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U.S. DEPARTMENT OF ENERGY

Nevada
Nuclear
Waste
Storage
Investigations
PROJECT
YUCCA MOUNTAIN

TECTONIC STABILITY AND EXPECTED GROUND MOTION AT YUCCA MOUNTAIN

Report of a Workshop at SAIC - La Jolla
August 7-8, 1984 and January 25-26, 1985

FINAL REPORT

December 1985

WORK PERFORMED UNDER CONTRACT NO. DE-AC08-83NV10270

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Prepared by Nevada Nuclear Waste Storage Investigations (NNWSI) Project participants as part of the Civilian Radioactive Waste Management Program. The NNWSI Project is managed by the Waste Management Project Office of the U. S. Department of Energy, Nevada Operations Office. NNWSI Project work is sponsored by the Office of Geologic Repositories of the DOE Office of Civilian Radioactive Waste Management.

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EXECUTIVE SUMMARY

The historic seismic record at Yucca Mountain is too brief and incomplete to provide an accurate assessment of the frequency/magnitude relationship of the quality required to extrapolate future seismicity. The present northwest-southwest extension rate in the general area of Yucca Mountain appears to be of the same order as that across that entire southern Great Basin averaged over the last 15 million years. Thus, Quaternary tectonic activity can be used as a rough indicator of future activity.

In situ stress measurements indicate that failure is possible along favorably oriented faults in the Yucca Mountain region. However, no quantitative statements about earthquake probability and magnitude (M) associated with the failure can be determined from in situ data alone. Both weapons tests at the Nevada Test Site (NTS) and impoundment of water at Lake Mead near Las Vegas have induced or triggered earthquakes of magnitudes as high as 4 or 5 within 14 kilometers of those locations.

It is quite likely that all faults with significant scarps indicative of large earthquakes ($M_s > 7$) during the Quaternary-Holocene have been located and mapped. However, fault segmentation and the possibility of strike-slip motion complicate the precise identification of active faults and potential fault rupture length. A magnitude 6 earthquake could plausibly occur within 15 kilometers of the site unassociated with a known fault and could possibly exceed 0.4g at the site. Such an event is unlikely during the preclosure phase of repository construction, operation, and closure. Present estimates of peak ground acceleration at Yucca Mountain are based on empirical relationships that were not specifically derived for normal, oblique-slip, or strike-slip faults within an intraplate extensional regime. Thus, they should be evaluated for application to the Yucca Mountain region, assessed for standard error and uncertainties, and updated with more recent empirical data as appropriate.

The Death Valley region is about 50 kilometers from Yucca Mountain. This region may have a potential for producing large earthquakes, but more study is required to assess its earthquake capability. Ground motion in compressional regimes such as southern California may have little relevance for predictions of ground motion in an extensional region similar to Yucca Mountain which could have diminished capacity for generating very high accelerations. In compensation, however, ground motion appears to attenuate less with distance in the southern Great Basin than in California.

The determination of the largest earthquake in the region is highly uncertain because of unknown fault characteristics at depth, and because of tenuous links between fault dimensions and earthquake capacity. To assure adequate design considerations, minor faults may, in some cases, be assigned large earthquake capacity. High-frequency ground motion appears to attenuate significantly with depth, but the site-specific attenuation properties at Yucca Mountain are poorly understood. To ignore potential changes with depth appears to be conservative and is probably the best approach to apply in the absence of site-specific information.

1.0 INTRODUCTION

At the direction of the U. S. Department of Energy (DOE), workshops were convened on August 7 and 8, 1984, and January 28 and 29, 1985, in La Jolla, California, to discuss effects of natural and artifical earthquakes and associated ground motion as related to siting of a high-level nuclear waste repository at Yucca Mountain, Nevada. A panel of experts in seismology and tectonics was assembled to review available data and analyses and to assess conflicting opinions on geologic and seismologic data.

The objective of the meeting was to advise the DOE Waste Management Project Office at Las Vegas, Nevada, about how to present a technically balanced and scientifically credible evaluation of the pre- and postclosure tectonics guidelines for the Nevada Nuclear Waste Storage Investigations (NNWSI) Project Environmental Assessment (EA). The workshop participants are listed in Appendix 1 along with the resumes of the panel of experts.

The group considered two central issues: (1) the overall tectonic stability of the site given the current geologic and seismologic data base and (2) the magnitude of ground motion at Yucca Mountain due to the largest expected earthquake. The group examined each question and prepared discussions which often included major recommendations for more geologic or seismologic studies. These responses have been edited by Drs. W. F. Brace, G. H. Frazier, and H. R. Pratt and are compiled into this report.

2.0 TECTONIC STABILITY ISSUE

Before discussing actual seismic effects at Yucca Mountain, such as ground motion, it is important to assess the likelihood of a major earthquake in the area. How large might such an earthquake be, how close to the site might it occur, and within what period of time? Such questions were examined from a number of different points of view using geologic, seismologic, and borehole data, and using observed seismic effects from the nearby Nevada Test Site (NTS) underground nuclear explosions.

Mapping of potential fault zones, estimates of extension rates in the southern Great Basin, and the general pattern of Holocene tectonic activity in the area are examined from the geologic and seismologic points of view. Borehole measurements of in situ stress might provide a more indirect assessment of earthquake hazard in the area, and the recent measurements made near the site are summarized. Underground nuclear explosions at the NTS might also provide a test of the tectonic stability of the area and data from these explosions are reviewed. Conclusions relevant to Yucca Mountain are presented in this report. Following the reviews of existing data and observations, recommendations for new or additional studies are given.

2.1 LOCATION OF POTENTIAL SEISMOGENIC FAULTS

The vicinity of the NTS and its surroundings shown in Figure 2-1 is one of the most scrutinized areas of the Great Basin in terms of the surface geology, tectonics, and seismicity. Although it is likely that all faults with significant Quaternary-Holocene scarps that are indicative of geologically recent large earthquakes ($M_s \geq 7$) are known, fault segmentation, strike-slip fault motion, and incomplete knowledge of the subsurface structure of the area need to be considered in evaluating the earthquake potential of faults in the region.

In the northern Great Basin (i.e., Wasatch Front), and at Borah Peak (figures 2-2 and 2-3), both historic and prehistoric large earthquakes have been observed or inferred to recur on the same segment of a larger fault. The magnitude of an earthquake on a given segment is likely to be controlled by the segment length. Application of this concept to the Yucca Mountain area requires careful evaluation because the geology of this region may be different than other areas of the Great Basin. Further, it is known that the fault segmentation concept does not apply to all Great Basin earthquakes. For instance, in the 1915 Pleasant Valley earthquake ($M = 7.6$), faulting occurred in a band 6 kilometers wide and 60 kilometers long that followed the trends of four separate fault-bounded range blocks (Wallace, 1979, 1984). The 1932 Cedar Mountain earthquake ($M = 7.3$) produced strike-slip faulting in a band roughly 6 to 14 kilometers wide and about 61 kilometers long on 60 individual traces that did not generate significant scarps or follow significant older scarps (Gianella and Callaghan, 1934). In contrast to these earthquakes, the 1934 Excelsior Mountain event ($M = 6.5$) produced only minor surface faulting.

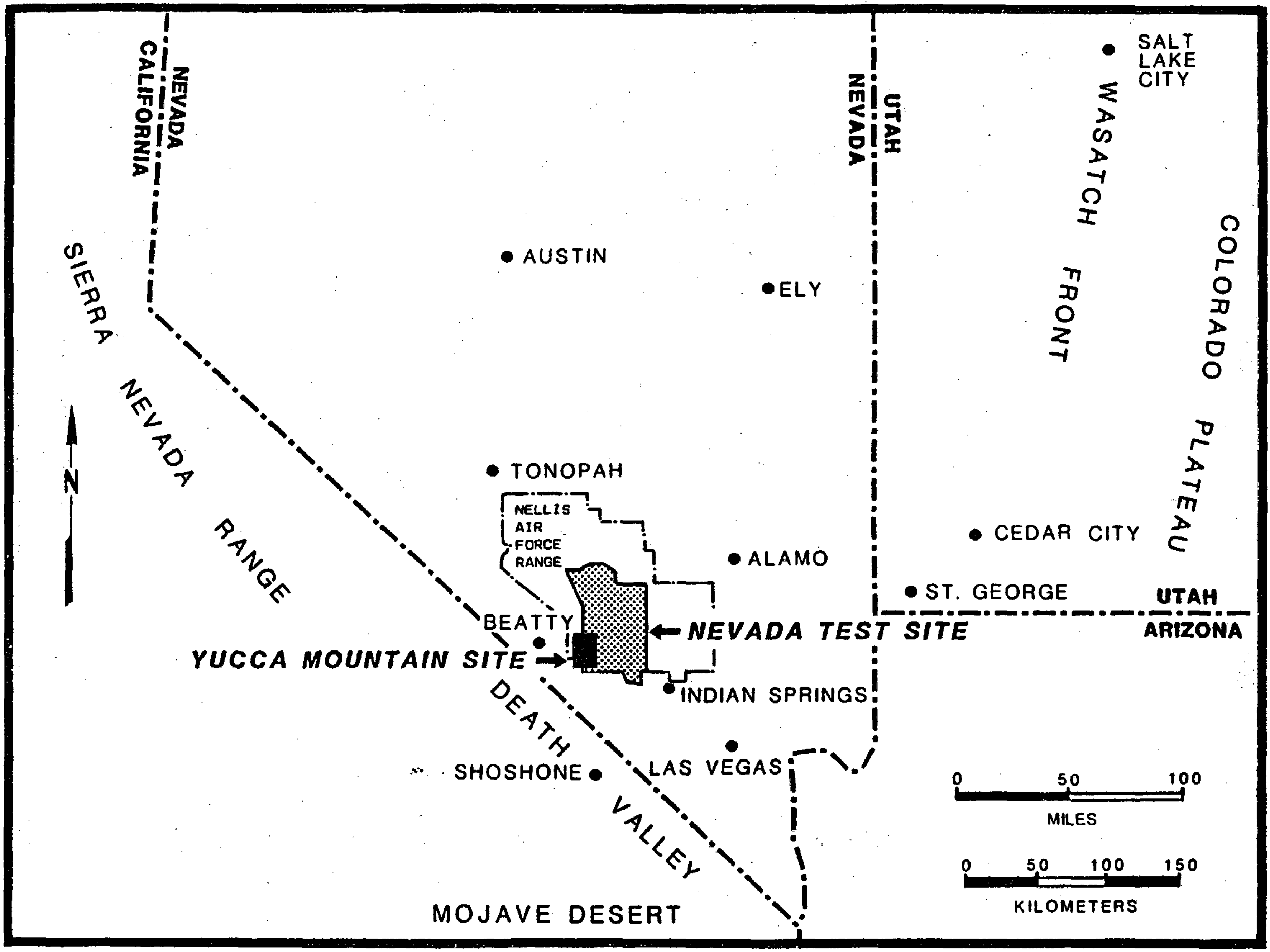


Figure 2-1. Location map showing Yucca Mountain site and Nevada Test Site.

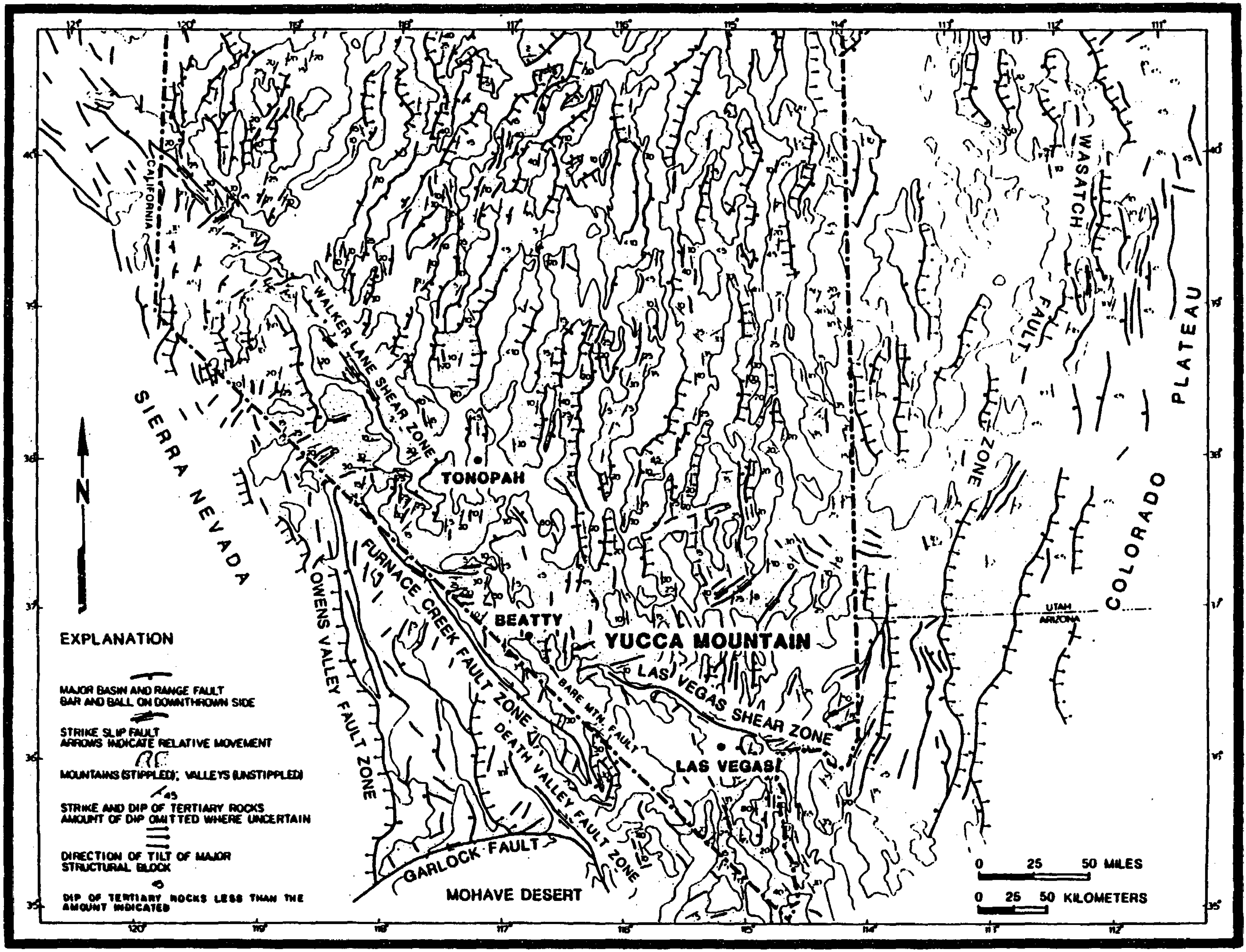


Figure 2-2. Map of southern Great Basin showing major Basin and Range faults, tilt of major structural blocks, and altitudes of Tertiary rocks. Modified from Stewart (1978).

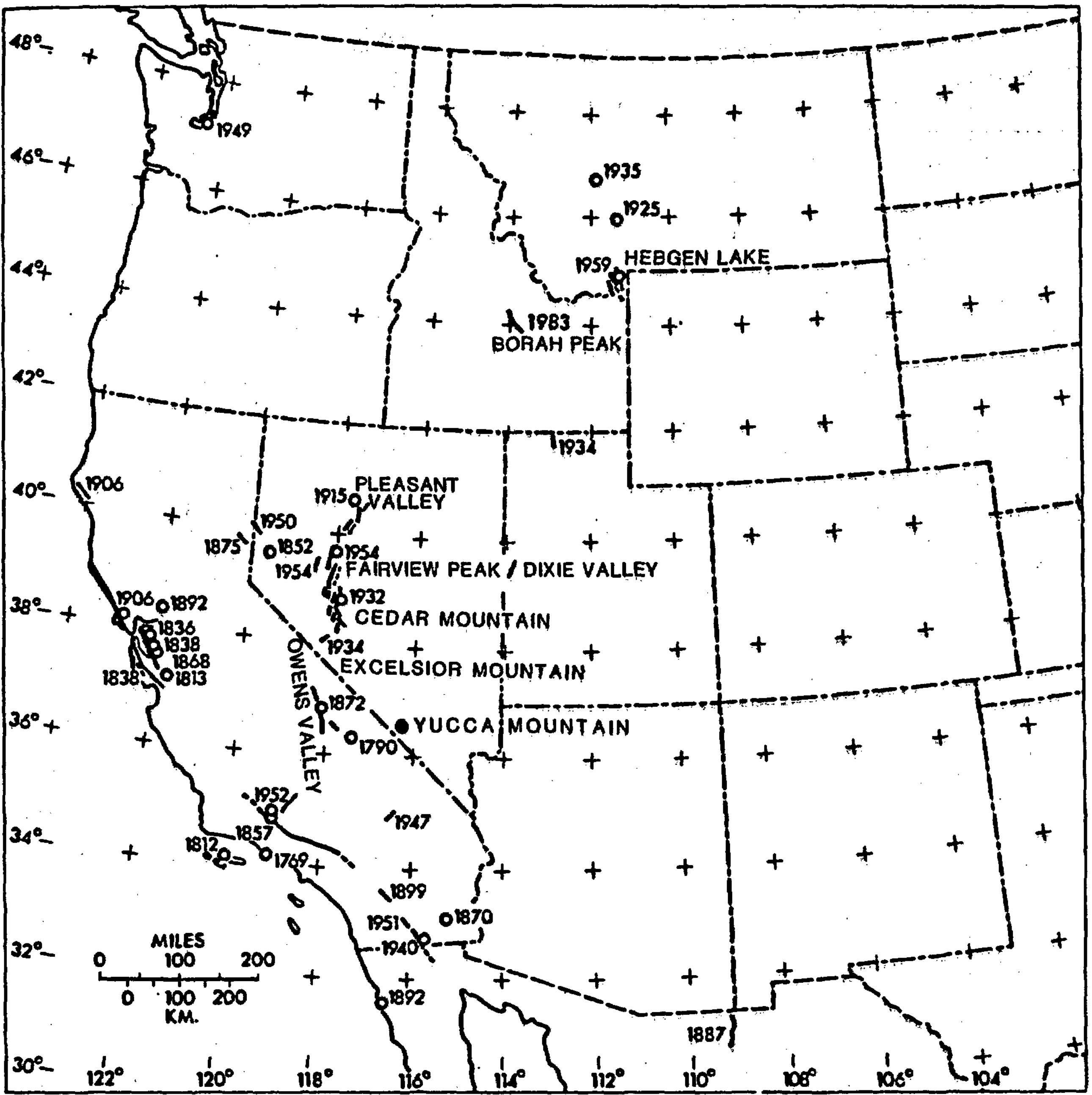


Figure 2-3. Historic faulting in the western United States. Modified from Thompson (1985).

The panel noted that analyses associated with the NNSWI Project have assumed failure over the entire fault length, whereas for other analyses, one-half the length has been used. Effort should be made to determine if faults of concern can be segmented on the basis of end points, intersection of pre-existing structures (lateral terminations), or other features. Lacking this, use of the entire fault length would provide a conservative maximum earthquake magnitude.

The potential of active faulting associated with seismicity has been examined using regional seismograph network data from southern Nevada and from detailed seismograph network studies in the immediate vicinity of the nuclear test site. In general, the seismicity of the Yucca Mountain vicinity appears to be associated with the western end of a general east-west trending zone of seismicity that extends across southern Nevada at the approximate latitude 37° commonly referred to as the Southern Nevada East-West Seismic Belt (Figure 2-4). A notable gravity lineament of approximately 90 milligals (Eaton et al., 1978) parallels the zone of seismicity; both trends are generally orthogonal to the structural grain of Quaternary-Holocene Basin and Range topography. This raises a question regarding the origin of the seismic zone in the deeper crust that cannot be answered at this time. Seismicity decreases westward from Yucca Mountain toward the Furnace Creek-Death Valley region. To the northwest and west, increased activity is associated with the Nevada Seismic Belt (Figure 2-4).

Fault plane solutions for central and western portions of the Basin and Range Province, including the Yucca Mountain site, show varied distributions of pure-normal, oblique-normal, and strike-slip solutions (Figure 2-5) (Smith and Lindh, 1978; VanWormer and Ryall, 1980; Rogers at al., 1983). While Quaternary faults show significant oblique-lateral-slip components, fault plane solutions for large earthquakes show major components of extension or normal faulting. The small events show northwest to west extension with a variety of fault plane solutions. The 1966 M = 6 earthquake in the eastern part of the Southern Nevada East-West Seismic Belt (Figure 2-5) was a strike-slip event (Wallace et al., 1983; Smith and Lindh, 1978) as were many nuclear explosion aftershocks and concurrent tectonic strain-release events at Pahute Mesa (Figure 2-5) (Hamilton and Healy, 1969; Wallace et al., 1985).

However, the consistent parameter of the fault plane solution distribution for the southern Great Basin is the general northwest-southeast direction of minimum stress in accordance with extension in that direction (Smith, 1978; Zoback and Zoback, 1980). Most large historic earthquakes in the western Great Basin that produce surface faulting show the primary displacement in the down-dip direction. The significance of the strike-slip solutions cannot be ascertained at this time; they may represent the accommodation of strain release along existing fault planes that are not now favorably oriented for strike-slip faulting, or they may represent the potential for large lateral slip along such fault systems as the Death Valley-Furnace Creek zone. Another possibility (Vetter and Ryall, 1983) is that strike-slip faulting in shallow, small magnitude events gives way to dip-slip normal faulting for large, deep events due to the increase in overburden pressure with depth.

Although detailed studies exist for the NTS and vicinity, the historical seismic record for the Great Basin is marked by a sparseness of data because of the incompleteness of both personal-felt reports that were used to prepare

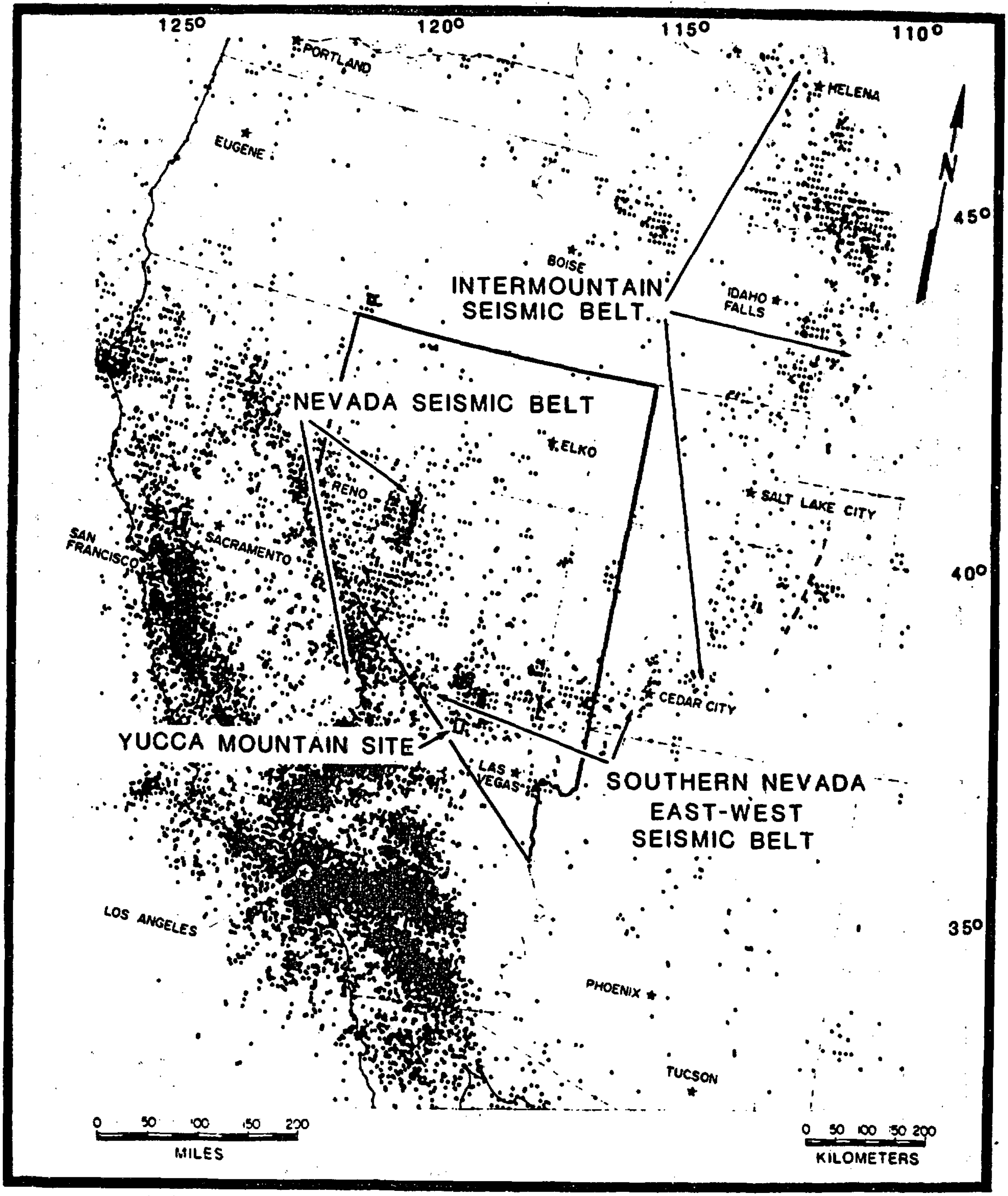


Figure 2-4. Historical seismicity in the western United States. Modified from Smith (1978).

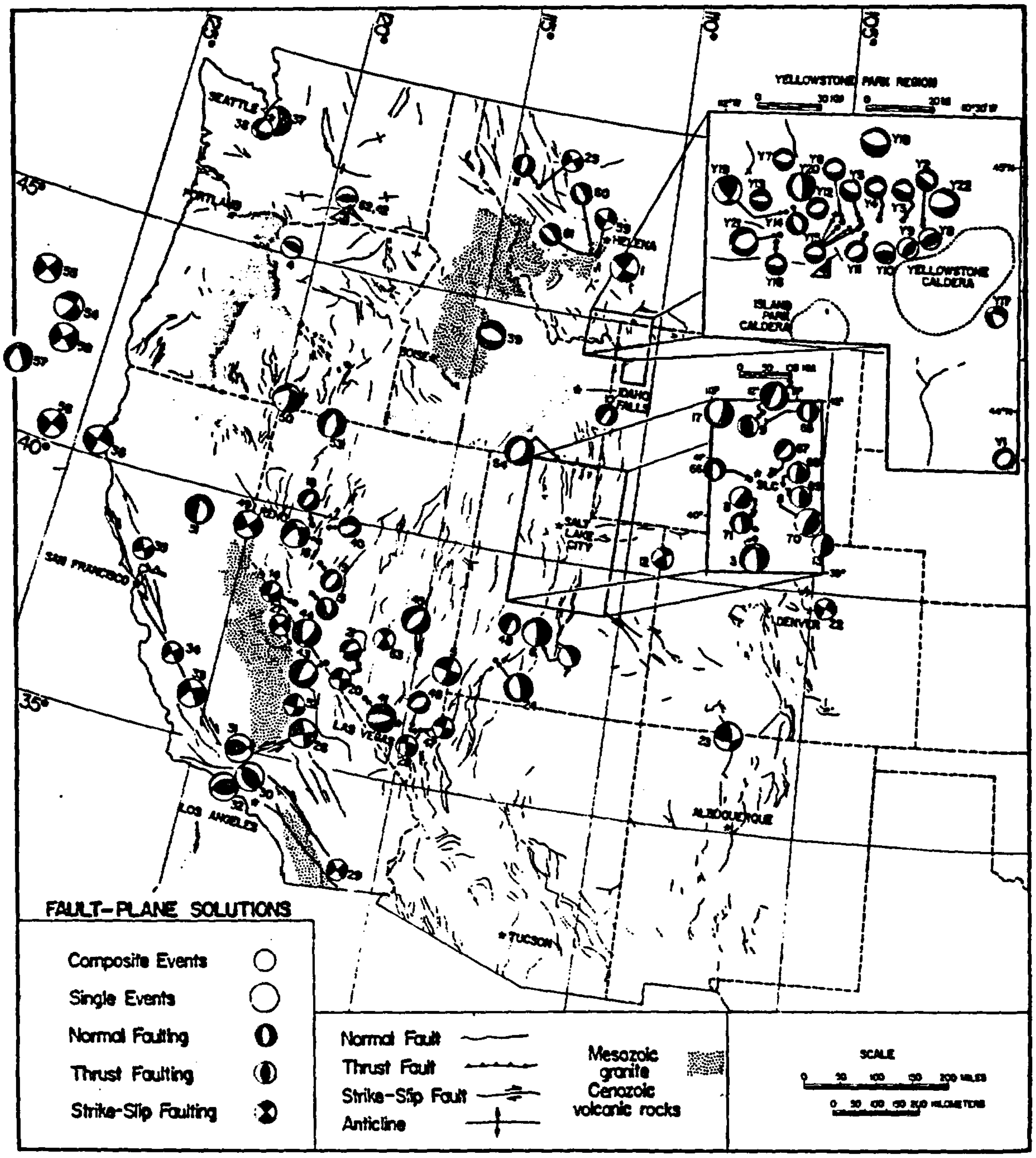


Figure 2-5. Map of fault plane solutions of the western United States. Projections are stereographic equal area, lower-hemisphere. Dark quadrants = compressional motion; light quadrants = dilatational motion. Dots = epicenter or area from which the fault plane solutions were determined. Solution number 5 is the 1966 event and solutions 20 and 21 are NTS aftershocks. From Smith and Lindh (1978).

early earthquake intensity maps, and the short length of time that regional networks have been established. It seems imperative to examine the historical earthquake record of the entire western and central Great Basin in order to ascertain the level of confidence for the assignment of statistical parameters such as the a and b values.

Focal depth distribution of earthquakes can provide information regarding correlations between surface geology and faulting at depth. Focal-depth control requires that a recording station be located in an epicentral region that is within a distance of a focal depth in order to obtain an accurate measurement of the focal-depth parameter. In general, the station distributions in the vicinity of Yucca Mountain have allowed for partial assessment of focal depth/surface faulting relationships. A new network operated recently by the U. S. Geological Survey (USGS) should provide new data on focal depths in the 5- to 10-kilometer range that are well constrained. Recommendations for continued efforts are given in Section 4.1 of this report.

2.2 EXTENSION RATES IN THE BASIN AND RANGE PROVINCE

An important parameter for seismic risk assessment of the Yucca Mountain area is the rate of regional strain release that is dominated by contemporary extension between the Colorado Plateau-Great Basin boundary and the Sierra Nevada front (Figure 2-2). Estimates of the paleostrain rates can be determined from Quaternary fault displacement rates. Strain release from earthquakes, geodetic surveys, and satellite baseline ranging provide estimates of contemporary deformation. Contemporary strain-rate tensor components can then be converted to deformation rates that can be compared to Quaternary paleodeformation rates, data that are useful for assessing expected strain release in the future.

Geologic reconstruction of strike-slip fault zones across the southern Great Basin provide estimates of regional Tertiary deformation indicating that there has been at least 140 kilometers of east-west extension between the Colorado Plateau and the southern Sierra Nevada (Wernicke et al., 1982) which are now about 350 kilometers apart. Extensional deformation began about 15 million years ago, thus the long-term extensional deformation rate is about 1 centimeter per year averaged across the southern part of the province for the past 15 million years.

Intraplate Quaternary deformation rates for the western United States were calculated by Minster and Jordan (1984) using rigid plate, kinematic models. For the Great Basin they calculated northwest (N 63° W) extension at a maximum of 1 centimeter per year based upon a statistical model. This extension rate compares well with other estimates of Great Basin opening rates from various geologic and geophysical data (summarized by Minster and Jordan, 1984) in Table 2-1.

Deformation rates in highly extended areas of the Great Basin can approach 2 centimeters per year every several million years (calculated from data in Anderson et al., 1972; Miller et al., 1983). A key geological observation is that the extension at any given time may be localized and confined in narrow belts, as appears to be the case today in the Death Valley region, rather than being uniformly distributed across the province. In addition, it is clear that some large blocks have remained strain free during Basin and Range tectonism.

The Yucca Mountain area is probably not within a strain-free block. It is unreasonable, however, to place bounds on the extension rate in the Yucca Mountain area via interpolation of province-wide strain rates because of the inhomogeneity of strain accommodation apparent from the geologic record.

Table 2-1. Estimates of Great Basin opening rates[a]

Period	Average Opening Rate (cm/yr)	Method
Late Cenozoic	0.3-2.0	Geological strain
Late Cenozoic	0.3-1.2	Heat flow
Holocene	0.1-1.2	Paleoseismicity
Historic (contemporary)	0.5-2.2	Seismicity

[a] Data from Minster and Jordan (1984).

The above approach for estimation of strain rates was based on the 15 million-year geologic record to obtain average extensional displacement. Another procedure is to consider the current deformation rates as determined by precise surveying and satellite laser ranging. Trilateration networks were established in the Yucca Flat and Pahute Mesa areas in 1971 and were reoccupied in 1972, 1973, and 1983. The geodolite measurements were conducted by J. Savage and co-workers at the USGS in Menlo Park, California. The data from Yucca Flat (W. Prescott, personal communication, 1984) were measured across a block about 40 kilometers long (north-south) and 20 kilometers long (east-west) for the 1971 to 1983 period. The data were fitted to a uniform strain field with the maximum principal strains being north-south and east-west to within the error of the measurements. The north-south strain rate was -0.10×10^{-6} per year and the east-west strain rate was $+0.08 \times 10^{-6}$ per year. The corresponding rates for the 15 million-year averages (cited above from geological determinations) are about $+0.02 \times 10^{-6}$ per year, a value that is of the same order as the east-west strain of $+0.08 \times 10^{-6}$ per year. Using earthquake and Quaternary geologic data for the eastern Great Basin in Utah, Smith, et al. (1984) reached a similar conclusion that the Quaternary and contemporary deformation rates were of the same order. These results imply that the Quaternary geologic record is a good key to the future.

Contemporary strain rates of the Great Basin have also been determined from calculations of cumulative moment tensors of earthquakes using the method of Anderson (1979). Greensfelder et al. (1980) applied Anderson's (1979) method and suggests strain rates across this region of 2×10^{-8} per year, but increasing by an order of magnitude southward toward the Garlock fault (Figure 2-2) to 10^{-7} per year. Minster and Jordan (1984) applied this method to the Greensfelder et al. (1980) data for the Great Basin and converted the strain rates to deformation rates that gave an average of 1 centimeter per year. Smith (1982) and Eddington et al. (1985) also applied a modification of the technique to homogeneous seismogenic regions of the southern Great Basin and calculated a principal strain direction at N 60°W and a rate of less than 1 centimeter per year for the Nevada Test Site (NTS) area.

Strain rates estimated by cumulative moment tensors of historic seismicity for other areas of the Great Basin (Smith, 1982, and unpublished data) suggest maximum displacement rates of about 0.2 to 0.4 centimeter per year associated with the areas of large ($M = 7+$) earthquakes in the central Nevada seismic belt, compared to 0.1 to 0.4 centimeter per year or less across the NTS area.

Constraints on contemporary deformation across the Great Basin have also been recently obtained from satellite laser ranging. This technique limits the extension rate to 0.9 centimeter per year, based on a sparse data set (Jordan et al., 1985). Thus the Quaternary (paleoseismic) estimates of deformation rates and contemporary extension rates estimated for the Great Basin provide similar values, on the order of 1 centimeter per year. Recommendations for continued efforts are given in Section 4.2 of this report.

2.3 ADJACENT SUBPROVINCES WITH HIGH POTENTIAL FOR A GREAT EARTHQUAKE

The Death Valley region contains numerous long, normal and strike-slip Quaternary faults associated with mountain block uplifts 2,000 to 3,000 meters high. The large historical earthquakes in the Basin and Range Province (Dixie Valley/Fairview Peak, Pleasant Valley, Owens Valley, and Borah Peak) (Figure 2-3) are associated with similar faults bounding large topographic escarpments. Although the Death Valley fault system has been considered to be relatively aseismic in the historical record, there is abundant evidence for major Quaternary displacements on these faults (Hunt and Mabey, 1966). It is highly significant that the Borah Peak event ($M = 7.3$) occurred in a region of little seismicity. In view of the youthfulness and large topographic escarpment associated with the Death Valley fault system, especially the Furnace Creek and Death Valley fault zones (Figure 2-2), the likelihood of a number of large events ($M = 7$ or greater) on these faults within the next 100,000 years should be considered high until proven otherwise. The recommendations from the workshop for inclusion of the Death Valley region in Yucca Mountain studies are given in Section 4.3.

2.4 IN SITU STRESS

Hydraulic fracturing stress measurements at Yucca Mountain have been made in four boreholes to depths of about 1.5 kilometers (Stock and Healy, 1984; Stock et al., 1985). The most important aspect of the stress measurements is that in each borehole, and at nearly every depth, the magnitude of the least horizontal principal stress was found to be considerably lower than the vertical (overburden) stress. As explained below, the large stress difference between the vertical stress and least horizontal stress implies that north-northeast striking normal faults in the vicinity of Yucca Mountain are potentially active.

The most important issue to consider is the basic validity of the stress measurements. The extremely deep water table in the Yucca Mountain area required several unique operational procedures during the hydraulic fracturing measurements, and introduced uncertainty into the measurement. Nevertheless, the measured low magnitudes of the least horizontal stress is consistent with other observations in the Yucca Mountain area. For example, in several of the wells, borehole televiewer surveys reveal that extensive hydraulic fractures were induced during drilling due simply to the pressure of the column of drilling mud in the boreholes (Stock and Healy, 1984). Some of the drilling-induced hydraulic fractures in boreholes USW G-1 and USW G-2 are shown in Figure 2-6. The drilling-induced hydraulic fractures require the magnitude of the least horizontal principal stress to be quite low. Thus, while the difficult testing conditions resulted in poorly constrained estimates for the greatest horizontal principal stress, the estimates of the least horizontal principal stress, which are most important to the normal faulting issue, seem to be confirmed by other data. The discovery of the drilling-induced hydraulic fractures explains the fact that no fluid could be circulated to the surface during drilling of the boreholes at Yucca Mountain because the fluid went out into the drilling-induced hydraulic fractures instead.

The stress measurements have been analyzed with a simple two-dimensional normal faulting model which is shown schematically in Figure 2-7. The equations shown in Figure 2-7 refer to the magnitude of the least horizontal principal stress at which frictional sliding on properly oriented normal faults is expected to occur for certain values of the vertical stress, pore pressure, and coefficient of friction of the fault. Several lines of evidence suggest that this simple model is applicable. First, the orientation of the least horizontal principal stress (N60°-65°W) is such that high-angle normal faults striking about N25°-30°E are appropriately oriented for a simple two-dimensional model to be applied. Considerable data from the drilling-induced hydraulic fractures and stress-induced wellbore breakouts support the estimate of the least horizontal principal stress orientation (Healy et al., 1984; Stock and Healy, 1984). Byerlee (1978) has made laboratory measurements on a wide variety of rock types and shown that coefficients of friction between 0.6 and 1.0 are typical. Second, the value of the greatest horizontal principal stress is intermediate between that of the least horizontal principal stress and the vertical stress as expected for normal faulting regions. Finally, similar models seem to adequately explain stress measurements in the vicinity of active faults in other regions (Zoback and Healy, 1984).

In the context of the simple model shown in Figure 2-7, the stress measurements at Yucca Mountain indicate that frictional sliding on properly oriented fault surfaces could be expected to occur if the coefficient of friction along the faults were close to 0.6. Figure 2-8 shows least principal stress and overburden stress data from wells USW G-1 and USW G-2. While Morrow and Byerlee (1984) indicate that the coefficient of friction for repository tuffs is about 0.85, the uncertainties in both the laboratory friction data and the stress measurement lead to the conclusion that frictional sliding on north-northeast trending normal faults should be considered to be possible. Note in Figure 2-8 that only a small difference distinguishes the stress necessary for frictional sliding at a coefficient of friction of 0.6 and that for 0.85. The stress data suggest that frictional sliding on properly oriented normal faults is possible. Such frictional sliding could be induced tectonically by a small change in regional stress or an increase in the local pore pressure.

On a regional scale, the magnitude and orientation of the in situ stress measured at Yucca Mountain are generally consistent with those throughout the Basin and Range Province. The orientation of the least principal stress is

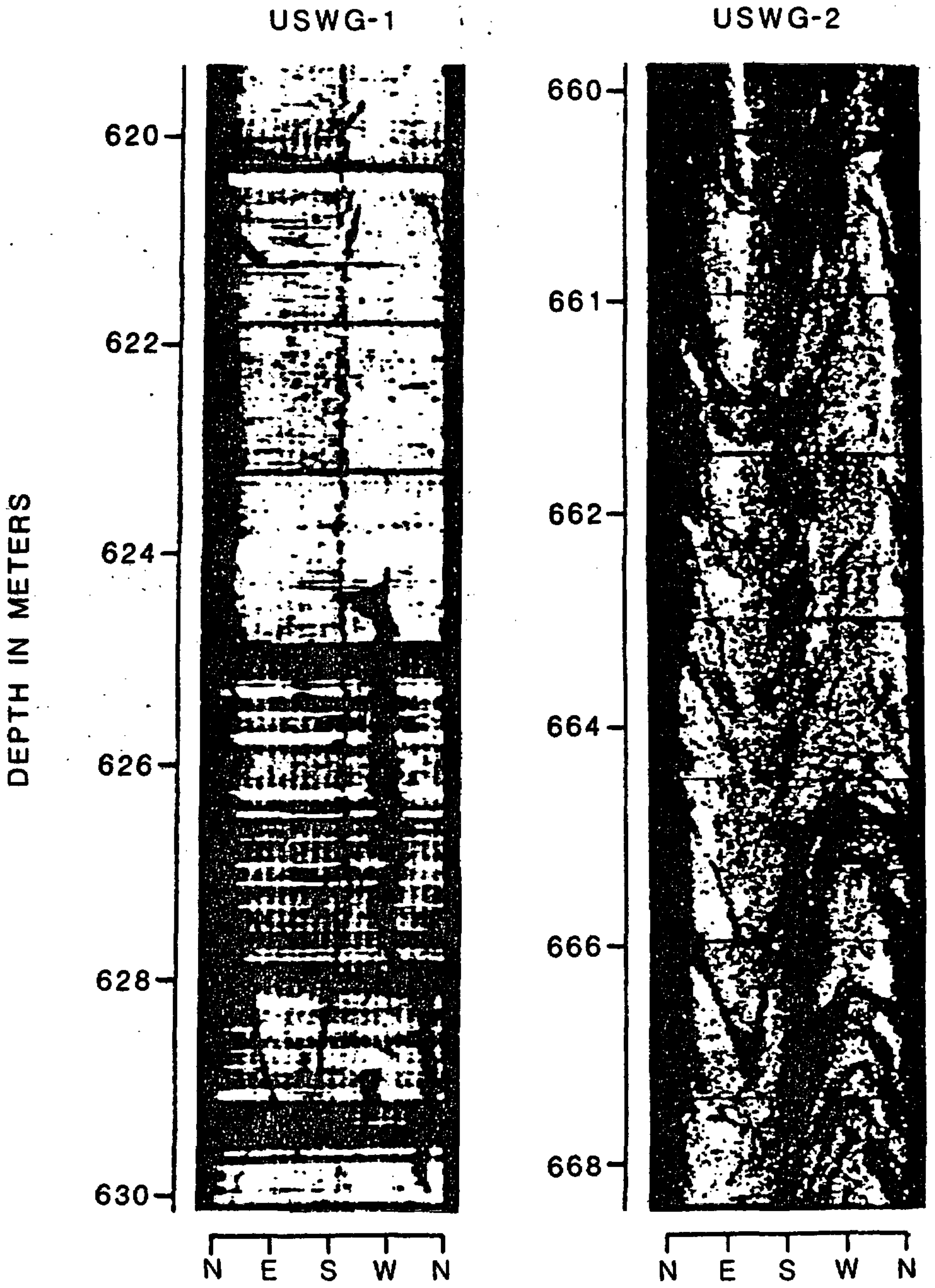
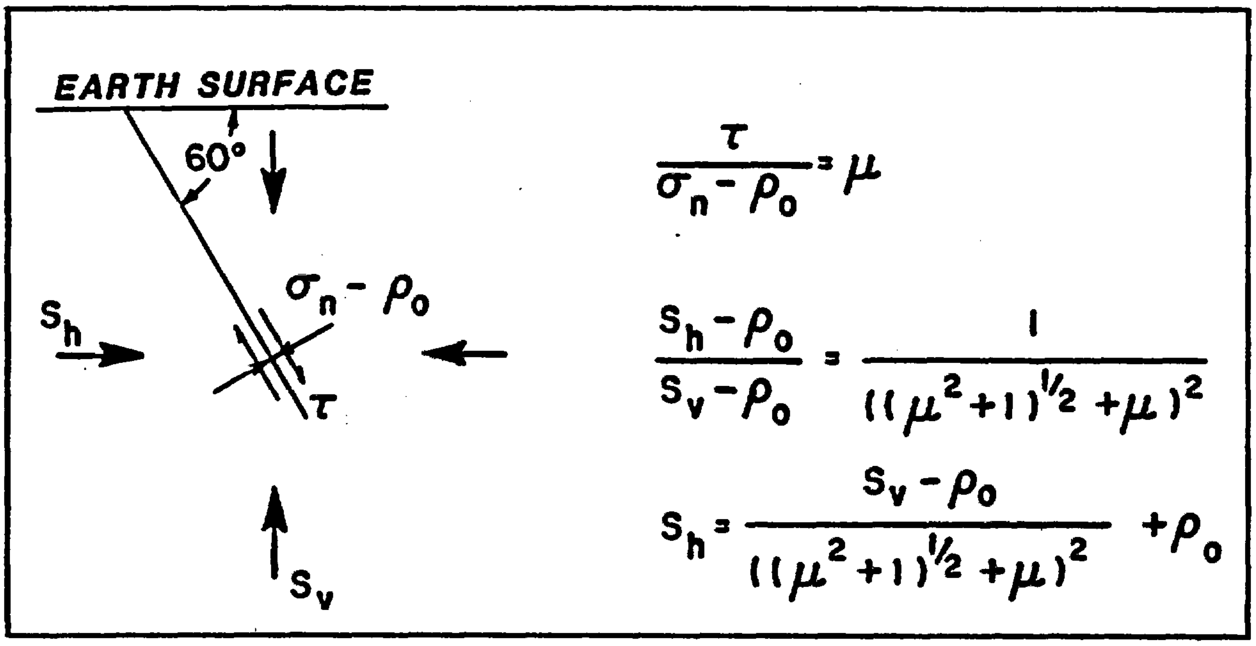


Figure 2-6. Borehole televiewer images of drilling-induced hydraulic fractures in boreholes USW G-1 and USW G-2. From Stock et al. (1985).



$$\frac{\tau}{\sigma_n - \rho_o} = \mu$$

$$\frac{S_h - \rho_o}{S_v - \rho_o} = \frac{1}{((\mu^2+1)^{1/2} + \mu)^2}$$

$$S_h = \frac{S_v - \rho_o}{((\mu^2+1)^{1/2} + \mu)^2} + \rho_o$$

Figure 2-7. Illustration of two-dimensional friction faulting model for analysis of normal faults in the vicinity of Yucca Mountain. The model is applicable for faults which strike about N25°-30°E and dip about 60°. It is straightforward to estimate the value of the least horizontal principal stress, S_h, when frictional sliding is expected to occur as a function of the vertical stress, S_v, the pore pressures, ρ_o, and the coefficient of friction, μ.

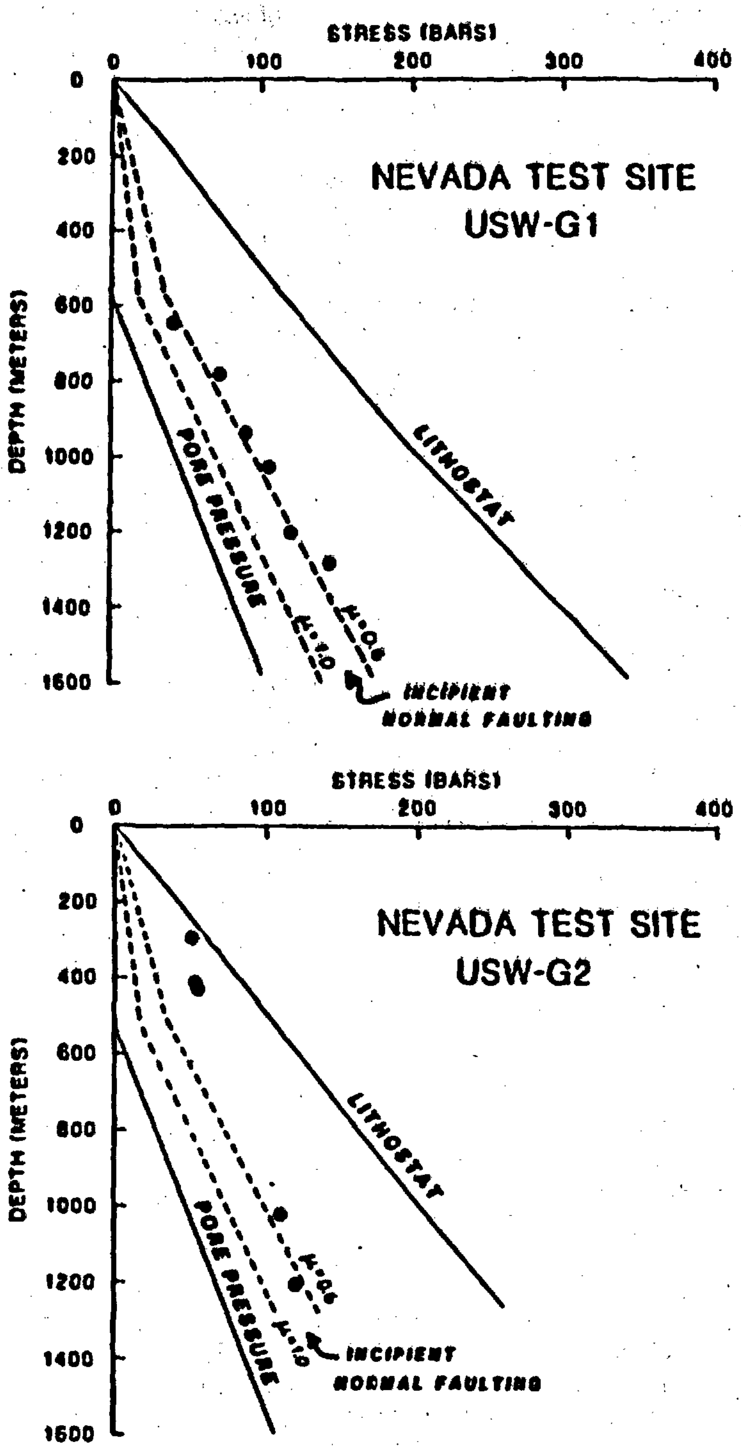


Figure 2-8. Least horizontal principal stress values (solid circles) for USW G-1 and USW G-2 as a function of depth. The vertical stress is labeled lithostat, based on density logs. The pore pressure is also shown, based on the depth to the water table in the hole. The dashed lines indicate the region where well oriented normal faults would be expected to slip for the range of fraction values shown.

similar to that throughout the province (Zoback and Zoback, 1980) and three sites along the Wasatch fault zone (Figure 2-2) have been found to have similar least principal stress magnitudes (M.L. Zoback, personal communication). Thus, the stress measurements are not anomalous near Yucca Mountain, but basically reflect regional tectonics. On a more local scale, Stock (written communication, 1984) has shown that the stress measurements are consistent with focal plane mechanisms of earthquakes that have occurred near Yucca Mountain in the past few years (Rogers et al., 1983). While the earthquake focal mechanisms indicate predominately strike-slip faulting with a component of normal faulting, Stock's analysis indicates that the relative components of strike-slip and dip-slip motion are primarily a function of the orientation of the fault plane. A similar conclusion was reached from a study of the aftershocks of the Benham nuclear explosion (Hamilton and Healy, 1969).

Accepting the interpretation that the stress measurements indicate that failure along favorably oriented faults is possible, what can be said about the magnitude of the potential earthquakes? Observations by Smith and Bruhn (1984) and Das and Scholz (1983) suggest that large ($M = 7+$) earthquakes nucleate at depths of the maximum extent of seismicity near the brittle/ductile transition zone. For the Great Basin, this appears to be at depths of approximately 15 kilometers (Smith and Bruhn, 1984). It is also clear that large earthquakes release stored stresses from a large volume of rock. Thus, if the measured stresses are only indicative of the upper 1 to 2 kilometers the maximum size earthquake would no doubt be quite moderate. Unfortunately, there is uncertainty on the extrapolation of shallow measurements to depths of 10 to 15 kilometers. In other parts of the world, such as South Africa where measurements to depths of 4 kilometers are available, no simple rules for extrapolation are evident. Thus, the only way to know if the stresses at greater depth also imply potential fault movement is to drill to greater depth and measure the stresses. The fact that similar stresses have been measured in all four boreholes investigated suggest a lateral continuity of the stress field, but it is simply not possible to extrapolate these data to depth without measurements at greater depths.

In summary, in situ stress measurements indicate that failure is possible along favorably oriented faults in the Yucca Mountain region. However, no quantitative statements about earthquake probability and magnitude associated with the failure can be determined from in situ data alone. For example, fault slip could occur through aseismic slip as in the Gulf Coast region where a similar state of stress exists (McGarr and Gay, 1978; Brace and Kohlstedt, 1980; Zoback and Healy, 1984). However, there is no documented evidence for appreciable aseismic slip in the brittle crust in the Great Basin and this possibility is probably slight. Another possibility is that relatively numerous earthquakes of small to moderate magnitude could occur. Finally, if high shear stresses were found at greater depth, it may be possible that the stored stresses in the vicinity of Yucca Mountain could be released in a few relatively large earthquakes.

2.5 WEAPONS TESTING

Underground nuclear explosions (UNEs) are expected to continue at the Nevada Test Site (NTS) as a part of the nuclear weapons program. The Threshold Test Ban Treaty does not permit yields in excess of 150 kilotons; however, the effects of larger tests should be considered in the event that the treaty is abrogated. Ground motion at Yucca Mountain could result from a test as large as 700 kilotons located at a distance of about 23 kilometers at the southern end of the Buckboard area which is reserved for future weapons tests.

The explosion-induced stress waves for such an event do not appear to pose an unmanageable hazard. At a distance of 23 kilometers from a 700 kiloton explosion, the P wave generates a peak stress of about 5.7 bars (Vortman, 1983) and a peak ground acceleration of about 0.06g (calculated from equation 7 in Vortman, 1980). The peak stress is only about 5 percent of the lithostatic stress at the repository depth of 300 to 400 meters, and the peak acceleration is well below values being considered for earthquakes. Spall closure and chimney collapse produce substantially smaller stress waves and, therefore, should pose no significant hazard.

Nuclear explosions at the NTS are frequently accompanied by tectonic release and earthquake aftershocks. Tectonic release results from rapid relaxation of elastic stresses stored in rocks close to the test and occurs almost coincident with the explosion-induced waves. Wallace et al. (1983, 1985) present new evidence and summarize earlier studies on the manifestations of tectonic release from nuclear explosions at the NTS. Although the waves induced by tectonic release are sometimes apparent in recordings of explosions at distances beyond a few kilometers, it seems unlikely that such effects could combine with the primary explosion-induced waves so as to significantly alter the peak values noted above for a 700 kiloton explosion at a distance of 23 kilometers.

Aftershocks result from the stress field around the explosion readjusting to the decrease in stress caused by the explosion. The 1.1 megaton nuclear explosion named Benham produced aftershocks for as long as 40 days (Hamilton et al., 1969; Aki et al., 1969). The 100 largest aftershocks ranged in magnitude from about 3 to 4.2. The aftershocks tended to delineate existing north-south faults, and migrated away from the area of the explosion with time. This spreading with time is consistent with strain release starting near the explosion and successively releasing less strain with increasing distance from the exlosion. Hamilton et al. (1969) noted that the aftershocks were confined to within 13 kilometers of ground zero at depths no greater than 6 kilometers.

Other studies indicate that aftershocks sometimes occur to 14 kilometers from ground zero and at depths shallower than 5 kilometers (Hamilton et al., 1971). Surface faulting has accompanied some of the higher-yield nuclear explosions at Pahute Mesa and at Yucca Flat. In some cases, this faulting had a lateral extent of as much as 10 kilometers and displacement on some faults has exceeded 100 centimeters (Maldonado, 1977; McKeown and Dickey, 1969; Dickey, 1968).

Similar triggering has resulted from the impoundment of water in Lake Mead (Carder, 1945; Rogers and Lee, 1976) in the southern part of the Great Basin. These earthquakes are due to a pore pressure increase, occur along preexisting faults, and are confined to shallow depth in the vicinity of the lake. Eight of the earthquakes were magnitude 5 and had slip direction similar to earthquakes observed throughout the Great Basin to the north and west suggesting a pattern consistent to the seismicity of the region.

In summary, neither explosion-induced aftershocks nor impoundment-produced earthquakes are necessarily indicative of the tectonic stability of the province in which they occur, but such events may provide insight into the state-of-stress of the region in which they occur. These observations do show, however, that explosions can produce fault slip and aftershocks at some distance from and at some time after the explosion. Such effects are best explained as readjustment of the stress field altered by the explosion. The slip is apparently assoicated with explosion-induced earthquakes with magnitudes in the 3 to 4 range occurring within about 14 kilometers of the largest weapons tests.

3.0 GROUND MOTION ISSUE

The tectonic stability of the region was reviewed in the previous section with a focus on its earthquake-generating characteristics. The review of ground motion in this section focuses on issues relevant to the establishment of ground motion criteria for the repository, utilizing information developed within the review of tectonic stability. Some of the same issues are examined in an effort to resolve differences in the estimates of fault characteristics, potential earthquake magnitudes, and credible levels of ground motion.

The examination of earthquake ground motion was focused on a number of questions.

1. What are the largest earthquakes unassociated with known faults to be expected within 15 kilometers of the site?
2. What is the largest earthquake of any type within 50 kilometers of the site?
3. What is the return period for large earthquakes?
4. What are the characteristics of ground motion to be expected for Yucca Mountain?
5. How will surface ground motion be attenuated at repository depth?

Current understanding of earthquake processes and data relevant to the site area were used to develop the following observations and recommendations to resolve relevant uncertainties.

3.1 UNASSOCIATED EARTHQUAKES

Yucca Mountain is interspersed with faults ranging outward from within a few hundred meters of the site. While there is no clear evidence to indicate that any of the faults within the immediate site area have had movement along them within 30,000 years, significant local earthquakes cannot be ruled out with the information currently available. The experts concluded that an earthquake of magnitude approximately 6 could plausibly occur at depth in this area without significant surface manifestations.

As a result of this evaluation, the issue of earthquakes unassociated with known faults was reviewed. To assess the importance of unassociated earthquakes, preliminary bounds are developed for the recurrence interval (I) of all earthquakes within a "typical" 1,000 square-kilometer area, and these bounds are used to estimate the likelihood of a magnitude 6 earthquake within a radius of about 18 kilometers (1,000 square kilometers) of the Yucca Mountain site.

The extension rate across the southern Great Basin (width 650 kilometers) can be used to estimate the recurrence interval for earthquakes in this area. An area 32 kilometers by 32 kilometers (1,000 square kilometers) is considered and the cumulative rate of earthquake-induced strains are constrained to match estimates for the regional strain rates, i.e.,

$$\dot{\varepsilon} = \int_{-\infty}^{MM} N(M) \frac{D(M)}{3Z} \frac{L(M)}{3Z} dM \qquad (1)$$

where the various terms are defined as follows:

MM is the maximum magnitude;
$\dot{\varepsilon}$ is the extensional rate of strain for the southern Great Basin (width 650 kilometers) in the east-west to north-west/south-east direction of 5×10^{-9} per year $< \dot{\varepsilon} < 3 \times 10^{-8}$ per year (see Section 1.2 and Minster and Jordan, 1984);
D(M) is the fault displacement (in kilometers) associated with an earthquake of magnitude M, where $D(M) = 10^{0.612M_s - 7.12}$ (Bonilla et al., 1984);
L(M) is the length (in kilometers) of the fracture zone for an earthquake of magnitude M, where $L(M) = 10^{0.566M_s - 2.44}$ (Bonilla et al., 1984);
and $N(M) = I^{-1}(M)$ is the number of magnitude M earthquakes (per unit magnitude interval) per 1,000 square kilometers per year, where $N(M) = 10^{a-bM}$ and where the b value is assumed to be unity and the a value is constrained by the regional strain rates expressed above in equation (1).

The relationships above are substituted into equation (1), an upper magnitude limit is set to 8, and the integration is performed to obtain

$$\begin{aligned} \dot{\varepsilon} &= 10^{a-10.39} = 10^{a-M}\, 10^{M-10.39} \\ &= N(M)\, 10^{M-10.39}. \qquad (2) \end{aligned}$$

The recurrence interval $I(M) = N^{-1}(M)$ is thereby related to the regional strain rate $\dot{\varepsilon}$, i.e.,

$$I(M) = \dot{\varepsilon}^{-1} 10^{M-10.94}.$$

Bounds on the recurrence interval (in years) per unit magnitude for earthquakes in a "typical" 1,000 square-kilometer area are estimated from the range of regional strain rates presented above. The results are presented in Table 3-1 along with estimates from other sources. Figure 2-4 shows the locations of the seismic belts listed in the table.

It is noted that the estimated recurrence intervals for magnitude 6 earthquakes in a 1,000 square-kilometer area range from several hundreds to several thousands of years. If 90 percent of these earthquakes were associated with identifiable seismogenic faults, then the recurrence intervals for magnitude 6 earthquakes unassociated with known faults would increase by a factor of 10, i.e., from several thousands to several tens of thousands of years. Because extension (and earthquakes) in the Great Basin has not been uniform but has varied spatially and temporally, it is difficult to assess the applicability of these bounds to any particular area within the region. That recent seismicity has been concentrated along the western and eastern margins of the basin could indicate lower strains and longer recurrence intervals for Yucca Mountain and vicinity than those listed above.

Table 3-1. Estimates of recurrence intervals for Great Basin earthquakes in years per 1,000 square kilometers

Region	M>5	M>6	M>7	Source
S. Great Basin	230	2,300	23,000	strain = 5×10^{-9} per year
S. Great Basin	38	380	3,800	strain = 3×10^{-8} per year
Southern Nevada E-W Seismic Belt 1932-1973	250	2,500	25,000	Greensfelder et al. (1980)
Intermountain Seismic Belt 1932-1970	120	1,100	10,000	Greensfelder et al. (1980)
Northern Nevada 1932-1969	100	830	6,700	Greensfelder et al. (1980)
S. Basin and Range 1932-1973	1,900	19,000	190,000	Greensfelder et al. (1980) (also Douglas and Ryall, 1975)
400-kilometer radius from NTS 1845-1974	72	490	3,900	Rogers et al. (1977)
E. California, Nevada, 1970-1974	780	6,900	61,000	Ryall (1977)

Based on these estimates for earthquake activity, the panel concludes that an earthquake capable of producing severe shaking at the site is unlikely during the preclosure period. Nevertheless, the potential for earthquakes unassociated with identified seismogenic faults should be considered in the development of ground motion criteria for the site. Although the seismogenic characteristics indicate that ground accelerations in excess of 0.4g are not likely during preclosure, more severe levels of ground motion cannot be ruled out. However, McGarr (1984) regards 0.5g as the maximum surface acceleration likely in an extensional regime, like Yucca Mountain. The working group recommended three approaches for dealing with the issue of unassociated earthquakes. These approaches are described in Section 4.4.

3.2 LARGEST EARTHQUAKES IN THE REGION

Knowledge of existing faults is based primarily on surface expression. Large scarps have been associated with both large earthquakes and cumulative displacements. Unless there is a clear surface manifestation of a fault terminus, the precise subsurface length will remain uncertain.

Relationships between surface fault rupture length and associated earthquake magnitude (Bonilla and Buchanan, 1970; Mark and Bonilla, 1977; Bonilla et al., 1984) result from data with considerable spread in the surface fault rupture length associated with a given magnitude, even when normal-slip, normal oblique-slip, and strike-slip faults are treated separately. For example, a predicted magnitude for 17 kilometers of fault rupture is 6.8 ± 0.8 based on standard errors of the estimates (Bonilla et al., 1984). Much of this spread is due to differences in the true fault rupture length and surface expression. Because of uncertainties in the actual extent of the seismogenic faults at depth, magnitudes from 6.6 to 6.8 have been estimated for faults within about 30 kilometers of the site. The relationship between earthquake fault rupture length and magnitude appears to be one of the most tenuous links in hazard assessment. The course of action recommended by the working group is defined in Section 4.5.

3.3 SEISMICITY

Estimates for the average rate and magnitude distribution of future earthquakes in the Great Basin can be extrapolated from the historic and geologic record. The historic record is too brief to represent the potential for earthquakes on individual faults or in a small region the size of Yucca Mountain. The historical record of the southern Great Basin is needed to assure complete sampling statistics, and the corollary follows that extrapolations of future earthquakes during preclosure (about 90 years) can only be applied with confidence over larger regions.

To demonstrate a reliable basis for extrapolating the rate and magnitude distribution of future earthquakes, alternate procedures for characterizing previous earthquake activity should be examined, and consistency should be established. Recommendations of the working group for developing the basis for assessing future seismicity are given in Section 4.6.

3.4 DETERMINATION OF PEAK GROUND MOTION

The expected peak acceleration specified in USGS (1984) for Yucca Mountain was based on the seismic hazard analysis developed by Rogers et al. (1977). This analysis utilized a ground motion attenuation relationship developed by Schnabel and Seed (1973). Although this relationship has been accepted in the past, other attenuation curves have been developed as a result of more recent data. Furthermore, the analysis does not include a specified standard error, thereby preventing estimates of uncertainty and influencing the accuracy of estimates for return periods. Recent attenuation relationships need to be utilized. Analysis by McGarr (1984) of the peak acceleration data in the context of crustal strength suggests that the stress state imposes bounds on the peak ground acceleration. Specifically, the bound on peak acceleration in a compressional regime such as southern California could be nearly three times greater than the bound in an extensional regime such as Nevada. This further suggests that the use of acceleration relationships from events in California may be misleading for hazard assessment at Yucca Mountain. Ongoing studies using the seismic network data by Rogers et al. (1985) should provide useful data on the characteristics of local ground motion and how it might differ from ground motion recorded in other areas. Specific recommendations to accomplish this are defined in Section 4.7.

3.5 ATTENUATION OF GROUND MOTION WITH DEPTH

Ground motions resulting from both earthquakes and underground nuclear explosions (UNEs) are important in the assessment of the underground repository facilities located at a depth of 350 meters. While motions at depth have been and continue to be recorded at the Nevada Test Site (NTS) for UNEs, few subsurface recordings of earthquakes have been made.

Japanese data on earthquakes, reported by Okamoto (1973), Kanai et al. (1951, 1953, 1966), and Iwasaki et al., (1977) indicated that motions in general decrease with depth, although little or no reduction was observed at isolated sites for some earthquakes. A velocity attenuation curve developed for a depth of 300 meters in rock, predicts velocities less than curves for surface rock velocities at the same focal distance (Pratt et al., 1978). Owen and Scholl (1980) have observed that the amount of reduction of motion with depth is dependent upon site geology, wave form, and motion duration. The latter two parameters are, in turn, dependent upon earthquake magnitude, source type, epicentral distances, and wave path geometry. King (1982) compared earthquake ground motions recorded at the ground surface and at a depth of 332 meters in a drill hole located at Calico Hills on the NTS. Comparing pseudo-relative velocity spectra, he found that the subsurface spectra were lower in amplitude across the recorded bandwidth by an average factor of 1.5. However, peak values in some subsurface velocity components were observed to be comparable or larger than the peak values in the corresponding surface components.

Given the uncertainties in modeling depth dependence and the sparsity of ground motion measurements at depth for earthquakes, it is not feasible at this time to provide precise predictions of the motions at depth from values at the surface. Current evidence indicates that acceleration at the repository depth will be significantly less than at the surface and that velocity will also attenuate with depth, but less significantly than for acceleration. Below the free surface of the earth, displacement will probably not be significantly reduced, but the data base is sparse.

Data summarized by Dowding (1978) indicate that, in general, underground structures are less likely to be damaged than surface structures at the same epicentral distance. Dowding found that tunnels sustained no damage for surface accelerations below 0.2g, minor damage between 0.2 and 0.5g, and major damage only above 0.5g. When major damage has occurred, it has been almost always associated with the portal regions and shallow cover. Also, observations demonstrate that tunnel systems are susceptible to damage at frequencies higher than those which typically damage surface structures and generally require higher levels of acceleration to initiate damage. Thus, the underground repository can be designed to accommodate ground motions as severe as those used to design surface structures.

The working group reviewed results of ground motion from UNEs and observed the trend of decrease in peak vector acceleration, velocity, and displacement with depth. On average, the peak vector acceleration at 350 meters is reduced by a factor of 2 relative to that at the surface. Reduction of peak vector velocity and displacement is less. All three parameters show strong effects of the geology at the point of measurement. Frequency content of the waves at the surface and at depth are different and vary significantly with the site conditions.

Because the depths of UNEs are ordinarily shallow compared to earthquake hypocenters and because the wave characteristics are significantly different, caution should be exercised in any effort to apply depth effects from UNEs to earthquakes. At intermediate and large distances, some comparisons could be made provided differences in the wave types and the frequency content are taken into account.

4.0 RECOMMENDATIONS

4.1 RECOMMENDATIONS FOR EVALUATING SEISMICITY AND FAULTING

4.1.1 Near-Term Investigations

Future investigations in the near term should address historic seismicity, current seismicity, and future seismicity as follows:

1. Historic seismicity within the Basin and Range Province should be carefully reviewed to refine or determine:
    - a) Estimates of recurrence interval.
    - b) Association of major earthquakes with faults of known length and preexisting fault scarps.
    - c) Source mechanisms of large earthquakes.
    - d) Intensities of ground motion associated with Basin and Range earthquakes compared to California earthquakes.
2. Current seismicity from the local Yucca Mountain network should be analyzed for:
    - a) Association of microearthquakes with known faults.
    - b) Source mechanisms as a function of depth to predict likely mode of rupture for possible future major earthquakes.
3. Future seismicity, namely recurrence intervals for earthquakes, should be established through:
    - a) Examination of historic seismicity concentrating on the Basin and Range Province and excluding San Andreas and related faults.
    - b) Estimation of fault slip for the Holocene in the Yucca Mountain area.
    - c) Estimation of the local and regional rate of deformation from geodetic, seismic moment release rate, and geologic data to the best possible degree of comparability. In particular, a careful analysis of existing geodetic data is needed.

4.1.2 Long-Term Investigations

Longer term investigations should include the following efforts:

1. Conduct detailed seismic reflection profiling across the faults responsible for the largest Basin and Range earthquakes (i.e., Hebgen Lake, Dixie Valley/Fairview Peak, Cedar Mountain, and Borah Peak). Conduct similar reflection profiling across Yucca Mountain area to determine whether structures similar to those found in the above areas exist. Because the great earthquakes had focal depths of

around 15 kilometers, it would be important to plan the profiling so as to penetrate to these depths in all the areas. Although the scope and expense of this suggested study are considerably greater than the other suggestion, the results could have a major impact on seismic assessment at the site.

2. Carry out detailed studies of Holocene faulting within 30 kilometers of Yucca Mountain using low-sun-angle aerial photography, radar surveys, and trenching to locate active faults in the alluvium and determine their rates of slip, earthquake recurrence intervals, and incremental displacements associated with individual events.

4.2 RECOMMENDATIONS FOR DETERMINING EXTENSION RATES

Although the east-west extension rate in the general Yucca Mountain area appears to be of the same order as that across the entire southern Great Basin, considerable variability would be expected on a small scale. To be useful in the present context, these variations should be carefully mapped by either existing methods, or by the new satellite laser ranging system. An east-west survey is recommended extending 30 kilometers on either side of Yucca Mountain with a station spacing of 5 kilometers, to help identify the variation in the present extension rate near the site.

4.3 RECOMMENDATIONS FOR STUDIES IN ADJACENT SUBPROVINCES

The workshop participants recommend the following efforts:

1. The implication of a large (M = 7 or 8) event in the Death Valley region should be carefully considered for the Yucca Mountain site. Expected ground motion should be estimated for a range of earthquake scenarios.

2. Furthermore, the recommendation in Section 4.1 regarding further geodetic studies of east-west extension should be broadened to include the Death Valley region.

4.4 RECOMMENDATION FOR UNASSOCIATED EARTHQUAKES

The working group recommended three approaches to deal with the issue of unassociated earthquakes. The recommended approaches are that:

1. The historic seismicity within the Basin and Range Province should be carefully reviewed for unassociated earthquakes of magnitude greater than 5.5. The frequency and magnitude of earthquakes not associated with faults within the Basin and Range could then be used to estimate the potential for unassociated earthquakes in the near-site region by scaling the results to the site area. Completeness of the seismic record is critical for these studies.

2. Extensive field investigations should be conducted within about 10 kilometers of the site to further assess the potential for significant local earthquakes. The investigations should identify any throughgoing fault-related features and characterize the local earthquake history using geologic evidence and a combination of

gravity and magnetic surveys, radar soundings, fault trenching, and age dating.

3. Ground motion criteria should be developed over a range that accommodates reasonably plausible earthquakes, including local earthquakes not associated with any identified seismogenic fault.

4.5 RECOMMENDATION FOR IDENTIFICATION OF RELATIONSHIP BETWEEN FAULT LENGTH, DISPLACEMENT, AND MAGNITUDE

The recommendations of the working group include the following actions:

1. A concerted effort should be made to identify the fault length and fault displacement relationship most applicable for estimating the largest credible magnitude on local seismogenic faults, and this relationship should be applied to evaluate current peak acceleration estimates.

   Field work should be initiated to establish constraints on the fault length that could plausibly fracture in a single earthquake. Trenching and age-dating of faults especially close to Yucca Mountain (Bow Ridge, Paintbrush Canyon, Solitario Canyon, Ghost Dance, etc.) should be evaluated. The effort should be extended to several locations along each capable fault longer than a few thousand feet whose displacement history makes it significant to facility design.

4.6 RECOMMENDATIONS FOR ASSESSMENT OF FUTURE SEISMICITY

The working group recommends the following studies to assess the potential for future seismicity:

1. Develop recurrence relations based on a and b values derived from historical magnitude and intensity data. Rogers et al. (1977) developed recurrence estimates using a data base containing earthquakes within 400 kilometers. This data base included large earthquakes on the San Andreas fault system, as well as earthquakes within the Basin and Range Province. This work should be revised to include data specific to the Basin and Range Province. Predictions of recurrence intervals on the basis of historical data should include a measure of the uncertainty.

2. Develop slip rates by dating fault offsets within the Basin and Range Province. Spatial variations in the rate of deformation should be estimated to identify the relative stability or instability of the area surrounding Yucca Mountain. Estimates of the uncertainty in slip rate estimates should also be developed. Both sensitivity and resolution of slip rate estimates should be determined using the extreme ranges of significant parameters.

3. Estimate the regional deformation rate using geodetic control and provide estimates of the uncertainties.

4. Compare the activity rates from historical seismicity, fault offsets, and geodetic surveys to test consistency. Also, compare the results with estimates of the Great Basin activity developed in other studies. Use these results to develop a range for the return period of the local earthquakes of varying magnitude and site-specific levels of ground motion.

4.7 RECOMMENDATIONS FOR GROUND MOTION ATTENUATION RELATIONSHIPS AND SEISMIC HAZARD ANALYSIS

The following recommendations were made by the working group in order to develop improved ground motion attenuation relationships and seismic hazard analyses:

1. It is recommended that updated attenuation relationships that include an estimate of standard error should be used to predict peak ground acceleration at Yucca Mountain. Campbell (1981) and Joyner and Boore (1981) provide such relationships; however, these relationships were developed from a data base that is dominated by data from southern California. The application of these relationships may introduce errors into hazard calculations because of differences between earthquake source properties and wave paths in southern California and those in the tectonic subprovince containing Yucca Mountain. The possibility of biasing the results with the application of these attenuation relationships should be investigated. Ongoing studies by Rogers et al. (1984) on attenuation within the southern Great Basin may provide attenuation relationships more applicable to the Yucca Mountain site.

2. Determination of peak ground motion values should utilize data recorded in the Basin and Range Province, supplemented by earthquake recordings in other extensional regimes, e.g., the magnitude 7 Naples, Italy, earthquake of November, 1980. In addition, the effect of site-specific conditions (rock, alluvium, etc.) should be considered in the development of site-specific ground motion criteria.

3. Without better predictors, it is reasonably conservative to ignore potential reduction of ground motion with depth for the purpose of design of tunnel and underground chambers.

4. The working group noted that currently no earthquake measurements are being made at the repository horizon in Yucca Mountain. Site-specific measurements are needed to utilize reductions in ground motion with depth in the design criteria.

5. Sensitivity studies should be conducted to determine which earthquake scenario is most likely during the next hundred years and which scenario constitutes the greatest hazard. Information currently available does not permit a determination of whether the local faults or the more-distant large faults (e.g., Furnace Creek) constitute the greater hazard to the Yucca Mountain site. A magnitude 6.5 earthquake at a distance of 15 kilometers would be expected to

generate higher accelerations than a magnitude 7.5 at 50 kilometers or greater. Furthermore, a magnitude 6 earthquake at distances less than 15 kilometers could produce even higher accelerations. A probabilistic hazard analysis should account for the hazard from both small local events and large distant events.

5.0 APPENDIX 1

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BACKGROUND DESCRIPTION OF PANEL OF EXPERTS

A brief background description of the members of the panel of experts is given below.

William F. Brace - Professor and Chairman, Department of Earth and Planetary Sciences, Massachusetts Institute of Technology at Cambridge, Massachusetts; member of the National Academy of Sciences; Fellow of American Academy of Arts and Sciences; President of Tectonophysics Section of the American Geophysical Union (1963-1969). Dr. Brace is an internationally known expert in the area of tectonophysics and the physical and mechanical properties of earth materials. He is Associate Editor of the Rock Mechanics Journal; Associate Editor of Tectonophysics, Bulletin of the Geological Society of America, and International Journal of Rock Mechanics and Mining Science. Dr. Brace is a leading member of the academic community in the role of in situ stresses as they relate to seismicity and tectonics. Ph.D., geology, Massachusetts Institute of Technology, 1953.

Gerald A. Frazier - Senior Scientist, Science Applications International Corporation, La Jolla, California. Dr. Frazier is an expert in the assessment of earthquake and explosion-induced ground motions. He has led several studies for evaluating potential earthquake hazards to nuclear power plants and has provided a lead role in the licensing pursuits for utility companies. He has developed technology for numerically simulating explosion-induced ground motions for both near- and far-field response. He is the lead research seismologist at the DARPA Center for Seismic Studies, Washington, D.C. Ph.D., civil engineering, Montana State University, 1969.

Howard R. Pratt - Corporate Vice President, Science Applications International Corporation, La Jolla, California. Dr. Pratt manages the Earth Sciences Operation which has six divisions specializing in (1) geology and geophysics, (2) instrumentation engineering and data processing, (3) civil engineering, (4) geotechnical engineering, geomechanics, and solid mechanics. Programs cover a wide range of calculational and experimental support efforts in areas such as nuclear weapons effects, nuclear waste isolation, nuclear power plant design, civil works projects, and energy resource exploration. He is a recognized expert in rock mechanics and engineering geology and has conducted active research in (1) large-scale field experiments to evaluate material properties in situ, (2) ground motions associated with earthquakes and explosive sources. Adjunct Professor University of Utah (1969 to present). Ph.D., geology, University of Rochester, 1966.

C. Barry Raleigh - Director Lamont-Doherty Geological Observatory of Columbia University and Professor, Department of Geological Sciences, Columbia University, New York, New York. Dr. Raleigh is an internationally known expert in the area of tectonophysics, earthquake prediction, and experimental rock mechanics. Author of over eighty papers in these technical areas, including many on in situ stress measurements. Fellow, American Geophysical Union and Geological Society of America, President, Tectonics section, American

Geophysical Union. Former Coordinator of the Earthquake Prediction Program, U.S. Geological Survey and Chief of the Branch of Earthquake Tectonics, Office of Earthquake Studies, U.S. Geological Survey. Ph.D., geology, geophysics, University of California at Los Angeles, 1963.

Al M. Rogers - Chief, Branch of Engineering Geology and Tectonics, U. S. Geological Survey, Denver, Colorado. Dr. Rogers manages the research efforts of 150 employees studying landslide processes, rock mechanics, seismic hazards, earthquake ground motion attenuation, geomorphology of young faulting, and regional tectonics. He has conducted studies related to seismic hazard and risk to high-level nuclear waste facilities at the Nevada Test Site and in Texas and New Mexico. Dr. Rogers has also engaged in seismic hazard and risk studies along the Wasatch Urban Front. Dr. Rogers has conducted research in scale model seismology and induced seismicity, both from natural and nuclear explosion sources. As part of these efforts, he has been responsible for the operation of four seismic networks and the ensuing research. Ph.D., geophysics, St. Louis University, 1970.

Robert B. Smith - Professor Geophysics, Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah and Director, University of Utah, Seismograph Stations. Dr. Smith's primary research areas are in theory and method in seismic reflection and refraction, earthquake seismology, and tectonophysics. His research interests are earthquake investigations of intraplate earthquakes with emphasis on intermountain seismic belt; seismological investigations of crustal structure of the western United States; and mechanical properties of mountain building uplift and magma placement from seismological data. Associate editor of the Journal of Geophysical Research, Member of the National Academy of Science Committee on Seismology, Ph.D., geophysics, University of Utah, 1967.

Brian P. Wernicke - Assistant Professor, Department of Geological Sciences, Harvard University, Cambridge, Massachusetts. Dr. Wernicke is an expert in the structural geology of the Basin and Range Province in the United States. He is nationally known for his work in extension tectonics of the Basin and Range Province of Nevada, Utah, and California and the author of many papers on that subject. Consulting geologist to oil companies on the structure and tectonics of the western United States. Ph.D., geology, Massachusetts Institute of Technology, 1982.

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6.0 REFERENCES

Aki, K., P. Reasenbert, T. De Fazio, and Y. B. Tsai, 1969. "Near-field and Far-field Seismic Evidences for Triggering of an Earthquake by the BENHAM Explosion," Bulletin of the Seismological Society of America, Vol. 59, No. 6, pp. 2197-2207.

Anderson, J. G., 1979. "Estimating the Seismicity from Geological Structure for Seismic Risk," Bulletin of the Seismological Society America, Vol. 69, pp. 135-158.

Anderson, R. E., C. R. Longwell, R. L. Armstrong, and R. S. Marvin, 1972. "Significance of K-Ar of Tertiary Rock from Lake Mead Region, Nevada, Arizona," Geological Society of American Bulletin, Vol. 83, pp. 273-288.

Bonilla, M. G. and J. M. Buchanan, 1970. Interim Report on Worldwide Historic Surface Faulting, U. S. Geological Survey Open-File Report, 32 pp.

Bonilla, M. G., R. K. Mark, and J. J. Lienkaemper, 1984. "Statistical Relations among Earthquake Magnitude, Surface Rupture Length and Surface Fault Displacement," Bulletin of the Seismological Society of America, Vol 74, pp. 2379-2411.

Brace, W. F. and D. L. Kolstedt, 1980. "Limits on Lithospheric Stress Imposed by Laboratory Experiments," Journal of Geophysical Research, Vol. 85, pp. 6248-6252.

Byerlee, J. D., 1978. "Friction of Rocks," Pure and Applied Geophysics, Vol. 116, pp. 615-626.

Campbell, K. W., 1981. "Near-Source Attenuation of Peak Horizontal Acceleration," Bulletin of the Seismological Society of America, Vol. 71, No. 6, pp. 2039-2070.

Carder, D. S., 1945. "Seismic Investigations in the Boulder Dam Area, 1940-1944, and The Influence of Reservoir Loading on Earthquake Activity," Bulletin of the Seismological Society of America, Vol. 35, pp. 175-192.

Das, S., and C. H. Scholtz, 1983. "Why Large Earthquakes Do Not Nucleate at Shallow Crustal Depths," Nature, Vol. 305, pp. 621-623.

Dickey, D. D., 1968. "Fault Displacement as a Result of Underground Nuclear Explosions," in Nevada Test Site, E. B. Eckel (ed.), Geological Society of America Memoir 110, pp. 219-232.

Dowding, C. H., 1978. "Seismic Stability of Underground Openings," Proceedings of the First International Symposium on Storage in Excavated Rock Caverns, Rockstore 77, Vol. 2, pp. 231-238.

Eaton, G. P., R. R. Wahl, H. J. Prostka, D. R. Mabey, and M. O. Kleinkopf, 1978. "Regional Gravity and Tectonic Patterns: Their Relation to Late Cenozoic Epeirogeny and Lateral Spreading in the Western Cordillera," in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, R. B. Smith and G. P. Eaton (eds.), Geological Society of America Memoir 152, pp. 51-91.

Eddington, P. K., R. B. Smith, and C. Renggli, 1985. "Kinematics of Basin-Range Intraplate Extension," in Proceedings of the Symposium on Continental Extension Tectonics, 18-20 April 1985, Geological Society of London, (in press).

Gianella, V. P., and E. Callaghan, 1934. "The Earthquake of December 20, 1932, at Cedar Mountain, Nevada and Its Bearing on the Genesis of Basin Range Structure," Journal of Geology, Vol. 42, No. 1, pp. 1-22.

Greensfelder, R. W., F. C. Kinster, and M. R. Somerville, 1980. "The Seismotectonic Regionalization of the Great Basin, and Comparison of Moment Rates Computed from Seismic Strain and Historic Seismicity: Summary," Geological Society of America Bulletin, Part I, Vol. 81, pp. 518-523.

Hamilton, R. M., and J. H. Healy, 1969. "Aftershocks of the BENHAM Nuclear Explosion," Bulletin of the Seismological Society America, Vol. 59, pp. 2271-2282.

Hamilton, R. M., F. A. McKeown, and J. H. Healy, 1969. "Seismic Activity and Faulting Associated with a Large Underground Nuclear Explosion," Science, Vol. 166, No. 3905, pp. 601-604.

Hamilton, R. M., B. B. Smith, F. G. Fischer, P. J. Papanek, 1971. Seismicity of the Pahute Mesa Area, Nevada Test Site, 8 December 1968 through 31 December 1970, U.S. Geological Survey Report USGS-474-138, 170 p.

Healy, J. H., S. H. Hickman, M. D. Zoback, and W. L. Ellis, 1984. Report on Televiewer Log and Stress Measurements in Core Hole USW G-1, Nevada Test Site, U. S. Geological Survey Open-File Report 84-15.

Hunt, C. B., and D. R. Mabey, 1966. Stratigraphy and Structure, Death Valley, CA, U.S. Geological Survey Professional Paper 494A, 162p.

Iwasaki, T., S. Wakabayashi, and F. Tatsuoka, 1977. Characteristics of Underground Seismic Motions at Four Sites Around Tokyo Bay, Wind and Seismic Effects, H. S. Lew (ed.), U.S. Department of Commerce, Washington, D.C.

Jordan, T. H., J. B. Minster, D.C. Christodoulidis, and D. E. Smith, 1985. "Constraints on Western U.S. Deformation from Satellite Laser Ranging," (preprint).

Joyner, W. B. and D. M. Boore, 1981. "Peak Horizontal Acceleration and Velocity from Strong Motion Records, including Records from the 1979 Imperial Valley, California Earthquake," Bulletin of the Seismological Society of America, Vol. 71, pp. 2011-2038.

Kanai, K., K. Osada, and S. Yoshizawa, 1953. "Observations Study of Earthquake Motion in the Depth of the Ground, IV (Relation Between the Amplitude at Ground Surface and the Period)," Bulletin of the Earthquake Research Institute, Vol. 31, pp. 228-234.

Kanai, K., T. Tanaka, S. Yoshizawa, T. Morishita, K. Osada, and T. Suzuki, 1966. "Comparative Studies of Earthquake Motions on the Ground and Underground II," Bulletin of the Earthquake Research Institute, Vol. 44, pp. 609-643.

Kanai, K., and T. Tanaka, 1951. "Observations of the Earthquake Motion at the Different Depths of the Earth, I," Bulletin of the Earthquake Research Institute, Vol. 29, pp. 107-113.

King, K. W., 1982. A Study of Surface and Sub-surface Ground Motion at Calico Hills, Nevada Test Site, USGS Open-File Report 82-1044.

Maldonado F., 1977. Composite Post Shot Fracture Map of Pahute Mesa, Nevada Test Site, June 1973 through March 1976, U.S. Geological Survey Report, USGS474-243, 11 p.

Mark, R. K., and M. G. Bonilla, 1977. Regression Analysis of Earthquake Magnitude and Surface Fault Length Using the 1970 Data of Bonilla and Buchanan, U.S. Geological Survey Open-File Report 77-614, 8 p.

McGarr, A., and N. C. Gay, 1978. "State of Stress in the Earth's Crust," Annual Review of Earth and Planetary Science, Vol. 6, pp. 405-436.

McGarr, A., 1984. "Scaling of Groundmotion Parameters, State of Stress and Focal Depth," Journal of Geophysical Research, Vol. 89, No. B8, pp. 6969-6979.

McKeown, F. A., and D. D. Dickey, 1969. "Fault Displacements and Motion Related to Nuclear Explosions," Bulletin of the Seismological Society of America, Vol. 59, No. 6, pp. 2253-2271.

Miller, E. L., T. B. Gans, and J. Garing, 1983. "The Snake Range Decollement; an Exhumed Mid-Tertiary Ductile Brittle Transition," Tectonics, Vol. 2, pp. 239-263.

Minster, J. B., and T. H. Jordan, 1984. "Vector Constraints on Quaternary Deformation of the Western United States East and West of the San Andreas Fault," in Tectonics and Sedimentation Along the California Margin: Pacific Section S.E.P.M., J. K. Crouch and S. B. Bachman (eds.), Vol. 38, pp. 1-16.

Morrow, C., and J. Byerlee, 1984. "Frictional Sliding and Fracture Behavior of Nevada Test Site Tuff," in 25th Symposium on Rock Mechanics, Evanston, Ill., pp. 467-474.

Okamoto, S., 1973. Introduction of Earthquake Engineering, John Wiley & Sons, New York, New York.

Owen, G. N., and R. E. Scholl, 1980. Earthquake Engineering, Large Underground Structures, Final Report No. FHWA-RD-80/195, January 1981, Prepared for Federal Highway Administration and National Science Foundation by URS/John A. Blume and Assoc., Engineers, Washington, D.C., 280 p.

Pratt, H. R., W. A. Hustrulid, and D. E. Stephenson, 1978. Earthquake Damage to Underground Facilities, Savannah River Laboratory Report DP-1513, pp. 20-25.

Richter, C. F., 1958. Elementary Seismology, W. H. Freeman and Company, San Francisco, CA, 768 p.

Rogers, A. M., D. M. Perkins, and F. A. McKeown, 1977. "A Preliminary Assessment of the Seismic Hazard of the Nevada Test Site Region," Seismological Society of America Bulletin, Vol. 67, No. 6, pp. 1587-1606.

Rogers, A. M., M. Meremonte, and R. B. Herrmann, 1984. "Wave Attenuation in the Southern Great Basin, Nevada-California," Earthquake Notes, Seismological Society of America, Vol. 55, No. 1., p. 24.

Rogers, A. M., S. C. Harmsen, W. J. Carr, 1981. Southern Areal Basin Seismological Data Report for 1981, USGS Open-File Report 83-669, 240 p.

Rogers, A. M., and W. H. K. Lee, 1976. "Seismic Study of Earthquakes in the Lake Mead, Nevada-Arizona Region," Bulletin of the Seismological Society of America, Vol. 66, pp. 1657-1681.

Rogers, A. M., S. C. Harmsen, R. B. Herrmann, and M. E. Meremonte, 1985. "A Study of Ground Motion Attenuation in the Southern Great Basin, CaliforniaNevada, Using Several Techniques for Estimates of Q_s Log A_0 and Coda A," (in preparation).

Schnabel, D. B., and H. B. Seed, 1973. "Accelerations in Rock for Earthquakes in the Western United States," Seismological Society of America Bulletin, Vol. 63, pp. 501-516.

Smith, R. B., 1978. "Seismicity, Crustal Structure, and Intraplate Tectonics of the Interior of the Western Cordillera," in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, R. B. Smith and G. P. Eaton (eds.), Geological Society of America Memoir 152, pp. 111-144.

Smith, R. B., and A. G. Lindh, 1978. "Fault Plane Solutions of the Western United States: A Compilation," in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, R. B. Smith and G. P. Eaton (eds.), Geological Society of America Memoir 152, pp. 107-110.

Smith, R. B., 1982. "Intraplate Seismo-Tectonics and Mechanisms of Extension in the Western United States," (abs), Chapman Conference on Fault Behavior and the Earthquake Generation Process, Alta, Utah, October, 1982, American Geophysical Union.

Smith, R. B., and R. L. Bruhn, 1984. "Intraplate Extensional Tectonics of the Eastern Basin-Range: Inferences on Structural Style from Seismic Reflection Data, Regional Tectonics, and Thermal-mechanical Models of Brittle-Ductile Deformation," Journal of Geophysical Research, Vol. 89, No. B7, pp. 5733-5762.

Smith, R. B., P. Eddington, and L. L. Leu, 1984. "Strain Rates in Utah from Seismic Moments, Paleoslip and Geodetic Surveys," in Proceedings of Workshop XXVI on Evaluating the Regional and Urban Earthquakes Hazards in Utah, USGS Open-File Report 84-763, pp. 422-437.

Stewart, J. H., 1978. "Basin-Range Structure in Western North America: A Review," in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, R. B. Smith and G. P. Eaton (eds.), Geological Society of America Memoir 152, pp. 1-31.

Stock, J. M., and J. H. Healy, 1984. Report on Televiewer Log and Stress Measurements in Core Hole USW G-2, Nevada Test Site October-November 1982, U.S. Geological Survey Open-File Report 84-172, 31 p.

Stock, J. M., J. H. Healy, S. H. Hickman, and M. D. Zoback, 1984. "Hydraulic Fracturing Stress Measurements at Yucca Mountain, Nevada and Relationship to the Regional Stress Field," Journal of Geophysical Research, Vol. 90, No. B10, pp. 8691-8706.

Thompson, G. A., 1985. "Perspective from the Fairview Peak - Dixie Valley Earthquakes of 1954," in Proceedings of Workshop XXVIII on the Borah Peak, Idaho, Earthquake, Stein, R. S. and R. C. Bucknam (eds.), U.S. Geological Survey Open-File Report 85-290, pp. 27-42.

VanWormer, J. D., and A. S. Ryall, 1980. "Sierra Nevada-Great Basin Boundary Zone: Earthquake Hazard Related to Structure, Active Tectonic Processes, and Anomalous Patterns of Earthquake Occurrence," Bulletin of the Seismological Society of America, Vol. 70, pp. 1557-1572.

U.S. Geological Survey, 1984. A Summary of Geologic Studies through January 1, 1983, of a Potential High-Level Radioactive Waste Repository Site at Yucca Mountain, Southern Nye County, Nevada, USGS Open-File Report 84-92, 103 p.

Vetter, V., and A. S. Ryall, 1983. "Systematic Change of Focal Mechanism with Length in the Western Great Basin," Journal of Geophysical Research, Vol. 88, pp. 8237-8250.

Vortman, L. J., 1980. Prediction of Ground Motion from Underground Nuclear Weapons Tests as it Relates to Siting of a Nuclear Waste Storage Facility at NTS and Compatibility with the Weapons Test Program, SAND80-1020/1, Sandia National Laboratories, Albuquerque, NM, April, 1980, 44 p.

Vortman, L. J., 1983. Stresses and Strains at Yucca Mountain from Underground Nuclear Explosions, SAND83-1553, Sandia National Laboratories, Albuquerque, NM, 54 p.

Wallace, R. B., 1979. "Earthquakes and the Prefractured State of the Western Part of the North American Continent," Proceedings of the International Research Conference on Intra-Continental Earthquakes, pp. 69-81.

Wallace, R. B., 1984. "Fault Scarps Formed During the Earthquakes of October 2, 1915, in Pleasant Valley, Nevada, and Some Tectonic Implications," in Faulting Related to the 1915 Earthquakes in Pleasant Valley, Nevada, U.S. Geological Survey Professional Paper No. 1274-A, pp. A1-A33.

Wallace, T. C., D. V. Helmberger, and G. R. Engen, 1983. "Evidence of Tectonic Release from Underground Nuclear Explosions in Long-Period P Waves," Bulletin of the Seismological Society of America, Vol. 73, pp. 593-614.

Wallace, T. C., D. V. Helmberger, and G. R. Engen, 1985. "Building of Tectonic Release From Underground Nuclear Explosions in Long-Period S Waves," Bulletin of the Seismological Society of America, Vol. 75, pp. 157-174.

Wernicke, B., and B. C. Burchfiel, 1982. "Modes of Extensional Tectonics," Journal of Structural Geology, Vol. 4, pp. 105-115.

Wernicke, B., J. E. Spencer, B. C. Burchfiel, and P. L. Guth, 1982. "Magnitude of Crustal Extension in the Southern Great Basin," Geology, Vol. 10, pp. 499-502.

Zoback, M. D., and J. H. Healy, 1984. "Friction, Faulting, and In Situ Stress," Annales Geophysicae, Vol. 2, pp. 689-698.

Zoback, M. L., and M. D. Zoback, 1980. "State of stress in the Conterminous United States," Journal of Geophysical Research, Vol. 85, pp. 6113-6156.