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# IDENTIFICATION OF TYPE II FAULTS (FAULTS THAT ARE CANDIDATES FOR DETAILED INVESTIGATIONS) IN THE YUCCA MOUNTAIN REGION

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# 1 INTRODUCTION

## 1.1 BACKGROUND

In order to provide guidance to the U.S. Department of Energy (DOE) on appropriate investigations for the identification of fault displacement hazards and seismic hazards at a generic geologic repository, the Nuclear Regulatory Commission (NRC) developed NUREG-1451 Staff Technical Position on Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository (McConnell et al., 1992). In the present letter report, guidance from McConnell et al. (1992) is used to classify faults in two electronic fault coverages in the Center for Nuclear Waste Regulatory Analyses (CNWRA) Geographic Information System (GIS) database and one U.S. Geological Survey (USGS) textual coverage.

## 1.2 SCOPE

The three coverages considered in this study include more than 400 faults within 100 km of the proposed Yucca Mountain (YM) repository site. Earthquakes and fault displacement on many of these faults will have no effect on the repository design or performance because they are either too far from the repository or are too small to generate a significant magnitude earthquake. In order to identify faults important to repository design or performance, this study applies a coarse screening criterion to the three fault coverages. The faults identified using the criteria of McConnell et al. (1992) as having the potential for little or no effect on the repository are removed from the total fault population. The remaining faults are those which require additional characterization or closer study to determine their potential effects on design and performance. In a future study (IM 5708-471-640) the faults in the remaining group will be reviewed individually in light of available information to again determine whether or not they have the potential to effect repository design or performance. Only the potential hazards associated with ground motion or fault displacement were considered in this study. Other disruptive conditions related to structural deformation, such as changes in rock properties and the effects of structural deformation on water and magma flow, are not considered in this assessment.

The principal intended outcome of this study is to provide a basis for NRC to review DOE determination of significant faults. With this information, NRC may be able to clarify or resolve technical concerns related to structural deformation and seismic hazards at the proposed repository by identifying faults for which additional information is required; and eliminate from further consideration those which will have little or no effect on repository design or performance.

In this report, the term "fault" is used under the definition as proposed by Groshong (1988) in which a fault is "a tabular region across which the displacement parallel to the zone is appreciably greater than the width of the zone and in which the deformation is greater than outside the zone" is accepted.

# 2 BACKGROUND OF STUDY

## 2.1 CLASSIFICATION OF FAULTS

NUREG-1451 developed a classification of faults, according to their potential to affect repository design or performance. The classification and distinguishing criteria are given in Table 1.

Type I faults are those faults or fault zones that must be characterized because their: (i) age of displacement, (ii) location with respect to the repository, (iii) length, (iv) orientation, or (v) historic seismicity indicate activity that could affect repository design or performance. Faults classified as Type I must be considered for detailed investigation to fully characterize them and assess their potential effects on the repository. Type I faults include faults within the controlled area which have demonstrable Quaternary (<2.0 m.y.) displacement. Outside the controlled area, Type I faults must show evidence of Quaternary displacement and be of sufficient length, have a location, or orientation to potentially affect the repository or be seismically active or have a direct (i.e., branching relationship) with an active fault.

Based on current information, Type III faults will not affect repository design or performance. Type III faults include faults that are located outside the faulting component; within the faulting component but are of insufficient length or have a location or orientation that would not affect repository design or performance; experienced most-recent displacement prior to the Quaternary; are unfavorably oriented in current stress field for displacement; or are demonstrably inactive seismically.

Type II faults are those faults that require additional characterization to determine whether their location, length, orientation, age of displacement, and seismicity will have a potential affect on repository design or performance. Faults classified as Type II require additional investigations to determine if they should be subsequently classified Type I or Type III faults for design and performance assessment. For the purposes of this screening study all faults are designated either Type II or Type III faults. It is recognized that many Type II faults may be classified in a subsequent study as Type I faults.

## 2.2 FAULT CLASSIFICATION APPROACH

The NRC approach to fault classification is given in NUREG-1451 (Figure 1). The first step is identification of the region to be investigated. That is done in Section 2.4 of this report. The second step is to screen fault populations and identify faults which meet screening criteria and, therefore, require extra investigation. This second step distinguishes Type III faults from Types I and II faults. For this study, all non Type III faults so identified are classified as Type II faults. The further separation of Type II faults into Type I and Type III will be accomplished in a subsequent study. NUREG-1451 recognized that analysis of fault displacement is necessarily an iterative process, because of accumulation of new data and understanding of tectonic processes, and that the classification of Type III faults should be subject to periodic re-evaluation.

## 2.3 DATA SOURCES

To classify faults according to the system described in NUREG-1451, Quaternary faults from three individual fault coverages were used. Regional coverage, out to 100 km, was provided by the map of Nakata et al. (1982) (Figure 2). This map coverage is at a scale of 1:2,500,000 and provides coverage for both the Basin and Range and the Rio Grande Rift provinces (Martin, 1995). Because of the scale, only major faults, generally in excess of 5 km, are shown. In addition, only faults known in 1982 to have experienced Quaternary displacement are included on the map. Thus, faults identified and characterized through YM site characterization efforts are not included because the results of this characterization effort for regional faults is still undergoing technical review and is not available electronically. Some geological interpretation of the electronic map was done to link segments of faults in order to maximize their length and thus their potential to be classified as Type II faults. For example, short segments of the Rock Valley fault were linked together to give single segment with a total length of 65 km. This conservative approach assures that the most prudent fault coverage was used in this first phase of analysis.

Local map coverage, around YM, was provided by Simonds et al. (1995) (Figure 3). This map was received in electronic format from the U.S. Geological Survey. Editing of the map was required to link segments of faults together separated by small offsets (i.e., 1–10 m). These separations resulted from the original digitization process and are not evident on the hard copy of the map, but show up in the electronic version. However, fault-digitization gaps in effect artificially reduce electronically determined fault lengths. This effect can be significant. In addition, some geologic interpretation of the map was done to link distinct segments of the same fault together to maximize their length. In addition, to allow ARC/INFO to unambiguously analyze the fault data, shorter branches of branching faults were electronically disconnected from the longer portion. If a short branch is electronically selected as the point of closest approach the associated length could be unrepresentatively short, resulting in misclassification of the fault. The electronic fault length is a function of the digitization procedure and is usually unknown. Nine faults extended beyond Simonds et al. (1995) map to the north and two to the south (Figure 3). The electronic coverage of Frizzell and Shulters (1990) was used to extend these specific faults beyond the Simonds et al. (1995) coverage to their mapped termination. Data acquired in this present study from maps of Nakata et al. (1982) and Simonds et al. (1995) were transferred into a spreadsheet in electronic format. These data were used to generate peak acceleration for each fault, based on fault length and closest approach of the fault to the repository using published scaling relations (Campbell, 1987). Additionally, screened faults of Nakata et al. (1982) and Simonds et al. (1995) were transferred electronically into the 3DSTRESS code (Ferrill, et al., 1995a; 1995b; Morris et al., 1996) for slip-tendency analysis. Faults remaining following the slip-tendency analysis are considered Type II faults.

The third fault coverage data set is textual data from Piety (1995). The maps that accompanied Piety's report are undergoing review and correction and are not available electronically. This suggests that textual data is also preliminary and subject to change. However, it provides coverage at an intermediate scale and provides a check on the other two coverages. Conclusions about faults in this coverage should also be considered preliminary and reanalysis should be performed once Piety's data is finalized. For this coverage, fault lengths and closest approach data were entered directly into a spreadsheet. Because electronic versions of Piety's maps are unavailable, slip-tendency analysis was not done on those faults.

## 2.4 IDENTIFICATION OF THE FAULTING COMPONENT OF THE GEOLOGIC SETTING

In NUREG-1451 the Geologic Setting is defined as consisting of three systems, the geologic, hydrologic and geochemical systems (NUREG-1451, Figure 2). The geologic system is subdivided into faulting, seismicity, volcanism, geomorphic, stratigraphic, and natural resources components (NUREG-1451, Figure 2). For the purposes of this report the faulting component is considered to extend out 100 km radially from the center of the repository [548371 m, 407744 m; Universal Transverse Mercator (UTM) coordinates] as shown in Figure 2. The area selected for the fault component is not unique and could be chosen differently in future analyses. Once the faulting component was defined, faults within it were screened. Those not meeting the Type III criteria are considered Type II faults.

## 2.5 FAULT LENGTH ANALYSIS

The peak acceleration at the center of the repository projected to the surface was used as the screening tool for fault length. Peak acceleration is a function of the magnitude of an earthquake and the distance of the rupture from the repository. The empirical relationship between maximum moment magnitude of a potential earthquake and surface rupture length have been most recently refined by Wells and Coppersmith (1994), who developed a median relationship through available observations. Maximum moment magnitude is the size of the largest possible earthquake given the length of the fault and can be estimated using the following equation from Wells and Coppersmith (1994):

$$M = 5.08 + 1.16 * \log L, \qquad \text{(Eq. 1)}$$

where $M =$ magnitude and $L$ is the length of the fault.

In their Probabilistic Seismic Hazard Analysis (PSHA) study of the exploratory studies facility (ESF) (Quittmeyer, 1994; Wong, et al., 1995) the DOE used magnitude $M = 6.25$ as the threshold value for distinguishing between earthquakes that occur on known faults (their fault-source term) and those that occur randomly or on unidentified faults (their area source term). This threshold is based on observations by (Smith and Arabasz, 1991) that $M \leq 6.0 - 6.5$ do not produce surface ruptures in the Basin and Range tectonic province. However, the Basin and Range earthquakes of this magnitude range lie on known faults and fault trends. Smaller-magnitude earthquakes ($M = 5.7$ - $M = 6.0$) can also produce surface rupture if they happen to have a shallow earthquake focus. Wells and Coppersmith (1994) concluded their regression statistics can be used below $M = 6.0$ and include several well-studied surface rupturing earthquakes of magnitude $< 6.0$ in their database. Hofmann and Ibrahim (1995) suggest a magnitude $M = 5.7$ as the lower limit to be assigned to individual faults and smaller magnitudes be allowed to occur randomly. Consistent with the preliminary nature of this study, a slightly more conservative value of 5.6 was used for the maximum moment magnitude for faults to be considered for fault-source term. Using the more conservative value and (Eq. 1) magnitude 5.6 earthquakes occur on faults with a mean length of slightly less than 4 km and have displacements of approximately $0.05 \times 10^{-1}$ m (Wells and Coppersmith, 1994). Therefore, in this study all faults capable of producing $M < 5.6$ earthquakes (i.e., fault $< 4$ km in length) were excluded from further consideration.

From magnitude (M) and distance to the fault, the median acceleration at the center (surface) of the repository is calculated from the attenuation formula, (Eq. 2) which is based on equation 5 of Campbell (1987). The first term is modified as required by the acceleration in the free field, constrained by far field recording as outlined in Tables 4 and 5 of Campbell (1987).

$$\ln A = (-2.893 + (0.85M) - 1.25\ln((r^2 + 16)^{1/2} + 0.0872e^{0.0678M}) - 0.059r)(1.12)), \qquad \text{(Eq. 2)}$$

where $A$ is peak acceleration, $M$ is magnitude from (Eq. 1), and $r$ is the closest approach of the fault to the center of the repository at the surface. Distance $((r^2 + 16)^{1/2})$ is modified in this equation to represent distance from the repository to a depth of 4 km on all faults. Four km is the shallowest depth at which peak acceleration can be generated (Campbell, 1987). To perform these calculations a table, for each electronic coverage, containing the fault length and closest approach, was exported into an Excel spreadsheet from the GIS database. After completion of the calculation the data were imported back into the GIS database for screening of faults. NUREG-1451 indicates "...an acceleration value of 0.1 g as a valid discriminator to determine the scope of investigation to be undertaken, or the type of information to be gathered..." To compensate for the closest approach distance being calculated from the fault to the center of the repository, rather than the boundary of the repository, 0.09 g, rather than 0.1 g, was used as the screening criterion. All faults with an acceleration below 0.09 g were classified as Type III faults and deleted from the maps (Figures 4 and 5). On the Nakata et al. (1982) map there are 9 faults with potential accelerations equal to or greater than 0.09 g. On Simonds' et al. (1995) map 28 faults remained after the 0.09 g criterion was applied.

Piety (1995) data were sorted and screened in the Excel program. Using the data from Piety (1995) and applying the same screening criteria, 32 faults were selected. They are listed in Table 2. The faults not selected are listed in Appendix B. All the faults selected from the Nakata (et al., 1982) coverage were also selected from the Piety (1995) data. The fault directly south of the controlled area boundary (Figure 4), is considered part of the Rock Valley fault system by Piety (1995), judging by the 65 km length attributed to it. In either interpretation the Rock Valley fault may be capable of generating greater than 0.09 g acceleration at YM and is therefore a Type II fault. Seven of 28 faults in the Simonds et al. (1995) coverage overlapped with the Piety (1995) coverage.

## 2.6 FAULT ORIENTATION ANALYSIS

The relative tendency of a fault to slip in a given *in situ* stress field is dependent on the magnitude of the principal stresses and orientation of the fault relative to the orientation of the three principal stress axes (Ferrill, et al., 1995a; 1995b; Morris et al., 1996). Slip-tendency analysis (Morris, et al., 1996) was used as a screening tool to evaluate the effect of orientation on fault type. The *in situ* stress state at YM (Morris, et al. 1996) is based on measurements of Stock et al. (1985). Maximum principal compressive stress ($\sigma_1$) = vertical = 90 MPa; intermediate principal compressive ($\sigma_2$) = N 28°E = 65 MPa; and minimum principal compressive stress ($\sigma_3$) = N 62° W = 25 MPa. Stock et al. (1985) measured *in situ* stress at depths of 1 and 1.3 km. Morris et al. (1996) extrapolated the data to 5 km. Because the western part of the regional fault coverage, which includes the Death Valley—Furnace Creek fault system, is in a region with a different stress field orientation (Zoback, 1992), a second slip-tendency analysis was required. This second analysis was identical to the first but with $\sigma_2$=NS and $\sigma_3$=EW (Morris et al., 1996).

The slip-tendency based screening criterion is the ratio of the maximum slip-tendency of the fault to the maximum slip-tendency for any fault in the specified stress field. For this study, faults with slip tendencies greater than 50 percent of maximum slip-tendency were taken as potentially significant and assigned as Type II faults. The 0.50 slip-tendency criterion was empirically chosen to eliminate only those faults that are nearly perpendicular to $\sigma_2$, the intermediate principal compressive stress (i.e., the maximum horizontal compressive stress) such as the Yucca Wash, Severe Wash, and Pagany Wash faults on the coverage of Simonds et al. (1995). However, because of the length and location of these faults and the state-of-the-art of slip-tendency analysis, it was decided to include these faults as Type II faults in this initial classification. On the coverage of Nakata of et al. (1982), no faults were eliminated based on slip-tendency analysis. In order to perform the slip-tendency analysis, it was necessary to export the faults screened for peak acceleration to the 3DSTRESS software. Results of slip-tendency analysis were not imported back into the ARC/INFO program, but were plotted directly as Figures 6, 7, and 8. As noted above, faults from the Piety (1995) coverage were not included in the slip-tendency analysis.

## 2.7 AGE OF FAULT DISPLACEMENT ANALYSIS

Maps and databases used in the present study contain only Quaternary faults (Nakata et al., 1982; Simonds et al., 1995; and Piety, 1995). Therefore, all faults in the present analysis meet the criterion of Quaternary displacement.

## 2.8 SEISMIC ACTIVITY ANALYSIS

The YMR is temporally and spatially in a period and region of low strain rate (Swan, 1995). As a result, microseismicity does not correlate well with most faults in the YMR (Rodgers et al., 1987). This poor correlation results from the relatively low seismicity, combined with poorly constrained hypocenters and a poorly defined complex subsurface geology.

For most faults, fault dips are only known at the surface. Tectonic models can provide an indication of dip. However, the downward projection of faults more than several hundred meters can result in substantial error in position of the fault plane at depths of several km. In addition, the depths of most earthquakes, especially small magnitude earthquakes, are poorly constrained. Poorly constrained positions of fault planes and poorly constrained vertical positions of earthquakes result in a large uncertainty when trying to correlate earthquakes with known faults. Rodgers et al. (1987) reported that the hypocenters of small earthquakes appear to occur in cylinders. Hofmann (1994) suggested that these zones may reflect intersections of fault planes, further complicating the assignment of seismicity to known faults.

A third complicating factor is the presence of blind faults (i.e., those with no surface expression) (Arabasz et al., 1992; Harmsen, 1994). Seismic events on these faults result in background seismic noise that is nearly impossible to clarify, especially for small random events. As a result, absence of seismicity along a fault cannot be used to screen Type III from Type II faults.

## 2.9 RESULTS

Two digital map coverages in the CNWRA electronic GIS database and one textual coverage of Quaternary faults within 100 km of YM were analyzed in order to identify and screen Type III faults in the YMR. The most effective screening criteria were peak acceleration, which is a function of fault length and closest approach of the fault, and slip-tendency, which is a function of the fault orientation and the *in situ* stress state. Other generic criteria recommended in NUREG-1451, such as age of last displacement and seismicity, were ineffective in screening the fault population in the YMR. All faults in the three coverages were considered to be Quaternary by their authors. Historic seismic activity in the area is minimal, diffuse, and, consequently, nondefinitive in screening faults. After screening, 54 faults of the estimated more than 400 present in the three coverages, were identified as Type II faults (Table 3). If Piety's (1995) coverage were included in the slip-tendency analysis the number of faults may decrease further.

The use of the CNWRA GIS database in the manner described in this report is new and broadens the use of the software. Several comments need to be made regarding this utilization. Before using data in the GIS database, it needs to be carefully reviewed. Data which had been used many times in the past for visual comparative analyses and preparation of graphics, were found to not be suitable for quantitative analysis. Specifically, small gaps in the digitized faults caused inaccurate results when fault lengths were queried. Thus, a necessary first step in this study was to edit these small digitizing errors from the data. In addition, because the goal was to identify Type II faults based on peak acceleration, it was necessary to determine the maximum length of the faults. This required linking fault segments together based on geologic interpretation of the maps.

Both peak acceleration and the slip-tendency are parameters derived from primary data in the GIS database (i.e., fault length and orientation). The success of electronic screening of faults using ARC/INFO, 3DSTRESS, and Excel illustrate the usefulness of such an integrated approach in future analyses of faults.

# 3 REFERENCES

Arabasz, W.J., J.C. Pechmann, and E.D. Brown. 1992. *Observational Seismology and the Evaluation of Earthquake Hazard and Risk in the Wasatch Front Area, Utah.* P.L. Gori and W.W. Hays, eds. Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah. USGS Professional Paper 1500-A-J. D1–D36. Washington, DC: Department of the Interior.

Campbell, K.W. 1987. Predicting strong ground motion in Utah. *Evaluation of Regional and Urban Earthquakes and Risk in Utah.* W.W. Hays and P.L. Gori, eds. USGS Professional Paper 87–585II, L1-L90. Washington, DC: Department of the Interior.

Ferrill, D.A., A.P. Morris, D.B. Henderson, and R.H. Martin. 1995a. Tectonic Processes in the Central Basin and Range Region. *NRC High-Level Radioactive Waste Research at CNWRA July-December 1994.* B. Sagar, ed. CNWRA 94-02S. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses: 122–134.

Ferrill, D.A., G.L. Stirewalt, D.B. Henderson, J.A. Stamatakos, A.P. Morris, B.P. Wernicke, and K.H. Spivey. 1995b. *Faulting in the Yucca Mountain Region: Critical Review and Analysis of Tectonic Data from the Central Basin and Range*. CNWRA 95-017. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Frizzell, V.A., Jr., and J. Shulters. 1990. *Geologic Map of the Nevada Test Site, Southern Nevada*. U.S. Geological Survey Miscellaneous Investigation Series Map I-2046. Scale 1:100,000. Reston, VA: U.S. Geological Survey.

Groshong, R.H., Jr. 1988. Low-temperature deformation mechanisms and their interpretation. *Geological Society of America Bulletin* 100: 1,329–1,360.

Harmsen, S.C. 1994. The Little Skull Mountain, Nevada, earthquake of 29 June 1992: Aftershock focal mechanisms and tectonic stress field implications. *Bulletin of the Seismological Society of America* 84(5): 1,484–1,505.

Hofmann, R.B. 1994. *Seism 1.1 Test Analysis*. CNWRA 94-014. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

Hofmann, R.B., and A.K. Ibrahim. 1995. Background zones for long-term PSHA at Yucca Mountain. *Proceedings of the Topical Meeting on Methods of Seismic Hazard Evaluation Focus '95*. La Grange Park, IL: American Nuclear Society: 81–88.

Martin, R. 1995. *GIS Library and Geospatial Database Description and Instructions for CDROM Version 0.12*. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses.

McConnell, K.I., M.E. Blackford, and A.K. Ibrahim. 1992. *Staff Technical Position on Investigations to Identify Fault Displacement Hazards and Seismic Hazards at a Geologic Repository*. NUREG-1451. Washington, DC: Nuclear Regulatory Commission.

Morris, A.P., D.A. Ferrill, and D.B. Henderson. 1996. Slip-tendency analysis and fault reactivation. *Geology* 24(3): 275–278.

Nakata, J.K., C.M. Wentworth, and M.N. Machette. 1982. *Quaternary Fault Maps of the Basin and Range and Rio Grande Rift Provinces, Western United States*. USGS Open-File Report 82-579. Scale 1:2,500,000. Denver, CO: U.S. Geological Survey.

Piety, L.A. 1995. *Compilation of Known and Suspected Quaternary Faults Within 100 km of Yucca Mountain*. USGS Open File Report 94-112: 31 Scale 1:250,000. Denver, CO: U.S. Geological Survey. (Draft)

Quittmeyer, R.C., T. Grant, C. Menges, R. Nolting, S. Pezzopane, P. Richter, W.J. Silva, D.B. Slemmons, P. Somerville, C.T. Statton, and I. Wong. 1994. *Seismic Design Inputs for the Exploratory Studies Facility at Yucca Mountain*. TRW Report BAB000000-01717-5705-00001 REV00. Las Vegas, NV: TRW Environmental Safety Systems.

Rodgers, A.M., S.C. Harmsen, and M.E. Mermonte. 1987. *Evaluation of the Seismicity of the Southern Great Basin and its Relationship to the Tectonic Framework of the Region*. USGS Open-File Report 87-408. Denver, CO: U.S. Geological Survey.

Simonds, W.F., J.W. Whitney, K. Fox, A. Ramelli, J. Yount, M.D. Carr, C.D. Menges, R. Dickerson, and R.B. Scott. 1995. *Map of Fault Activity of the Yucca Mountain Area, Nye County, Nevada*. U.S. Geological Survey Miscellaneous Investigations Series Map 1-2520, Scale 1:24,000. Denver, CO: U.S. Geological Survey.

Smith, R., and W. Arabasz. 1991. Seismicity of intermountain seismic belt. D.B. Slemonds, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds. Neotectonics of North America. *Geological Society of America* 185–228.

Stock, J.M., J.H. Healy, S.H. Hickman, and M.D. Zoback. 1985. Hydraulic fracturing stress measurements at Yucca Mountain, Nevada, and relationship to regional stress field. *Journal of Geophysical Research* 90: 8,691–8,706.

Swan, F.H. 1995. Approaches for characterizing fault-displacement hazard at Yucca Mountain. *Proceedings of the Topical Meeting on Methods of Seismic Hazard Evaluation Focus '95*. La Grange Park, IL: American Nuclear Society: 13–21.

Wells, D.L., and K.J. Coppersmith. 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America* 84: 974–1,002.

Wong, I.G., S.K. Pezzopane, C.M. Menges, R.K. Green, and R.C. Quittmeyer. 1995. Probabilistic seismic hazard analysis of the exploratory studies facility at Yucca Mountain, Nevada. *Proceedings of the Topical Report Meeting on Methods of Seismic Hazard Evaluation Focus '95*. La Grange Park, IL: American Nuclear Society: 51–63.

Zoback, M.L. 1992. First and second-order patterns of stress in the lithosphere: The world stress map project. *Journal of Geophysical Research* 97(B8): 11,703–11,728.

# 4 ACKNOWLEDGEMENTS

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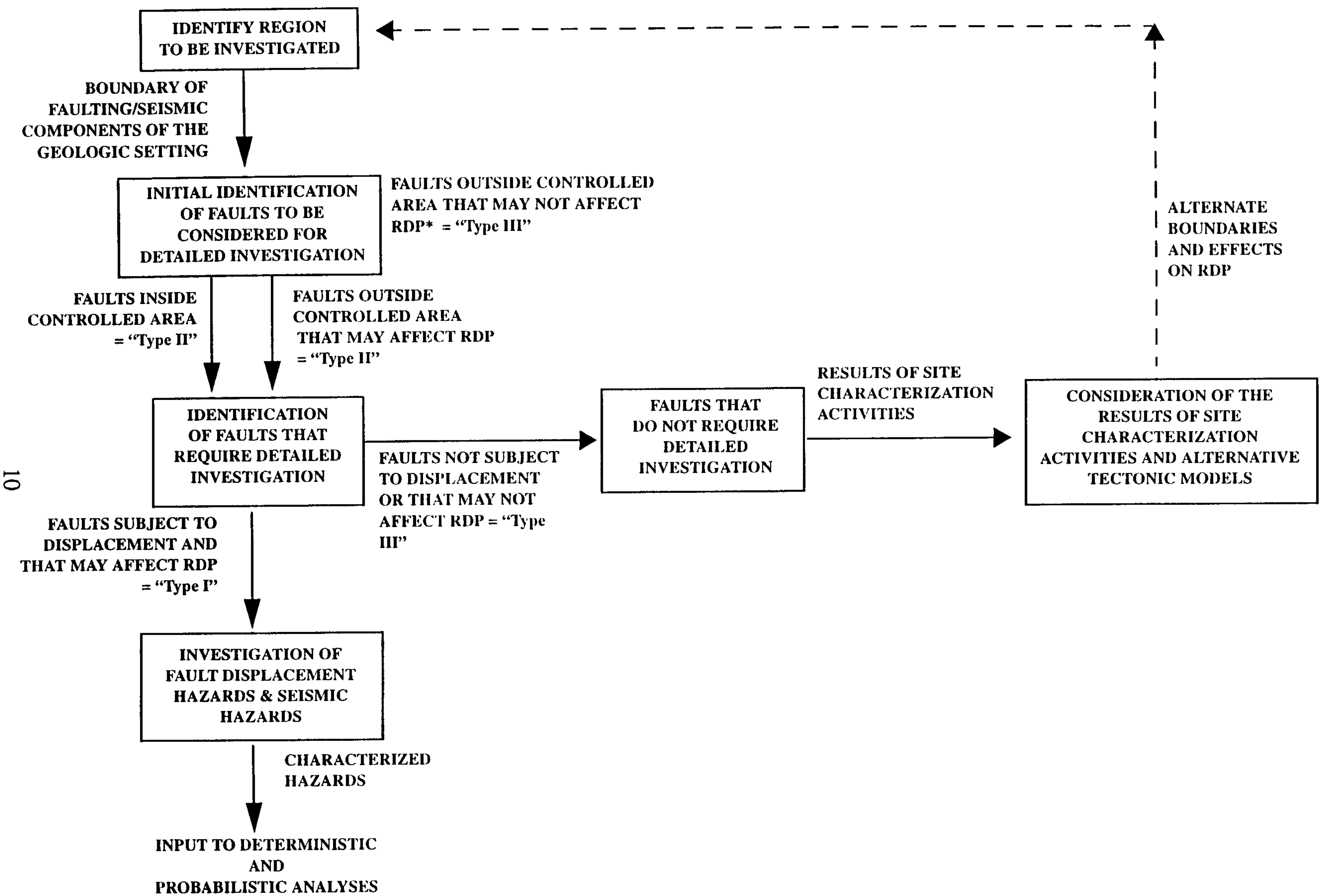
This study required the application of several different computer techniques and procedures. Without the excellent cooperation of a number of CNWRA staff, this study could not have been completed. R. Martin not only processed the fault map data, but was also instrumental in providing guidance in the use and pitfalls of ARC/INFO. P. Maldonado used Excel to calculate moment magnitudes and peak accelerations. R. Hofmann provided the peak acceleration formula and guidance in its use. E. Cantu prepared the spreadsheet from the Piety (1995) report and prepared the final draft of this report. B. Henderson applied the 3DSTRESS code to the data for the slip-tendency analysis and prepared some of the figures.




*"RDP" Means Repository Design and/or Performance

**Figure 1. Example of an acceptable approach to the identification of fault displacement hazards and seismic hazards (after McConnell et al., 1992).**

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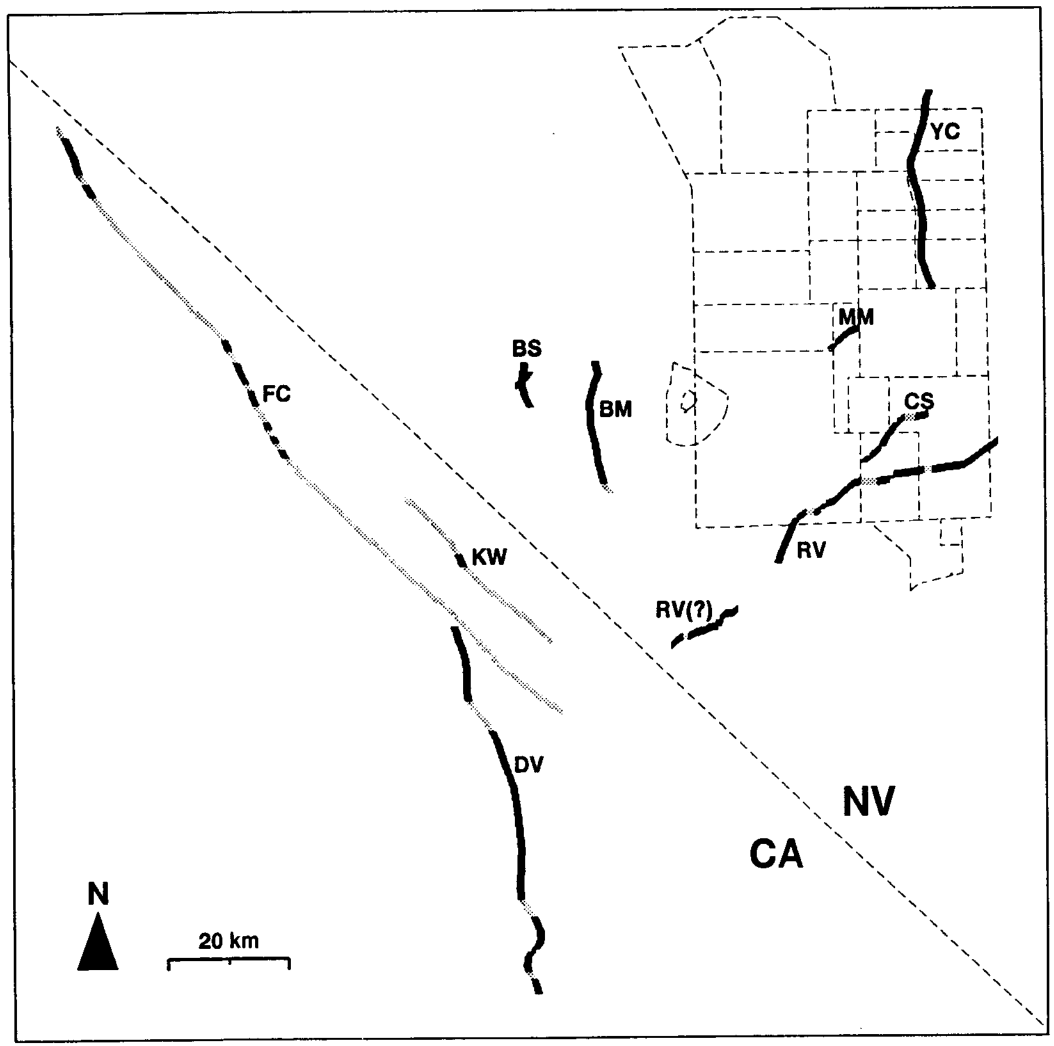


**Figure 6. Results of slip–tendency analysis on faults from Nakata et al. (1982), with $\sigma_2$ oriented N 28°E. This orientation applies to all faults shown in Nevada. In the present analysis, all faults shown in Nevada have a slip–tendency ratio greater than 0.50 (indicated by solid black lines) and are classified as Type II faults. Fault names for abbreviations are given in Appendix A.**

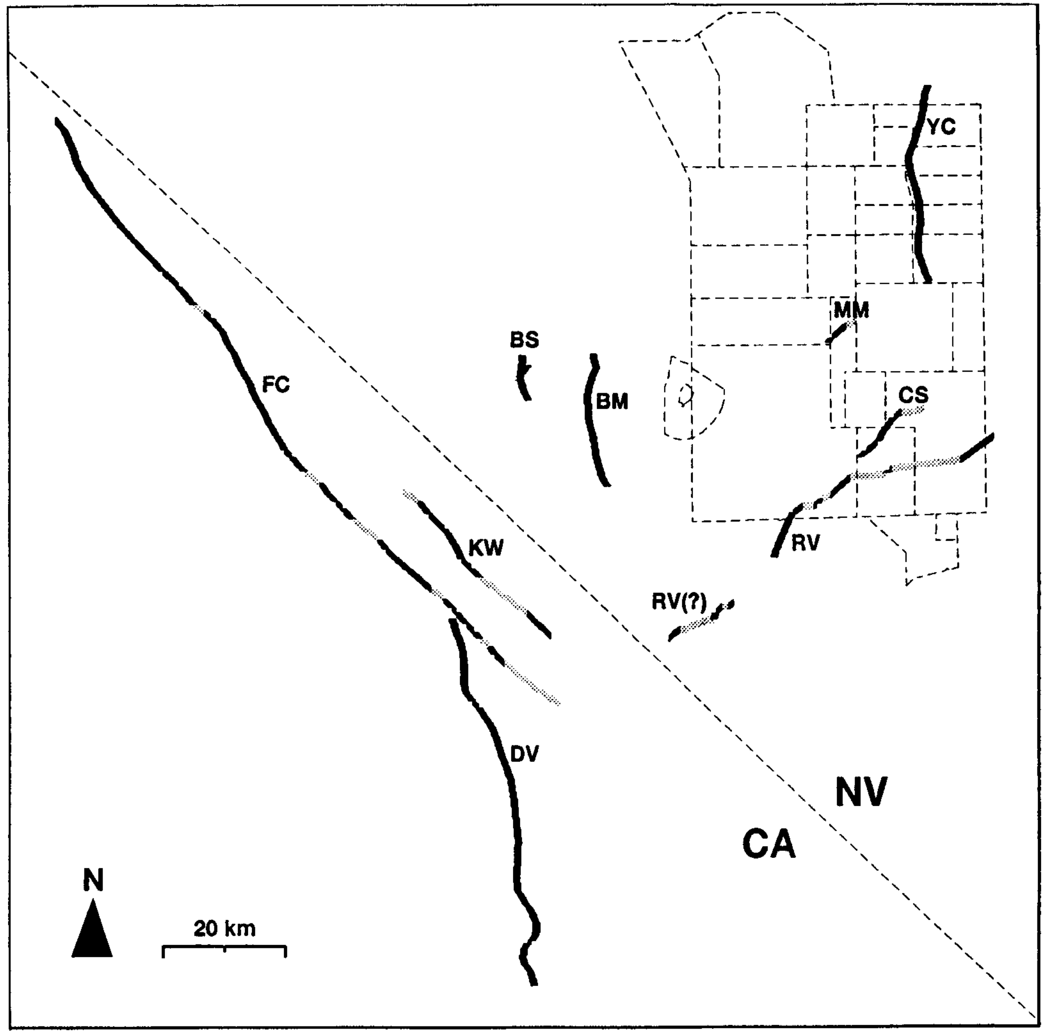


**Figure 7. Results of slip–tendency analysis on faults from Nakata et al. (1982) coverage. In model stress fie[illegible] $\sigma_1$ is oriented north–south, to approximate stress state in eastern California shear zone (Zoback, 1992) and is applicable to faults [illegible]n in CA. Black faults have a slip–tendency ratio of greater than 0.50 and are more likely to slip than faults shown in gray. All faults in the area where a N–S stress field is assumed (CA) have a slip–tendency greater than 0.50 and are classified as Type II faults. Fault names for abbreviations are given in Appendix A.**

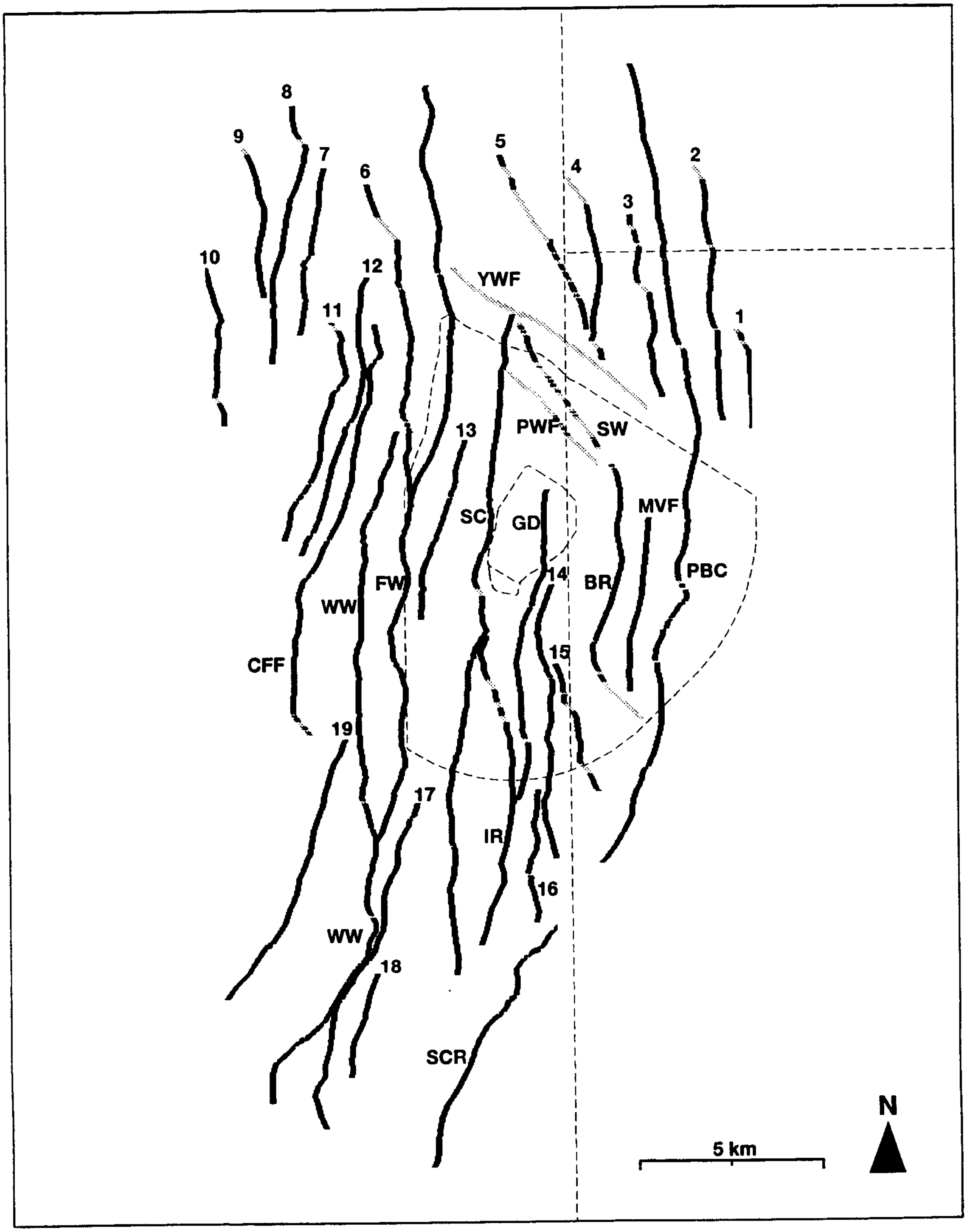


**Figure 8. Results of slip–tendency analysis on fault coverage from Simonds et al. (1995). Black faults have a slip–tendency ratio of greater than 0.50 and are more likely to slip than gray faults with a slip–tendency ratio of less than 0.50. Gray faults (PWF, YWF) have a low slip–tendency, but are considered Type I faults. Fault names for abbreviations are given in Appendix A.**

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Table 1. **Description of fault type and criteria for their classification based on NUREG-1451 (McConnell et al., 1992)**

| Fault Type | Criteria |
|---|---|
| **Type 1** - Faults which could affect repository design or performance and must be characterized to determine consequence of displacement. | 1. Faults or fault zones within the controlled area(1) that are or could be subject to displacement as demonstrated by evidence of Quaternary displacement (< 2.0 m.y.).<br><br>2. Fault or faults outside the controlled area, but within the faulting component,(2) of sufficient length and location that they may affect repository design and/or performance.<br><br>3. Favorably oriented in the current stress field for fault displacement. Seismically active. Have a direct relationship with an active fault. |
| **Type II** - Faults for which there is a high degree of uncertainty as to their possible affects on the repository. Further studies or characterization need to determine whether fault meets Type I criteria or not. | 1. Faults or fault zones outside the controlled area, but within the faulting component, that are of sufficient length and located such that they may affect repository design and/or performance<br><br>2. Evidence of displacement in the last 2 m.y. |
| **Type III** - Faults which will not, based on current information, affect repository design or performance. | 1. Faults outside of faulting component.<br><br>2. Faults or fault zones located within the faulting component of insufficient length and orientation such that displacement along them could not affect repository design or performance.<br><br>3. Displacement demonstrably not Quaternary or younger.<br><br>4. Unfavorably oriented in current stress field for fault displacement.<br><br>5. Demonstrably seismically inactive. |

(1) "Controlled" area means a surface location, to be marked by suitable monuments, extending horizontally no more than 10 km in any direction from the outer boundary of the underground facility.
(2) "Faulting Component" means that portion of the earth's crust that needs to be investigated to encompass those faults that might have an effect on repository design and/or performance or provide significant input into models used to assess repository performance due to fault displacement.

**Table 2. List of faults with potential to generate an earthquake grater than or equal to 0.09g from Piety (1995). Fault names for abbreviations are given in Appendix A.**

| Fault Name | Closest Approach (km) | Length (Max) (km) | Magnitude | Peak Acceleration |
|---|---|---|---|---|
| AM | 34 | 60 | 7.14 | 0.19 |
| AR | 40 | 15 | 6.44 | 0.10 |
| BLR | 55 | 54 | 7.09 | 0.10 |
| BM | 14 | 15.5 | 6.46 | 0.30 |
| BR | 1 | 10 | 6.24 | 0.69 |
| BS | 26 | 25 | 6.70 | 0.19 |
| CB | 43 | 30 | 6.79 | 0.11 |
| CS | 36 | 27 | 6.74 | 0.13 |
| DV | 55 | 104 | 7.42 | 0.12 |
| ER | 37 | 13 | 6.37 | 0.10 |
| FC | 50 | 170 | 7.67 | 0.17 |
| FW | 2 | 7.5 | 6.10 | 0.62 |
| GD | 0 | 9 | 6.19 | 0.69 |
| KR | 57 | 84 | 7.31 | 0.11 |
| KW | 43 | 25 | 6.70 | 0.10 |
| MM | 19 | 27 | 6.74 | 0.27 |
| OSV | 24 | 16 | 6.48 | 0.18 |
| PBC | 3 | 25 | 6.70 | 0.72 |
| PRP | 70 | 130 | 7.53 | 0.10 |
| PVNH | 46 | 26 | 6.72 | 0.10 |
| RV | 27 | 65 | 7.18 | 0.25 |
| RWBW | 19 | 17 | 6.51 | 0.23 |
| SC | 0.5 | 12 | 6.33 | 0.72 |
| SCR | 10 | 31 | 6.81 | 0.46 |
| SF | 52 | 51 | 7.06 | 0.10 |

**Table 2. List of faults with potential to generate an earthquake grater than or equal to 0.09g from Piety (1995). Fault names for abbreviations are given in Appendix A. (Cont'd)**

| Fault Name | Closest Approach (km) | Length (Max) (km) | Magnitude | Peak Acceleration |
|---|---|---|---|---|
| TOL | 42 | 22 | 6.64 | 0.10 |
| WAH | 22 | 15 | 6.44 | 0.19 |
| WSM | 53 | 60 | 7.14 | 0.11 |
| WW | 3 | 25 | 6.70 | 0.72 |
| YC | 40 | 40 | 6.94 | 0.13 |
| YCL | 36 | 17 | 6.51 | 0.11 |

Table 3. List of Type II faults within 100 km of proposed repository at Yucca Mountain

| No. | Fault Name |
|---|---|
| **Nakata et al. (1982) – Regional Coverage** | |
| 1 | Bare Mountain Fault **(P)** |
| 2 | Beatty Scarp Fault **(P)** |
| 3 | Cane Springs Fault **(P)** |
| 4 | Death Valley Fault |
| 5 | Furnace Creek Fault **(P)** |
| 6 | Keane Wonder Fault **(P)** |
| 7 | Mine Mountain Fault **(P)** |
| 8 | Rock Valley Fault **(P)** |
| 9 | Yucca Fault **(P)** |
| **Simonds et al. (1995) – Local Coverage** | |
| 10 | Bow Ridge Fault **(P)** |
| 11 | Crater Flat Fault **(P – East Crater Flat Fault of Piety)** |
| 12 | Fatigue Wash Fault **(P)** |
| 13 | Ghost Dance Fault **(P)** |
| 14 | Iron Ridge Fault |
| 15 | Paintbrush Canyon Fault **(P)** |
| 16 | Pagany Wash Fault **(P)** |
| 17 | Severe Wash Fault **(P)** |
| 18 | Stage Coach Road Fault **(P)** |
| 19 | Solitario Canyon Fault **(P)** |
| 20 | Windy Wash Fault **(P)** |
| 21 | 1 |
| 22 | 2 |
| 23 | 3 |
| 24 | 4 |
| 25 | 5 |
| 26 | 6 |

Table 3. List of Type II faults within 100 km of proposed repository at Yucca Mountain (Cont'd)

| No. | Fault Name |
|---|---|
| 27 | 7 |
| 28 | 8 |
| 29 | 9 |
| 30 | 10 |
| 31 | 11 |
| 32 | 12 |
| 33 | 13 |
| 34 | 14 |
| 35 | 15 |
| 36 | 16 |
| 37 | 17 |
| 38 | 18 |
| 39 | 19 |
| **Piety (1995) Regional Coverage** | |
| 40 | Ash Meadows Fault |
| 41 | Amargosa River Fault |
| 42 | Belted Range Fault |
| 43 | Carpetbag Fault |
| 44 | Eleana Range Fault |
| 45 | Kawich Range |
| 46 | Oasis Valley Fault |
| 47 | Pahrump Fault |
| 48 | Plutonium Valley - North Halfpint Range Fault |
| 49 | Rocket Wash - Beatty Wash Fault |
| 50 | Sarcobatus Flat Fault |
| 51 | Tolicha Peak Fault |
| 52 | Wahmonie Fault |
| 53 | West Spring Mountain Fault |

**Table 3. List of Type II faults within 100 km of proposed repository at Yucca Mountain (Cont'd)**

| No. | Fault Name |
|---|---|
| 54 | Yucca Lake Fault |

**(P) Indicates overlap with Piety (1995) coverage. Simonds numbered faults correspond with the numbers on Figure 8.**

## APPENDIX A

## LIST OF FAULTS AND ABBREVIATIONS FROM PIETY (1995)

| Fault Name | Fault Abbreviation |
|---|---|
| Airport Lake Fault | AIR |
| Amargosa River Fault | AR |
| Area Three Fault | AT |
| Ash Hill Fault | AH |
| Ash Meadows Fault | AM |
| Badger Wash Faults | BDG |
| Bare Mountain Fault | BM |
| Beatty Scarp | BS |
| Belted Range Fault | BLR |
| Bonnie Claire Fault | BC |
| Boundary Fault | BD |
| Bow Ridge Fault | BR |
| Bullfrog Hills Faults | BUL |
| Buried Hills Fault | BH |
| Cactus Flat Fault | CF |
| Cactus Flat—Mellan Fault | CFML |
| Cactus Range—Wellington Hills Fault | CRWH |
| Cactus Springs Fault | CAC |
| Cane Spring Fault | CS |
| Carpetbag Fault | CB |
| Cedar Mountain Fault | CM |
| Central Pintwater Range Faults | CPR |
| Central Reveille Fault | CR |
| Central Spring Mountains Faults | CSM |
| Chalk Mountain Fault | CLK |
| Checkpoint Pass Fault | CP |
| Chert Ridge Faults | CHR |
| Chicago Valley Faults | CHV |

| Fault Name | Fault Abbreviation |
|---|---|
| Clayton—Montezuma Valley Fault | CLMV |
| Clayton Ridge—Paymaster Ridge Fault | CRPR |
| Clayton Valley Fault | CV |
| Cockeyed Ridge—Papoose Lake Fault | CRPL |
| Crater Flat Fault* | CFF |
| Crossgrain Valley Fault | CGV |
| Death Valley Fault | DV |
| Deep Springs Fault | DS |
| East Belted Range Fault | EBR |
| East Crater Flat Faults | ECR |
| East Magruder Mountain Fault | EMM |
| East Nopah Fault | EN |
| East Pintwater Range Fault | EPR |
| East Reveille Fault | ERV |
| East Stone Cabin Fault | ESC |
| Eleana Range Fault | ER |
| Emigrant Fault | EM |
| Emigrant Peak Faults | EPK |
| Emigrant Valley North Fault | EVN |
| Emigrant Valley South Fault | EVS |
| Eureka Valley East Fault | EURE |
| Eureka Valley West Fault | EURW |
| Fallout Hills Faults | FH |
| Fatigue Wash Fault | FW |
| Fish Lake Valley Fault | FLV |
| Freiburg Fault | FR |
| Frenchman Mountain Fault | FM |
| Furnace Creek Fault | FC |

| Fault Name | Fault Abbreviation |
|---|---|
| Garden Valley Fault | GRD |
| General Thomas Hills Fault | GTH |
| Ghost Dance Fault | GD |
| Gold Flat Fault | GOL |
| Gold Mountain Fault | GOM |
| Golden Gate Faults | GG |
| Grapevine Fault | GV |
| Grapevine Mountains Fault | GM |
| Groom Range Central Fault | GRC |
| Groom Range East Fault | GRE |
| Hidden Valley—Sand Flat Faults | HVSF |
| Hiko Fault | HKO |
| Hiko—South Pahroc Faults | HSP |
| Hot Creek—Reveille Fault | HCR |
| Hunter Mountain Fault | HM |
| Indian Springs Valley Fault | ISV |
| Iron Ridge Fault* | IR |
| Jumbled Hills Fault | JUM |
| Kawich Range Fault | KR |
| Kawich Valley Fault | KV |
| Keane Wonder Fault | KW |
| La Madre Fault | LMD |
| Lee Flat Fault | LEE |
| Lida Valley Faults | LV |
| Little Lake Fault | LL |
| Lone Mountain Fault | LMT |
| McAfee Canyon Fault | MAC |
| Midway Valley Fault* | MVF |

| Fault Name | Fault Abbreviation |
|---|---|
| Mine Mountain Fault | MM |
| Monitor Hills East Fault | MHE |
| Monitor Hills West Fault | MHW |
| Monotony Valley Fault | MV |
| Montezuma Range Fault | MR |
| Mud Lake—Goldfield Hills Fault | MLGH |
| North Desert Range Fault | NDR |
| Oak Spring Butte Faults | OAK |
| Oasis Valley Faults | OSV |
| Owens Valley Faults | OWV |
| Pagany Wash Fault* | PWF |
| Pahranagat Fault | PGT |
| Pahroc Fault | PAH |
| Pahrock Valley Faults | PV |
| Pahrump Fault | PRP |
| Pahute Mesa Faults | PM |
| Paintbrush Canyon Fault | PBC |
| Palmetto Mountains—Jackson Wash Fault | PMJW |
| Palmetto Wash Fault | PW |
| Panamint Valley Fault | PAN |
| Penoyer Fault | PEN |
| Plutonium Valley—North Halfpint Range Fault | PVNH |
| Quinn Canyon Fault | QC |
| Racetrack Valley Faults | RTV |
| Ranger Mountains Faults | RM |
| Rock Valley Fault | RV |
| Rocket Wash—Beatty Wash Fault | RWBW |
| Saline Valley Faults | SAL |

| Fault Name | Fault Abbreviation |
|---|---|
| Sarcobatus Flat Fault | SF |
| Seaman Pass Fault | SPS |
| Severe Wash Fault* | SW |
| Sheep Basin Fault | SB |
| Sheep—East Desert Ranges Fault | SEDR |
| Sheep Range Fault | SHR |
| Sierra Nevada Fault | SNV |
| Silver Peak Range Faults | SIL |
| Six-Mile Flat Fault | SMF |
| Slate Ridge Faults | SL |
| Solitario Canyon Fault | SC |
| South Ridge Faults | SOU |
| Southeast Coal Valley Fault | SCV |
| Southern Death Valley Fault | SDV |
| Spotted Range Faults | SPR |
| Stagecoach Road Fault | SCR |
| State Line Fault | SL |
| Stonewall Flat Fault | SWF |
| Stonewall Mountain Fault | SWM |
| Stumble Fault | STM |
| Sylvania Mountains Fault | SYL |
| Tem Piute Fault | TEM |
| Three Lakes Valley Fault | TLV |
| Tikaboo Fault | TK |
| Tin Mountain Fault | TM |
| Tolicha Peak Fault | TOL |
| Towne Pass Fault | TP |
| Tule Canyon Fault | TLC |

| Fault Name | Fault Abbreviation |
|---|---|
| Wahmonie Fault | WAH |
| Weepah Hills Fault | WH |
| West Pintwater Range Fault | WPR |
| West Railroad Fault | WR |
| West Spring Mountains Fault | WSM |
| Wilson Canyon Fault | WIL |
| Windy Wash Fault | WW |
| Yucca Fault | YC |
| Yucca Lake Fault | YCL |
| Yucca Wash Fault* | YWF |

* Faults from Simonds et al. (1995)

# APPENDIX B

## FAULTS FROM PIETY (1995) THAT PROBABLY LACK THE POTENTIAL TO GENERATE PEAK ACCELERATION AT YUCCA MOUNTAIN GREATER THAN 0.09 G (FAULT ABBREVIATIONS GIVEN IN APPENDIX A)

| Fault Name | Closest Approach (km) | Length (Max) (km) | Magnitude | Peak Acceleration |
|---|---|---|---|---|
| AH | 105 | 45 | 7.00 | 0.03 |
| AIR | 138 | 60 | 7.14 | 0.02 |
| AT | 44 | 5.2 | 5.91 | 0.06 |
| BC | 74 | 27 | 6.74 | 0.05 |
| BD | 51 | 6.5 | 6.02 | 0.05 |
| BDG | 111 | 13 | 6.37 | 0.02 |
| BH | 53 | 26 | 6.72 | 0.08 |
| BUL | 38 | 7 | 6.06 | 0.08 |
| CAC | 59 | 12 | 6.33 | 0.05 |
| CF | 84 | 50 | 7.05 | 0.05 |
| CFML | 80 | 35 | 6.87 | 0.05 |
| CGV | 48 | 8.5 | 6.16 | 0.06 |
| CHR | 65 | 14 | 6.41 | 0.05 |
| CHV | 90 | 20 | 6.59 | 0.03 |
| CLK | 87 | 20 | 6.59 | 0.03 |
| CLMV | 126 | 14 | 6.41 | 0.02 |
| CM | 200 | 60 | 7.14 | 0.01 |
| CP | 44 | 6.5 | 6.02 | 0.06 |
| CPR | 79 | 16 | 6.48 | 0.04 |
| CR | 108 | 29 | 6.78 | 0.03 |
| CRPL | 53 | 21 | 6.61 | 0.07 |
| CRPR | 126 | 53 | 7.08 | 0.03 |
| CRWH | 87 | 29 | 6.78 | 0.04 |
| CSM | 76 | 16 | 6.48 | 0.04 |
| CV | 132 | 27 | 6.74 | 0.02 |
| DS | 148 | 27 | 6.74 | 0.01 |
| EBR | 80 | 26 | 6.72 | 0.04 |

| Fault Name | Closest Approach (km) | Length (Max) (km) | Magnitude | Peak Acceleration |
|---|---|---|---|---|
| EM | 73 | 13 | 6.37 | 0.04 |
| EMM | 113 | 7 | 6.06 | 0.01 |
| EN | 85 | 19 | 6.56 | 0.03 |
| EPK | 166 | 26 | 6.72 | 0.01 |
| EPR | 81 | 58 | 7.13 | 0.06 |
| ERV | 112 | 22 | 6.64 | 0.02 |
| ESC | 115 | 35 | 6.87 | 0.03 |
| EURE | 110 | 50 | 7.05 | 0.03 |
| EURW | 140 | 22 | 6.64 | 0.01 |
| EVN | 60 | 28 | 6.76 | 0.07 |
| EVS | 66 | 20 | 6.59 | 0.05 |
| FH | 70 | 8 | 6.13 | 0.03 |
| FLV | 135 | 80 | 7.29 | 0.03 |
| FM | 146 | 20 | 6.59 | 0.01 |
| FR | 133 | 19 | 6.56 | 0.02 |
| GG | 144 | 24 | 6.68 | 0.01 |
| GM | 67 | 23 | 6.66 | 0.05 |
| GOL | 65 | 16 | 6.48 | 0.05 |
| GOM | 90 | 18 | 6.54 | 0.03 |
| GRC | 82 | 31 | 6.81 | 0.04 |
| GRD | 126 | 12 | 6.33 | 0.01 |
| GRE | 85 | 20 | 6.59 | 0.04 |
| GTH | 137 | 26 | 6.72 | 0.02 |
| GV | 58 | 30 | 6.79 | 0.07 |
| HCR | 103 | 83 | 7.31 | 0.04 |
| HKO | 131 | 47 | 7.02 | 0.02 |
| HM | 95 | 85 | 7.32 | 0.05 |

| Fault Name | Closest Approach (km) | Length (Max) (km) | Magnitude | Peak Acceleration |
|---|---|---|---|---|
| HSP | 130 | 27 | 6.74 | 0.02 |
| HVSF | 87 | 13 | 6.37 | 0.03 |
| ISV | 67 | 28 | 6.76 | 0.06 |
| JUM | 77 | 27 | 6.74 | 0.05 |
| KV | 61 | 43 | 6.97 | 0.08 |
| LEE | 113 | 7 | 6.06 | 0.01 |
| LL | 163 | 30 | 6.79 | 0.01 |
| LMD | 82 | 33 | 6.84 | 0.05 |
| LMT | 165 | 70 | 7.22 | 0.02 |
| LV | 115 | 10 | 6.24 | 0.02 |
| MAC | 155 | 17 | 6.51 | 0.01 |
| MER | 48 | 10 | 6.24 | 0.06 |
| MHE | 125 | 8 | 6.13 | 0.01 |
| MHW | 124 | 15 | 6.44 | 0.02 |
| MLGH | 113 | 33 | 6.84 | 0.03 |
| MR | 121 | 33 | 6.84 | 0.02 |
| MV | 103 | 5.5 | 5.94 | 0.02 |
| NDR | 61 | 24 | 6.68 | 0.06 |
| OAK | 57 | 21 | 6.61 | 0.07 |
| OWV | 126 | 110 | 7.45 | 0.03 |
| PAH | 144 | 74 | 7.25 | 0.02 |
| PAN | 95 | 80 | 7.29 | 0.05 |
| PEN | 97 | 56 | 7.11 | 0.04 |
| PGT | 106 | 45 | 7.00 | 0.03 |
| PM | 48 | 9 | 6.19 | 0.06 |
| PMJW | 112 | 12 | 6.33 | 0.02 |
| PV | 155 | 11 | 6.29 | 0.01 |

| Fault Name | Closest Approach (km) | Length (Max) (km) | Magnitude | Peak Acceleration |
|---|---|---|---|---|
| PW | 131 | 16 | 6.48 | 0.01 |
| QC | 127 | 19 | 6.56 | 0.02 |
| RM | 49 | 5 | 5.89 | 0.05 |
| RTV | 97 | 22 | 6.64 | 0.03 |
| SAL | 108 | 21 | 6.61 | 0.02 |
| SB | 112 | 47 | 7.02 | 0.03 |
| SCV | 132 | 19 | 6.56 | 0.02 |
| SDV | 105 | 300 | 7.95 | 0.07 |
| SEDR | 104 | 45 | 7.00 | 0.03 |
| SHR | 122 | 50 | 7.05 | 0.03 |
| SIL | 142 | 24 | 6.68 | 0.01 |
| SL | 130 | 32 | 6.83 | 0.02 |
| SLR | 87 | 24 | 6.68 | 0.04 |
| SMF | 138 | 24 | 6.68 | 0.02 |
| SNV | 154 | 25 | 6.70 | 0.01 |
| SOU | 55 | 19 | 6.56 | 0.07 |
| SPR | 59 | 20 | 6.59 | 0.06 |
| SPS | 153 | 34 | 6.86 | 0.01 |
| STM | 74 | 33 | 6.84 | 0.05 |
| SWF | 101 | 22 | 6.64 | 0.03 |
| SWM | 92 | 22 | 6.64 | 0.03 |
| SYL | 111 | 14 | 6.41 | 0.02 |
| TEM | 101 | 22 | 6.64 | 0.03 |
| TK | 92 | 33 | 6.84 | 0.04 |
| TLC | 104 | 14 | 6.41 | 0.02 |
| TLV | 84 | 27 | 6.74 | 0.04 |
| TM | 90 | 29 | 6.78 | 0.04 |

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| Fault Name | Closest Approach (km) | Length (Max) (km) | Magnitude | Peak Acceleration |
|---|---|---|---|---|
| TP | 76 | 38 | 6.91 | 0.05 |
| WH | 145 | 15 | 6.44 | 0.01 |
| WIL | 140 | 42 | 6.96 | 0.02 |
| WPR | 76 | 60 | 7.14 | 0.06 |
| WR | 112 | 42 | 6.96 | 0.03 |