PROBABILISTIC FAULT DISPLACEMENT HAZARDS

OF THE WASATCH FAULT, UTAH

by

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ABSTRACT

This study develops a quantitative probabilistic assessment of the fault displacement hazard along the Wasatch fault, Utah. The displacement hazards associated with the Wasatch fault are important to consider based on the fault's potential seismic activity, the proximity to the Wasatch Front population, and the number of critical "lifeline" utilities (i.e., roads, pipelines, power lines, railroads) that cross the fault.

A probabilistic displacement hazard analysis (PDHA) has not been done on the Wasatch Front until now; only probabilistic seismic hazard analyses (PSHA) associated with ground shaking have been done.

The results of this study are the generation of fault displacement hazard curves for the Brigham City, Weber, Salt Lake City, Provo, and Nephi segments of the Wasatch fault. These hazard curves allow the determination of the annual frequency of exceeding a specified fault displacement at any location along these segments of the Wasatch fault.

The input data and parameters used in this study are based on existing paleoseismic data from the Wasatch fault, an elliptical fault displacement distribution along fault length, fault displacement-magnitude scaling relationships, and slip rate and recurrence intervals from paleoseismic studies. Additionally, this study took into

consideration both single segment fault rupture and multisegment fault rupture scenarios. Although this study considered these select parameters and scenarios when developing the hazard curves, the model developed in this study allows for the incorporation of as few or as many scenarios as a user might need.

Depending on which specific scenario is considered and the specific location along the Wasatch fault, the results from this study yield annual frequency of exceeding 1 meter of displacement between the range of 10^{-4}/year to 10^{-7}/year. For 2 meters of displacement the annual frequency of exceedance ranged between 10^{-5} /year to 10^{-9}/year. For 3 meters, the values ranged between 10^{-6} /year to 10^{-11} /year. Since this is the first PDHA to be done for the Wasatch fault, the results of this study could not be compared directly to other studies. However, an indirect comparison to other types of hazard studies (including PSHA) done on the Wasatch fault yields similar values.

Given the results of this study, the distribution of the Wasatch Front population, and the proximity of the lifeline utilities to the fault, the Wasatch fault displacement hazards could have a much more profound effect than considered heretofore. Disruption of the Wasatch Front's critical lifeline utilities from fault displacement may very well have as large of an impact on a the Wasatch Front population as ground shaking.

The results of the PDHA, in combination with the PSHA, an exposure analysis and review of the economic impact, can be used to evaluate the overall earthquake risk on the Wasatch fault.

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My accomplishments would not have been possible without my parents' lifetime emphasis and example regarding education. I will strive to be equally as influential in instilling the same positive values in my future family. I thank them and my husband, Robert, for their patience, understanding, and support during my tenure as a graduate student.

INTRODUCTION

This study develops a quantitative probabilistic assessment of the fault displacement hazard along the Wasatch fault, Utah and complements previous probabilistic assessments of ground motion hazards on the Wasatch fault. In combination, these assessments will make possible a comprehensive review of earthquake related hazards.

Wasatch Fault Displacement Hazards

The displacement hazards associated with the Wasatch fault are important to consider due to the proximity of the fault to the populated Wasatch Front and its rupture effects on the "lifeline" utilities (i.e., roads, pipelines, power lines, railroads) that cross it.

The Wasatch fault is a 370-kilometer long, normal fault zone (Hecker, 1993) (Figure 1). More than 80 percent of Utah's 2.1 million people live within 50 miles of the Wasatch Fault. Figure 2 shows the large number of "lifeline" utilities that cross the fault and their proximity to the Wasatch Front population base (personal communication, V. Solomon, 1999).

The maximum credible earthquake that has been estimated for the Wasatch fault is a moment magnitude, M_w, 7.3 on the basis of Wong and others (1995). Using

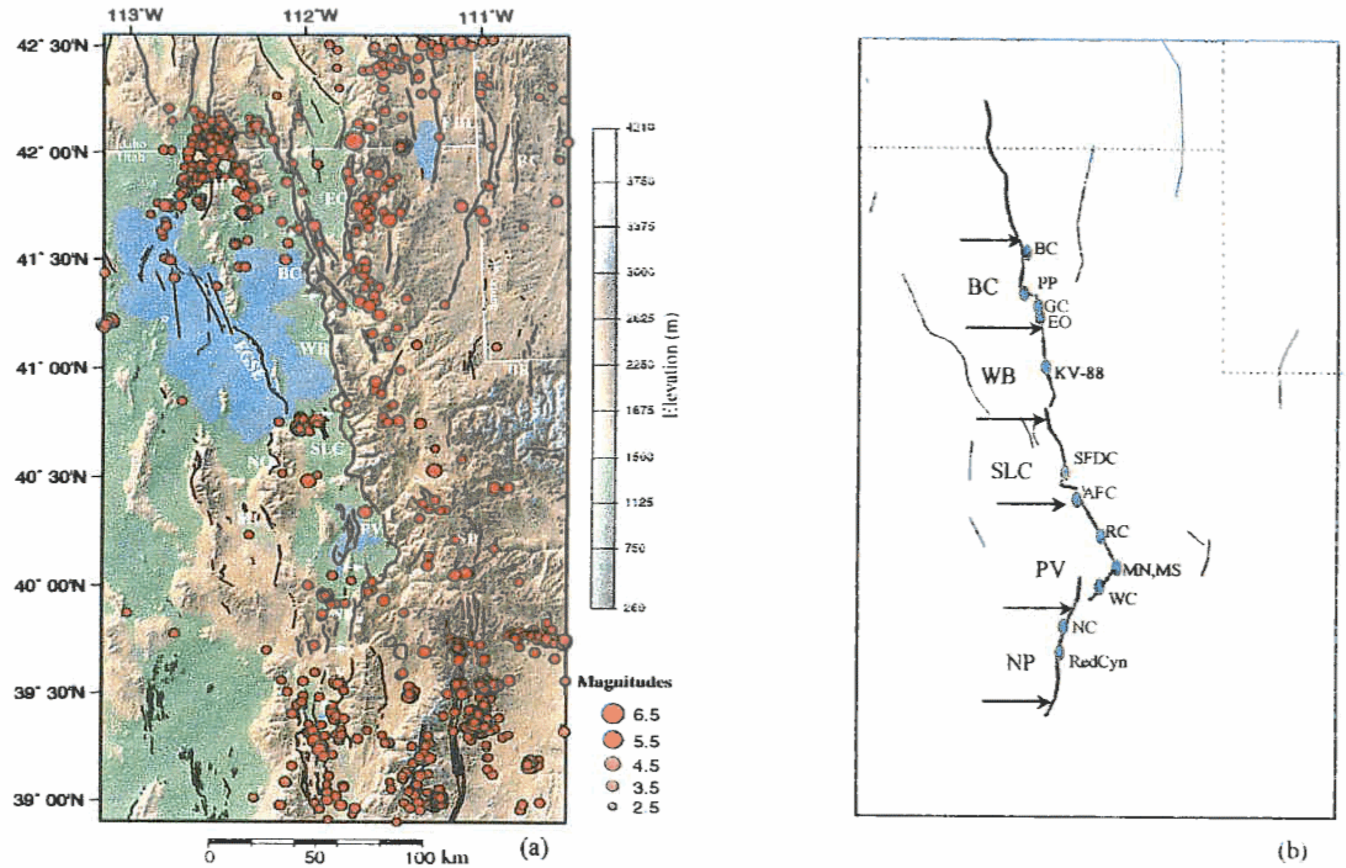
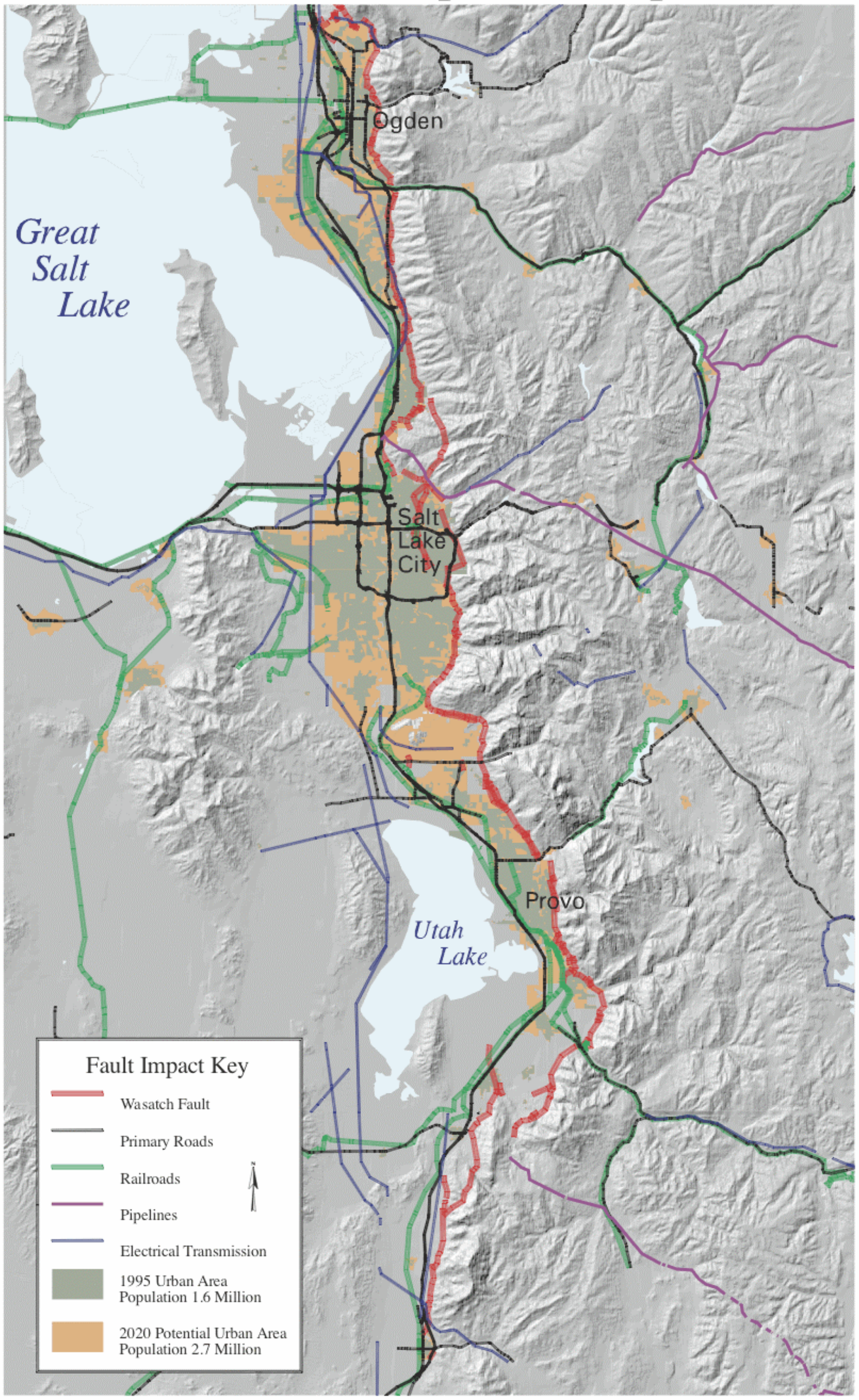


Figure 1. (a) Wastach Front topography and instrumental seismicity (July 1962 – Dec. 1996) and faults. (b) Wasatach fault segments (heavy line) used for this study include: Brigham City (BC), Weber (WB), Salt Lake City (SLC), Provo (PV), Nephi (NP). Trenches or exposure sites: Brigham City (BC), Pole Patch (PP), Garner Canyon (GC), East Ogden (EO), Kaysville 1998 (KV88), South Fork Dry Creek (SFDC), American Fork Canyon (AFC), Rock Creek (RC), Mapleton North and South (MN, MS), Water Canyon (WC), North Creek (NC), Red Canyon (RC). Map information and format from Chang (personal communication).

Wasatch Front Lifeline and Wasatch Fault Exposure Map



Braun and Smith (2001, preparation)

Figure 2. Wasatch Front "lifeline" utility and population base map. Map generated from existing utility datebase and may not be complete (V. Solomon, personal communication, 1999).

Wells and Coppersmith's (1994) scaling relationship (discussed in detail later) between M_w and maximum displacement yields a maximum displacement of 3.6 meters for the maximum expected magnitude. A conservative range of possible (not maximum) magnitude earthquakes on the Wasatch fault is M_w 6.8 to a M_w 7.0. Again, using Wells and Coppersmith's (1994) scaling relationship, these magnitude values correspond to 1.4 meters and 2.1 meters, respectively.

In regards to the integrity of the lifeline utilities, this range of fault displacements (1.4 – 3.6 meters) would most certainly jeopardize the integrity of the facilities, if not sever them completely. This could have a potential devastating impact of the Wasatch Front population.

Seismicity of the Wasatch Front

The Wasatch fault is part of the Intermountain Seismic Belt (ISB), which is a well-studied zone of seismicity that extends from southern Nevada and northern Arizona, through the major fault zones of Utah and eastern Idaho, to northwestern Montana. The ISB is estimated to be at least 1,500 kilometers in length and 100 to 200 kilometers wide (Smith, 1971; Smith and Arabasz, 1991). From studies of other normal faults in the ISB, Smith and Arabasz (1991) modeled the Wasatch fault as a 55-degree, west dipping, planar, normal fault that extends approximately 15 kilometers deep to the brittle ductile transition zone.

Smith (1971) evaluated the potential for the occurrence of an earthquake on the Wasatch fault by considering seismic gaps, or the lack of seismic activity in a known seismically active zone. Areas with unusually low seismicity and evidence of previous large earthquakes may be indicative of an area with a relatively higher probability for future large earthquakes (Smith, 1971; Smith and Sbar, 1974). With respect to the Wasatch fault and Utah's population base, Smith (1971) concluded that, based on a gap of seismic activity of the central Wasatch Front, there could be a raised potential for a major earthquake in this area. The central Wasatch Front is shown to include Utah's most heavily populated area between Ogden and Provo (Smith, 1971).

Furthermore, Chang and Smith (1998) compared rates of historic and paleoearthquakes and concluded that the estimated annual frequency of large paleoearthquakes is about a factor of four times higher than that extrapolated by historic seismicity. Additionally, Chang and Smith (1998) derived the frequency of earthquakes on the Wasatch fault from geodetic and GPS data and found that these rates do not match those of paleoearthquakes and may form the upper bound of earthquake occurrence.

Given this background and the possible future seismic activity on the Wasatch fault and the critical location of the fault in relation to Utah's population base and lifeline utilities, the potential consequence of fault displacement hazards along the Wasatch fault is justification for this study.

Seismic Hazard Studies of the Wasatch Fault

A probabilistic displacement hazard analysis (PDHA) of the Wasatch fault has not been conducted; this study is the first PDHA on the Wasatch fault. Several probabilistic seismic hazard analyses (PSHA) of the Wasatch fault have been conducted (Youngs and others, 1987; Wong and others, 1995), but have been limited to ground shaking hazards. PSHA ground motion studies have been used for the past 20 to 30 years (Kramer, 1996), and the methodologies are quite well developed. Probabilistic seismic hazard analyses that consider the fault displacement hazard (PDHA), on the other hand, have not often been considered in the past, and the development of this methodology is of current interest.

Specific to the Wasatch fault zone, several ground shaking seismic hazard studies have been completed. Youngs and others (1987) made the first comprehensive, quantitative assessment of the ground-shaking hazard on the Wasatch Fault. Youngs and other's (1987) method was probabilistic in nature and the results of the study were expressed as the probability of exceeding a specified level of ground motion. The study produced a set of maps showing the probability of exceeding specified peak ground accelerations of 10 percent in 10 years, 50 years, 250 years at specified locations.

Wong and others (1995) conducted a seismic hazard analysis of the Magna Tailings impoundment near Magna, Utah. Wong and other's (1995) study included both a deterministic ground motion assessment and a probabilistic seismic hazard analysis. Wong and others (1995) considered several seismic sources around the Salt Lake Valley, including the Wasatch fault. In their hazard analysis, Wong and others (1995) determined the source, magnitude, and peak ground acceleration of the maximum earthquake at the site and the operating basic earthquake at the site, and they concluded that there is a low potential for surface rupture at the impoundment site.

With respect to evaluating different types of earthquake hazards (e.g., ground motion and fault displacement), Ward's (1994) study presented the idea of a multidisciplinary approach to evaluating seismic hazards in Southern California. Ward's study described the importance of developing a "master model", which combines geodetic, geologic, and seismic information to evaluate earthquake hazards. Subsequent to Ward's (1994) work, the Working Group on California Earthquake completed a multidisciplinary report that addressed the probable seismic hazards in Southern California for the period of time between 1994 and 2024. Ward's (1994) work and the Working Group's (1995) is the basis for much of the probabilistic earthquake hazard studies in the United States today.

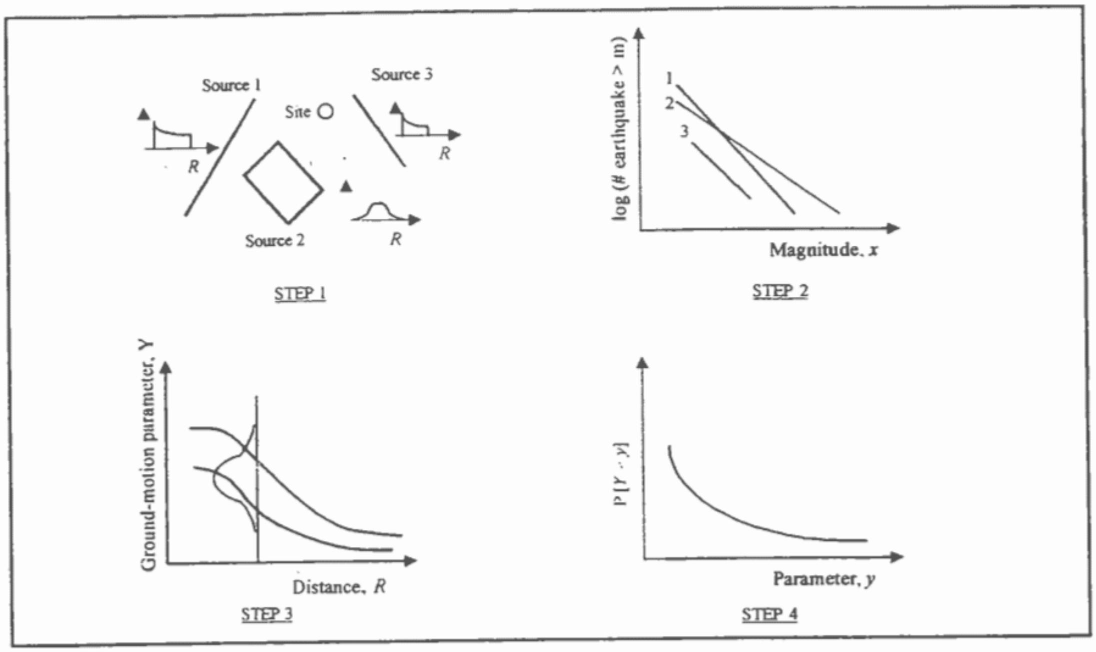
General Approach to Probabilistic Displacement Hazard Analyses

A displacement hazard analysis model specifically developed for fault displacement hazards has been limited to the 1997 development of a preliminary probabilistic model for the proposed nuclear repository at Yucca Mountain, Nevada. This model is summarized by Coppersmith and Youngs (1997) and detailed in the Yucca Mountain Reports (CRWMS M&O, 1998). In essence, this methodology used for the Yucca Mountain was adapted from the traditional PSHA as is discussed in greater detail later in this section. Based on the information available, the traditional PSHA methods and the recent Yucca Mountain Report (CRWMS M&O, 1998) provided the framework for the study presented here.

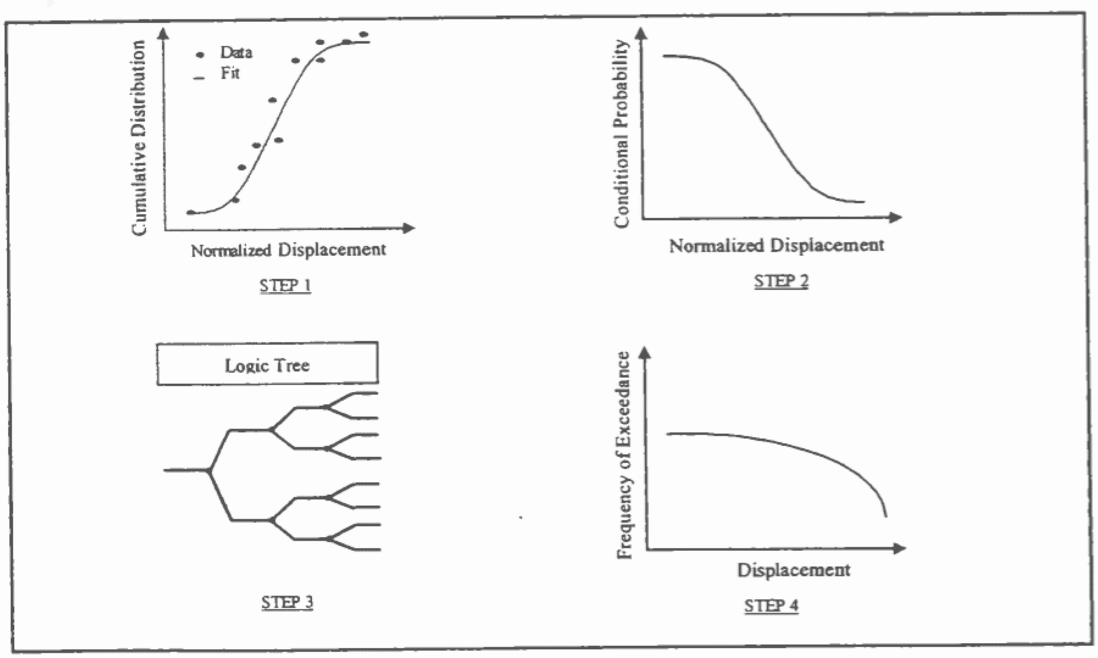
The traditional approach to PSHA has been summarized by Kramer (1996) and includes four general steps (Figure 3a). The first step includes the identification, characterization, and probability distribution of the potential rupture location. Next is the development of a recurrence relationship. Third is the determination of ground motion potential at specified sites, and the last step is the incorporation of the uncertainties associated with the calculations.

The general steps used for the PDHA, as adapted from Kramer's (1996) summary of the PSHA methodology (Figure 3(a)), are shown in Figure 3(b). Following these general steps, the approach for assessing the annual frequency of exceeding a specified displacement, d, first involved developing an empirical distribution for the available normalized fault displacement data. The displacement data were normalized with two normalizing parameters: the average displacement, D_{avg}, and the maximum displacement, D_{max}. The normalized data were fit with empirical distribution models to develop a cumulative distribution function for the displacement data. The resulting function was used to compute the conditional probability of exceeding a specified displacement, given a displacement event, D_E, which when multiplied by the frequency of displacement events, λ_{DE}, lead to the determination of the annual frequency of displacement exceedance.

Finally, this model allows the uncertainties inherent in estimating seismic events to be methodically evaluated by means of a logic tree. A logic tree is a tool used for calculating the cascade of uncertainties associated with multiple scenario models. The uncertainties were identified, quantified, and systematically evaluated in



(a)



(b)

Figure 3. Cartoon illustration of (a) the four steps of a PSHA (Kramer, 1996) and (b) the four steps of PDHA used in this study.

order to provide a comprehensive view of the fault displacement hazards along the Wasatch fault. With this, the logic tree took into account the uncertainties associated with estimating the probability of fault rupture, contagion effects, frequency estimates, and the normalizing parameters.

This probabilistic displacement hazard analysis (PDHA) develops hazard curves that quantify the probability of exceeding specified fault displacements at various locations along the Wasatch fault. The results of this study will enable an analytical evaluation of the potential degree of physical property risk associated with fault displacement. The information from this study combined with the information from a PSHA, exposure analysis, and the economic impact, can be used to evaluate the overall risk due to fault displacement hazards on the Wasatch fault.

EARTHQUAKE HAZARD ASSESSMENTS AND MODEL PARAMETERS

Approaches to Earthquake Hazard Analyses

In general, there are two approaches to assessing earthquake hazards: deterministic and probabilistic. Hanks and Cornell (1999) describe that for earthquake hazards, the fundamental difference between deterministic and probabilistic analyses is that a deterministic analysis is time independent, whereas a probabilistic analysis is time dependent. In other words, a deterministic analysis allows for an infinite time window and a probabilistic analysis is dependent upon time or the frequency of the occurrence of events. In essence, the deterministic analysis considers the maximum or worst case, i.e., it is viable for all time. Both types of analysis allow for the incorporation of uncertainties; however, deterministic studies typically have not incorporated them. The systematic inclusion of uncertainties has more commonly been associated with probabilistic analyses.

The probabilistic approach is well suited to this study in that it allows for the consideration of a range of displacements at various locations where there are time-dependent rates of earthquake occurrences. This is in comparison to a deterministic approach, which would consider only the maximum displacement at a specific location or limited locations.

Approaches to Fault Displacement Hazard Analyses

More specific to fault displacement hazards, Youngs and others (in preparation) describe that there are two basic approaches to fault displacement hazards: earthquake and displacement. Young and others (in preparation) describe that the earthquake approach is related explicitly to the occurrence of an earthquake. In contrast, the displacement approach uses characteristics of fault displacement site observations, and is not explicitly related to the occurrence of an earthquake. The methodology for both the earthquake and displacement approaches has been adapted from traditional PSHA processes. Since the fault displacement data are available for this study, the fault displacement approach was utilized.

Principal and Secondary Faults

This study considers only principal faults and neglects secondary faults such as the West Valley Fault and other faults beneath the valley fill (Figure 1). In describing the methods for PDHA, Youngs and Coppersmith (in preparation) and the Yucca Mountain Reports (CRWMS M&O, 1998) differentiate between principal and distributed faults. Principal faults are considered to be the faults located at the source of the seismicity. Distributed faults are considered to be secondary faults, both in time and space, i.e., secondary faults may not occur coincident with primary faults and are not located at the seismic source, but can be a distance from and can be triggered by activity on the principal fault. The subject segments of the Wasatch fault are considered the principal fault source and the outlying faults shown in Figure 1 are considered to be distributed faults. Additionally, the model developed for this study is limited to normal faulting earthquakes, characteristic of the Wasatch fault.

Earthquake Magnitude Scales

Earthquake magnitude values used in this study are based on the worldwide moment magnitude scale, M_w. It should be noted that much of the data that is used in this study is based on the commonly used surface wave magnitude, M_s and Richter local magnitude, M_L, scales. Mason (1996) notes that others (Kanamori, 1977; Hanks and Kanamori, 1979; Wells and Coppersmith, 1994) describe a close one to one correlation between M_s and M_w and Wells and Coppersmith (1994) derived a one to one relationship between M_L and M_w, both for the magnitude range $6.0<M<8.0$. With this, magnitude data values given in the M_s *or* M_L scale between the range $6.0<M<8.0$ were given an equal M_w value (Appendix B). For values less than M 6.0, there are empirical scaling relationships between these different magnitude scales; however, they are not needed for this study.

Magnitude and Displacement Scaling Relationships

Scaling relationships between magnitude, fault rupture length, and fault displacement for normal faults have been developed by Wells and Coppersmith (1994) and Mason (1996). These empirical equations and comparisons of their values are given in Appendix B. For the purpose of this study, the magnitude-length-displacement relationship described by Mason (1996) was used, in that both length and magnitude are available (Appendix B).

Fault Displacement Distribution along Fault Length

Currently, there are several methods in use for modeling the distribution of fault displacement along fault length. Cowie and Scholz (1992) describe that observed data indicate that fault displacement is proportional to fault length, however, there are various interpretations of how to model this relationship. Cowie and Scholz (1992) further describe that, when compiling published data sets relating fault displacement and fault length, some describe the relationship as linear and others as nonlinear. Further, others describe that this relationship is dependent upon rock properties.

Although any of these methods could be used, this study considers only the model that describes an elliptical fault displacement distribution along the fault length. The elliptical distribution model, described by Wheeler (1989), was based on normal fault slip data from the ISB. It represents that the maximum fault displacement occurs at the midpoint of the fault length and the displacement tapers at the segment endpoints (Figure 4). Furthermore, by fitting an elliptical distribution to existing Wasatch fault displacement data, Chang and Smith (1998) describe it as a plausible distribution for the fault displacement on the Wasatch fault.

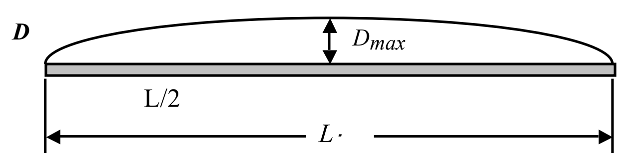


Figure 4. Cartoon illustration of elliptical fault displacement, *D*, distribution along fault length, *L*.

FAULT DISPLACEMENT DATA

Although the Wasatch fault has not ruptured historically, detailed paleoseismic studies at various sites along the fault show evidence of late Holocene surface faulting. These surface faults have allowed insight into the magnitude, timing, and fault displacement of these events.

Hecker (1993) describes that the geologic information used for the characterization of fault-related hazards includes the timing and time distribution between successive events, the fault displacement and fault length of each event, and the rate at which the fault slips. Numerous studies have published these characteristic data for each of the Wasatch fault segments.

Five main segments of the Wasatch fault were considered in this study. The five segments from north to south are the Brigham City segment, Weber segment, the Salt Lake City segment, the Provo segment, and the Nephi segment (Figure 1). From Chang and Smith's (1998) summary of published fault information, the approximate delineated lengths of each of these segments are 38, 61, 46, 70, and 40 kilometers, respectively, with a total length of approximately 255 kilometers.

Chang and Smith (1998), working informally with J. McCalpin, compiled published trench/exposure information from the following sources: Personius (1991), Machette and others (1992), McCalpin and others (1994), Black and others (1995), Lund and others (1991), and Jackson (1991). Chang and Smith's (1998) compilation of paleoseismic event data for each of the study segments, including the event's limiting age and net vertical displacement, is shown in Table 1.

Using the elliptical fault displacement distribution model described earlier, average and maximum displacement values, D_{avg} and D_{max} respectively, were determined for each of the five subject segments. Chang and Smith (1998) calculated the maximum displacement values for each segment by fitting an elliptical envelope to existing fault displacement data. The average displacement values were calculated as the average value under elliptical envelope. Table 2 shows the fault length, maximum displacement, and average displacement for each segment.

TABLE 1
Paleoseismic data from the Wasatch fault

Fault*	Trench/ Exposure*	Limiting Ages (cal. Yr. B.P)**	Net Total Vertical Displacement (m)**
Brigham	BC	2,125 ± 104	1.0
		3,434 ± 142	2.5
		4,674 ± 108	2.5
	PP	4,600 ±500	0.7 ~ 1.3
Weber	GC	1,016 ± 62	1.0
		1,500 ~ 2,000	1.0
	EO	800 ~ 1,200	0.9 ~ 2.2
		2,500 ~ 3,000	2.2 ~ 3.5
		3,500 ~ 4,000	2.2 ~ 2.5
	KV-88	600 ~ 800	1.7 ~ 1.9
		2,800 ± 700	2.3 ~ 3.4
		5,700 ~ 6,100	1.4
Salt Lake City	SFDC	1,230 ± 62	0.9 ~ 2.7
		2,499 ± 138	0.5 ~ 3.8
		3,940 ± 216	0.8
		5,381 ± 136	1.4 ~ 2.2

* See Figure 1
** Published data compiled and tabulated Chang and Smith (1998)

TABLE 1 *continued*

Fault*	Trench*	Limiting Ages (cal. Yr. B.P)**	Net Total Vertical Displacement (m)**
Provo	AFC	618 ± 30	2.2 ~ 2.7
		2,842 ± 72	2.2 ~ 2.7
		5,481 ± 152	2.2 ~ 2.7
	RC	950 ~ 1,150	2.5
	MN, MS	600 ± 80	1.4 ~ 3.0
		2,820 (+150/-130)	0.8 ~ 2.8
	WC	1000 ± 200	0.75 ~ 1.0
Nephi	NC	1148 ± 68	2.0 ~ 2.2
		3,864 ± 238	2.0 ~ 2.5
		4,500 ~ 5,000	2.6
	Red Cyn	1,300 (+600/-700)	1.4 ± 0.3
		3,000 ~ 3,500	1.5 ± 0.2
		4,000 ~ 4,500	1.7 ± 0.3

*See Figure 1
** Published data compiled and tabulated by Chang and Smith (1998)

TABLE 2

Fault length, average displacement and maximum displacement values for Wasatch fault segments

Fault Segment	Fault Length (km)*	Maximum Displacement, D_{max} (m)**	Average Displacement, D_{avg} (m)***
Brigham City	38	1.7	1.2
Weber	61	2.5	1.7
Salt Lake City	46	2.0	1.4
Provo	70	3.0	2.1
Nephi	40	2.4	1.7

* Fault length values documented by Chang and Smith (1998)
** Maximum displacement values were calculated using elliptical distribution for fault displacement along fault length as calculated by Chang and Smith (1998).
*** Average displacement values were calculated as average value under elliptical envelope

METHODOLOGY

Cumulative Distribution

The initial step taken to calculate the annual frequency of exceedance was to determine the statistical cumulative distribution function of the normalized fault displacement data, $\boldsymbol{F}(d/D_{norm})$. Benjamin and Cornell (1970) describe that for discrete, random variables the cumulative distribution is the sum of the probability mass function values over the values less than or equal to a specified value that a random variable can assume. This relationship is given by:

$$F_X(x) = \sum_{x_i < x} p_X(x_i) \qquad [1]$$

where X is a random variable and x is the specified value of the random variable. Thus for this study the cumulative distribution function takes on the following form:

$$F_D(d / D_{norm}) = \sum_{d / D_{norm}} p_D(d / D_{norm}) \qquad [2]$$

where D is the random variable (occurrence of displacement) and d is the specified value of the random variable (threshold displacement). D_{norm} is the normalizing variable.

As shown by equation [2], the cumulative distribution for the Wasatch fault displacement data was determined using normalized trench displacement data. This was done by normalizing the mean displacement data, D, from each of the trench sites (Table 1), with the average displacement, D_{avg}, and maximum displacement, D_{max}, values for each segment (Table 2). The normalized data (for each segment) were then pooled together to develop a cumulative distribution for all five segments, under the assumption that the same normalized distribution applies to each of the each individual fault segments.

Distributions for Normalized Displacement Data

To determine the cumulative distribution function, $\boldsymbol{F}(d/D_{norm})$, the normalized displacement data, D/D_{norm}, was plotted and fit with the following empirical distribution models: normal, gamma, lognormal, and exponential. These distributions are commonly used in engineering applications when representing discrete, random processes. All except the normal distribution assign zero probability to negative values of the variable; however, D/D_{norm} is limited to non-negative values. The normal distribution is symmetrical and the others are skewed to the right. For these reasons, these four distribution models were used to fit the statistical displacement data.

The normal distribution is defined by the mean and standard deviation of the random variable and is given by Equation [3]:

$$F(x) = \frac{1}{\sqrt{2\pi\sigma}} \int_0^x e^{-1/2\left(\frac{x-\mu}{\sigma}\right)^2} dx \qquad [3]$$

where x was set equal to D/D_{norm} and μ is the mean value of D/D_{norm} and σ is the standard deviation of $D/D_{norm.}$

The gamma distribution is given by Equation [4]:

$$F(x) = \frac{1}{\Gamma(a)} \bullet \int_0^{x/b} e^{-t} t^{a-1} dt \qquad [4]$$

where Γ(a) is the gamma function. In this model, x was set equal D/D_{norm} and the function constants, *a* and *b*, were determined using the method of moments.

The lognormal distribution, like the normal distribution, is completely defined by the mean and standard deviation of the random variable. It is given by Equation [5]:

$$F(x) = \frac{1}{\sqrt{2\pi\sigma_{\ln(x)}}} \int_0^{\ln(x)} e^{-1/2\left(\frac{z-\mu_{\ln(x)}}{\sigma_{\ln(x)}}\right)^2} dz \qquad [5]$$

where x was set equal to D/D_{norm} , z was set equal to the natural log of D/D_{norm}, and μ and σ are the mean and standard deviation, respectively.

The exponential distribution is given by Equation [6]:

$$F(x) = 1 - e^{-x/\mu} \qquad [6]$$

F(x) is the cumulative distribution function where *x* is set equal D/D_{norm} and μ is the mean value of D/D_{norm}.

The statistical and empirical cumulative distribution functions for the displacement data normalized with D_{avg} and D_{max} are shown in Figures 5 and 6, respectively. Based on regression correlation coefficients, r^2, (shown on each plot in Figures 5 and 6) the gamma distribution showed the best empirical fit to the statistical distribution for the displacement data normalized with D_{avg} (Figure 5). The lognormal distribution showed the best empirical fit to the statistical distribution for the displacement data normalized with D_{max} (Figure 6).

Conditional Probability

Given the cumulative distribution function, $\boldsymbol{F(d/D_{norm})}$, the conditional probability that D/D_{norm} exceeds a specified threshold value of d/D_{norm}, given a displacement event, D_E, is shown by the expression

$$P\left[(D / D_{norm} > d / D_{norm}) \middle| D_E \right] = 1 - F(d / D_{norm}) \qquad [7]$$

It should be noted that the difference between the *probability* and the *conditional probability* is the dependence upon a specified condition. In this study, the

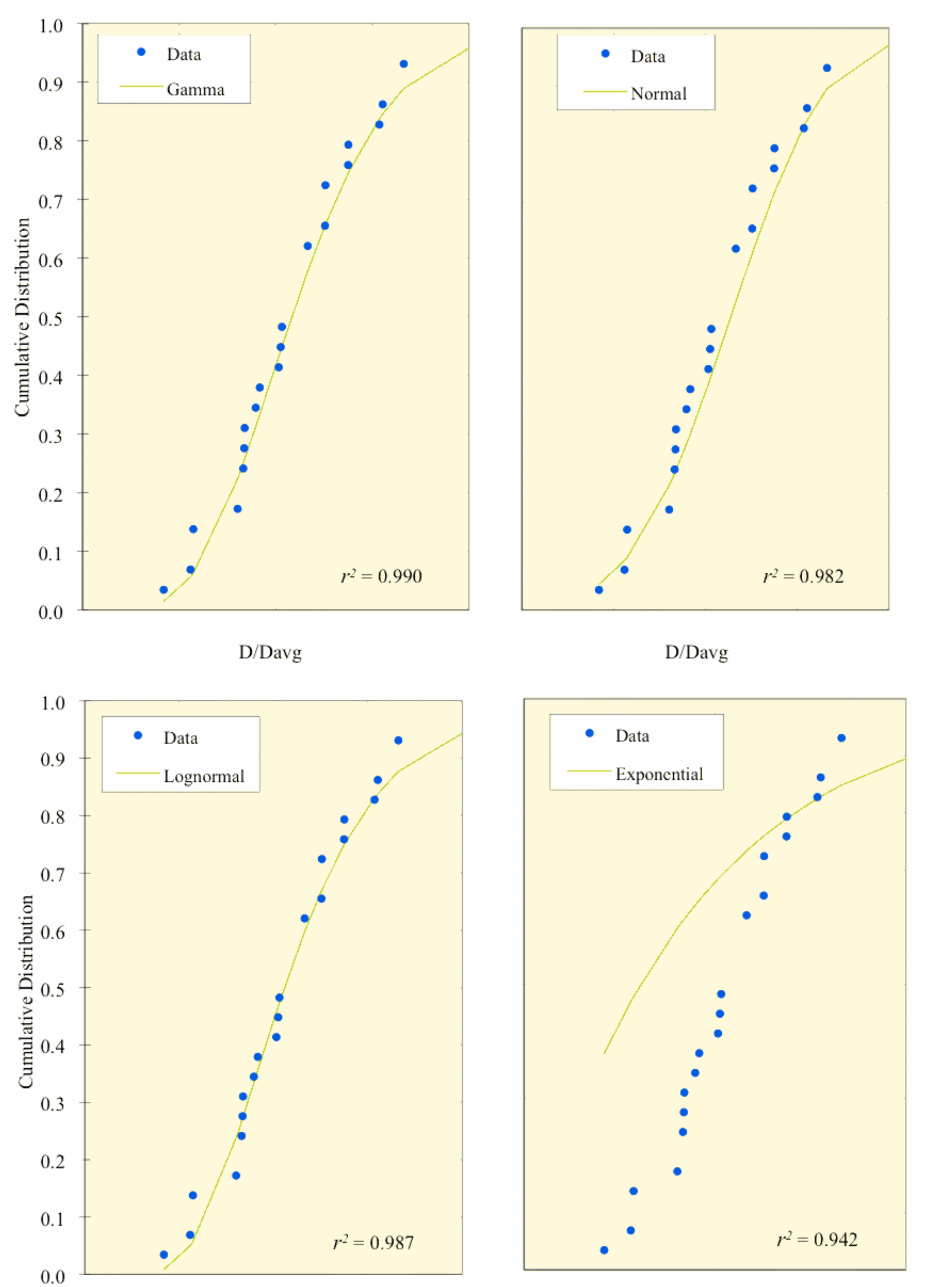


Figure 5. Statistical and empirical cumulatative distribution functions for D/Davg.

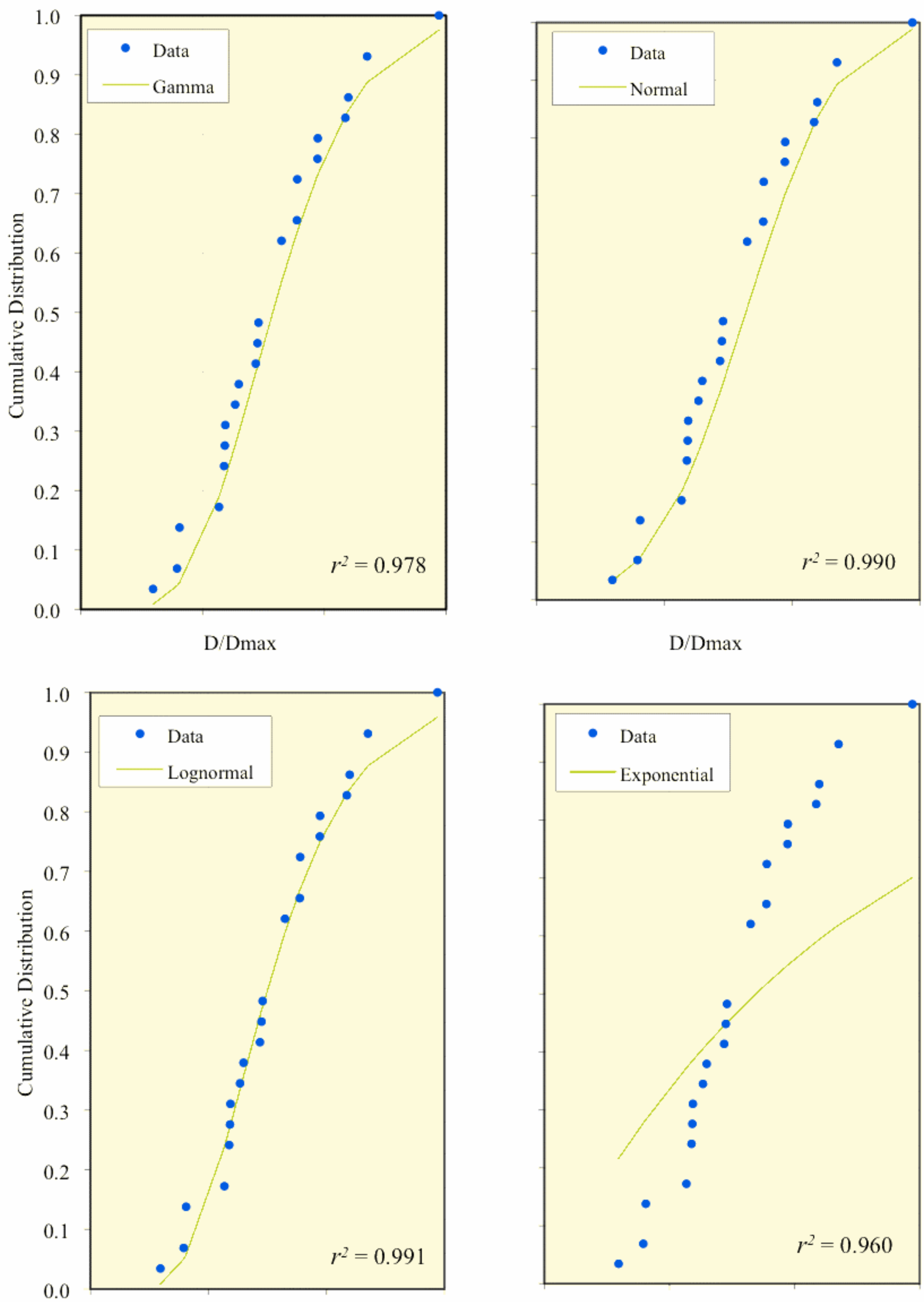


Figure 6. Statistical and empirical cumulative distribution functions for $D/D_{max.}$

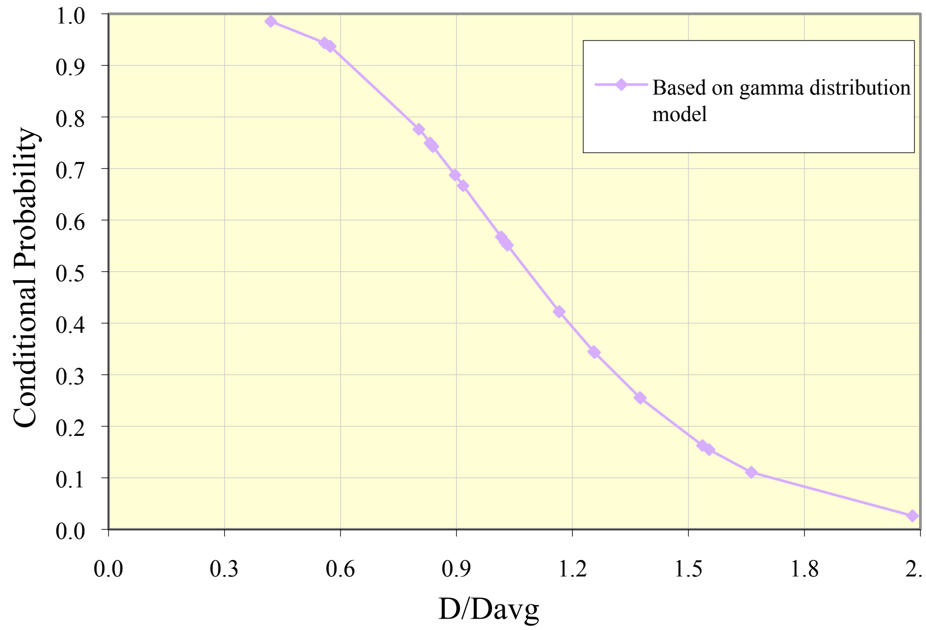
probability that D/D_{norm} will exceed d/D_{norm}, given a displacement event, is a conditional consideration.

Using the empirical distributions with the highest correlation coefficients, the conditional probability curves for d/D_{norm} used for this study were generated using the gamma distribution model for $\boldsymbol{F}(d/D_{avg})$ and the lognormal distribution model for $\boldsymbol{F}(d/D_{max})$ (Figure 6). It should be noted that the curves shown in Figures 6 represent the conditional probability of exceeding the specified normalized displacement value at any point along the fault, with the assumption that the cumulative distributions used to generate the curves represent the cumulative distribution of each individual segment.

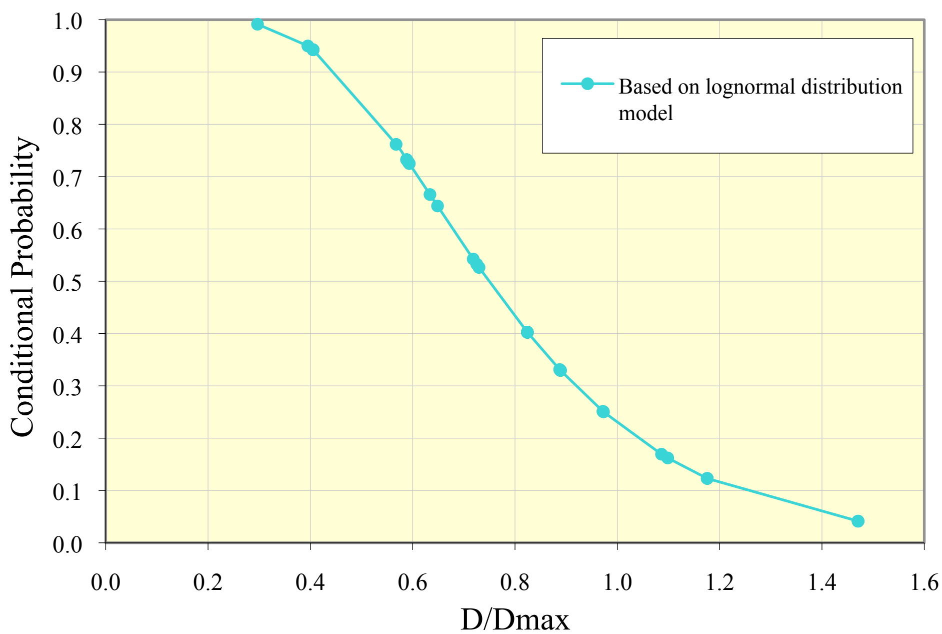
With this, the conditional probability of a given displacement exceeding a specified displacement, given a displacement event, $P(D>d \mid D_E)$, can be determined by applying the conditional probability for the normalized displacement (Equation 7 and Figure 7) to displacement distribution for each segment. Thus, a specific conditional probability curve for each segment can be generated. Individual conditional probability curves are not shown for each segment, but the values are incorporated into the final annual frequency of exceedance calculations (Appendix D).

<u>Annual Frequency of Exceedance</u>

The ultimate value of interest is the expected annual frequency of exceedance of a specified displacement, $\nu(d)$, and the resulting hazard curves. This study considers this value on a segment specific basis. As outlined in general by Kramer (1996) and



(a)



(b)

Figure 7. Conditional probability curves for (a) *D/Davg* and (b) *D/Dmax*.

more specifically in the Yucca Mountain reports (CRWMS M&O, 1998), $\nu(d)$ can be estimated by taking the product of the frequency of displacement events, λ_{DE}, and the conditional probability, $P(D>d|D_E)$, as expressed by Equation [8]:

$$\nu(d) = \lambda_{DE} \cdot P\left[(D/D_{norm} > d/D_{norm})\middle|D_E\right] = \lambda_{DE} \cdot [1 - F(d/D_{norm})] \qquad [8]$$

The frequency of displacement events, λ_{DE}, for each segment was calculated by one of two methods: 1) fault slip rate and 2) recurrence interval. According to McCalpin and Nishenko (1996), these are both fundamental descriptors of seismic activity, and both are critical components to be considered when determining hazards associated with earthquakes.

Other methods for evaluating the frequency of displacement events could be used, but were not considered in this study. One such method is the renewal time method, which considers fault stress loads. By considering only the slip rate and recurrence interval methods for estimating the frequency of events, the assumption is made that the calculated frequency of displacement events is valid for all time, i.e., long term and short term.

Slip Rate

Kramer (1996) describes that the fault slip rate, *SR*, is a measure of the amount of slip on a segment averaged over a time period that encompasses multiple ruptures. Also explained by Kramer (1996), this method does not require the recognition of the date of the activity, but more simply, the displacement and time between individual events. Youngs and Coppersmith (1985) considered the implications of using fault slip rate and recurrence models on a PSHA. In their discussion, Youngs and Coppersmith (1985) describe that using the slip rate to estimate earthquake recurrence assumes that the long-term average slip rate is representative of the "overall" slip rate (i.e., the short-term slip rate).

It should be noted that geologic data assume that the full vertical offset is coseismic, meaning that all of the vertical fault displacement occurs with the earthquake. However, recent findings suggest that as much as 20 percent of fault slip may occur after the initial fault rupture and displacement (personal communication, R. Smith, 1999). Since we are not able to distinguish coseismic versus noncoseismic slip from geologic data, this study assumes that the full displacement offset occurs during the fault rupture.

When using the slip rate method to determine the frequency of displacement events, λ_{DE}, the frequency can be calculated by dividing the D_{avg} value of each segment, into the *SR* for that same segment as given by the following expression:

$$\lambda_{DE} = \frac{SR}{D_{avg}} \qquad [9]$$

The slip rates for each segment were calculated by Chang and Smith (1998) and are shown in Table 3. The mean slip rate values were used in the frequency of

TABLE 3

Slip rate and recurrence interval values for the Wasatch fault

Fault Segment	Slip Rate (mm/year)*	Recurrence Intervals (year)**
Brigham City	0.94 ± 0.03	1,558 ± 49
Weber	1.71 ± 0.69	1,468 ± 528
Salt Lake City	1.48 ± 0.53	1,345 ± 112
Provo	2.17 ± 1.20	1,827 ± 1,067
Nephi	1.74 ± 0.93	1,932 ± 1,109

* Average slip rate for fault segment from Chang and Smith (1998)
** Average recurrence intervals on fault segment (includes time to present) from Chang (1999, unpublished)

exceedance calculations. The D_{avg} values were determined using the previously described elliptical distribution model (Table 2).

Recurrence Interval

Like the slip rate method, the recurrence interval is an important tool in estimating the frequency of events. Keller (1996) defines the average recurrence interval on a fault or fault segment as the average time span between two earthquakes. For the purpose of this study, the recurrence interval used is the average time interval between two fault displacement events.

The recurrence values used for this study were taken as the average of the time difference between two successive displacement events in a particular fault segment.

Again, the recurrence interval was used under the assumption that the calculated recurrence interval is representative of the near-term interval. The recurrence intervals shown in Table 3 used for this study are from Chang and Smith (1998) and were derived using the previously described elliptical model.

Logic Tree Development

When conducting studies involving natural phenomena, there is considerable uncertainty incorporated into calculations when selecting accurate models and parameters to characterize the natural phenomena. In this case, it is the characterization of the displacement hazards along the Wasatch Fault. Youngs and others (1987) explain that this uncertainty may arise from limited statistical information or there may be multiple interpretations of the information that is available.

To further describe the uncertainties inherent in these calculations, Hanks and Cornell (1999) make the distinction between aleatory uncertainty and epistemic uncertainty. *Aleatory* uncertainty relates to the uncertainty in the randomness associated with natural events; whereas, the *epistemic* uncertainty relates to the uncertainty in the information describing or characterizing natural event. Given this description of uncertainties, the uncertainties associated with this study are epistemic in nature. For this study, the sources of uncertainty include the errors in estimating the rupture scenarios, estimating of the frequency of displacement events, errors in the fault displacement data, and the variables used for normalizing the displacement data.

The epistemic uncertainties inherent with these types of calculations are commonly incorporated by means of a logic tree. As described by Youngs and others (1987), logic trees are a methodical means to express uncertainties associated with scientific calculations. For the purpose of this study, the epistemic uncertainty was incorporated using a logic tree.

Logic trees systematically allow for the mathematical formulation of probability multiplication and are comprised of a sequence of nodes and branches. Every node has a single branch or a series of branches extending from it. Also, each node represents an input parameter used in the analysis. Each node represents discrete events and each branch represents one possible interpretation of the parameter under evaluation. Probabilities or weights are assigned to each branch coming off of the node. The probability, or weight, represents the relative likelihood of that branch having the accurate representation of the parameter under consideration. With each branch carrying a relative weight, there is a conditional assumption that, at each node, the sum of the weights is unity. Therefore, logic tree probabilities take into consideration the probabilities associated with each sequence of nodes and branches.

The uncertainty or relative weight assigned to each branch will be carried through the calculations for the entire branch. Slight variations in an assigned branch weight (i.e., 0.8 versus 0.9) will have differing impacts on the end result, or value at the end of a logic tree branch. For example, as branch weights of 0.8 and 0.9 are multiplied through the branch calculations the end value will not vary only by the percent difference between 0.8 and 0.9. The percent difference between these values will propagate through the calculations and the end results will be less than just the percent difference between 0.8 and 0.9. With this, careful consideration should be taken when assigning relative weights to each branch.

In constructing the logic tree, a sufficient number of branches and nodes should be selected to accurately reflect the uncertainty in estimating the hazard probability. The general layout of the logic tree used in this study is displayed in Appendix A.

The point should be heavily emphasized that with the logic tree, any number or combination of scenarios can be considered. The scenarios that are considered in this study should by no means be considered the limit. Additional or different scenarios can and should be considered in subsequent studies.

Logic Tree Parameters

Fault Rupture Scenario

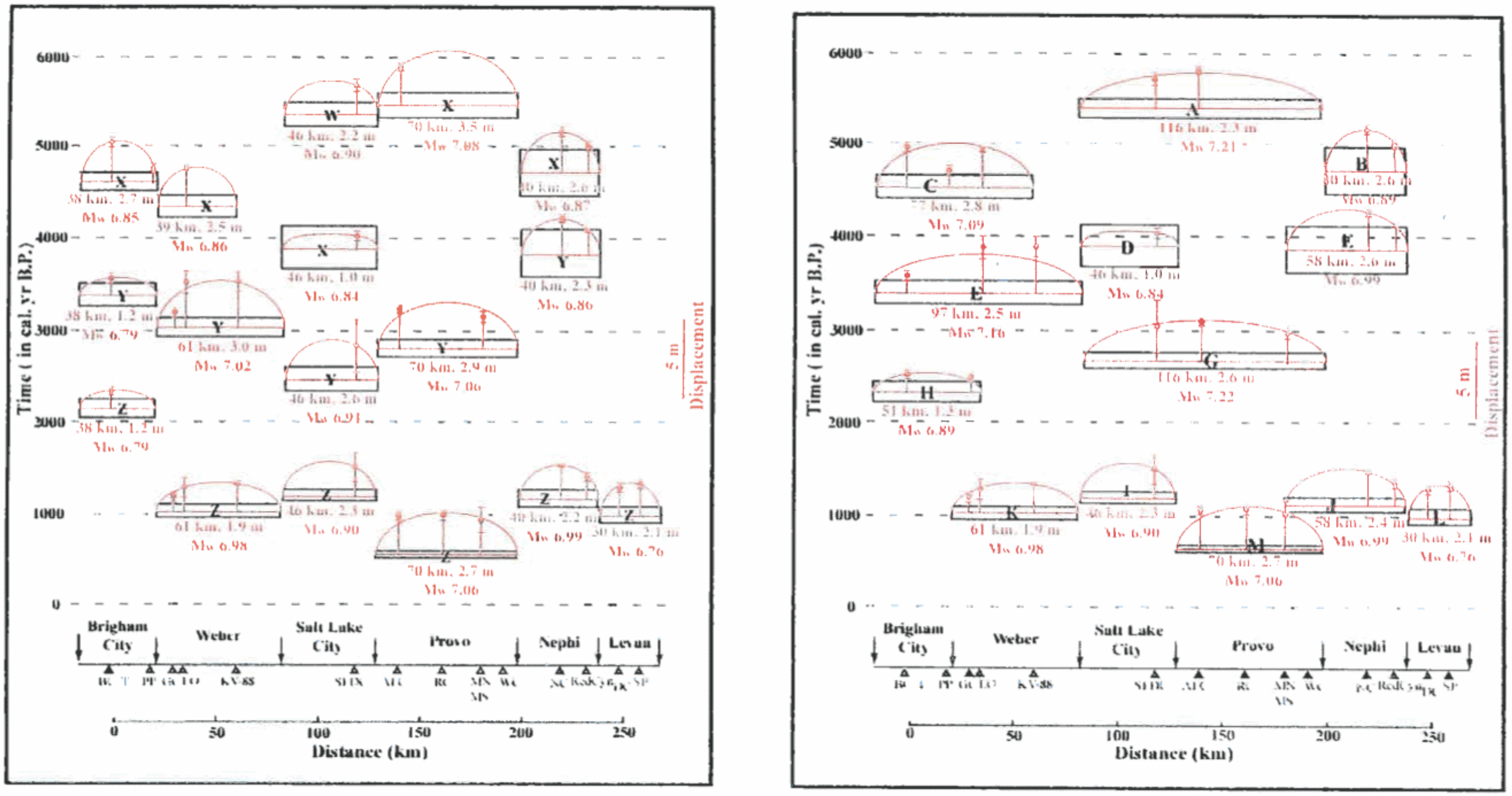
The Wasatch fault was first characterized as being comprised of six to ten discrete segments (Swan and others, 1980; Schwartz and Coppersmith, 1984). It has been proposed that these segments are independent of each other, both seismically and structurally. A related hypothesis by Schwartz and Coppersmith (1984) describes that "characteristic" earthquakes, or earthquakes of a given magnitude, are characteristic of an entire, individual fault segment. With this, Schwartz and Coppersmith (1984) proposed that a "characteristic" earthquake would rupture the whole length of a segment and would not rupture across segment boundaries. Both of these proposed theories support the idea that the Wasatch fault is comprised of discrete, single segments.

Chang and Smith (1998) considered the possibility of multisegment earthquakes on the Wasatch fault. Although multisegment earthquakes on the Wasatch fault have not been observed directly, Chang and Smith (1998) postulated a multisegment scenario based on the effects of stress loading and concluded that there are various possible multisegment scenarios on the Wasatch fault.

In addition to the results of stress modeling, Chang and Smith (1998) evaluated the Wasatch fault paleoseismic data, which included time and displacement data from the individual segments. By fitting the displacement data with the elliptical fault displacement along strike model, Chang and Smith (1998) concluded that there is a possibility of multisegment earthquakes on the Wasatch fault (Figure 8).

Furthermore, Pezzopane and Dawson (1996), in a summary report addressing the Yucca Mountain Repository fault displacement hazard, describe how fault segments were addressed in the Yucca Mountain study by CRWMS M&O (1998). In an attempt to define fault segments that may rupture together, Pezzopane and Dawson (1996) defined fault segments on the basis of discontinuities in the geometry of normal faults.

With this background information, this study considered characteristic and non-characteristic, or single segment and multisegment, models. The single and multisegment scenarios were taken into consideration in the logic tree by considering the scenario of single and mulitsegment rupture. Each rupture scenario branch



(a) (b)

Figure 8. Distributions of fault slip based on (a) single segment and (b) multisegment paleoearthquakes of the Wasatch fault. Vertical bars show earthquake displacements measured from trenches (see Table 1). The rupture length (km), maximum displacement (m), and magnitude (Mw) are shown under each event. Elliptical envelopes were used to fit the displacement data of each event. Magnitude calculated based on displacements the rupture lengths (see Appendix B). Figures are printed with permission from Chang (1998). (Also see Figure 2).

coming from the same node represents a possibility of that scenario occurring, relative to the scenarios represented by the other branches.

The branch weight values used for each of these models are based on work done by McCalpin and Nishenko (1996) and Chang (personal communication, 1999). McCalpin and Nishenko estimated the probability of future large (M_w>7) earthquakes that completely ruptured each segment of the Wasatch fault. Chang (personal communication, 1999) incorporated the contagion effects, i.e., the effect that one segment has on the adjacent segment, or segments.

McCalpin and Nishenko's (1996) Wasatch fault zone earthquake probability estimates considered Poisson models, lognormal renewal models, and Weibull renewal models, all with 20, 50, and 100 year repeat times. McCalpin and Nishenko (1996) considered the recurrence interval data available for each segment alone and also pooled or grouped all of the recurrence interval data into a single distribution, under the assumption that the recurrence intervals are all part of the same population.

McCalpin and Nishenko's (1996) study included three direct approaches for calculating the probability of rupture: 1) regional, 2) fault-specific, and 3) segment-specific. Based on the source of the data and the nature of this segmented-fault study, this hazard model incorporated the segment-specific probabilities, the rupture probability data modeled with the lognormal distribution, and an intrinsic variable, σ, equal to 0.5. McCalpin and Nishenko (1996) state that the intrinsic variability is a parameter that describes the natural variation of recurrence intervals and is independent of the errors associated with estimating recurrence intervals.

McCalpin and Nisheko's (1996) probability of rupture values used in this study are based on a 50-year renewal interval. It should be noted that there may be implications to using this short-term interval. As discussed previously, the frequency of displacement events is calculated using the slip rate and recurrence interval methods, which assumes that the "overall" rate is representative of the short-term rate. Additional branches in the logic tree could be added, or a subsequent study could be done to consider the implications to using these models in combination.

Finally, McCalpin and Nishenko (1996) indicate that the probability of earthquake estimates do not account for contagion effects, which are described in the following paragraphs.

Chang (personal communication, 1999) used McCalpin and Nishenko's (1996) data and applied the contagion effects to the probability of rupture values to develop weights for each rupture scenario. Contagion is described as the "nonrandom" influence that one fault segment may have one or more adjacent or nearby fault segments (Perkins, 1987).

From Perkins' (1987) work, fault contagion is the current term used to represent the process of one earthquake influencing the occurrence or initiation of another earthquake on an adjacent fault segment or nearby fault. The idea of contagion refers not only to one segment initiating a fault rupture on an adjacent segment, but also to the effects on stress levels in adjacent or nearby faults.

Cornell and others (1993) developed a model to evaluate the earthquake recurrence processes and fault segment interaction. Cornell and other's (1993) single segment model assumes that individual fault segments are independent of adjacent segments and are surrounded by nonslipping segments; whereas their multisegment model is are dependent upon fault segment interaction. Cornell and others (1993) further describe that for a multisegment scenario, the stress loading and unloading effects on a fault segment from adjacent fault segment rupture may influence a single segment both positively and negatively, meaning the accumulated stress is either increased or decreased, respectively. Cornell and others (1993) suggest that positive interactions will typically reduce the times between events on any segment and negative interactions will typically increase the times between events. The variable effect of fault contagion can be determined and represented with contagion values or factors.

In order to account for the uncertainties associated with contagion effects, both single segment and a multisegment models were included in the logic tree uncertainty calculations. The single segment model does not consider fault contagion, but takes into account only the variables and parameters associated with individual segments, (i.e., the characteristic model) meaning that the segments will behave independent of one another. The single-segment approach assumes that the entire length of the discrete fault will rupture and will not cross fault segment boundaries, nor will it affect recurrence intervals of adjacent segments.

The multisegment model considers fault contagion by taking into account the possibility of rupture across the segment boundaries during a single event and for the rupture of one fault to affect the stress level in adjacent segments. With this, the rupture of either of the adjacent fault segments may affect a single fault segment or there may be a combined effect from both of the adjacent segments. The contagion values used in the logic tree were provided by Chang (personal communication, 1999) and take each of these scenarios into consideration (Table 4). The branch weight values represent the possibility that the adjacent fault segment or segments will affect any single segment. Historical information and work by Chang (1998) has shown that the energy released by the initiating segment dissipates in approximately 15 kilometers (this is independent of the segment length). Thus, the model assumes full rupture of the initiating segment and initiation of and rupture on 15 kilometers on the adjacent segment or segments (Figure 9).

These normalized weights for each of the fault rupture scenarios were incorporated into the first branch of the logic tree (Fault Rupture Scenario). Note that the sum of the normalized weights for each segment is one.

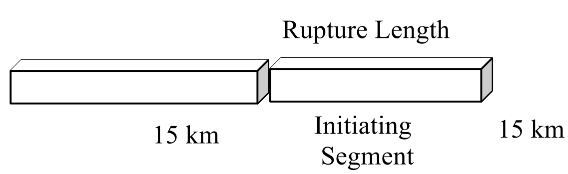


Figure 9. Cartoon illustration of multisegment rupture. Fault initiation on main segment and 15 kilometers of adjacent segment or segments.

TABLE 4

Normalized weights for various rupture scenarios on the Wasatch fault

Rupturing fault segment	Rupture Scenario Rupturing segment initiating rupture on closest 15 km of adjacent fault segment(s) (percent of adjacent segment length shown)*	Normalized weights**
Brigham City	Brigham City alone	0.953
	Brigham City and Weber (25%)	0.047
Weber	Weber alone	0.878
	Weber and Brigham City (39%)	0.014
	Weber and Salt Lake City (33%)	0.014
	Weber and Brigham City and Salt Lake City	0.054
Salt Lake City	Salt Lake City alone	0.937
	Salt Lake City and Weber (25%)	0.025
	Salt Lake City and Provo (21%)	0.012
	Salt Lake City and Weber and Provo	0.026
Provo	Provo alone	0.945
	Provo and Salt Lake City (33%)	0.009
	Provo and Nephi (38%)	0.008
	Provo and Salt Lake City and Nephi	0.038
Nephi	Nephi alone	0.971
	Nephi and Provo (21%)	0.029

*Study considers full rupture of initiating fault segment with simultaneous rupture initiation on closest 15 kilometers of adjacent segment(s).

** Weight values calculated from W. Chang (personal communication, 1999) based on probability of segment rupture values from McCalpin and Nishenko (1996). From McCalpin and Nishenko (1996) values are based on lognormal distribution with $\sigma = 0.5$ and 50 year repeat time.

Frequency of Displacement Events

As discussed earlier, the frequency of displacement events, λ_{DE}, was used to calculate the annual frequency of exceedance and was calculated by one of two methods: 1) fault slip rate and 2) recurrence interval. Each of these methods was considered in the logic tree calculations. Based on the accuracy of the trench information available and the relative certainties in the slip rate and recurrence interval values (Table 3), the slip rate method received a relative weight of 0.70 and the recurrence interval received a relative weight of 0.30. Obviously, these two total unity.

Again, it is noted that there are other methods for evaluating the frequency of displacement events; however, only the slip rate and recurrence interval methods were considered in this study.

Normalizing Variable

The determination and use of the displacement normalizing variables D_{avg} and D_{max} were discussed in detail earlier in this report. These variables were used to normalize the displacement data for the determination of the cumulative distribution function. In the logic tree, each of these normalizing variables received a weight of 0.5, thus inferring that each of these normalizing variables is equally as likely to represent the most accurate method of normalizing the fault displacement.

Sample Logic Tree Calculation

To illustrate the function of the logic tree, this section of the report demonstrates the logic tree calculations for one of the logic tree branches used in this study. Figure 10 shows the Brigham City segment branch of the Wasatch fault displacement hazard logic tree (see Appendix A). Take, for instance, the top (or first) branch shown in Figure 10. This branch accounts for the full rupture of the Brigham City segment alone (no contagion effects), slip rate frequency estimation, and normalizing using the average displacement.

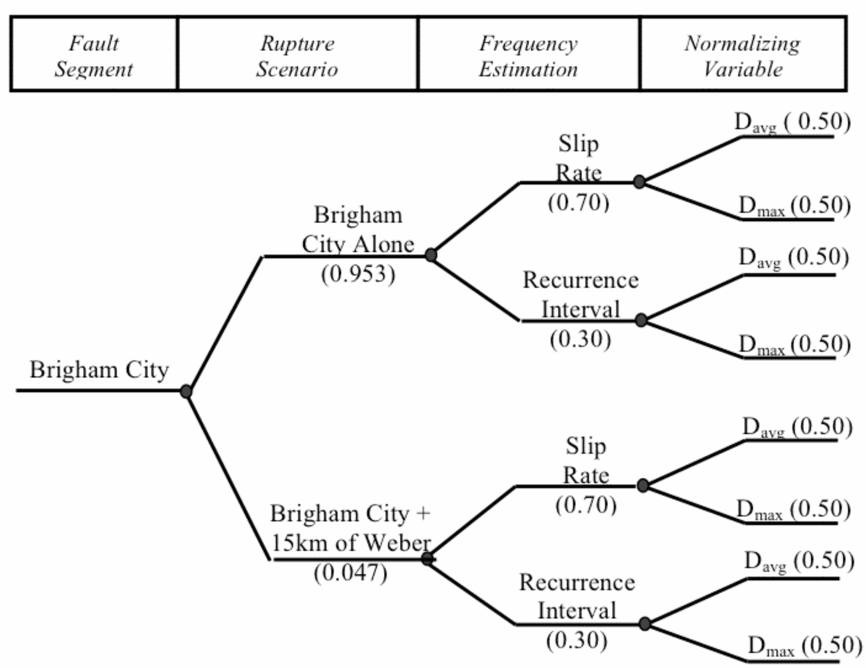


Figure 10. Brigham City segment branch of the Wasatch fault displacement hazard tree used for sample calculation.

If the top branch of the Brigham City segment is followed through, the calculations are as follows:

(Probability of Rupture) x (Frequency Estimation) x (Normalizing Variable) =

1.953 x 0.70 x 0.50 = 0.334.

Now follow the last branch of the Weber segment. This branch accounts for the full rupture of the Brigham City segment and initiation of rupture on the closest 15 kilometers of the Weber segment, recurrence interval frequency estimation, with the maximum displacement as the normalizing variable. These calculations are as follows:

(Probability of Rupture) x (Frequency Estimation) x (Normalizing Variable) =

0.047 x 0.30 x 0.50 = 0.007.

Notice that these two branches are the extreme values; i.e., the maximum and minimum values for the Brigham City segment branch. As this example illustrates, the uncertainty values calculated from the logic tree vary substantially. The relative weights assigned to the individual branches can make a substantial impact on the overall branch calculations.

FAULT DISPLACEMENT RESULTS FOR SEGMENTS

Brigham City Segment

Brigham City Segment Fault Information

The Brigham City segment is located at the northern-most end of the Wasatch Fault and is estimated to be 38 kilometers in length (Table 2). There is documented displacement data from two trenches or exposed sites (Figure 1). Based on the elliptical fault displacement distribution along the length of the fault used by Chang and Smith (1998) and considering a single segment scenario, the maximum displacement is located at the midpoint of the fault and is estimated to be 1.7 meters (mean value) and the average displacement located at the midpoint of the fault was estimated to be 1.2 meters (mean value). These maximum and average displacements correlate to M_s 7.0 and M_s 6.9 earthquakes, respectively, as described by an empirical scaling relationship for normal faults derived by Mason (1996) (Appendix B). This relationship is given by:

$$M_s = 0.55\log(DL) + 5.95. \qquad [10]$$

where D is the fault displacement and L is the fault length From recurrence data calculations for the Wasatch fault done by Chang and Smith (1998) and assuming a one to one relationship between M_s and M_w, the annual frequency of a M_s 7.0 and 6.9 earthquake is 8.93×10^{-4} and 2.32×10^{-3}, respectively, for a single segment model. For a multisegment model, Chang and Smith (1998) shows the annual frequency to be 1.43×10^{-3} and 1.96×10^{-3}, respectively.

Based on the results of McCalpin and Nishenko (1996) the most recent faulting event on this segment was 2125 ± 104 years before present, which, relative to the other Wasatch fault segments, is a much longer period of time since the last event.

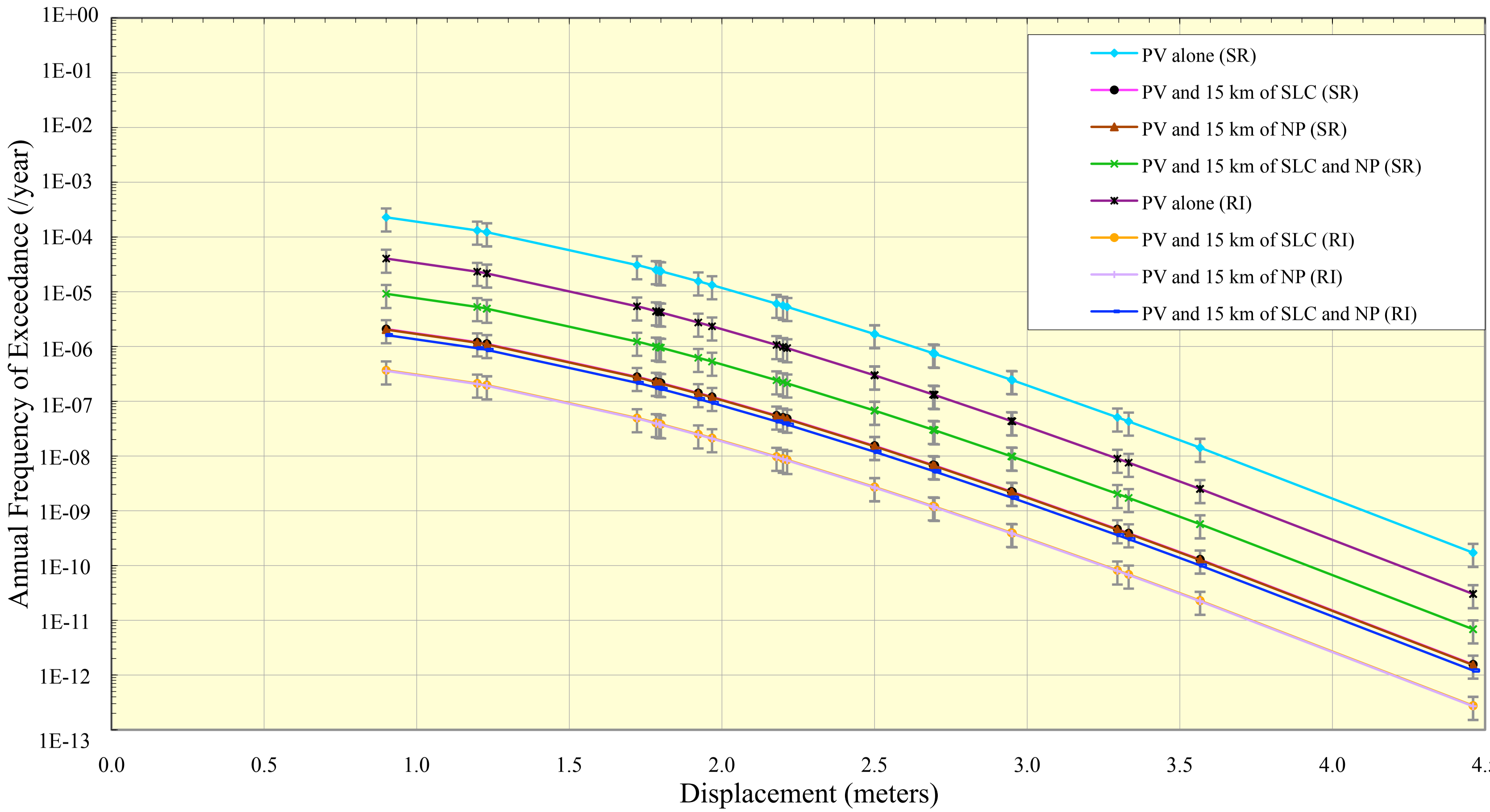


Figure 17. Provo segment hazard curves with D_{avg} as the normalizing factor. D_{avg} for the segment is 2.1 meters and D_{max} for the segment is 3.0 meters. Abbreviations: NP = Nephi segment, PV = Provo Segment, SLC = Salt Lake City Segment SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

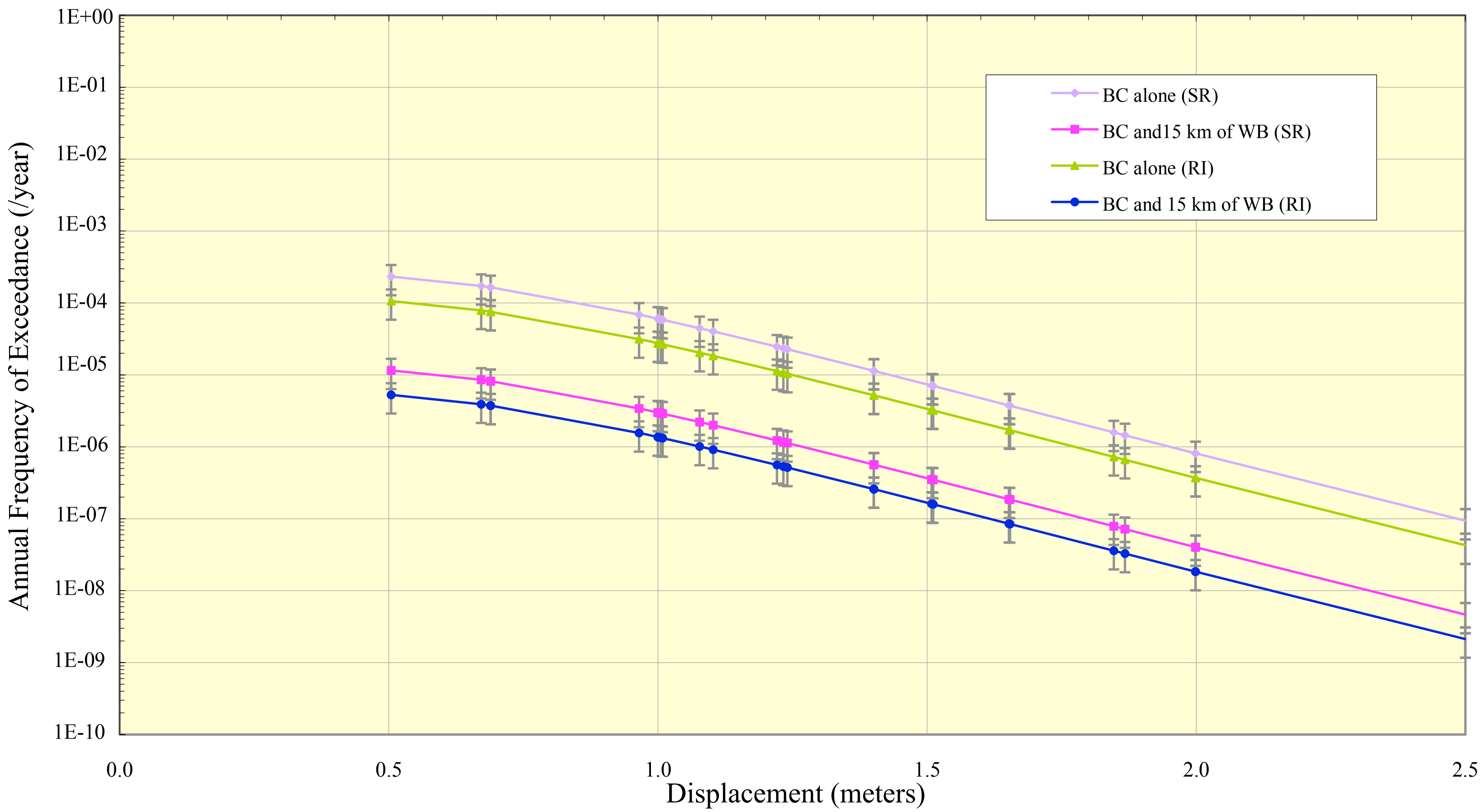


Figure 12. Brigham City segment hazard curves with D_{max} as the normalizing factor. D_{avg} for the segment is 1.2 meters and D_{max} for the segment is 1.7 meters. Abbreviations: BC = Brigham City Segment, WB = Weber Segment, SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

Weber Segment

Weber Segment Fault Information

The Weber Segment is located between the Brigham City and Salt Lake City segments (Figure 1). Paleoseismic data indicate that the Weber segment is 61 kilometers in length (Table 2). The last documented event on the Weber segment was 1016 ± 62 years before present (Table 1). Chang and Smith's (1998) elliptical fault displacement model estimates that the mean maximum displacement at the midpoint of the fault is 2.5 meters whereas the mean average displacement at the same position on the fault is 1.7 meters. According Equation [10], as defined by Mason (1996) (Appendix B), the maximum and average displacements correlate to M_s 7.2 and M_s 7.1 seismic events, respectively. From Chang and Smith (1998), these magnitudes relate to an annual frequency of zero and 5.36×10^{-4}, for the single segment model and for the multisegment model the frequencies are 5.36×10^{-4} and 8.93×10^{-4}, respectively.

Weber Segment Fault Displacement Hazard Results

This segment has adjacent segments on both ends; therefore contagion effects were considered for each of the adjacent segments alone and in combination. With this, four scenarios were considered for this segment. The four scenarios are shown in the logic tree in Appendix A. Full rupture of the Weber segment alone (61 kilometers) was considered. Full rupture on the Weber segment with initiation of rupture on the closest 15 kilometers of the Brigham City or Salt Lake City segments were two options considered (76 kilometers). The final consideration was the scenario of full rupture on the Weber segment and simultaneous initiation of the closest 15 kilometers on both the Brigham City and Salt Lake City segments (91 kilometers).

The full set of hazard curves for the Weber City segment is shown in Figure 13 and 14. These curves resulted from the calculations that considered D_{avg} and D_{max} as the normalizing variable. The results from all of the various scenarios from the Weber segment branch of the logic tree are captured in these curves.

Salt Lake City Segment

Salt Lake City Segment Fault Information

The Salt Lake City segment is positioned between the Weber segment to the north and the Provo segment to the south (Figure 1). Paleoseismic events on this segment indicate that it is 46 kilometers in length (Table 2). The South Fork Dry Creek (SFDC) trench is the only trench in this segment with documented displacement data (Figure 1). Chang and Smith (1998) documents work by McCalpin and Nishenko (1996) which indicates that the most recent event on the Salt Lake City Segment was 1230 ± 62 years before present time. As was calculated for each segment, based on the elliptical distribution described by Chang and Smith (1998), the maximum and average displacements at the midpoint of the length of the Salt Lake segment is 2.0 meters and 1.4 meters, respectively. These displacements correlate to M_s 7.0 and M_s 6.9 earthquakes, as related by Mason (1996) (Appendix B). Again, as for the other single segment models, a M_s 7.0 and M_s 6.9 earthquake relate to an

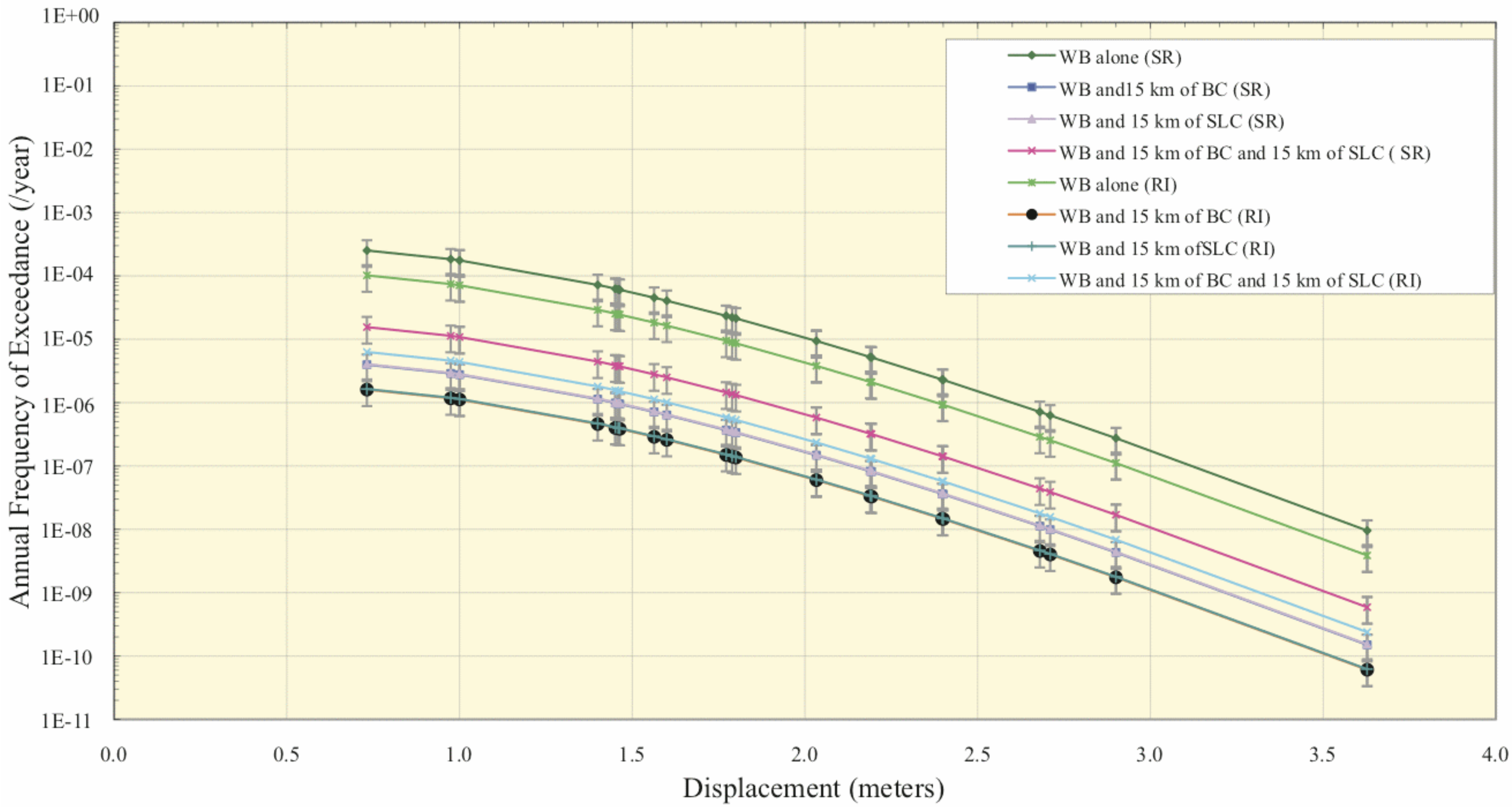


Figure 13. Weber segment hazard curves with D_{avg} as the normalizing factor. D_{avg} for the segment is 1.7 meters and D_{max} for the segment is 2.5 meters. Abbreviations: WB = Weber Segment, SLC = Salt Lake City segment, BC = Brigham City Segment, SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

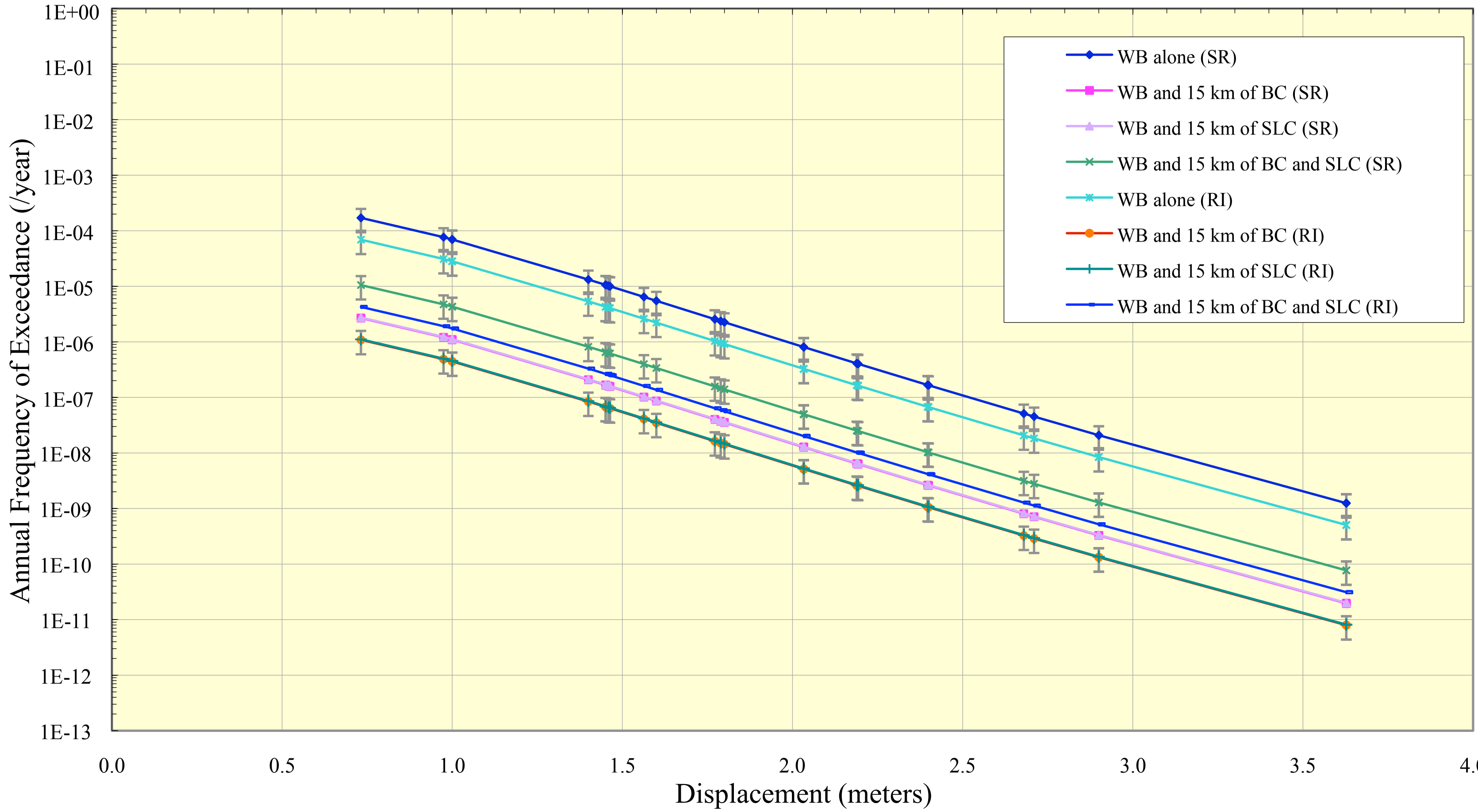


Figure 14. Weber segment hazard curves with D_{max} as the normalizing factor. D_{avg} for the segment is 1.7 meters and D_{max} for the segment is 2.5 meters. Abbreviations: WB = Weber Segment, SLC = Salt Lake City segment, BC = Brigham City Segment, SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

annual frequency of 8.93×10^{-3} and 2.32×10^{-3}, respectively, and 1.43×10^{-3} and 1.96×10^{-3} for the multisegment model, respectively (Chang and Smith, 1998).

As was the case with the Weber segment, the Salt Lake City segment has adjacent segments on both ends; therefore contagion effects were considered for each of the adjacent segments alone and in combination. With this, four scenarios were considered for this segment (see Appendix A). Full rupture of the Salt Lake segment alone was considered (46 kilometers). Full rupture on the Salt Lake City segment with initiation of rupture on the closest 15 kilometers of either the Weber or Provo segments were two options considered (61 kilometers each). The final consideration was the scenario of full rupture on the Salt Lake City segment and simultaneous initiation of the closest 15 kilometers on both the Weber and Provo segments (76 kilometers).

The full set of hazard curves for the Salt Lake City segment are shown in Figures 15 and 16. These curves resulted from the calculations that considered D_{avg} and D_{max} as the normalizing variable. The results from all of the various scenarios from the Salt Lake City segment branch of the logic tree are captured in these figures.

Provo Segment

Provo Segment Fault Information

The Provo segment is positioned between the Salt Lake and Nephi segments. paleoseismic data suggests that the Provo segment is 40 kilometers in length (Table 2) with the last recorded event occurring 618 ± 30 years before present (Table 1). It should be noted that this interval of time since the last is event is substantially less

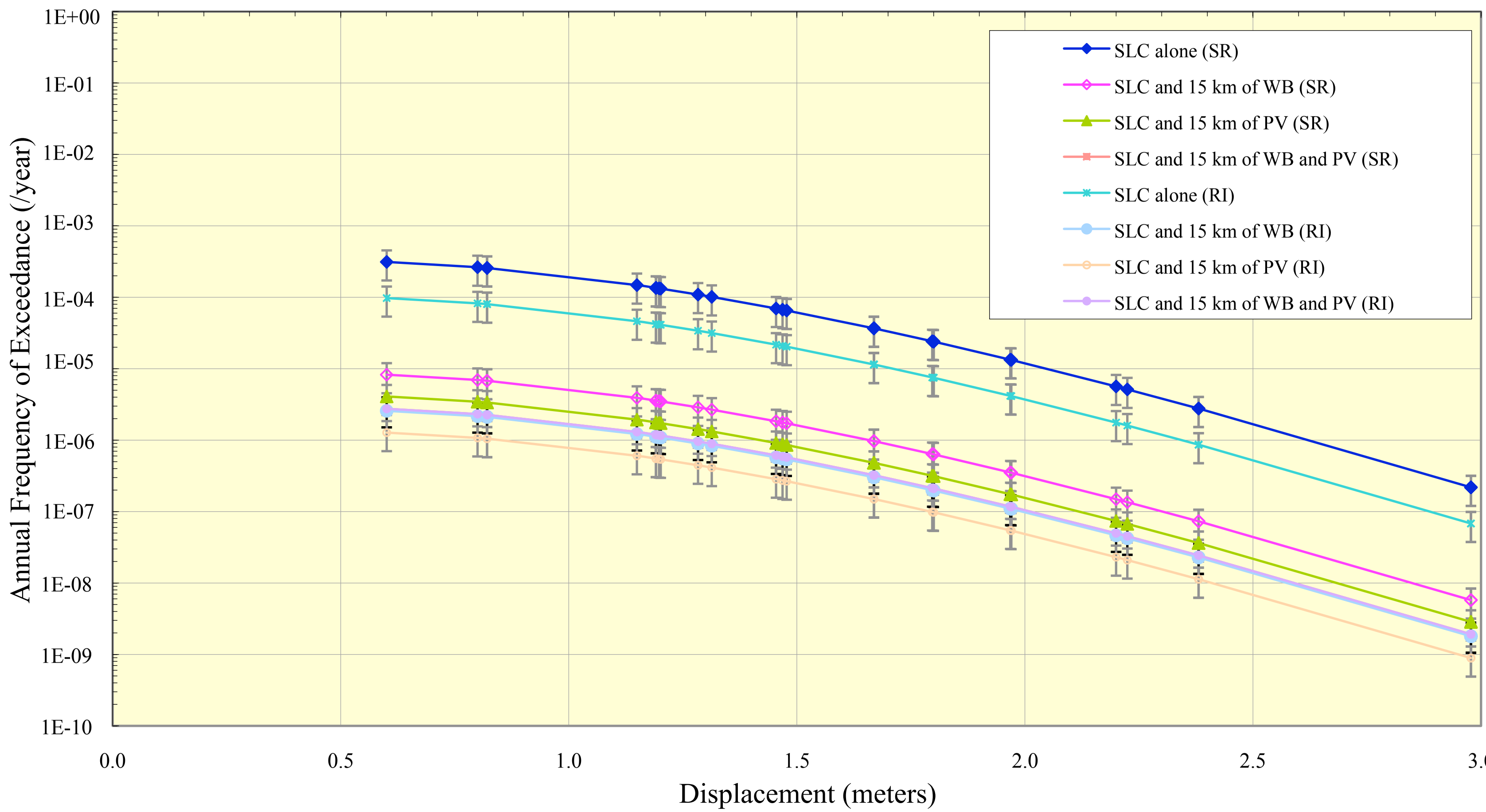


Figure 15. Salt Lake City segment hazard curves with D_{avg} as the normalizing factor. D_{avg} for the segment is 1.4 meters and D_{max} for the segment is 2.0 meters. Abbreviations: SLC = Salt Lake City segment, PV = Provo Segment, WB = Weber Segment, SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

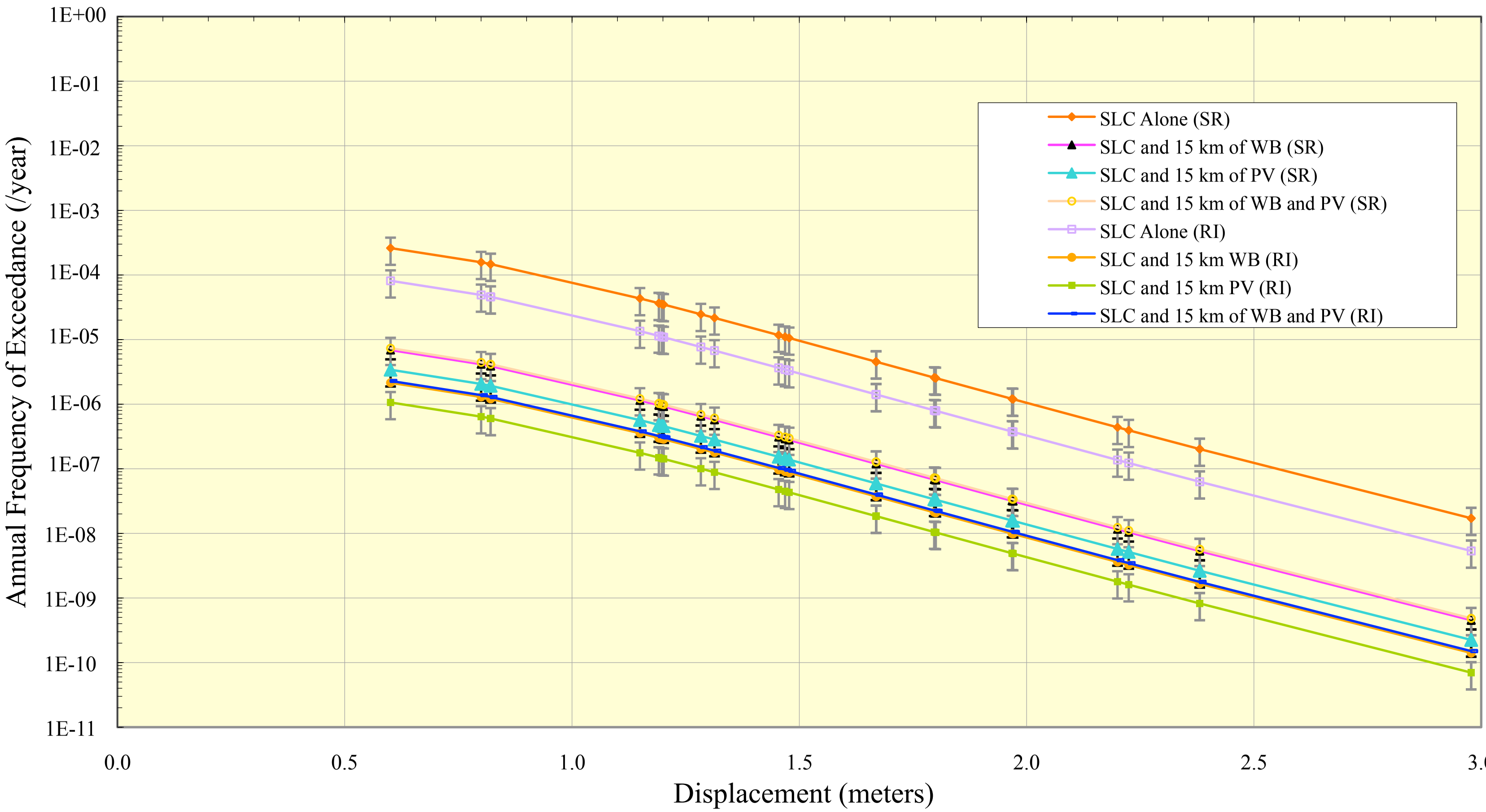


Figure 11. Brigham City segment hazard curves with D_{avg} as the normalizing factor. D_{avg} for the segment is 1.2 meters and D_{max} for the segment is 1.7 meters. Abbreviations: BC = Brigham City Segment, WB = Weber Segment, SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

than the other subject segments. Based on Chang and Smith's (1998) proposed elliptical displacement distribution model, at the midpoint of the fault the average displacement is estimated to be 2.1 meters and the maximum displacement is estimated to be 3.0 meters. These values correspond to a M_s 7.1 earthquake for the average displacement and a M_s 7.2 earthquake for the maximum displacement according to the empirical relationship developed by Mason (1996). From Chang and Smith (1998) M_s 7.2 and M_s 7.1 earthquakes correlate with approximate annual frequencies of zero and 5.36×10^{-4} for the single segment model, respectively, and 5.36×10^{-4} and 8.93×10^{-4} for the multisegment model, respectively.

Provo Segment Fault Displacement Hazard Results

As was the case with the Weber and Salt Lake City segments, this segment has adjacent segments on both ends; therefore contagion effects were considered for each of the adjacent segments alone and in combination. With this, four scenarios were considered for this segment. The four scenarios are shown in the logic tree in Appendix A. Full rupture of the Provo segment alone was considered (70 kilometers). Full rupture on the Provo segment with initiation of rupture on the closest 15 kilometers of the Salt Lake City or Nephi segments (85 kilometers each) were two options considered. The final consideration was the scenario of full rupture on the Weber segment and simultaneous initiation of the closest 15 kilometers on both the Salt Lake City and Nephi segments (100 kilometers).

The full set of hazard curves for the Provo segment is shown in Figures 17 and 18. These curves resulted from the calculations that considered D_{avg} and D_{max} as the

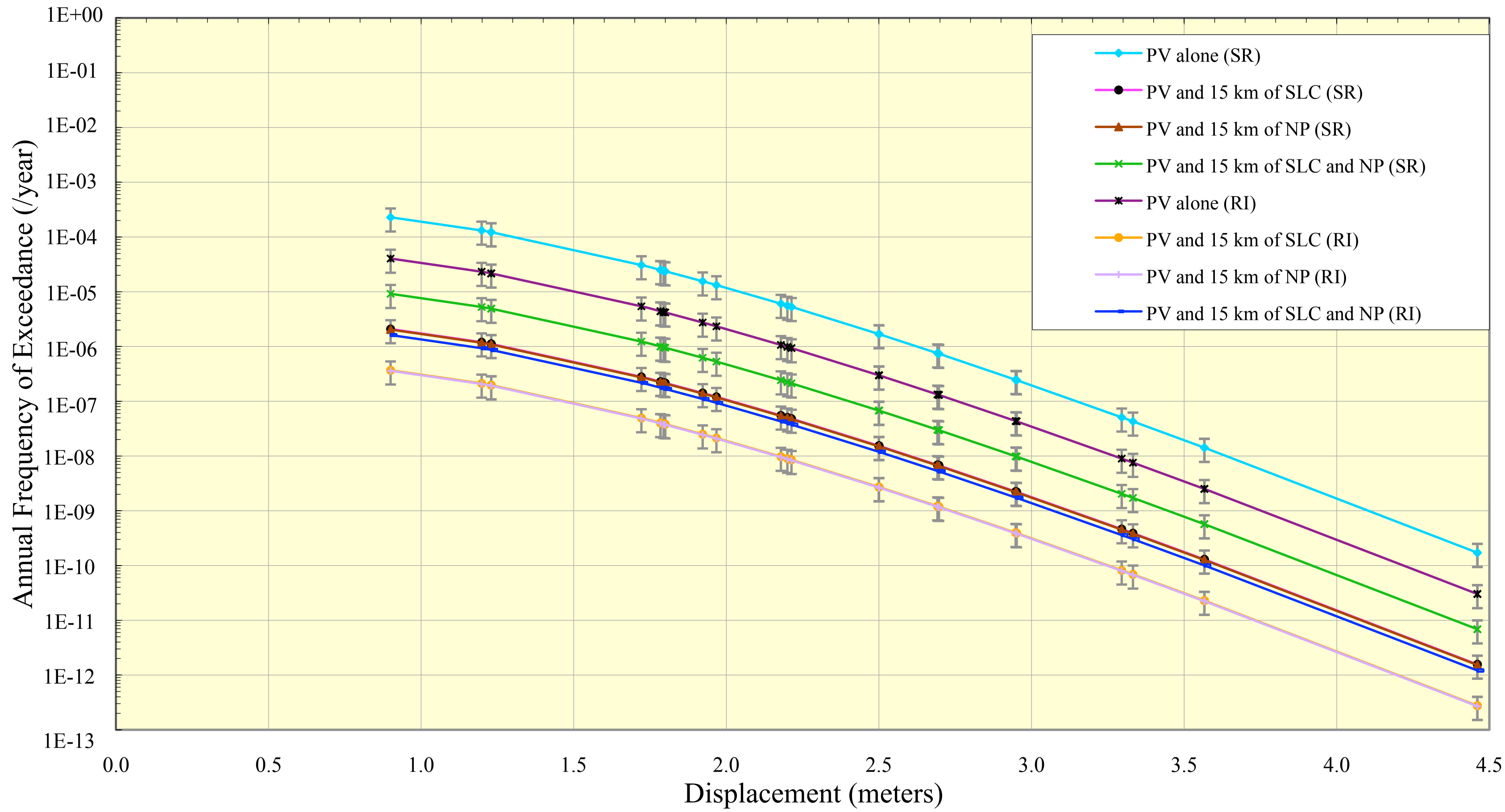


Figure 17. Provo segment hazard curves with D_{avg} as the normalizing factor. D_{avg} for the segment is 2.1 meters and D_{max} for the segment is 3.0 meters. Abbreviations: NP = Nephi segment, PV = Provo Segment, SLC = Salt Lake City Segment SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

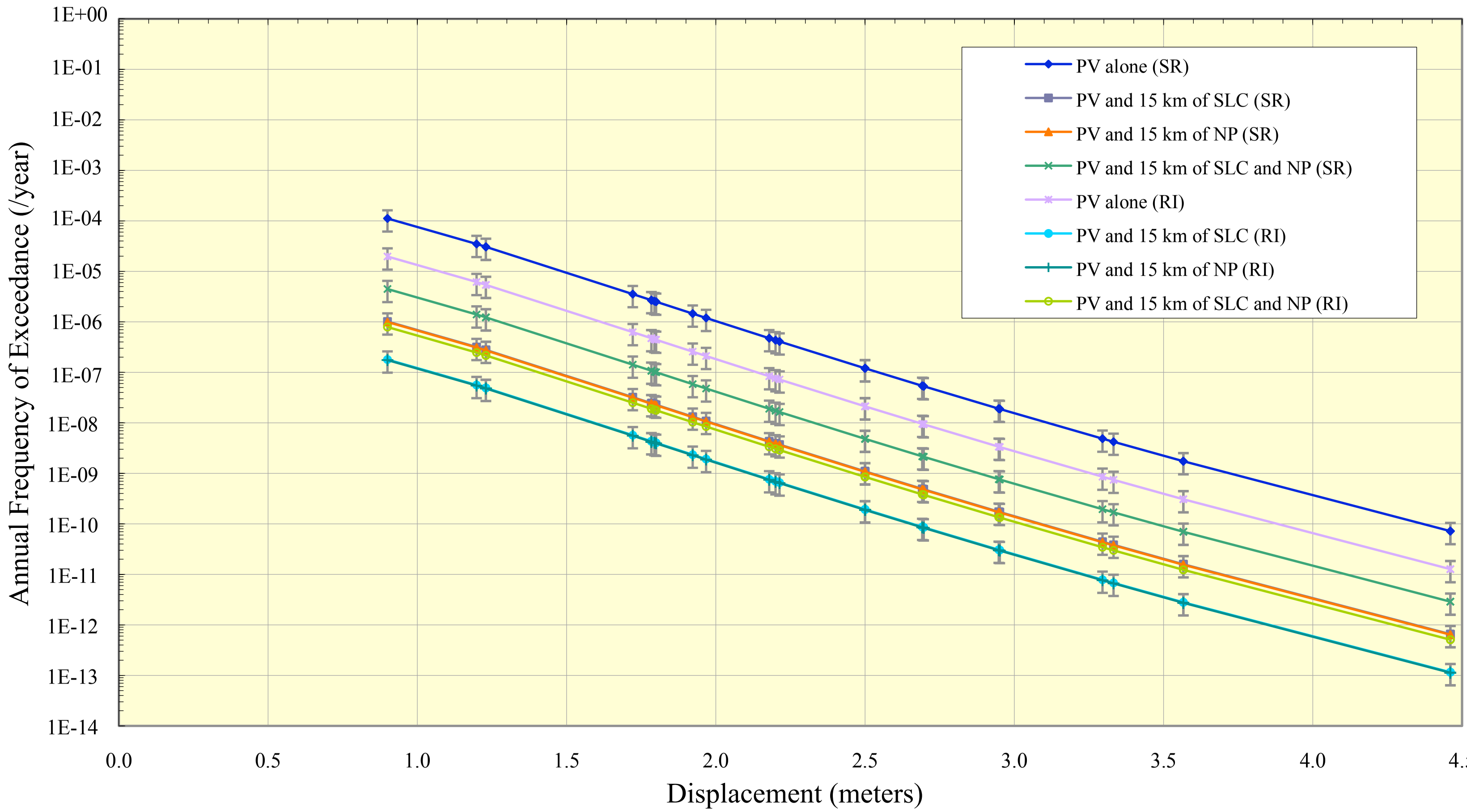


Figure 18. Provo segment hazard curves with D_{max} as the normalizing factor. D_{avg} for the segment is 2.1 meters and D_{max} for the segment is 3.0 meters. Abbreviations: NP = Nephi segment, PV = Provo Segment, SLC = Salt Lake City Segment SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

normalizing variable. The results from all of the various scenarios from the Salt Lake City segment branch of the logic tree are captured in these curves.

Nephi Segment

Nephi Segment Fault Information

The Nephi segment, located to the south of the Provo segment, was the southern most end segment considered in this study (Figure 1). This is 40 kilometers long (Table 2). The most recent event on this segment was1148 ± 68 years before present (Table 1). The maximum and average fault displacements at the midpoint of the segment were estimated to be 2.4 meters and 1.7 meters, respectively. Again, Chang and Smith (1998) estimated the maximum fault displacement and the average displacement value were estimated from the maximum value, assuming an elliptical fault displacement distribution. These displacement values correlate to M_s 7.0 and M_s 6.9 earthquakes (Mason, 1996), respectively, with annual frequencies of 8.93×10^{-4} and 2.32×10^{-3} based on Chang and Smith's (1998) single segment model. For the multisegment model, these magnitudes correspond to annual frequencies of 5.36×10^{-4} and 8.93×10^{-3}, respectively.

Nephi Segment Fault Displacement Hazard Results

As was the case with the Brigham City Segment, the Nephi segment is an end segment and therefore only two scenarios were considered. The first is the full rupture of the Nephi segment alone (40 kilometers). The second is the full rupture of the Nephi segment and consideration of the initiation of simultaneous rupture on the closest 15 kilometers on the Provo segment to the north (55 kilometers).

The full set of hazard curves for the Nephi segment are shown in Figures 19 and 20. These curves resulted from the calculations that considered D_{avg} and D_{max} as the normalizing variable. The results from all of the various scenarios from the Nephi segment branch of the logic tree are captured in these curves.

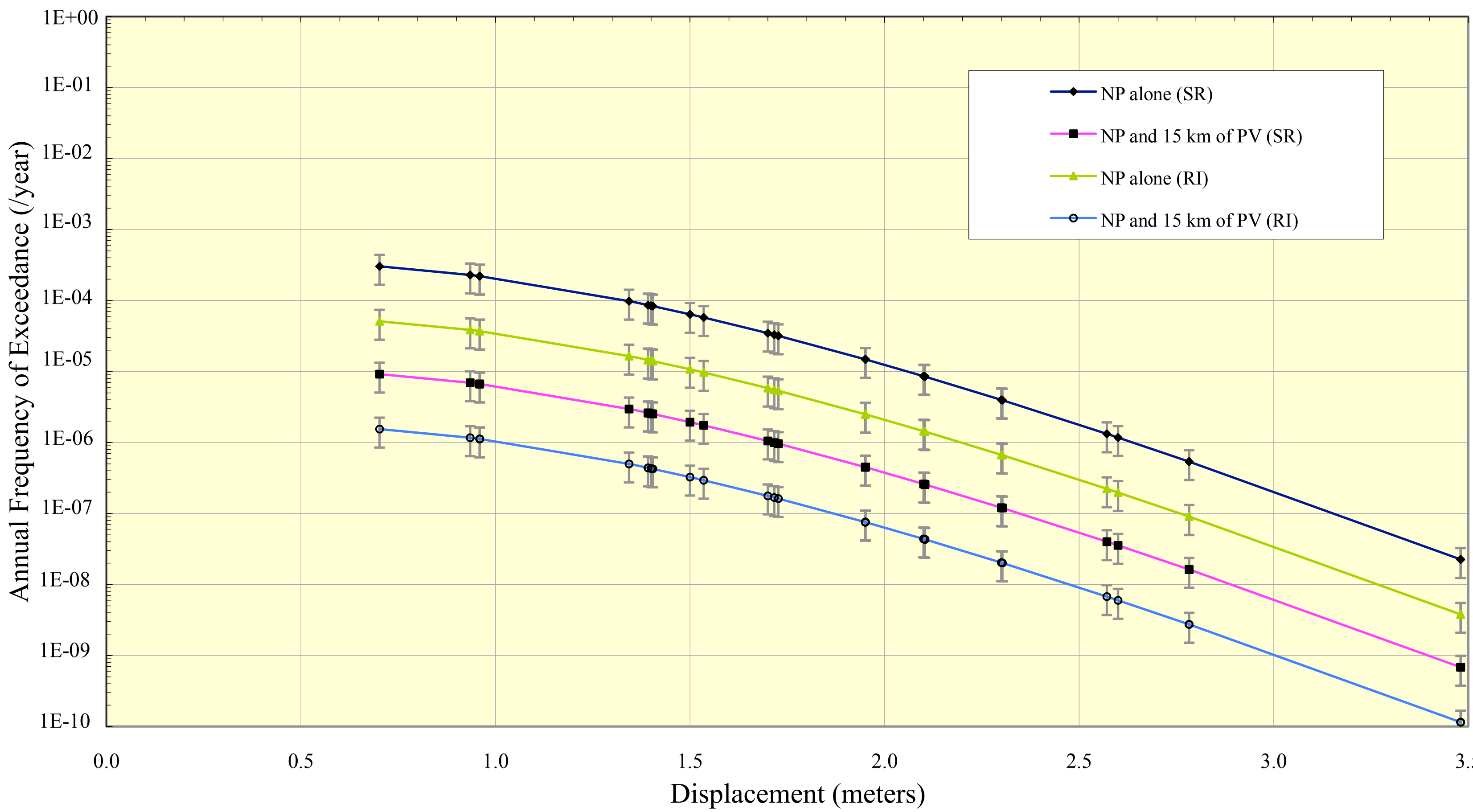


Figure 19. Nephi segment hazard curves with D_{avg} as the normalizing factor. D_{avg} for the segment is 1.7 meters and D_{max} for the segment is 2.4 meters. Abbreviations: NP = Nephi segment, PV = Provo Segment, SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

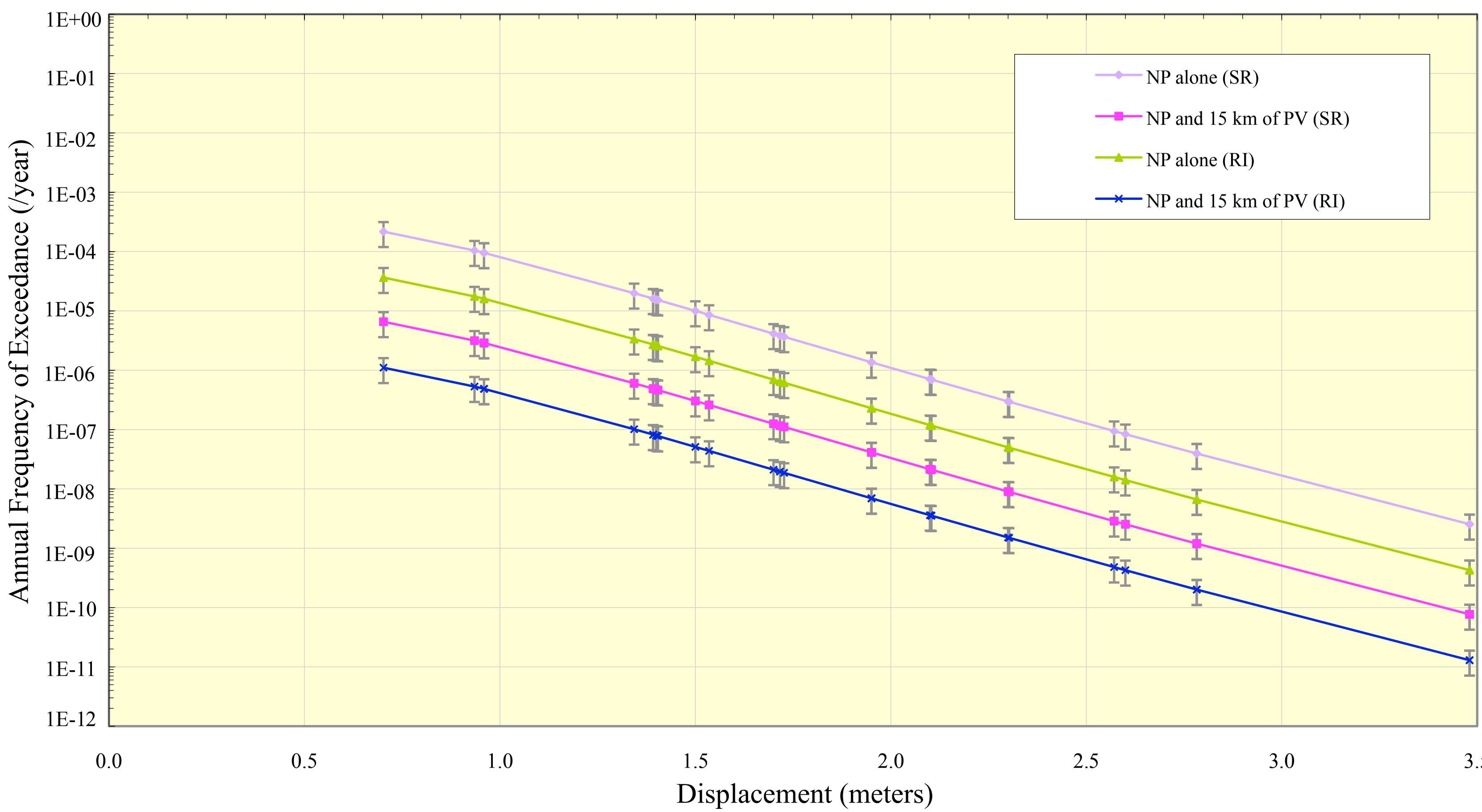


Figure 20. Nephi segment hazard curves with D_{max} as the normalizing factor. D_{avg} for the segment is 1.7 meters and D_{max} for the segment is 2.4 meters. Abbreviations: NP = Nephi segment, PV = Provo Segment, SR = Slip Rate model used for frequency estimation, RI = Recurrence model used for frequency estimation. Uncertainty bands (5% and 95%) shown.

DISCUSSION OF RESULTS

The values from which the hazard curves (Figures 11-20) were generated are tabulated in Appendix D. For a comparative review of the information calculated in the hazards curves, Table 5 and Figures 21, 22, 23 and 24 were generated. They display the relative annual frequency of exceeding 1, 2, and 3 meters of displacement on each if the five subject segments of the Wasatch fault using four variations of the model. They allow for a relative survey of the frequency of exceeding the specified displacements between each of the five subject fault segments.

Figure 21 accounts for the set of calculations that considered the single segment, slip rate model, with D_{avg} as the normalizing factor. Figure 22 accounts for the set of calculations that considered the single segment, recurrence interval model, with D_{avg} as the normalizing factor. Figure 23 accounts for the set of calculations that considered the single segment, slip rate model, with D_{max} as the normalizing factor. Finally, Figure 24 accounts for the set of calculations that considered the single segment, recurrence interval model, with D_{max} as the normalizing factor. Note that the values displayed on these four summary plots relate to the displacement at the midpoint of length of the fault segment and values for other locations along the fault can be extrapolated using the elliptical displacement distribution discussed earlier.

TABLE 5

Summary of results comparing annual frequency of exceeding 1, 2, and 3 meters of displacement *single segment* model*

Segment Name	Rupture Scenario	Rupture Length (km)	Fault Displacement (m)	Annual Frequency of Exceedance based on Davg SR model	Annual Frequency of Exceedance Based on Davg RI model	Annual Frequency of Exceedance based on Dmax SR model	Annual Frequency of Exceedance based on Dmax RI model
Brigham City (BC)	BC alone	38	1	1.5e-4	6.95e-5	6.03e-5	2.76e-5
			2	9.2e-6	4.21e-6	8.12e-7	3.71e-7
			3	5.6e-7	3.57e-8	1.04e-9	2.36e-10
Weber (WB)	WB Alone	61	1	1.76e-4	7.11e-5	6.97e-5	2.82e-5
			2	9.40e-6	3.80e-6	8.07e-7	3.27e-7
			3	4.75e-7	1.11e-7	2.08e-8	8.44e-9
Salt Lake City (SLC)	SLC alone	46	1	1.48e-4	4.62e-5	4.33e-5	1.35e-5
			2	1.33e-5	4.14e-6	1.02e-6	3.73e-7
			3	2.19e-7	6.81e-8	1.72e-8	5.39e-9
Provo (PV)	PV alone	70	1	2.00e-4	3.13e-5	2.56e-4	1.97e-5
			2	5.40e-6	1.96e-6	2.99e-7	8.34e-8
			3	2.43e-7	4.01e-8	1.88e-8	3.33e-9
Nephi (NP)	NP alone	40	1	1.03e-4	2.47e-5	1.00e-4	1.35e-5
			2	8.60e-6	1.45e-6	7.06e-7	1.19e-7
			3	3.85e-7	4.36-8	1.35e-8	4.43e-9

* See Figures 21, 22, 23, and 24

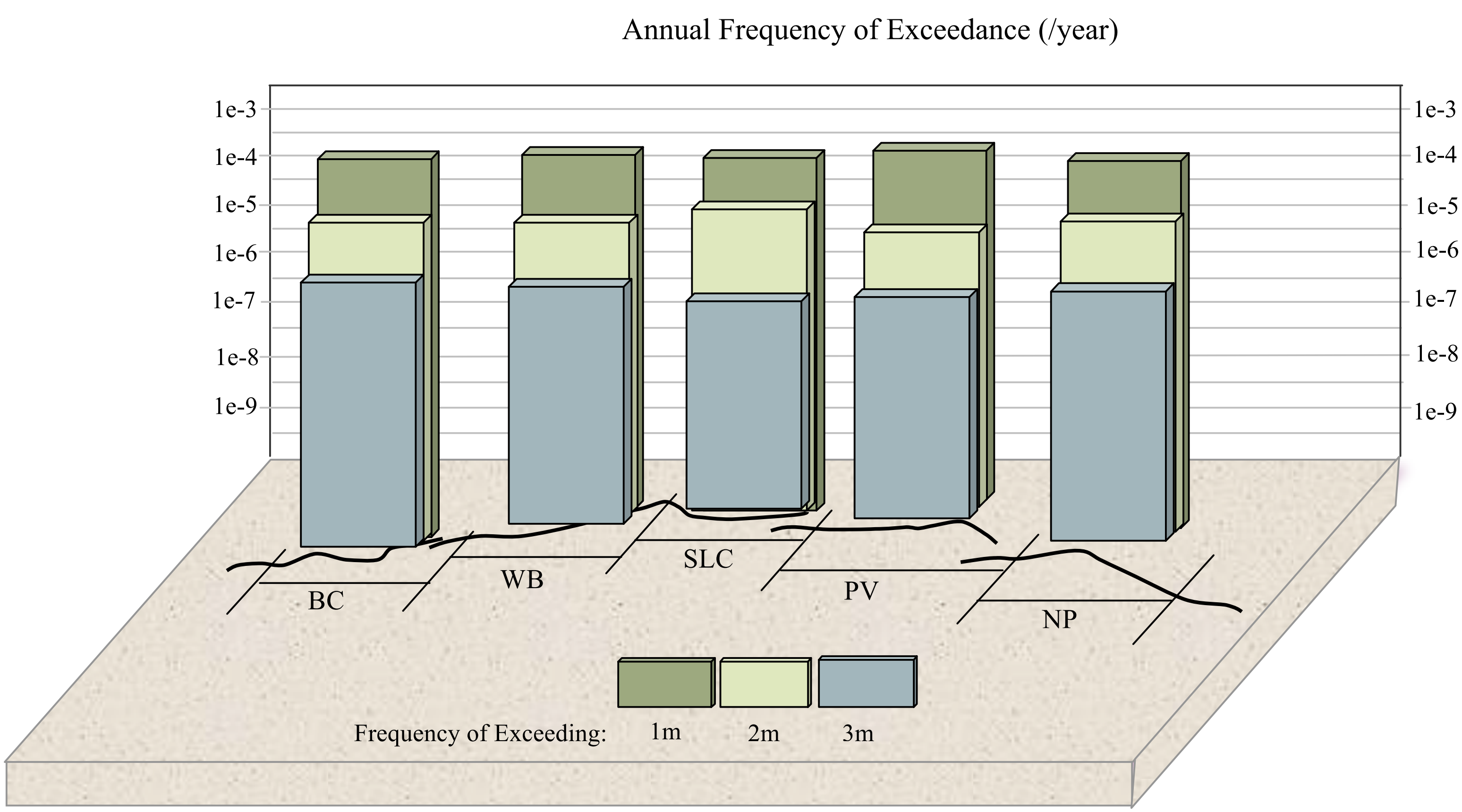


Figure 21. Comparative annual frequency of exceeding 1 meter, 2 meters, and 3 meters of displacement using single segment model, slip rate model, and D_avg as the normalizing factor. Abbreviations: BC=Brigham City Segment, WB= Weber Segment, SLC= Salt Lake City Segment, NP= Nephi segment, Pv= Prove Segment.

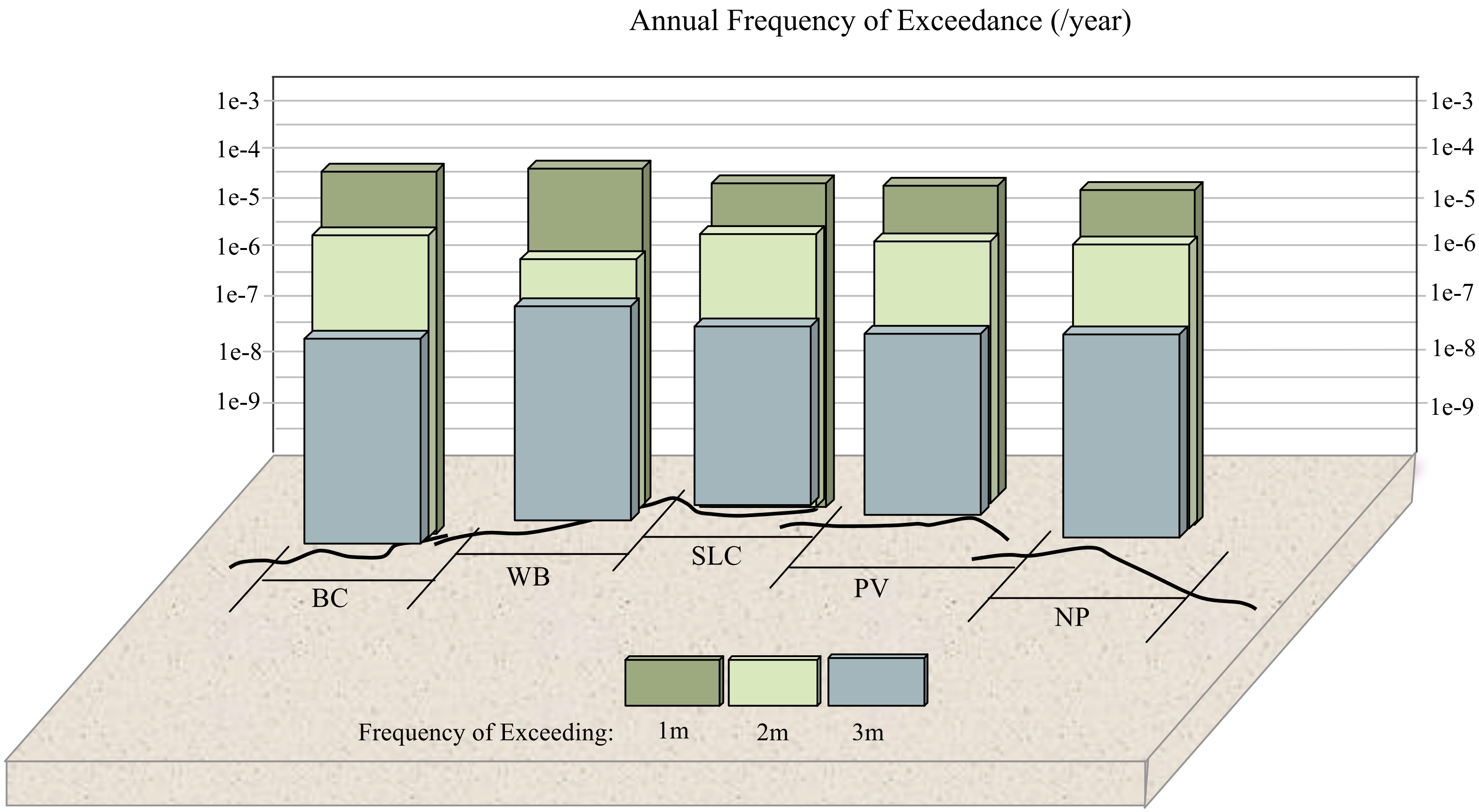


Figure 22. Comparative annual frequency of exceeding 1 meter, 2 meters, and 3 meters of displacement using single segment model, slip rate model, and D_avg as the normalizing factor. Abbreviations: BC=Brigham City Segment, WB= Weber Segment, SLC= Salt Lake City Segment, NP= Nephi segment, Pv= Prove Segment.

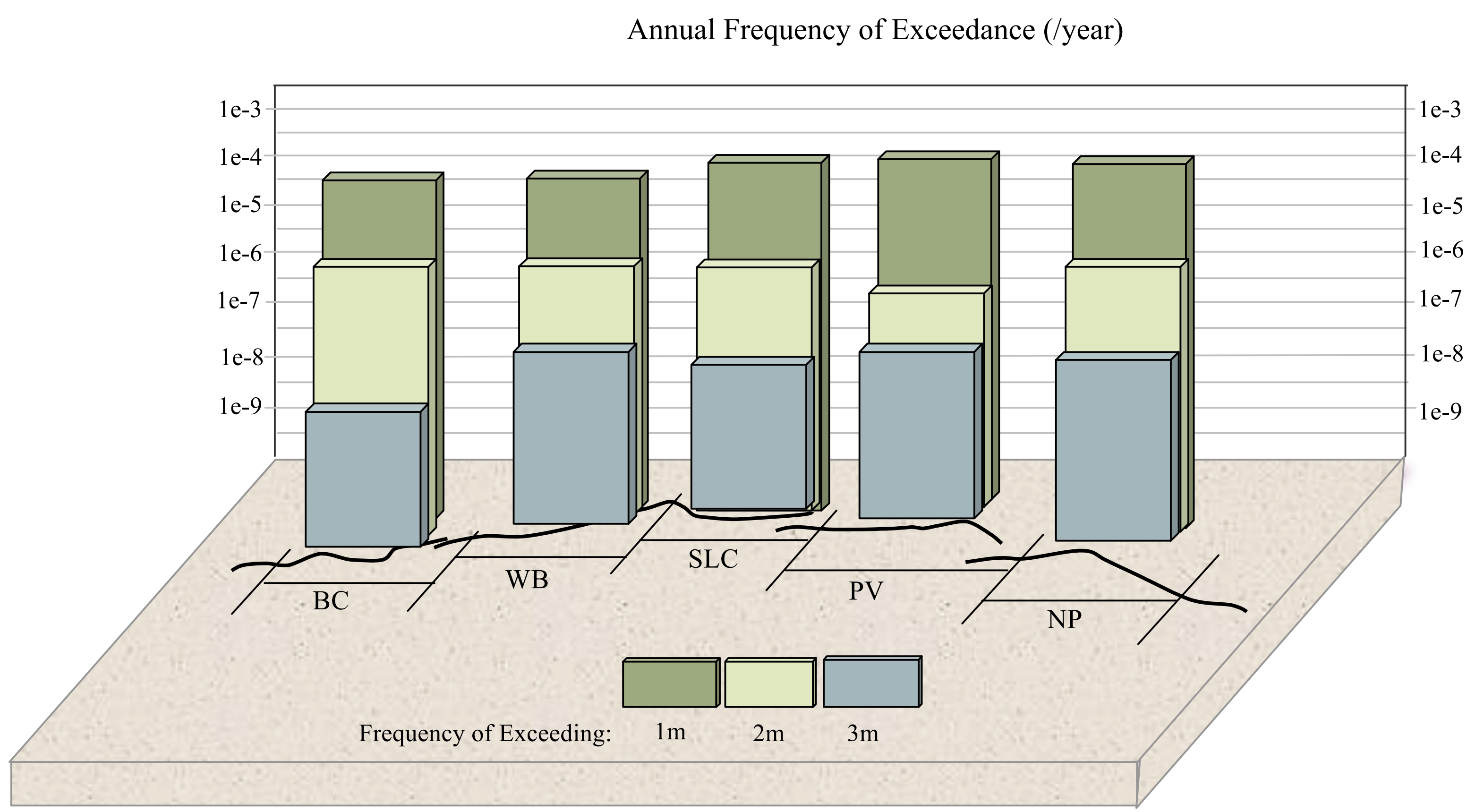


Figure 23. Comparative annual frequency of exceedign 1 meter, 2 meters, and 3 meters of displacement using single segment model, slip rate model, and D_avg as the normalizing factor. Abbreviations: BC=Brigham City Segment, WB= Weber Segment, SLC= Salt Lake City Segment, NP= Nephi segment, Pv= Prove Segment.

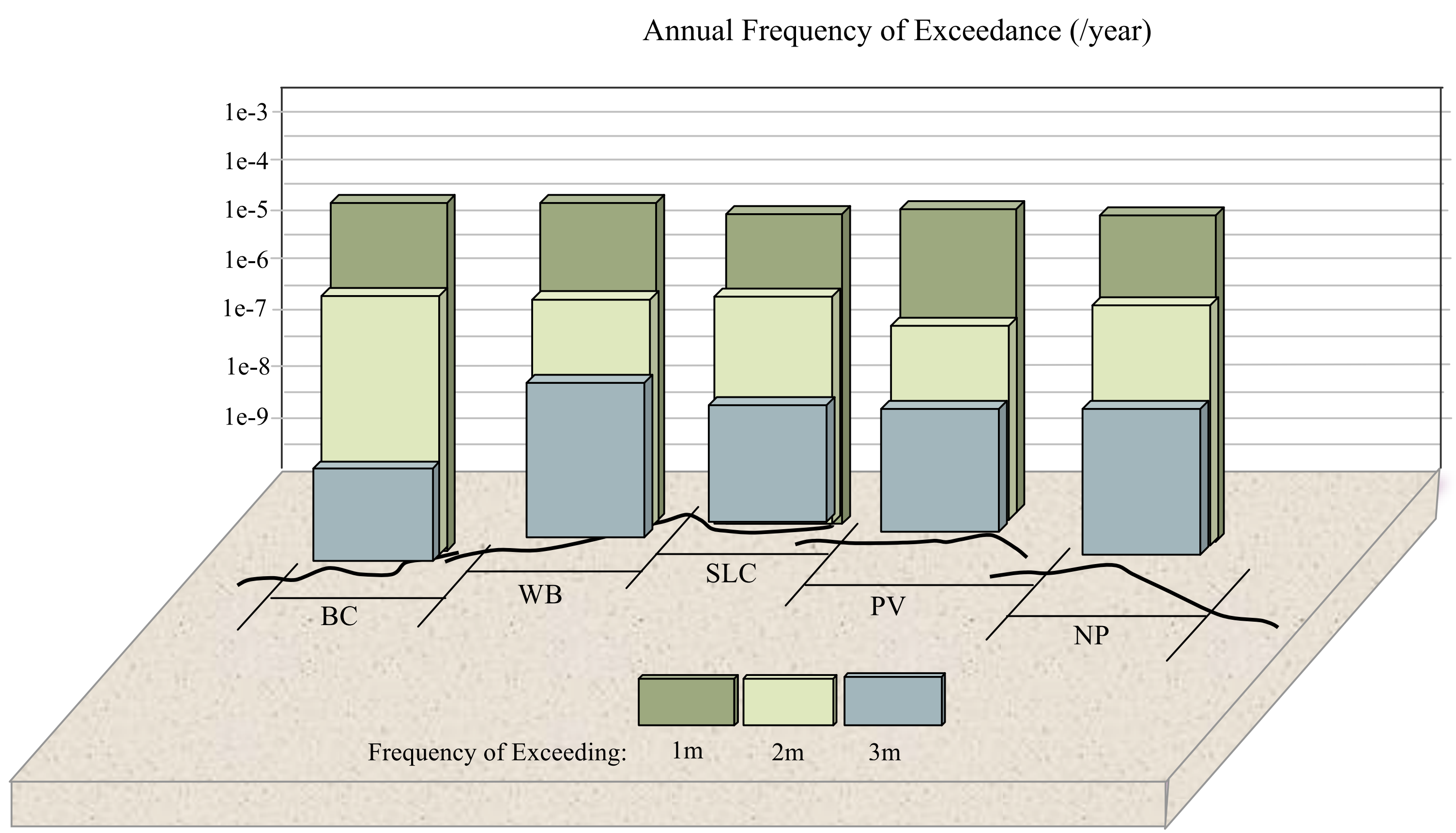


Figure 24. Comparative annual frequency of exceedign 1 meter, 2 meters, and 3 meters of displacement using single segment model, reoccurance interval model, and D_avg as the normalizing factor. Abbreviations: BC=Brigham City Segment, WB= Weber Segment, SLC= Salt Lake City Segment, NP= Nephi segment, Pv= Prove Segment.

For a relative review of the multisegment model, Table 6 and Figure 25 show the relative frequencies of exceeding 2 meters of displacement for the Salt Lake City segment and considers the single segment and multisegment models for the Salt Lake City segment. For simplicity, only the results from the model that used the slip rate to estimate the recurrence of earthquakes and D_{avg} to normalize the fault displacement data are displayed.

Similar figures could be developed for the other segments to display the variations of this model. The annual frequency of exceedance values for 1, 2, and 3 meters of displacements for all of the segments and models are tabulated in Appendix C.

TABLE 6

Summary of results comparing annual frequency of exceeding 2 meters of displacement for the Salt Lake City segment*

Rupture Scenario	Annual Frequency of Exceeding 2 meters of displacement**
SLC alone	1.33×10^{-5}
SLC and 15 km of WB	3.50×10^{-7}
SLC and 15 km of PV	1.75×10^{-7}
SLC and 15 km of WB and PV	3.70×10^{-7}

* See Figure 25
**Annual frequency values based on slip rate model and displacement values normalized with the average displacement

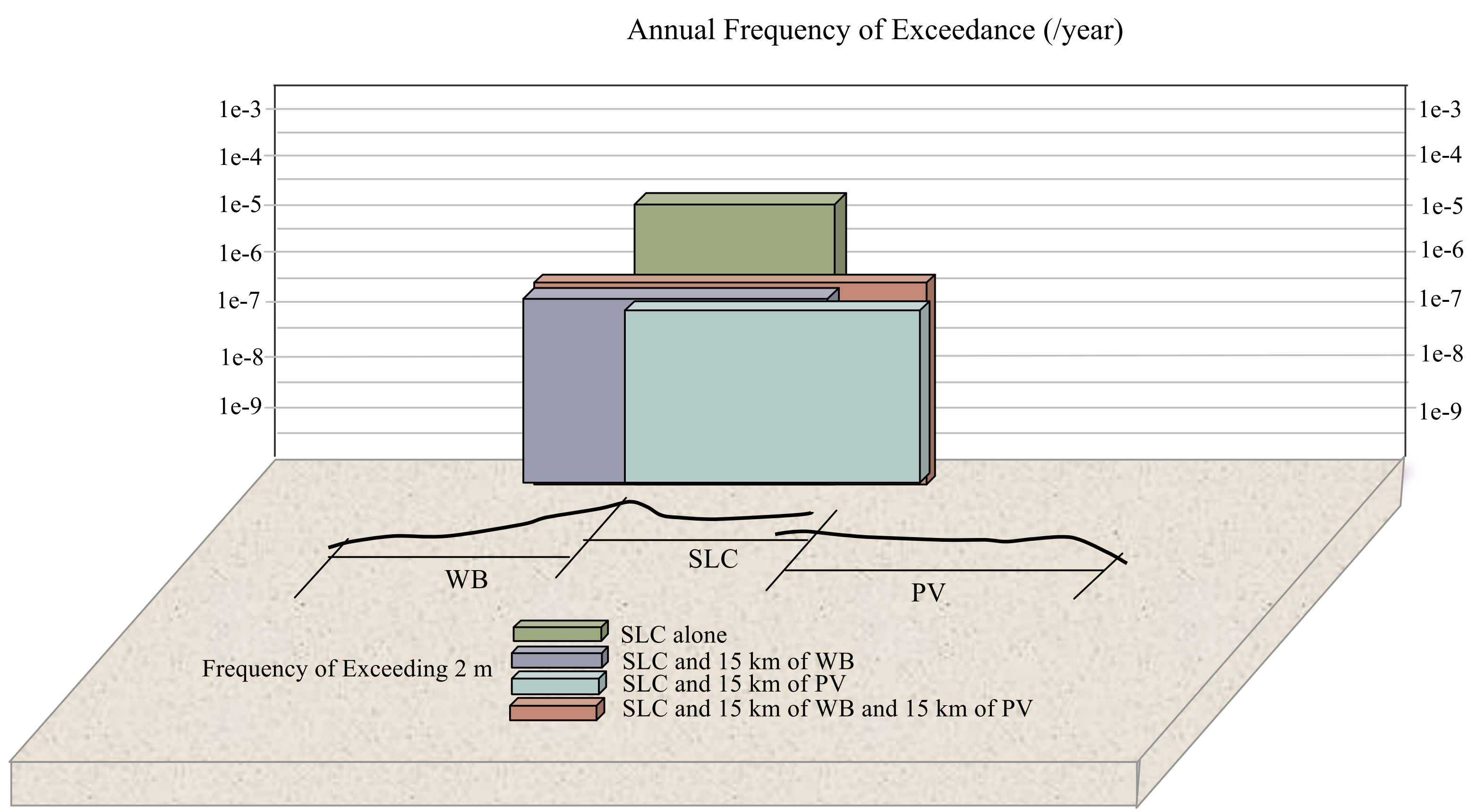


Figure 25. Comparative annual frequency of exceedign 1 meter, 2 meters, and 3 meters of displacement using single segment model, slip rate model, and D_avg as the normalizing factor. Abbreviations: BC=Brigham City Segment, WB= Weber Segment, SLC= Salt Lake City Segment, NP= Nephi segment, Pv= Prove Segment.

From inspection of Figures 21, 22, 23, and 24, the expected trend of decreasing annual frequency of exceedance with increasing fault displacement is clearly displayed. Additionally, for each model used for evaluation, the frequency of exceeding 1 meter of displacement is consistent across all five segments (i.e., they are all on the same order of magnitude). However this value does generally vary by an order of magnitude when using the slip rate model versus the recurrence interval model (10^{-4} /year versus 10^{-5} /year, respectively).

The frequency values for exceeding 2 meters are relatively consistent across the segments; they vary by one order of magnitude between the different segments. As was the case with 1 meter of displacement, with 2 meters there is also an approximate variation of one order of magnitude when comparing the values calculated using the slip rate model to those calculated using the recurrence interval model.

In contrast to the extremely consistent (same order of magnitude) frequency estimates across the segments for 1 meter and even the relatively consistent (within an order of magnitude) frequency estimates for 2 meters of displacement, the frequency estimates for 3 meters of displacement vary substantially between the different segments ($\sim 10^{-5} - \sim 10^{-9}$). Again values calculated using the slip rate model are consistently approximately an order of magnitude higher than for those values calculated using the recurrence interval model.

To substantiate the results of this model, a comparison of these results was made to the expected annual frequency values from Chang and Smith (1998) previously discussed for each segment. Between all of the segments, the expected average and maximum displacement values vary between 1.2 and 3.0 meters, which correspond to earthquakes of M_s 6.9 and M_s 7.2 (Mason, 1996) (Appendix B), respectively, and single segment model annual frequencies of 10^{-4} and zero (Chang and Smith, 1998), respectively. For the single segment model used in this study, the range of annual frequencies is 10^{-4} to 10^{-9} for displacement values between 1 and 3 meters of displacement (Figure 21, 22, 23, and 24, Table 5, and Appendix C). This yields a high correlation (on the same order of magnitude) between Chang and Smith's (1998) single segment model annual frequency values and the values generated by this model.

Less specific comparisons were made to existing PSHA studies on the Wasatch fault. Youngs and others (1987) describe the recurrence rate of a M_s 7 earthquake to be on the order of 10^{-4}/year based on a single segment model of the Wasatch fault. Wong and others (1995) found similar results. Their estimated return period for a M_s 7 earthquake (~10^{-4}/year) is consistent with the single segment results of this study.

A similar, substantiating comparison was made for the multisegment model. From the previous discussion of annual frequency values for the expected average and maximum displacement for each segment, the range of 1.2 to 3.0 meters of displacement correspond to Chang and Smith's (1998) multisegment model annual frequencies of 10^{-3} and 10^{-4}, respectively. The corresponding values from this study's multisegment model are 10^{-5} to 10^{-10}. In contrast to the single segment model, this yields a low correlation (vary by several orders of magnitude) between Chang and Smith's (1998) multisegment model annual frequency values and the values generated by this model.

The low correlation between this and Chang and Smith's (1998) multisegment model may, in part, be due to the disparities in the models used. The annual frequencies generated by this study are dependent upon the probability of segment rupture (single segment) and rupture across segment boundaries (multisegment). The probability of rupture across the segment boundaries was substantially lower than those for the single segments (Table 4). In contrast, Chang and Smith's (1998) annual frequencies are calculated based on magnitude and its scaled dependency upon rupture length and fault displacement.

The results of this study's multisegment model are not consistent with current empirical length and displacement to magnitude scales. The rupture scenario weights for rupture across segment boundaries limits this model; the frequency of rupture across segments is less likely to occur than a M_w 7 earthquake, regardless of segment boundaries. With this, a direct comparison should and cannot be made.

CONCLUSIONS

To understand the results of this study, a comparison was made between the annual frequencies of exceeding 1, 2, and 3 meters of displacement. Depending on which specific scenario is considered and the specific location along the Wasatch fault, the results from this study yield annual frequency of exceeding 1 meter of displacement between the range of 10^{-4}/year to 10^{-7}/year. For 2 meters of displacement the annual frequency of exceedance ranged between 10^{-5} /year to 10^{-9} /year. For 3 meters, the values ranged between 10^{-6} /year to 10^{-11} /year.

The results suggest that the frequency of exceeding 3 meters of displacement is very dependent upon the specific fault segment length; whereas the frequency of exceeding 1 or 2 meters of displacement is relatively independent of the specific segment length. This comparative trend is independent of the model used (e.g., single segment, multisegment), but is more likely dependent up the direct empirical scaling relationship between fault length and fault displacement.

In contrast, this study shows that the actual annual frequencies of exceedance values are dependent upon the uncertainties in the source and interpretation of the variables in the calculations. When looking at the calculated results from the various branches of the logic tree, there appears to be no significant variance in the frequency estimates when using D_{avg} as the normalizing variable versus using D_{max} as the normalizing variable. To the contrary, there is at least one order of magnitude variance in the frequency estimates when using the slip rate method for determining the frequency of events, versus the recurrence interval method for estimating the frequency of events. This calculated discrepancy is obviously, in part, due to the relative weights assigned to the frequency of events branch of the logic tree. The results of this study clearly show the role and importance of the uncertainties as they are incorporated into the hazard calculations.

A high correlation (same order of magnitude) was found between the concluding values from this study's single segment model and other existing single segment models (Chang and Smith, 1998; Youngs and others, 1987; Wong and others, 1995). Thus, this high correlation substantiates the results of the single segment model.

A considerable discrepancy was found, however, between this study's multisegment results and those from Chang and Smith (1998). The low correlation (vary by several orders of magnitude) is most likely due to the selection of model parameters. This multisegment model is dependent upon the probability of rupture across segments and Chang and Smith's (1998) is dependent upon magnitude-length scaling. A comparison and correlation between the results of the two models is perhaps a subject for further consideration. The results of this should be considered with the input and model parameters in mind.

Despite the low probability of annual exceedance values (10^{-5}–10^{-10}/year) generated by the multisegment model, it is likely of most importance for assessing the displacement hazards on the Wasatch fault. The longer fault rupture lengths associated with the multisegment model combined with the scaled fault displacement values, yield a higher risk of significant damage to structures that cross the fault.

An important point to note is that this study considered only select scenarios when developing the hazard curves. Heavy emphasis should be placed on the fact that any number of scenarios could potentially be evaluated. The methods used to develop this PDHA model allows the user to incorporate as few or as many scenarios as are necessary for their purpose.

A PDHA study has not been done on the Wasatch Front until now. With respect to the Wasatch Front, the hazards associated with fault displacement will have a significant impact on the Wasatch Front population as a whole. The Wasatch Front is unique in that the majority of the critical lifeline utilities that serve the Wasatch Front cross the fault. Compare this to other seismically active communities like Los Angeles or San Francisco where the lifeline utilities are much more distributed around the communities.

Along these same lines, but outside the scope of this study is the consideration of the effects of the Wasatch fault on its associated distributed faults. A scaled comparison of the effects of fault displacement hazards on the West Valley and other valley faults would show the potential impact that activity on the Wasatch fault might have on these secondary faults and their associated impact on utilities. The results from such a study would further substantiate the hazards associated with displacement on the Wasatch fault.

Given the annual frequency of exceedance results from this study, the distribution of the Wasatch Front population, and the proximity of the lifeline utilities, the Wasatch fault displacement hazards could have a much more profound effect than considered heretofore. Disruption of the Wasatch Front's critical lifeline utilities from fault displacement may very well have as large of an impact on a the Wasatch Front population as ground shaking (although the nature, duration, and severity of impact may vary).

The PDHA, in combination with a PSHA, exposure analysis, and review of the economic impact, can be used to evaluate the overall risk due to fault displacement hazards on the Wasatch fault.

APPENDIX A

WASATCH FAULT DISPLACEMENT HAZARDS

LOGIC TREE

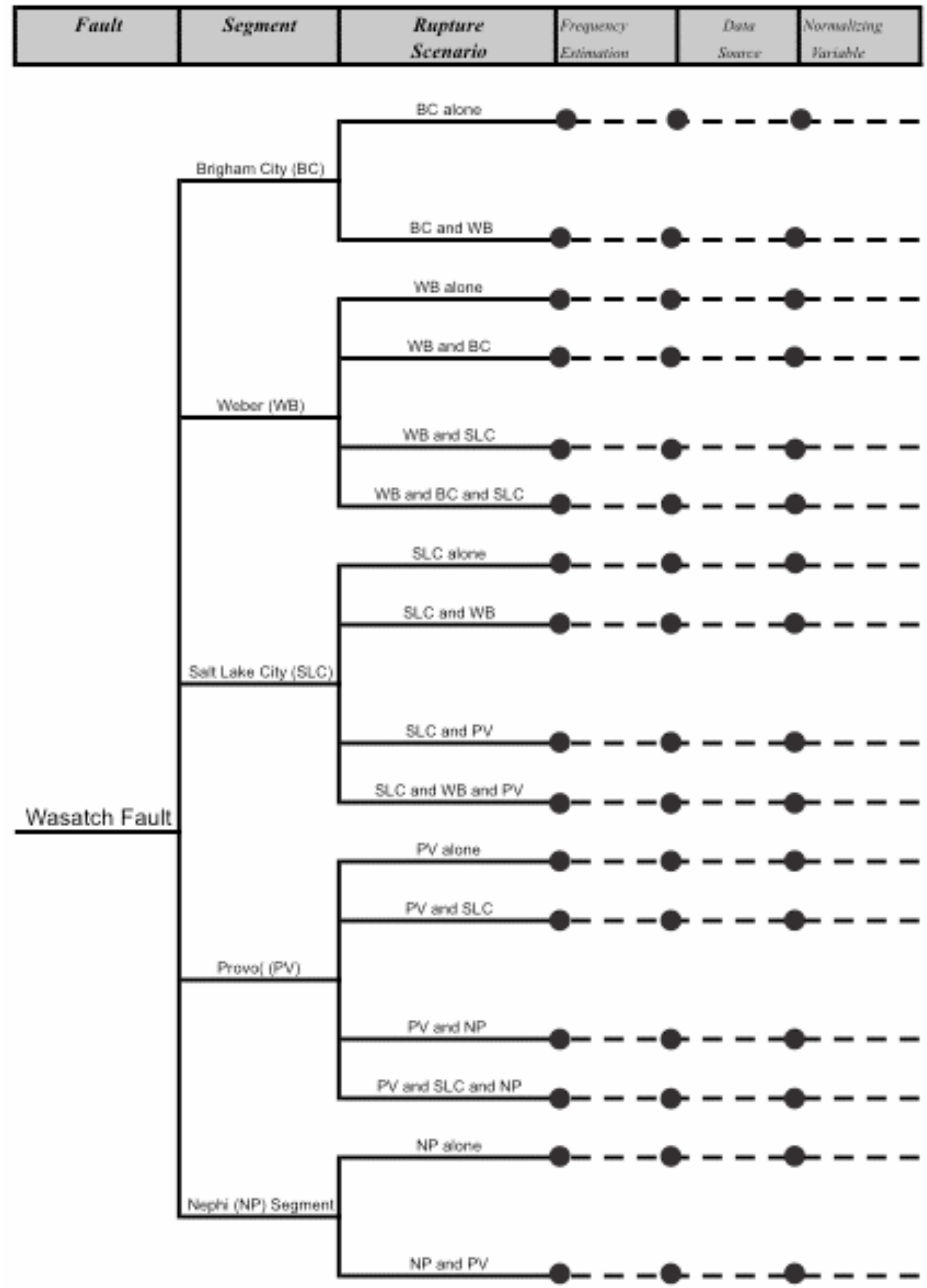


Figure 26. General layout for the Wasatch fault displacement hazard logic tree.

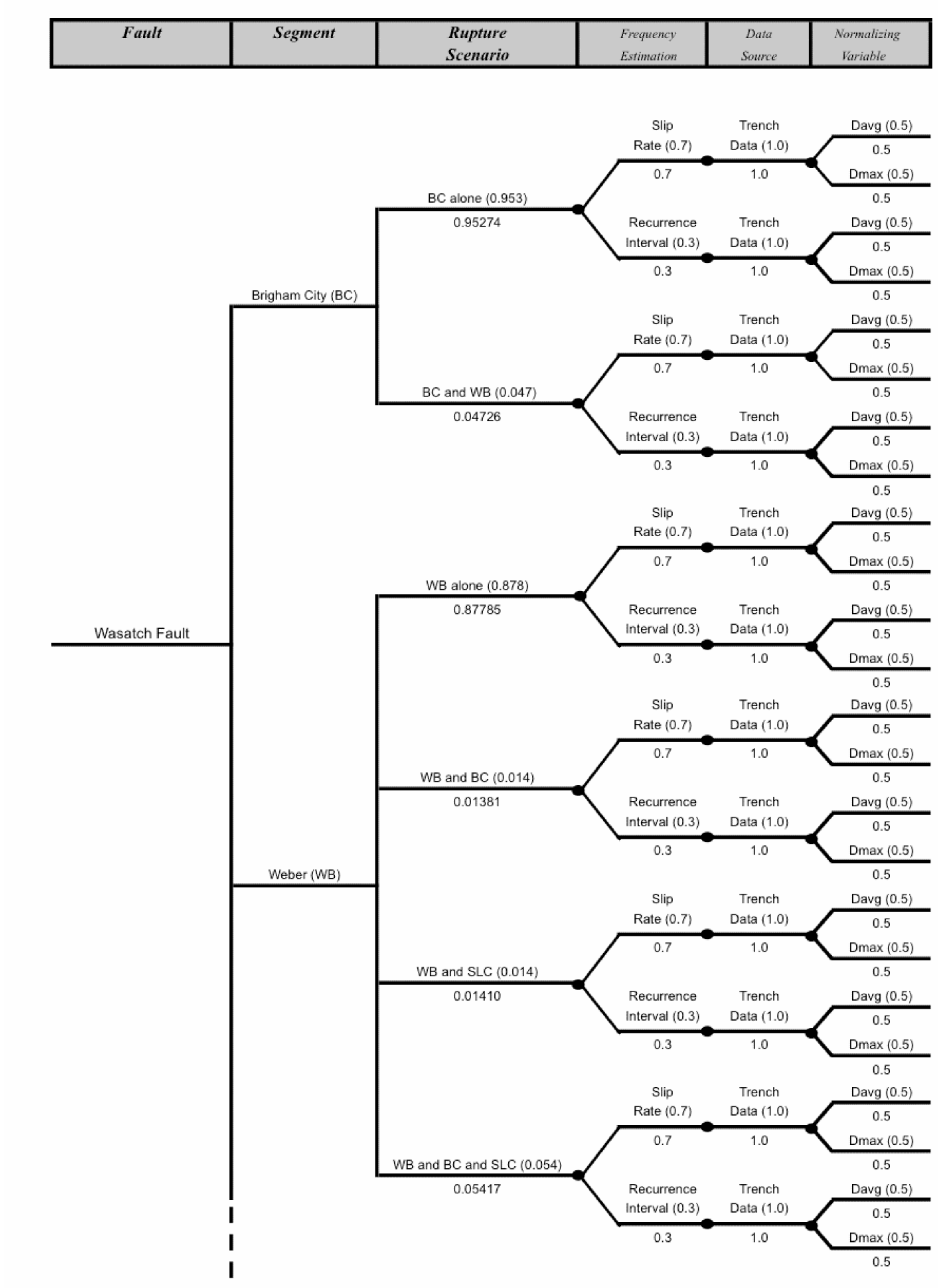


Figure 27. Detailed Wasatch Fault displacemant hazard logic tree.

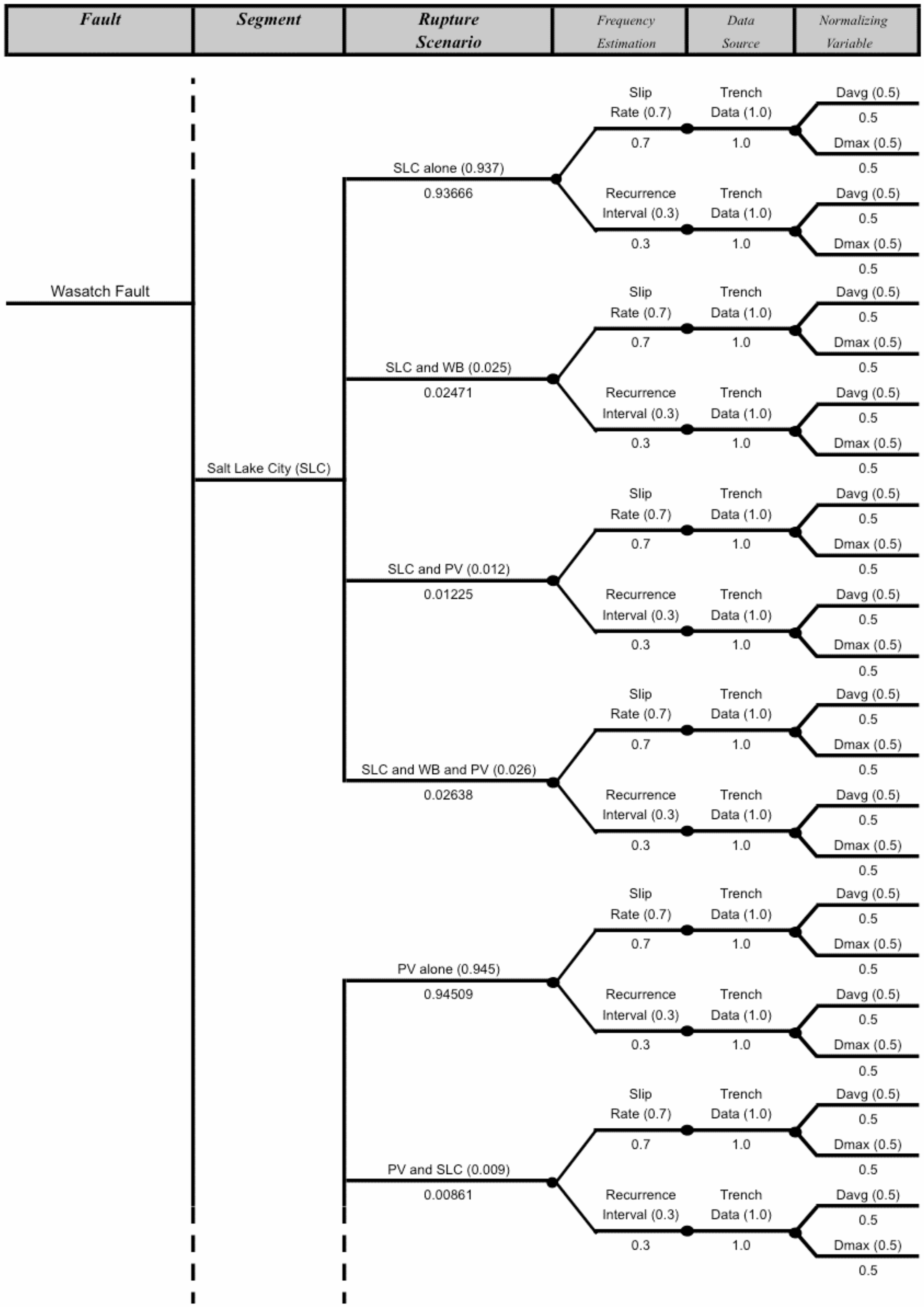


Figure 27. Detailed Wasatch Fault displacemant hazard logic tree *CONTINUED*

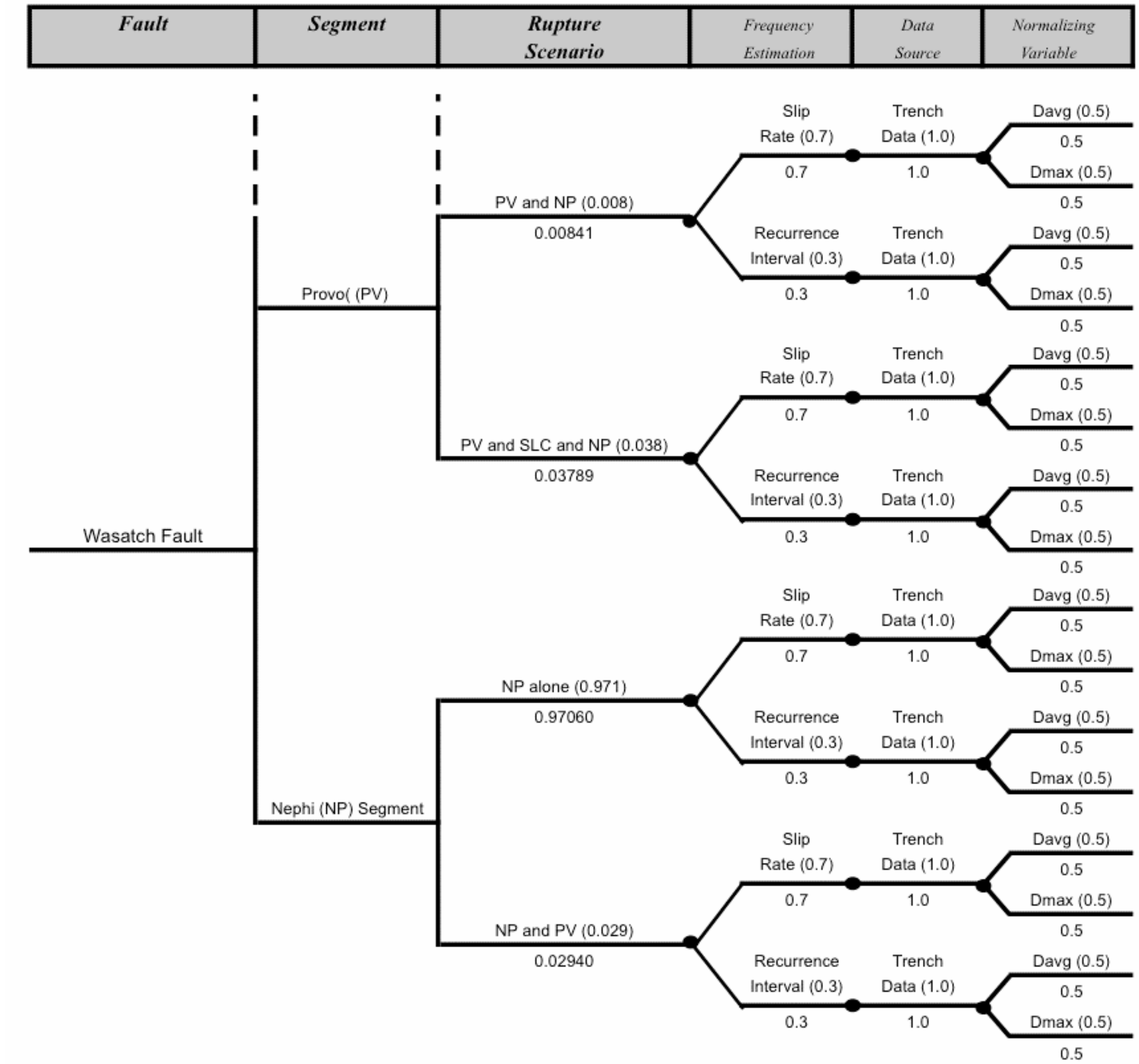


Figure 27. Detailed Wasatch Fault displacemant hazard logic tree *CONTINUED*

APPENDIX B

COMPARISON OF EARTHQUAKE MAGNITUDE BASED ON EMPIRICAL RELATIONSHIPS

TABLE 7

Comparison of earthquake magnitudes based on empirical relationships

Rupture Scenario *	D** (m)	L** (km)	Ms(1)	Mw(2)	Mw(3)
BC alone	1	38	6.82	6.61	6.95
	2	38	6.98	6.82	6.95
	3	38	7.08	6.95	6.95
BC and 15 km of WB	1	53	6.90	6.61	7.14
	2	53	7.06	6.82	7.14
	3	53	7.16	6.95	7.14
WB alone	1	61	6.93	6.61	7.22
	2	61	7.10	6.82	7.22
	3	61	7.19	6.95	7.22
WB and 15 km of BC *or* WB and 15 km of SLC	1	76	6.98	6.61	7.34
	2	76	7.15	6.82	7.34
	3	76	7.25	6.95	7.34
WB and 15 km of BC *and* 15 km of SLC	1	91	7.03	6.61	7.45
	2	91	7.19	6.82	7.45
	3	91	7.29	6.95	7.45
SLC alone	1	46	6.86	6.61	7.05
	2	46	7.03	6.82	7.05
	3	46	7.13	6.95	7.05
SLC and 15 km of WB *or* 15 km of PV	1	61	6.93	6.61	7.22
	2	61	7.10	6.82	7.22
	3	61	7.19	6.95	7.22
SLC and 15 km of WB *and* 15 km of PV	1	76	6.98	6.61	7.34
	2	76	7.15	6.82	7.34
	3	76	7.25	6.95	7.34
PV alone	1	70	6.96	6.61	7.30
	2	70	7.13	6.82	7.30
	3	70	7.23	6.95	7.30
PV and 15 km of SLC *or* 15 km of NP	1	85	7.01	6.61	7.41
	2	85	7.18	6.82	7.41
	3	85	7.27	6.95	7.41
PV and 15 km of SLC and 15 km of NP	1	100	7.05	6.61	7.50
	2	100	7.22	6.82	7.50
	3	100	7.31	6.95	7.50
NP alone	1	40	6.83	6.61	6.97
	2	40	7.00	6.82	6.97
	3	40	7.09	6.95	6.97
NP and 15 km of PV	1	55	6.91	6.61	7.16
	2	55	7.07	6.82	7.16
	3	55	7.17	6.95	7.16

* See Figure 1

** D = vertical fault displacement; L = surface rupture length

(1) $Ms = 0.55 Log(DL) + 5.95$ (Mason, 1996)

(2) $Mw = 0.71 Log(D) + 6.61$ (Wells and Coppersmith, 1994)

(3) $Mw = 1.32 Log(L) + 4.86$ (Wells and Coppersmith, 1994)

APPENDIX C

SUMMARY OF RESULTS COMPARING ANNUAL FREQUENCY OF EXCEEDING 1, 2, AND 3 METERS OF DISPLACMENT USING VARIOUS MODELS

TABLE 8

Summary of results comparing annual frequency of exceeding 1, 2, and 3 meters of displacement using various models

Segment Name	Rupture Scenario	Rupture Length (km)	Fault Displacement (m)	Annual Frequency of Exceedance based on Davg SR model	Annual Frequency of Exceedance Based on Davg RI model	Annual Frequency of Exceedance based on Dmax SR model	Annual Frequency of Exceedance based on Dmax RI model
Brigham City (BC)	BC alone	38	1	1.56e-4	6.95e-5	6.03e-5	2.76e-5
			2	9.21e-6	4.21e-6	8.12e-7	3.71e-7
			3	5.64e-7	3.57e-8	1.04e-9	2.36e-10
	BC and 15 km of WB	53	1	7.55e-6	3.45e-6	2.99e-6	1.37e-6
			2	4.57e-7	2.09e-7	4.03e-8	1.84e-8
			3	6.01e-8	2.13e-8	2.17e-9	1.42e-10
Weber (WB)	WB Alone	61	1	1.76e-4	7.11e-5	6.97e-5	2.82e-5
			2	9.40e-6	3.80e-6	8.07e-7	3.27e-7
			3	4.75e-7	1.11e-7	2.08e-8	8.44e-9
	WB and 15 km of BC	76	1	2.76e-6	1.12e-6	1.10e-6	4.44e-7
			2	1.48e-7	5.98e-8	1.27e-8	5.14e-9
			3	4.32e-9	1.75e-9	3.28e-10	1.33e-10
	WB and 15 km of SLC	76	1	2.82e-6	1.14e-6	1.12e-6	4.53e-7
			2	1.51e-7	6.11e-8	1.30e-8	5.25e-9
			3	4.41e-9	1.79e-9	3.35e-10	1.36e-10
	WB and 15 km of both BC and SLC	91	1	1.08e-5	4.40e-6	4.30e-6	1.74e-6
			2	5.80e-7	2.35e-7	5.00e-8	2.02e-8
			3	1.69e-8	6.86e-9	1.29e-9	5.21e-6
Salt Lake City (SLC)	SLC alone	46	1	1.48e-4	4.62e-5	4.33e-5	1.35e-5
			2	1.33e-5	4.14e-6	1.20e-6	3.73e-7
			3	2.19e-7	6.81e-8	1.72e-8	5.35e-9
	SLC and 15 km of WB	61	1	3.91e-6	1.22e-6	1.14e-6	3.56e-7
			2	3.50e-7	1.09e-7	3.15e-8	9.83e-9
			3	5.77e-9	1.80e-9	4.53e-10	1.41e-10

TABLE 8 *continued*

Segment Name	Rupture Scenario	Rupture Length (km)	Fault Displacement (m)	Annual Frequency of Exceedance based on Davg SR model	Annual Frequency of Exceedance Based on Davg RI model	Annual Frequency of Exceedance based on Dmax SR model	Annual Frequency of Exceedance based on Dmax RI model
	SLC and 15 km of PV	61	1	1.94e-6	6.04e-7	5.66e-7	1.77e-7
			2	1.74e-7	5.41e-8	1.56e-8	4.85e-9
			3	2.86e-9	8.91e-10	2.24e-10	7.00e-11
	SLC and 15 km of both WB and PV	76	1	4.17e-6	1.30e-6	1.22e-6	3.80e-7
			2	3.74e-7	1.17e-7	3.37e-8	1.00e-8
			3	6.16e-6	1.92e-9	4.83e-10	1.501e-10
Provo (PV)	PV alone	70	1	2.00e-4	3.13e-5	2.56e-4	1.97e-5
			2	5.40e-6	1.96e-6	2.99e-7	8.34e-8
			3	2.43e-7	4.01e-8	1.88e-8	3.33e-9
	PV and 15 km of SLC	85	1	2.00e-6	3.41e-7	1.01e-6	1.80e-7
			2	1.03e-7	1.46e-8	9.72e-9	1.90e-9
			3	2.21e-9	3.91e-10	1.72e-10	3.03e-11
	PV and 15 km of NP	85	1	1.54e-6	2.55e-7	9.93e-7	1.75e-7
			2	9.63e-8	1.42e-8	1.01e-8	1.02e-9
			3	2.16e-9	3.80e-10	1.68e-10	2.93e-11
	PV and 15 km of both SLC and NP	100	1	7.29e-6	1.20e-6	4.47e-6	7.89e-7
			2	3.11e-7	7.32e-8	1.90e-8	3.36e-9
			3	7.36e-9	9.37e-10	5.02e-10	1.00e-10
Nephi (NP)	NP alone	40	1	1.03e-4	2.47e-5	1.00e-4	1.35e-5
			2	8.60e-6	1.45e-6	7.06e-7	1.19e-7
			3	3.85e-7	4.36-8	1.35e-8	4.43e-9
	NP and 15 km of PV	55	1	5.12e-6	9.08e-7	2.02e-6	2.47e-7
			2	2.61e-7	4.38e-8	2.14e-8	3.60e-9
			3	3.29e-9	2.08e-9	7.70e-10	8.47e-11

APPENDIX D

WASATCH FAULT DISPLACEMENT HAZARD

EXCEL PROGRAM SPREADSHEETS

WASATACH FAULT DATA

D(m) = mean value of original fault displacement data

Dmax = average value of maximum displacement valuefor each segment from elliptical distribution (Chang and Smith, 1998)

Davg = average displacement values under elliptical curve

SR = mean value of slip rate (Chang and Smith, 1998)

RP = mean value of return period (Chang, 1999)

freq = SR/Davg or 1/RP

DETERMINE THE CUMULATIVE DISTRIBUTION FUNCTION

STATISTICAL DISTRIBUTION

Cumulative %

* *=HISTOGRAM(D/Dnorm, Cumulative Percentage)*

EMPIRICAL DISTRIBUTION

Gamma Distribution

* *=GAMMADIST[D/Dnorm, a, b, true]*

where a=[mean(D/Dnorm)/stdev(D/Dnorm)]^2 and b=a/mean(D/Dnorm)

Normal Distribution

* *=NORMDIST[D/Dnorm, mean(D/Dnorm)), stdev(D/Dnorm), true]*

* Lognormal Distribution

=NORMDIST[ln(D/Dnorm), mean(lnD/Dnorm), stdev(lnD/Dnorm), true]

* Exponential Distribution

=EXPONDIST[D/Dnorm, mean(D/Dnorm), true)

CALCULATE FREQUENCY OF EXCEEEDANCE

d=(D/Dnorm)*Dnorm*[displacement distribution for each segment]*

P(D>d) = 1-gamma *[for D/Dnorm]*

P(D>d) = 1-lognormal *[for D/Dmax]*

[apply empirical cumulative distributions to individual segment displacment distributions]

Frequency of Exceedance = P(D>d)*freq*Logic Tree Value [for each segment]

Plot d versus Frequency of Exceedance *[for each segment]*

WASATCH FAULT DATA

Original Data			*Noramlizing Variable*		*Normalized Data*		*Calc frequency from slip rate*		*Calc frequency from return period*	
Fault Name	*Trench Name*	*D(m) [mean]*	*Dmax [mean]*	*Davg [mean]*	*D/Dmax*	*D/Davg*	*SR (mm/yr) [mean]*	*freq = SR/Davg (/yr)*	*Return Period (RP) (yr) [mean]*	*Recurrence Interval RI = 1/RP (/yr)*
Brigham	BC	1			0.59	0.83				
		2.5			1.47	2.08				
		2.5			1.47	2.08				
	PP	1	1.70	1.20	0.59	0.83	0.94	7.82E-04	1200	8.33E-04
Weber	GC	1			0.41	0.57				
		1			0.41	0.57				
	EO	1.6			0.65	0.92				
		2.9			1.18	1.66				
		2.4			0.97	1.38				
	KV-88	1.8			0.73	1.03				
		2.9			1.18	1.66				
		1.4	2.47	1.74	0.57	0.80	1.71	9.80E-04	1080	9.26E-04
Salt Lake	SFDC	1.8			0.89	1.26				
		2.2			1.09	1.54				
		0.8			0.40	0.56				
		1.8	2.03	1.43	0.89	1.26	1.48	1.03E-03	1330	7.52E-04
Provo	AFC	2.5			0.82	1.17				
		2.5			0.82	1.17				
		2.5			0.82	1.17				
	RC	2.5			0.82	1.17				
	MN, MS	2.2			0.73	1.03				
		1.8			0.59	0.84				
	WH	0.9	3.03	2.14	0.30	0.42	2.17	1.01E-03	2400	4.17E-04
Nephi	NC	2.1			0.89	1.25				
		2.3			0.97	1.37				
		2.6			1.10	1.55				
	RedCyn	1.4			0.59	0.84				
		1.5			0.63	0.90				
		1.7	2.37	1.67	0.72	1.02	1.74	1.04E-03	2450	4.08E-04

Determine the Cumulative Distribution Function, F(d/Davg)

Original Data				Sorted Data		Statistical Distribution		Empirical Distribution			
Fault	***Trench***	***D(m)***	***D/Davg***	***D/Davg***	***ln D/Davg***	***D/Davg***	***Cumulative %***	***Gamma***	***Normal***	***Lognorm.***	***Expon.***
Brigham	BC	1.00	0.8319	0.4196	-0.8685	0.4196	0.0345	0.0147	0.0441	0.0087	0.3789
		2.50	2.0797	0.5587	-0.5821	0.5587	0.0690	0.0565	0.0848	0.0502	0.4696
		2.50	2.0797	0.5733	-0.5563	0.5733	0.1379	0.0631	0.0904	0.0574	0.4783
	PP	1.00	0.8319	0.5733	-0.5563	0.5733	0.1379	0.0631	0.0904	0.0574	0.4783
Weber	GC	1.00	0.5733	0.8027	-0.2198	0.8027	0.1724	0.2240	0.2143	0.2383	0.5979
		1.00	0.5733	0.8319	-0.1840	0.8319	0.2414	0.2507	0.2351	0.2676	0.6110
	EO	1.60	0.9173	0.8319	-0.1840	0.8319	0.2414	0.2507	0.2351	0.2676	0.6110
		2.90	1.6627	0.8366	-0.1784	0.8366	0.2759	0.2551	0.2386	0.2724	0.6130
		2.40	1.3760	0.8392	-0.1753	0.8392	0.3103	0.2576	0.2405	0.2751	0.6142
	KV-88	1.80	1.0320	0.8963	-0.1095	0.8963	0.3448	0.3127	0.2848	0.3342	0.6384
		2.90	1.6627	0.9173	-0.0863	0.9173	0.3793	0.3335	0.3020	0.3561	0.6469
		1.40	0.8027	1.0158	0.0157	1.0158	0.4138	0.4326	0.3883	0.4575	0.6842
Salt Lake	SFDC	1.80	1.2571	1.0257	0.0254	1.0257	0.4483	0.4426	0.3974	0.4674	0.6878
		2.20	1.5364	1.0320	0.0315	1.0320	0.4828	0.4489	0.4032	0.4737	0.6900
		0.80	0.5587	1.1656	0.1532	1.1656	0.6207	0.5777	0.5292	0.5975	0.7336
		1.80	1.2571	1.1656	0.1532	1.1656	0.6207	0.5777	0.5292	0.5975	0.7336
Provo	AFC	2.50	1.1656	1.1656	0.1532	1.1656	0.6207	0.5777	0.5292	0.5975	0.7336
		2.50	1.1656	1.1656	0.1532	1.1656	0.6207	0.5777	0.5292	0.5975	0.7336
		2.50	1.1656	1.2549	0.2271	1.2549	0.6552	0.6551	0.6126	0.6688	0.7593
	RC	2.50	1.1656	1.2571	0.2288	1.2571	0.7241	0.6569	0.6146	0.6704	0.7599
	MN, MS	2.20	1.0257	1.2571	0.2288	1.2571	0.7241	0.6569	0.6146	0.6704	0.7599
		1.80	0.8392	1.3744	0.3180	1.3744	0.7586	0.7443	0.7160	0.7487	0.7898
	WH	0.90	0.4196	1.3760	0.3192	1.3760	0.7931	0.7454	0.7173	0.7497	0.7902
Nephi	NC	2.10	1.2549	1.5364	0.4294	1.5364	0.8276	0.8373	0.8307	0.8307	0.8251
		2.30	1.3744	1.5536	0.4406	1.5536	0.8621	0.8453	0.8409	0.8378	0.8285
		2.60	1.5536	1.6627	0.5084	1.6627	0.9310	0.8893	0.8958	0.8770	0.8485
	RedCyn	1.40	0.8366	1.6627	0.5084	1.6627	0.9310	0.8893	0.8958	0.8770	0.8485
		1.50	0.8963	2.0797	0.7322	2.0797	1.0000	0.9737	0.9878	0.9586	0.9056
		1.70	1.0158	2.0797	0.7322	2.0797	1.0000	0.9737	0.9878	0.9586	0.9056
			meanavg =	1.1349		a =	7.3172	R^2 =	R^2 =	R^2 =	R^2 =
			stdev =	0.4195		b =	0.1551	0.990	0.982	0.987	0.942

Determine the Cumulative Distribution Function, F(d/Dmax)

Original Data				*Sorted Data*		*Statistical Distribution*		*Empirical Distributions*			
Fault	*Trench*	*D(m)*	*D/Dmax*	*D/Dmax*	*ln D/Dmax*	*D/Dmax*	*Cumulative %*	*Normal*	*Gamma*	*Lognorm.*	*Expon.*
Brigham	BC	1.0	0.5882	0.2967	-1.2150	0.2967	0.0345	0.0332	0.0087	0.0087	0.2161
		2.5	1.4706	0.3951	-0.9286	0.3951	0.0690	0.0680	0.0399	0.0502	0.2769
		2.5	1.4706	0.4054	-0.9029	0.4054	0.1379	0.0729	0.0453	0.0574	0.2830
	PP	1.0	0.5882	0.4054	-0.9029	0.4054	0.1379	0.0729	0.0453	0.0574	0.2830
Weber	GC	1.0	0.4054	0.5676	-0.5663	0.5676	0.1724	0.1878	0.1898	0.2383	0.3723
		1.0	0.4054	0.5882	-0.5307	0.5882	0.2414	0.2078	0.2155	0.2676	0.3828
	EO	1.6	0.6486	0.5882	-0.5307	0.5882	0.2414	0.2078	0.2155	0.2676	0.3828
		2.9	1.1757	0.5915	-0.5251	0.5915	0.2759	0.2111	0.2197	0.2723	0.3845
		2.4	0.9730	0.5934	-0.5219	0.5934	0.3103	0.2131	0.2222	0.2751	0.3855
	KV-88	1.8	0.7297	0.6338	-0.4560	0.6338	0.3448	0.2565	0.2765	0.3342	0.4055
		2.9	1.1757	0.6486	-0.4329	0.6486	0.3793	0.2735	0.2973	0.3561	0.4127
		1.4	0.5676	0.7183	-0.3309	0.7183	0.4138	0.3601	0.3987	0.4576	0.4453
Salt Lake	SFDC	1.8	0.8889	0.7253	-0.3212	0.7253	0.4483	0.3693	0.4090	0.4675	0.4485
		2.2	1.0864	0.7297	-0.3151	0.7297	0.4828	0.3751	0.4155	0.4736	0.4505
		0.8	0.3951	0.8242	-0.1933	0.8242	0.6207	0.5051	0.5513	0.5975	0.4915
		1.8	0.8889	0.8242	-0.1933	0.8242	0.6207	0.5051	0.5513	0.5975	0.4915
Provo	AFC	2.5	0.8242	0.8242	-0.1933	0.8242	0.6207	0.5051	0.5513	0.5975	0.4915
		2.5	0.8242	0.8242	-0.1933	0.8242	0.6207	0.5051	0.5513	0.5975	0.4915
		2.5	0.8242	0.8873	-0.1196	0.8873	0.6552	0.5925	0.6344	0.6688	0.5172
	RC	2.5	0.8242	0.8889	-0.1178	0.8889	0.7241	0.5947	0.6363	0.6704	0.5178
	MN, MS	2.2	0.7253	0.8889	-0.1178	0.8889	0.7241	0.5947	0.6363	0.6704	0.5178
		1.8	0.5934	0.9718	-0.0286	0.9718	0.7586	0.7020	0.7308	0.7487	0.5495
	WH	0.9	0.2967	0.9730	-0.0274	0.9730	0.7931	0.7034	0.7320	0.7497	0.5499
Nephi	NC	2.1	0.8873	1.0864	0.0829	1.0864	0.8276	0.8242	0.8315	0.8307	0.5899
		2.3	0.9718	1.0986	0.0940	1.0986	0.8621	0.8350	0.8402	0.8378	0.5940
		2.6	1.0986	1.1757	0.1619	1.1757	0.9310	0.8933	0.8873	0.8770	0.6189
	RedCyn	1.4	0.5915	1.1757	0.1619	1.1757	0.9310	0.8933	0.8873	0.8770	0.6189
		1.5	0.6338	1.4706	0.3857	1.4706	1.0000	0.9886	0.9755	0.9586	0.7008
		1.7	0.7183	1.4706	0.3857	1.4706	1.0000	0.9886	0.9755	0.9586	0.7008
			meanavg =	0.8205	a =	8.2655		R^2 =	R^2 =	R^2 =	R^2 =
			stdev =	0.2854	b =	0.0993		0.978	0.990	0.987	0.960

BRIGHAM CITY *FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Davg*

d=(d/Davg)*Davg(BC)	Gamma Dist.	P(D> d) = 1-Gamma	No Contagion		WB Contagion	
Displacement (m)	[Calc for BC d]	[Calc for BC d]	SR AD	RI AD	SR AD	RI AD
0.5044	0.0357	0.9643	2.514E-04	1.148E-04	1.247E-05	5.697E-06
0.6717	0.1197	0.8803	2.295E-04	1.048E-04	1.139E-05	5.201E-06
0.6892	0.1319	0.8681	2.264E-04	1.034E-04	1.123E-05	5.129E-06
0.6892	0.1319	0.8681	2.264E-04	1.034E-04	1.123E-05	5.129E-06
0.9649	0.3813	0.6187	1.613E-04	7.369E-05	8.004E-06	3.656E-06
0.9999	0.4166	0.5834	1.521E-04	6.948E-05	7.546E-06	3.447E-06
0.9999	0.4166	0.5834	1.521E-04	6.948E-05	7.546E-06	3.447E-06
1.0056	0.4223	0.5777	1.506E-04	6.880E-05	7.473E-06	3.413E-06
1.0088	0.4255	0.5745	1.498E-04	6.841E-05	7.431E-06	3.394E-06
1.0775	0.4940	0.5060	1.320E-04	6.027E-05	6.546E-06	2.990E-06
1.1026	0.5184	0.4816	1.256E-04	5.735E-05	6.230E-06	2.845E-06
1.2211	0.6268	0.3732	9.732E-05	4.445E-05	4.828E-06	2.205E-06
1.2330	0.6369	0.3631	9.468E-05	4.324E-05	4.697E-06	2.145E-06
1.2405	0.6432	0.3568	9.304E-05	4.249E-05	4.616E-06	2.108E-06
1.4011	0.7618	0.2382	6.210E-05	2.836E-05	3.081E-06	1.407E-06
1.4011	0.7618	0.2382	6.210E-05	2.836E-05	3.081E-06	1.407E-06
1.4011	0.7618	0.2382	6.210E-05	2.836E-05	3.081E-06	1.407E-06
1.4011	0.7618	0.2382	6.210E-05	2.836E-05	3.081E-06	1.407E-06
1.5084	0.8234	0.1766	4.604E-05	2.103E-05	2.284E-06	1.043E-06
1.5111	0.8248	0.1752	4.568E-05	2.086E-05	2.266E-06	1.035E-06
1.5111	0.8248	0.1752	4.568E-05	2.086E-05	2.266E-06	1.035E-06
1.6521	0.8855	0.1145	2.986E-05	1.364E-05	1.481E-06	6.764E-07
1.6541	0.8862	0.1138	2.966E-05	1.355E-05	1.472E-06	6.721E-07
1.8469	0.9396	0.0604	1.574E-05	7.190E-06	7.810E-07	3.567E-07
1.8676	0.9438	0.0562	1.466E-05	6.695E-06	7.273E-07	3.321E-07
1.9987	0.9646	0.0354	9.220E-06	4.211E-06	4.574E-07	2.089E-07
1.9987	0.9646	0.0354	9.220E-06	4.211E-06	4.574E-07	2.089E-07
2.5000	0.9950	0.0050	1.314E-06	6.000E-07	6.518E-08	2.977E-08
2.5000	0.9950	0.0050	1.314E-06	6.000E-07	6.518E-08	2.977E-08

***BRIGHAM CITY** FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Dmax*

d=(d/Dmax)*Dmax (BC)	Lognormal Dist.	P(D>d) = 1-Lognorm	No Contagion		WB Contagion	
Displacement (m)	[Calc for BC d]	[Calc for BC d]	SR MD	RI MD	SR MD	RI MD
0.5044	0.1070	0.8930	2.329E-04	1.064E-04	1.155E-05	5.276E-06
0.6717	0.3390	0.6610	1.724E-04	7.872E-05	8.550E-06	3.905E-06
0.6892	0.3666	0.6334	1.652E-04	7.543E-05	8.193E-06	3.742E-06
0.6892	0.3666	0.6334	1.652E-04	7.543E-05	8.193E-06	3.742E-06
0.9649	0.7362	0.2638	6.880E-05	3.142E-05	3.413E-06	1.559E-06
0.9999	0.7687	0.2313	6.031E-05	2.755E-05	2.992E-06	1.367E-06
0.9999	0.7687	0.2313	6.031E-05	2.755E-05	2.992E-06	1.367E-06
1.0056	0.7736	0.2264	5.904E-05	2.696E-05	2.929E-06	1.338E-06
1.0088	0.7764	0.2236	5.831E-05	2.663E-05	2.893E-06	1.321E-06
1.0775	0.8290	0.1710	4.458E-05	2.036E-05	2.212E-06	1.010E-06
1.1026	0.8454	0.1546	4.031E-05	1.841E-05	2.000E-06	9.132E-07
1.2211	0.9052	0.0948	2.471E-05	1.129E-05	1.226E-06	5.599E-07
1.2330	0.9099	0.0901	2.350E-05	1.073E-05	1.166E-06	5.325E-07
1.2405	0.9127	0.0873	2.277E-05	1.040E-05	1.130E-06	5.159E-07
1.4011	0.9563	0.0437	1.139E-05	5.204E-06	5.653E-07	2.582E-07
1.4011	0.9563	0.0437	1.139E-05	5.204E-06	5.653E-07	2.582E-07
1.4011	0.9563	0.0437	1.139E-05	5.204E-06	5.653E-07	2.582E-07
1.4011	0.9563	0.0437	1.139E-05	5.204E-06	5.653E-07	2.582E-07
1.5084	0.9727	0.0273	7.112E-06	3.248E-06	3.528E-07	1.611E-07
1.5111	0.9731	0.0269	7.027E-06	3.209E-06	3.486E-07	1.592E-07
1.5111	0.9731	0.0269	7.027E-06	3.209E-06	3.486E-07	1.592E-07
1.6521	0.9856	0.0144	3.764E-06	1.719E-06	1.867E-07	8.528E-08
1.6541	0.9857	0.0143	3.730E-06	1.704E-06	1.850E-07	8.451E-08
1.8469	0.9939	0.0061	1.586E-06	7.243E-07	7.867E-08	3.593E-08
1.8676	0.9945	0.0055	1.447E-06	6.608E-07	7.178E-08	3.278E-08
1.9987	0.9969	0.0031	8.118E-07	3.708E-07	4.027E-08	1.839E-08
1.9987	0.9969	0.0031	8.118E-07	3.708E-07	4.027E-08	1.839E-08
2.5000	0.9996	0.0004	9.373E-08	4.281E-08	4.650E-09	2.124E-09
2.5000	0.9996	0.0004	9.373E-08	4.281E-08	4.650E-09	2.124E-09

WEBER *FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Davg*

d= (d/Davg)*Davg(WB)	Gamma Dist.	P(D>d) = 1-Gamma	No Contagion		BC Contagion		SL Contagion		BC & SL Contagion	
Displacement (m)	[Calc for WB d]	[Calc for WB d]	SR AD	RI AD	SR AD	RI AD	SR AD	RI AD	SR AD	RI AD
0.7319	0.1640	0.8360	2.518E-04	1.019E-04	3.961E-06	1.603E-06	4.046E-06	1.638E-06	1.554E-05	6.290E-06
0.9745	0.3909	0.6091	1.835E-04	7.426E-05	2.886E-06	1.168E-06	2.948E-06	1.193E-06	1.132E-05	4.583E-06
0.9999	0.4166	0.5834	1.757E-04	7.113E-05	2.764E-06	1.119E-06	2.823E-06	1.143E-06	1.084E-05	4.389E-06
0.9999	0.4166	0.5834	1.757E-04	7.113E-05	2.764E-06	1.119E-06	2.823E-06	1.143E-06	1.084E-05	4.389E-06
1.4001	0.7611	0.2389	7.195E-05	2.912E-05	1.132E-06	4.581E-07	1.156E-06	4.679E-07	4.440E-06	1.797E-06
1.4510	0.7922	0.2078	6.260E-05	2.534E-05	9.846E-07	3.985E-07	1.006E-06	4.071E-07	3.863E-06	1.564E-06
1.4510	0.7922	0.2078	6.260E-05	2.534E-05	9.846E-07	3.985E-07	1.006E-06	4.071E-07	3.863E-06	1.564E-06
1.4592	0.7969	0.2031	6.118E-05	2.476E-05	9.624E-07	3.895E-07	9.830E-07	3.979E-07	3.776E-06	1.528E-06
1.4637	0.7995	0.2005	6.041E-05	2.445E-05	9.502E-07	3.846E-07	9.706E-07	3.929E-07	3.728E-06	1.509E-06
1.5633	0.8497	0.1503	4.526E-05	1.832E-05	7.119E-07	2.882E-07	7.272E-07	2.943E-07	2.793E-06	1.131E-06
1.6000	0.8655	0.1345	4.052E-05	1.640E-05	6.374E-07	2.580E-07	6.510E-07	2.635E-07	2.501E-06	1.012E-06
1.7718	0.9222	0.0778	2.343E-05	9.484E-06	3.686E-07	1.492E-07	3.765E-07	1.524E-07	1.446E-06	5.853E-07
1.7890	0.9266	0.0734	2.212E-05	8.954E-06	3.480E-07	1.408E-07	3.554E-07	1.439E-07	1.365E-06	5.525E-07
1.8000	0.9292	0.0708	2.132E-05	8.630E-06	3.354E-07	1.357E-07	3.426E-07	1.387E-07	1.316E-06	5.326E-07
2.0330	0.9688	0.0312	9.399E-06	3.804E-06	1.478E-07	5.984E-08	1.510E-07	6.112E-08	5.800E-07	2.348E-07
2.0330	0.9688	0.0312	9.399E-06	3.804E-06	1.478E-07	5.984E-08	1.510E-07	6.112E-08	5.800E-07	2.348E-07
2.0330	0.9688	0.0312	9.399E-06	3.804E-06	1.478E-07	5.984E-08	1.510E-07	6.112E-08	5.800E-07	2.348E-07
2.0330	0.9688	0.0312	9.399E-06	3.804E-06	1.478E-07	5.984E-08	1.510E-07	6.112E-08	5.800E-07	2.348E-07
2.1888	0.9826	0.0174	5.242E-06	2.122E-06	8.246E-08	3.338E-08	8.423E-08	3.409E-08	3.235E-07	1.309E-07
2.1926	0.9829	0.0171	5.166E-06	2.091E-06	8.125E-08	3.289E-08	8.300E-08	3.359E-08	3.188E-07	1.290E-07
2.1926	0.9829	0.0171	5.166E-06	2.091E-06	8.125E-08	3.289E-08	8.300E-08	3.359E-08	3.188E-07	1.290E-07
2.3972	0.9923	0.0077	2.308E-06	9.342E-07	3.631E-08	1.470E-08	3.708E-08	1.501E-08	1.424E-07	5.765E-08
2.4000	0.9924	0.0076	2.282E-06	9.238E-07	3.590E-08	1.453E-08	3.667E-08	1.484E-08	1.408E-07	5.701E-08
2.6798	0.9976	0.0024	7.141E-07	2.890E-07	1.123E-08	4.546E-09	1.147E-08	4.644E-09	4.407E-08	1.784E-08
2.7098	0.9979	0.0021	6.282E-07	2.543E-07	9.881E-09	3.999E-09	1.009E-08	4.085E-09	3.876E-08	1.569E-08
2.9001	0.9991	0.0009	2.745E-07	1.111E-07	4.317E-09	1.747E-09	4.410E-09	1.785E-09	1.694E-08	6.856E-09
2.9001	0.9991	0.0009	2.745E-07	1.111E-07	4.317E-09	1.747E-09	4.410E-09	1.785E-09	1.694E-08	6.856E-09
3.6274	1.0000	0.0000	9.549E-09	3.865E-09	1.502E-10	6.079E-11	1.534E-10	6.210E-11	5.893E-10	2.385E-10
3.6274	1.0000	0.0000	9.549E-09	3.865E-09	1.502E-10	6.079E-11	1.534E-10	6.210E-11	5.893E-10	2.385E-10

WEBER *FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Dmax*

d=(d/Dmax)*Dmax	Lognorm Dist.	P(D>d) = 1-Lognorm	No Contagion		BC Contagion		SL Contagion		BC & SL Contagion	
Displacement (m)	[Calc for WB d]	[Calc for WB d]	SR MD	RI MD	SR MD	RI MD	SR MD	RI MD	SR MD	RI MD
0.7319	0.4336	0.5664	1.706E-04	6.906E-05	2.684E-06	1.086E-06	2.741E-06	1.109E-06	1.053E-05	4.262E-06
0.9746	0.7455	0.2545	7.666E-05	3.103E-05	1.206E-06	4.881E-07	1.232E-06	4.986E-07	4.731E-06	1.915E-06
1.0000	0.7687	0.2313	6.966E-05	2.820E-05	1.096E-06	4.435E-07	1.119E-06	4.530E-07	4.299E-06	1.740E-06
1.0000	0.7687	0.2313	6.966E-05	2.820E-05	1.096E-06	4.435E-07	1.119E-06	4.530E-07	4.299E-06	1.740E-06
1.4001	0.9561	0.0439	1.322E-05	5.353E-06	2.080E-07	8.419E-08	2.125E-07	8.600E-08	8.161E-07	3.303E-07
1.4509	0.9649	0.0351	1.058E-05	4.284E-06	1.665E-07	6.739E-08	1.701E-07	6.883E-08	6.532E-07	2.644E-07
1.4509	0.9649	0.0351	1.058E-05	4.284E-06	1.665E-07	6.739E-08	1.701E-07	6.883E-08	6.532E-07	2.644E-07
1.4590	0.9661	0.0339	1.021E-05	4.134E-06	1.606E-07	6.502E-08	1.641E-07	6.641E-08	6.302E-07	2.551E-07
1.4637	0.9668	0.0332	1.000E-05	4.049E-06	1.574E-07	6.369E-08	1.607E-07	6.506E-08	6.174E-07	2.499E-07
1.5634	0.9786	0.0214	6.443E-06	2.608E-06	1.013E-07	4.102E-08	1.035E-07	4.190E-08	3.976E-07	1.609E-07
1.5999	0.9818	0.0182	5.481E-06	2.218E-06	8.621E-08	3.489E-08	8.806E-08	3.564E-08	3.382E-07	1.369E-07
1.7718	0.9915	0.0085	2.555E-06	1.034E-06	4.019E-08	1.627E-08	4.105E-08	1.662E-08	1.577E-07	6.382E-08
1.7891	0.9921	0.0079	2.367E-06	9.580E-07	3.723E-08	1.507E-08	3.803E-08	1.539E-08	1.461E-07	5.912E-08
1.7999	0.9925	0.0075	2.256E-06	9.130E-07	3.548E-08	1.436E-08	3.624E-08	1.467E-08	1.392E-07	5.634E-08
2.0330	0.9973	0.0027	8.066E-07	3.265E-07	1.269E-08	5.136E-09	1.296E-08	5.246E-09	4.978E-08	2.015E-08
2.0330	0.9973	0.0027	8.066E-07	3.265E-07	1.269E-08	5.136E-09	1.296E-08	5.246E-09	4.978E-08	2.015E-08
2.0330	0.9973	0.0027	8.066E-07	3.265E-07	1.269E-08	5.136E-09	1.296E-08	5.246E-09	4.978E-08	2.015E-08
2.0330	0.9973	0.0027	8.066E-07	3.265E-07	1.269E-08	5.136E-09	1.296E-08	5.246E-09	4.978E-08	2.015E-08
2.1887	0.9986	0.0014	4.093E-07	1.657E-07	6.439E-09	2.606E-09	6.577E-09	2.662E-09	2.526E-08	1.022E-08
2.1926	0.9987	0.0013	4.024E-07	1.629E-07	6.330E-09	2.562E-09	6.465E-09	2.617E-09	2.483E-08	1.005E-08
2.1926	0.9987	0.0013	4.024E-07	1.629E-07	6.330E-09	2.562E-09	6.465E-09	2.617E-09	2.483E-08	1.005E-08
2.3971	0.9994	0.0006	1.673E-07	6.773E-08	2.632E-09	1.065E-09	2.688E-09	1.088E-09	1.033E-08	4.180E-09
2.4001	0.9995	0.0005	1.652E-07	6.688E-08	2.599E-09	1.052E-09	2.655E-09	1.075E-09	1.020E-08	4.127E-09
2.6798	0.9998	0.0002	5.118E-08	2.072E-08	8.050E-10	3.258E-10	8.223E-10	3.328E-10	3.158E-09	1.278E-09
2.7099	0.9998	0.0002	4.521E-08	1.830E-08	7.111E-10	2.878E-10	7.264E-10	2.940E-10	2.790E-09	1.129E-09
2.9001	0.9999	0.0001	2.083E-08	8.433E-09	3.277E-10	1.326E-10	3.347E-10	1.355E-10	1.286E-09	5.204E-10
2.9001	0.9999	0.0001	2.083E-08	8.433E-09	3.277E-10	1.326E-10	3.347E-10	1.355E-10	1.286E-09	5.204E-10
3.6275	1.0000	0.0000	1.247E-09	5.048E-10	1.962E-11	7.941E-12	2.004E-11	8.111E-12	7.697E-11	3.115E-11
3.6275	1.0000	0.0000	1.247E-09	5.048E-10	1.962E-11	7.941E-12	2.004E-11	8.111E-12	7.697E-11	3.115E-11

SALT LAKE CITY *FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Davg*

d=(d/Davg)*Davg (SLC)	Gamma Dist.	P(D> d) = 1 - Gamma	No	Contagion	WB	Contagion	PV	Contagion	WB & PV	Contagion
Displacement (m)	[Calc for SLC d]	[Calc for SLC d]	SR AD	RI AD	SR AD	RI AD	SR AD	RI AD	SR AD	RI AD
0.6008	0.0768	0.9232	3.128E-04	9.752E-05	8.252E-06	2.573E-06	4.091E-06	1.275E-06	8.810E-06	2.747E-06
0.8000	0.2216	0.7784	2.638E-04	8.223E-05	6.959E-06	2.169E-06	3.450E-06	1.075E-06	7.429E-06	2.316E-06
0.8209	0.2405	0.7595	2.573E-04	8.023E-05	6.789E-06	2.117E-06	3.366E-06	1.049E-06	7.248E-06	2.260E-06
0.8209	0.2405	0.7595	2.573E-04	8.023E-05	6.789E-06	2.117E-06	3.366E-06	1.049E-06	7.248E-06	2.260E-06
1.1494	0.5627	0.4373	1.482E-04	4.619E-05	3.909E-06	1.219E-06	1.938E-06	6.041E-07	4.173E-06	1.301E-06
1.1912	0.6007	0.3993	1.353E-04	4.218E-05	3.570E-06	1.113E-06	1.769E-06	5.517E-07	3.811E-06	1.188E-06
1.1912	0.6007	0.3993	1.353E-04	4.218E-05	3.570E-06	1.113E-06	1.769E-06	5.517E-07	3.811E-06	1.188E-06
1.1979	0.6066	0.3934	1.333E-04	4.155E-05	3.516E-06	1.096E-06	1.743E-06	5.434E-07	3.754E-06	1.170E-06
1.2016	0.6099	0.3901	1.322E-04	4.121E-05	3.487E-06	1.087E-06	1.729E-06	5.389E-07	3.723E-06	1.161E-06
1.2834	0.6779	0.3221	1.091E-04	3.402E-05	2.879E-06	8.976E-07	1.427E-06	4.449E-07	3.074E-06	9.582E-07
1.3135	0.7010	0.2990	1.013E-04	3.159E-05	2.673E-06	8.333E-07	1.325E-06	4.131E-07	2.854E-06	8.896E-07
1.4545	0.7942	0.2058	6.973E-05	2.174E-05	1.840E-06	5.735E-07	9.119E-07	2.843E-07	1.964E-06	6.123E-07
1.4687	0.8022	0.1978	6.701E-05	2.089E-05	1.768E-06	5.512E-07	8.764E-07	2.732E-07	1.887E-06	5.884E-07
1.4777	0.8072	0.1928	6.533E-05	2.037E-05	1.723E-06	5.373E-07	8.543E-07	2.664E-07	1.840E-06	5.736E-07
1.6690	0.8915	0.1085	3.678E-05	1.147E-05	9.703E-07	3.025E-07	4.810E-07	1.500E-07	1.036E-06	3.229E-07
1.6690	0.8915	0.1085	3.678E-05	1.147E-05	9.703E-07	3.025E-07	4.810E-07	1.500E-07	1.036E-06	3.229E-07
1.6690	0.8915	0.1085	3.678E-05	1.147E-05	9.703E-07	3.025E-07	4.810E-07	1.500E-07	1.036E-06	3.229E-07
1.6690	0.8915	0.1085	3.678E-05	1.147E-05	9.703E-07	3.025E-07	4.810E-07	1.500E-07	1.036E-06	3.229E-07
1.7969	0.9285	0.0715	2.424E-05	7.556E-06	6.394E-07	1.993E-07	3.170E-07	9.882E-08	6.827E-07	2.128E-07
1.8000	0.9292	0.0708	2.398E-05	7.477E-06	6.327E-07	1.972E-07	3.136E-07	9.778E-08	6.755E-07	2.106E-07
1.8000	0.9292	0.0708	2.398E-05	7.477E-06	6.327E-07	1.972E-07	3.136E-07	9.778E-08	6.755E-07	2.106E-07
1.9680	0.9605	0.0395	1.338E-05	4.172E-06	3.530E-07	1.101E-07	1.750E-07	5.456E-08	3.769E-07	1.175E-07
1.9703	0.9608	0.0392	1.327E-05	4.138E-06	3.501E-07	1.092E-07	1.736E-07	5.411E-08	3.738E-07	1.165E-07
2.2000	0.9833	0.0167	5.650E-06	1.761E-06	1.490E-07	4.647E-08	7.389E-08	2.303E-08	1.591E-07	4.961E-08
2.2246	0.9848	0.0152	5.138E-06	1.602E-06	1.355E-07	4.226E-08	6.719E-08	2.095E-08	1.447E-07	4.511E-08
2.3808	0.9918	0.0082	2.774E-06	8.648E-07	7.318E-08	2.281E-08	3.628E-08	1.131E-08	7.813E-08	2.436E-08
2.3808	0.9918	0.0082	2.774E-06	8.648E-07	7.318E-08	2.281E-08	3.628E-08	1.131E-08	7.813E-08	2.436E-08
2.9779	0.9994	0.0006	2.186E-07	6.814E-08	5.766E-09	1.798E-09	2.858E-09	8.911E-10	6.156E-09	1.919E-09
2.9779	0.9994	0.0006	2.186E-07	6.814E-08	5.766E-09	1.798E-09	2.858E-09	8.911E-10	6.156E-09	1.919E-09

***SALT LAKE CITY** FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Dmax*

d=(d/Dmax)*Dmax(SLC)	Lognorm Dist.	P(D>d) = 1 - Lognorm	No	Contagion	WB	Contagion	PV	Contagion	WB & PV	Contagion
Displacement (m)	[Calc for SLC d]	[Calc for SLC d]	SR MD	RI MD	SR MD	RI MD	SR MD	RI MD	SR MD	RI MD
0.6008	0.2305	0.7695	2.607E-04	8.129E-05	6.879E-06	2.145E-06	3.410E-06	1.063E-06	7.344E-06	2.290E-06
0.8001	0.5360	0.4640	1.572E-04	4.902E-05	4.148E-06	1.293E-06	2.056E-06	6.411E-07	4.428E-06	1.381E-06
0.8209	0.5654	0.4346	1.473E-04	4.591E-05	3.885E-06	1.211E-06	1.926E-06	6.004E-07	4.148E-06	1.293E-06
0.8209	0.5654	0.4346	1.473E-04	4.591E-05	3.885E-06	1.211E-06	1.926E-06	6.004E-07	4.148E-06	1.293E-06
1.1494	0.8722	0.1278	4.329E-05	1.350E-05	1.142E-06	3.561E-07	5.662E-07	1.765E-07	1.219E-06	3.801E-07
1.1911	0.8925	0.1075	3.642E-05	1.135E-05	9.608E-07	2.995E-07	4.763E-07	1.485E-07	1.026E-06	3.198E-07
1.1911	0.8925	0.1075	3.642E-05	1.135E-05	9.608E-07	2.995E-07	4.763E-07	1.485E-07	1.026E-06	3.198E-07
1.1978	0.8955	0.1045	3.542E-05	1.104E-05	9.343E-07	2.913E-07	4.632E-07	1.444E-07	9.975E-07	3.110E-07
1.2016	0.8972	0.1028	3.485E-05	1.086E-05	9.194E-07	2.866E-07	4.558E-07	1.421E-07	9.815E-07	3.060E-07
1.2834	0.9273	0.0727	2.464E-05	7.683E-06	6.501E-07	2.027E-07	3.223E-07	1.005E-07	6.941E-07	2.164E-07
1.3134	0.9361	0.0639	2.167E-05	6.755E-06	5.716E-07	1.782E-07	2.834E-07	8.834E-08	6.103E-07	1.903E-07
1.4546	0.9654	0.0346	1.172E-05	3.653E-06	3.091E-07	9.637E-08	1.532E-07	4.777E-08	3.300E-07	1.029E-07
1.4687	0.9675	0.0325	1.101E-05	3.432E-06	2.904E-07	9.054E-08	1.440E-07	4.488E-08	3.101E-07	9.666E-08
1.4776	0.9688	0.0312	1.059E-05	3.300E-06	2.792E-07	8.706E-08	1.384E-07	4.316E-08	2.981E-07	9.294E-08
1.6690	0.9866	0.0134	4.537E-06	1.414E-06	1.197E-07	3.731E-08	5.933E-08	1.850E-08	1.278E-07	3.983E-08
1.6690	0.9866	0.0134	4.537E-06	1.414E-06	1.197E-07	3.731E-08	5.933E-08	1.850E-08	1.278E-07	3.983E-08
1.6690	0.9866	0.0134	4.537E-06	1.414E-06	1.197E-07	3.731E-08	5.933E-08	1.850E-08	1.278E-07	3.983E-08
1.6690	0.9866	0.0134	4.537E-06	1.414E-06	1.197E-07	3.731E-08	5.933E-08	1.850E-08	1.278E-07	3.983E-08
1.7968	0.9924	0.0076	2.573E-06	8.021E-07	6.788E-08	2.116E-08	3.365E-08	1.049E-08	7.247E-08	2.259E-08
1.8000	0.9925	0.0075	2.536E-06	7.907E-07	6.691E-08	2.086E-08	3.317E-08	1.034E-08	7.143E-08	2.227E-08
1.8000	0.9925	0.0075	2.536E-06	7.907E-07	6.691E-08	2.086E-08	3.317E-08	1.034E-08	7.143E-08	2.227E-08
1.9679	0.9964	0.0036	1.208E-06	3.766E-07	3.187E-08	9.934E-09	1.580E-08	4.925E-09	3.402E-08	1.061E-08
1.9703	0.9965	0.0035	1.195E-06	3.726E-07	3.153E-08	9.829E-09	1.563E-08	4.872E-09	3.366E-08	1.049E-08
2.2000	0.9987	0.0013	4.385E-07	1.367E-07	1.157E-08	3.607E-09	5.735E-09	1.788E-09	1.235E-08	3.850E-09
2.2247	0.9988	0.0012	3.941E-07	1.229E-07	1.040E-08	3.241E-09	5.154E-09	1.607E-09	1.110E-08	3.460E-09
2.3808	0.9994	0.0006	2.018E-07	6.290E-08	5.323E-09	1.659E-09	2.639E-09	8.226E-10	5.682E-09	1.772E-09
2.3808	0.9994	0.0006	2.018E-07	6.290E-08	5.323E-09	1.659E-09	2.639E-09	8.226E-10	5.682E-09	1.772E-09
2.9780	0.9999	0.0001	1.714E-08	5.345E-09	4.523E-10	1.410E-10	2.242E-10	6.990E-11	4.829E-10	1.505E-10
2.9780	0.9999	0.0001	1.714E-08	5.345E-09	4.523E-10	1.410E-10	2.242E-10	6.990E-11	4.829E-10	1.505E-10

PROVO *FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Davg*

d=(d/Davg)*Davg (PV)	Gamma Dist.	P(D>d) = 1-Gamma	No Contagion		SLC Contagion		NP Contagion		SLC and NP Contagion	
Displacement (m)	[Calc for PV d]	[Calc for PV d)	SR AD	RI AD	SR AD	RI AD	SR AD	RI AD	SR AD	RI AD
0.9000	0.3163	0.6837	2.288E-04	4.039E-05	2.085E-06	3.680E-07	2.037E-06	3.595E-07	9.172E-06	1.619E-06
1.1984	0.6070	0.3930	1.315E-04	2.321E-05	1.198E-06	2.115E-07	1.171E-06	2.066E-07	5.272E-06	9.305E-07
1.2297	0.6341	0.3659	1.225E-04	2.161E-05	1.116E-06	1.969E-07	1.090E-06	1.924E-07	4.909E-06	8.665E-07
1.2297	0.6341	0.3659	1.225E-04	2.161E-05	1.116E-06	1.969E-07	1.090E-06	1.924E-07	4.909E-06	8.665E-07
1.7217	0.9083	0.0917	3.068E-05	5.415E-06	2.795E-07	4.934E-08	2.731E-07	4.820E-08	1.230E-06	2.171E-07
1.7843	0.9254	0.0746	2.496E-05	4.406E-06	2.275E-07	4.015E-08	2.222E-07	3.922E-08	1.001E-06	1.766E-07
1.7843	0.9254	0.0746	2.496E-05	4.406E-06	2.275E-07	4.015E-08	2.222E-07	3.922E-08	1.001E-06	1.766E-07
1.7944	0.9279	0.0721	2.414E-05	4.260E-06	2.199E-07	3.882E-08	2.149E-07	3.792E-08	9.676E-07	1.708E-07
1.8000	0.9292	0.0708	2.369E-05	4.181E-06	2.158E-07	3.810E-08	2.109E-07	3.722E-08	9.496E-07	1.676E-07
1.9225	0.9536	0.0464	1.554E-05	2.742E-06	1.416E-07	2.499E-08	1.383E-07	2.441E-08	6.228E-07	1.099E-07
1.9675	0.9604	0.0396	1.324E-05	2.337E-06	1.206E-07	2.129E-08	1.178E-07	2.080E-08	5.307E-07	9.367E-08
2.1788	0.9819	0.0181	6.052E-06	1.068E-06	5.514E-08	9.733E-09	5.387E-08	9.508E-09	2.426E-07	4.282E-08
2.2000	0.9833	0.0167	5.579E-06	9.847E-07	5.083E-08	8.972E-09	4.966E-08	8.765E-09	2.236E-07	3.947E-08
2.2135	0.9842	0.0158	5.296E-06	9.347E-07	4.825E-08	8.517E-09	4.714E-08	8.320E-09	2.123E-07	3.747E-08
2.5001	0.9950	0.0050	1.686E-06	2.975E-07	1.536E-08	2.711E-09	1.501E-08	2.648E-09	6.757E-08	1.193E-08
2.5001	0.9950	0.0050	1.686E-06	2.975E-07	1.536E-08	2.711E-09	1.501E-08	2.648E-09	6.757E-08	1.193E-08
2.5001	0.9950	0.0050	1.686E-06	2.975E-07	1.536E-08	2.711E-09	1.501E-08	2.648E-09	6.757E-08	1.193E-08
2.5001	0.9950	0.0050	1.686E-06	2.975E-07	1.536E-08	2.711E-09	1.501E-08	2.648E-09	6.757E-08	1.193E-08
2.6916	0.9977	0.0023	7.543E-07	1.331E-07	6.872E-09	1.213E-09	6.714E-09	1.185E-09	3.024E-08	5.337E-09
2.6963	0.9978	0.0022	7.392E-07	1.305E-07	6.735E-09	1.189E-09	6.580E-09	1.161E-09	2.963E-08	5.230E-09
2.6963	0.9978	0.0022	7.392E-07	1.305E-07	6.735E-09	1.189E-09	6.580E-09	1.161E-09	2.963E-08	5.230E-09
2.9479	0.9993	0.0007	2.467E-07	4.354E-08	2.248E-09	3.967E-10	2.196E-09	3.876E-10	9.889E-09	1.745E-09
2.9514	0.9993	0.0007	2.429E-07	4.288E-08	2.214E-09	3.907E-10	2.163E-09	3.817E-10	9.739E-09	1.719E-09
3.2954	0.9998	0.0002	5.084E-08	8.973E-09	4.632E-10	8.176E-11	4.525E-10	7.987E-11	2.038E-09	3.597E-10
3.3323	0.9999	0.0001	4.282E-08	7.558E-09	3.902E-10	6.887E-11	3.812E-10	6.728E-11	1.717E-09	3.030E-10
3.5663	1.0000	4.2455E-05	1.421E-08	2.508E-09	1.295E-10	2.285E-11	1.265E-10	2.232E-11	5.696E-10	1.005E-10
3.5663	1.0000	4.2455E-05	1.421E-08	2.508E-09	1.295E-10	2.285E-11	1.265E-10	2.232E-11	5.696E-10	1.005E-10
4.4607	1.0000	5.1195E-07	1.713E-10	3.024E-11	1.561E-12	2.755E-13	1.525E-12	2.692E-13	6.868E-12	1.212E-12
4.4607	1.0000	5.1195E-07	1.713E-10	3.024E-11	1.561E-12	2.755E-13	1.525E-12	2.692E-13	6.868E-12	1.212E-12

PROVO FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Dmax

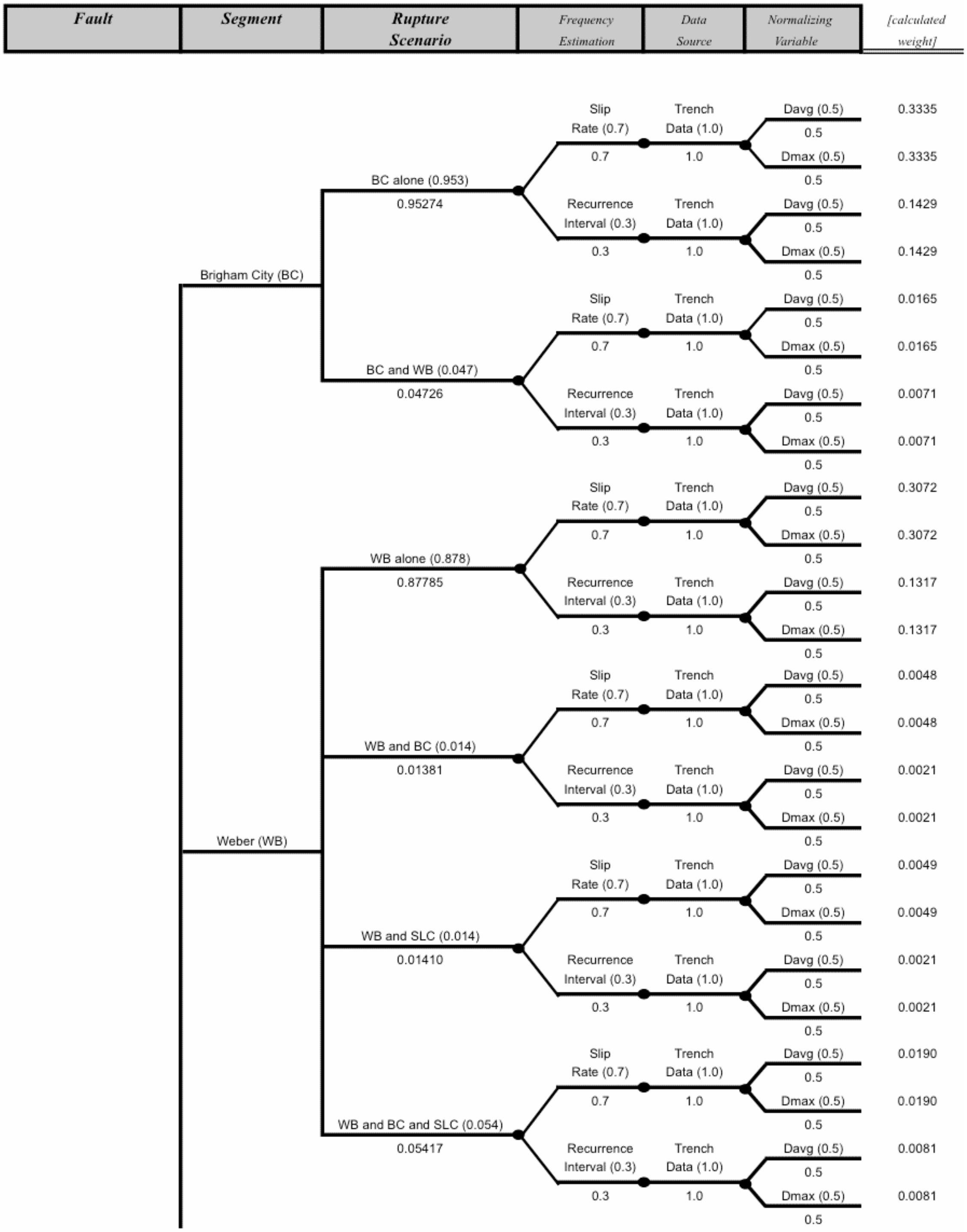
d=(d/Dmax)*Dmax(PV)	Lognorm Dist	P(D>d) = 1-Lognorm	No Contagion		SLC Contagion		NP Contagion		SLC and NP Contagion	
Displacement (m)	[Calc for PV d]	[Calc for PV d)	SR MD	RI MD	SR MD	RI MD	SR MD	RI MD	SR MD	RI MD
0.9000	0.6665	0.3335	1.116E-04	1.970E-05	1.017E-06	1.795E-07	9.934E-07	1.753E-07	4.474E-06	7.897E-07
1.1985	0.8958	0.1042	3.488E-05	6.156E-06	3.178E-07	5.609E-08	3.105E-07	5.480E-08	1.398E-06	2.468E-07
1.2297	0.9086	0.0914	3.059E-05	5.398E-06	2.787E-07	4.919E-08	2.723E-07	4.805E-08	1.226E-06	2.164E-07
1.2297	0.9086	0.0914	3.059E-05	5.398E-06	2.787E-07	4.919E-08	2.723E-07	4.805E-08	1.226E-06	2.164E-07
1.7217	0.9894	0.0106	3.545E-06	6.258E-07	3.230E-08	5.702E-09	3.156E-08	5.570E-09	1.421E-07	2.509E-08
1.7842	0.9920	0.0080	2.687E-06	4.742E-07	2.448E-08	4.321E-09	2.392E-08	4.221E-09	1.077E-07	1.901E-08
1.7842	0.9920	0.0080	2.687E-06	4.742E-07	2.448E-08	4.321E-09	2.392E-08	4.221E-09	1.077E-07	1.901E-08
1.7942	0.9923	0.0077	2.570E-06	4.536E-07	2.342E-08	4.133E-09	2.288E-08	4.038E-09	1.030E-07	1.819E-08
1.8000	0.9925	0.0075	2.505E-06	4.422E-07	2.283E-08	4.029E-09	2.230E-08	3.936E-09	1.004E-07	1.773E-08
1.9225	0.9956	0.0044	1.457E-06	2.572E-07	1.327E-08	2.343E-09	1.297E-08	2.289E-09	5.840E-08	1.031E-08
1.9674	0.9964	0.0036	1.195E-06	2.110E-07	1.089E-08	1.923E-09	1.064E-08	1.878E-09	4.792E-08	8.458E-09
2.1788	0.9986	0.0014	4.746E-07	8.376E-08	4.324E-09	7.632E-10	4.224E-09	7.456E-10	1.902E-08	3.358E-09
2.2001	0.9987	0.0013	4.329E-07	7.640E-08	3.944E-09	6.962E-10	3.853E-09	6.801E-10	1.735E-08	3.063E-09
2.2134	0.9988	0.0012	4.086E-07	7.212E-08	3.723E-09	6.571E-10	3.637E-09	6.420E-10	1.638E-08	2.891E-09
2.5001	0.9996	0.0004	1.203E-07	2.123E-08	1.096E-09	1.934E-10	1.071E-09	1.890E-10	4.821E-09	8.510E-10
2.5001	0.9996	0.0004	1.203E-07	2.123E-08	1.096E-09	1.934E-10	1.071E-09	1.890E-10	4.821E-09	8.510E-10
2.5001	0.9996	0.0004	1.203E-07	2.123E-08	1.096E-09	1.934E-10	1.071E-09	1.890E-10	4.821E-09	8.510E-10
2.5001	0.9996	0.0004	1.203E-07	2.123E-08	1.096E-09	1.934E-10	1.071E-09	1.890E-10	4.821E-09	8.510E-10
2.6915	0.9998	0.0002	5.418E-08	9.564E-09	4.937E-10	8.714E-11	4.823E-10	8.513E-11	2.172E-09	3.834E-10
2.6963	0.9998	0.0002	5.311E-08	9.374E-09	4.839E-10	8.541E-11	4.728E-10	8.344E-11	2.129E-09	3.758E-10
2.6963	0.9998	0.0002	5.311E-08	9.374E-09	4.839E-10	8.541E-11	4.728E-10	8.344E-11	2.129E-09	3.758E-10
2.9478	0.9999	0.0001	1.911E-08	3.372E-09	1.741E-10	3.073E-11	1.701E-10	3.002E-11	7.659E-10	1.352E-10
2.9514	0.9999	0.0001	1.883E-08	3.323E-09	1.716E-10	3.028E-11	1.676E-10	2.958E-11	7.548E-10	1.332E-10
3.2954	1.0000	1.4551E-05	4.869E-09	8.595E-10	4.437E-11	7.831E-12	4.335E-11	7.651E-12	1.952E-10	3.445E-11
3.3324	1.0000	1.2620E-05	4.223E-09	7.454E-10	3.848E-11	6.792E-12	3.759E-11	6.635E-12	1.693E-10	2.988E-11
3.5663	1.0000	5.2014E-06	1.741E-09	3.072E-10	1.586E-11	2.799E-12	1.549E-11	2.735E-12	6.978E-11	1.232E-11
3.5663	1.0000	5.2014E-06	1.741E-09	3.072E-10	1.586E-11	2.799E-12	1.549E-11	2.735E-12	6.978E-11	1.232E-11
4.4608	1.0000	2.1488E-07	7.191E-11	1.269E-11	6.552E-13	1.156E-13	6.401E-13	1.130E-13	2.883E-12	5.088E-13
4.4608	1.0000	2.1488E-07	7.191E-11	1.269E-11	6.552E-13	1.156E-13	6.401E-13	1.130E-13	2.883E-12	5.088E-13

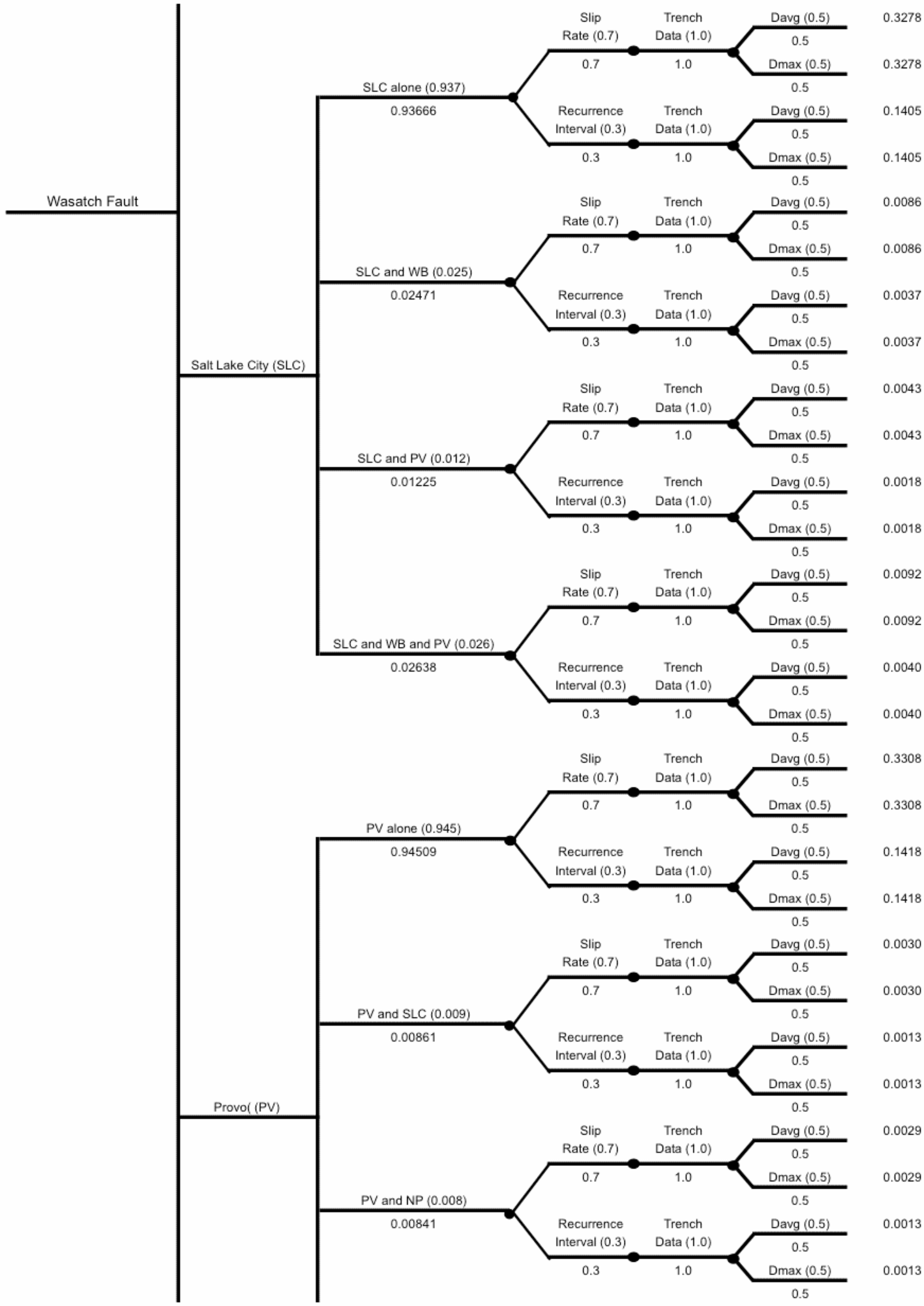
NEPHI *FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Davg*

d=(d/Davg)*Davg(NP)	Gamma Dist.	P(D>d) = 1 - Gamma	No Contagion		PV Contagion	
Displacement (m)	[Calc For NP d]	[Calc For NP d]	SR AD	RI AD	SR AD	RI AD
0.7022	0.1413	0.8587	3.033E-04	5.103E-05	9.186E-06	1.545E-06
0.9350	0.3511	0.6489	2.292E-04	3.856E-05	6.941E-06	1.168E-06
0.9594	0.3757	0.6243	2.205E-04	3.710E-05	6.678E-06	1.124E-06
0.9594	0.3757	0.6243	2.205E-04	3.710E-05	6.678E-06	1.124E-06
1.3433	0.7228	0.2772	9.792E-05	1.647E-05	2.966E-06	4.990E-07
1.3922	0.7560	0.2440	8.617E-05	1.450E-05	2.610E-06	4.391E-07
1.3922	0.7560	0.2440	8.617E-05	1.450E-05	2.610E-06	4.391E-07
1.4000	0.7611	0.2389	8.437E-05	1.420E-05	2.555E-06	4.299E-07
1.4044	0.7639	0.2361	8.339E-05	1.403E-05	2.526E-06	4.249E-07
1.4999	0.8191	0.1809	6.391E-05	1.075E-05	1.936E-06	3.256E-07
1.5351	0.8366	0.1634	5.770E-05	9.708E-06	1.748E-06	2.940E-07
1.6999	0.9016	0.0984	3.474E-05	5.845E-06	1.052E-06	1.770E-07
1.7165	0.9068	0.0932	3.293E-05	5.541E-06	9.974E-07	1.678E-07
1.7270	0.9099	0.0901	3.183E-05	5.354E-06	9.639E-07	1.622E-07
1.9506	0.9580	0.0420	1.484E-05	2.497E-06	4.495E-07	7.563E-08
1.9506	0.9580	0.0420	1.484E-05	2.497E-06	4.495E-07	7.563E-08
1.9506	0.9580	0.0420	1.484E-05	2.497E-06	4.495E-07	7.563E-08
1.9506	0.9580	0.0420	1.484E-05	2.497E-06	4.495E-07	7.563E-08
2.1001	0.9756	0.0244	8.601E-06	1.447E-06	2.605E-07	4.383E-08
2.1037	0.9760	0.0240	8.484E-06	1.427E-06	2.569E-07	4.323E-08
2.1037	0.9760	0.0240	8.484E-06	1.427E-06	2.569E-07	4.323E-08
2.3000	0.9887	0.0113	3.988E-06	6.710E-07	1.208E-07	2.032E-08
2.3027	0.9888	0.0112	3.946E-06	6.639E-07	1.195E-07	2.011E-08
2.5711	0.9962	0.0038	1.325E-06	2.229E-07	4.012E-08	6.750E-09
2.5999	0.9967	0.0033	1.174E-06	1.975E-07	3.556E-08	5.983E-09
2.7825	0.9985	0.0015	5.384E-07	9.057E-08	1.631E-08	2.743E-09
2.7825	0.9985	0.0015	5.384E-07	9.057E-08	1.631E-08	2.743E-09
3.4803	0.9999	0.0001	2.256E-08	3.795E-09	6.831E-10	1.149E-10
3.4803	0.9999	0.0001	2.256E-08	3.795E-09	6.831E-10	1.149E-10

NEPHI *FREQUENCY OF EXCEEDANCE CALCULATIONS BASED ON Dmax*

d=(d/Dmax)*Dmax(NP)	*Lognormal Dist.*	*P(D> d) = 1 - Lognorm*	No Contagion		PV Contagion	
Displacement (m)	*[Calc For Nephi d]*	*[Calc For Nephi d]*	SR MD	RI MD	SR MD	RI MD
0.7022	0.3871	0.6129	2.165E-04	3.642E-05	6.556E-06	1.103E-06
0.9351	0.7057	0.2943	1.040E-04	1.749E-05	3.149E-06	5.297E-07
0.9594	0.7308	0.2692	9.510E-05	1.600E-05	2.880E-06	4.845E-07
0.9594	0.7308	0.2692	9.510E-05	1.600E-05	2.880E-06	4.845E-07
1.3433	0.9438	0.0562	1.985E-05	3.339E-06	6.012E-07	1.011E-07
1.3921	0.9545	0.0455	1.606E-05	2.702E-06	4.863E-07	8.182E-08
1.3921	0.9545	0.0455	1.606E-05	2.702E-06	4.863E-07	8.182E-08
1.3999	0.9561	0.0439	1.552E-05	2.611E-06	4.700E-07	7.908E-08
1.4044	0.9569	0.0431	1.522E-05	2.560E-06	4.609E-07	7.754E-08
1.5000	0.9717	0.0283	9.999E-06	1.682E-06	3.028E-07	5.095E-08
1.5350	0.9758	0.0242	8.565E-06	1.441E-06	2.594E-07	4.364E-08
1.7000	0.9883	0.0117	4.121E-06	6.934E-07	1.248E-07	2.100E-08
1.7165	0.9892	0.0108	3.829E-06	6.442E-07	1.160E-07	1.951E-08
1.7270	0.9896	0.0104	3.656E-06	6.151E-07	1.107E-07	1.863E-08
1.9506	0.9962	0.0038	1.359E-06	2.286E-07	4.115E-08	6.923E-09
1.9506	0.9962	0.0038	1.359E-06	2.286E-07	4.115E-08	6.923E-09
1.9506	0.9962	0.0038	1.359E-06	2.286E-07	4.115E-08	6.923E-09
1.9506	0.9962	0.0038	1.359E-06	2.286E-07	4.115E-08	6.923E-09
2.0999	0.9980	0.0020	7.059E-07	1.188E-07	2.138E-08	3.597E-09
2.1037	0.9980	0.0020	6.944E-07	1.168E-07	2.103E-08	3.538E-09
2.1037	0.9980	0.0020	6.944E-07	1.168E-07	2.103E-08	3.538E-09
2.2999	0.9992	0.0008	2.971E-07	4.999E-08	8.999E-09	1.514E-09
2.3028	0.9992	0.0008	2.935E-07	4.938E-08	8.890E-09	1.496E-09
2.5711	0.9997	0.0003	9.423E-08	1.585E-08	2.854E-09	4.801E-10
2.6000	0.9998	0.0002	8.354E-08	1.406E-08	2.530E-09	4.257E-10
2.7825	0.9999	0.0001	3.936E-08	6.623E-09	1.192E-09	2.006E-10
2.7825	0.9999	0.0001	3.936E-08	6.623E-09	1.192E-09	2.006E-10
3.4804	1.0000	0.0000	2.537E-09	4.268E-10	7.684E-11	1.293E-11
3.4804	1.0000	0.0000	2.537E-09	4.268E-10	7.684E-11	1.293E-11


Fault
Segment
Rupture Scenario
Frequency Estimation
Data Source
Normalizing Variable
[calculated weight]
Brigham City (BC)
BC alone (0.953)
0.95274
Slip Rate (0.7)
0.7
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.3335
Dmax (0.5)
0.5
0.3335
Recurrence Interval (0.3)
0.3
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.1429
Dmax (0.5)
0.5
0.1429
BC and WB (0.047)
0.04726
Slip Rate (0.7)
0.7
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.0165
Dmax (0.5)
0.5
0.0165
Recurrence Interval (0.3)
0.3
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.0071
Dmax (0.5)
0.5
0.0071
Weber (WB)
WB alone (0.878)
0.87785
Slip Rate (0.7)
0.7
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.3072
Dmax (0.5)
0.5
0.3072
Recurrence Interval (0.3)
0.3
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.1317
Dmax (0.5)
0.5
0.1317
WB and BC (0.014)
0.01381
Slip Rate (0.7)
0.7
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.0048
Dmax (0.5)
0.5
0.0048
Recurrence Interval (0.3)
0.3
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.0021
Dmax (0.5)
0.5
0.0021
WB and SLC (0.014)
0.01410
Slip Rate (0.7)
0.7
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.0049
Dmax (0.5)
0.5
0.0049
Recurrence Interval (0.3)
0.3
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.0021
Dmax (0.5)
0.5
0.0021
WB and BC and SLC (0.054)
0.05417
Slip Rate (0.7)
0.7
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.0190
Dmax (0.5)
0.5
0.0190
Recurrence Interval (0.3)
0.3
Trench Data (1.0)
1.0
Davg (0.5)
0.5
0.0081
Dmax (0.5)
0.5
0.0081


Wasatch Fault
Salt Lake City (SLC)
SLC alone (0.937)
0.93666
SLC and WB (0.025)
0.02471
SLC and PV (0.012)
0.01225
SLC and WB and PV (0.026)
0.02638
Provo((PV)
PV alone (0.945)
0.94509
PV and SLC (0.009)
0.00861
PV and NP (0.008)
0.00841
Slip Rate (0.7)
0.7
Recurrence Interval (0.3)
0.3
Trench Data (1.0)
1.0
Davg (0.5)
Dmax (0.5)
0.5
0.3278
0.3278
0.1405
0.1405
0.0086
0.0086
0.0037
0.0037
0.0043
0.0043
0.0018
0.0018
0.0092
0.0092
0.0040
0.0040
0.3308
0.3308
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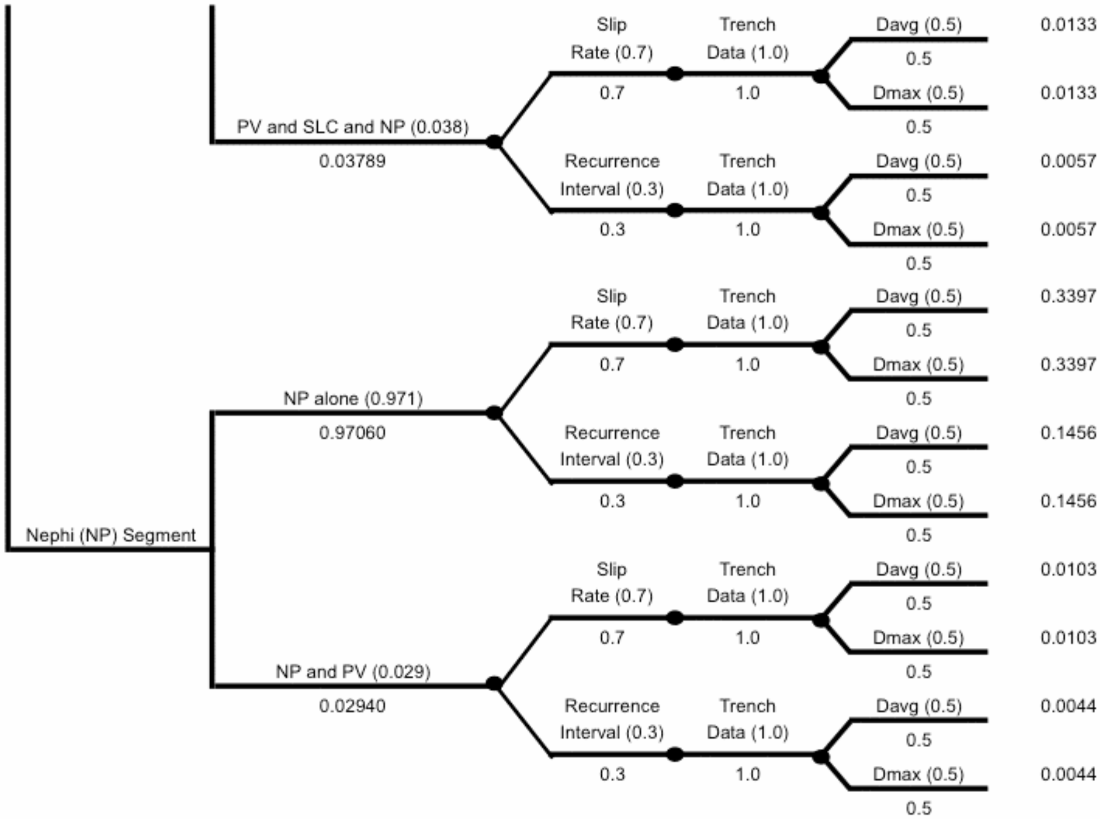
0.1418
0.0030
0.0030
0.0013
0.0013
0.0029
0.0029
0.0013
0.0013


Slip
Rate (0.7)
0.7
Trench
Data (1.0)
1.0
Davg (0.5)
0.5
0.0133
Dmax (0.5)
0.5
0.0133
PV and SLC and NP (0.038)
0.03789
Recurrence
Interval (0.3)
0.3
Trench
Data (1.0)
1.0
Davg (0.5)
0.5
0.0057
Dmax (0.5)
0.5
0.0057
Slip
Rate (0.7)
0.7
Trench
Data (1.0)
1.0
Davg (0.5)
0.5
0.3397
Dmax (0.5)
0.5
0.3397
NP alone (0.971)
0.97060
Recurrence
Interval (0.3)
0.3
Trench
Data (1.0)
1.0
Davg (0.5)
0.5
0.1456
Dmax (0.5)
0.5
0.1456
Nephi (NP) Segment
Slip
Rate (0.7)
0.7
Trench
Data (1.0)
1.0
Davg (0.5)
0.5
0.0103
Dmax (0.5)
0.5
0.0103
NP and PV (0.029)
0.02940
Recurrence
Interval (0.3)
0.3
Trench
Data (1.0)
1.0
Davg (0.5)
0.5
0.0044
Dmax (0.5)
0.5
0.0044

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