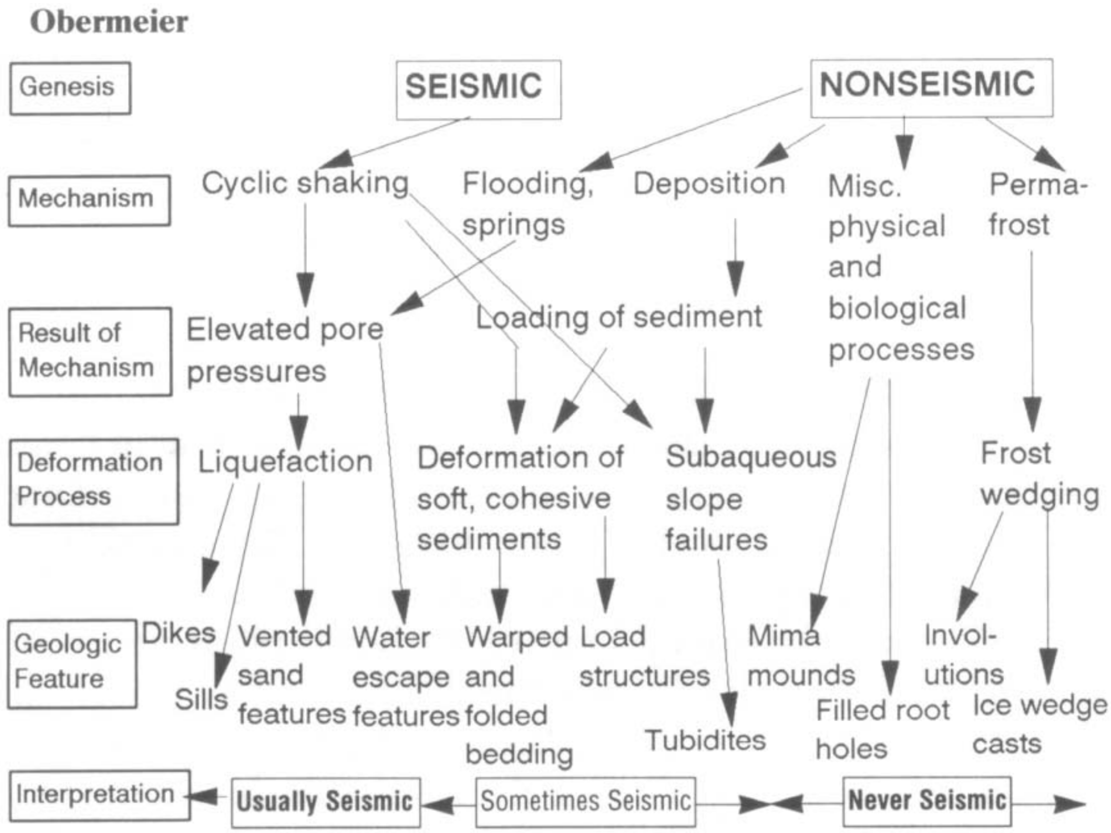


Modified from Obermeier (1996)

s:\7900\7935\7935.000\03_0303_sectb1_fig_b1-12.ai (2003-05-29, 11:07)

A

B

Bank rises approximately 12 feet above water level

Note that:
1. Dike widens downward.
2. Gravelly sand fill fines upward.
3. Dike walls are sharp and irregular.
4. Dike is roughly tabular.
5. Dike occurs in clear association with source material.
6. Weathering within dike suggests it is relatively old.

Seismic Hazards Report for the EGC ESP Site

Photographs of Dike 1 at Locality SC 25

Figure **B-1-13**

s:\7900\7935\7935.000\03_0303_sectb1_fig_b1-13(09,10).ai (2003-05-29, 11:09)

Detrital plant material

Filled Krotovina

Krotovina

Note that:

1. Dike widens downward.
2. Sand in filling fines upwards.
3. Contacts are sharp and irregular.
4. Dike occurs in clear association with source material.
5. Dike includes clasts of silty clay, apparently ripped from its walls.
6. Maximum dike width is 1.5 in.

s:\7900\7935\7935.000\03_0303_sectb1_fig_b1-14(07).ai (2003-05-29, 11:10)

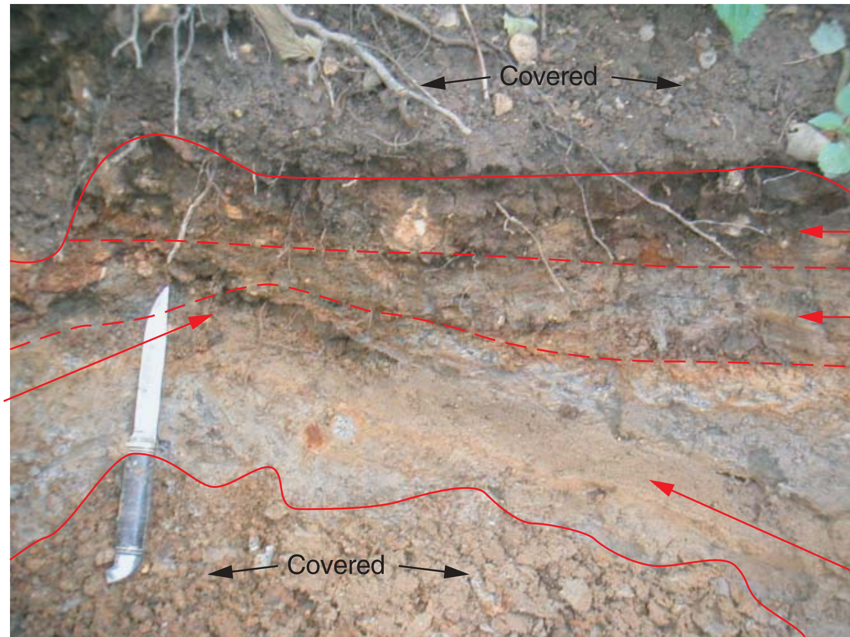
Seismic Hazards Report for the EGC ESP Site

Photograph of Dike 2 at Locality SC 19

Figure

B-1-14

A.



B.

Note: Knife is 8 in. long

s:\7900\7935\7935.000\03_0303_sectb1_fig_b1-15(13,12).ai (2003-05-29, 11:12)

Photographs of Parts of Dike 1 at Locality M 6

Figure **B-1-15**

Artificial fill

Cross-bedded sand and gravel indicates fluvial deposition

No liquefaction features were observed in this ~4 ft thick silt layer that overlies thick sequence of fluvial sand and gravel.

s:\7900\7935\7935.000\03_0303_sectb1_fig_b1-16(14).ai (2003-05-29, 11:14)

Seismic Hazards Report for the EGC ESP Site

Photograph of Thick Silt Layer Overlaying Fluvial Deposit at Locality S14

Figure
B-1-16

Exhibit 1 to Attachment 1
to the Seismic Hazards Report
for the Exelon Generation Company, LLC
Early Site Permit

Site Safety Analysis Report
Appendix B

EXHIBIT 1

Radiocarbon Dating

Beta Analytic Inc.
4985 SW 74 Court
Miami, Florida 33155 USA
Tel: 305 667 5167
Fax: 305 663 0964
beta@radiocarbon.com
www.radiocarbon.com

BETA
Consistent Accuracy Delivered On Time.

MR. DARDEN HOOD
Director

Mr. Ronald Hatfield
Mr. Christopher Patrick
Deputy Directors

December 6, 2002

Mr. Hans Abramson
Geomatrix Consultants, Incorporated
2101 Webster Street, 12th Floor
Oakland, CA 94612
USA

RE: Radiocarbon Dating Results For Samples 7935_SC-19-2.1, 7935_SC-19-2.2

Dear Mr. Abramson:

Enclosed are the radiocarbon dating results for two samples recently sent to us. They each provided plenty of carbon for accurate measurements and all the analyses went normally. The report sheet also contains the method used, material type, applied pretreatments and, where applicable, the two sigma calendar calibration range.

As always, this report has been both mailed and sent electronically. All results (excluding some inappropriate material types) which are less than about 20,000 years BP and more than about ~250 BP include this calendar calibration page (also digitally available in Windows metafile (wmf) format upon request). The calibrations are calculated using the newest (1998) calibration database with references quoted on the bottom of each page. Multiple probability ranges may appear in some cases, due to short term variations in the atmospheric 14C contents at certain time periods. Examining the calibration graphs will help you understand this phenomenon. Don't hesitate to contact us if you have questions about calibration.

We analyzed these samples on a sole priority basis. No students or intern researchers who would necessarily be distracted with other obligations and priorities were used in the analyses. We analyzed them with the combined attention of our entire professional staff.

Information pages are also enclosed with the mailed copy of this report. If you have any specific questions about the analyses, please do not hesitate to contact us.

Our invoice is enclosed. Please, forward it to the appropriate officer or send VISA change authorization. Thank you. As always, if you have any questions or would like to discuss the results, don't hesitate to contact me.

Sincerely,

Darden Hood

BETA

BETA ANALYTIC INC.

DR. M.A. TAMERS and MR. D.G. HOOD

UNIVERSITY BRANCH
4985 S.W. 74 COURT
MIAMI, FLORIDA, USA 33155
PH: 305/667-5167 FAX: 305/663-0964
E-MAIL: beta@radiocarbon.com

REPORT OF RADIOCARBON DATING ANALYSES

Mr. Hans Abramson — Report Date: 12/6/02

Geomatrix Consultants, Incorporated — Material Received: 10/25/02

Sample Data	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age(*)
Beta - 171950	9620 +/- 40 BP	-29.4 o/oo	9550 +/- 40 BP
Beta - 171951	10260 +/- 40 BP	-26.6 o/oo	10230 +/- 40 BP

Beta - 171950
SAMPLE : 7935_SC-19-2.1
ANALYSIS : AMS-Standard delivery
MATERIAL/PRETREATMENT : (plant material): acid/alkali/acid
2 SIGMA CALIBRATION : Cal BC 9150 to 8750 (Cal BP 11100 to 10700)

Beta - 171951
SAMPLE : 7935_SC-19-2.2
ANALYSIS : AMS-Standard delivery
MATERIAL/PRETREATMENT : (plant material): acid/alkali/acid
2 SIGMA CALIBRATION : Cal BC 10390 to 9780 (Cal BP 12340 to 11730)

Dates are reported as RCYBP (radiocarbon years before present, "present" = 1950A.D.). By International convention, the modern reference standard was 95% of the C14 content of the National Bureau of Standards' Oxalic Acid & calculated using the Libby C14 half life (5568 years). Quoted errors represent 1 standard deviation statistics (68% probability) & are based on combined measurements of the sample, background, and modern reference standards.

Measured C13/C12 ratios were calculated relative to the PDB-1 international standard and the RCYBP ages were normalized to -25 per mil. If the ratio and age are accompanied by an (*), then the C13/C12 value was estimated, based on values typical of the material type. The quoted results are NOT calibrated to calendar years. Calibration to calendar years should be calculated using the Conventional C14 age.

CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-29.4:lab. mult=1)

Laboratory number: **Beta-171950**

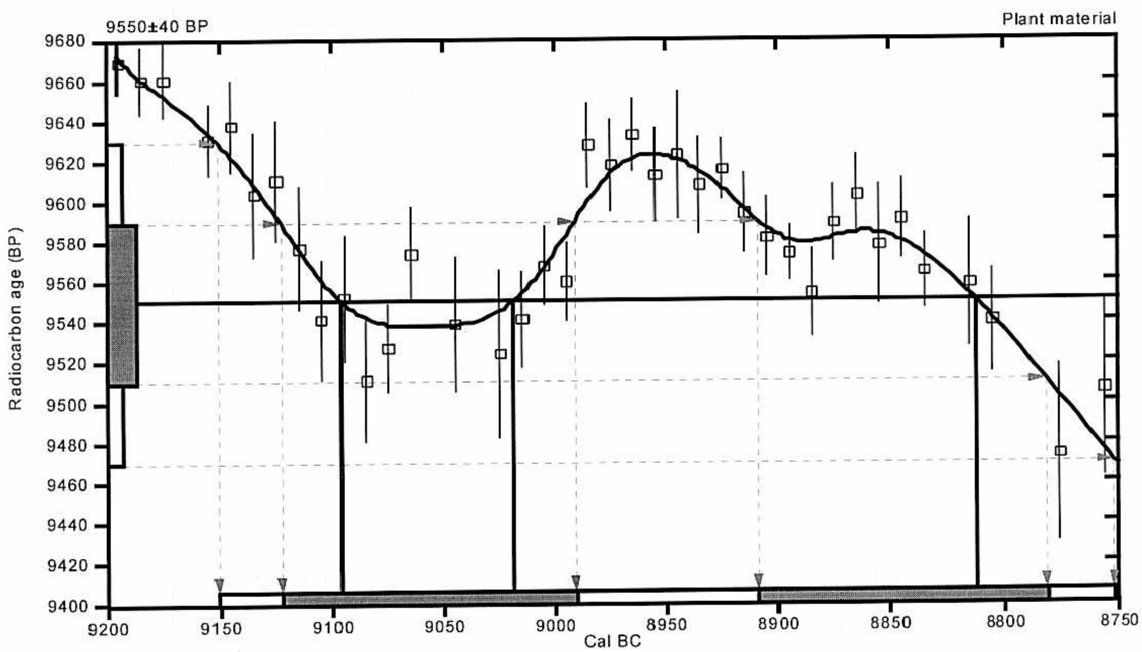
Conventional radiocarbon age: **9550±40 BP**

2 Sigma calibrated result: (95% probability) **Cal BC 9150 to 8750 (Cal BP 11100 to 10700)**

Intercept data

Intercepts of radiocarbon age with calibration curve: Cal BC 9100 (Cal BP 11050) and
Cal BC 9020 (Cal BP 10970) and
Cal BC 8810 (Cal BP 10760)

1 Sigma calibrated results: (68% probability) Cal BC 9120 to 8990 (Cal BP 11070 to 10940) and
Cal BC 8910 to 8780 (Cal BP 10860 to 10730)



References:
Database used

Calibration Database
Editorial Comment
Stuiver, M., van der Plicht, H., 1998, Radiocarbon 40(3), pxii-xiii
INTCAL98 Radiocarbon Age Calibration
Stuiver, M., et. al., 1998, Radiocarbon 40(3), p1041-1083
Mathematics
A Simplified Approach to Calibrating C14 Dates
Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2), p317-322

Beta Analytic Inc.

4985 SW 74 Court, Miami, Florida 33155 USA • Tel: (305) 667 5167 • Fax: (305) 663 0964 • E-Mail: beta@radiocarbon.com

CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12=-26.6:lab. mult=1)

Laboratory number: **Beta-171951**

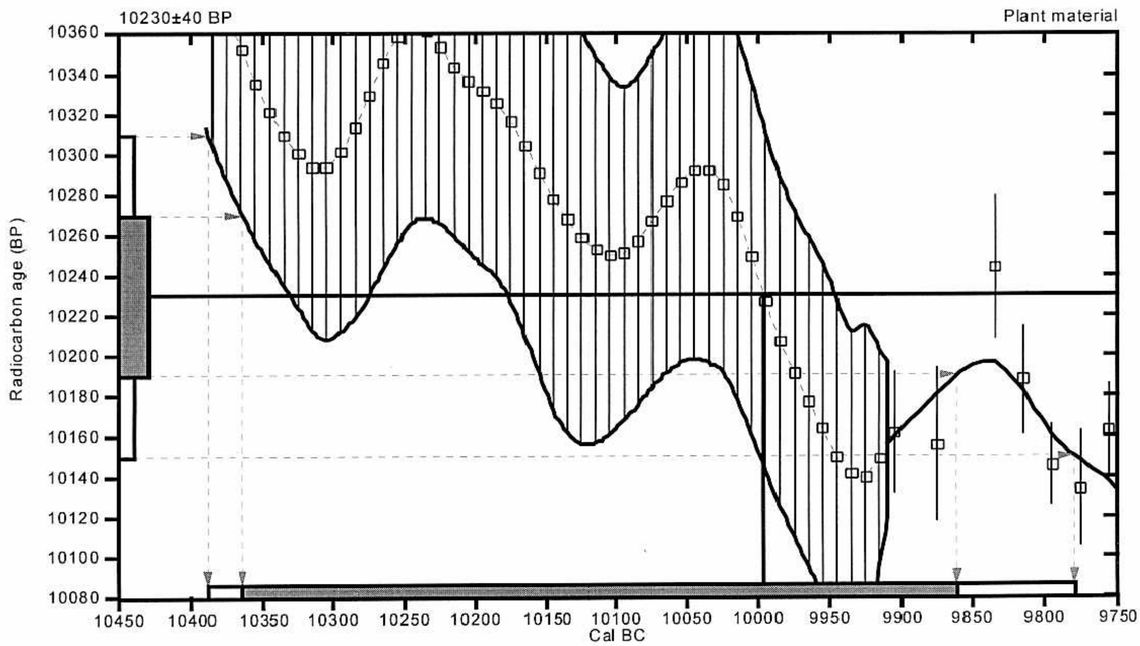
Conventional radiocarbon age: **10230±40 BP**

2 Sigma calibrated result: (95% probability) **Cal BC 10390 to 9780 (Cal BP 12340 to 11730)**

Intercept data

Intercept of radiocarbon age with calibration curve: Cal BC 10000 (Cal BP 11950)

1 Sigma calibrated result: (68% probability) Cal BC 10360 to 9860 (Cal BP 12310 to 11810)



References:

Database used

Calibration Database

Editorial Comment

Stuiver, M., van der Plicht, H., 1998, Radiocarbon 40(3), pxii-xiii

INTCAL98 Radiocarbon Age Calibration

Stuiver, M., et. al., 1998, Radiocarbon 40(3), p1041-1083

Mathematics

A Simplified Approach to Calibrating C14 Dates

Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2), p317-322

Beta Analytic Inc.

4985 SW 74 Court, Miami, Florida 33155 USA • Tel: (305) 667 5167 • Fax: (305) 663 0964 • E-Mail: beta@radiocarbon.com

BETA

Consistent Accuracy Delivered On Time.

Beta Analytic Inc.
4985 SW 74 Court
Miami, Florida 33155 USA
Tel: 305 667 5167
Fax: 305 663 0964
beta@radiocarbon.com
www.radiocarbon.com

MR. DARDEN HOOD
Director

Mr. Ronald Hatfield
Mr. Christopher Patrick
Deputy Directors

December 12, 2002

Mr. Hans Abramson
Geomatrix Consultants, Incorporated
2101 Webster Street, 12th Floor
Oakland, CA 94612
USA

RE: Radiocarbon Dating Result For Sample 7935_S-6-2

Dear Mr. Abramson:

Enclosed is the radiocarbon dating result for one sample recently sent to us. It provided plenty of carbon for an accurate measurement and the analysis went normally. As usual, the method of analysis is listed on the report sheet and calibration data is provided where applicable.

As you may remember we discussed the sample material, as we were not sure of the actual origin given the lack of normal wood grain or striations. I contacted you to express my concerns as to if the material might be coal or some other geologic material. SEM analysis performed prior to the dating indicated that the material did indeed appear to be charcoal, although possessing little actual structure. Per your instructions we proceeded with the dating. As you see the age is quite a bit older than expected and this probably indicates re-depositing or re-use of material from a previous time.

As always, no students or intern researchers who would necessarily be distracted with other obligations and priorities were used in the analysis. It was analyzed with the combined attention of our entire professional staff.

If you have specific questions about the analyses, please contact us. We are always available to answer your questions.

The cost of analysis was previously invoiced. As always, if you have any questions or would like to discuss the results, don't hesitate to contact me.

Sincerely,

Darden Hood

BETA

BETA ANALYTIC INC.

DR. M.A. TAMERS and MR. D.G. HOOD

UNIVERSITY BRANCH
4985 S.W. 74 COURT
MIAMI, FLORIDA, USA 33155
PH: 305/667-5167 FAX: 305/663-0964
E-MAIL: beta@radiocarbon.com

REPORT OF RADIOCARBON DATING ANALYSES

Mr. Hans Abramson — Report Date: 12/12/02

Geomatrix Consultants, Incorporated — Material Received: 10/25/02

Sample Data	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age(*)
Beta - 171952 SAMPLE : 7935_S-6-2 ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid	35510 +/- 1200 BP	-25.4 o/oo	35500 +/- 1200 BP

Dates are reported as RCYBP (radiocarbon years before present, "present" = 1950A.D.). By International convention, the modern reference standard was 95% of the C14 content of the National Bureau of Standards' Oxalic Acid & calculated using the Libby C14 half life (5568 years). Quoted errors represent 1 standard deviation statistics (68% probability) & are based on combined measurements of the sample, background, and modern reference standards.

Measured C13/C12 ratios were calculated relative to the PDB-1 international standard and the RCYBP ages were normalized to -25 per mil. If the ratio and age are accompanied by an (*), then the C13/C12 value was estimated, based on values typical of the material type. The quoted results are NOT calibrated to calendar years. Calibration to calendar years should be calculated using the Conventional C14 age.

Attachment 2 to the Seismic Hazards Report for the Exelon Generation Company, LLC Early Site Permit

Site Safety Analysis Report Appendix B

Contents

1. **Recurrence for New Madrid Characteristic Earthquakes B2-1-1**
  1.1 Estimation of the Time Interval between Prehistoric New Madrid Earthquakes B2-1-1
  2.1 Estimation of Recurrence Model Parameters B2-1-2
    2.1.1 Time-Independent (Poisson) Recurrence B2-1-3
    2.1.2 Time-Dependent Recurrence B2-1-4
2. References B2-2-1

Tables

B-2-1 Age Constraints Used for Assessment of Recurrence of New Madrid Characteristic Earthquakes....B2.T-1
B-2-2 Discrete Distributions for Rate of Characteristic New Madrid Earthquakes....... B2.T-3

Figures

B-2-1 Illustration of Simulation Process for Evaluating Time Intervals Between Characteristic New Madrid Earthquakes

B-2-2 Mean Repeat Time for New Madrid Characteristic Earthquakes

CHAPTER 1

Recurrence for New Madrid Characteristic Earthquakes

This attachment to Appendix B of the Site Safety Analysis Report (SSAR) for the Exelon Generating Company (EGC) Early Site Permit (ESP) Site presents an assessment of the recurrence of characteristic earthquakes on the central faults of the New Madrid seismic zone (NMSZ). Section 2.1.5.2.1 of Appendix B describes the paleoliquefaction investigations that have been conducted in the NMSZ region. These investigations have identified a number of paleoliquefaction features interpreted to have been caused by earthquakes and that have provided estimated age dates for these features. Table 2.1-5 of Appendix B summarizes the age dates for samples taken from these features, including the 95-percent confidence interval on the corrected calendar year for each sample. Various assessments of the paleoliquefaction features have interpreted them to be due to recurrence of characteristic earthquakes on the central faults of the NMSZ. The characteristic earthquake interpretation has been used for the EGC ESP analysis discussed in this Attachment. The first step in the recurrence assessment is to use these age dates and their uncertainties to provide constraints on the dates for prehistoric earthquakes. The intervals between these estimated dates then provide a sample of the repeat times between assumed characteristic earthquakes on the central New Madrid faults. The second step is to use these repeat times to estimate the parameters of appropriate recurrence models for the earthquakes. For this assessment, the uncertainties in the estimated dates were propagated through the estimation process using Monte Carlo simulation.

1.1 Estimation of the Time Interval between Prehistoric New Madrid Earthquakes

The process used to estimate the time interval between prehistoric New Madrid liquefaction events is illustrated on Figure B-2-1. Part (a) shows an example data set of dates and their 95-percent confidence intervals for samples taken from individual paleoliquefaction features. The various symbols indicate whether the feature is identified to have formed before or after event ‘Y’ (the earthquake of ~ AD 1450) or event ‘X’ (the earthquake of ~ AD 900). The first step was to simulate a set of possible dates for each sample using the defined uncertainty limits. A normal distribution for the sample date was for the date estimation error assumed, and the 95-pecent confidence interval was used to define the $\pm 2\sigma$ range for the age. Part (b) of Figure B-2-1 shows such a simulation using the data set from part (a).

The possible set of dates for individual samples in part (b) can now be used to constrain the possible ages for the prehistoric earthquakes. The oldest post-liquefaction date and the youngest pre-liquefaction date define the range of possible dates for each paleoearthquake. For example, the solid circles shown in part (b) of Figure B-2-1 indicate samples taken from features that postdate event Y. The oldest of these is considered to provide an estimate of

the youngest date for event Y. The solid squares shown in part (b) of Figure B-2-1 indicate samples taken from features that predate event Y and the youngest of these provides an estimate of the oldest date for event Y. These two sample dates thus provide a date range for event Y, shown by dashed lines. A similar assessment provides an estimated data range for event X.

The actual dates for the individual events were then simulated from these date ranges. The true date was assumed to be uniformly distributed within the possible date range. The uniform distribution represents the maximum uncertainty distribution for a parameter when all that is known is the range of possible values. Part (c) of Figure B-2-1 shows an example simulation result for the dates of the prehistoric earthquakes. The simulated dates for the prehistoric events, along with the 1811 to 1812 earthquake sequence date, define a sample of the time interval between characteristic earthquakes that can be used to estimate the parameters of a recurrence model. This estimation can include the open interval from 1811-1812 to the present.

The uncertainty in estimated time intervals between prehistoric earthquakes was captured through Monte Carlo simulation. One hundred sets of sample ages (part b of Figure B-2-1) were simulated. For each set of simulated sample ages, 100 simulations of prehistoric earthquake dates were created. The resulting 10,000 samples of time intervals between characteristic earthquakes were then used to develop 10,000 estimates of recurrence parameters as described in Section 1.2 of this attachment. The simulations were performed using data from the northeastern portion of the NMSZ where at least three prehistoric earthquake sequences were identified, events Y and X described above and an earlier event W (~ AD 300) (see Figure 2.1-26 of Appendix B). The individual samples used in the analysis are given in Table B-2-1. The statistics of the simulated ages for the prehistoric earthquakes are summarized in the following table.

Statistics of Estimated Dates for Prehistoric NMSZ Characteristic Earthquakes

Event	Event Date
Y	1454 AD± 55 years
X	917 AD ± 28 years
W	325 AD ± 252 years

1.2 Estimation of Recurrence Model Parameters

Two general types of recurrence models have been used to characterize the occurrence of characteristic earthquakes, time-independent and time-dependent. The time independent or Poisson model is the recurrence model commonly use in probabilistic seismic hazard analysis (PSHA) formulations for earthquakes of all sizes and was the recurrence model used in the Electric Power Research Institute Seismic Owner Group (EPRI-SOG) characterization of earthquake recurrence for all sources. The implication of this model is that the time interval between events is exponentially distributed (with the mode at zero), and a coefficient of variation of the time intervals is equal to 1.0. The likelihood of

occurrence of an earthquake in any time interval is independent of when the previous event occurred. However, the physics of the process of stress accumulation followed by release in characteristic earthquake ruptures on faults has led a number of investigators to consider time-dependent recurrence models for these sources. In the simplest form, time-dependent recurrence models are cast as a renewal model in which the likelihood of the next characteristic event occurring in a specified time interval is dependent only on the elapsed time since the previous characteristic event (e.g., Cornell and Winterstein, 1988; Wu et al., 1995). These models typically use a skewed distribution, such as the lognormal, Weibull, or gamma, to represent the distribution of times between characteristic earthquakes. Recently the Working Group on California Earthquake Probabilities (Working Group, 2003) has used these types of models to characterize the likelihood of large earthquakes on faults in the San Francisco Bay area. Cramer (2001) used a lognormal distribution to estimate the average repeat time for large earthquake in the NMSZ based on the estimated earthquake dates presented in Tuttle and Schweig (2000). In the following, recurrence model parameters are estimated for characteristic New Madrid earthquakes using both time independent and time-dependent recurrence models.

1.2.1 Time-Independent (Poisson) Recurrence

For the time-independent or Poisson recurrence model, the time interval between earthquakes, t, is exponential distributed with probability density given by:

$$f(t) = \lambda e^{-\lambda t} \qquad \text{(Eq. B-2-1)}$$

and cumulative probability given by

$$F(t) = 1 - e^{-\lambda t} \qquad \text{(Eq. B-2-2)}$$

where λ is the average rate of characteristic events ($1/\lambda$ is the average time between events).

Given a sample of n time intervals and one open interval, t_0, the likelihood function for the observed data set is given by:

$$L(\lambda) = \left\{ \prod_{i=1}^{n} f(t_i) \right\} \left\{ 1 - F(t_0) \right\} \qquad \text{(Eq. B-2-3)}$$

The maximum likelihood solution for the mean rate is given by the expression:

$$\lambda_{\text{maximum likelihood}} = \frac{n}{\sum_{i=1}^{n} t_i + t_0} \qquad \text{(Eq. B-2-4)}$$

An empirical uncertainty distribution for the parameter λ can be determined by computing the likelihood of observing the sample of event inter-arrival times (t_i ..t_n and t_0) for a range values of λ, and then normalizing these likelihoods to form a discrete probability distribution. This process was used to develop a probability distribution for λ for each set of simulated prehistoric earthquake dates. The resulting 10,000 likelihood distributions were then averaged to produce a composite uncertainty distribution for λ. Figure B-2-2 shows the resulting cumulative distribution for the average time between events, $1/\lambda$, estimated from

the simulation of times for events W, X, and Y, and the open interval post 1811-1812. This distribution was represented in the hazard analysis by a five-point discrete approximation to a continuous distribution defined by Miller and Rice (1983). This discrete distribution is listed in Table B-2-2.

1.2.2 Time-Dependent Recurrence

For the time-dependent renewal recurrence model, there are a variety of distributions that have been used to model the variability in the time between events, such as the lognornmal, Weibull, and gamma distributions. Recently, Matthews et al. (2002) have proposed a model based on the inverse Gaussian distribution for inter-arrival times of repeated large ruptures on a fault. This model, termed the Brownian Passage Time (BPT) model was used by the Working Group (2003) to assess the probabilities of large earthquakes in the San Francisco Bay area. The examples given in Matthews et al. (2002) show that the BPT and lognormal distributions produced very similar estimates of hazard for elapsed times less that the average time between events. The lognormal model was used in this analysis because of its simpler form and the fact that the elapsed time since the 1811-1812 sequence is less than the expected repeat time for large New Madrid earthquakes.

For the lognormal model, the time interval between earthquakes, *t*, is distributed with probability density given by:

$$f(t) = \frac{\exp\left(-\frac{(\ln t - \mu_{\ln t})^2}{2\sigma^2_{\ln t2}}\right)}{\sqrt{2\pi}t\sigma_{\ln t}}\lambda e^{-\lambda t} \quad \text{(Eq. B-2-5)}$$

and cumulative probability given by

$$F(t) = \int_{-\infty}^{t} f(t)dt \quad \text{(Eq. B-2-6)}$$

where $\mu_{\ln t}$ and $\sigma_{\ln t}$ are the mean log inter-arrival time and its standard deviation, respectively. The mean inter-arrival time, $\bar{t}$ is given be the expression:

$$\bar{t} = \exp\left(\mu_{\ln t} + \sigma^2_{\ln t2}/2\right) \quad \text{(Eq. B-2-7)}$$

Given a sample of *n* time intervals and one open interval, t_0, the likelihood function for the observed data set is again given by equation (B-2-3) with $f(t)$ and $F(t)$ replaced by equations (B-2-5) and (B-2-6). The maximum likelihood solution must be found by numerical methods. Because of the very limited data set, the estimate of the standard deviation is highly uncertain. Therefore, the standard deviation has been constrained for the assessment described in this Attachment to values reported from examination of larger data sets. Based on examination of a number of data sets, the Working Group (2003) developed an uncertainty distribution for the coefficient of variation of for the BTP model consisting of three weighted values of 0.3 (0.2), 0.5 (0.5), and 0.7 (0.3). (The standard deviation of ln(*t*) is approximately equal to the coefficient of variation for $\sigma_{\ln t}$<1.) The Working Group (2003) weighted distribution was adopted to constrain the standard deviation of $\sigma_{\ln t}$.

The process described in Section 1.2.1 of this Attachment was repeated to develop an empirical distribution for $\mu_{\ln t}$, given a specified value of $\sigma_{\ln t}$. Dates were simulated for events X and Y. Event W was not used in estimating the parameters for the renewal process because of the limited information to constrain its timing. For each simulated set of dates for the prehistoric New Madrid earthquakes, equations (B-2-3), (B-2-5), and (B-2-6) were used to compute the likelihood of observing the sample for a range of values of $\mu_{\ln t}$. These likelihoods were normalized to define a discrete distribution for $\mu_{\ln t}$. The estimation process was repeated for each of the 10,000 simulated sets of dates and the resulting distributions averaged to produce a composite distribution for $\mu_{\ln t}$. These distributions are plotted on Figure B-2-2 where equation (B-2-7) has been used to convert $\mu_{\ln t}$ into $\bar{t}$, the average time between events, for comparison with the Poisson values of $1/\lambda$. These distributions were represented in the hazard analysis by the five-point discrete approximations to a continuous distribution listed in Table B-2-2.

For the renewal recurrence model, the probability of an earthquake in the next time interval Δt is given be the expression:

$$P_{renewal}(\text{event in time } t_0 \text{ to } t_0 + \Delta t) = \frac{F(t_0 + \Delta t) - F(t_0)}{1 - F(t_0)} \qquad \text{(Eq. B-2-8)}$$

The basic PSHA formulation used to assess the site hazard assumes that the occurrence of individual earthquakes conforms to a Poisson process. In order to combine the hazard from earthquakes defined by a renewal process into the total hazard, an equivalent Poisson rate is defined such that a Poisson process will given a probability of at least one earthquake in time interval Δt is that is equal to the probability given by equation (B-2-8). The equivalent Poisson rate, $\lambda_{renewal}$, is given by the expression:

$$\lambda_{renewal} = -\ln\left[1 - P_{renewal}(\text{event in time } t_0 \text{ to } t_0 + \Delta t)\right] / \Delta t \qquad \text{(Eq. B-2-9)}$$

A time period of 50 years was chosen as the time period of interest for the ESP application. The corresponding estimates of $\lambda_{renewal}$ are listed in Table B-2-2.

The last column of Table B-2-2 lists the average equivalent repeat time for characteristic earthquakes derived from the discrete distributions for λ or $\lambda_{renewal}$. The values in bold are the inverse of the weighted average event frequency for each model. Assigning equal weight to the Poisson and renewal models, the resulting weighted average frequency of characteristic events is 1/465 events per year.

CHAPTER 2

References

Cornell, C.A., and S.R. Winterstein. "Temporal and Magnitude Dependence in Earthquake Recurrence Models." *Bulletin of the Seismological Society of America*. Vol. 78, No. 4. pp. 1522-1537. 1988.

Cramer, C.H. "A Seismic Hazard Uncertainty Analysis for the New Madrid Seismic Zone." *Engineering Geology*. Vol. 62. pp. 251-266. 2001.

Kelson, K.I., R.B. Van Arsdale, G.D. Simpson, and W.R. Lettis. "Assessment of the Style and Timing of Surficial Deformation along the Central Reelfoot Scarp, Lake County, Tennessee." *Seismological Research Letters*. Vol. 63, No. 3. pp. 349-356. 1992.

Kelson, K.I., G.D. Simpson, R.B. Van Arsdale, C.C. Haraden, and W.R. Lettis. "Multiple Late Holocene Earthquakes along the Reelfoot Fault, Central New Madrid Seismic Zone." *Journal of Geophysical Research*. Vol. 101, No. B3. pp. 6151-6170. 1996.

Li, Y., E.S. Schweig, M.P. Tuttle, and M.A. Ellis. "Evidence for Large Prehistoric Earthquakes in the Northern New Madrid Seismic Zone, Central United States." *Seismological Research Letters*. Vol. 69. pp. 270-276. 1998.

Matthews, M.V., W.L. Ellsworth, and P.A. Reasenberg. "A Brownian Model for Recurrent Earthquakes." *Bulletin of the Seismological Society of America*. Vol. 92. No. 6. pp. 2233-2250. 2002.

Miller, A.C., and T.R. Rice. Discrete Approximations of Probability Distributions." *Management Science*. Vol. 29, No. 3, pp. 352-362. 1983.

Tuttle, M.P. *Late Holocene Earthquakes and their Implications for Earthquake Potential of the New Madrid Seismic Zone, Central United States*. Ph.D. Dissertation. University of Maryland. 250 pp. 1999.

Tuttle, M.P. "The Use of Liquefaction Features in Paleoseismology: Lessons Learned in the New Madrid Seismic Zone, Central United States." *Journal of Seismology*. Vol. 5. pp. 361-380. 2001.

Tuttle, Martitia P. M. Tuttle & Associates. Written (Electronic) Communication. February 27, 2003.

Tuttle, M.P., and E.S. Schweig. "The Earthquake Potential of the New Madrid Seismic Zone." *American Geophysical Union, EOS Transactions*. Vol. 81, No. 19, p. S308. 2000.

Tuttle, M.P., and E.S. Schweig. *Towards a Paleoearthquake Chronology for the New Madrid Seismic Zone*. Collaborative Research, M. Tuttle & Associates and Eastern Region Hazards Team, U.S. Geological Survey. Annual Report Submitted to the U.S. Geological Survey. USGS External Project No. 1434-99HQGR0022. 18 pp. 2001.

Tuttle, M.P., and L.W. Wolf. *Towards a Paleoearthquake Chronology for the New Madrid Seismic Zone.* Progress Report Submitted to the U.S. Geological Survey NEHRP. USGS External Project No. 1434-01HQGR0164. 36 pp. 2003.

Tuttle, M.P., J.D. Sims, K. Dyer-Williams, R.H. Lafferty III, and E.S. Schweig III. *Dating of Liquefaction Features in the New Madrid Seismic Zone.* U. S. Nuclear Regulatory Commission Report NUREG/GR-0018. 42 pp. (plus appendices). 2000.

Working Group on California Earthquake Probabilities (Working Group). "Earthquake Probabilities in the San Francisco Bay Region: 2002-2031." U.S. Geological Survey Open-File Report 03-214. 2003.

Wu, S.-C., CA. Cornell, and S.R. Winterstein. "A Hybrid Recurrence Model and Its Implication on Seismic Hazard Results." *Bulletin of the Seismological Society of America*. Vol. 85, No. 1. pp. 1-16. 1995.

TABLE B-2-1

AGE CONSTRAINTS USED FOR ASSESSMENT OF RECURRENCE OF NEW MADRID CHARACTERISTIC EARTHQUAKES

Seismic Hazards Report for the ECG ESP Site

Name of Site	Lab Sample Number[1]	Material	Time Relationship of Sample to Liquefaction	^{14}C Age, years BP ± 1-sigma	Calibrated Age 2-sigma (95% Probability)[2]	Age Estimate Based on Ceramics and Points	Maximum Age Range (published correlation, comments)	Estimated Event Correlation	Reference
Amanda	Beta-133006 (T2-C14)	Charcoal (top of lower sand blow)	Preliquefaction (event 2) Postliquefaction (event 1)	240 ± 50	AD 1520 to 1590 AD 1620 to 1690 *AD 1740 to 1810* *AD 1930 to 1950*	NA	Event in trench T2, followed by event in trench T1, occurred during or soon after AD 1000 to 1400 (Middle Mississippian)	Two events: 1811-1812 and event Y, 1450 ± 150 yr.	Tuttle et al. (2000)
	Beta-133005 (T2-C13)	Charcoal (19 cm below sand blow)	Preliquefaction (event 1)	920 ± 40	AD 1020 to 1210	NA			
		Artifacts, including diagnostic ceramics	Preliquefaction (event 1)	NA	NA	AD 800 to 1400 (Early and Middle Mississippian)			
Burkett	TR-6	Artifacts-Burkett phase	Preliquefaction (event 3)	NA	NA	~ 400 BC to AD 330 Early-Middle Woodland (radiocarbon dating of horizon by Prentice Thomas)	Event 3 probably occurred at end of Burkett phase (AD 300 ± 200 yr.)	Event W AD 300 ± 200 yr. May be same event as older Towosaghy S1 event	Tuttle and Schweig (2001) Tuttle (M. Tuttle and Associates, electronic commun. to Kathryn Hanson, February 27, 2003).
Hillhouse	Beta-102500	Charcoal and ceramics	Postliquefaction	1150 ± 50	AD 780 to 1000	AD 400 to 1000 Late Woodland	AD 790 to 1000	Event X 900 ± 100 yr.	Tuttle (1999)
	Beta-102499	Charcoal	Preliquefaction	1140 ± 50	AD 790 to 1010	NA			
Johnson 5	Beta-102505	Soil	Preliquefaction	1110 ± 80	AD 770 to 1040	AD 800 to 1000 Late Woodland-Early Mississippian	AD 770 to 1670 Minimum age not well constrained; probably formed during Late Woodland-Early Mississippian. Soil development suggests sand blow formed prior to 1811 and was exposed at the surface for at least 670 years	Event X 900 ± 100 yr.	Tuttle (1999)
K1 Champey Pocket	Beta-49608	Charcoal	Post-monoclinal folding; colluvium	-	AD 1430 to 1650	NA	Event Y AD 1220 to 1650; ~AD 1400	Event Y (1450 ± 150 yr.)	Kelson et al. (1992 and 1996)
	Beta-49609	Charcoal	Pre-monoclinal folding	-	AD 1220 to 1390	NA			

TABLE B-2-1

CONSTRAINTS USED FOR ASSESSMENT OF RECURRENCE OF NEW MADRID CHARACTERISTIC EARTHQUAKES

Seismic Hazards Report for the ECG ESP Site

Name of Site	Lab Sample Number[1]	Material	Time Relationship of Sample to Liquefaction	^{14}C Age, years BP ± 1-sigma	Calibrated Age 2-sigma (95% Probability)[2]	Age Estimate Based on Ceramics and Points	Maximum Age Range (published correlation, comments)	Estimated Event Correlation	Reference
	Beta-48553	Charcoal; artifacts	Postliquefaction	-	AD 430 to 890	AD 800 to 1000 Close minimum (third most recent event)	Event X AD 780 to 1000	Event X 900 ± 100 yr.	
K2 Proctor City	CAMS-13559	Charcoal	Pre-scarp formation and re-development of graben (event Y)	660 ± 60	AD 1260 to 1410	NA	Event post-dates AD 1260	Event Y (1450 ± 150 yr.)	Kelson et al. (1996)
	CAMS-13540	Charcoal	Post-graben formation (event X)	960 ± 60	AD 980 to 1220	NA	Event X AD 780 to 1000; close minimum	Event X 900 ± 100 yr.	
	CAMS-13537	Charcoal	Pre-graben formation (event X)	1110 ± 60	AD 780 to 1030	NA	Close maximum		
L2 (Site WD)	Beta-71234	Soil (dispersed carbon)	Postliquefaction (event 1)	1140 ± 60	AD 770 to 1040	NA	Two sand blows, 1811-1812 and 900 ± 100 yr. Lower sand blow exposed at surface ~ 800 ± 100 yr. prior to burial by younger sand blow	1811-1812 (event 2) Event X 900 ± 100 yr. (event 1)	Li et al. (1998)
Obion 200	Beta-146738	Wood W2 collected from silt deposit above sand blow	Postliquefaction	230 ± 40	AD 1530 to 1550 AD 1640 to 1680 *AD 1740 to 1810* *AD 1930 to 1950*	NA	Before AD 1810 and After AD 1300 (based on probability distribution)	Event Y (1450 ± 150 yr.)	Tuttle and Schweig (2001)
	Beta-146737	Wood W1 collected within 1 cm of base of sand blow	Preliquefaction	590 ± 40	Close maximum AD 1300 to 1420	NA			
Obion 216	Beta-152008	Wood (W2 from outer 1 cm of horizontally bedded log buried by sand blow)	Preliquefaction	800 ± 60	AD 1060 to 1080 AD 1150 to 1290	NA	Event soon after AD 1300 (based on probability distribution)	Event Y (1450 ± 150 yr.)	Tuttle and Schweig (2001); Tuttle and Wolf (2003)
	Beta-152009	Wood (W4 from outer 1 cm of tree trunk in growth position in clay deposit beneath sand blow.	Preliquefaction	730 ± 60	AD 1160 to 1300	NA			
Towosaghy (re-excavate S1 site)	Dating underway	Artifacts	Postliquefaction (event 1)	NA	NA	Late Woodland to Early Mississippian (AD 400 to 1000) above sand blow; few artifacts below sand blow	Evidence for event 1 but not event 2 of Saucier	May correlate to event W AD 300 ± 200 yr. (event 1)	Tuttle and Wolf (2003)

1 Beta—Beta Analytic, Inc. (Miami, FL); CAMS—Center for Accelerator Mass Spectrometry (Livermore, CA)

2 Intervals that can be eliminated based on stratigraphic or historical evidence are shown in italics.

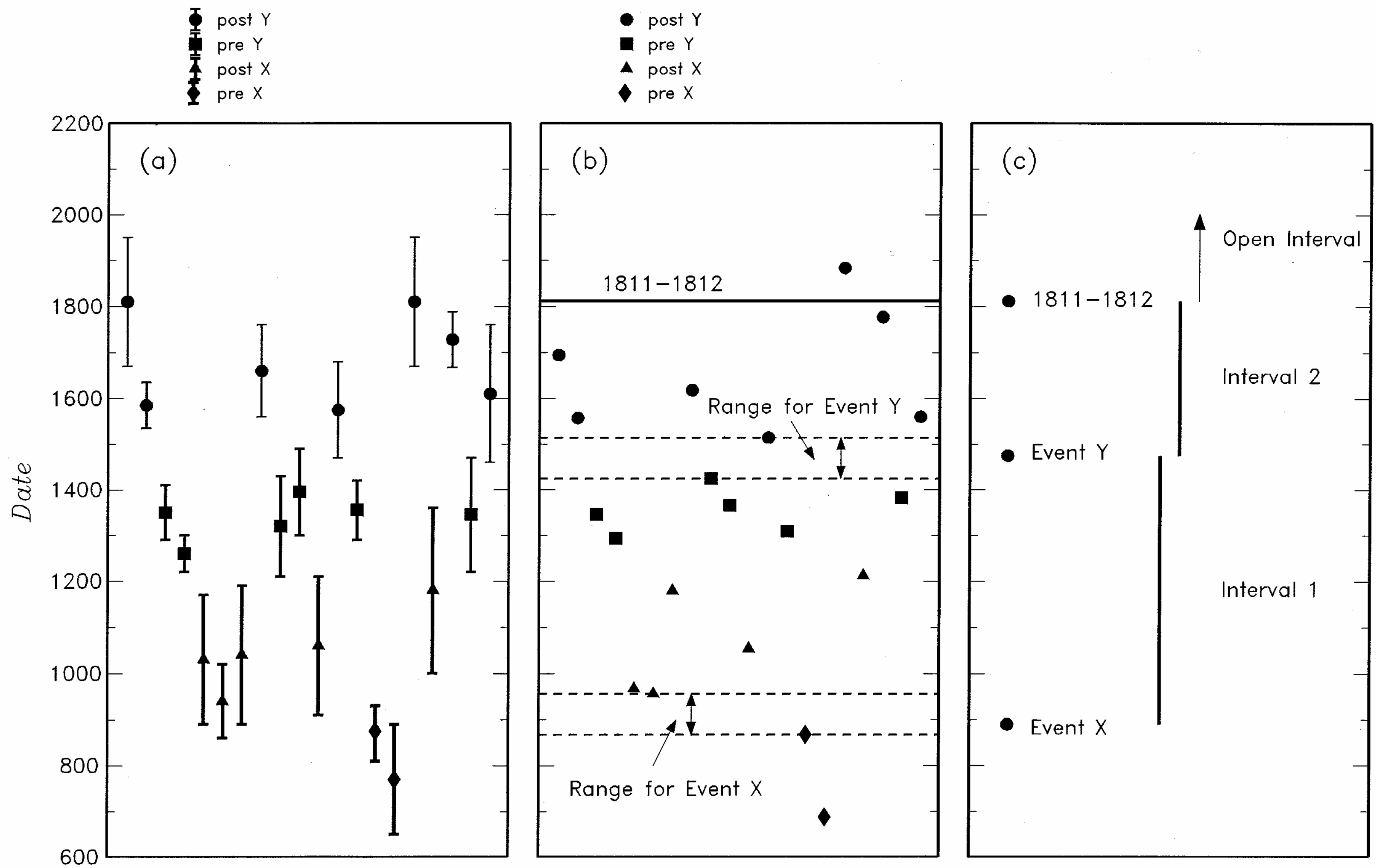
TABLE B-2-2

DISCRETE DISTRIBUTIONS FOR RATE OF CHARACTERISTIC NEW MADRID EARTHQUAKES

Seismic Hazards Report for the ECG ESP Site

Recurrence Model	**$1/\lambda$ (events/year)**	**$\exp(\mu_{\ln t})$ (years)**	**Event Frequency λ or $\lambda_{renewal}$ (events/year)**	**Weight**	**Equivalent Average Repeat Time (years)**
Poisson	186.6		0.005359	0.10108	187
	294.1		0.003400	0.24429	294
	442.5		0.002256	0.30926	443
	704.2		0.001420	0.24429	704
	1388.9		0.000720	0.10108	1,389
					401
Renewal (Lognormal $\sigma_{\ln t}$ = 0.3)		294.3	0.004273	0.10108	234
		365.3	0.001420	0.24429	704
		435.7	0.000430	0.30926	2,323
		515.4	0.000104	0.24429	9,638
		644.9	0.000010	0.10108	101,591
					1,066
Renewal (Lognormal $\sigma_{\ln t}$ = 0.5)		233.3	0.006478	0.10108	154
		334.5	0.003102	0.24429	322
		446.2	0.001390	0.30926	720
		590.6	0.000503	0.24429	1,988
		846.7	0.000091	0.10108	10,988
					506
Renewal (Lognormal $\sigma_{\ln t}$ = 0.7)		189.5	0.006080	0.10108	164
		313.7	0.003246	0.24429	308
		464.5	0.001676	0.30926	597
		693.1	0.000691	0.24429	1,447
		1147.8	0.000155	0.10108	6,453
					474

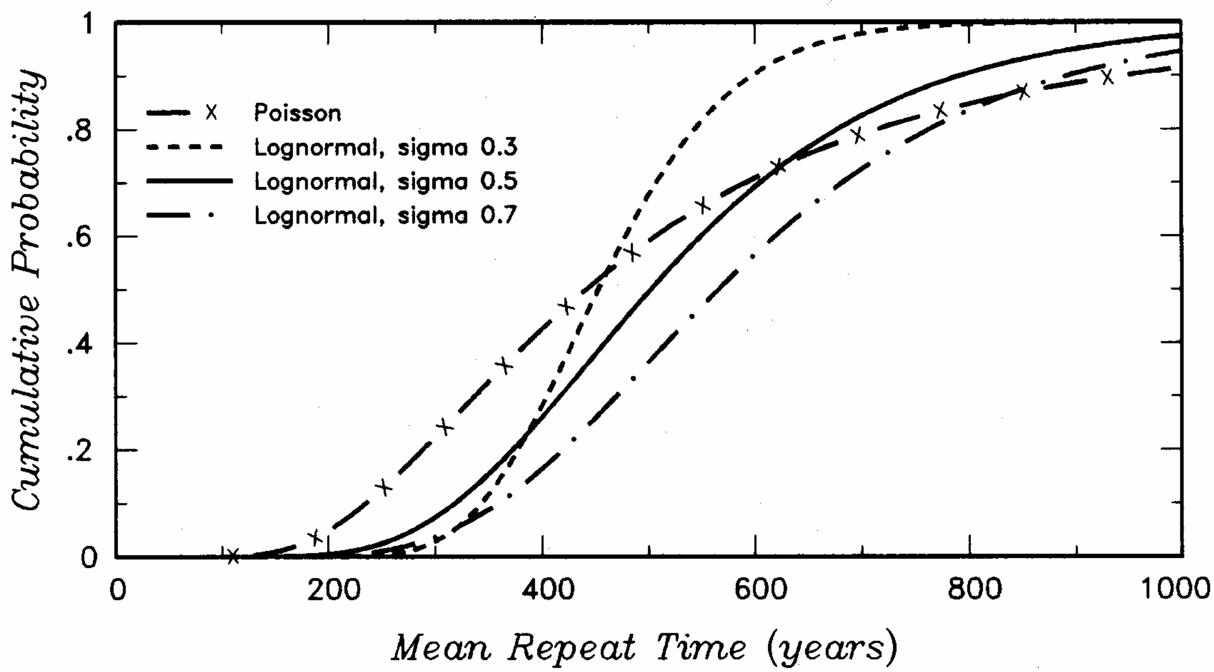
Non-GDS



Seismic Hazards Report for the EGC ESP Site

Illustration of Simulation Process for Evaluating Time Intervals between Characteristic New Madrid Earthquakes

Figure **B-2-1**



Seismic Hazards Report for the EGC ESP Site

Mean Repeat Time for New Madrid Characteristic Earthquakes

Figure
B-2-2