southern California, shunting a sizeable fraction of the relative plate motion east of the Sierra Nevada block (Figure 1A). The Walker Lane essentially accommodates dextral motion of the Sierra Nevada block relative to the central Great Basin. The entire system of dextral faults in the Walker Lane terminates, however, in northeast California directly inland of the northern end of the San Andreas fault, which ends at the Mendocino triple junction. The coincidence between the northern end of the San Andreas fault system offshore of the northern California coast and the inland termination of the Walker Lane in northeast California (Figure 1A) suggests that the Walker Lane is intimately related to the San Andreas. However, in contrast to the 1,100-km-long (685 miles) continuous San Andreas system, discontinuous dextral faults with relatively short lengths (<100-200 km [60-120 miles]) characterize the Walker Lane (Wesnousky, 2005). The Walker Lane can thus be characterized as a poorly developed analogue to the San Andreas and represents one of the youngest and least developed parts of the Pacific-North America plate boundary. As such, it is a natural laboratory for studying the incipient development and maturation of a major strike-slip fault system (e.g., Faulds et al., 2005).

The periodic inland steps of the San Andreas fault system are noteworthy, as they have transferred sizeable parts of North America to the Pacific plate (Figure 1A). The most significant step occurred ~13-6 million years ago in the southern part of the transform, as dextral shear shifted inland from off the western shore of Baja California to the east of the Baja Peninsula, ultimately leading to opening of the Gulf of California (Oskin and Stock, 2003; Fletcher et al., 2007). Considering this history, the Walker Lane may represent a nascent transform fault, which could ultimately evolve into the primary plate boundary (Faulds et al., 2005). The spatial and temporal evolution of the Walker Lane suggests that it is the heir apparent to the San Andreas fault, and that this shift in the plate boundary configuration may occur in about 7 to 8 million years in the future (Faulds and Henry, 2008).

Similar to the San Andreas fault system, the Walker Lane has lengthened through time and essentially grown from south to north (Faulds and Henry, 2008). The first major episode of deformation in the Walker Lane began ~13 million years ago along major fault zones in southern Nevada, particularly in the Las Vegas Valley area. The Las Vegas Valley shear zone accommodated ~60 km (40 miles) of right slip from ~13 to 6 million years ago. During this time period, however, the southern part of the Pacific-North American plate boundary was shifting eastward into the Gulf of California, and the Big Bend in the San Andreas fault was developing in southern California (Figure 1A). These events favored a westward shift in deformation in the Walker Lane to eastern California and western Nevada, as these areas aligned more directly with both the Gulf of California and the relative plate motion. Consequently, dextral shear shifted westward to the western Great Basin between about 11 and 6 million years ago, with southern reaches of the Walker Lane in eastern California and western Nevada becoming active approximately 11 to 9 million years ago. By about 4 million years ago, dextral shear had propagated northwestward into northwestern Nevada and northeastern California in concert with the northward lengthening of the San Andreas fault. In all areas of the Walker Lane, dextral shear has continued to the present day. Deformation rates have decreased through time in the Las Vegas area, but have probably increased through time in the western Great Basin region.

As a result of the plate boundary motions and growth of the San Andreas fault over the past 30 million years, Nevada has also been undergoing crustal extension or lengthening in the horizontal dimension. In fact, Nevada is currently the fastest growing state in the nation, tectonically speaking, as approximately two basketball courts are added to the state each year in response to this crustal stretching (Kreemer et al., 2012). This extension has been accommodated by a myriad of northerly striking normal faults that typically bound the many mountain ranges and basins across the state. Because of the many alternating mountain ranges and basins, the region is aptly referred to as the Basin and Range province. Nearly all of the faults bounding the major basins and ranges have been active in the recent geologic past or Quaternary time period. Extensional strain rates appear to be greatest proximal to the Walker Lane (Kreemer et al., 2012). Notably, as a result of the strike-slip faulting along the Walker Lane in the western Great Basin and crustal extension across the entire region, Nevada is the third most seismically active state in the country.

The Yucca Mountain area epitomizes the complex and active tectonic setting of Nevada. It lies in the easternmost part of the Walker Lane at the transition between strike-slip faulting and crustal extension (e.g., Schweickert and

Lahren, 1997; Fridrich, 1999; Wernicke et al., 2004; Guest et al., 2007; McKague et al., 2010). Northwest-striking right-lateral strike-slip faults dominate to the southwest of Yucca Mountain in the Death Valley and Owens Valley areas of California, whereas crustal extension and northerly striking normal faults dominate to the northeast through much of central and northern Nevada. The geologic setting of Yucca Mountain is further explored in the following section.

GEOLOGIC SETTING OF YUCCA MOUNTAIN

Owing to relatively detailed geologic mapping (see Figure 2 and bibliography of geologic mapping at the end of the references section) and geophysical surveys, the geologic setting of Yucca Mountain is generally well documented. Geologic maps show the surficial distribution of rock units and faults, which are critical for assessing both geologic hazards (e.g., earthquakes) and groundwater flow regimes, as well as constraining geologic features in the subsurface. Geologic mapping at 1:24,000 scale (i.e., 1 inch equals 2,000 ft) was published between the 1960s and 2004 for nearly the entire area. Finer-scale maps (1:6,000) were completed for the south-central part of Yucca Mountain (Dickerson and Drake, 2004). In addition, Potter et al. (2002) compiled a geologic map at 1:50,000 scale for much of the Yucca Mountain area. Geophysical surveys (e.g., gravity, magnetic, and seismic reflection data) complement the geological maps and constrain the subsurface location and configuration of strata, volcanic centers, and faults, as well as the general subsurface architecture of major basins (e.g., Brocher et al., 1998; Blakely et al., 2000; O'Leary et al., 2002).

The geologic setting of the Yucca Mountain area is dominated by a series of north-trending, gently tilted fault blocks and related basins. The fault blocks are largely composed of rhyolitic ash-flow tuffs (Scott and Bonk, 1984; Carr, 1988; Potter et al., 2002), which range in age from ~15 to 11 million years old (i.e., Miocene age). The Miocene rocks rest on folded and highly faulted Proterozoic and Paleozoic (i.e., more than 1 billion to ~250 million years old) sedimentary and metamorphic rocks, which are exposed to the west at Bare Mountain and to the southeast in the Specter Range (e.g., Carr and Monsen, 1988; Monsen et al., 1992). Most of the exposed tuffs are outflow sheets erupted from calderas (e.g., Claim Canyon and Timber Mountain/Oasis Valley calderas), which lie directly north of Yucca Mountain (Byers et al., 1976; Christiansen et al., 1977; Carr, 1988). Crater Flat, Jackass Flats/Midway Valley, and Amargosa Valley are broad basins directly west, east, and south of Yucca Mountain, respectively. The basins contain varying thicknesses of late Tertiary to Quaternary (~10 million to less than 10 thousand years old) alluvium dominated by coalescing alluvial fans, which mantle the older volcanic, sedimentary, and metamorphic rocks. Some of the basins contain relatively thick (>1 km [3,300 ft]) sequences of alluvium.

Several relatively young (3.7 million to 76,000 years old) volcanic centers lie directly west of Yucca Mountain in the Crater Flat basin and directly south of Yucca Mountain near Lathrop Wells (Figure 2). In the southeastern part of Crater Flat, 3.7 million year old basalts were erupted from a 4-kmlong (2.5 miles) north-trending fissure (Vaniman et al., 1982). Quaternary basalts, ranging from 0.7 to 1.1 million years old, were erupted from four centers in a 12-km-long (7.5 miles) northeast-trending arcuate belt in the central and southwestern parts of Crater Flat (Bradshaw and Smith, 1994; Faulds et al., 1994; Valentine et al., 2006). A much younger volcanic center near Lathrop Wells in the southern part of Yucca Mountain ~18 km (12 miles) south of the proposed repository is ~76,000 years old and may have formed during a relatively short eruptive episode spanning several months (Valentine et al., 2007).

The major structural features in the Yucca Mountain area include several relatively narrow, generally east-tilted fault blocks bounded by closely spaced, moderately to steeply dipping, north-northwest to northeaststriking generally west-dipping normal faults. Normal faults accommodate extension of the crust. Tilting of exposed units generally does not exceed ~20°. Crustal extension in the Yucca Mountain region probably began more than 20 million years ago (Schweickert and Caskey, 1990) and has continued to the present. A major episode of extension accompanied caldera activity between ~13 and 11 million years ago (Carr, 1988; Scott, 1990; Potter et al., 2002). Significant extension continued with a second major pulse likely occurring ~10 to 8 million years ago (e.g., Scott, 1990; Faulds et al., 1994). More than a dozen faults in the area cut Quaternary alluvial units, thus indicating continued, relatively active tectonism and associated earthquakes to the present, as discussed in greater detail in the following sections. The closely spaced faults are arranged in an en echelon pattern and display significant along-strike displacement gradients. In many cases, displacement varies by orders of magnitude within individual fault segments. Displacement on many of the faults decreases northward across the region. Although most faults accommodated normal slip and crustal extension, northeast- and northweststriking faults commonly show components of left and right slip, respectively.

Although no major strike-slip faults of the Walker Lane have been observed in the immediate vicinity of Yucca Mountain, major strike-slip faults may cut through Amargosa Valley directly to the south and may also underlie Yucca Mountain itself. On the basis of patterns of recent faulting and volcanism, major geophysical features, and clockwise vertical-axis rotations of fault blocks in the area (e.g., Hudson et al., 1994), Schweickert and Lahren (1997) concluded that a major right-lateral fault of the Walker Lane underlies the Yucca Mountain/Crater Flat area. This fault may have accommodated as much as 25 km (~16 miles) of displacement in the past ~12 million years. Such a fault could account for the array of active faults and recent volcanism in the area and the northward decrease in Quaternary faulting in the broader Yucca Mountain region. Wernicke et al. (2004) and Guest et al. (2007) also noted geodetic and geologic evidence, respectively, for right-lateral strike-slip faulting in the region. Potter et al. (2002) noted on the basis of geologic and geophysical data that a major east-striking fault, which has probably accommodated right-lateral and normal offset, underlies surficial deposits in the northern part of Amargosa Valley. An incipient underlying strike-slip fault is compatible with the overall youthful nature of the Walker Lane fault system.

Data Gaps, New Technologies, and Recommendations

Although the general geologic setting of Yucca Mountain is well established, the subsurface geologic framework could be enhanced through acquisition of additional geophysical datasets and integration of those datasets with available geological data. For example, modern techniques of imaging the subsurface through acquisition and/or reprocessing of gravity, magnetic, electromagnetic, tomographic, and seismic reflection data can further constrain the extent, age, and subsurface geometries of faults, as well identify potential magma bodies in the deeper parts of the crust. Thanks to significant technological advancements in recent years, all of these datasets can now be integrated into detailed 3D models that can be extended to sufficient depths to more fully evaluate seismic and volcanic hazards, as well as groundwater flow regimes. We also recommend inclusion of nearby parts of the Amargosa Valley and other nearby basins in these models, as they may harbor concealed Walker Lane faults. Detailed accounts of the recommended data acquisitions, reprocessing, and modeling will be provided in a subsequent report.

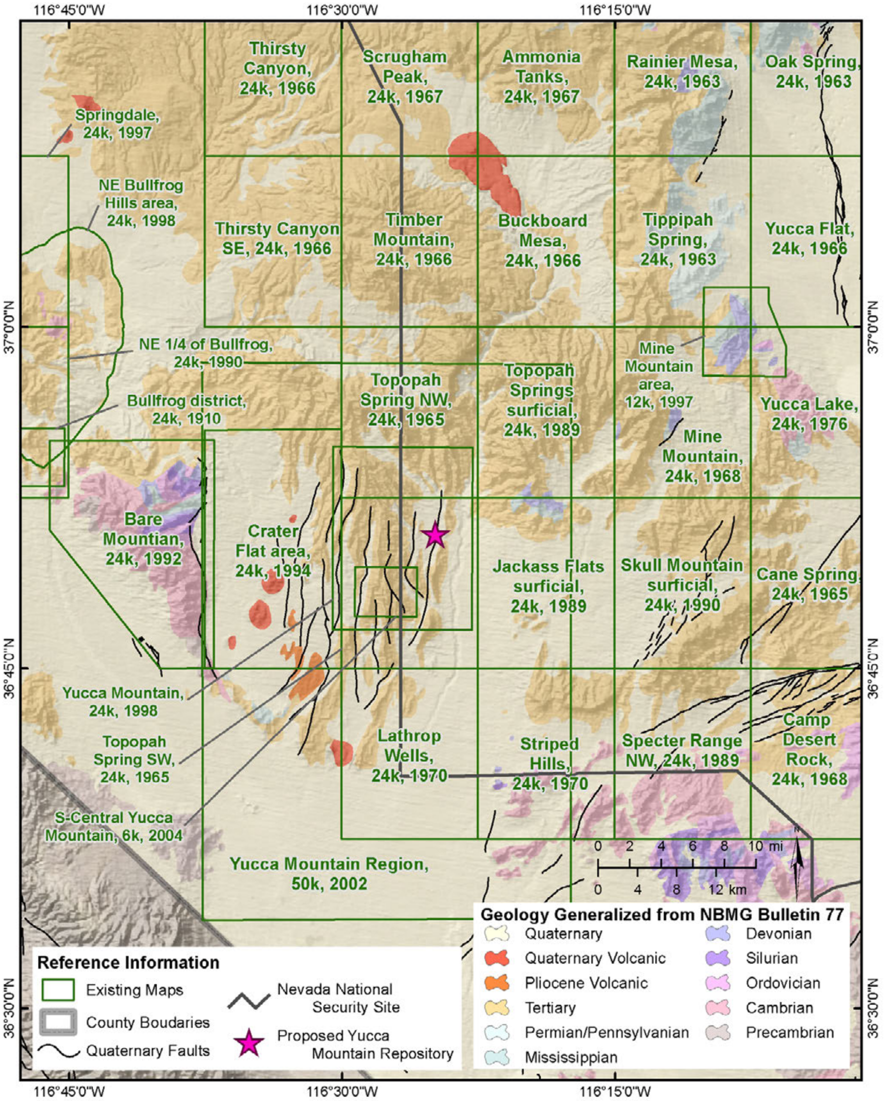

Figure 2. Generalized geologic map of the Yucca Mountain area showing major rock units and Quaternary faults (black lines). Note the Quaternary volcanic centers directly west and south of Yucca Mountain. Green lines show outlines and scales of completed geologic mapping in the area (see geologic map bibliography at the end of the references section for a list of these maps).

PALEOSEISMOLOGY AND FAULT CHARACTERIZATION FOR EARTHQUAKE POTENTIAL

Active tectonic studies were conducted in the Yucca Mountain region from the late 1970's to the mid 1990's as part of a larger site characterization program developed by the DOE and administered by the USGS aimed at evaluating seismic hazards that could affect the potential repository and its components (Pezzopane et al., 1995). The investigations included detailed Quaternary geologic and fault mapping, paleoseismic trenching, and fault rupture parameter characterization for seismic sources within 100 km (62 miles) of the proposed repository, as well as reconnaissance fault evaluations in the surrounding region. The Quaternary time period spans the past 2.6 million years of the Earth's history and thus includes the youngest geologic deposits and most recently active faults in a given region. A regional map showing Quaternary active faults is shown on Figure 3, and fault maps showing locations of previous paleoseismic studies are shown on Figure 4 for reference.

Quaternary geologic and fault mapping was conducted to develop a regional stratigraphic framework and an understanding of the evolution of surficial deposits, data useful in understanding the relative activity of tectonic faults (e.g., Swadley et al., 1984) (Figure 3). The mapping also placed constraints on fault locations, geometries, and maximum potential rupture lengths. Based on the mapping observations, sites were identified for detailed paleoseismic investigations (Figure 4). These studies focused on developing information on fault rupture parameters, including fault slip rates, earthquake timing and recurrence intervals, amounts of displacement per event, cumulative offsets, and elapsed time since the most-recent event. Comprehensive fault characterization information was developed based on the results of the Quaternary mapping and paleoseismic investigations (Keefer et al., 2004; Piety, 1994; Anderson et al., 1995a, 1995b). The developed fault characterization data were ultimately combined with seismicity, geodetic, and geophysical observations, along with ground motion attenuation models, to develop probabilistic fault displacement and ground motion hazard calculations applicable to seismic design considerations (Youngs et al., 2003; Stepp et al., 2001; Wong and Stepp, 1998).

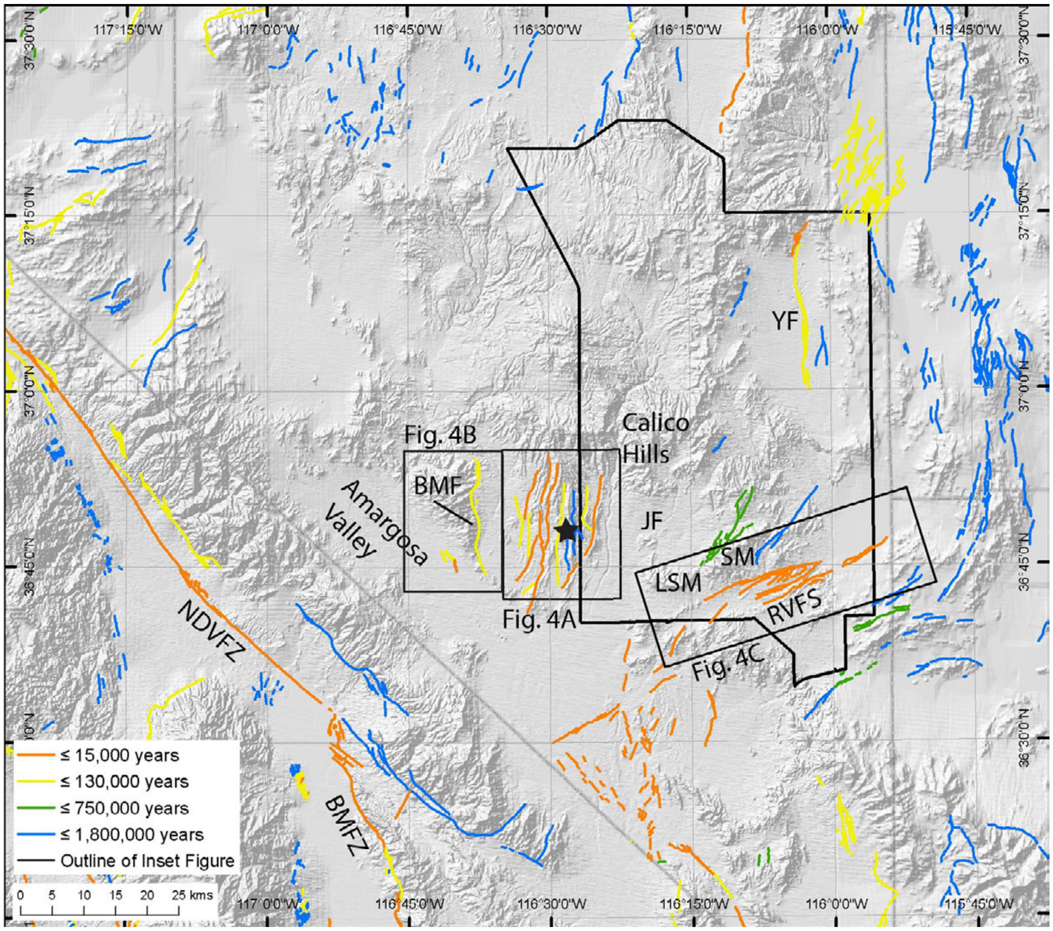

Figure 3. Hillshade map of the Yucca Mountain region showing Quaternary active faults. Age of most recent deformation shown by color and taken from the USGS Quaternary fault and fold database. Black rectangles show outlines of Figures 4A, 4B, and 4C, and irregular polygon shows outline of the NNSS. Black star is Yucca Mountain. Yf, Yucca fault; BMFZ, Black Mountain fault zone; NDVFZ, Northern Death Valley fault zone; BMF, Bare Mountain fault; RVFS, Rock Valley fault system; SM, Skull Mountain; LSM, Little Skull Mountain.

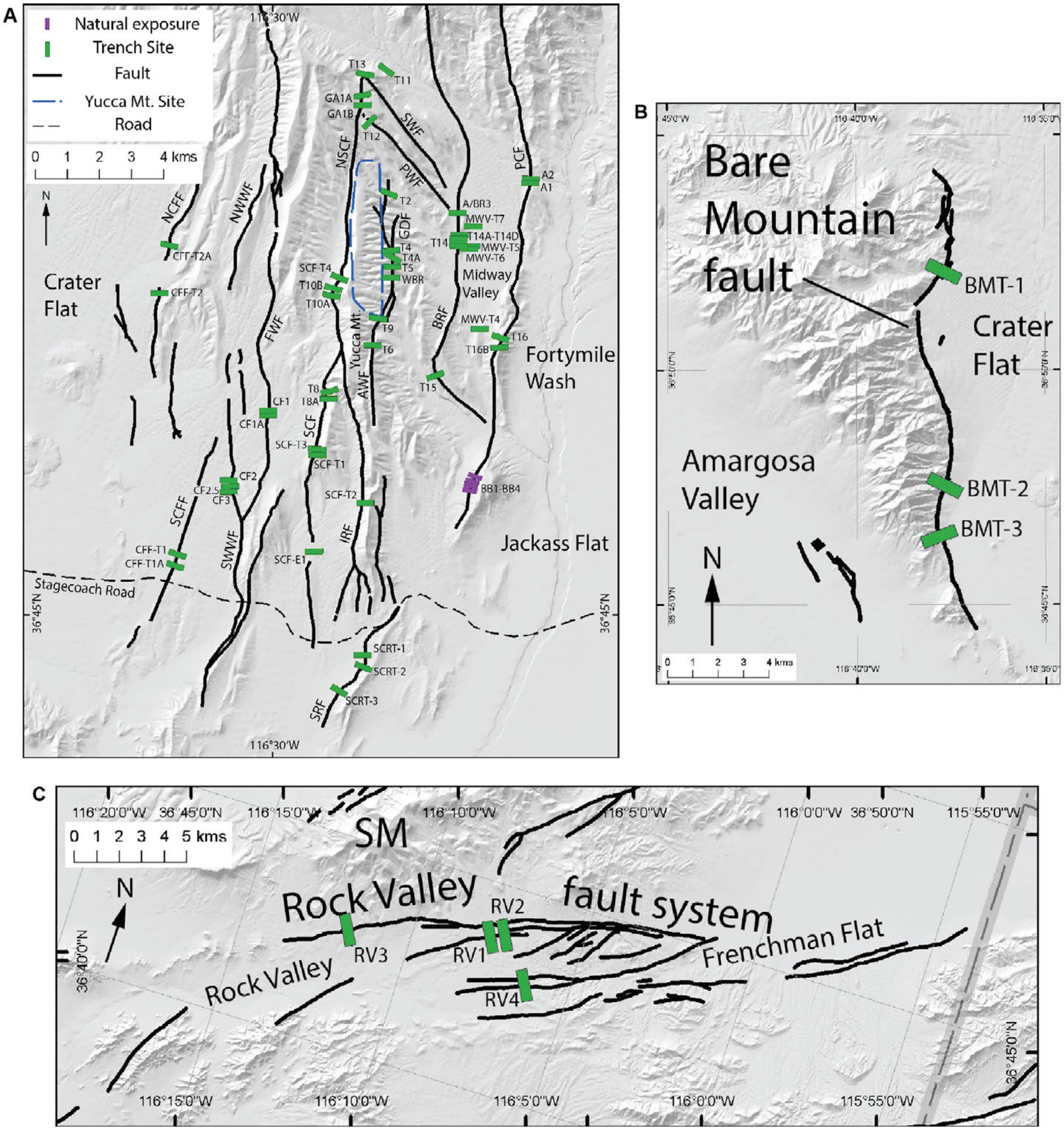

Figure 4. Hillshade maps of Yucca Mountain area showing Quaternary faults and sites of paleoseismic trench investigations (green rectangles) and natural exposures (purple rectangles). Locations of maps shown on Figure 3. Trench locations and names from Keefer et al. (2004). **A.** Immediate vicinity of Yucca Mountain. NCFF, northern Crater Flat fault; SCFF, southern Crater Flat fault; SWWF, southern Windy Wash fault; NWWF, northern Windy Wash fault; FWF, Fatigue Wash fault; SCF, Solitario Canyon fault; NSCF, northern Solitario Canyon fault; IRF, Iron Ridge fault; SRF, Stagecoach Road fault; AWF, Abandoned Wash fault; GDF, Ghost Dance fault; PWF, Pagany Wash fault; SWF, Sever Wash fault; BRF, Bow Ridge fault; PCF, Paintbrush Canyon fault. **B.** Bare Mountain fault along western margin of Crater Flat basin. **C.** Rock Valley fault system to the southeast of Yucca Mountain. SM, Skull Mountain.

Purpose and Approach of Review

The purpose of this review is to examine the relative completeness and scientific merit of preexisting Quaternary mapping and paleoseismic studies conducted in the Yucca Mountain area, as well as to identify key uncertainties and any data or information gaps that may not have been included in the original seismic hazards assessment. Our approach included the assembly of publicly available maps, reports, and scientific literature, review of those documents, as well as identification of additional data sources (technical reports, DOE documents, etc.) that would further assist a more comprehensive review. A total of 41 data sources related to Yucca Mountain were evaluated, and 20 additional data sources were identified but were not available at the time of this review. In the 25+ years since paleoseismic studies at Yucca Mountain ended, there have been many advances in paleoseismic techniques, imagery and topographic data quality, and geochronologic methods for estimating the ages of faulted deposits. Thus, this initial review focuses on reporting on the key aspects of the seismic source characterization, the adequacy of the methodologies applied, and recommendations for improving the current state of knowledge on seismic hazards in the Yucca Mountain area. The results of this review will be expanded upon and incorporate assessment of additional data sources in a subsequent version of this report.

Key Findings of Previous Investigations

QUATERNARY GEOLOGIC AND FAULT MAPPING: During the site characterization program, a comprehensive Quaternary stratigraphic framework was developed and refined over the years through detailed mapping in the region surrounding the NNSS and proposed repository (Figure 2). For the immediate vicinity of Yucca Mountain, maps were developed depicting the late Cenozoic stratigraphy (Hoover et al., 1981; Swadley et al., 1984) and Quaternary geologic units at the 1:48,000 scale (Swadley, 1983; Swadley and Carr, 1987; Swadley and Parrish, 1988) and 1:24,000 scale (Swadley and Hoover, 1989a, b; Swadley and Huckins, 1989, 1990). This stratigraphy was further subdivided by Taylor (1986) and Wesling et al. (1992), who distinguished Quaternary deposits in Midway Valley, Yucca Wash, and Fortymile Wash east of Yucca Mountain, and Faulds et al. (1994) and Petersen et al. (1995), who defined six additional stratigraphic units in Crater Flat west of Yucca Mountain.

These mapping efforts were primarily based on interpretation of air photos, field surveys, and application of established methodologies of using geomorphic and stratigraphic characteristics to distinguish deposits. These techniques are still in use today and include observations on relative stratigraphic and geomorphic position, cross cutting relations, lithology, soil-profile development and degree of calcic soil horizon development, degree of desert-pavement development, and degree of preservation of original bar-and-swale topography, among others. These characteristics provided relative ages for the various stratigraphic units and insight into the depositional history of the region. Where available, the relative ages were calibrated by relations with numerically dated volcanic ash deposits (e.g. Bishop Tuff, 760 thousand years old), providing broadly constrained absolute ages.

The stratigraphic relations and age determinations (relative and numerical) defined in the mapping efforts around Yucca Mountain were synthesized by Whitney et al. (2004), who defined eight stratigraphic units ranging in age from Pliocene (?) to Holocene (about 5 million years to less than 10,000 years). This Quaternary stratigraphic framework became generally accepted as representative of the depositional history of the region. Correlation of the stratigraphic framework to areas with less comprehensive mapping provided essential data to help evaluate the history of Quaternary faulting during subsequent paleoseismic studies throughout the region.

Extensive fault mapping was also conducted during the site characterization program at Yucca Mountain, locally in conjunction with the Quaternary geologic mapping efforts. The fault mapping significantly improved the understanding of the distribution of Quaternary active faults near the proposed repository and the surrounding region, and the results were eventually incorporated into the USGS Quaternary fault and fold database for the nation (Figure 3). For the Yucca Mountain area, faults with evidence potentially indicating Quaternary activity were mapped by Swadley and Hoover (1983), Swadley et al. (1984), and Scott and Bonk (1984). These initial observations were examined in the field and compiled into a 1:24,000 scale map of probable and suspected Quaternary active faults (Simonds et al., 1995b) that helped inform prioritization of paleoseismic trenching sites. Major faults in the Yucca Mountain area are shown on Figure 4A. Faults proximal to and/or with the potential to intersect the repository included the Solitario Canyon, Ghost Dance, Drill Hole Wash, Abandoned Wash, Dune Wash, and Sundance faults (Pezzopane et al., 1995). Other active faults proximal to the proposed repository that were shown to have demonstrable evidence of recent activity include the Paintbrush Canyon, Bow Ridge, Stagecoach Road, Fatigue Wash, Windy Wash, and southern and northern Crater Flat faults.

Efforts to understand and map the distribution of faults located at greater distances from the proposed repository and their implications for seismic hazard calculations were conducted for the 400 km2 (154 square miles) area centered on Yucca Mountain (Simonds et al., 1995b), which includes the Saline Valley, Darwin Hills, Benton Range, Goldfield, Last Chance Range, Beatty, and Death Valley Junction 1:100,000 scale quadrangles (Reheis, 1991; Reheis and Noller, 1991). These fault maps were compiled by Piety (1994), who evaluated published literature and synthesized available information on fault length, recency of movement, slip rate, and other parameters for all faults within 100 km (62 miles) of Yucca Mountain.

PALEOSEISMIC TRENCHING: Trenching involves narrow excavations across faults designed to reveal offset deposits and ultimately the timing, frequency, and approximate magnitudes of recent earthquakes. Trenching and description of natural exposures was conducted in conjunction with some of the early mapping programs (Swadley et al., 1984; Swadley and Hoover, 1983). In some cases, these trench results guided subsequent site selection for more detailed trenching activities (Keefer et al., 2004). Between the early 1980's and mid 1990's, over 50 trenches and natural exposures were examined in the Yucca Mountain area (Figure 4). Descriptions of these studies vary in quality and level of reporting, ranging from field notebook sketches of natural exposures to full trenching studies using state-of-the-art techniques of the era. Techniques employed included construction of string grid reference frames and theodolite surveying of trench walls, manual and digital production of trench logs showing stratigraphic and structural relations, numerical dating techniques, and vetted, peer-reviewed reporting. The majority of the trenching studies were collaborative efforts between the USGS, U.S. Bureau of Reclamation, NBMG at UNR, and other professional experts in the fields of paleoseismology, geochronology, geomorphology, and stratigraphy. Field reviews of trench interpretations were an integral part of the program and contributed to intense scrutiny of interpretations and conclusions.

A comprehensive review of each exposure is beyond the scope of this report. Complete summaries of the trenching results from fault investigations within and around the Yucca Mountain area are contained in Pezzopane (1995) and Menges et al. (1994). However, we could not identify publicly accessible copies of these reports at the time of this initial review. The most comprehensive and available summary of paleoseismic trenching results for the immediate area around Yucca Mountain is provided in Keefer et al. (2004), complete with individual chapters describing the site geomorphology, subsurface stratigraphic and structural relations, geochronologic analyses, and tectonic interpretations for specific faults. The paleoseismic results and interpretations contained in Keefer et al. (2004) include studies along the Paintbrush Canyon, Bow Ridge, Stagecoach Road, Ghost Dance, Solitario Canyon, Fatigue Wash, Windy Wash, Bare Mountain, Pagany Wash, Exile Hill, Iron Ridge, Sever Wash, Abandoned Wash, Drill Hole Wash, southern and northern Crater Flat faults, and Rock Valley fault system (Figure 4).

A primary focus of these studies was to develop data on fault geometry and displacements, ages of faulted deposits, recurrence intervals, and slip rates (Whitney et al., 2004). Rigorous treatment of displacement observations was applied, including assessment of individual, cumulative, and net cumulative displacements. Geochronologic analyses on stratigraphic deposits included: 1) U-Th-disequilibrium-series (U series) analyses of pedogenic carbonate-silica laminae and clast rinds, matrix soil carbonate, and rhizoliths; 2) thermoluminescence analyses of fine-grained polymineralic material; 3) carbon-14 analyses of rock varnish and charcoal; 4) tephrochronology; and 5) archaeological relations. Standard techniques were employed to compute recurrence intervals and slip rates.

Eight faults showed demonstrable surficial evidence of Quaternary activity, and at least 25 trench exposures showed clear evidence of Quaternary displacement on their respective faults (Whitney et al., 2004; Keefer et al., 2004). These faults include Paintbrush Canyon, Bow Ridge, Stagecoach, Solitario Canyon, Fatigue Wash, Windy Wash, and southern and northern Crater Flat faults. In general, each of these faults has produced two to three earthquakes in the last 100 thousand years. Figure 5 shows the ages and age uncertainty of these earthquakes. Similar earthquake chronologies were documented for the Bare Mountain fault and Rock Valley fault system located to the west and east of Yucca Mountain, respectively (Yount et al., 1987; Anderson and Klinger, 1996; Keefer et al., 2004) (Figure 4B-C).

A number of trenches did not show evidence for Quaternary displacement, in some cases along faults shown to be active at other trench locations along strike. The absence of faulting could be due to a variety of factors, including but not limited to (1) gaps or termination of ruptures along strike, (2) lack of Quaternary deposits (i.e., faults in bedrock), (3) imprecise fault location and/or poor trench site selection, and/or (4) no faulting has occurred since the deposition of Quaternary deposits at the site. Thus, the apparent lack of faulting at some sites does not necessarily indicate that a particular fault is not active and suggests that improved mapping and better trench site selection could lead to improved tectonic interpretations.

Given the experts involved in the paleoseismic studies, the large number of trench investigations, and the application of proven mapping and trenching techniques, the interpretations and conclusions with respect to the number of paleoseismic events and amount of displacement observed in trenches is considered robust. However, limitations in the geochronologic techniques available at the time, which were largely experimental, caused considerable uncertainty in the ages of paleoseismic events. As shown on Figure 5, the large age uncertainties for the timing of events along individual faults overlap in time with the ages of events along adjacent faults. This poses difficulty in assessing whether seismic events were synchronous (multiple faults moving during the same earthquake) or non-synchronous (separate earthquakes on different faults closely spaced in time), which has implications for estimating maximum expected magnitudes in future earthquakes. Additionally, earthquake timing data are essential for evaluating both recurrence and slip rate parameters and are therefore fundamental in assessing the earthquake hazard and strong ground motions that inform the seismic engineering of the proposed repository facility. Thus, the dating uncertainties contributed to greater uncertainty in these essential modeling products.

Despite the uncertainties in earthquake timing, similarities in the ages of paleoearthquakes across multiple faults interpreted from the trenches within and near Yucca Mountain has led to several speculative ideas related to synchronous and/or distributive surface ruptures over the last 100,000 years (Figure 6). Based on the observation of basaltic ash from the 76,000 year old Lathrop Wells volcanic center in fissure fills along three faults, Keefer and Menges (2004) inferred contemporaneous rupture of all three faults at the time of the eruption. Several other events or sequence of events observed along two or more faults occurred around 50,000 years ago on the east side and 30,000-20,000 thousand years ago on the west side of Yucca Mountain, respectively. The most recent faulting episode occurred between 13,000 and 3,000 years ago in the immediate vicinity of Yucca Mountain and was also observed along multiple faults. This suggests that rupture could have occurred on multiple faults contemporaneously or closely spaced in time and that the separate surface ruptures may potentially be linked at depth (Keefer and Menges, 2004). A cartoon showing these relations is depicted in Figure 6. These inferences have implications for the assessment of potential rupture lengths, displacements, and size (magnitude) of future earthquakes and the potential of active volcanism to trigger seismic events. Although intriguing, the uncertainties in the age estimates of paleoearthquakes precludes definitive correlation of ruptures on multiple faults. Tighter constraints on the ages of paleoearthquakes would contribute toward refining these ideas and lead to a better characterization of the earthquake and volcanic hazards at the proposed Yucca Mountain site.

In the second phase of this review we will provide a summary of the paleoseismic data from the Yucca Mountain study and indicate where new research can improve the hazard assessment. This will include an assessment of which sites may be amenable to additional dating studies.

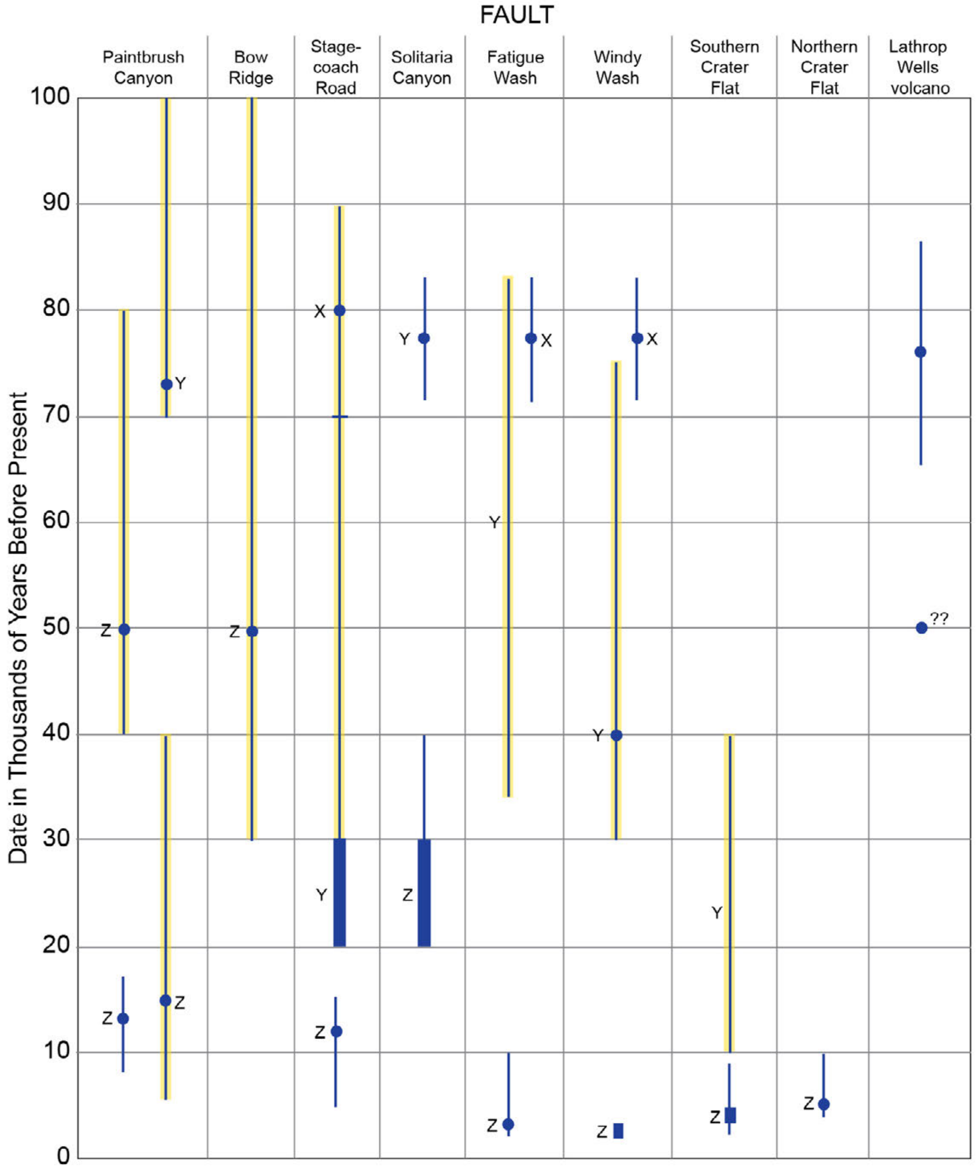

Figure 5. Ranges in estimated dates of Quaternary faulting events identified in trenches excavated in the Yucca Mountain area. The events are shown in columns associated with their respective faults. Circles show preferred age; bold blue lines show preferred age range; thin blue lines show the uncertainty in age estimates; bold yellow lines show any uncertainties that are 20,000 years or greater. Letters "X–Z" refer to event-labeling nomenclature with "Z" representing the youngest event on a particular fault. Also shown is the age of the most recent volcanic eruption at Yucca Mountain, the Lathrop Wells cone. Modified from Keefer et al. (2004).

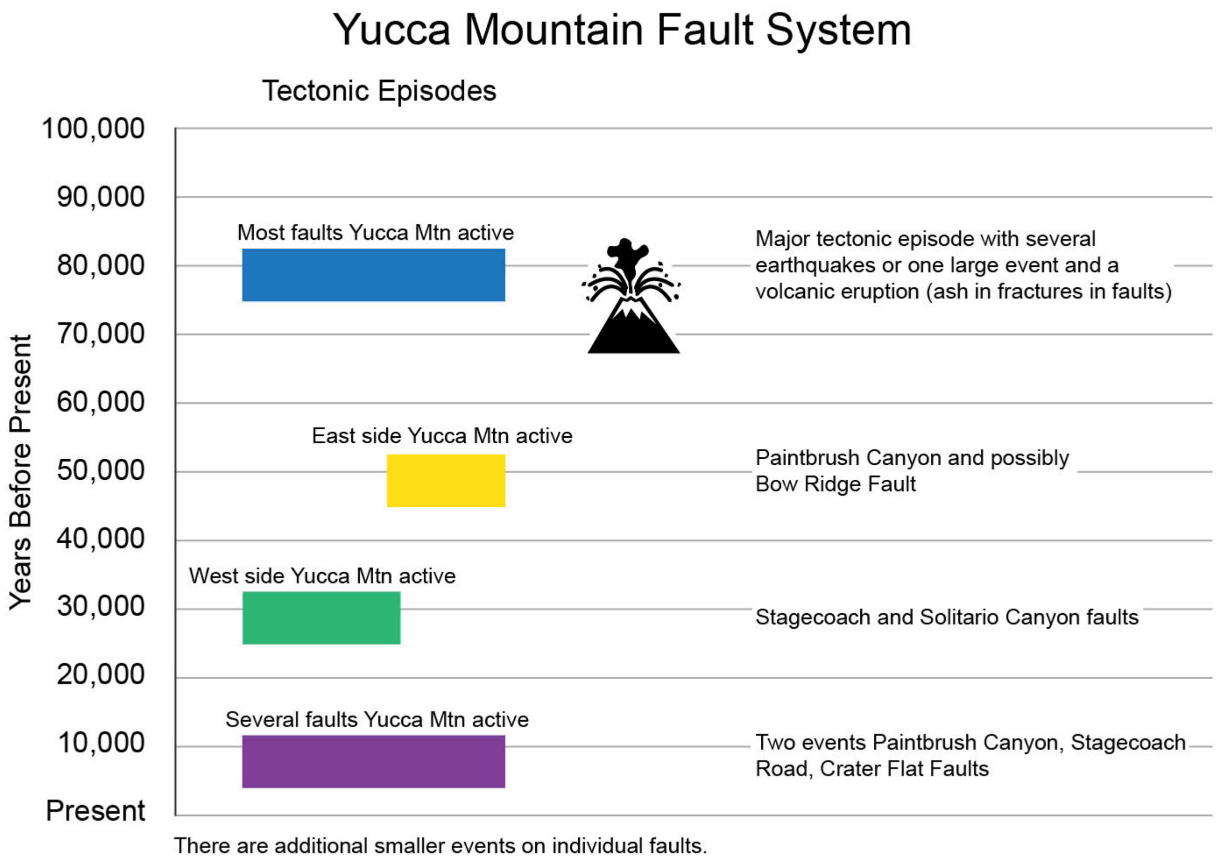

Figure 6. Schematic diagram illustrating large tectonic events that occurred at Yucca Mountain over the last 100,000 years and may have involved multiple faults and/or volcanic eruptions, as inferred by Keefer and Menges (2004). These events could also represent periods of time when multiple earthquakes occurred on individual faults closely spaced in time. The volcanic eruption shown is the Lathrop Wells cone directly south of Yucca Mountain that erupted approximately 76,000 years ago.

FAULT CHARACTERIZATION: Based on the results of the decades-long mapping and trenching programs, multiple compilations of fault parameters were amassed and have provided the basis for the Yucca Mountain seismic source characterization. Data from the seismic source characterization provided critical input data for probabilistic seismic hazards assessments and seismic risk analyses for the proposed repository (e.g., Wong and Stepp, 1998). The fault parameter compilations included detailed descriptions of known or suspected Quaternary faults, including their map trace extent, evidence supporting relative activity, slip per event, slip rate, recurrence, and supporting references (Piety, 1994; Pezzopane et al., 1994, 1995; Anderson et al., 1995a, 1995b).

Piety (1994) compiled information for 145 faults within 100 km (62 miles) of Yucca Mountain and determined that ten faults within 50 km (31 miles) and fifteen faults between 50 and 100 km (31-62 miles) of the proposed repository had clear evidence of Holocene or Late Pleistocene (<130 thousand years) displacement. However, Piety (1994) acknowledged that the majority of the faults in the compilation had not been studied in sufficient detail to determine robust fault rupture parameters. Anderson et al. (1995a, 1995b) conducted additional Quaternary geologic and paleoseismic studies to address regional faults identified by Piety (1994) as lacking paleoseismic information. These studies expanded the knowledge of regional Quaternary faults in the Amargosa and Oasis Valley-Beatty Wash areas and included assessment of fault rupture parameters, including information on fault length and the age of displacements. Since these studies, new techniques for fault characterization have been developed and applied to the regional faults of southern Nevada (e.g., dePolo, 1998).

Pezzopane et al. (1996) synthesized these fault rupture parameter compilations and assessed potential maximum magnitudes for 88 faults and/or rupture sources that had the potential to generate peak ground accelerations at the Yucca Mountain site that equal or exceed 10-percent gravity (0.1 g). The compilation used all of the data available up to the early 1990's. Although there were significant uncertainties in the fault parameters for individual faults, the database of faults that were assessed for the seismic source characterization (Piety, 1994; Pezzopane et al., 1996) is considered generally complete for the time. Since the mid 1990's, additional research has been conducted on these faults, and some have had major earthquakes. Thus, a modern compilation updating seismic source information for these faults is warranted.

The Pezzopane et al. (1996) fault characterization became the authoritative seismic source model for Yucca Mountain and, after expert review, was used in probabilistic fault displacement and ground motion hazard calculations (Stepp et al., 2001; Wong and Stepp, 1998). Unfortunately, at the time of this review, we were unable to identify a publicly accessible copy of the Pezzopane et al. (1996) report or several other related reports (Pezzopane et al., 1994; Pezzopane 1995). It is anticipated that these reports will be acquired and contribute to additional review in a subsequent version of this report.

LOW-ANGLE DETACHMENT FAULT MODEL: The detachment normal fault model was developed and became popular in the 1970s and 1980s. It was applied to several areas of Nevada to interpret geologic structure. The model was also strongly considered in the characterization of the tectonic model of Yucca Mountain (c.f., Simonds et al., 1995a). A detachment fault is a low-angle normal fault that commonly has steeper faults merging into it from above. The concept has several facets, such as whether the detachment fault was formed initially as a low-angle fault or was subsequently rotated into that geometry from a steeper fault. Yucca Mountain lies in a region that has some well-defined detachment faults, and the geometry of normal faults in the area could be consistent with an underlying detachment fault. Whether or not a detachment fault exists at Yucca Mountain has many implications for potential hazards to the proposed high-level waste repository. The seismic hazard could be increased if a detachment exists, as it could rupture in large, shallow earthquakes below the site (e.g., Wernicke, 1995), closer than earthquakes that would occur deeper in the seismogenic crust. Such an event could activate multiple faults at Yucca Mountain, which could serve as pathways for radionuclide release. On the other hand, an earthquake on a shallow low-angle fault would be contrary to earthquakes recorded in the Basin and Range, with the great majority occurring on steeply dipping faults, and thus might be considered unlikely. If faults at Yucca Mountain sole into a shallow fault (<4 km [2.5 miles]) that slips aseismically or during infrequent large earthquakes, the seismic hazard potential at Yucca Mountain could either decrease or increase. Thus, determining whether or not a detachment fault underlies Yucca Mountain was an important consideration for site characterization studies.

More recent studies indicated that although there are regional detachment faults in southern Nevada, it seemed unlikely that such a fault existed directly below Yucca Mountain. To the west, in the Bare Mountain and Bullfrog Hills area, Miocene volcanic rocks are faulted against Paleozoic rocks that have been uplifted from deeper levels. This detachment fault has been well documented and is related to the gold deposits that are mined in Bullfrog Hills. At Yucca Mountain, geologists mapping the bedrock hypothesized that the faults that accommodate offset of Miocene volcanic rocks and Quaternary deposits were listric and likely soled into a detachment fault beneath the mountain (Scott, 1990). Site characterization studies were conducted at Yucca Mountain to verify or refute the existence of a detachment fault. These included mapping of the contact between Miocene and Paleozoic rocks around Yucca Mountain to determine if it was a fault contact and mapping the eastern part of the detachment fault in the Bare Mountain and Bullfrog Hills areas. Simonds et al. (1995a) reported that the studies of the contact between Miocene and Paleozoic rocks to the east and south of Yucca Mountain were demonstrably, or likely, depositional with no fault present, and that the easternmost part of the detachment surfaced to the west just north of Bare Mountain, indicating that it did not extend under Yucca Mountain. No subsequent studies have changed this general thinking, but a fresh review of the data considering contemporary fault modeling and imaging at depth would be prudent.

VOLCANIC HAZARDS: Although this review primarily focuses on previous fault mapping and paleoseismic studies, the Yucca Mountain site is also potentially exposed to volcanic hazards. As described above, volcanoes are present directly south of Yucca Mountain (Lathrop Wells cone) and just west of Yucca Mountain (Crater Flat volcanoes). These volcanoes are thought to be the waning activity of a much larger Miocene volcanic field (the southwest Nevada volcanic field) that was once as large as the volcanoes at Yellowstone (Valentine and Perry, 2006). Quaternary activity has continued in the Yucca Mountain area with four basaltic volcanoes in Crater Flat that produced eruptions between 700,000 and 1.1 million years ago along a 12 km (7.5 mile) long northeast-trending belt and eruption of the Lathrop Wells cone ~76,000 years ago (±5,000 years) (Faulds et al., 1994; Crowe and Carr, 1980; Heizler et al., 1999). The presence of volcanic ash from the Lathrop Wells eruption in fissure fills observed in paleoseismic trenches along multiple faults indicates possible structural linkages and temporally synchronous activity. Although a drastic change in the volcanic history and hazard is not anticipated, the studies mentioned above and others are dated, and a review of imaging techniques for magma bodies in the lower crust coupled with modern probabilistic volcanic hazard assessments would be judicious.

Data Gaps, New Technologies, and Recommendations

The previous efforts to understand the seismic hazards at Yucca Mountain, including fault mapping, paleoseismic trenching, and fault parameter characterization, represent a massive effort conducted over several decades by multiple agencies and many experts. These studies utilized established state-of-the-science techniques available at the time. However, advancements in methodologies and technology related to mapping and trenching over the last 25 years indicates that improvements can be made to the analyses. A number of uncertainties and limitations have been identified and constitute data gaps that could be further investigated to develop a better characterization of the seismic hazards at Yucca Mountain and potential risk to the proposed repository and facilities.

Lidar is a remote sensing technology that uses 3-D laser scanning to make high resolution maps, which became a standard tool in paleoseismic investigations (e.g., Haugerud et al., 2003) generally after studies at Yucca Mountain ended. Today, lidar is the industry standard for site characterization studies for major infrastructure projects. Lidar data generates bare-earth hillshade images of the Earth's surface (removes vegetation) and provides an unparalleled means to identify subtle topographic features, such as fault scarps. Derivative base maps can be generated from lidar data, including slope, aspect, surface roughness, and intensity, allowing more detailed topographic analyses and fault assessment (Koehler and Ferrell-Woods, 2013; Frankel and Dolan, 2007).

Acquisition of lidar for the region surrounding Yucca Mountain could help improve the understanding of seismic hazards in two primary ways. First, inspection of lidar hillshade images and derivative products would improve the accuracy of fault location mapping and facilitate recognition of subtle fault traces and subsidiary strands not easily identifiable on aerial photographs or in the field. Lidar mapping also has the potential to identify previously unrecognized faults. Second, the improved mapping would provide a basis for more precisely locating sites for paleoseismic trenching studies. This is particularly important for potentially reevaluating sites previously determined to not contain evidence of Quaternary faulting and potentially investigating faults not previously trenched.

The experimental dating techniques applied in the previous paleoseismic studies are well established today. In particular, advances in U-series dating of pedogenic (soil) opaline silica, chlorine-36 depth profile dating of geomorphic surfaces, optically and infrared stimulated luminescence (OSL and IRSL), and amino acid racemization (AAR) dating of subsurface sediments and fossils now have the ability to constrain ages to 1,000's of years as opposed to the tens of thousands of years previously obtainable (Maher et al., 2007, 2014; Kurth et al., 2011; Redwine et al., 2020). Additionally, modern modeling of radiocarbon dates can now place statistical constraints on the timing of paleoearthquakes (Lienkaemper and Ramsey, 2009). Thus, these modern dating and modeling techniques can greatly reduce the uncertainties in earthquake timing data evaluated from trenches, and their application would improve assessment of the seismic hazards at Yucca Mountain.

RECOMMENDATIONS FOR ADDITIONAL STUDIES: Based on this initial review, several recommendations that could be applied to future investigations to improve the seismic hazards characterization at Yucca Mountain have been developed. During the second phase of this review, we plan to acquire additional identified sources of data pertaining to paleoseismic trenching and fault parameter characterization and summarize these data in a more comprehensive report. It is anticipated that the next phase of the review will result in additional recommendations for the types of investigations that could be conducted to expand the observations and interpretations of the previous studies into a more complete seismic hazards assessment. In particular, the review will highlight which faults are the least characterized providing a basis for determining where additional focused studies and/or trenching may be warranted.

A paramount first step toward improving the seismic hazards characterization is the acquisition of lidar data for Yucca Mountain and the surrounding area. It is recommended that the lidar data be processed to develop base maps (hillshade and other derivative products) in order to highlight subtle features in the landscape indicative of active tectonics. These maps could be compared to previous fault trace mapping to refine the location of active faults and potentially identify previously unrecognized faults and/or subsidiary fault traces. The maps would also be helpful in identifying and assessing the suitability of sites for paleoseismic investigations aimed at better characterizing fault rupture parameters. This is particularly important for faults in which the characterization was based on only a few trench sites that may or may not have intersected the fault due to imprecise mapping.

Natural exposures of faults in the Yucca Mountain area that have previously been described and interpreted provide a cost-effective opportunity to re-evaluate the timing of paleoearthquakes using modern dating techniques. It is recommended that an assessment of which exposures would be amenable to such a study be performed to assess the level of effort that would be required. This assessment could be performed by a combination of office-based imagery inspection and field reconnaissance. Additionally, some of the trench exposures may not have been completely backfilled, and it is recommended that these be inspected for the potential to date exposed deposits with more precise modern techniques to improve earthquake timing information.

Fault rupture parameters determined in the previous studies have been recorded in multiple compilation reports but have not been incorporated into a modern database. It is recommended that the existing data be compiled into a geodatabase in the ArcGIS platform, including fault location, fault parameter data, trench locations, and references. This will allow sorting, querying, and relational analyses that will in turn permit comparison of paleoseismic records across the region and help evaluate the potential of synchronous ruptures.

Finally, additional studies should be guided and reviewed by a Seismic Hazard Expert Elicitation Panel. Such a panel would include experts from multiple agencies and institutions from across the U.S.

SEISMIC MONITORING

Beginning in the 1960s various levels of seismic monitoring have been conducted by a number of organizations in the vicinity of the NNSS and Yucca Mountain. Early monitoring efforts were driven primarily by underground nuclear testing programs. Meremonte and Rogers (1987) compiled the first comprehensive earthquake catalog in southern Nevada covering 1868-1978 and summarized in von Seggern and Brune (2000). The locations and magnitudes for pre-instrumental historical earthquakes are highly uncertain. These commonly rely on published accounts, felt reports or, beginning in the mid-1900s, on estimates from early instrumentation monitoring efforts in California. Early instrumental catalogs of notable seismicity on the NNSS in the 1960s and early 1970s were published by the Atomic Energy Commission in regular reports and included in the Meremonte and Rogers (1987) compilation. A notable early earthquake monitoring effort was conducted by the USGS following the triggering of significant seismicity after megaton underground nuclear explosions (UNEs) in 1969 on Pahute Mesa in the northwestern NNSS (Hamilton et al., 1969, 1971). UNEs in the 1960s at Pahute Mesa triggered 1000s of microearthquakes over a wide area with some as large as ~M3.5; a temporary network was deployed in the northern

NNSS area by the USGS to record this triggered seismicity. By late-1995 digital seismographs and digital telemetry formed the basis of NNSS area seismic monitoring and building the regional earthquake catalog.

Yucca Mountain Probabilistic Seismic Hazard Analysis (PSHA) Overview

A formal Probabilistic Seismic Hazard Analysis (PSHA) was conducted for the Yucca Mountain site by the DOE in the mid-1990s and followed recommendations of the Senior Seismic Hazard Analysis Committee (SSHAC) of the Nuclear Regulatory Commission. The YM PSHA followed a subject matter expert solicitation process organized around the two fundamental elements of PSHA, seismic source identification and ground motion predictions and their uncertainties. The source identification component involved six teams composed of three subject matter experts covering geology/tectonics, fault analysis, and seismicity. Seismic sources and their parameters in the Yucca Mountain region capable of producing notable ground motions at the site were compiled and assigned weights in a logic tree format. Seismic source parameters included identified seismogenic faults, fault geometries (including dip), and fault extent as well as the potential for fault segmentation during rupture. Areal sources were identified based on historical and instrumental seismicity catalogs developed for the PSHA by DOE; areal sources address buried faults with no known surface expression and earthquakes of a limited magnitude (generally < M6.5) that would not produce surface rupture and therefore have no geologic record. These sources would generally be confined close to Yucca Mountain, although regional areal source zones were recognized by the panels. A technical facilitator compiled information from the subject matter experts into logic trees as input to PSHA calculations that were, in turn, provided to ground motion experts to calculate expected ground motions from identified sources. Six ground motion subject matter experts computed expected ground motions and their uncertainties at specified locations within the Yucca Mountain block. PSHA results, as a compilation of all input from subject matter experts, are the expected annual exceedance probabilities and their uncertainties at a range of frequencies. These results (the computational input and the disaggregation of individual source contributions to the final hazard curves) are covered in detail in the final PSHA report (DOE Civilian Radioactive Waste Management - CRWMS, 1998).

The PSHA results included a set of expected mean and median peak ground accelerations (PGV) and peak ground velocities (PGV) and uncertainties for a range of annual exceedance probabilities (AEP). For nearby faults, high frequency peak motions, 5-20Hz, were controlled and derived from faults near Yucca Mountain. These faults have relatively long recurrence intervals as determined from fault studies and slip rate estimates. The Death Valley fault system was the primary source of ground motions at longer periods, in the 1-2 Hz range. The slip rate and short recurrence intervals for the Death Valley fault system are significantly higher and shorter, respectively, than faults in the Yucca Mountain area. Based on the methodologies applied in the mid-1990s PSHA, 10-4, 10-6 and 10-8 AEP at rock sites were calculated at 0.7g, 3.0g and 10g, respectively. The very high motions are the result of extending the range and uncertainties of ground motion estimates to the tails of lognormal distributions at low probabilities. These ground motions were understood to be non-physical and initiated the USGS extreme ground motion study (Hanks et al., 2013). A number of physical assessments of rock units at Yucca Mountain were applied to determine if the high ground motions determined in the PSHA were actually experienced through the geologic history of site.

An important constraint on the recent geologic history of ground motions in the Yucca Mountain area were derived from the observations and studies of the fragility of precariously balanced rocks, initiated at UNR. The initial studies were motivated by observations of rock falls at Little Skull Mountain following the 1992 M5.7 earthquake, where some rocks units failed and others survived earthquake ground shaking. The implied that ground motion constraints from the earthquake could be determined by evaluating the fragilities of balanced rock units and their survival history. The volcanic tuff geology and terrain at Little Skull Mountain is very similar to the steep rock faces and cliffs at Yucca Mountain, where precarious balanced rock units were also identified. Age dating of the structural support and fragilities of balanced rock units were determined to estimate the time length that rock units had been in place. A methodology was developed, and field studies were conducted to provide constraints on the level ground motions experienced at precarious rock locations over time (Anooshehpoor et al., 2004, Purvance et al., 2006, 2012). These results were associated with PSHA hazard curves, where balanced rock studies showed that the PSHA generally overestimated ground motions, for those return intervals, or that motions were at the low end of the PSHA probability curves.

Updates to recommendations to the SSHAC expert solicitation process, as a result of the Yucca Mountain PSHA, are reported in Budnitz et al. (1997). Stamatakos (2017 and references therein) provided an excellent summary of the YM PSHA process and results and also summarized studies motivated by the findings of the Yucca Mountain PSHA.

The information provided in this report on the history of seismic networks and earthquake monitoring in the Yucca Mountain area relates to input to both the seismic source and ground motion prediction elements of the Yucca Mountain PSHA. In other words, comprehensive instrumental monitoring provides a catalog of the location of seismic sources, both fault confined seismicity and areal sources, within the tectonic environment and an archive of ground motions measured on seismic sensors within the network.

Yucca Mountain Project (YMP) Analog Seismic Network 1978-1995

Beginning in 1978 under the Yucca Mountain Site Characterization Program the USGS installed the first regional seismic network (Figure 7A), which was referred to as the Southern Great Basin Seismic Network (SGBSN). This network covered roughly a 400x400 km (~250x250 miles) region and was configured with then state-of-the-art analog technology seismographs and telemetry systems. Much of this early network was telemetered on phone-lines and archived on photo-chemical processed 'develocorder' film; these film records were intended to be the permanent data archives. This was the primary network for regional and NNSS area earthquake monitoring through the latter half of the 1990s. Early seismic processing systems to digitize analog signals were designed for 'event-based' triggering and creating waveform event sub-sets from network stations. Unlike modern digital network systems that maintain continuous waveform records, early digital processing therefore relied on a triggering algorithm and returned incomplete records of ongoing seismicity. Various processing and archiving techniques evolved from these early systems through late-1995, when a digital network became the 'official' (YMP Quality Assurance [QA] Program) source of regional network catalog.

The Nevada Seismological Laboratory (NSL) at the University of Nevada Reno (UNR) assumed operations of the SGBSN for YMP in September of 1992. This was coincidentally ~4 months after the M5.7 June 29, 1992 Little Skull Mountain earthquake (Smith et al., 2001), the most significant historical earthquake on the NNSS. NSL conducted operations of the SGBSN to include station operations, telemetry, and regional catalog compilation, under YMP QA. NSL extended its analog microwave telemetry systems into the NNSS, Death Valley, and eastern Nevada, replacing phone-line based seismic network data communications. Routine data analysis was conducted on a USGS Caltech-USGS seismic processing (CUSP) VMS based processing system - A/D processor, phase picking, earthquake locations and magnitudes. An overlap in operations with the USGS from mid-1992 confirmed the consistency of catalog completeness and magnitudes through the USGS-NSL transition. Earthquake location routines, magnitude estimates, and short-period focal mechanism algorithms are summarized in regular reports (see references). The Yucca Mountain Probabilistic Seismic Hazard Analysis (PSHA) 'seismic source zone/background seismicity component' was based on seismicity through August 1996 and was therefore nearly completely analog-network-era seismicity catalogs.

YMP Digital Network 1995 to 2008 – Installation/Operations

By FY96 YMP (October 1, 1995) regional seismic monitoring transitioned to digital seismographs and digital communications. Shortly thereafter, most of the original SGBSN analog network, near Yucca Mountain, was removed. Some analog stations have remained (some are in place today), but beginning Q1 FY96 the QA YMP earthquake catalog was developed strictly from the digital network (Figure 7B; the completed digital network). Analog stations return only about 10bit resolution data and are subject to radio frequency (RF) interference at any point along the telemetry path. Also, all but a few analog stations in the SGBSN were configured with a single vertical component 'L4' 1Hz velocity sensors. Southern Nevada strong motion stations (which would remain on scale even for large events) were operated for the DOE UNE program by Blume and Associates, and the data were not generally available. This network was removed in late-1992 following the end of the UNE testing at NNSS. Digital era stations were re-sited to address YMP seismic research needs (i.e., analog stations were not simply replaced). The YMP digital monitoring network was a first-of-its-kind digital seismic network in the U.S.

Digital seismograph stations provide on-scale high-dynamic range recordings. When strong motion sensors are coupled with velocity sensors at 6-channel sites (i.e., two sets of ZNE channels), all ground motion levels recorded at a site are assured to be on-scale. In comparison, nearly all analog network recordings from significant events (e.g., M > 2) are 'clipped', exceed the dynamic recording range of the system, and therefore provide no direct amplitude information. To account for 'clipping' of the signal, duration magnitude algorithms are applied to analog station data for event magnitude determinations. Digital network stations in the 1995 YMP digital upgrade were configured with 3- or 6-channel 24bit RefTek digitizers and 3-component S-13 sensors, from which Richter local magnitudes could be determined. The digital network included new power system designs, secure buried sensor vaults, and digital radios for data communications. The telemetry system was redesigned to accommodate digital data along the microwave data path from NNSS to the NSL data center in Reno.

An important part of the transition to digital operations in 1995 was adopting the BRTT (Boulder Real-Time Systems) 'Antelope' seismic data processing system. A current version of Antelope is in operation today. It is a robust relational database system and real-time processing front-end that provides the tools to operate in a modern digital data collection environment. All event data, phase arrivals, station metadata/history, etc., are complete for all NSL and NNSS seismic monitoring since 1995 to present. Post processing and analysis of seismic data is conducted using Application Programming Interfaces (APIs) provided in the 'Antelope' system. 'Antelope' seismic network processing, phase picking, and event locations and magnitudes were incorporated in formal YMP QA network operation procedures.

With the transition to a digital network, numerous strong motion sensors were added to the network. Three borehole accelerometers ('uphole/downhole' pairs) were installed in boreholes in the Midway Valley area for assessing upward propagating seismic energy and site effects. In the 2000s additional 'uphole/downhole' sets of instruments were installed at the surface and within the ESF (Exploratory Studies Facility) at depth for evaluation of repository level ground motions. To further assess ground motions through the repository block, a number of levels of sensors in borehole UZ16 (central repository block) were instrumented to record upward propagating weak motion energy (UZ16 was instrumented with 4.5Hz geophones to a depth of ~2000 ft for engineering studies). Many of the studies anticipated with these data were never carried out with project close out in 2008.

Regular seismicity reports were submitted to the YMP on seismicity in the NNSS vicinity beginning in the late-1980s through late-2000s (see Harmsen, 1987-1993; Rogers et al., 1983; von Seggern and Smith, 1997-2007), when the YMP was discontinued. These reports described seismic monitoring efforts, including network operations and processing procedures for the YMP area earthquake catalog and short-period focal mechanisms database. These reports also summarize notable events and earthquake sequences.

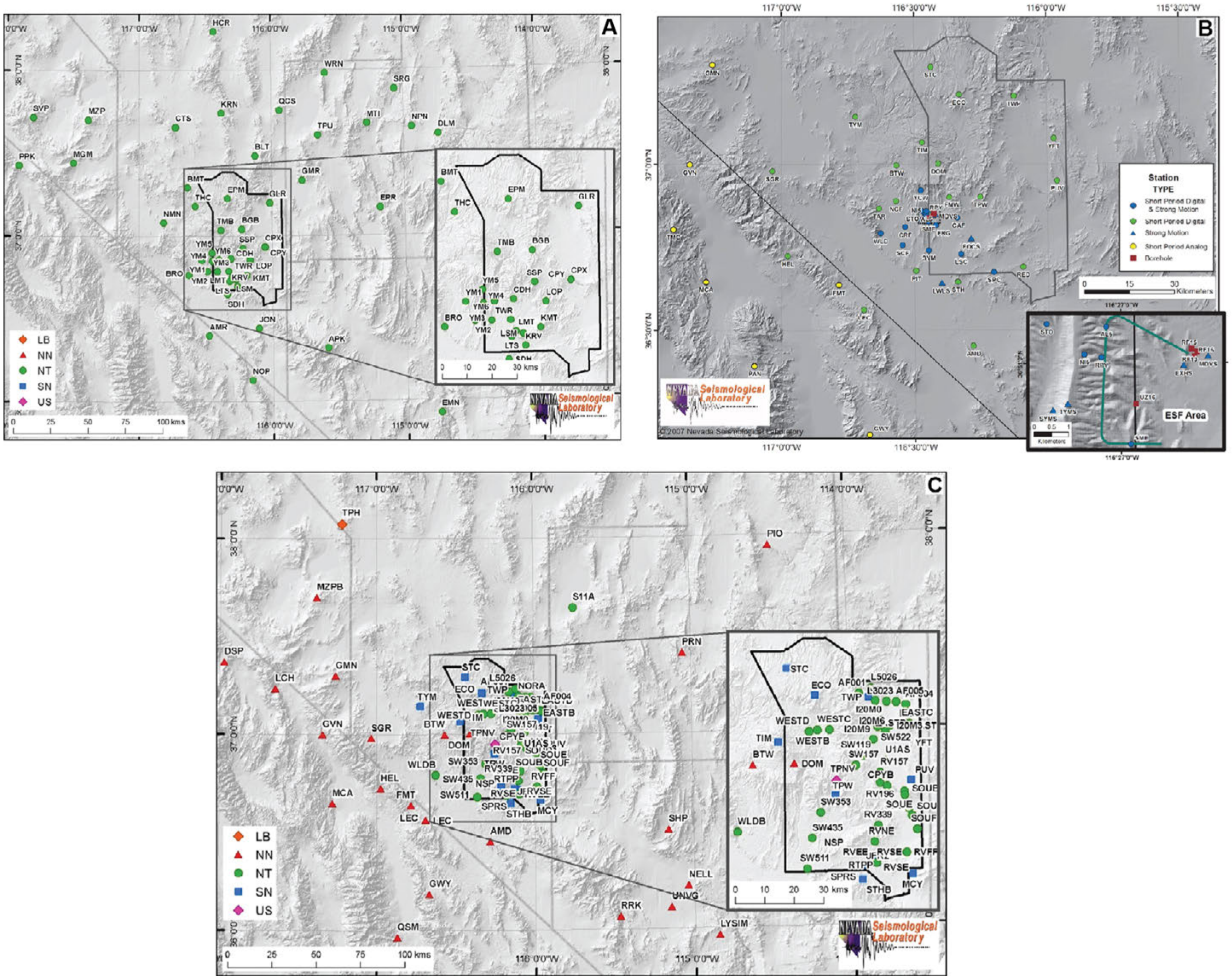

Figure 7. A. 1978-1996 analog seismic network, SGBSN. **B.** Yucca Mountain Project digital seismic network, 1995-2008. Borehole denotes approximate location of proposed repository. **C.** Current seismic monitoring networks in southern Nevada. Legend shows contributing networks; LB: Leo Brady Network, NN: Nevada Network, NT: NNSS Network (SPE), SN: NNSS NSL operated; US: U.S. Geological Survey National Network.

Post-YMP Seismic Monitoring in the NNSS Region

At the end of the YMP, most digital seismic stations operated by NSL on NNSS were removed. Coincidently, the DOE, led by the National Laboratories, retained eight on-site NNSS YMP stations to maintain the NNSS area catalog and to support ongoing DOE experiments. That support has continued under the Source Physics Experiment (SPE; https://www.nnss.gov/docs/fact_sheets/DOENV_1564.pdf) and has essentially assured a level of continuous seismic monitoring since the late 1970s. NSL has continued to provide support for SPE data collection, network operations, and data archives. Under SPE objectives stations have been added to the NSL-operated digital microwave network on NNSS (Figure 7C). This high quality, primarily broadband sensor network, is operated continuously for the SPE mission, and many stations are incorporated into NSL routine monitoring for developing the Nevada regional earthquake catalog, with the permission of DOE. The SPE project also added seismic stations at regional distances improving seismic monitoring throughout southern Nevada. The current high performance real-time seismic network on NNSS under the SPE program does not include stations directly at Yucca Mountain.

Summary of the Seismicity in the Vicinity of NNSS

Figure 8A and 8B show seismicity during the SGBSN and digital network eras, respectively, in an approximately 150x150 km (93x93 miles) region surrounding NNSS. There were 8,096 events in the 1978-1999 analog recording period and 67,958 (as of July 23, 2020) in the 2000-current earthquake catalog. Those numbers can be misleading with respect to activity rates. For one, the digital network (1996-present) is configured with modern 24-bit multi-channel dataloggers and more sensitive seismic sensors. In addition, digital telemetry improves signal/noise levels. Modern processing software is significantly more efficient for capturing regional seismicity at small magnitudes. Also, the Little Skull Mountain aftershock sequence is still a persistent source of small magnitude earthquakes and has been active since 1992.

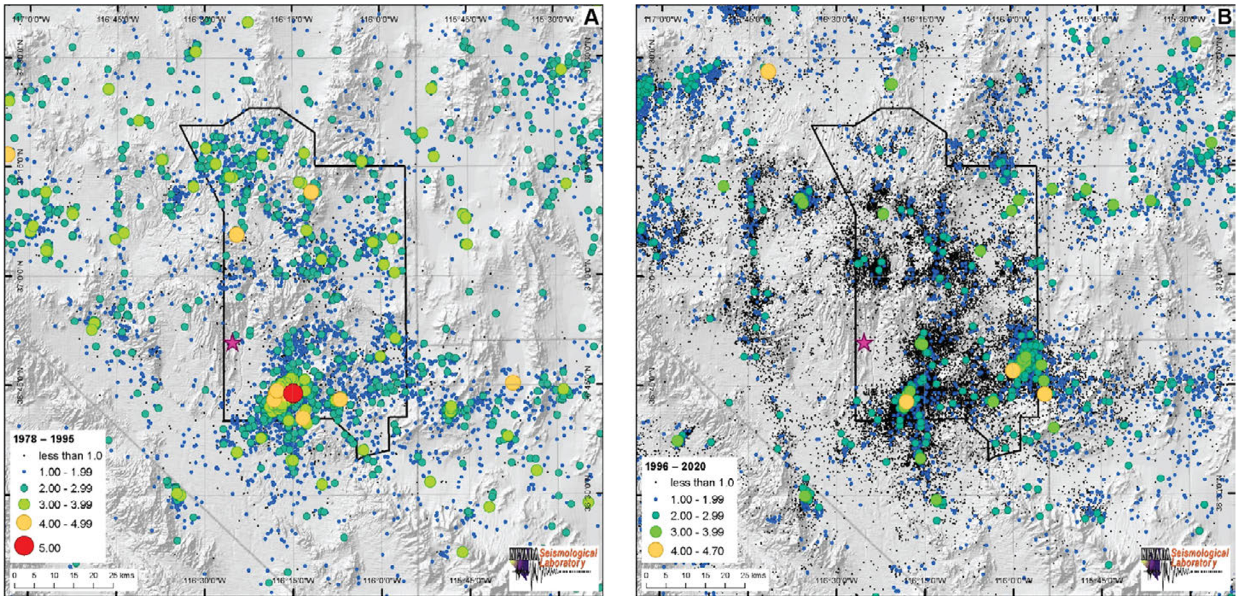

Figure 8. A. 1978-1995 seismicity. **B.** 1996-200 seismicity. Pink star denotes the location of Yucca Mountain and the proposed repository in both A and B.

NOTABLE RECENT EARTHQUAKES IN THE VICINITY OF NNSS

- **1992 Little Skull Mountain Earthquake:** The most significant historic event near Yucca Mountain was the June 29, 1992 M5.7 Little Skull Mountain (LSM) earthquake (Meremonte et al., 1985; Smith et al., 2001) in southwestern NNSS. The LSM earthquake involved normal faulting on a northeast-striking fault dipping southeast. Temporary stations were deployed in the aftershock zone shortly after the event by NSL and the USGS. The earthquake was strongly felt in Las Vegas and was well recorded on the Blume regional strong motion network. The LSM earthquake occurred about 22 hours following the 1992 M7 Landers, California earthquake and was one of a number of earthquakes in the Walker Lane region apparently triggered by the Landers event (Anderson et al., 1992). LSM Foreshock activity began shortly after the Landers event and include several M3 events.
- **1999 Frenchman Flat earthquake:** The M4.7 Frenchman Flat earthquake occurred just east of the eastern extent of the Rock Valley fault zone. The earthquake involved relatively shallow normal movement along a northeast-striking fault dipping northwest near the southern edge of Frenchman Flat. This event was felt in the Las Vegas area.
- **1999 Scottys Junction earthquake:** The August 2, 1999 M5.6 Scottys Junction earthquake, about 55 km (34 miles) northwest of Yucca Mountain, was also felt in the Las Vegas area. It was also a normal faulting event with an extended aftershock sequence. It was well recorded on the SGBSN.

- **1993 Rock Valley sequence:** A sequence of very shallow earthquakes occurred along the Rock Valley fault zone about 30 km (20 miles) southeast of Yucca Mountain beginning in May of 1993 (Smith et al., 2000; Shields, 1999; Walter et al., 2012). The mainshock was moment magnitude (Mw) 3.8 (Richter local magnitude [ML] 4.1), and the sequence was associated with a fairly larger number of small events. A portable network stations deployed in the sequence area recorded 100s of small events with short S-wave minus P-wave arrival times confirming the shallow character of the sequence. The Rock Valley earthquake has been of interest in discrimination studies (Walter et al., 2012), source studies (Shields, 1999), and for evaluating the seismic hazard near Yucca Mountain.
- **1998 Sequence in northern Jackass Flat:** A M3.9 earthquake and associated aftershock in northern Jackass Flat southeast of Calico Hills is of interest due to its proximity to the YMP site (von Seggern et al., 2001). The earthquake occurred about 20 km (12 miles) east of Yucca Mountain.
- **Little Skull Mountain aftershock zone:** The aftershock zone of the 1992 M5.7 LSM earthquake has been a persistent source of seismicity in the NNSS area since 1992. This source zone has been the dominant component of the NNSS area earthquake catalog since the LSM event.

ESTIMATE OF EARTHQUAKE CATALOG COMPLETENESS

The completeness levels (minimum magnitude of detection) have varied through the years of monitoring. As discussed above, the sensitivity of the digital network over the older analog network accounts for a substantial difference. The completeness level will vary geographically. During the 1996-2008 period, with a high density of stations at Yucca Mountain, the detection threshold was close to M -0.5. Following the end of the YMP from 2008-present, the new network configuration improved the detection threshold in eastern and southeastern NNSS, whereas it is now higher in magnitude at Yucca Mountain. References to the magnitude completeness level during the YMP phase of monitoring is included in yearly project reports. The detection threshold currently at Yucca Mountain is roughly, and subjectively, near M ~0.0. We can say with confidence that no significant events at or near Yucca Mountain, since the project end, have been missed.

SIGNIFICANT NEVADA AND SOUTHERN BASIN AND RANGE EARTHQUAKES SINCE 1993

- **1993 Mw6.1** Eureka Valley, California, 125 km (78 miles) west of Yucca Mountain.
- **2008 Mw6.0** Wells, Nevada; 500 km (311 miles) northeast of Yucca Mountain.
- **2019 Mw 6.4** Ridgecrest, California (foreshock); 165 km (103 miles) southwest of Yucca Mountain.
- **2019 Mw7.1** Ridgecrest, California; 165 km (103 miles) southwest of Yucca Mountain.
- **2020 Mw6.5** Monte Cristo Range, Nevada; 195 km (121 miles) northwest of Yucca Mountain.

Although not generating ground motions to impact NNSS or the Yucca Mountain site, scientific studies of these Basin and Range earthquake sequences are relevant to understanding expected ground motions at NNSS for nearby earthquakes of equivalent size. However, due to the unpredictable and unexpected nature of circumstances and personal situations, it is worth noting that a fatality in Pahrump, Nevada was caused by ground motions from the larger Ridgecrest earthquake. A gentleman happened to be working underneath his car when his support structures failed.

Data Gaps, New Technologies, and Recommendations

Some new technologies that could impact scientific assessments of Yucca Mountain include the following:

- **Ground motion prediction:** There has been a revolution in seismic network operations, software systems, data acquisition systems, and data access/archive since the end of YMP. For example, significant limits in computation power were a reality in the early 1990s PSHA ground motion calculations, when ground motion prediction results were incorporated in license documents. Due to these limitations it is obvious that ground motion predictions were limited in the PSHA and should be revisited with modern applications. At any rate, these modern applications should be used to validate PSHA results. Modern multi-processor forward modeling codes (e.g., SW4; https://geodynamics.org/cig/files/3715/0593/5513/SW4-UsersGuide.pdf) can efficiently model numerous potential fault sources and provide a means to validate Earth models necessary to generate meaningful high-frequency synthetic waveforms. NSL researchers are actively engaged with National Lab researchers using the SW4 forward modeling code to model ground motions from Source Physics Experiment explosion sources. We have had had the luxury of using LLNL supercomputer run-time for some of the models. As with these ground motion tools, the objective is to define success by matching true recorded ground motion at seismograph stations. This underscores the need for high-quality, well spatially-sampled network stations to validate model input parameters. Forward modeling tools, such as SW4, will bring to Yucca Mountain ground motion prediction studies far advanced of those in the early 1990s.
- **Earthquake early warning (EEW):** The USGS in partnership with regional seismic networks is bringing EEW on-line. It is now a functioning system in some parts of California. NSL is a participant, implementing the system for the eastern California region. We envision EEW as a necessity for any Yucca Mountain activities from underground construction and engineering to handling high-level waste. It is a general safety feature for all citizens to have several seconds to 10s of seconds for warning prior to the arrival of strong ground shaking. EEW does not predict an earthquake but serves as a system engineered to record and identify the magnitude and location of a significant event. With this information, the arrival of strong shaking at any location can be determined, and warning can be issued.
- **High-Bandwidth Wireless Microwave Networks:** In the 1990s digital data acquisition systems were fairly limited and required dedicated telemetry systems. Bandwidth limitations in unreliable communications systems limited what scientific data could be collected. As with many data intensive programs, high-speed dedication private networks are a necessary component of any scientific program requiring robust, high-availability managed networks for real-time information. This has been implemented at NSL. NSL is currently operating a regional high-speed private wireless network that includes 650 real-time wildland fire cameras in NV-CA-OR-ID, about 100 high sample rate seismic and infrasound sensors on NNSS, a variety of weather stations, and about 150 real-time high-dynamic range digital seismographs and strong motion stations. The network is robust and manages injects, and archives about 2TB per day of time-series and video. We make this point because NSL is well poised to implement a world-class data environment within the Yucca Mountain area.

GEODESY (CURRENT DEFORMATION)

Plate tectonics is a generally slow and steady process. As described above, the motion of the Pacific plate relative to the North American plate is the main driver for crustal deformation in Nevada. Over long periods of geologic time, this movement results in the development of the geologic framework, and over shorter time scales it drives slip on faults to generate earthquakes.

The main method of measuring the current accumulation of strain in the Earth's crust is by tracking the positions of GPS monuments with great precision over time and then to compare the motions of different monuments. GPS networks consist of different types of monuments and measurements. Those with the highest fidelity measure continuously, and the monuments are drilled deep into the ground; these are called continuous GPS stations. In the Yucca Mountain area, a network of continuous GPS instruments was installed during the repository site evaluation phase. This network extended into the surrounding region and has recently been complemented by other networks that have been installed under separate initiatives. These combined networks now offer an important perspective of the seismic hazard that is both regionally consistent and relevant to the present day, making them highly complementary to the neotectonic, paleoseismic, and seismic studies.

Data Availability

The locations of continuous GPS stations surrounding the Yucca Mountain repository site are shown in Figure 9. The map also shows semi-continuous stations operated by the Nevada Geodetic Laboratory (NGL) that are occupied for periods of weeks to months when observation is needed (e.g., if a large earthquake occurs). The USGS also has geodetic markers around Yucca Mountain that can be surveyed with campaign-style tripod-mounted systems (Figure 10A).

For the continuous and semi-continuous GPS stations, the velocities of active tectonic motion derived from the data are shown in Figure 10A. These results are publicly available from the NGL website (http://geodesy.unr.edu). GPS is capable of obtaining site positions with a precision better than 1 mm in a global frame of reference every day and velocities to near 0.1 mm/yr (Davis et al., 2003; Hill et al., 2009). Recent years have seen further technical progress in the accuracy of the GPS system, global reference frame, software, and data processing strategies, which collectively provide even better positioning (Blewitt et al., 2019).

The continuous stations belong to different networks, and not all of them are currently operating. Many stations around Yucca Mountain were initially installed to monitor crustal deformation within and around the repository. When Yucca Mountain funding was discontinued, the majority of these stations stopped operating in ~2010 (Figure 9). All these continuous GPS monuments still exist, and for some of them NGL has been able to periodically collect data. Potentially, all the stations currently off-line could be brought back on-line by installing a new GPS receiver and by re-configuring the telecommunications.

The existing network does not provide complete coverage, with notable large gaps east and north of the repository site and NNSS (Figure 10A). This design was likely derived from the state of knowledge at the time of construction that considered most active deformation to be confined to parts of the Walker Lane west of the Death Valley fault. Since that time, data from the GPS network has clearly established that active strain penetrates into Nevada east of Yucca Mountain (Wernicke et al., 2004; Hill and Blewitt, 2006; Kreemer et al., 2010; Hammond et al., 2014). Thus, future extensions of the geodetic work should consider extending the network with additional stations in these directions.

GPS Velocities

Figure 10A shows the velocities of the continuous and semi-continuous stations, obtained from the NGL, and given relative to stable North America. While the velocities of these stations were not necessarily measured over the same time spans, to first order they all indicate steady strain accumulating in the crust that is expected between (large) earthquakes. This can be seen by the fact that velocities increase when taking a transect from the Basin and Range province to the Sierra Nevada (Figure 10B).

The profile in Figure 10B shows the portion (~25%) of the relative motion between the Pacific and North American tectonic plates accommodated across the southern Walker Lane, between the Sierra Nevada and the eastern Basin and Range. These data indicate a general steepening of the velocity gradient (i.e., greater strain rate) toward the Sierra Nevada, and more gradual (but greater than zero) gradients around Yucca Mountain. The gradients amount to ~1 mm/yr across ~70 km. The hazard implications of these measurements are important, because they indicate a greater amount of seismic potential than those from paleoseismic studies, which indicate individual faults in the Yucca Mountain area have slip rates below 0.1 mm/yr (Wernicke et al., 2004; Hill and Blewitt, 2006).

Strain Rates

While the geodetic velocity field (Figures 10A-B) does not uniquely indicate which faults will rupture or when, many studies have indicated a close spatial relationship between strain buildup and release on faults. Higher strain rates are associated with higher seismic moment release rates, and non-zero strain rates indicate non-zero seismic hazard (e.g., Kreemer et al. 2014). Thus, maps of crustal strain rate derived from geodetic data are an excellent proxy for seismic potential and can be combined with other data to form a more integrated picture of hazard associated with regional tectonics. The geodetic data form a separate and highly complementary corroboration of geologic and seismic data by revealing the active deformation field, which sheds light on the style and causes of the underlying processes that drive strain accumulation that is ultimately released in earthquakes.

For the Yucca Mountain area, two strain rate models are readily accessible (Kreemer et al., 2012; 2014). The results for the most recent of the two, which is part of a global model, is shown in Figure 11, together with the velocities at GPS stations that were the input to that model. Strain rates in the Yucca Mountain area are ~15 nanostrains per year. For comparison, strain rates in the San Andreas fault system in California are a couple hundred nanostrains per year, and in stable tectonic plate interiors are only ~1 nanostrain per year. Figure 11 also shows the location of some prominent recent earthquakes, underscoring that large earthquakes occur where strain rates are significant.

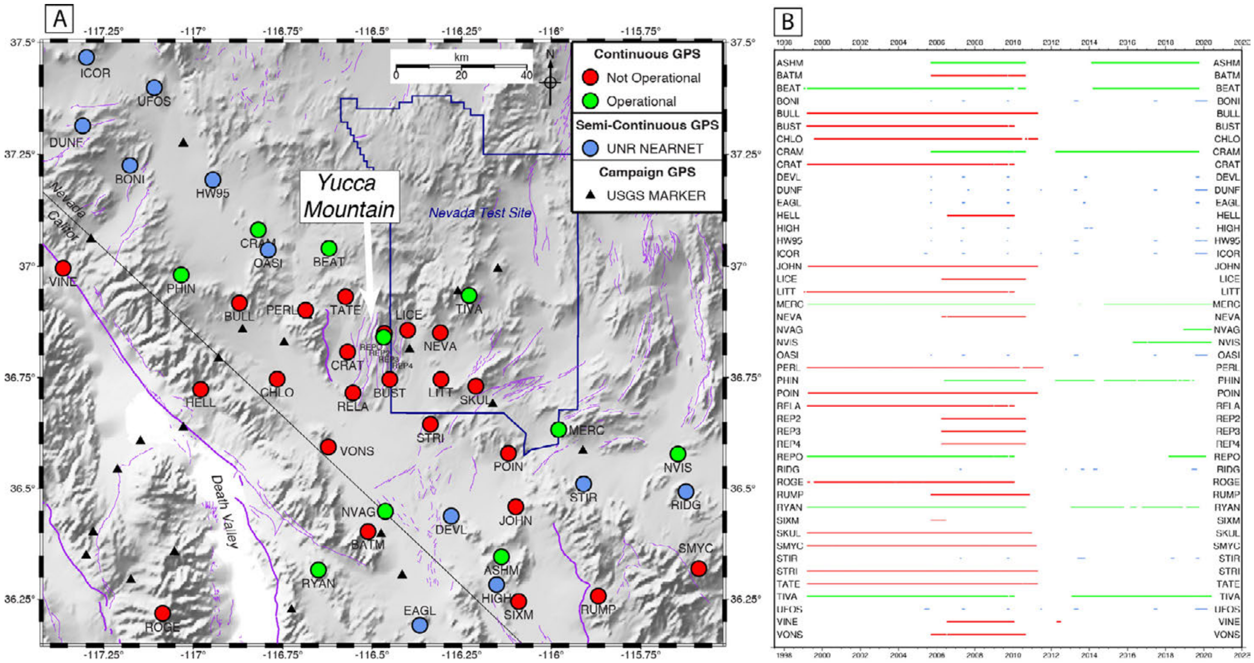

Figure 9. A. Map of Yucca Mountain GPS network station locations. B. Data availability of stations shown on left with corresponding colors (e.g., continuous GPS stations currently not operating are shown in red). Thick purple lines indicate faults from USGS Quaternary fault and fold database [USGS, CGS, and NBMG, 2020] with slip rates available; light purple indicates faults without slip rates.

Transient Deformation

After a large earthquake, there is typically a long-lasting, temporally decaying deformation signal in a large area around the earthquake. This post-seismic deformation is the result of the viscous relaxation of stresses in the Earth's mantle (e.g., Pollitz, 1997; Pollitz et al., 2001). One consequence of lingering post-seismic strain is that the contemporary field that we measure with GPS geodesy may include transients that reflect not only steady strain accumulation, but also include a transient component that can bias the inference of fault slip rates. Earlier modeling found that some, but not all of the measured strain rate may be attributable to the integrated relaxation sequences of the seven most recent large earthquakes in Nevada and California (Hammond et al., 2010). However, those conclusions were based on previous-generation geodetic velocity fields, did not account for all aspects of Earth structure, and did not take advantage of knowledge gained from more recent earthquakes. Unlike the 20th century earthquakes in the Basin and Range, events such as the 2019 Ridgecrest M 7.1 event have excellent constraints on coseismic slip distribution and deformation, promising better constraint on Earth's viscoelastic structure. More research on the relationship between the geodetic measurements and the Earth's rheological properties is needed to better untangle the various sources that contribute to crustal deformation at the Yucca Mountain site.

Other types of transient (not steady) deformation have been observed to occur in the western Great Basin. One example that has been recently shown to have significant impacts is the effect of the load of snow and water in the Sierra Nevada. This occurs as the weight of seasonal snow pack pushes the Earth's crust downward, which redistributes stress on faults in the shallow crust (Kreemer and Zaliapin, 2018). The reverse effect has also been shown to occur over drought periods, cumulatively unloading the crust to effect seismicity and an active volcanic system near Mammoth, California (Hammond et al., 2019). These effects have not yet been detected at Yucca Mountain but could have under-appreciated impacts and should be better understood as part of a comprehensive evaluation of the regional tectonic system.

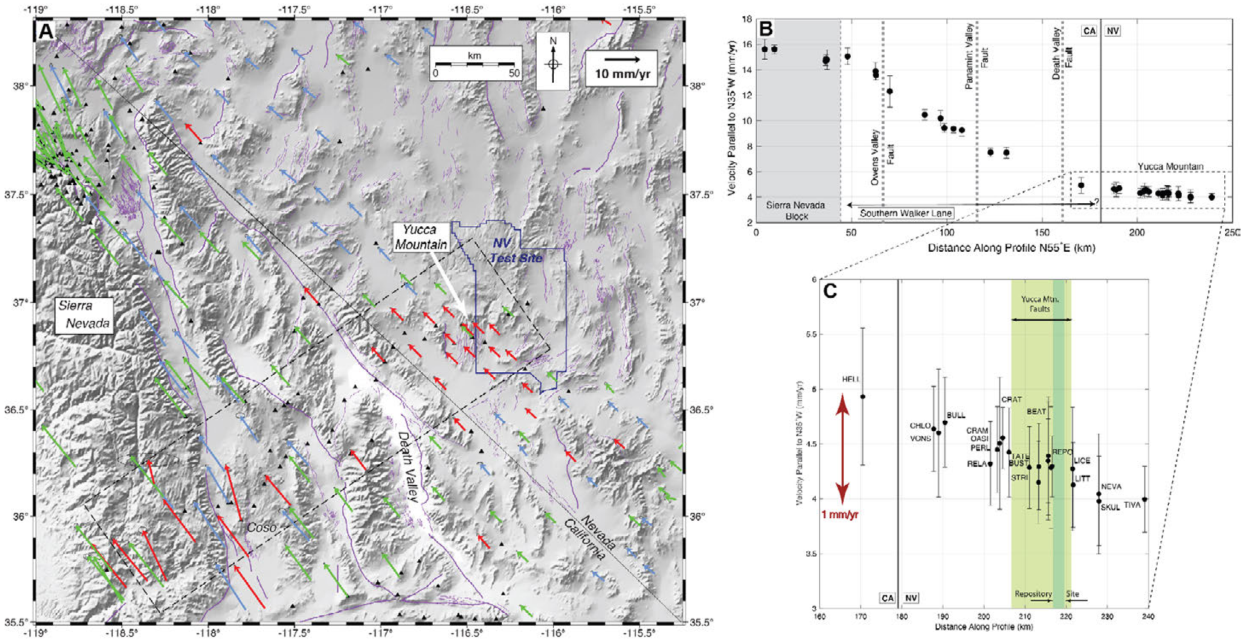

Figure 10. A. GPS velocities from the Nevada Geodetic Lab. Velocities are relative to stable North America and are shown in an oblique Mercator projection around the Pacific-North America pole of rotation. Colors correspond to those in Figure 9. The general increase of the velocity from the NNSS to the Sierra Nevada reveals active deformation. Dashed line encapsulates sites selected for profile shown in B. Faults same as in Figure 9. **B.** Geodetic velocity profile across southern Walker Lane, from the Yucca Mountain area on the east to the Sierra Nevada block on the west (location shown in A). Data indicate a general decrease of the velocity gradient (i.e., lower strain rate) toward the Yucca Mountain region. Error bars indicate 2σ uncertainty bounds on GPS velocity in direction parallel to N35W°, perpendicular to the profile. Profile indicates relative motion of ~12 mm/yr across the area. **C.** Close-up of area immediately surrounding Yucca Mountain and repository site indicating ~1 mm/yr of crustal deformation across 70 km wide region. Four-character names are given for GPS stations in the Yucca Mountain network.

Data Gaps, New Technologies, and Recommendations

The continuous GPS stations around Yucca Mountain were installed in ~1999, spanned the southern Basin and Range province, and were distributed more densely around the future repository. Later, in ~2006 another 14 were installed to densify the network. Unfortunately, most of them became inactive in ~2010 when funding halted (Figure 9). All these stations are of the highest possible quality, and nearly all the monuments are still intact so that measurements could be resumed with a reasonably small investment.

While we have velocities for all discontinued stations, it is important to have most of them back on-line. One reason for a dense high-quality network is the importance of measuring and understanding seismic cycle deformation, such as investigated by Hammond et al. (2010), but also for delineating other potential transient motions that may have heretofore escaped detection. Another example: the absence of this network during the 2019 Ridgecrest earthquake meant that a study improving on recent work at Yucca Mountain was not possible, creating a missed opportunity to constrain Earth's viscosity structure underneath southern Nevada. Such information is paramount to better determine the long-term strain accumulation (which leads to earthquakes) from what is actually measured.

On the basis of our review and the current state of knowledge regarding current deformation in the Yucca Mountain area, we recommend the following tasks for the next phase of this analysis.

- Lay out specific steps that will need to be taken to revive and update the continuous GPS network in the Yucca Mountain area. This would include planned efforts to replace obsolete instrumentation, reestablish telecommunications, and plan continued maintenance of the network.
- Outline a program for analysis of geodetic data, including processing of GPS data, development of higher-level data products such as velocities, strain rate maps, characterization of transient motions including seasonality, earthquake co- and post-seismic displacements, and climate-related signals that are present in the geodetic data.
- Design frameworks and processes for integration of geodetic data with geological, seismic, and other geophysical data into models of structure and active tectonic deformation, including models for slip rates and transient processes.
- Design frameworks and processes to assess implications that the models of physical structure and tectonic systems have for seismic and volcanic hazard of the repository site.

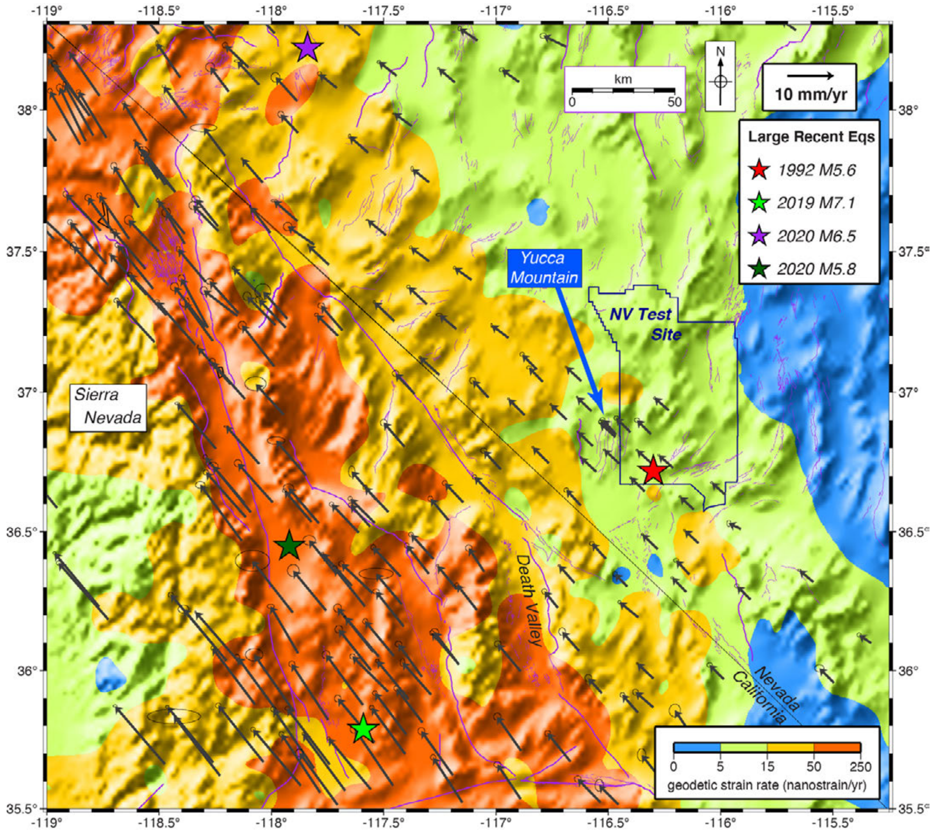

Figure 11. Results from the Global Strain Rate Map (Kreemer et al., 2014). Gray vectors are GPS velocities relative to North America used to make the map. Color contours are second-invariant (i.e., total amplitude) of strain rates derived from the GPS velocities. Also shown are locations of recent relevant earthquakes. Faults same as in Figure 9.

CONCLUSIONS

Yucca Mountain lies in an active tectonic setting within a segment of the Pacific – North American plate boundary (Figure 1A). Consequently, active faults and recent volcanic activity characterize the area (Figure 1B). From the late 1970's to mid-1990's, the history and extent of deformation related to active faulting in the region was extensively studied. Although these studies applied the most advanced techniques and methodologies available at the time, significant advances over the last two decades suggest that previous studies may not completely describe the seismic hazards in the region. We reviewed the tectonic and geologic setting, recent history (i.e., past tens to hundreds of thousands of years) of faulting (paleoseismology), seismic monitoring of earthquake activity over the past several decades, and GPS geodetic data reflecting current crustal deformation in the region. An over-arching theme resulting from this analysis is the need for development of a master geodatabase in the ArcGIS platform for all existing datasets for the area in order to facilitate data integration, synthesis, and innovative modeling techniques (e.g., 3D modeling and machine learning). Key points from analysis of the individual disciplines addressed in this report include the following.

REGIONAL AND LOCAL GEOLOGIC SETTING:

- Yucca Mountain occupies a complex and active tectonic setting in the easternmost part of the Walker Lane at the transition between areas of active strike-slip faulting and crustal extension.
- The Walker Lane currently accommodates ~20-25% of the Pacific-North American plate motion. It began developing ~10 million years ago and is likely to accommodate increasing amounts of plate boundary motion over the next several million years.

- The geologic setting of the Yucca Mountain area is dominated by a series of north-trending, gently tilted fault blocks and related basins, which are generally bounded by active faults that have ruptured in earthquakes in the past thousands to tens of thousands of years.
- Major strike-slip faults of the Walker Lane may underlie Amargosa Valley directly south of Yucca Mountain and may possibly project into the subsurface in the vicinity of Yucca Mountain.
- Several relatively young volcanic centers, ranging from 1.1 million to 76,000 years old, occur in the Yucca Mountain area.
- Published geologic maps (Figure 2) and previous geologic studies have adequately established the geologic setting of Yucca Mountain.
- The subsurface geologic framework could be enhanced through acquisition of additional geophysical datasets and integration of those datasets with available geological data such that both detailed and crustal-scale 3D models can be constructed for the area.

PALEOSEISMOLOGY:

- Detailed investigations from the 1970s to 1990s included Quaternary fault mapping, paleoseismic trenching, and fault rupture characterization for seismic sources within 100 km (62 miles) of Yucca Mountain. The fault rupture studies included analysis of fault slip rates, earthquake timing and recurrence intervals, amounts of displacement per event, cumulative offsets, and elapsed time since the most-recent event.
- The fault characterization data were combined with seismicity, geodetic, and geophysical observations, along with ground motion attenuation models, to develop probabilistic fault displacement and ground motion hazard calculations applicable to seismic design considerations (Youngs et al., 2003; Stepp et al., 2001; Wong and Stepp, 1998).
- Eight faults showed demonstrable surficial evidence of Quaternary activity, and at least 25 trench exposures showed clear evidence of Quaternary displacement on their respective faults (Whitney et al., 2004; Keefer et al., 2004).
- Available data suggest that several seismic events or sequence of events occurred 13,000-3,000, 30,000-20,000, about 50,000, and approximately 76,000 years ago in the Yucca Mountain area (Figure 7; Keefer and Menges, 2004).
- Although previous studies were robust, limitations in the techniques available at the time of the studies results in considerable uncertainty in the ages of events (Figure 5), which has implications for estimating maximum expected magnitudes and resulting ground motions in future earthquakes.
- In the 25+ years since paleoseismic studies at Yucca Mountain ended, there have been many advances in paleoseismic techniques, imagery and topographic data quality, and geochronologic methods for estimating the ages of faulted deposits.

RECOMMENDATIONS TO IMPROVE SEISMIC HAZARDS CHARACTERIZATION AT YUCCA MOUNTAIN INCLUDE:

- Lidar (high resolution topographic imaging) acquisition to refine the location of active faults, identify previously unrecognized faults, and assess the suitability of sites for additional paleoseismic investigations.
- Assess which faults are conducive to utilization of modern dating techniques such that the location, timing, and frequency of paleoearthquakes in the region can be better defined.
- Compile all fault rupture parameters (e.g., location, age relations, trench sites, references, etc.) into a modern geodatabase ArcGIS platform to facilitate synthesis of datasets.

SEISMIC MONITORING:

- Beginning in the 1960s various levels of seismic monitoring have been conducted by a number of organizations in the vicinity of the NNSS and Yucca Mountain. Beginning in 1978 under the Yucca Mountain Site Characterization Program, the USGS installed the first regional seismic network (SGBSN; Figure 7A). The NSL at UNR assumed operations of the SGBSN in 1992. By 1995 digital seismographs and digital telemetry formed the basis of NNSS area seismic monitoring and building the regional earthquake catalog.
- A formal Probabilistic Seismic Hazard Analysis (PSHA) was conducted by the DOE in the mid-1990s (DOE Civilian Radioactive Waste Management - CRWMS, 1998; Budnitz et al., 1997; Stamatakos, 2017). Seismic sources and their parameters capable of producing notable ground motions were compiled and assigned weights in a logic tree format. The 'seismic source zone/background seismicity component' of the PSHA was based on seismicity through August 1996 and was thus nearly completely based on analog-network-era seismicity catalogs.
- The digital seismic network has provided a robust relational database system with real-time processing. With the transition to a digital network, numerous strong motion sensors were added, including instruments in boreholes to assess upward propagating seismic energy and site effects.
- In the 2000s additional 'uphole/downhole' sets of instruments were installed at the surface and at depth for evaluation of repository level ground motions. Many of the studies anticipated with these data were never carried out with project close out in 2008.
- Regular seismicity reports were submitted to the YMP on the seismicity in the vicinity of NNSS beginning in the late-1980s through the late-2000s (Harmsen, 1987 to 1993; Rogers et al., 1983; von Seggern and Smith, 1997 to 2007).
- At the end of the YMP in 2008, most digital seismic stations operated by NSL on NNSS were removed. The DOE retained eight on-site NNSS YMP stations to maintain the NNSS area catalog and to support ongoing experiments. NSL has continued to provide support for data collection, network operations, and data archives. Additional stations have been added to the NSL operated digital microwave network on NNSS (Figure 7C). This high quality, primarily broadband sensor network, is operated continuously. However, the current high performance real-time seismic network on NNSS does not include stations directly at Yucca Mountain.
- In an approximately 150x150 km (93x93 miles) region surrounding NNSS, there have been 67,958 recorded seismic events since the year 2000 (Figure 8B) and six notable earthquakes or earthquake sequences since 1992, ranging from M3.8 to M5.7.
- Five significant earthquakes, ranging from M6.1 to M7.1, have occurred in broad region surrounding Yucca Mountain since 1993 (125 to 500 km [78 to 311 miles] from Yucca Mountain).
- Some new technologies that could impact seismic monitoring of Yucca Mountain include ground motion prediction, earthquake early warning, and high-bandwidth wireless microwave networks.

GEODESY:

- A network of continuous GPS instruments was installed during the repository site evaluation phase. This network has recently been complemented by other networks (Figure 9). The combined networks offer an important perspective of the current deformation and seismic hazard in the area.
- GPS is capable of obtaining site positions with precisions <1 mm and velocities to near 0.1 mm/yr.
- The existing network does not provide complete coverage, with notable large gaps east and north of Yucca Mountain and the NNSS (Figure 10A).

- The GPS data (Figure 10B) show that ~25% of the relative motion between the Pacific and North American tectonic plates is accommodated across the southern Walker Lane between the Sierra Nevada and eastern Basin and Range province. These data indicate a general increase of the strain rate toward the Sierra Nevada and more modest gradients of ~1 mm/yr around Yucca Mountain. These strain rates indicate a greater amount of seismic potential than those derived from paleoseismic studies.
- Most of the GPS stations in the Yucca Mountain area became inactive in ~2010 when funding halted (Figure 9).
- Recommendations for future geodetic analysis in the Yucca Mountain area include 1) revive and update the continuous GPS network, 2) outline a comprehensive program for analysis of geodetic data that includes development of velocities, strain rate maps, and characterization of transient motions, and 3) design frameworks and processes for integration of geodetic data with geological, paleoseismic, seismic, and other geophysical data into models of active tectonic deformation.

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