# Appendix B

# Probabilistic Seismic Hazard Assessment for Appraisal Studies of the Proposed Black Rock Dam

Technical Memorandum No. D-8330-2004-14

# Black Rock Dam
# Yakima River Basin Storage Feasibility Study, Washington

## Probabilistic Seismic Hazard Assessment for Appraisal Studies of the Proposed Black Rock Dam

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

July 2004

## MISSION STATEMENTS

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

# Probabilisitic Seismic Hazard Assessment for the Proposed Black Rock Dam, Yakima River Basin Storage Feasibility Study, Washington

Bureau of Reclamation
Technical Service Center
Seismotectonic and Geophysics Group
Denver, Colorado

**Technical Memorandum No. D8330-2004-014**
**July 2004**

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# 1.0 INTRODUCTION

An initial probabilistic seismic hazard assessment (PSHA) has been conducted for use in appraisal-level studies of the proposed Black Rock Dam. The proposed dam would be located in the vicinity of Horse Thief Point in Black Rock Valley (Plate 1). Specific alignment locations and designs are not yet determined, but current evaluations are considering dams with structural heights as large as 500 to 600 ft that could provide a reservoir capacity near 1.5 million acre-ft.

The primary product of this assessment is a preliminary hazard curve for peak horizontal acceleration (PHA) for use in the initial appraisal-level engineering studies. Also included is a de-aggregation by source, which shows the relative contributions of the various seismic sources to the total PHA hazard. At this stage of the evaluation, existing data indicate that some faults in the immediate site vicinity may need to be considered as potential earthquake sources. Thus, issues such as surface faulting and secondary coseismic folding and faulting may also be of potential engineering significance to the proposed dam. A brief discussion of these issues is included below.

## 1.1 Basis for this Evaluation

The current evaluation is based on limited, readily available data from existing studies and limited, preliminary evaluation thereof. These studies include probabilistic seismic hazard assessments for facilities at DOE Hanford (Geomatrix, 1996), several Bureau of Reclamation dams northwest of Yakima (Wong and others, 2002), and USGS and Canadian Geological Survey national seismic hazard mapping programs (Haller and others, 2002; Adams and Halchuk, 2002). At this stage of the evaluation, it is clear that while there is broad consistency between these previous studies, there are also numerous differences and gaps that are clearly significant to assessments at the Black Rock site that are not resolved in this assessment. Limited explorations and site characterization of the potential Black Rock damsite have been done to date (Washington Infrastructure Services, Inc., 2003; Columbia Geotechnical Asssociates, 2004; BOR, 2004). These data indicate that a major thrust fault is involved with folding of the basalt units on the right abutment of the damsite, and that this fault extends up valley along the southern edge of the proposed reservoir. Basalt on the left abutment mostly dips gently to the south towards Black

Rock Valley, where locally derived Quaternary alluvium and older sedimentary units appear to thicken to the south beneath the valley.

The current evaluation is based on the relatively limited characterization of the geologic structure of the Black Rock Valley and damsite area and the seismogenic potential of the faults in the immediate area contained in the existing reports. The structural setting of the damsite area is complex and further evaluations will undoubtedly result in significant changes to the assessments contained in this evaluation.

# 2.0 SEISMIC SOURCE CHARACTERIZATION

## 2.1 Significant Potential Fault Sources near the Proposed Black Rock Damsite

There are several issues that contribute uncertainty to the seismic source characterization that are not fully accounted for in this preliminary analysis. More comprehensive seismic hazard analysis will be required to resolve and characterize these uncertainties.

**Regional Seismotectonic Setting and Tectonic Models.** Regionally, Black Rock damsite lies within the Yakima fold belt, a group of mostly east-west striking folds which formed during and subsequent to eruption of the Columbia River Basalts, about 10-15 million years ago (Reidel and others, 2003). The geometry of the folds is consistent with activity shown by regional seismicity and stress data which is dominated by north-south compression. However, there are significantly differing interpretations published in the technical literature regarding the origin and age of these folds that have profound implications for seismic hazard assessment. At one extreme are models that indicate that faults associated with the folds are planar features that extend 20+ km to the base of the brittle seismogenic crust. In that model, large-magnitude earthquakes are plausible on these faults. Such faults would be considered fully "coupled" to stresses within the upper crust. An alternative model holds that most or all of the folding and faulting is limited to a relatively thin upper crustal layer composed mostly of basalts which is effectively "decoupled" from underlying, less competent rocks and deeper crustal stresses. In that model, faults that involve the basalts at the surface have limited depth extent and area, and hence limited potential to produce large magnitude earthquakes. In the decoupled model, surface deformation rates are the same, but this deformation is accommodated through significantly higher rates of moderate-magnitude earthquakes at shallow depths. In the Geomatrix (1996) assessments for Hanford, most of the faults closest to the Black Rock damsite were assigned a probability of coupling of only 0.15, while other faults in the region were assigned probability of coupling as high as 0.95. Assessments by Wong and others (2002) and Haller and others (2002) did not consider probability of coupling as a separate factor (hence, the probability of coupling = 1.0). For this preliminary assessment, we follow the lead of more recent assessments and assume that all faults are fully coupled. If indeed the fold/fault sources within the Yakima fold belt are a complex mixture of coupled and decoupled structures as portrayed by Geomatrix (1996) for the Hanford assessments,

then at certain sites, inclusion of highly decoupled sources could result in higher rates of occurrence for some ground motion parameters, including PHA, than are obtained for coupled models. This is because sites very close to the decoupled sources would be subject to much higher rates of moderate-magnitude seismicity than in alternative models where larger magnitude earthquakes occurred, but less frequently.

**Structural Setting of the Site.** Previous seismic hazard assessments have either lumped together or neglected the details of potential seismic sources in the immediate vicinity, 0-10 km, of Black Rock damsite (e.g., Geomatrix, 1996; Wong and others, 2002). Existing regional mapping including the area of Black Rock Valley does not appear to resolve many structural details, and these detail were not highly important to prior assessments at other sites. Mapping in progress for the damsite area has indicated that a thrust fault along the south margin of the valley which extends through the area of the proposed dam foundation, may be part of a fault of regional extent (Columbia Geotechnical Associates, 2004). As the PHA hazard curves developed in the following section of this report demonstrate, because of the close proximity of the site to this fault, judgements on the potential activity and geometry of the nearby faults controls the seismic hazard and ground motion estimates for the site. For the present evaluation, each major fold near the site has been treated as an independent structure, essentially a single planar fault dipping beneath the fold. Alternative, potentially more complex characterization of the structure of nearby fold such as Yakima Ridge, could include backthrusts or "blind" structures that could have significant influences on estimates of seismic hazard for the site. These more complex fault geometries would significantly affect seismic hazard estimates because changes in fault dip and location would affect site-to-source distances and fault areas (size) considered in magnitude estimates. In addition, other potentially seismogenic faults could be present in the site area which have not been accounted for in the present analyses.

**Slip Rates and Fault Activity.** Fault assessments used for this evaluation are derived from data compiled from three previous regional hazard studies (Geomatrix, 1996; Haller and others, 2002; Wong and others, 2002) which are summarized in Tables 2-1 and 2-2 and portrayed on Plate 1. For most of the faults used in this seismic hazard analyses, slip rates are primarily based on estimated offsets of basalt units that range in age between 10-17 Ma. Little data are

currently available to constrain offsets for shorter time periods. In general, arguments for or against more recent fault activity on most of the faults and folds considered as seismic sources in this assessment are based on indirect or sparse evidence.

In the previous seismic hazard studies, faults along the northern side of the Rattlesnake Hills near the Black Rock Valley have not been defined in great detail because they were not close to the sites of interest or not considered highly significant for those studies. Preliminary engineering studies at the damsite have provided some further details on the Black Rock Valley faults (Washington Infrastructure Services, Inc., 2003; Columbia Geotechnical Asssociates, 2004; BOR, 2004). However, existing estimates of potential activity and slip rates on the Black Rock Valley fault remain extremely preliminary and potentially speculative due to the limited data. Based on the present site investigations, the youngest rocks at the site which can be conclusively shown to be folded and faulted by the Black Rock Valley fault are basalts which are as young as about 10 Ma (Columbia Geotechnical Associates, 2004). Faulting and folding that is significantly younger than this age may be suggested by geomorphic features above Horse Thief Point and by possible faults scarps west of the damsite. However, no investigations of these features to determine their age or relationship to the Black Rock Valley fault have yet been undertaken. Evidence for deformation of post-basalt units including deposits that are probably Ringold Fm. at and near the damsite is mostly indirect. There has been no direct observation of faulted Ringold Fm. deposits in the site vicinity or inferred in direct association with the Black Rock Valley fault. However, the inferred Ringold Fm. deposits at the site consist of fluvial sands with Columbia River provenance. Correlation to apparently similar deposits described from cores at the Hanford site (Lindsey, 1996) would appear to indicate several hundred meters of relative structural uplift and subsidence of these deposits since 6-10 Ma. Ringold deposits at the damsite lie on the apparent footwall block of the surface trace of the Black Rock Valley fault, thus other faults would need to be active to produce this uplift. Prior to about 6.5 Ma, the ancestral Columbia River likely flowed through the Sunnyside Gap area south of the damsite (Lindsey, 1996). Since that time, at least a few hundred meters of relative uplift of the Sunnyside Gap area are required to explain the present elevations of the gap and correlative Ringold Deposits. Folding and uplift associated with the Black Rock Valley fault could potentially be consistent with this evidence.

**Table 2-1: Black Rock Dam - Preliminary PSHA fault source slip rate and probability of activity assessment**

| Fault | Closest Distance to Black Rock damsite (km) | Geomatrix (1996) | | | Wong and others (2002)[1] | | Haller and others. (2002) | This Study[1] | |
|---|---|---|---|---|---|---|---|---|---|
| | | Slip Rate[2] range (mm/yr) | Probability of Activity (Revised)[3] | Probability of Coupling | Slip Rate[2] mean, range (mm/yr) | Probability of Activity[3] | Slip Rate[2] (mm/yr) | Slip Rate[2] mean, range (mm/yr) | Probability of Activity |
| Black Rock Valley | 0 | Not characterized separately | | | Not characterezed separately | | Not characterized | 0.1, 0.05-0.8 | 1.0 |
| Rattlesnake Hills | 4 | 0.103 | 0.25 (0.50-0.75) | 0.15 | Included with Ahtanum Creek | | Not characterized | Included with Black Rock Valley fault | |
| Ahtanum Creek | 40 | Included as Rattlesnake Hills | | | 0.05, 0.01-0.2 | 0.7 | Not characterized | 0.15, 0.01-0.65 | 1.0 |
| Yakima Ridge (East and West) | 5 | 0.024-0.067 | 0.25 (0.50) | 0.15 | Not characterized | | Not characterized | 0.05, 0.01-0.1 | 1.0 |
| Umtanum Ridge and Gable Mtn. | 10 | 0.024-0.117 | 0.25 (0.50-0.75) | 0.15 | 0.04, 0.01-0.1 | 0.7 | Not characterized | 0.04, 0.01-0.1 | 1.0 |
| Rattlesnake-Wallula Trend (RAW) REVERSE | 5 | 0.02-0.086 | 0.25 (0.50) | 0.30 | 0.05, 0.04-0.1 | 1.0 | 0.073 | 0.08, 0.04-0.1 | 1.0 |
| Rattlesnake-Wallula Trend (RAW) STRIKE-SLIP | 5 | 0.08-0.2 | 0.25 (0.50) | 0.05 | 0.14, 0.08-0.2 | 1.0 | Not characterized | Not evaluated separately | |
| Toppenish Ridge[4] | 36 | 0.024-0.067 | 1.0 | 0.95 | 0.2, 0.01-1 | 1.0 | 0.065 | 0.2, 0.01-1 | 1.0 |

Notes:
[1] Probability of Coupling not estimated separately.
[2] Slip rate is estimated for 45° -dipping fault.
[3] Revised values for Probability of Activity are from DOE (2002).
[4] Source parameters from Wong and others (2002) are attributed to Satus Peak (Toppenish Ridge), Smyrna Bench and Saddle Gap (Saddle Mountains), or West Canal (Frenchman Hills) segments but are applied to weighted rupture length scenarios that include other sections of these structures.
[5] Closest distance of the section of Columbia Hills fault characterized by Wong and others (2002) is approximately 100 km from Black Rock Dam.

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|---|---|---|---|---|---|---|---|---|---|
| | | Slip Rate[2] range (mm/yr) | Probability of Activity (Revised)[3] | Probability of Coupling | Slip Rate[2] mean, range (mm/yr) | Probability of Activity[3] | Slip Rate[2] (mm/yr) | Slip Rate[2] mean, range (mm/yr) | Probability of Activity |
| Saddle Mountains[4] | 31 | 0.037-0.152 | 0.50 (0.50-0.75) | 0.60 | 0.15, 0.01-0.65 | 1.0 | 0.088 | 0.15, 0.01-0.65 | 1.0 |
| Frenchman Hills[4] | 50 | 0.009-0.056 | 0.25 (0.50) | 0.15 | 0.05, 0.01-0.1 | 0.7 | Not characterized | 0.05, 0.01-0.1 | 1.0 |
| Manastash Ridge | 24 | 0.014-0.085 | 0.25 (0.50) | 0.15 | Not characterized | | Not characterized | 0.05, 0.01-0.1 | 1.0 |
| Horse Heaven Hills NE | 39 | 0.044-0.050 | 0.25 (0.50) | 0.70 | Not characterized | | Not characterized | 0.05, 0.01-0.1 | 1 |
| Horse Heaven Hills NW | 41 | 0.044 | 0.25 (0.50) | 0.15 | 0.05, 0.01-0.1 | 0.7 | 0.053 | 0.05, 0.01-0.1 | 1 |
| Arlington -Shutler Buttes fault zone | 78 | Not characterized | | | 0.05, 0.01-0.1 | 0.4 | Not characterized | 0.05, 0.01-0.1 | 1.0 |
| Oak Flat - Luna Buttes fault zone | 90 | Not characterized | | | 0.05, 0.01-0.1 | 0.4 | Not characterized | 0.05, 0.01-0.1 | 1.0 |

Notes:
[1] Probability of Coupling not estimated separately.
[2] Slip rate is estimated for 45° -dipping fault.
[3] Revised values for Probability of Activity are from DOE (2002).
[4] Source parameters from Wong and others (2002) are attributed to Satus Peak (Toppenish Ridge), Smyrna Bench and Saddle Gap (Saddle Mountains), or West Canal (Frenchman Hills) segments but are applied to weighted rupture length scenarios that include other sections of these structures.
[5] Closest distance of the section of Columbia Hills fault characterized by Wong and others (2002) is approximately 100 km from Black Rock Dam.

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|---|---|---|---|---|---|---|---|---|---|
| | | Slip Rate[2] range (mm/yr) | Probability of Activity (Revised)[3] | Probability of Coupling | Slip Rate[2] mean, range (mm/yr) | Probability of Activity[3] | Slip Rate[2] (mm/yr) | Slip Rate[2] mean, range (mm/yr) | Probability of Activity |
| Columbia Hills | 67[5] | 0.017-0.144 | Not characterized | | 0.05, 0.01-0.1 | 0.3 | Not characterized | Not characterized | |
| Hog Ranch | ~30 | ? | 0.10 (0.10-0.50) | 0.50 | Not characterized | | Not characterized | Not characterized | |

Notes:
[1] Probability of Coupling not estimated separately.
[2] Slip rate is estimated for 45° -dipping fault.
[3] Revised values for Probability of Activity are from DOE (2002).
[4] Source parameters from Wong and others (2002) are attributed to Satus Peak (Toppenish Ridge), Smyrna Bench and Saddle Gap (Saddle Mountains), or West Canal (Frenchman Hills) segments but are applied to weighted rupture length scenarios that include other sections of these structures.
[5] Closest distance of the section of Columbia Hills fault characterized by Wong and others (2002) is approximately 100 km from Black Rock Dam.

**Table 2-2: Black Rock Dam - Preliminary PSHA fault source rupture length and maximum magnitude assessment**

| Fault | Closest Distance to Black Rock damsite (km) | Geomatrix (1996)[1] | | | Wong and others (2002)[1] | | This Study | |
|---|---|---|---|---|---|---|---|---|
| | | Segmented (Probability of Activity) | Rupture length[2] (km) | Maximum Magnitude[2] ($M_w$) | Rupture length (km) | Maximum Magnitude ($M_w$) | Maximum Rupture length (km) | Maximum Magnitude ($M_w$) |
| Black Rock Valley | 0 | Not characterized separately; partly included with Rattlesnake Hills | | | Not characterized separately; partly included with Ahtanum Cr. | | 38 | 6.7 |
| Rattlesnake Hills | 4 | no | 36[1] | 7.1,7.3 | Included with Ahtanum Creek | | Included with Black Rock Valley fault | |
| Ahtanum Creek | 40 | Included as Rattlesnake Hills | | | 28-36 | 6.8-6.9 | 33 | 6.6 |
| Yakima Ridge (East and West) | 5 | no | 39-46 | 7.1-7.4 | Not characterized | | 48 (East)<br>30 (West) | 6.9 (East)<br>6.6 (West) |
| Umtanum Ridge and Gable Mtn. | 10 | yes (0.6)<br>no (0.4) | 11-43<br>71 | 6.5-7.1<br>7.3 | 35,110[1] | 6.9,7.4[1] | 117 | 7.5 |
| Rattlesnake-Wallula Trend (RAW) REVERSE | 5 | yes(0.7)<br>no (0.3) | 20,45,50<br>58 | 6.8,7.2<br>7.2,7.3 | 20,50 | 6.6,7.1 | 125 | 7.5 |
| Rattlesnake-Wallula Trend (RAW) STRIKE-SLIP | 5 | no | 58 | 7.1 | 45,115 | 7.0, 7.5 | Not evaluated separately | |
| Toppenish Ridge[3] | 36 | no | 25 | 6.9 | 30,50[1] | 6.8,7.0[1] | 56 | 7.0 |

Notes:

[1] Multiple values in these columns include alternate characterizations given weights >0.1 in the probabilistic characterizations of Geomatrix (1996) and Wong and others (2002). Scenarios weighted 0.1 each are not included.

[2] All fault lengths and Maximum Magnitudes are based on 45° dip scenarios except for Rattlesnake-Wallula Trend (RAW) STRIKESLIP, Arlington - Shutler Buttes and Oak Flat -Luna Buttes fault zones which assume a dip of 90°, and Hog Ranch which includes dips of 60°,75° and 90°. Maximum magnitude is also constrained by fault width which is determined by fault dip and an assumed seismogenic crustal thickness of 21 km.

[3] Source parameters from Wong and others (2002) are attributed to Satus Peak (Toppenish Ridge), Smyrna Bench and Saddle Gap (Saddle Mountains), or West Canal (Frenchman Hills) segments but are applied to weighted rupture length scenarios that include other sections of these structures.

[4] Closest distance of the section of Columbia Hills fault characterized by Wong and others (2002) is approximately 100 km from Black Rock Dam.

**Table 2-2: Black Rock Dam - Preliminary PSHA fault source rupture length and maximum magnitude assessment**

| Fault | Closest Distance to Black Rock damsite (km) | Geomatrix (1996)[1] | | | Wong and others (2002)[1] | | This Study | |
|---|---|---|---|---|---|---|---|---|
| | | Segmented (Probability of Activity) | Rupture length[2] (km) | Maximum Magnitude[2] ($M_w$) | Rupture length (km) | Maximum Magnitude ($M_w$) | Maximum Rupture length (km) | Maximum Magnitude ($M_w$) |
| Saddle Mountains[3] | 31 | yes (0.6)<br>no (0.4) | 19-26<br>58[1] | 6.8-6.9<br>7.3[1] | 16,44,116 | 6.5,7.0,7.5 | 89 | 7.3 |
| Frenchman Hills[3] | 50 | no | 39 | 7.1,7.3 | 30,90 | 6.8,7.3 | 69 | 7.1 |
| Manastash Ridge | 24 | 40[1] | 7.1[1] | no | Not characterized | | 67 | 7.1 |
| Horse Heaven Hills NE | 39 | yes (0.8)<br>no (0.2) | 100,70<br>85[1] | 7.3,7.5<br>7.3,7.4[1] | Not characterized | | 78 | 7.2 |
| Horse Heaven Hills NW | 41 | no | 35[1] | 7.0[1] | 14,28,48 | 6.4,6.8,7.0 | 86 | 7.3 |
| Arlington -Shutler Buttes fault zone | 78 | Not characterized | | | 25,45,70 | 6.7,7.0,7.2 | 63 | 7.1 |
| Oak Flat - Luna Buttes fault zone | 90 | Not characterized | | | 17,40[1] | 6.5,6.9 | 30 | 6.6 |
| Columbia Hills | 67[4] | | Not characterized | | 9,17,72[1] | 6.2,6.5,7.2[1] | Not characterized | |
| Hog Ranch | ~30 | no | 75 | 7.0-7.6 | Not characterized | | Not characterized | |

Notes:

[1] Multiple values in these columns include alternate characterizations given weights >0.1 in the probabilistic characterizations of Geomatrix (1996) and Wong and others (2002). Scenarios weighted 0.1 each are not included.

[2] All fault lengths and Maximum Magnitudes are based on 45° dip scenarios except for Rattlesnake-Wallula Trend (RAW) STRIKESLIP, Arlington - Shutler Buttes and Oak Flat -Luna Buttes fault zones which assume a dip of 90°, and Hog Ranch which includes dips of 60°,75° and 90°. Maximum magnitude is also constrained by fault width which is determined by fault dip and an assumed seismogenic crustal thickness of 21 km.

[3] Source parameters from Wong and others (2002) are attributed to Satus Peak (Toppenish Ridge), Smyrna Bench and Saddle Gap (Saddle Mountains), or West Canal (Frenchman Hills) segments but are applied to weighted rupture length scenarios that include other sections of these structures.

[4] Closest distance of the section of Columbia Hills fault characterized by Wong and others (2002) is approximately 100 km from Black Rock Dam.

**Potential Surface Faulting at the Site.** Preliminary geologic investigations at the site indicate that at least one significant thrust fault is present in the lower right abutment. If this fault is considered a part of a larger, more extensive fault that might be potentially active along the margin of Black Rock Valley or part of the Rattlesnake Hills structure, there is a potential for surface faulting within the dam foundation as a result of a large earthquake on these structures. Potential displacements could range from a few cm to several meters depending on the earthquake magnitude and details of the structural setting. Existing data are not sufficient to further define this potential at this time. The probability of surface faulting at the site is not separately analyzed at this time because there is insufficient information presently available on the age, slip rate, geometry, and extent of faults in the dam foundation.

# 3.0 PRELIMINARY HAZARD CURVES FOR PHA

A probabilistic seismic hazard analysis was performed, using an areal source zone presented in Wong and others (2002), the fault sources shown in the attached map (Plate 1), and Cascadia subduction zone sources as depicted on Figure 3-1.

## 3.1 Areal Source Zone

The areal zone, termed the Fold and Thrust Belt, covers an area of about 75,000 $km^2$. Earthquakes occurring through 2000 were compiled, declustered, and a recurrence curve fit to the data by the maximum likelihood method. Earthquakes with magnitudes between 5.0 and 6.5 were modeled in the probabilistic analysis by distributing them uniformly throughout the region. Depths were modeled as a triangular distribution with a maximum depth of 20 km, a peak at 5 km, and a near-surface magnitude-dependent depth restriction.

## 3.2 Fault Sources

Fault sources modeled are those shown in the attached map (Plate 1). Slip rates were modeled as asymmetric triangular distributions, according to the "range" and "mean" values shown in the "this study, slip rate" column of Table 2-1. Faults were assumed to have dips of $45^{o}$, and extend to 20 km in depth. Two recurrence models were used: the characteristic model of Youngs and Coppersmith (1985), and the maximum moment model (e.g., Wesnousky, 1986). The characteristic model assumes that earthquakes have a bimodal distribution, with smaller earthquakes occurring as an exponential distribution, but a range of largest, "characteristic" magnitudes occurring at a rate more frequent than the exponential portion of the recurrence relation would predict. The maximum moment model assumes that all slip on a fault is released in a narrow range of largest possible earthquakes, with the magnitude estimated from fault length-magnitude regressions (Wells and Coppersmith, 1994). The magnitudes used as "maximum" or "characteristic" in these models are shown in Table 2-2 under "this study". For the final hazard curves the results from the two models were weighted equally.

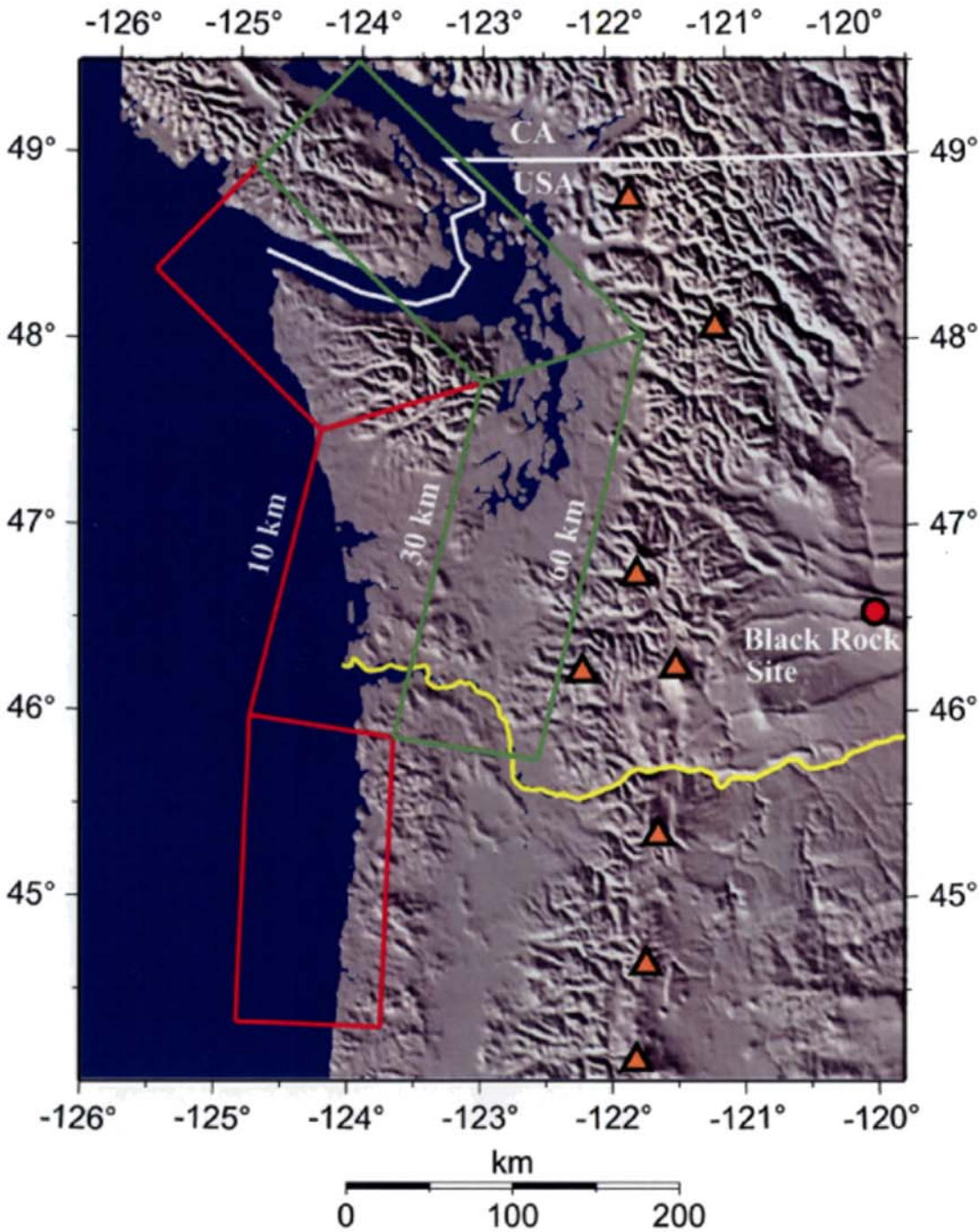


**Figure 3-1: Cascadia subduction zone as modeled for this study. Red lines show plate interface zone; green lines the deep zone. Volcanoes are shown as orange triangles, the Black Rock Site as a red circle.**

### 3.3 Cascadia Subduction Zone

The Cascadia subduction zone, site of the collision between the northeast moving Juan de Fuca plate relative to the North American plate, lies off the Washington coast, about 200 km east of the Black Rock Site. The Juan de Fuca plate descends into the upper mantle about as far as the Cascade range (in map view).

For this preliminary study we model an upper plate interface zone, the location of contact between the two plates and potential site of large thrust earthquakes, and a deep zone, site of earthquakes associated with deformation in the downgoing slab as it descends into the upper mantle. The plate interface zone was the site of a $M_w$ 9 event in January, 1700 (Satake and others, 1996), and the deeper slab has produced damaging events in the 6-7 range (e.g., Seattle, 1965; Nisqually, 1991). The model, shown in Figure 3-1, is an approximation based on Flück and others (1997). The area outlined in red represents the plate interface zone, which dips $13^{o}$ to the east between depths of 10 and 30 km. The blue zone represents the deep zone, dipping $19^{o}$ between depths of 30 and 60 km.

Two equally weighted recurrence models were used for the plate interface zone, the characteristic model (Youngs and Coppersmith, 1985) and the maximum moment model (Wesnousky, 1986). The characteristic model assumed earthquakes between 6.5 and three equally weighted upper bound magnitudes, 8.0, 8.5, and 9.0. The maximum moment model assumed a trapezoidal distribution of earthquakes between 6.5 and 9.5. Both models used an asymmetrical triangular slip rate distribution with a lower bound of 7 mm/yr, and upper bound of 25 mm/yr, and a peak at 13 mm/yr. This recurrence scheme is described in LaForge (2000).

An exponential distribution between magnitudes 6.0 and 7.5 was assumed for the deep zone, with recurrence parameters taken from the Adams and Halchuk (2002) PUG zone, scaled for the different fault area used here.

### 3.4 Attenuation

Two attenuation functions were used; Sadigh and others (1997), and Abrahamson and Silva (1997). These are current relations based on largely California earthquakes. The Abrahamson and Silva (1997) relation contains correction factors for increased amplitudes near thrust faults, which

were applied to the Black Rock Valley fault. Soft rock or stiff soil site conditions were assumed for both. The two relations were weighted equally in the analysis. For the Cascadia sources, the relations of Youngs and others (1997) were used.

### 3.5 Results

Figure 3-2 shows mean PHA hazard curves for all sources, and the total. It is clear that due to its proximity to the site the Black Rock Valley fault is the dominant contributor to the PHA hazard at all but very short return periods. The Cascadia deep zone is significant at PHA of 0.2 g and less. This is illustrated in Figure 3-3, which shows the relative contributions to the total hazard as a function of ground motion amplitude. It is likely that the Cascadia source would be more important at longer period response periods, due to the large magnitude events generated there. At ground motions of about 0.3 g and above (which corresponds to return periods greater than about 1000 years, the Black Rock Valley fault comprises about 70% of the hazard. The next most significant source is the Yakima Ridge East fault. At a return period of 10,000 years, the total PHA amplitude level is about 0.95 g. The mean PHA curve, along with 16th and 84th percentile curves, is shown in Figure 3-4. These fractiles represent epistemic uncertainties, due to the variability in slip rate and choice of attenuation function, in the mean hazard from the local fault sources. The Cascadia sources and random seismicity source are not included in this plot, but they are not significant at PHA's of about 0.3 g and greater.

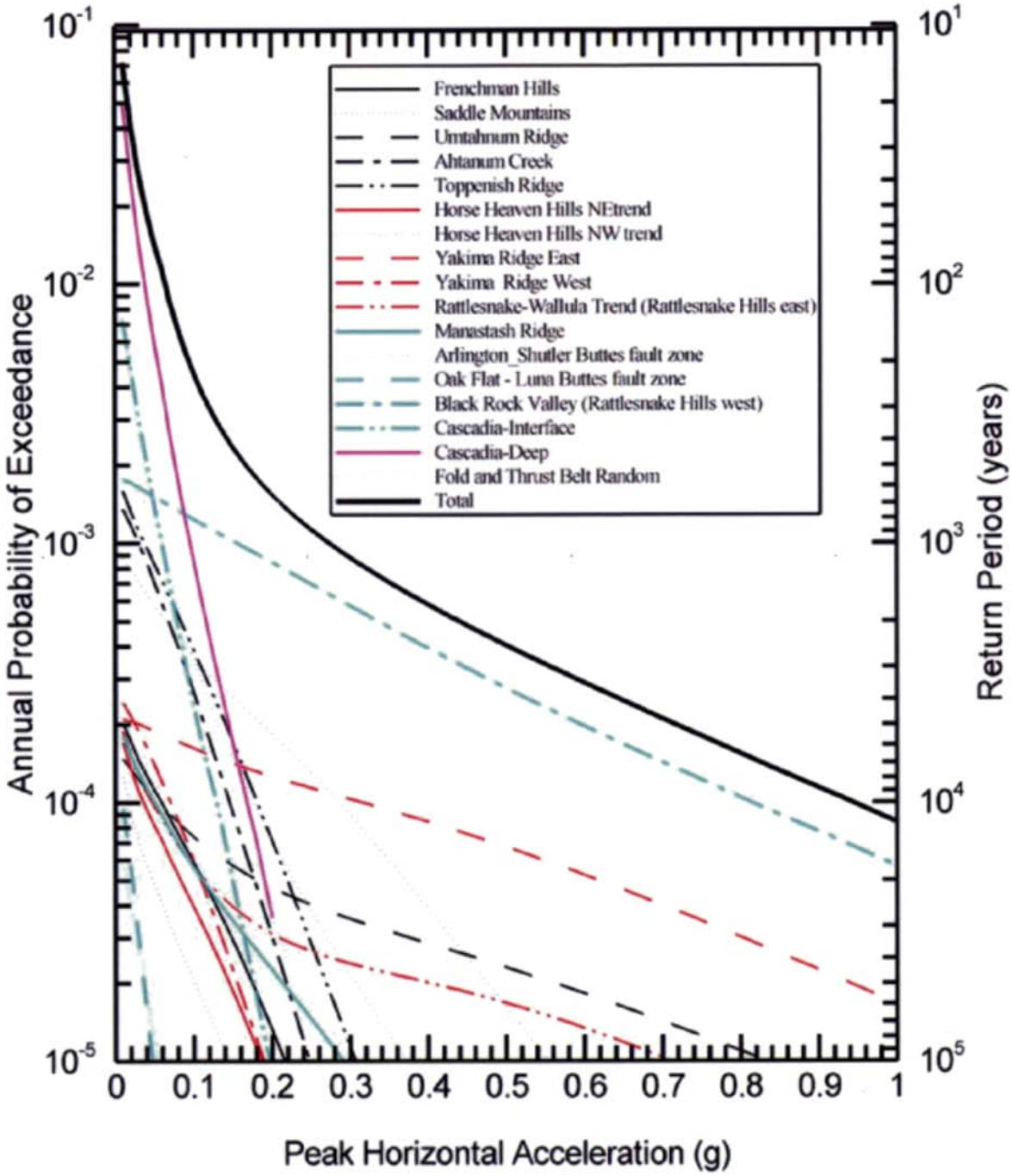


**Figure 3-2: Preliminary mean hazard curves for PHA, Black Rock Site.**

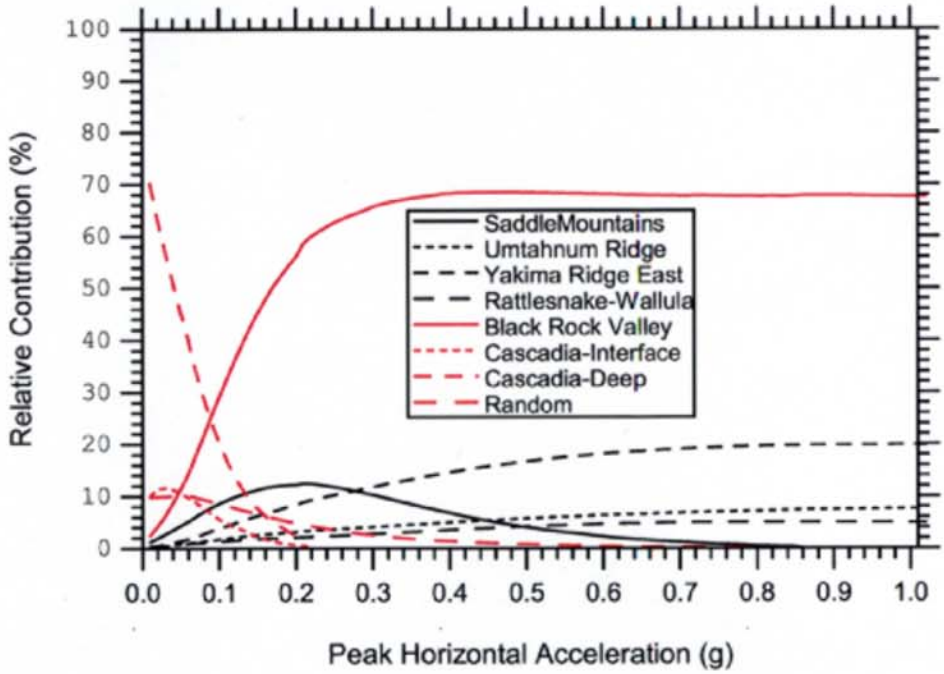


**Figure 3-3: Relative contributions by source to the PHA hazard.**

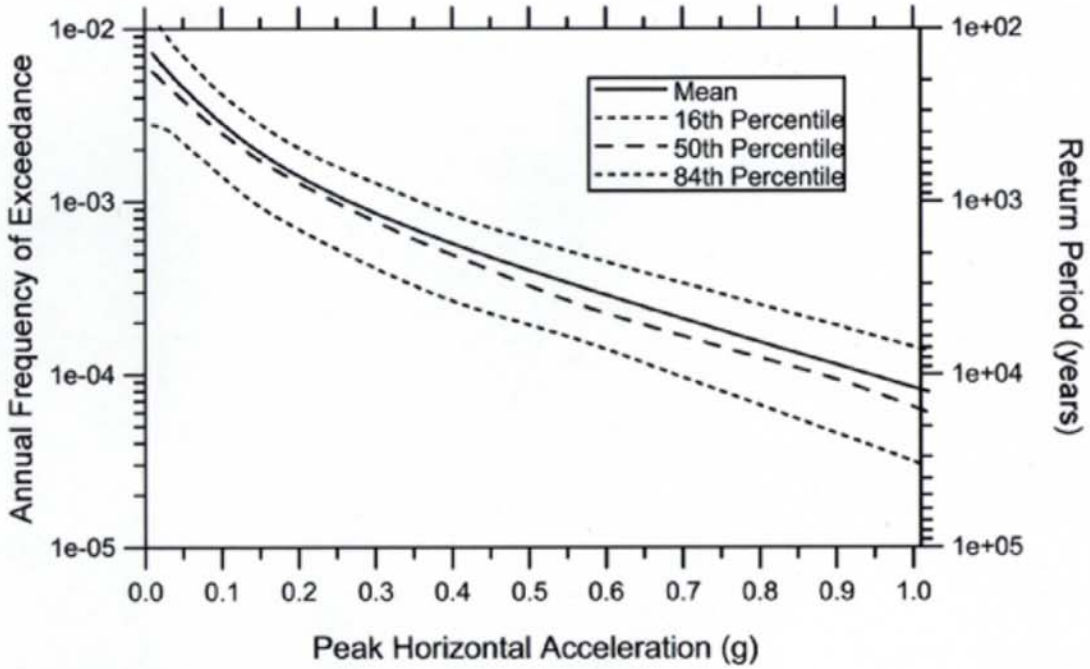


**Figure 3-4: Mean PHA hazard curve, with 16th, 50th, and 84th fractiles of mean hazard. Cascadia and local random sources not included.**

## 4.0 CONCLUSIONS AND ISSUES FOR FURTHER STUDY

Preliminary characterization of potential earthquake sources near the proposed Black Rock damsite shows that potential ground motions at the site are greatly influenced by the characterization of nearby potential seismic sources. Specifically, at return periods of about 10,000 years, total PHA is about 0.95 g. For motions greater than about 0.3 g, about 70% of the total hazard is derived from the current characterization of the Black Rock Valley fault. Further evaluation of these sources, or identification of additional sources, may significantly alter the preliminary results developed in this study.

Regional mapping indicates that contemporary deformation is compressional. Structures that are potentially consistent with the contemporary stress field are apparently present on both abutments. Initial mapping near the damsite area indicates that a significant thrust fault is present in the right abutment. For the present characterization, this fault is included as part of the Black Rock Valley fault and considered as a potential earthquake source. If large earthquakes occur on this fault they could potentially be accompanied by up to several meters of surface faulting. The age and characteristics of this fault need further study for issues related to seismic source characterization at the site.

A hypothesis developed from currently in-progress mapping at the damsite indicates that the large fold on Horse Thief Mountain, the right abutment of the proposed dam, is related to the thrust fault that daylights in the lower portion of the right abutment and dips to the south beneath Horse Thief Mountain. Several secondary faults, scarps, and lineaments that appear to be related to secondary extension along the fold atop Horse Thief Mountain may be related to Quaternary deformation of this fault/fold. These features are also potential sites of coseismic secondary faulting, fissuring, and landslides.

Cascadia seismic sources do not appear to be significant for the PHA hazard at the site for PHA of 0.3 or greater. However, these sources may be important at longer periods; periods which may be significant in more detailed analyses of engineered structures at the Black Rock site.

Although the present study has focused primarily on probabilistic PHA, more detailed engineering analyses will require more complete descriptions of ground motion parameters

including time histories. Characterization of these motions will be greatly influenced by details of the structural details of local faults including directivity or hanging wall amplification effects. In addition, studies of site response will be needed for more detailed ground motion evaluations.

Although not addressed in this memorandum, baseline studies for potential reservoir-induced seismicity will be needed. The setting of site in a region of tectonic compression, very large and deep reservoir, and operations that may involve large fluctuations in depth and volume, all indicate that the probability of induced seismicity may be significant.

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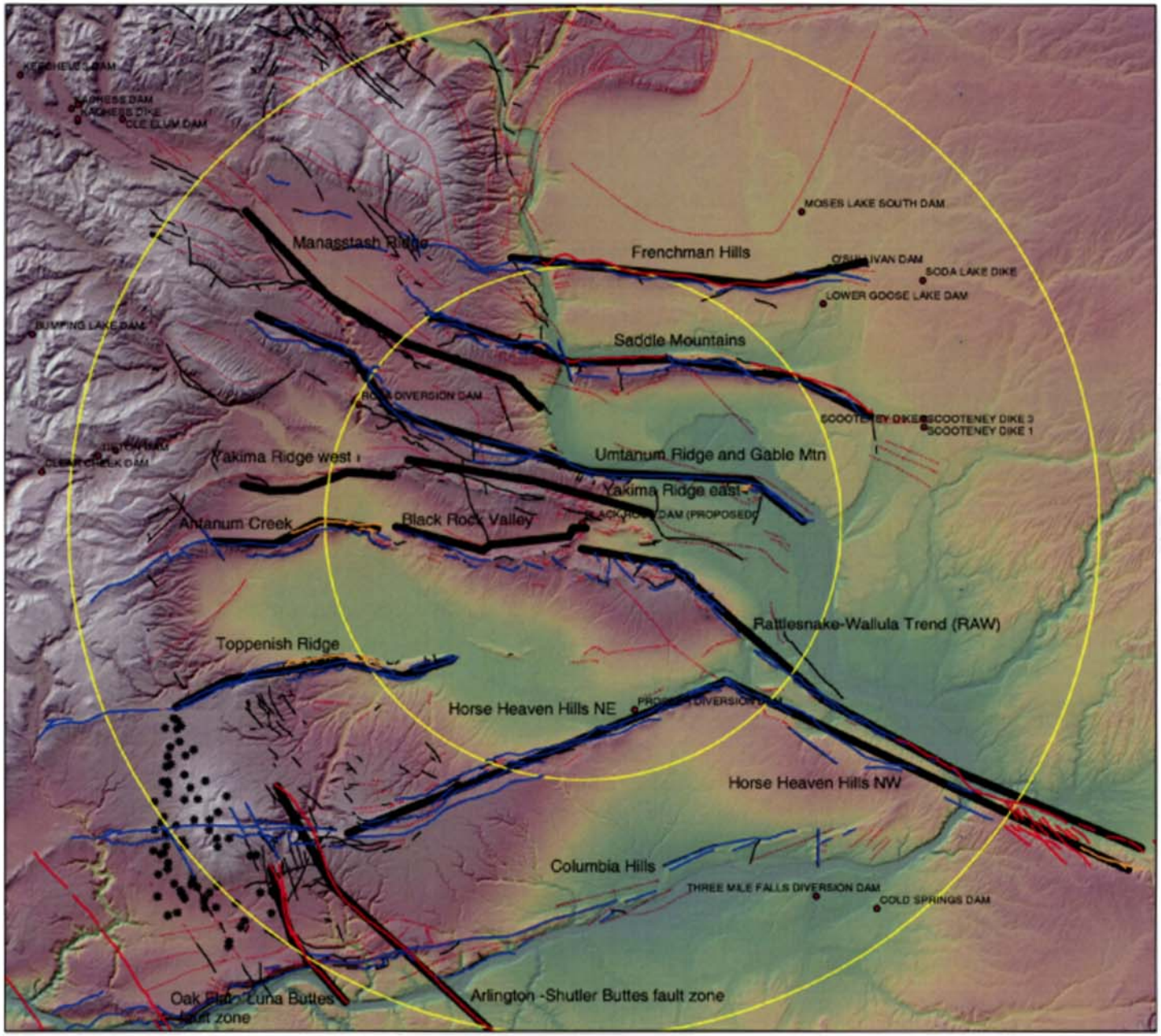


Yellow circles are 50 km (inner) and 100 km (outer) radius from site.

Kilometers
03.57 14 21 28

**Legend**

- PSHA Faults
- 100k map sheet vents
- 100k map sheet faults
- 100k map sheet folds
- USBR DAMS nr BLACKROCK
- USGS faults - Holocene and Late Quaternary
- USGS faults - Mid Quaternary and Quaternary
- USGS faults - Tertiary or Questionable

Plate 1