From: Loren Morton
To: Harold Roberts
Date: 6/23/06 4:20:14 PM
Subject: Fwd: Seismic analysis info (39400166-out)

Harold,

As promised during our 6/21/06 conference call, attached is the seismic information that Britt talked about - see Britt's email. The PDF file is an article on Colorado Plateau seismicity. The Word file is an outline that Ivan Wong (URS) provided as a guide - so that you could see what kind of information he looks at when examining these kinds of problems.

Also, Ivan later provided another article that is related - its the PDF file that is directly attached herewith.

If we need further discussions, please call me or Dave Rupp to arrange them.

thanks,

Loren

CC: Britt Quinby; Dave Rupp; Dean Henderson

From: <Britt_Quinby@URSCorp.com>
To: "Loren Morton" <lmorton@utah.gov>
Date: 6/23/06 8:11:58 AM
Subject: Seismic analysis info (39400166-out)

CC: "John Hultquist" <JHULTQUIST@utah.gov>, <Robert_D_Baird@URSCorp.com>, <Janet_Redden@URSCorp.com>, <Ivan_Wong@URSCorp.com>

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<FONT face="Default Sans Serif,Verdana,Arial,Helvetica,sans-serif" size=2><DIV>Loren-
</DIV><DIV>&nbsp;</DIV><DIV>Here is an outline of the what needs to be done for the IUC seismic
hazard analysis.&nbsp; Ivan Wong worked this up.&nbsp; Also included is an example paper on the same
type on analysis done for the Moab site (as an example).</DIV><DIV>&nbsp;</DIV><DIV>This is
provided to you and John for review and comment before it goes on to Harold.&nbsp; If you have no
comments, please feel free to forward it on.&nbsp;</DIV><DIV>&nbsp;</DIV><DIV>I am in and out of the
office this morning, and traveling this afternoon.&nbsp; If you would like to discuss this, I can be reached
on my cell.</DIV><DIV>&nbsp;</DIV><DIV>Regards<BR></DIV><DIV>J. Britt Quinby, PE<BR>Principal
Environmental Engineer<BR>URS Corporation<BR>77 Goodell Street<BR>Buffalo, NY 14203<BR>716-
923-1264<BR>716-923-1398 fax<BR>716-698-9701cell<BR></DIV></FONT><BR><table border="0"
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Sans Serif"><br />This e-mail and any attachments are confidential. If you receive this message in error or
are not the intended recipient&#44; you should not retain&#44; distribute&#44; disclose or use any of this
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Geology and Resources of the Paradox Basin:
Utah Geological Association Guidebook 25
A. C. Huffman,Jr., W. R. Lund, and L. H. Godwin

Earthquake Potential and Seismic Hazards in the Paradox Basin, Southeastern Utah

Ivan G. Wong[1], Susan S. Olig[1], and Jacqueline D.J. Bott[1]

ABSTRACT

As part of a seismic hazards evaluation for a site in Moab, Utah, we have characterized potential seismic sources in much of the southeastern Utah portion of the Paradox Basin in terms of their probability of being active, geometry, maximum earthquake, and slip rates. These potential seismic sources included 11 faults and two seismic source zones. Ten of the faults including the Moab, Lisbon Valley, Salt Valley, and Paradox Valley faults are associated with salt structures and are probably not seismogenic. To accommodate the remote possibility, however, that these faults could generate earthquakes, they were considered in the seismic hazard analysis at low probabilities. Seismogenic structures included the frontal faults associated with the Uncompahgre uplift.

Although the Colorado Plateau interior in which the Paradox Basin is located is seismically active, very little seismicity has been definitively associated with known faults. The contribution to seismic hazard from such "background" earthquakes was incorporated into the hazard analysis as the Colorado Plateau interior seismic source zone. We adopted a maximum earthquake of moment magnitude (M_w) 6 ± 1/2 for this zone. The second seismic source zone (maximum magnitude M_w 5¾ ± ¾) included in this analysis was a northeast-trending zone of microseismicity aligned approximately along the stretch of the Colorado River southwest of Moab.

Due to the large uncertainties in characterizing seismic sources, a probabilistic seismic hazard analysis using a logic tree approach was performed to estimate the ground motions at the Moab site. Based on the estimated seismic source parameters and empirical relations for seismic wave attenuation, ground shaking, in terms of peak horizontal acceleration, at Moab was estimated as a function of return period. For return periods of 500 to 10,000 years, the peak horizontal accelerations ranged from about 0.05 to 0.18 g. The largest contributor to the seismic hazard at Moab were the background earthquakes of the Colorado Plateau interior.

INTRODUCTION

In terms of earthquakes and their associated hazards, the Colorado Plateau, particularly its interior, has generally been considered to be seismically inactive and devoid of large earthquakes. Seismological studies performed in the past decade (Wong and others, 1987; Wong and Humphrey, 1989), however, indicate that seismicity is widespread throughout the Plateau interior, albeit at a low to moderate level, and that earthquakes up to M_L 6 have occurred (Brumbaugh, 1991). Although detailed paleoseismic studies have not been performed to date, a limited amount of geologic data suggests that a few late-Quaternary faults may exist in the Colorado Plateau interior (Hecker, 1993). Thus there appears to be at least some low level of earthquake hazard within the Colorado Plateau. In this paper, we describe a seismic hazard evaluation of a site near the town of Moab, Utah, which attempts to quantify the level of ground shaking hazard that may exist in this portion of the Paradox Basin and the Colorado Plateau interior.

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[1] Woodward-Clyde Federal Services
500 12th Street, Suite 100, Oakland, CA 94607

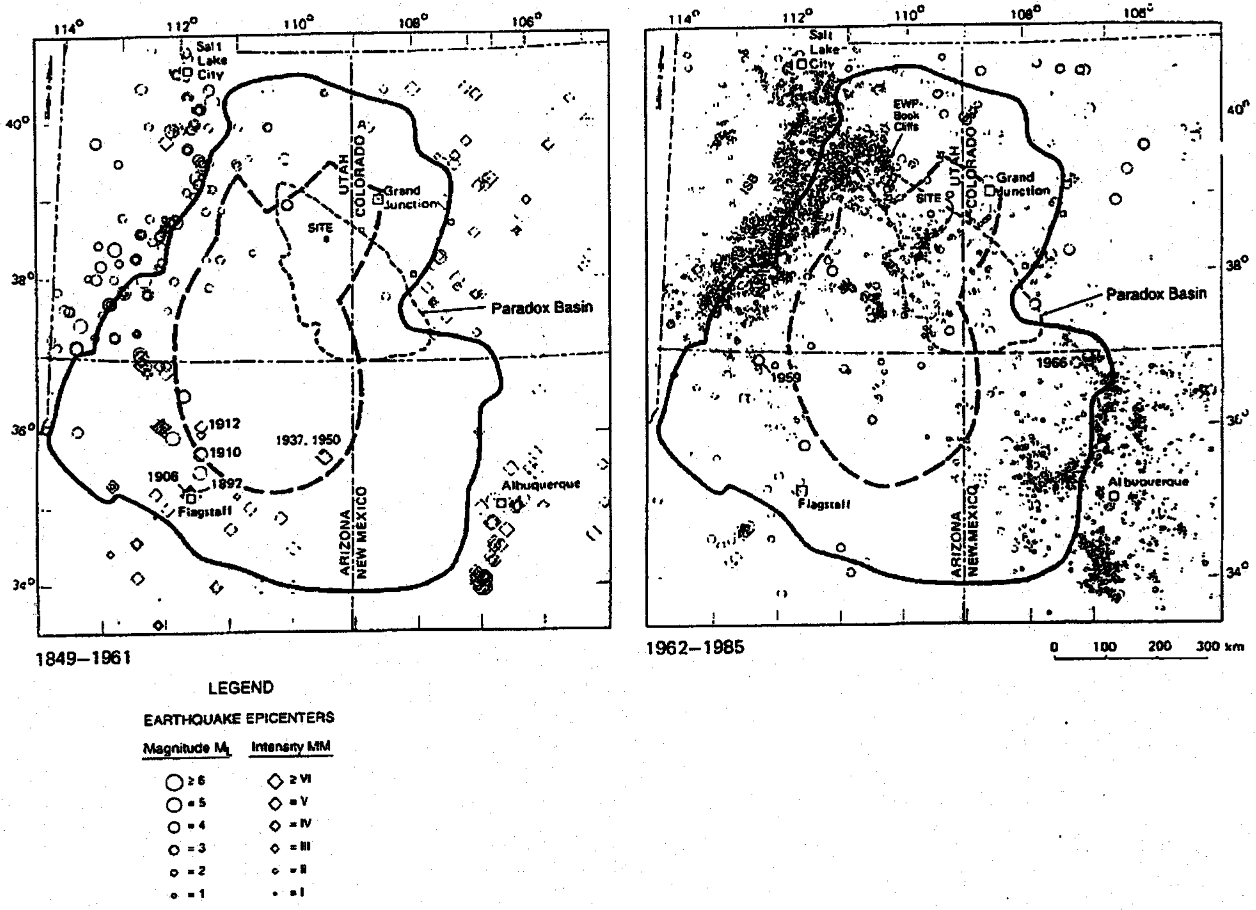

Figure 1. Historical and contemporary seismicity of the Colorado Plateau (bold line), 1849 to 1985, modified from Wong and Humphrey (1989). Also shown is the Plateau interior seismic zone (dashed line) as defined in this study. The apparent higher level of seismicity from 1962 to 1985 in southeastern Utah is due to monitoring by the Paradox Basin network.

SEISMOTECTONIC SETTING

The Paradox Basin is located physiographically within the interior of the Colorado Plateau (Fig. 1). Zoback and Zoback (1989) distinguish the Colorado Plateau interior from the surrounding Cordilleran extensional province based on differences in tectonic stresses. The Plateau interior is characterized by a distinct north-northeast-trending minimum principal stress, which is orthogonal to that of the surrounding regions, and probably low deviatoric stresses (Wong and Humphrey, 1989; Zoback and Zoback, 1989). The Colorado Plateau interior is also characterized by low average heat flow, less than 60 milliwatts per square meter (mWm^{-2}) (Bodell and Chapman, 1982), and a thick, 25 to 31 mi (40 to 50 km), continental crust (Smith and others, 1989). This low heat flow is symptomatic of a strong cold crust which exhibits low levels of tectonism and which can explain the relatively deep, up to 31 mi (50 km), earthquakes in the Plateau interior (Wong and Humphrey, 1989; Wong and Chapman, 1990).

Zoback and Zoback (1989) suggested that the transition between the Colorado Plateau interior and the more tectonically active surrounding regions may be quite broad, on the order of 60 to 90 mi (100 to 150 km) wide (Fig. 1). The Plateau's margins appear to be transitional in nature in terms of their levels of seismicity and tectonism. In terms of seismogenic potential, the most significant transition zone is between the Colorado Plateau interior and the Basin and Range province which is defined by the Intermountain seismic belt (Smith and Sbar, 1974; Smith and Arabasz, 1991) (Fig. 1).

HISTORICAL SEISMICITY

The Colorado Plateau interior has been sparsely populated throughout historical times and seismographic coverage likewise has been sparse (Wong and

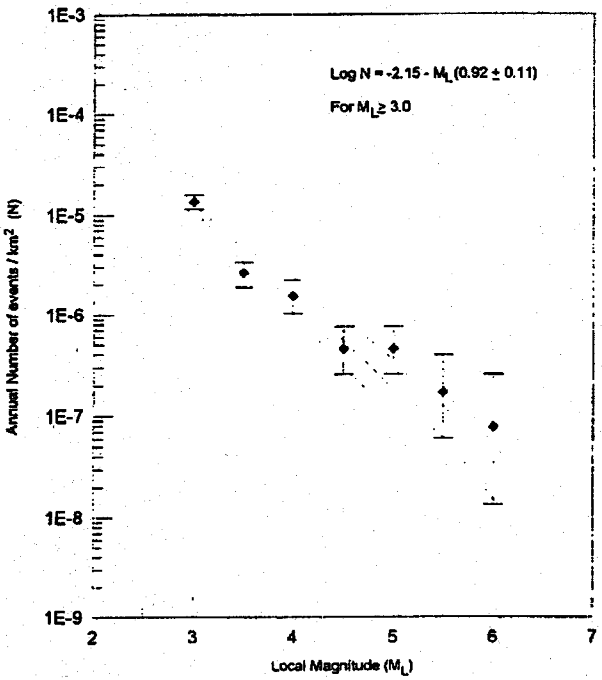

Figure 2. Earthquake recurrence relationship for the Colorado Plateau interior. The *b*- and *a*-values were calculated to be 0.2 and -2.15, respectively, based on the maximum likelihood technique of Weichert (1980). The data points are shown with their standard errors.

Simon, 1981). Thus, we judge that the historical seismicity record for the Plateau interior is probably only complete for Richter magnitude (M_L) ≥ 6 events since 1890, after more widespread settlement in southeastern Utah. Earthquakes of $M_L \geq 5$ (or Modified Mercalli [MM] intensity VI and greater) have probably only been completely recorded since about 1940 for the whole of the Colorado Plateau province (Arabasz and others, 1979).

The historical seismicity record of the Colorado Plateau interior consists of 1,658 earthquakes from 1896 through 1994, ranging in size from an approximate M_L 0 to 6.1. An area of intense seismicity in the eastern Wasatch Plateau-Book Cliffs, in the vicinity of Price, in the northwestern corner of the Colorado Plateau is associated with coal mining (Wong and Humphrey, 1989; Wong and others, 1989). These events were excluded from the historical catalogue used in our analysis.

There are only five known earthquakes of reported MM VI intensity or M_L 5 and greater within the Colorado Plateau interior (Fig. 1). The first moderate sized earthquake occurred in 1910 in the Coconino Forest, about 45 mi (72 km) north of Flagstaff, Arizona. The observed maximum intensity was MM VI (DuBois and others, 1982) and recently, Brumbaugh (1991) has estimated its size to be surface-wave magnitude (M_S) 5.6. In 1912, a maximum MM VII-VIII intensity earthquake occurred at Lockett Tanks in Arizona (Fig. 1), and was felt over an area of 55,000 mi² (142,450 km².). Brumbaugh (1991) estimated a M_S 6.1 for this earthquake. Other earthquakes of moderate size include two MM VI intensity earthquakes which occurred in 1937 and 1950 in northern Arizona. The 1988 M_L 5.3 San Rafael, Utah earthquake (Pechmann and others, 1991) is the most recent moderate-sized earthquake to occur in the Plateau interior.

Of note is the fact that four of the five $M_L \geq 5$ earthquakes in the Colorado Plateau interior have occurred in northern Arizona with only the 1988 San Rafael earthquake occurring in Utah. The 1910 and 1912 northern Arizona earthquakes occurred towards the southwestern edge of the Colorado Plateau interior, northeast of Flagstaff, in the vicinity of the San Francisco Peaks volcanic field (Fig. 1). The seismicity of this portion of the Plateau interior may be anomalously high due to its close proximity to this Plio-Quaternary volcanic field.

Earthquake recurrence was estimated for the Colorado Plateau interior for incorporation into the seismic hazard analysis. Following the maximum likelihood procedure developed by Weichert (1980), the recurrence was calculated in the form of the truncated Gutenberg-Richter exponential distribution for the occurrence of independent earthquakes (Fig. 2). After correcting for catalogue completeness and removal of dependent events, only 37 independent earthquakes remained to estimate recurrence. The resulting recurrence relationship on an annual basis and per km² is shown in Figure 2. The computed *b*-value is 0.92 (± 0.11) and the normalized *a*-value is -2.15. Based on these recurrence parameters, return periods for earthquakes in specified magnitude ranges for the Plateau interior can be estimated (Table 1).

SEISMIC SOURCES

Potentially seismogenic faults and seismic source zones significant to the site were identified, characterized, and incorporated into our hazard analysis. These seismic sources included 11 faults, most of which are shown in Figure 3, the microseismicity along the Colorado River, and the Colorado Plateau interior source zone.

Faults

For faults considered in the seismic hazard analysis, the following parameters were generally required

Table 1. Recurrence intervals for earthquakes in the Colorado Plateau interior.

M_L	Interval (yrs)
5.0	50 (14-178)*
5.5	144 (36-582)
6.0	417 (91-1904)
6.25	708 (145-3447)

*Range of interval when incorporating the standard error of the *b*-value

as input: fault activity, fault dip, depth of faulting, maximum magnitude, recurrence model, and slip rates (Table 2 and Fig. 4). Information on the Moab Fault was based on ours and previous studies (Olig and others, this volume), whereas information on the other faults was obtained from studies by Woodward-Clyde Consultants, as part of the U.S. Department of Energy's underground nuclear waste repository site characterization in the Paradox Basin (Hecker, 1993; Kirkham and Rogers, 1981). We considered segmented and unsegmented models for the Moab Fault because of its length and proximity to the site (Fig. 4). The *b*-value calculated from the historical seismicity record (Fig. 2) is used to anchor both the fault and seismic source zone recurrence curves. Detailed discussion of these parameters can be found in Woodward-Clyde Federal Services (1996).

Except for the Tenmile Graben faults, Shay Graben faults, and some faults in Fisher Valley, all faults generally strike northwest (Fig. 3). The most recent movement on all the structures is dominantly normal slip which is compatible with the modern regional stress field (Wong and Humphrey, 1989). However, with the exception of the Uncompahgre fault zone, we believe all of the faults are associated with salt structures within the Paradox Basin. In addition, all definitive evidence for late-Quaternary deformation is associated with either salt-dissolution collapse (for example, Moab Fault-Olig and others, this volume; and Salt Valley Graben faults-Oviatt, 1988) or salt diapirism (for example, Onion Creek diapir and faults of Fisher Valley; Colman and others, 1986). Except for possibly the Shay graben faults, no earthquakes have been definitively associated with any of the faults. Thus, these faults have been assigned a low probability of 0.10 that they are seismogenic (Table 2). Only the Uncompahgre fault zone is considered to be seismogenic in the site region and was given an activity weight of 1.

The Needles fault zone and the Lockhart Fault (Fig. 3) were not considered in our hazard analysis because they are not seismogenic (Wong and others, 1987). The Needles fault zone is well known to be a product of salt movement and confined to the sedimentary rocks above the evaporites of the Paradox Formation (Huntoon, 1982). The Lockhart fault is the result of salt dissolution and collapse of Lockhart Basin (McCleary and others, 1987).

Best estimate fault dips of 60° to 65° with uncertainties of 15° to 20° were adopted for the faults in the site region when fault-specific information was not available. The range of dips used in the analysis is similar to that typically observed in the western Cordillera (Doser and Smith, 1989).

The seismogenic crust in the Colorado Plateau interior may be as thick as 19 mi (30 km) or more based on observations of microearthquakes (Wong and Humphrey, 1989). We have assumed, however, that faulting observed at the surface only extends to a depth of 9 to 12 mi (15 to 20 km) typical of much of the western U.S. (Wong and Chapman, 1990).

Preferred or best estimate maximum magnitudes for the faults were estimated based upon the empirical relationship derived by Wells and Coppersmith (1994) for surface rupture length. The rupture lengths were assumed to be the mapped lengths of the faults. We also incorporated a ± 0.25 magnitude uncertainty into the analysis. This value approximates the standard error in the Wells and Coppersmith (1994) relationship.

The recurrence relationships for the faults are modeled using both the exponentially truncated Gutenberg-Richter relationship and the "characteristic" earthquake model. No detailed paleoseismic studies have been performed along any of the 11 faults in the site region and therefore an appropriate recurrence model for these faults, assuming they are seismogenic, is not known. For this study, we have adopted an often used weighting for the Basin and Range province of 0.70 for the characteristic model and 0.30 for the exponential model (Wong and others, 1995). We have used the numerical model of Youngs and Coppersmith (1985) to simulate the characteristic model.

Seismic Source Zones

In addition to the faults, two seismic source zones were defined in this study and input into the hazard analysis. In contrast to discrete faults, source zones are areal sources which are considered to be uniform in terms of tectonic and seismogenic characteristics. Earthquakes are assumed to occur randomly throughout these zones unless they are specifically associated

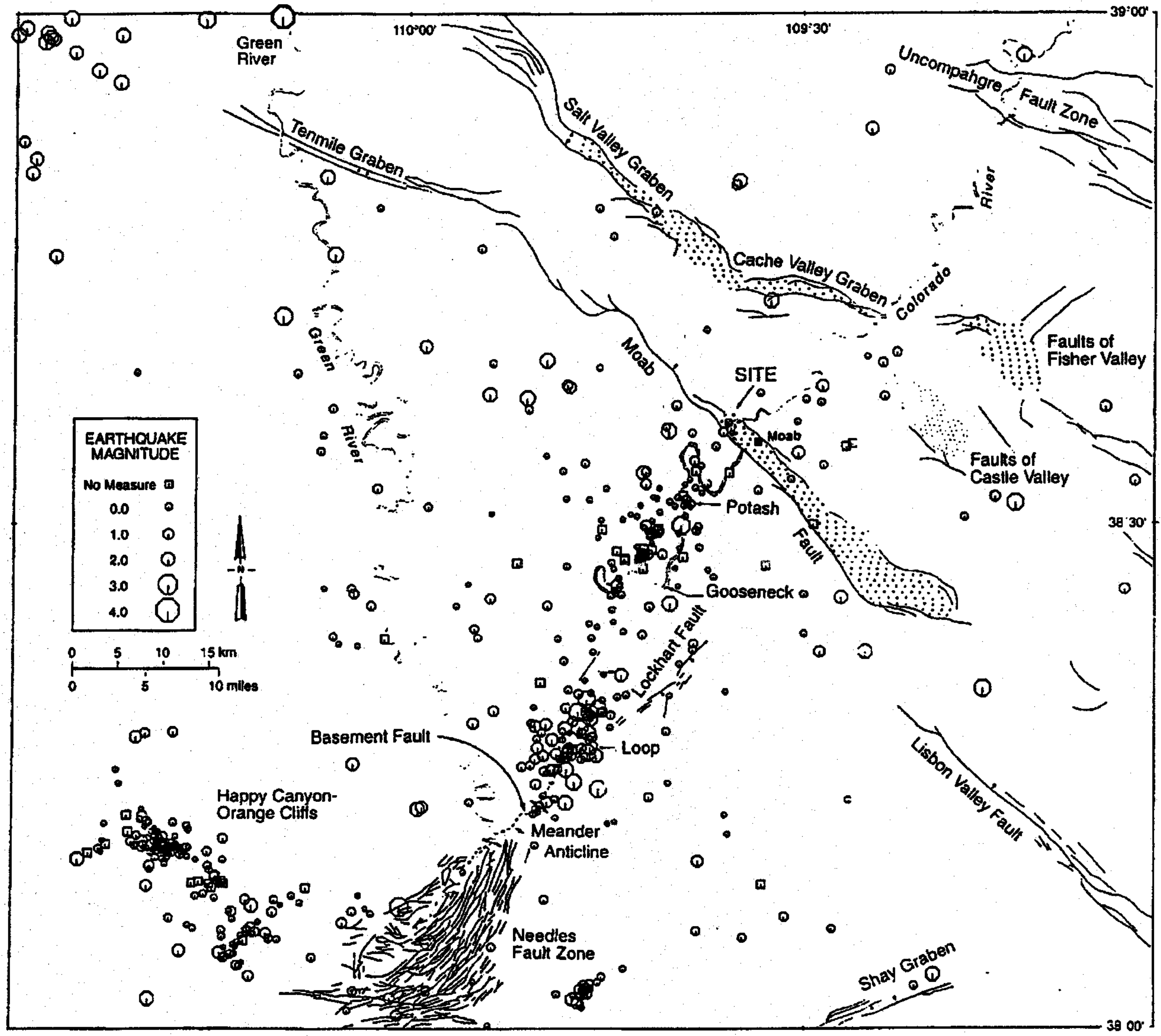

Figure 3. Seismicity (1953 to 1994) and selected Cenozoic faults (after Hecker, 1993) in the Paradox Basin, southeastern Utah. Stippled areas represent areas of distributed deformation (see Olig and others, this volume). Ball on normal faults is on downthrown side. Possible induced seismicity associated with the Cane Creek mine at Potash is not shown.

with known geologic structures To characterize the two areal source zones, only the maximum magnitude, seismogenic depth, and recurrence parameters were required. The recurrence is modeled using the truncated Gutenberg-Richter exponential model with the rates defined by the historical seismicity as previously described.

Seismicity Along the Colorado River

The first long-term seismographic network operated within the Colorado Plateau was installed in July 1979 by Woodward-Clyde Consultants in the site region (Wong and Simon, 1981; Wong and others, 1987; Wong and Humphrey, 1989). Prior to this monitoring, no earthquakes are know to have occurred in southeastern Utah south of the town of Green River (Wong and Simon, 1981). The network consisted of 12 to 24 high-gain, short-period stations covering an approximate area of 12,000 mi^2 (30,000 km^2) with a detection threshold of about M_L 0.5.

During the period of network operation from late July 1979 through June 1987, approximately 1,100 microearthquakes (smaller than M_L 3) were recorded and located in the region (Wong and Humphrey, 1989). A low rate of occurrence (approximately 10 events/month) punctuated by episodic bursts or swarms of as many as 35 events/day characterized the temporal

Table 2. Faults considered in hazard analysis.

Name	Probability of Activity	Total Fault Length (km)	Best Estimate Maximum Magnitude[1] (M_w)	Best Estimate Slip Rate (mm/yr)
Moab	0.1	54	6½ to 7	0.015[2]
Cache Valley Graben	0.1	16	6½	0.006
Castle Valley	0.1	17	6½	0.006
Salt Valley Graben	0.1	44	7	0.006
Fisher Valley	0.1	29	6¾	0.006
Tenmile Graben	0.1	35	6¾	0.008
Lisbon Valley	0.1	53	7	0.04
Uncompahgre[3]	1.0	33	6¾	0.1
Paradox Valley	0.1	48	7	0.04
Shay Graben	0.2	34	7	0.01
Gypsum Valley	0.1	39	7	0.04

[1] Uncertainty of maximum magnitude is ± 0.25 magnitude unit.
[2] For the unsegmented model. See Figure 4 for slip rates for the segmented model.
[3] Includes Ute graben, Granite Creek, and Ryan Creek fault zones.

behavior of seismicity in the region. Microearthquakes were generally widely distributed with major concentrations in: (1) the vicinity of the Cane Creek mine at Potash; (2) a 12 mi (20-km) stretch of the Colorado River northeast of its confluence with the Green River; (3) the vicinity of Happy Canyon and the Orange Cliffs (Fig. 3); and (4) southwest of Mancos Mesa in the Glen Canyon area (Wong and Humphrey, 1989).

The most seismically active area observed in the Canyonlands region was in the vicinity of the Cane Creek mine (Wong and others, 1989) (Fig. 3). The 3,300 ft (1 km) deep potash mine is operated using a solution extraction technique. The vast majority of the Potash events have been less than M_L 1.0 although several events have been almost M_L 3 in size. Events were scattered throughout the Potash area without any obvious concentration in the mine vicinity. Focal depths ranged from the near-surface to 12 mi (20 km). The temporal pattern of the Potash seismicity exhibited a fairly strong correlation with the solution mining at the Cane Creek mine; thus many of the microearthquakes are probably induced or triggered events possibly associated with subsidence that was observed occurring over the mine (Wong and others, 1989). Those events deeper than 3,000 to 6,500 ft (1 to 2 km) and more than a few kilometers away from the mine are most likely tectonic in origin.

In addition to the Potash area, microearthquakes were also concentrated along the stretch of the Colorado River near the Loop, 6 mi (10 km) northeast of the Confluence, and to a lesser extent, the Gooseneck (Wong and Humphrey, 1989) (Fig. 3). Focal depths in the Loop area generally range from 6,500 ft (2 km), the top of the Precambrian basement, to 9 mi (15 km). Focal mechanisms for Loop events suggest right-lateral strike-slip faulting on northeast-striking planes consistent with the epicentral trend. Based on aeromagnetic data, Case and Joesting (1972) suggested that a northeast-striking Precambrian basement fault zone exists beneath the Loop area (Fig. 3). This fault zone may have been reactivated and could be the source of the Loop seismicity (Wong and Humphrey, 1989).

In contrast, the microearthquakes in the vicinity of the Gooseneck (Fig. 3) were unusually shallow, generally less than 6,500±3,000 ft (2 ± 1 km) deep, placing the events within the sedimentary section above the Precambrian basement. A composite focal mechanism suggests left-lateral strike-slip faulting on a north-south-trending plane parallel to the epicentral alignment.

Wong and Humphrey (1989) concluded that the sources of seismicity along the Colorado River are most likely reactivated Precambrian basement faults with the possible exception of the Gooseneck area. The available data suggest there are multiple faults of undefined physical dimensions in a relatively broad zone underlying portions of the Colorado River. The seismicity in the Loop area and the possible coincidence with the postulated basement fault zone (Fig. 3) is probably the most convincing case for a seismogenic zone of multiple northeast-striking faults.

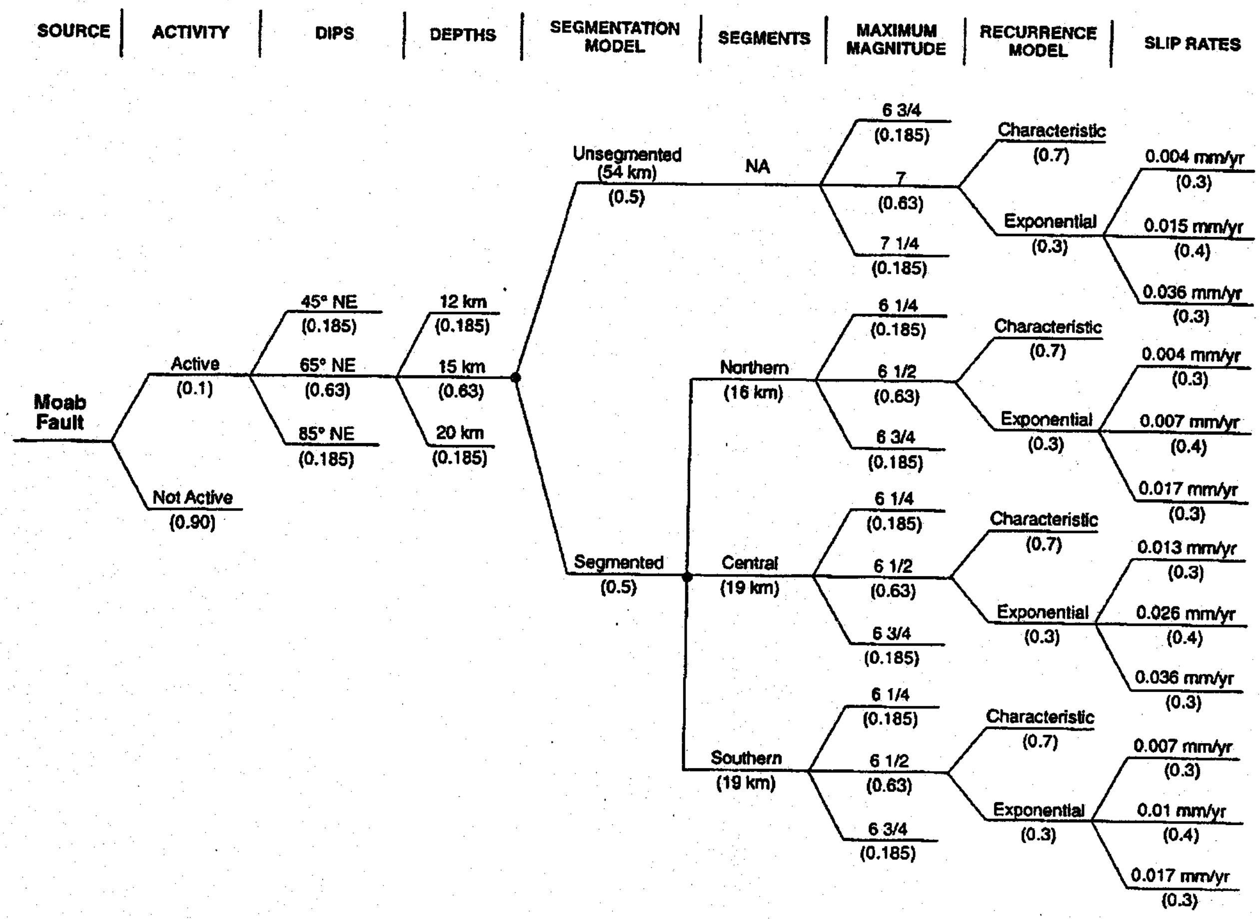

Figure 4. Logic tree for the Moab fault. See Woodward-Clyde Federal Services (1996) for detailed discussion.

For the seismicity along the Colorado River, we have allowed for the small possibility that there may be other seismogenic basement faults beneath the river in addition to the structure beneath the Loop. Thus, we have varied the closest approach of the Colorado River zone to the Moab site from 3 to 18 mi (5 to 30 km). The seismogenic depth of 7.5 to 9 mi (12 to 15 km) beneath the river is based on the observed microseismicity (Wong and Humphrey, 1989). Because the largest known earthquake associated with the Colorado River seismicity trend is no larger than M_L 3.0, a conservative maximum magnitude of M_L 5 (or moment magnitude M_w 5) was adopted as a preferred value in the seismic hazard analysis. To allow for the unlikely possibility that a larger earthquake could occur, up to M_w 6½, a range of values was incorporated into the hazard analysis.

To characterize the earthquake recurrence of the Colorado River seismicity, parameters were estimated based on the historical seismicity using a similar approach as applied to the Colorado Plateau interior. Shallow earthquakes, less than 2 mi (3 km) deep, spatially and temporally associated with the Cane Creek mine, which were probably induced, were removed from the catalogue. The computed *b*-value was 0.76 (±0.12) and the normalized *a*-value is -1.62 (Woodward-Clyde Federal Services, 1996).

Background Seismicity of the Colorado Plateau Interior

To date, few earthquakes have been definitively associated with any geologic structures within the Colorado Plateau interior probably in large part due to the general absence of mapped active faults. The contribution to seismic hazard from such "background" seismicity is incorporated into hazard analysis through the use of a Colorado Plateau interior source zone.

In most regions of the western U.S., events of about M_L 6½ and larger are usually accompanied by surface rupture and thus repeated events of this size will produce recognizable fault or fold-related features at the earth's surface (Doser, 1985; Smith and Arabasz, 1991; dePolo, 1994). In more tectonically and seismically active areas, such as the neighboring Basin and Range province, a maximum magnitude of M_L 6½ is often adopted. In contrast, a lower value for the relatively stable Colorado Plateau interior is warranted and thus, we adopt a maximum magnitude of M_W 6¼ based principally on the historical seismicity record and the absence of geologic structures exhibiting clear evidence for Quaternary surface rupture or surface deformation. The largest historical earthquake within the Plateau interior was the 1912 M_s 6.1 Lockett Tanks earthquake (Fig. 1).

PROBABILISTIC SEISMIC HAZARD ANALYSIS

To evaluate the levels of ground motions at the Moab site associated with a probability or likelihood of being exceeded in a specified time period, a probabilistic seismic hazard analysis was performed using a logic tree approach. This methodology allows for the explicit inclusion of the range of possible interpretations in components of the model including seismic source characterization and ground motion estimation. The probabilistic methodology used in this study is similar to other probabilistic approaches (Cornell, 1968; McGuire, 1978).

Uncertainties in the source parameters are included in the hazard model using logic trees (Fig. 4). In the logic tree approach, discrete values of the source input parameters have been included along with our estimate of the likelihood that the discrete value represents the actual value. Generally, all input parameters have been represented by three values: a central value, which represents our best estimate of the parameter, and lower and higher values to represent the probability distribution around the best estimate.

As seismic waves generated from an earthquake propagate through the earth, they diminish in amplitude with high frequency energy being damped at a greater rate. This attenuation is the result of geometrical spreading, dispersion, and damping. For the probabilistic analysis, we used three empirically-based soil attenuation relationships including Boore and others (1993), Campbell and Bozorgnia (1994) and Sadigh (1987; described in Joyner and Boore, 1988). Each relationship was weighted equally in the analysis.

Results

The seismic hazard was calculated at the Moab site assuming soil site conditions for peak horizontal ground acceleration. The results of the hazard analysis are presented in terms of the annual number of events exceeding the mean peak horizontal acceleration (Fig. 5). The annual number of events is the reciprocal of the average return period. The mean values are the result of the distribution of the many end branches of the logic trees. At return periods of 500, 1,000, 5,000, and 10,000 years, the mean peak horizontal accelerations are 0.05, 0.07, 0.14, and 0.18 g., respectively.

The contributions of the most significant seismic sources to the total peak acceleration hazard are also presented in Figure 5. The seismic hazard is usually dominated by the closest sources with the highest likelihood of producing large earthquakes. For return periods of less than one million years, the Colorado Plateau interior source zone dominates the hazard at the Moab site. The Moab Fault, the closest fault to the site (Olig and others, this volume), is the dominant contributor for return periods greater than about one million years (Fig. 5). The Colorado River zone contributes a higher hazard than the Moab Fault for return periods less than 100,000 years, but still contributes an order of magnitude less than the background earthquakes of the Colorado Plateau interior. The Uncompahgre fault zone, despite its assigned activity weight of 1.0 and slip rate comparable to that of the Moab Fault (Table 2), produces an insignificant hazard as it is too distant from the site. The remaining faults do not contribute significantly to the total mean hazard because of their low slip rates and large distances from the site.

PRECARIOUSLY BALANCED ROCKS AND STRONG GROUND SHAKING

Brune (1996) has suggested that groups of precariously balanced rocks can be indicators of past strong earthquake shaking. In his studies of such rocks in California and Nevada, he found none within 9 mi (15 km) of historic large earthquakes. Based on both *in situ* physical tests and computer modeling, the precariously balanced rocks that were evaluated in California would have been toppled by peak horizontal accelerations as low as about 0.10 g (Anooshehpoor and Brune, 1996). Thus, Anooshehpoor and Brune (1996) concluded that the presence of precarious rocks implies that strong ground shaking has not occurred since the rocks reached their balanced state, which they inferred was thousands of years.

The location of Moab in the Canyonlands region where probably hundreds of precariously balanced rocks occur, some very delicately, suggests that the site region has not been subjected to strong earthquake ground shaking for at least several thousands of years. These observations are consistent with the computed

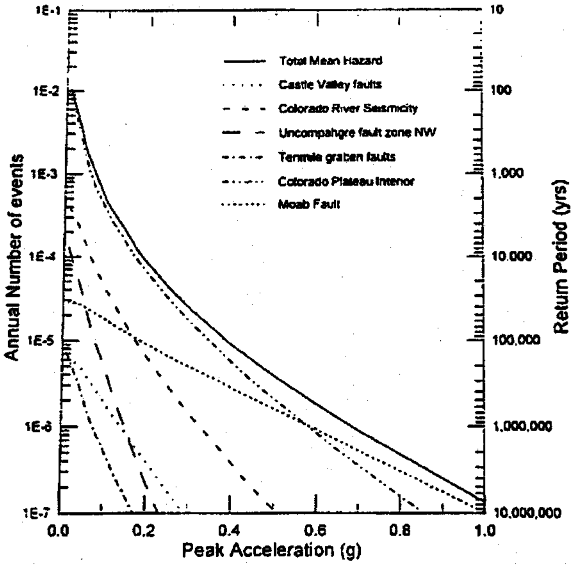

Figure 5. Mean probabilistic peak accelerations and contributions of significant seismic sources.

probabilistic peak accelerations. For example, the peak horizontal acceleration of 0.10 g cited above has a return period of about 2,500 years and 0.20 g has a return period slightly more than 10,000 years (Fig. 5).

CONCLUSIONS

Although located within the interior of the tectonically stable Colorado Plateau, the southeastern Utah portion of the Paradox Basin possesses a low level of seismic hazard. Although known active seismogenic faults appear to be few in number in the Plateau interior, it is possible that background earthquakes as large as M_w 6½ could occur, albeit infrequently. Thus potential earthquake hazards such as earthquake ground shaking, landslides, and liquefaction should be mitigated for in this portion of the Paradox Basin particularly for important and critical facilities.

ACKNOWLEDGEMENTS

The studies described in this paper were performed for Smith Environmental Technologies on behalf of Atlas Corporation. Our thanks to Rich Blubaugh of Atlas for his support and Bruce Hassinger of Smith Environmental for his assistance. Assistance in our studies was provided by Andrew Gorton, Ann Becker, Clark Fenton, Bob Green, Jeff McCleary, Sue Penn, Doug Wright, Richard Ely, Fumiko Goss, and Sadako McInerney of Woodward-Clyde. Our appreciation to Mike Ross and Gary Christenson of the Utah Geological Survey; Sue Nava and Jim Pechmann of the University of Utah; Jon Ake of the U.S. Bureau of Reclamation; and Jim Cooksley of Cooksley Geophysics for providing information and data. We appreciate the review of this paper by Ann Becker.

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SCOPE OF WORK
FOR SITE-SPECIFIC SEISMIC HAZARD ANALYSES

Prepared by
Ivan G. Wong
Seismic Hazards Group, URS Corporation
1333 Broadway, Suite 800, Oakland, CA 94612
(510) 874-3014
ivan_wong@urscorp.com

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Tasks

1. Identify and characterize the seismic source parameters for all local and regional faults that may be significant to the site in terms of ground shaking hazard. These fault parameters will include geometry and rupture dimensions, maximum earthquake, nature and amount of slip for the maximum earthquake, and rate and nature of earthquake recurrence. Background seismicity should also be characterized for the hazard analysis.

2. Compile and evaluate the historical seismicity for the region out to at least a distance of 200 km from the site. Evaluate the seismicity in the immediate vicinity of the site. Characterize any historical ground shaking at the site from past events. Calculate the recurrence rates of the historical seismicity for defined regions of common seismotectonic characteristics..

3. Perform a probabilistic seismic hazard analysis to evaluate the probabilities of exceeding certain ground motion levels at each site based on the available information and data on seismic sources and historical seismicity using the most up-to-date and accepted ground motion attenuation relationships. Evaluate the appropriateness of the attenuation relationships selected for use in the hazard analysis.

4. Review the available geologic, geotechnical, and geophysical data and information to characterize the geologic conditions at the site. Of particular importance if the site is underlain by soil, are the physical characteristics of the soil, depth to bedrock, depth to the water table, and shear-wave velocity profile to rock. If the information are deemed insufficient, further site investigations may be recommended after consultation with the Structural Engineer. Classify the soil at the site using the NEHRP categories.

5. Evaluate whether a site response analysis is required based on the results of Task 4. If such an analysis is necessary to accurately estimate the site response, use an accepted equivalent-linear or nonlinear code and determine, in consultation with the Structural Engineer, if the structure under evaluation should be included in the analysis. In most cases, a shear-wave velocity profile and shear modulus reduction and damping curves will be required. Incorporate the site variabilities into the ground motions estimates. If an analysis is not required, available published amplification factors may be used or the probabilistic seismic hazard analysis can be performed using appropriate soil attenuation relationships.

6. Address and incorporate the possible effects on ground motions from fault rupture directivity and/or basin effects as may be deemed applicable to the site.

7. Develop site-specific Safety Evaluation Earthquake (SEE) acceleration response spectra for both the horizontal and vertical components. The ground motions shall be developed for the annual exceedance probability that is established by regulations, e.g., 10^{-4}. Spectra will be calculated for 5% damping unless specified otherwise.

8. If determined to be needed by the Structural Engineer, develop a suite of seven site-specific SEE three-component time histories for use in nonlinear time history dynamic analysis.

9. Evaluate other earthquake hazards, based on available information and data, including the potential for liquefaction and lateral spreading, surface fault rupture, earthquake-induced settlement, landsliding, and tsunamis. Provide conceptual mitigation recommendations as required for these hazards.

10. Describe the approach and results of all tasks in a Final Report.

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Earthquake hazards in the Intermountain US: Issues relevant to uranium mill tailings disposal

Ivan G.Wong & Susan S.Olig
Seismic Hazards Branch, Woodward-Clyde Federal Services, Oakland, Calif., USA
Bruce W.Hassinger
Smith Environmental Technologies Corporation, Englewood, Colo., USA
Richard E.Blubaugh
Environmental and Government Affairs, Atlas Corporation, Denver, Colo., USA

ABSTRACT: In the past two decades, a tremendous amount of new information and data has emerged on seismic sources in the Intermountain United States and their associated processes of earthquake generation. Consequently, the seismic safety of U.S. uranium mill tailings sites, which are located almost exclusively in this region, are being reviewed by the U.S. Nuclear Regulatory Commission (NRC). Based on a deterministic and probabilistic re-evaluation of potential seismic hazards at a Title II site in southeastern Utah, three significant issues have been raised which will impact other sites in the Intermountain U.S. required to revisit their seismic design criteria by the NRC. These issues are: (1) whether the NRC's required use of a deterministic approach for assessing seismic hazards is appropriate for Title II uranium mill tailings sites in a region such as the Intermountain U.S.; (2) is the alternative approach of probabilistic seismic hazard analysis acceptable to the NRC for uranium mill tailings sites; and (3) what is the appropriate return period that should be used. Based on our evaluation, we conclude that deterministic ground motion approaches such as the NRC's 10 CFR 40 Appendix A can result in overly conservative seismic design criteria for Title II sites in the Intermountain U.S. and that instead, probabilistic seismic hazard analysis should provide the bases for such criteria. Additionally, as in all decisions of this nature, the selection of a return period for a specific site should be based on what is deemed an acceptable level of risk. Such levels may vary from site to site depending on the consequences of radionuclide release into the environment. However, the values of 200 and 1000 years cited in the Environmental Protection Agency's (EPA) 40 CFR 192.02 and NRC's Appendix A Criterion 6(1) should form the basis for the selected return period.

1 INTRODUCTION

Many portions of the Intermountain region of the western United States (Figure 1) exhibit geologic evidence for large prehistoric earthquakes although they may lack even low levels of historical and/or contemporary seismicity. Such areas are subject to future seismic hazards. Large events such as the 1959 magnitude (M) 7.3 Hebgen Lake, Montana and 1983 M 6.8 Borah Peak, Idaho earthquakes attest to the earth's potential to damage both natural and man-made environments. The recurrence intervals of such large events on a specific fault in the Intermountain U.S., however, may span from a few thousands to more than 100,000 years. Hence, one of the most significant problems

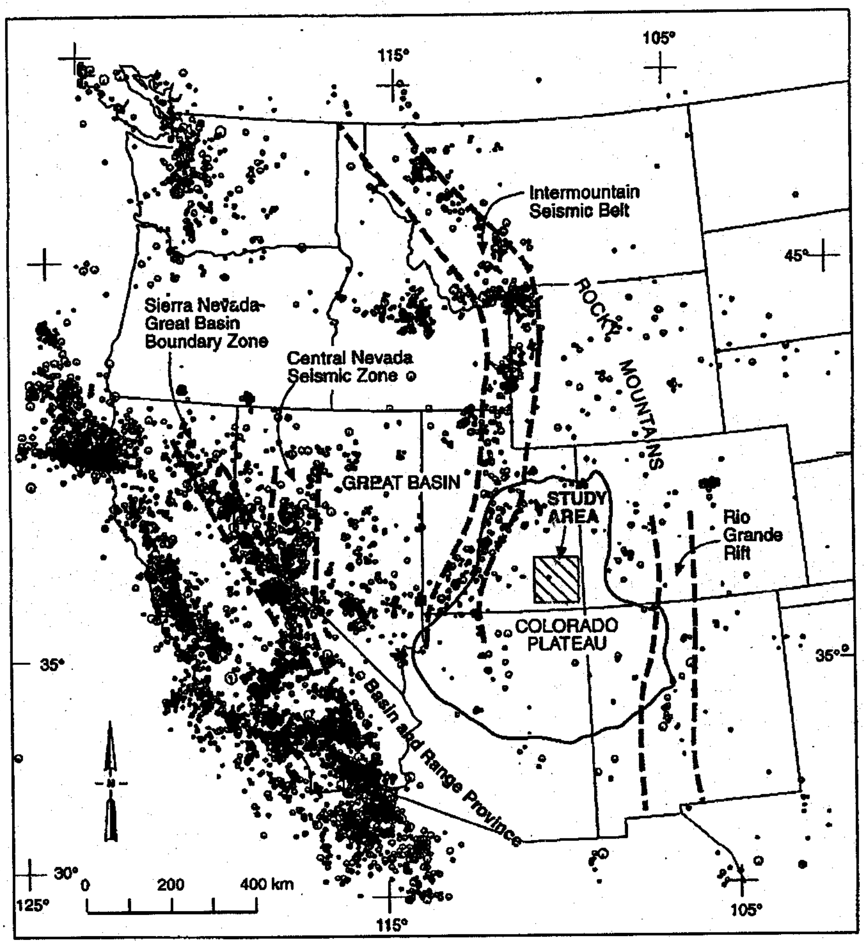


Figure 1. Seismicity of the western U.S. (1808 to 1996) and physiographic provinces and major seismic source zones located in the Intermountain U.S. Also shown is the study area around the Moab site in southeastern Utah. Earthquake data courtesy of the National Earthquake Information Center.

facing the community involved in earthquake hazard mitigation is how to address the hazard from large but infrequent earthquakes. In contrast, there also exist portions of the Intermountain U.S., such as the interior of the Colorado Plateau, where the earthquake potential is low based on both recent geologic and seismologic data.

In 1978, Congress enacted the Uranium Mill Tailings Radiation Control Act (UMTRCA) to provide for the disposal, long-term stabilization, and control of uranium mill tailings. The NRC, which regulates UMTRCA uranium mill tailing sites, has initiated a program of re-evaluating the seismic design criteria of Title II (licensed) sites based on the results of a recent study performed by Lawrence Livermore National Laboratory (LLNL) (Bernreuter *et al.* 1995). In the LLNL study, "simplified" site-specific probabilistic seismic hazard analyses were performed for 19 Title II sites located in Utah, Wyoming, South Dakota, and New Mexico based on readily available information. Bernreuter *et al.* (1995) concluded that at most sites, their estimates of probabilistic peak ground acceleration at return periods of 2,000 years and more were higher than the values used in design.

In a recent re-evaluation of a Title II site in Moab, Utah, three key seismic hazard issues have emerged in our interactions with the NRC. These issues will significantly impact most, if not all, other sites in the Intermountain U.S. This paper describes these issues and our approach to resolving them.

2 EARTHQUAKE HAZARDS IN THE INTERMOUNTAIN U.S.

The Intermountain U.S., as defined in this paper, consists of the states of Idaho, Nevada, Arizona, Utah, Montana, New Mexico, Colorado, and Wyoming. Physiographically, the region consists principally of the Basin and Range province, Colorado Plateau, Rocky Mountains, and Great Plains. Four major seismic zones are located within or border the Intermountain U.S. including: (1) the Sierra Nevada-Great Basin boundary zone; (2) the Intermountain seismic belt including the Centennial Tectonic Belt; (3) the Central Nevada seismic zone; and (4) the Rio Grande rift (Wong *et al.* 1982) (Figure 1). Elsewhere, away from these zones, the level of historical seismicity is more subdued but there still exists the potential for the occurrence of large but infrequent earthquakes as indicated by the presence of late-Quaternary faults. For example, the 1887 Sonoran earthquake of estimated M 7.4 occurred as a result of rupture along the Pitaycachi fault just south of the Arizona-Mexico border (Bull and Pearthree 1988) in an area characterized by a low level of historical and contemporary seismicity.

Of greatest relevance to the Intermountain Title II sites are the Intermountain seismic belt and Rio Grande rift. The Intermountain seismic belt is one of the most extensive zones of seismicity within the continental United States (Figure 1). It trends 1300 km northward from northwestern Arizona through central Utah, straddles the Idaho-Wyoming border, and turns northwestward through Montana in the vicinity of Yellowstone National Park (Smith and Sbar 1974; Smith and Arabasz 1991). Much of the Intermountain seismic belt is characterized by generally north- to northwest-trending normal faults. Prominent fault zones include the Sevier and Hurricane faults in northern Arizona and southern Utah, the Wasatch fault zone in central Utah, and the Madison and Hebgen faults near Yellowstone. Since the beginning of the historical record in the mid-1800's, about 25 earthquakes of M 6 or greater have occurred along the Intermountain seismic belt (Smith and Arabasz 1991). The largest event in historical time was the 1959 Hebgen Lake earthquake.

The Rio Grande rift extends for approximately 600 km from south-central New Mexico northward to south-central Colorado (Figure 1). Most of New Mexico's population is concentrated along the Rio Grande rift in cities such as Albuquerque and Santa Fe. The earliest report of earthquake activity was a sequence of 22 events felt in 1849 to 1850 near the town of Socorro (Sanford *et al.* 1991). The largest earthquakes observed to date are three events that occurred on 12 and 16 July and 15 November 1906 near Socorro. The estimated size of the latter event, the largest of the trio, is about M 6.

3 SEISMIC HAZARD EVALUATION OF THE MOAB SITE

In response to a request by the NRC, an up-to-date seismic hazards evaluation of the Title II Moab site was performed (Wong *et al.* 1996). This site, owned by Atlas Corporation, consists of a 130-acre pile consisting of 10½ million tons of processed tailings derived from the past operation of the Atlas uranium mill. The tailings were emplaced over alluvial soils and the disposal area was developed from 1956 to 1984. The site is in the process of final closure and the Remedial Action Plan (Reclamation Plan) requires NRC approval.

According to the Standard Review Plan (SRP June 1993), "there are no NRC regulatory guidelines directly applicable to the geologic and seismologic aspects of the UMTRA Program". However, the basic acceptance criteria pertinent to the geologic and seismic stability aspects are provided in the EPA's 40 CFR Part 192, Subpart A and according to section 192.02, "control of residual radioactive materials and their listed constituents shall be designed to be effective for up to 1000 years, to the extent reasonably achievable, and in any case, for at least 200 years". NRC staff has interpreted this standard to mean that certain geologic and seismic conditions must be met in order to have reasonable assurance that the long-term performance objectives will be achieved (NRC 1994).

The SRP states that NRC staff review of seismotectonic stability must conclude whether the information and investigations in the Remedial Action Plan provide an adequate basis for selection of the Maximum Credible Earthquake (MCE) and determination of the resulting vibratory ground motion at the site. The NRC defines the MCE as the "earthquake which would cause maximum vibratory ground motion based upon an evaluation of earthquake potential considering the regional and local geology and seismology and specific characteristics of local subsurface material" (10 CFR 40 Appendix A). The NRC's Appendix A approach, which basically requires the determination of the 84th percentile MCE ground motions, is a deterministic approach. It requires the use of the worst case earthquake with no consideration for its frequency of occurrence.

Although Appendix A stipulates that a tailings pile be designed for the MCE, the Introduction to Appendix A allows for alternatives to be proposed by the licensee. These alternatives "may take into account local or regional conditions, including geology, topography, hydrology, and meteorology. The commission may find that the proposed alternatives meet stabilization and containment of the site concerned, and a level of protection for public health, safety, and the environment from radiological and non-radiological hazards associated with the sites, which is equivalent to, to the extent practicable, or more stringent than the level which would be achieved by the requirements of this Appendix and the standards promulgated by the EPA in 40 CFR Part 192." Furthermore, Appendix A Criterion 6(1) specifies that the regulatory standard is "reasonable assurance" of stability of the tailings disposal for the 200 to 1,000 year period.

Moab is located within the interior of the Colorado Plateau which has been generally considered to be seismically inactive and devoid of large earthquakes. Seismological studies performed in the past decade, however, indicate that seismicity is fairly widespread throughout the Plateau interior, albeit at a low to moderate level, and that earthquakes up to M 6 have occurred in historical times (Wong and Humphrey 1989). Although detailed fault studies have not been performed to date within the Colorado Plateau, the available geologic data suggests that only a few significant late-Quaternary faults may exist in the Plateau interior (Hecker 1993). Thus there appears to be at least a low level of earthquake hazard within the Plateau.

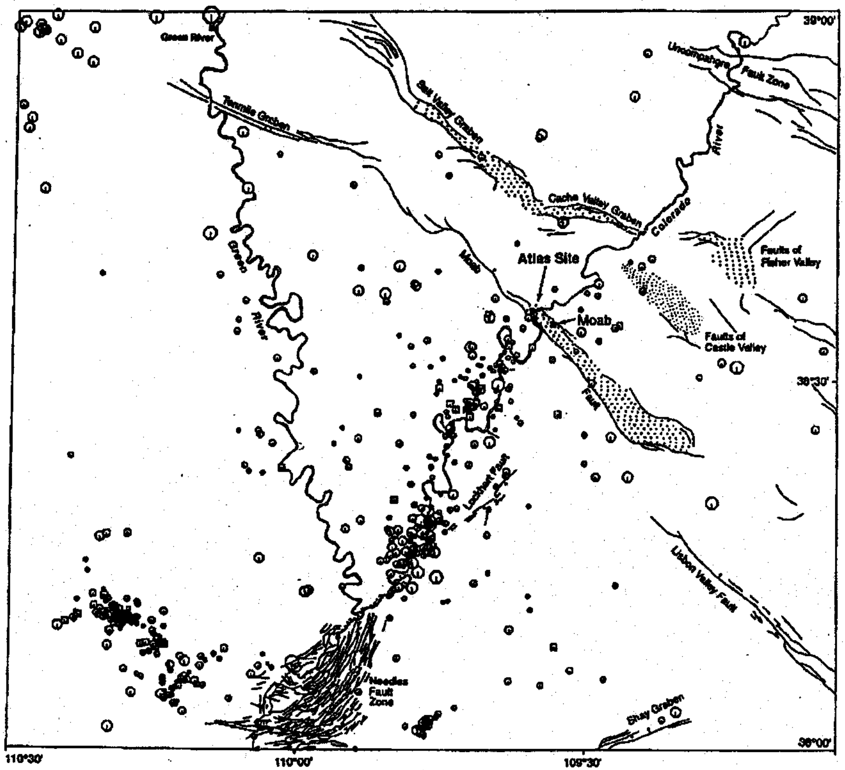
In our seismic hazard evaluation of the Moab site, potentially seismogenic faults and seismic source zones (areal sources) significant to the site were identified, characterized, and considered in the analysis. These seismic sources included 11 faults, a zone of microseismicity along the Colorado River southwest of Moab, and a seismic source zone for the Colorado Plateau which represents unknown earthquake sources having no geologic surficial expression (Figure 2). The closest fault to the site is the Moab fault which trends beneath the northeastern corner of the site. Available geologic and geophysical evidence, however, indicates that the fault is not capable of producing significant earthquakes (Olig *et al.* 1996). In fact, 10 of the 11 faults considered in our evaluation are associated with salt structures and are probably not seismogenic (Wong *et al.* 1996).

Based on an Appendix A approach, ground motions, as characterized by peak horizontal acceleration, were estimated for three potential earthquake scenarios: (1) a M 5.0 earthquake at a source-to-distance of 30 km, our proposed largest event along the Colorado River seismicity trend; (2) a M 6½ earthquake along this same zone at a distance of 5 km from the site as proposed by the NRC; and (3) a "floating" earthquake of M 6¼ at a distance of 15 km. In the absence of any nearby capable faults, the NRC's policy requires that the MCE be represented by a floating (random) earthquake. For the second scenario, the NRC assumed that half of the seismicity zone along the Colorado River could rupture in a single large earthquake. Based on geological and seismological arguments presented in Woodward-Clyde Federal Services (1996), we consider this scenario to be extremely unlikely.

Given a maximum magnitude and source-to-site distance, empirically-based attenuation relationships can be used to estimate median (50th percentile) and median plus one standard deviation (84th percentile) ground motions for a site. The NRC-stipulated 84th percentile peak horizontal accelerations at the Moab site were 0.06 g, 0.63 g, and 0.29 g, respectively for the above earthquake scenarios. Based on this analysis, the MCE for the site would be the NRC's M 6½ earthquake occurring along the Colorado River seismicity trend at a source-to-site distance of 5 km.

As an alternative approach, we evaluated the earthquake hazard at the Moab site probabilistically similar to, but in a more rigorous manner than was done by LLNL. In a probabilistic seismic hazard analysis, levels of ground motions associated with a probability or likelihood of being exceeded in a specified time period (or inversely, return period) can be calculated. This approach also allows for the explicit inclusion of the range of possible interpretations and uncertainties in components of the model including seismic source characterization and ground motion estimation. The probabilistic seismic hazard model used in our study is similar to the hazard model originally developed by Cornell (1968) and refined by McGuire (1974).

All seismic sources within a distance of about 150 km from the site were characterized and input into the analysis (Wong *et al.* 1996). This included the 11 faults such as the Moab fault, the Colorado River seismicity trend, and the Colorado Plateau source zone. Ten of the 11 faults were assigned low probabilities of being seismogenic because they show no evidence for Quaternary activity except deformation related to shallow salt dissolution and flowage (Wong *et al.* 1996). The attenuation of ground motions was addressed through the use of state-of-the-art empirical relationships for peak horizontal acceleration and stiff soil conditions.



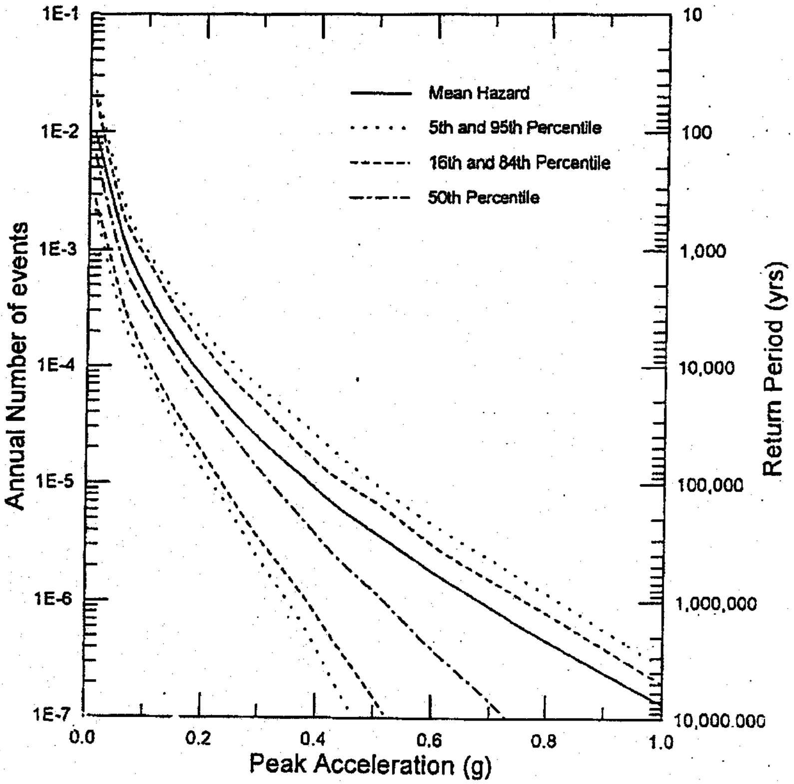
(Source: Wong et al. 1996)

Figure 2. Seismicity (1953 to 1994) and selected Cenozoic faults (after Hecker 1993) in the Moab study area. Stippled areas represent areas of distributed deformation due to salt dissolution. Ball on normal faults is on downthrown side.

The probabilistic seismic hazard analysis resulted in peak horizontal accelerations at the Moab site of 0.05 to 0.18 g for return periods ranging from 500 to 10,000 years (Figure 3). The MCE 84th percentile peak horizontal acceleration of 0.63 g has a return period of about 750,000 years (Figure 3) or 750 times greater than the 1000-year design life stipulated in 40 CFR 192.02 and Appendix A Criterion 6(1). The major contributor to peak acceleration hazard at 10,000 years is the background earthquake in the Colorado Plateau source zone. The Colorado River seismicity trend and the Moab fault contribute little to the hazard at the Moab site at this return period (Wong *et al.* 1996).

4 SEISMIC HAZARD ISSUES IN THE INTERMOUNTAIN U.S.

In the seismic hazard evaluation of the Moab site, three significant issues were raised due to NRC regulations governing Title II sites. The first issue stems from the NRC's current position of requiring the seismic design of Title II sites be based on a deterministic Appendix A approach incorporating the concept of the MCE. In such an approach, the 84th percentile ground motions generated by the MCE provide the basis for the Design Basis Earthquake. Intertwined in this issue is also the issue of the reasonableness of the 15 km source-to-site for the floating earthquake in areas of low seismicity.



(Source: Wong et al. 1996)

Figure 3. Probabilistic seismic hazard curves for the Moab site. The fractile curves give the range of uncertainty about the mean or median (50th percentile) values. The peak horizontal acceleration of 0.18 g at a 10,000 year return period, our recommended seismic design value, can be read from the mean hazard curve.

We believe the MCE peak horizontal acceleration for the Moab site (0.63 g) and even the value estimated for the floating earthquake (0.29 g) are overly conservative for seismic design purposes given the low seismic potential that exists within the interior of the Colorado Plateau. This latter observation is supported by the available seismological and geological data. In particular, the location of the Moab site in the Canyonlands region where many precariously balanced rocks occur throughout the area, some very delicately, suggests that this portion of the Colorado Plateau interior has not been subjected to strong earthquake ground shaking for at least several thousands of years (Wong *et al.* 1996).

As described earlier, the NRC's policy specifies the 15 km source-to-site distance for the floating earthquake. This distance is rather arbitrary because it is independent of the seismic potential of the region being considered. Thus whether a site is located along the more seismically active Wasatch Front in central Utah or the much less active Moab area, the 15-km distance is fixed. In general, deterministic approaches such as dictated in the NRC's Appendix A can result in overly-conservative seismic design criteria in areas of low earthquake potential. Even for sites in more seismically active areas of the Intermountain U.S., deterministically-based ground motions can also be too high for seismic design because the majority of late-Quaternary faults are characterized by long recurrence intervals far exceeding the lifetimes of engineered structures.

The second issue is whether probabilistic seismic hazard analysis is acceptable to the NRC as an alternative to their Appendix A deterministic approach for developing seismic design criteria at Title II sites. The NRC has endorsed the use of probabilistic risk assessment in nuclear regulatory matters as specified in their final policy statement in the Federal Register (16 August 1995). At this time, however, the NRC has not officially established a policy for Title II sites. Probabilistic analysis has become increasingly used in seismic hazard analysis for a wide range of facilities and structures. It provides the basis for the Uniform Building Code and is now become acceptable for evaluating the potential seismic hazards to nuclear reactors.

Given the uncertainties in seismic source characterization and ground motion estimation in the Intermountain U.S., probabilistic seismic hazard analysis is well suited to addressing these uncertainties. For example, given the observation that the largest known earthquake along the Colorado River is less than M 3, there is considerable uncertainty in the assumption that the maximum earthquake for this zone is M 5 relevant to the Moab site. As previously discussed, the NRC's position that a maximum earthquake of M 6½ could occur within this zone is even more uncertain. Additionally, because the acceptable risk of Title II sites has been defined in terms of time (200 to 1000 years), it is best evaluated through probabilistic analysis which incorporates the recurrence of earthquake sources.

If probabilistic analysis is acceptable for Title II sites, a significant issue is at what return period (or alternatively a probability of nonexceedance) is deemed appropriate by the NRC. It was our recommendation that the seismic design criteria for the Moab site be based on a return period of 10,000 years (corresponds to a 10% chance of exceedance in 1000 years). We selected and recommended this very conservative return period based on the fact that the Moab site is located adjacent to the Colorado River and that radionuclide release into the major water source, if possible, might be considered higher risk than other Title II sites. In the probabilistic seismic hazard analysis performed by Bernreuter *et al.* (1995) for Title II sites, they calculated peak horizontal accelerations assuming a return period of 10,000 years. They adopted this value because, in their opinion, it satisfied the criteria cited in Appendix A. Furthermore, they stated that such a probability of exceedance may be too conservative for design because of the "relatively low risk posed by the tailings piles." For comparison, the current design life for the proposed underground nuclear waste repository at Yucca Mountain, Nevada is 10,000 years.

Because we considered a 10,000 return period to be very conservative compared to the required 1,000 years cited in 40 CFR 192.02 and Appendix A and because both EPA and NRC considered but explicitly rejected a 10,000 year control period for uranium mill tailings, our recommended seismic design value of 0.18 g for the Moab site provides "reasonable assurance" of a level of protection "equivalent to, to the extent practicable" stipulated in Appendix A. We believe that selection of longer return periods, which correspond to lower probabilities of exceedance, would certainly result in overly conservative seismic design criteria not consistent with the available geologic, seismologic, and geophysical data pertinent to earthquake hazards in the vicinity of the Moab site and the interior of the Colorado Plateau.

5 CONCLUSIONS

Probabilistic seismic hazard analysis has been increasingly accepted as an approach often superior to deterministic methods alone for evaluating seismic hazards for a wide variety of facilities and structures. The probabilistic methodology is particularly well suited in applications for uranium mill tailings sites because of their generally lower risk and locations in the Intermountain U.S. In this region, large damaging earthquakes are possible but relatively infrequent. There are also considerable uncertainties in characterizing seismic sources and estimating ground motions which can be explicitly incorporated into probabilistic seismic hazard analysis. Finally, because the level of acceptable risk for Title II sites has been expressed in a time frame of 200 to 1000 years (40 CFR 192.02), probabilistic seismic hazard analysis is better suited to providing the basis for seismic design criteria than deterministic approaches, which are time independent.

6 ACKNOWLEDGMENTS

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