FINAL TECHNICAL REPORT
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Title: "Proposal to the USGS to Complete 12 St. Louis Area Earthquake Hazards Mapping Project Seismic Hazard Maps"

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**Summary**

The St. Louis Area Earthquake Hazards Mapping Project (SLAEHMP) is a key part of the U.S. Geological Survey's (USGS) Earthquake Hazards Program, which seeks to reduce the Nation's risk from earthquake hazards. The greater St. Louis, MO area has the highest earthquake risk of any metropolitan area in the eastern U.S. (FEMA, 2008). This agreement by SLAEHMP is for the completion of seismic hazard maps for the 17 eastern-most study-area quadrangles. As part of the first year's efforts, a Major River Flood Plain Depth-to-Bedrock and Water Table Model for the St. Louis area have been developed for combining with surficial geology mapping efforts by the Illinois and Missouri geological surveys to form a uniform depth-to-bedrock model, with uncertainty, for the SLAEHMP study area. This major river flood plain model is needed because borehole data there is sparse and sharp transitions at the edges of these flood plains are difficult to model directly from available borehole information. As part of the second year's efforts, the geologic model and information for Illinois and Missouri for the 17 easternmost quadrangles of the 29-quadrangle study area were developed and initial soil response calculations done as a quality control check on the geologic information. As part of the third and final year's efforts, site amplification models were finalized, probabilistic and scenario seismic and liquefaction hazard maps were generated, and a draft Open File Report prepared.

FEMA, 2008, *HAZUS MH Estimated Annualized Earthquake Losses for the United States*, FEMA 366, Federal Emergency Management Agency, Washington, DC, 66 p.

## Major River Flood Plain Model
## (work by Jae-Won Chung and Dave Rogers, MST)

### 1. Introduction

This report is intended to describe the methods used to map the depth-to-bedrock along major river channels in the St. Louis metro area, and summarize our progress to date, for the period from May 2010 to January 2011.

Work during the previous four years has shown that the ordinary kriging method could grossly overestimate or underestimate the actual depths-to-bedrock, most often, in areas where there is the irregular distribution and/or paucity of borings piercing the bedrock-alluvium interface. The greatest uncertainties in depth-to-bedrock exist in the confluence between the upper Mississippi, lower Missouri, and lower Illinois Rivers, where there are very few borings piercing the bedrock. Similar problems were encountered along transitional zones, such as the lateral margins of the major floodplains, where the depths-to-bedrock slope increases markedly, and along drowned 'feeder streams" [tributaries] that pierce the cliffy escarpments.

### 2. Data

The alluvial floodplains along the major river channels were delineated where the ground elevation lies below 145 m (**Figure 1**). The boring logs used in this study were supplied by the US Geological Survey (Conor Watkins, 2010 personal communication),

Missouri (MoDGLS 2007; Palmer et al., 2006), and Illinois (ISGS) state geological surveys, the Missouri and Illinois departments of transportation (MoDOT and IDOT), and other governmental agencies. Existing seismic reflection profiles and interpretation (Williams et al., 2007; Ali Atef, 2010 personal communication) were collected as well.

Lithologic descriptions contained in these geotechnical borings were evaluated and reviewed to determine bedrock elevations. Some of the geodata previously gleaned from the Missouri MEGA-CD database (MoDNR-DGLS, 2007) were removed after determining they were unreliable, based on comparisons with adjacent reliable data. These deleted data points are shown in **Figure 1**. Of 2,103 geodata points (borings) recording the Paleozoic age bedrock elevations, 1,990 were sampled within the 29 project quads, and another 113 were sampled within four adjacent quads (Winfield, Brussels, Eureka, and Pacific), in order to better determine the bedrock depths for the confluences of Mississippi-Illinois Rivers, and along the valleys cut by the Meramec River and Big Creek.

## 3. Methodology

In the vicinity of the Mississippi-Missouri-Illinois Rivers confluences, ice dams formed during the late Pleistocene, which resulted in short-term flow diversions (Goodfield, 1965), and temporary flow reversals during glacial ice advances (Elfrink and Siemens, 1998). These events appear to have played significant roles in shaping the channel morphology of this transitional area.

Geomorphic analyses of fluvial or glaciated river valleys are typically performed to fit empirical data from valley profiles, using to regression equations such as polynomial or power-law functions (James, 1996; Li et al., 2001; Merwade, 2004). Because bedrock topography is rather asymmetric and does not follow a simple parabolic form (Emmett and Jeffrey, 1968), the morphometrical analysis used in this study was accomplished by employing polynomial regression.

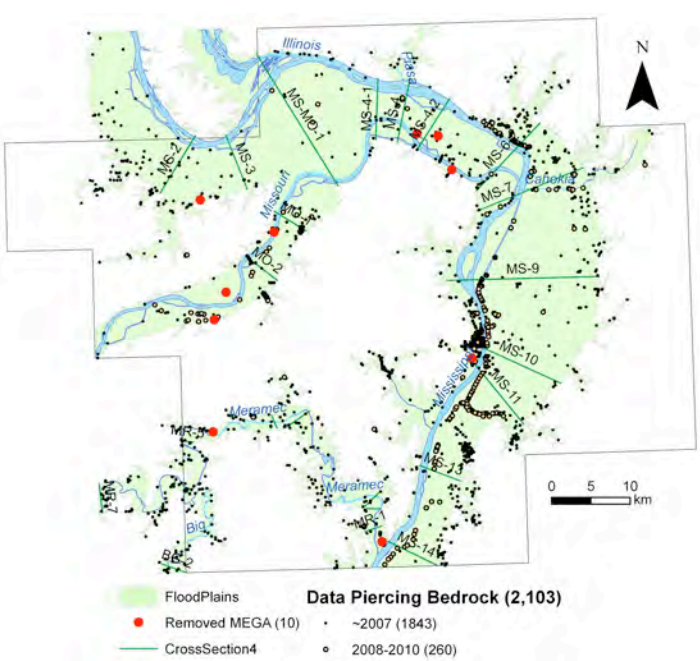


**Figure 1.** Map showing locations of data points piercing the Paleozoic bedrock units in the principal floodplains. The yellow and brown dots represent new data points, while the red dots denote suspicious data that was excised from the dataset.

We developed an analytical procedure that interpolates the likely depth-to-bedrock using the cross-sectional shape of the bedrock profile at discrete intervals.

1) 25 bedrock channel sections were constructed across the Missouri, Mississippi, and Meramec River valleys, based on clusters of adjacent borings that pierce the alluvial floodplains in those areas (shown as MS lines on **Figure 1**). These cross sections were constructed more or less perpendicular to the run of the river valley (their orientations are all unique).

2) The 2D cross-sectional convexities of each bedrock channel profile were analytically derived from polynomial regression graphs, based on bedrock depth and distance from floodplain boundaries. An example is presented in **Figure 2**.

3) A grid spacing of 200m × 200m was established within the defined floodplains. The regression model of the nearest channel cross-section was then used to estimate values of depth-to-bedrock at the grid points between adjacent cross sections.

4) The preliminary 3D bedrock surface between adjacent cross sections was then generated on 200 m grid spacings using ordinary kriging, to allow construction of isopleths defining the "statistical mean contact" between the alluvium and the underlying bedrock. This is intended to serve as a preliminary "smoothed estimate" of the bedrock surface useful for seismic site response modeling on a regional scale (1:24,000).

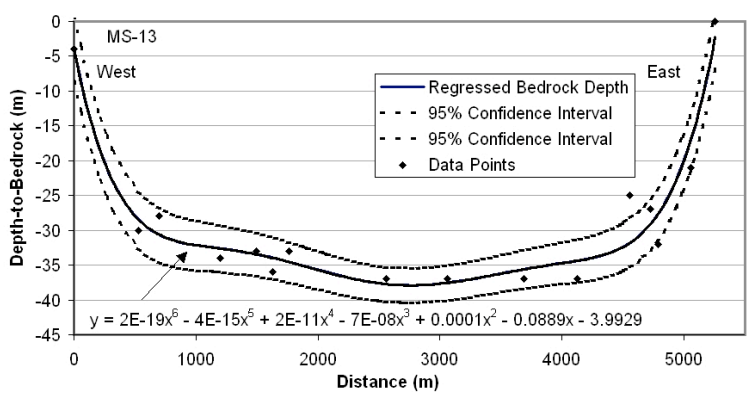


**Figure 2.** Regressed and adjusted bedrock depths for one of the channel cross-sections along the Mississippi River, showing the uncertainty bands with a 95% confidence interval. Note the actual data points, shown as black dots.

5) The difference (residual) between actual and regressed values at sampled site was calculated and interpolated using ordinary kriging. The regressed values ($Z_R$) were adjusted with the kriged values of the residuals (ε) to give the final estimated values of the depth-to-bedrock ($Z_{RK}$);

$$Z_{RK}(u) = Z_R(u) + \varepsilon(u)$$

**Figure 3** shows the preliminary map of depth-to-bedrock map for the major river valleys, interpolated by the five steps described above.

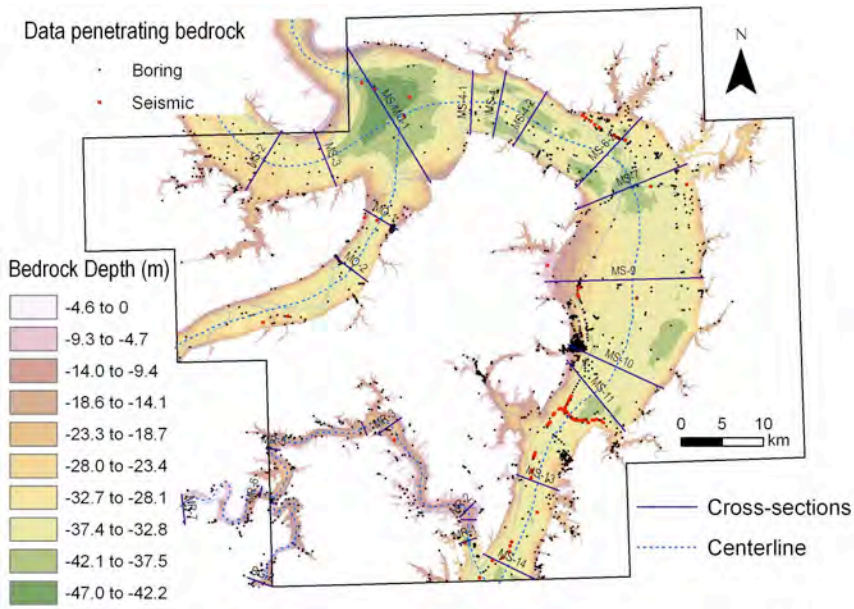


**Figure 3**. Depth-to-bedrock map in major river valleys, estimated by polynomial regression to obtain the statistical mean contact and ordinary kriging.

## 4. Uncertainty

This model cannot perfectly depict the actual bedrock boundary at unsampled sites; it is simply intended to provide a "best fit" estimate, assuming geometric continuity between the reliable data points, which have been smoothed using polynomial regression. This is intended to replicate what a geologist does by hand when considering data points with varying horizontal offsets, upstream and downstream of a cross section. The uncertainty as a lack of confidence arises from natural variability, interpolation errors, and limitations of insufficient data (Heuvelink, 1998; Gomberg et al., 2003; Odeh et al 1995; Elith et al., 2002; Regan et al, 2002).

The uncertainty arising from curve-fitting, including interpolation, is a prime example of model uncertainty. One way to illustrate the relative uncertainty is to present confidence intervals bounding the estimated bedrock surfaces (Elith et al., 2002; Regan et al., 2002). Confidence intervals for the individual parameters provides a relative indication of how well the surface can be estimated. If the fit is good, the confidence interval bands with upper and lower bounds will be close to the polynomial fit line. The polynomial fit of the cross-sections we analyzed in the major river valleys were constructed (**Figure 4**) with 95 % confidence interval bands, which depict the probable range of the polynomial fit for the underlying data population (as shown in **Figure 2**).

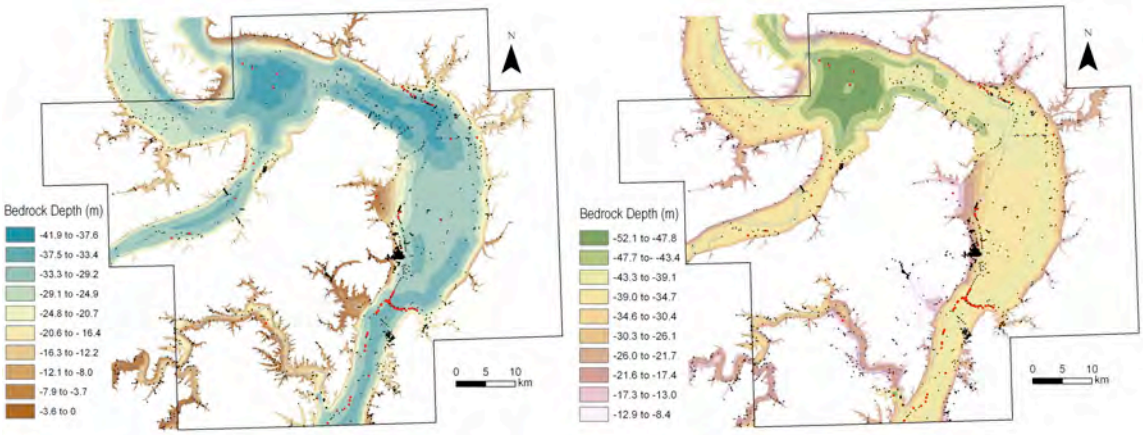


**Figure 4**. Upper (left) and lower (right) bounds of the 95% confidence interval of depth-to-bedrock map, shown in **Figure 3**.

## 5. Completed Tasks (May 2010 thru March 2011)

- Data collection: A total of 2,103 boring logs piercing bedrock surface have been analyzed and entered for 33 quadrangles (**Figure 1**).
- The alluvial floodplains along the major river channels were delineated where the ground elevation lies below 145 m (**Figure 1**).
- 25 Channel cross-sections were constructed across the four major river valleys (**Figure 2**).
- A preliminary depth-to-bedrock map was produced and then revised, based on comments of the SLAEHMP-Technical Working Group (**Figure 3**).
- Preliminary upper and lower bound maps of 95% confidence interval were prepared to evaluate the uncertainties (**Figure 4**).
- Final adjustments to our work products. These include the bedrock depth map and its upper and lower bound maps. These were presented to the SLAEHMP-Technical Working Group and adjusted in accordance with their comments.

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## Illinois Quadrangles
## (work by Robert Bauer and ISGS staff)

In order to produce the hazard maps for the St. Louis Urban Hazard Mapping project, three products for the 16 Illinois 7.5 minute quadrangles are being provided by the Illinois State Geological Survey. The grant for this work was finalized on September 29, 2010 six months into the proposed scope of work presented in the proposal and work was completed under the second year funding of this agreement.

The three overall products are: (1) Depth-to-bedrock with uncertainty in the estimated depth, (2) Vs reference profiles keyed to geologic province types – representing simplified 3-D stratigraphy and (3) Geologic province map (polygons) representing simplified 3-D stratigraphy corresponding to the Vs reference profiles.

### Depth elevation map

The depth-to-bedrock product is generated by first production of a bedrock elevation map. For the 16 quadrangles in Illinois, the Illinois State Geological Survey (ISGS) is generating a contoured elevation map of the bedrock surface by populating a database with borehole information, generating a computerized surface from the database, checking any surface anomalies for problems with the borehole information and lastly modifying this surface using judgment and hand methods incorporating geomorphic principles by the mappers who are responsible for the data collection, selection of drilling sites, core descriptions, seismic profiles selection and database population. Borehole data continues to be added to the database for the quadrangles from available borehole descriptions in house and provided by Conor Watkins of the USGS who is securing additional data from Federal agencies and private consulting firms. The Illinois part of the Grafton, Oakville and Elsah quadrangles need to be added to previous mapping work. Oakville (Figure 5), Grafton, and Elsah have now been completed. New data added to

the database are also being transmitted to the Missouri Science and Technology participants in this overall proposal. A draft map of completed work is shown in Figure 6.

**Depth and location uncertainty**

Previous hazard mapping work in the Central U.S. has incorporated an estimate of uncertainty associated with only depth of lithologic contacts. But that depth location is also controlled by the location uncertainties of the borehole at the ground surface. The ISGS has a draft report (Appendix A) on depth and location uncertainties of each of its types of borehole information which includes water wells; geotechnical borings for private and public projects such as buildings, levees, bridges and other structures; hydrocarbon (coal and oil) exploration and data produced by seismic profiles for determination of the stratigraphy of the near surface sediments and top of bedrock.

**Vs reference profiles**

The ISGS is collecting additional existing shear wave velocity information from the bridge projects in the Central U.S. and from the Missouri Geological Survey. This data has been combined to produce the known variations in the values with depth in materials that are found in the Illinois quadrangles. Previous reference profiles for the St. Louis Urban Hazard Mapping defined only an upland and alluvium (lowland) profiles from velocity measurement compiled and averaged from a very large region in Illinois and Missouri. The uplands "soil" sequence is very different in Missouri versus Illinois. The Central U.S. Earthquake Consortium (CUSEC) shear wave velocity database has been used, which is downhole and crosshole shear wave velocity data (Figure 7a) and newly acquired date (Figure 7b) that has been evaluated for this project.

**Geologic province map**

The geologic province map representing simplified 3-D stratigraphy has now been completed for all 16 Illinois 7.5 minute quadrangles mapped. Grafton and Elsah quadrangles are now included in the geologic province map (see geologic model inputs to hazard maps below).

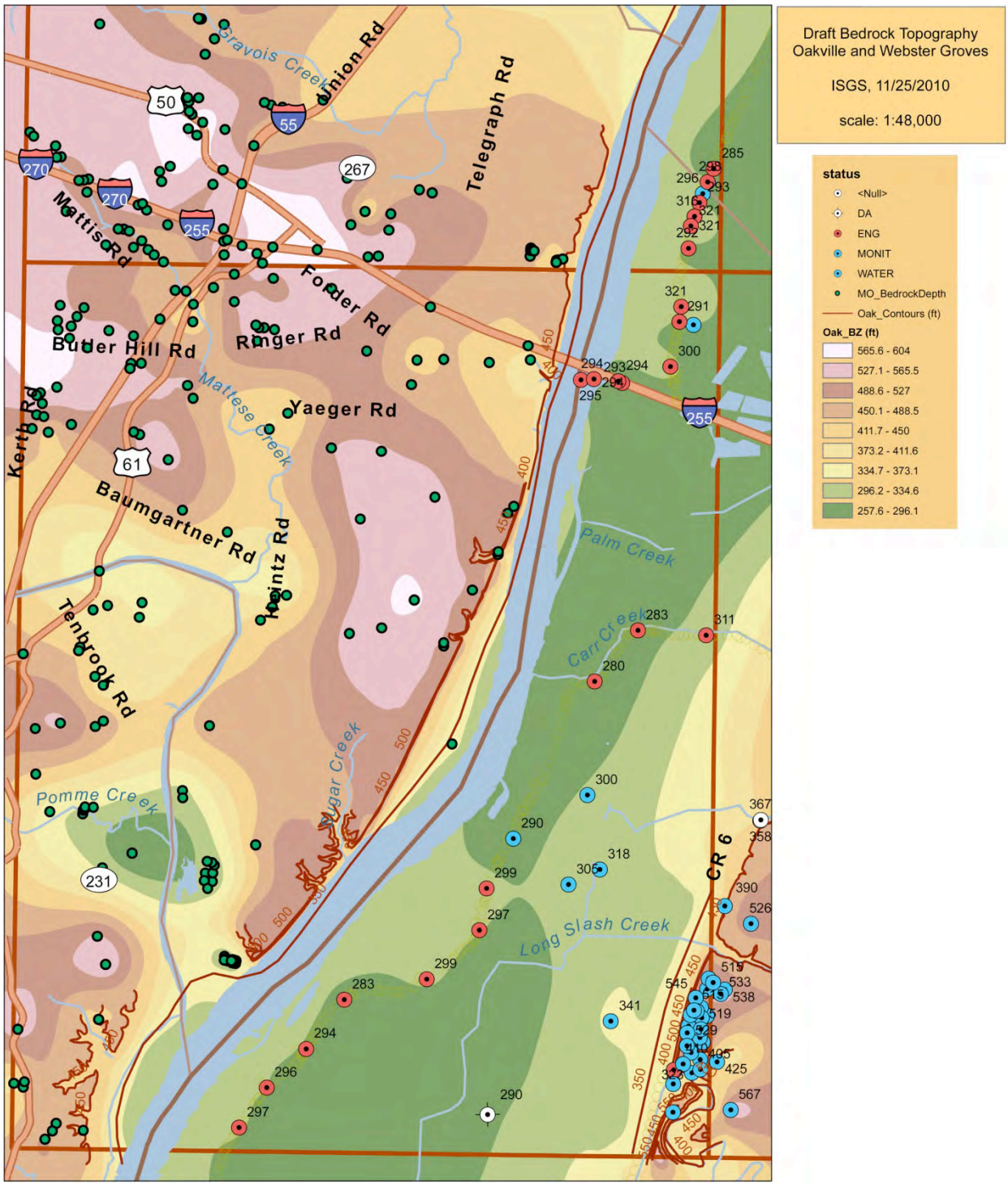



Figure 5. Draft Oakville quadrangle map showing bedrock elevations in feet and location of boreholes that encountered bedrock.

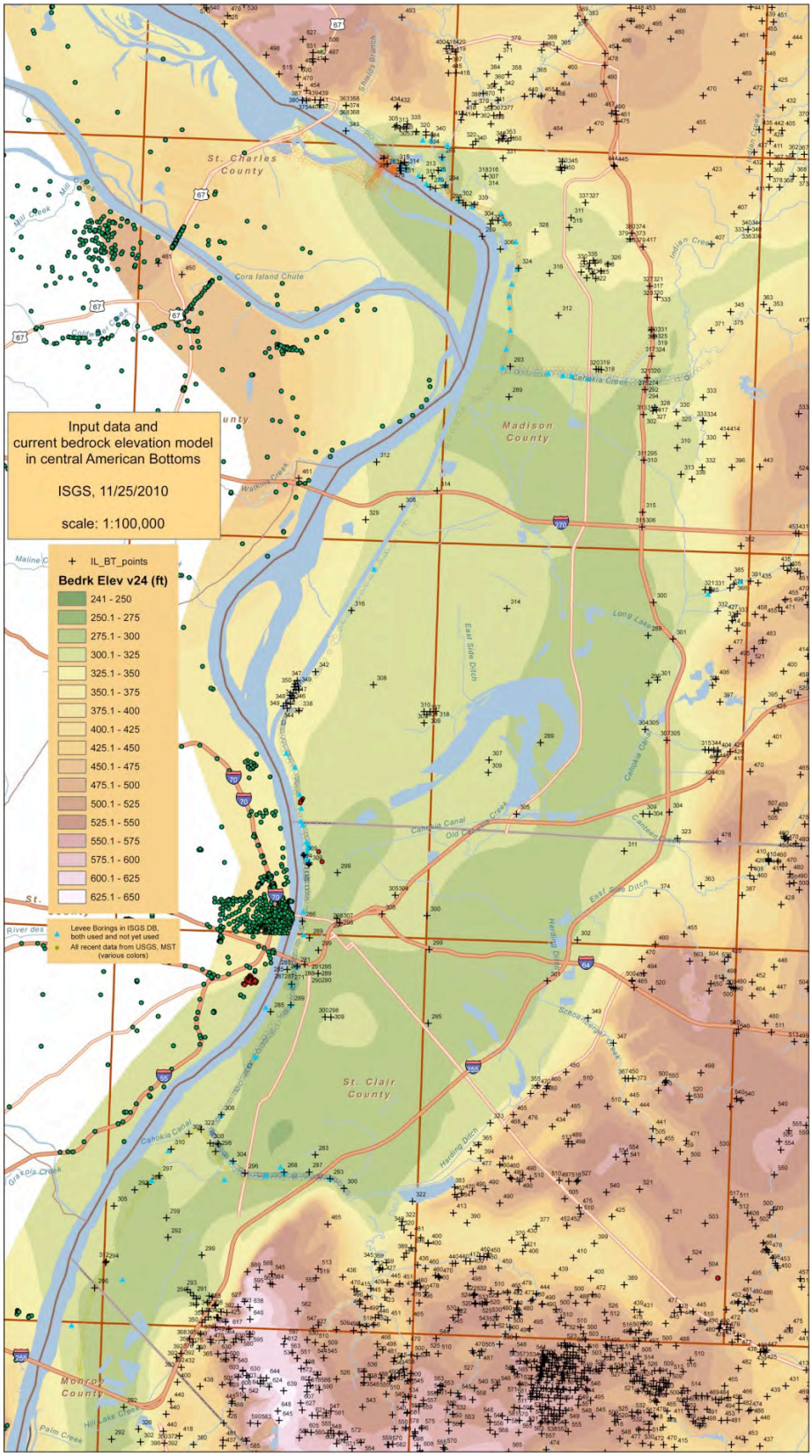



Figure 6. Draft map showing bedrock elevations in feet.

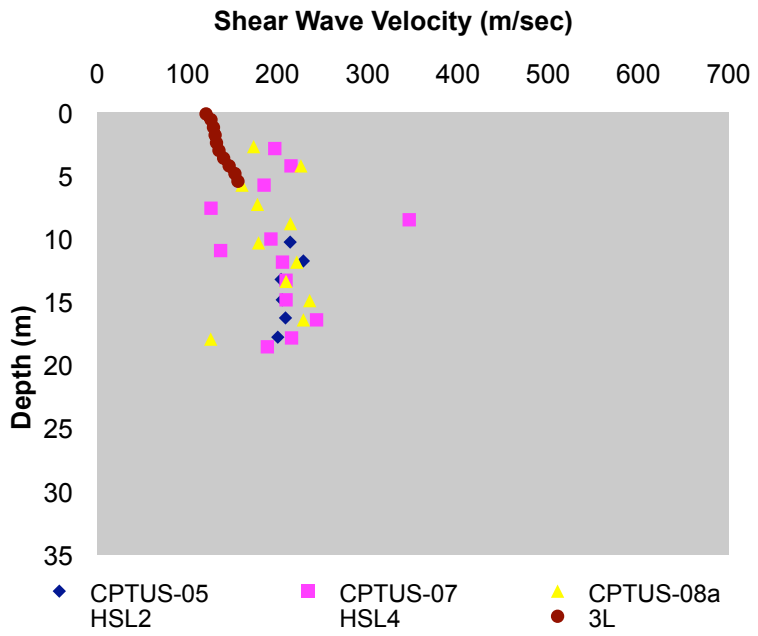



Figure 7a. Example of some of the Downhole, Seismic CPT and Crosshole shear wave velocity data from the Mississippi River floodplain deposits.

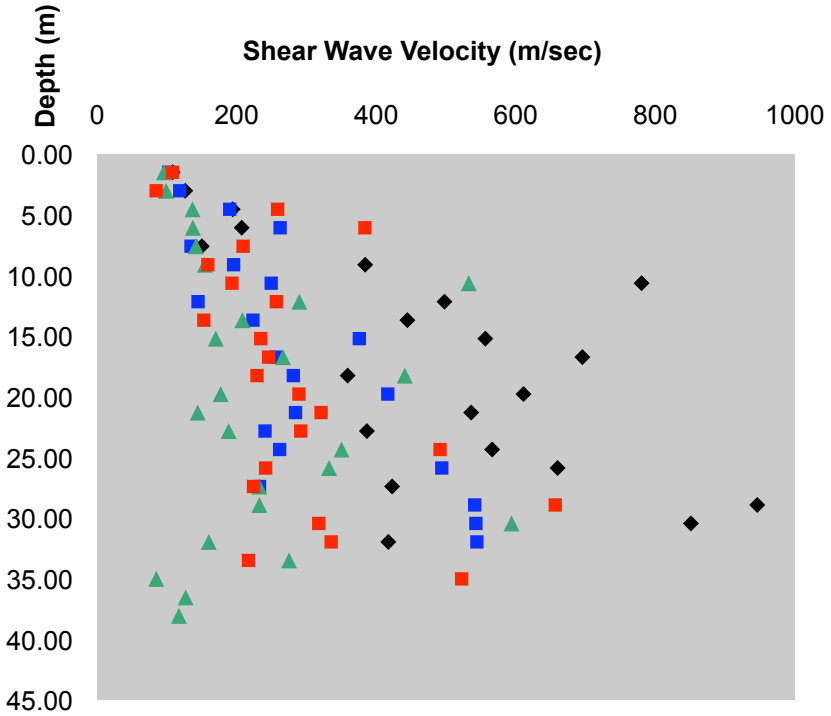



Figure 7b. Example of some of the Downhole shear wave velocity data from the New Mississippi River bridge project showing wide variation in values in floodplain deposits.

## Matching Across State Boundaries
## (work by SLAEHMP TWG)

We have matched the bedrock models across the Illinois and Missouri state boundary. The geology on each side the Illinois and Missouri state boundary is significantly different in terms of bedrock and soil type, which have been incorporated into the final hazard maps. After we determined the degree of mismatch, the impact of the mismatch on the hazard maps was evaluated, appropriate adjustments made, and a final seamless bedrock model produced.

## Geologic Model Input to Urban Hazard Maps
## (work by ISGS and MoDGLS)

Figures 8 and 9 present the final Illinois and Missouri surface geology maps for the eastern 17 quadrangles covered in this report. The geology has been matched at the state boundary. These geology maps were digitized on a uniform location grid at a 50 m and 250 m spacing for Illinois and Missouri, respectively, and provided for the urban hazard map calculations.

Figures 10 and 11 present the final Illinois and Missouri soil thickness maps for the 17 eastern quadrangles of the study area. Again these soil thickness maps have been matched at the state boundary and the information provided on a uniform location grid for urban hazard maps calculations.

Because of the differences in bedrock geology and the interpretation of the degree of bedrock weathering across state boundaries, ISGS provided a bedrock geology map for use in urban hazard map calculations (Figure 12). In the geology model used in the hazard calculations, the presence of shale bedrock meant an additional 25 m of weathered bedrock transition below the soil thickness shown in Figure 10, while the presence of limestone/dolomite bedrock meant only an additional 10 m of weathered bedrock. On the Missouri side, the interpretation by MoDGLS geologists is that there is no bedrock weathering below the indicated soil thickness and that any bedrock weathering has been incorporated into the soil thickness model. For the Mississippi floodplain deposits on the Missouri side, the Illinois interpretation of 10 m of bedrock weathering was applied to maintain the matching of geology across state boundaries.

## Reference Vs Profiles
## (work by ISGS and MoDGLS)

Associated with the surface geology and geologic province maps (Figures 8 and 9) are a set of shear-wave velocity (Vs) reference profiles representing the geotechnical properties of the represented soils with depth. The reference Vs profiles are shown in Figure 13 in summary form. These reference Vs profiles were provided by ISGS and MoDGLS along with the geologic province maps for use in the urban hazard map calculations. At a given grid point, the geologic province the grid point falls within is used to access the proper reference Vs profile for that grid point. The reference profile consists of both a geologic

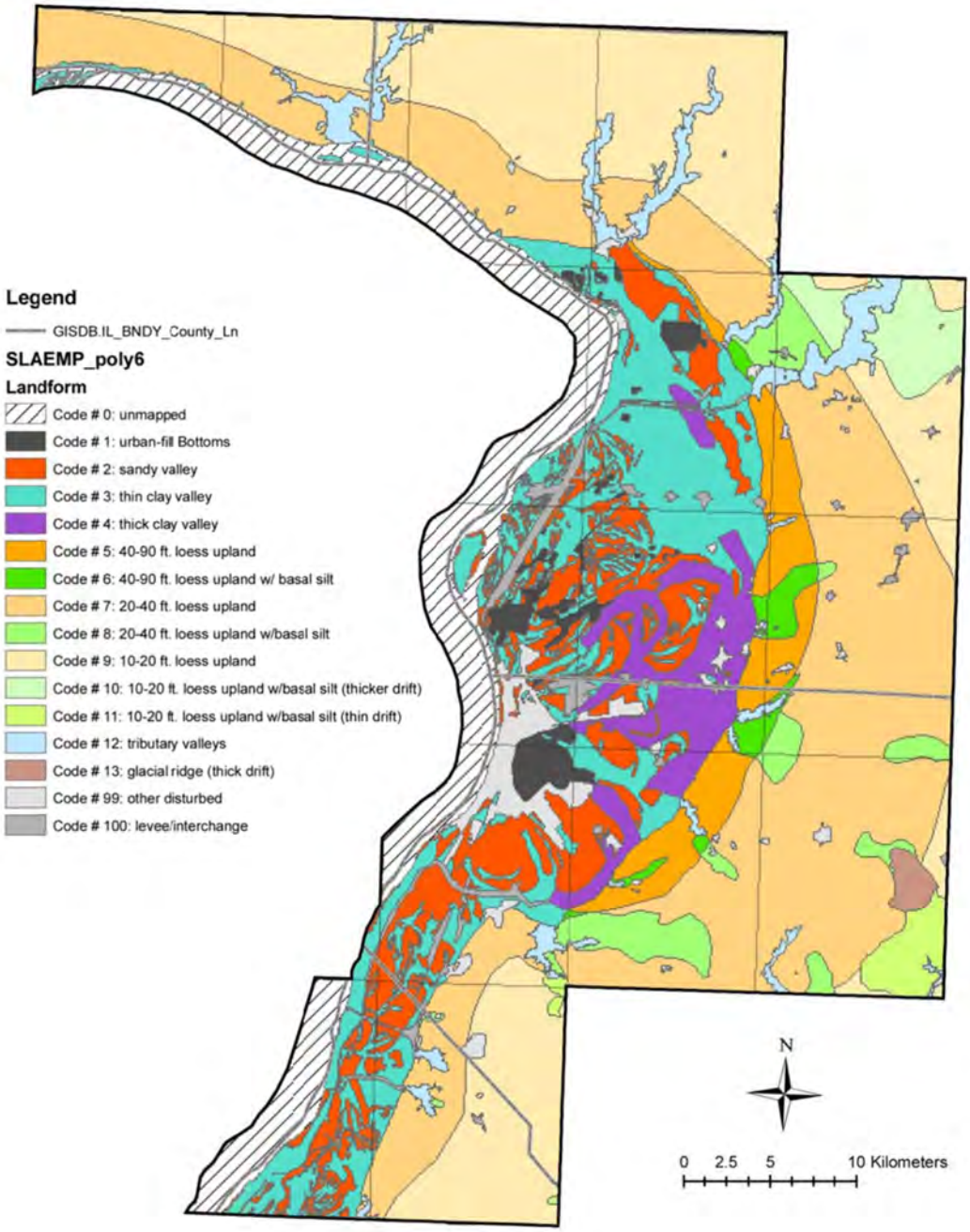



Figure 8. Illinois surface geology with geologic provinces tied to shear-wave velocity reference profiles used in seismic hazard map calculations.

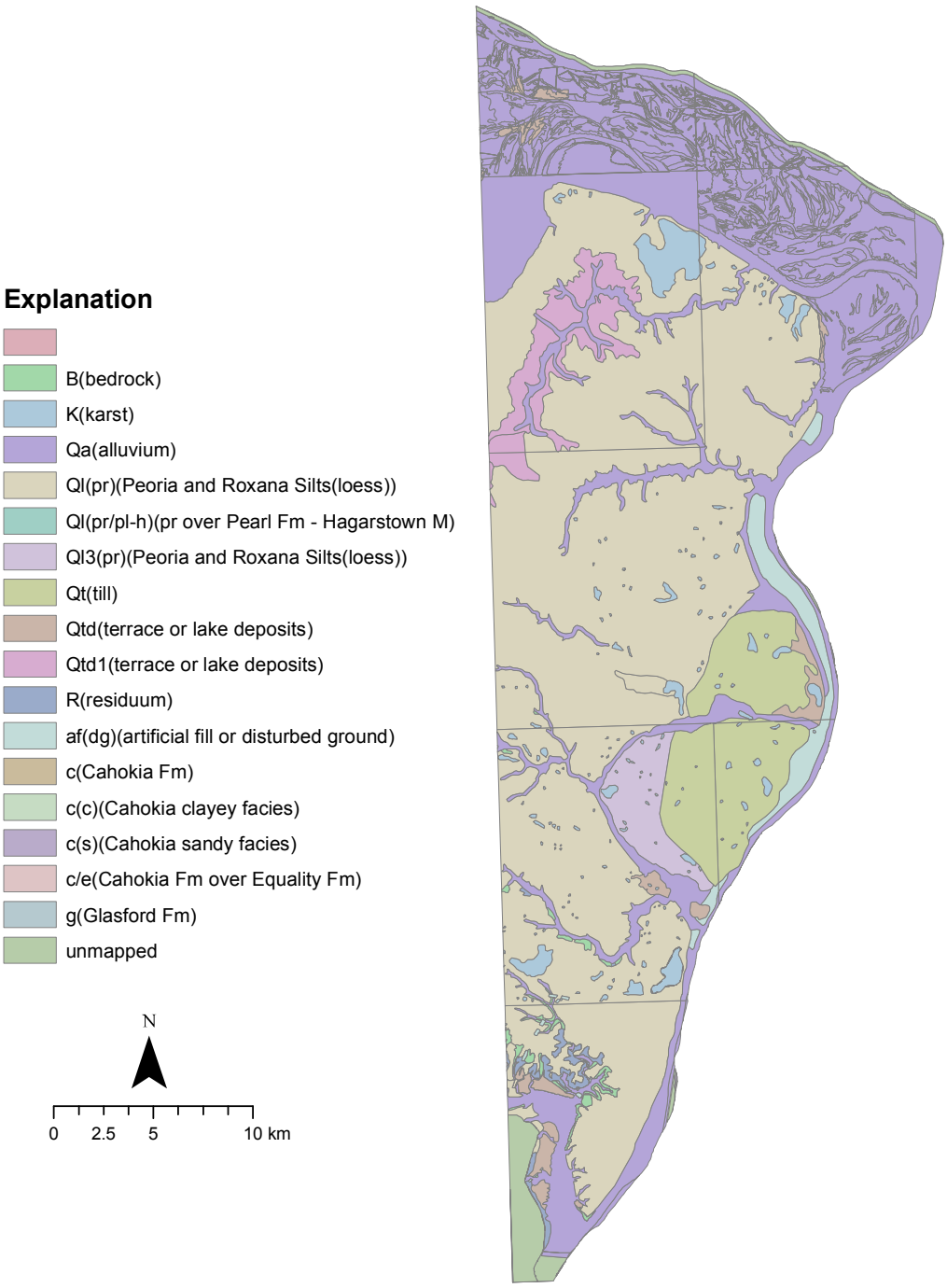



Figure 9. Missouri surface geology for Missouri portion of the 17 eastern quadrangles. Surface geology has been tied to shear-wave reference profiles used in urban hazard map generation.

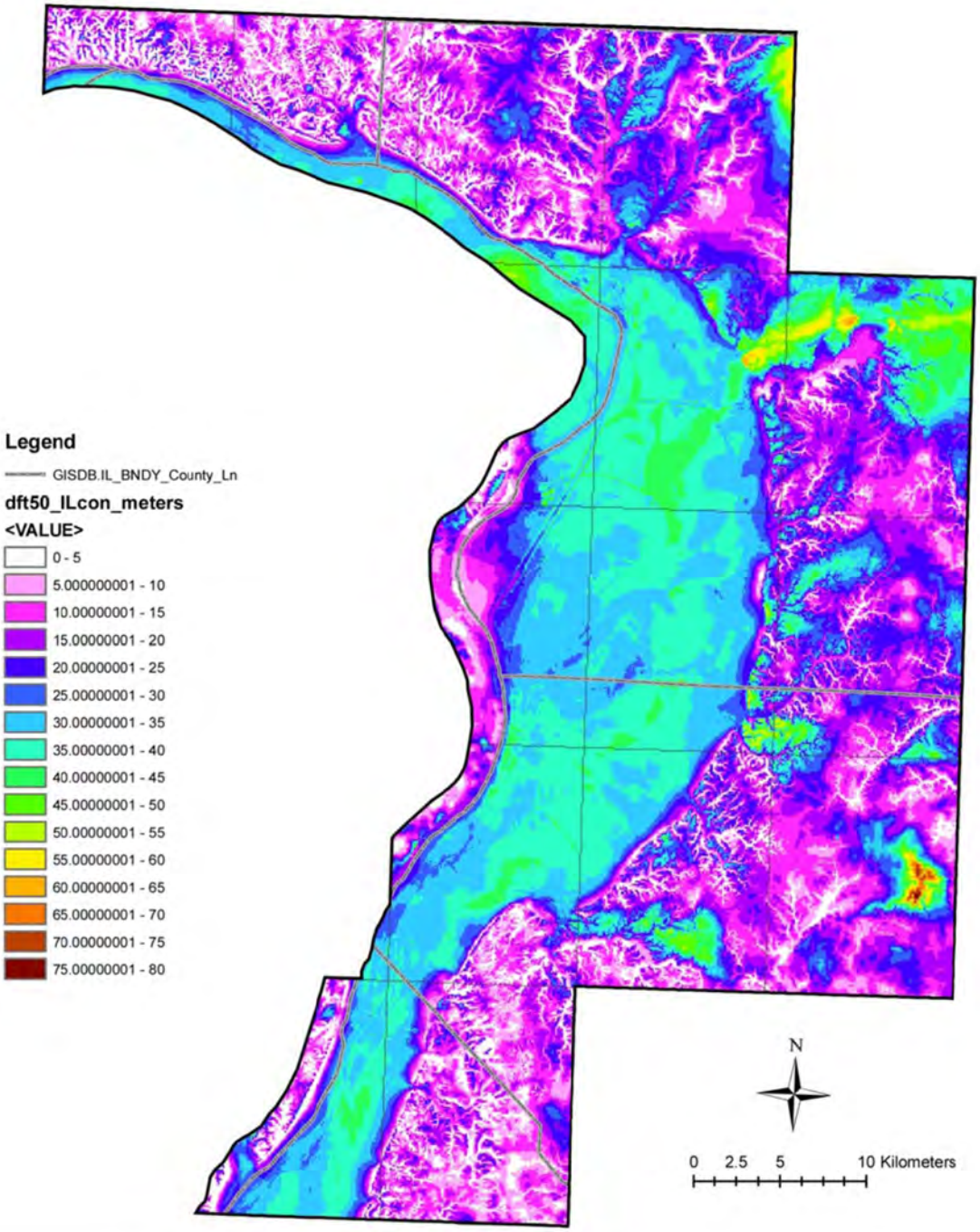



Figure 10. Sediment thickness in meters resting on bedrock in the Illinois study area.

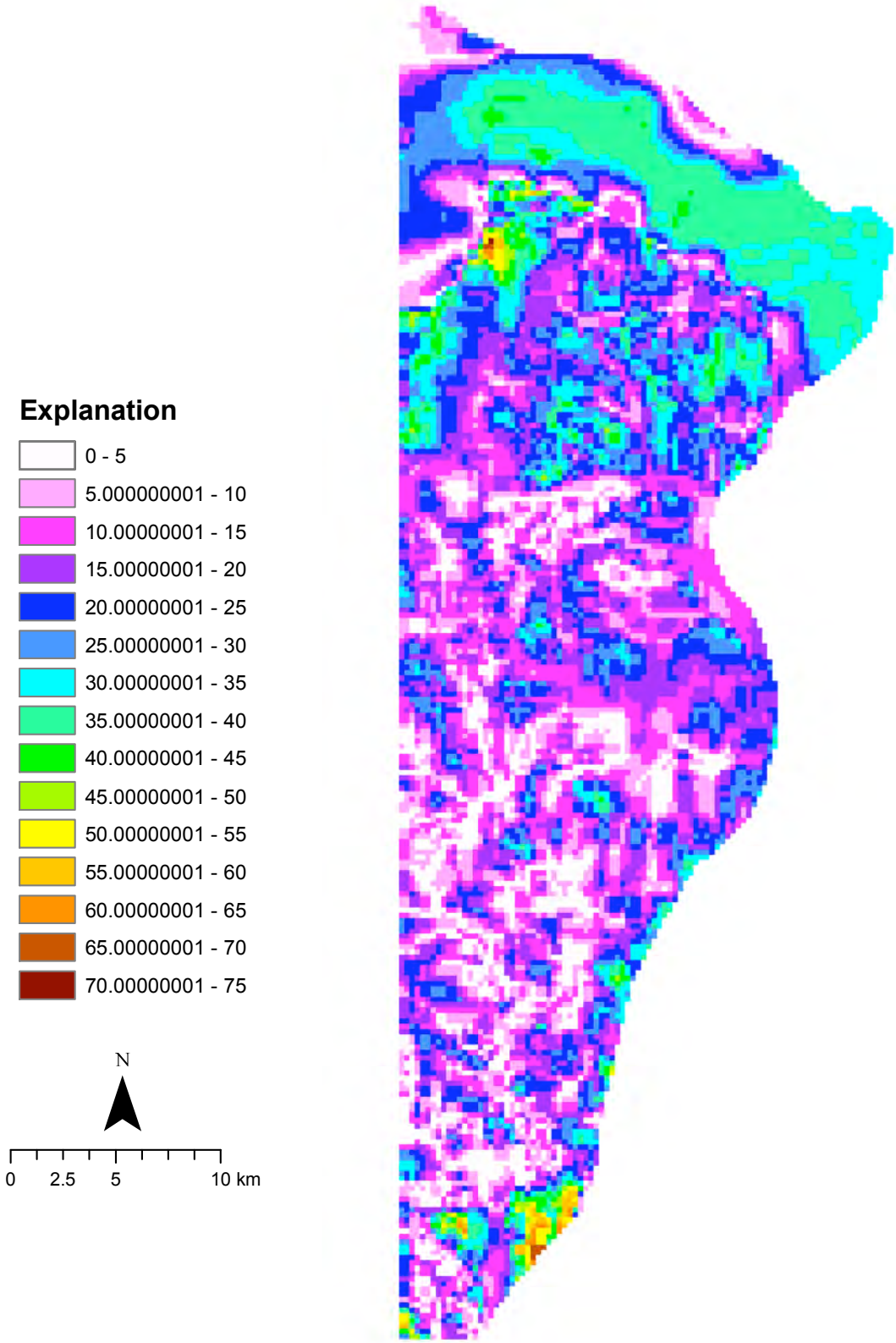
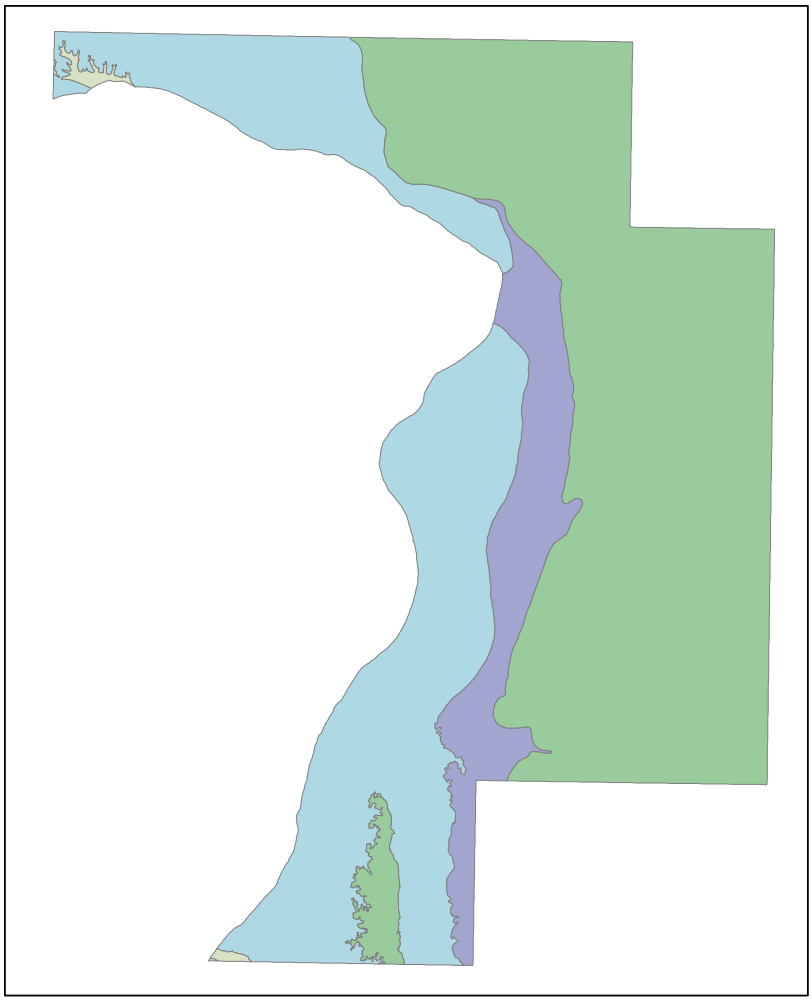



Figure 11. Sediment thickness in meters resting on bedrock in the Missouri portion of the eastern 17 quadrangles of the SLAEHMP study area. Scale similar to that of Figure 10.



**Explanation**

- Lower Pope Group (sandstone, shale, and limestone)
- Maquoketa Shale Group (shale and dolomite)
- Mississippian rocks (mainly limestone) or Silurian dolomite
- Pennsylvanian rocks (mostly shale)

Figure 12. Illinois bedrock geology map provided for relating bedrock geology to bedrock weathering model selected in urban hazard map calculations.

soil layer/Vs model file and a soil geotechnical model file (SHAKE91 input file), both with uncertainties. The soil thickness at the grid point is used to truncate the reference profile at the proper depth, the profile adjusted at the bottom for the appropriate bedrock weathering model if needed, and the information passed on to the site amplification calculation. The resulting site amplification distribution for that grid point is based on 200 randomizations of the grid's soil profile using the uncertainty information. This is done for each period of interest (PGA and 0.1, 0.2, 0.3, 0.5, 1.0, and 2.0 s Sa) at each grid point. The resulting site amplification distributions are then passed on to the hazard calculations using the approach of Cramer et al. (2004, 2006) and Cramer (2009).

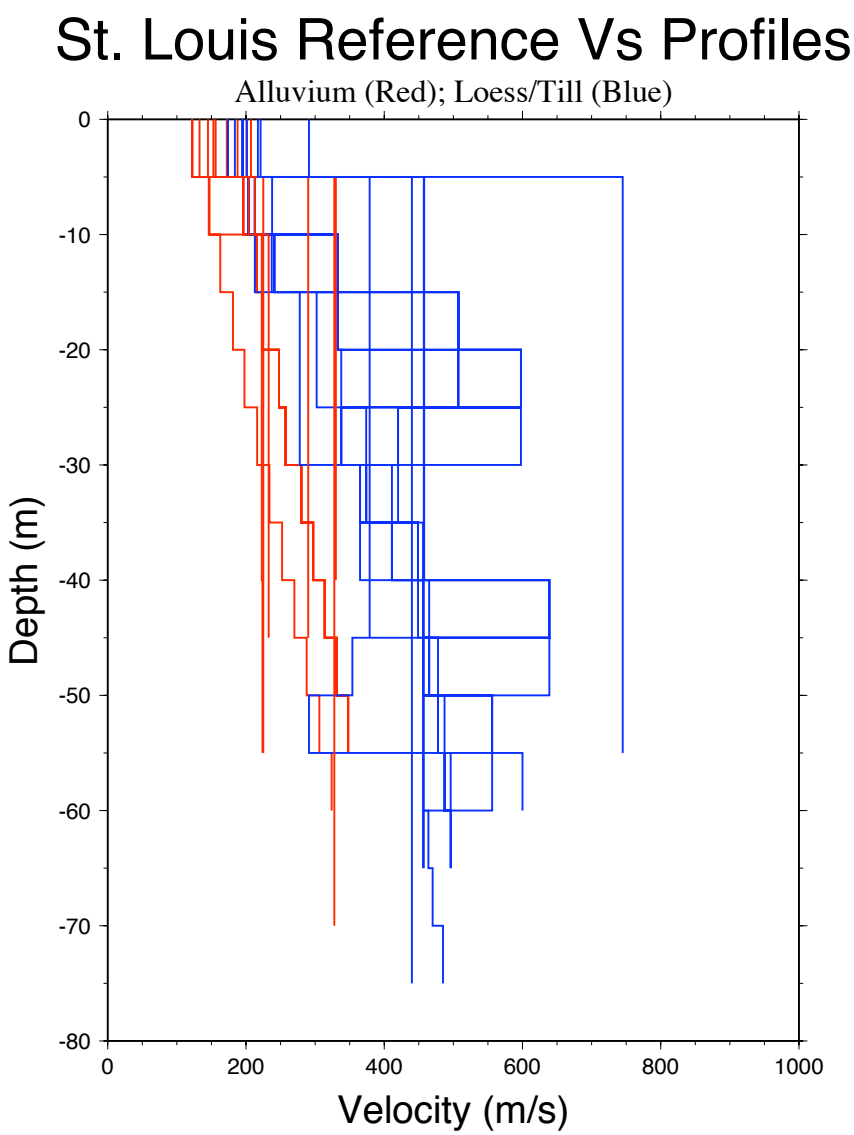



Figure 13. Summary of reference Vs profiles used in hazard calculations, lowlands (alluvium) profiles in red and uplands (loess/till) profiles in blue.

Vs Reference Profile section references:

Cramer, C.H., 2009, Final Technical Report, a proposal in support of the St. Louis Area Earthquake Hazards Mapping Project: suite of CEUS-specific hard-rock time-histories and seismic hazard model updates, USGS grant 08HQGR0016, February 20, 2009, CERI, 24 pp (available at http://earthquake.usgs.gov/research/external/reports/08HQGR0016.pdf).

Cramer, C.H., J.S. Gomberg, E.S. Scheig, B. A. Waldron, and K. Tucker, 2004, *Memphis, Shelby County, Tennessee, seismic hazard maps*, U.S. Geological Survey, Open-File Report 04-1294, 41pp.

Cramer, C.H., G. Rix, and K. Tucker, 2008, Probabilistic liquefaction hazard maps for Memphis, Tennessee, *Seis. Res. Lett.* **79**, 416-423.

## Seismic Hazard Maps
## (work by Chris Cramer of CERI, Univ. of Memphis)

*Site Amplification*

The method used to calculate site amplification was similar to those employed in the Memphis seismic hazard maps, summarized in Cramer et al. (2004). Time histories (see below) were input into the one-dimensional site-response software program SHAKE91, which calculates the propagation of the wave through the soil column and estimates the site-specific amplification factors and other parameters.

Anytime we perform a series of calculations that utilize a series of input variables, uncertainties with each of those variables will be compounded, leading to a greater range of uncertainty, bracketing the calculated/reported values. In the assessment of site amplification, uncertainties exist in the following input parameters: 1) natural variations in shear-wave velocity (for example, horizontal versus vertically propagating shear waves, effects of fracture intensity, weathering, and so forth), 2) natural variations in bulk density (especially, with preferential weathering), 3) the techniques used to estimate the depth and thickness of the soil layers, and 4) the differences in the earthquake time-history records used in the 1-D shaking analyses. When combined together, these uncertainties may cause large differences in amplification calculations. To account for this variability and uncertainties, a random sampling method is usually applied. Cramer et al. (2004) used amplification distributions to account for the uncertainties associated with the amplification calculations. Cramer (2003) asserted that this method of calculating the hazard was the most dependable because it incorporates the uncertainties in the amplification factor. When a truly probabilistic site-specific ground motion is desired, the state-of-the-art approach should be used to estimate the site-specific amplification factor distributions for use in the probabilistic calculations (Cramer, 2003; Cramer et al. 2004).

The site amplification calculations were performed using the site amplification code (siteampunc.f) developed by Chris Cramer. In this code, input site response parameters

are randomly selected from a range of Vs profiles, dynamic soil properties, geologic boundaries, and a set of earthquake acceleration time-histories. The code then inputs these randomly selected parameters into Shake91 and calculates the response. The process for selecting input parameters is explained in the next paragraphs and the results are summarized.

The amplification distributions were calculated based on a grid of 0.005° or for about every 500 m. There were a total of 10,202 grid points encompassing the 17 eastern quadrangles. For every grid point the site amplifications and distributions were calculated first, then the seismic hazard calculations. The amplification distributions were generated for 24 distinct geologic units (see geology section above), and the 500-m grid is thought to be sufficient enough to capture the differences between these units.

In this study, 12 recordings from six real earthquakes were selected in an attempt to capture the complexity of earthquake-time histories at epicentral distances close to 200 km. These recordings were obtained from the PEER strong-motion database. In addition to these earthquake recordings, two synthetically generated M7.5 and M8.0 records, from Atkinson and Beresnev (2002) were selected. These synthetic recordings were chosen because they were felt to be more representative of the CEUS source characteristics and attenuation/damping properties. St. Louis is located approximately 200 km from the New Madrid and Wabash Valley Seismic Zones and, hence, recordings located at a distance of 180 to 220 km were selected, with magnitudes as close to 7.5 as possible.

To characterize the ground shaking in a fully probabilistic approach, the areal distribution of site amplification was required. To capture the amplification distributions, the above mentioned earthquake time-histories were scaled. This was accomplished on the actual ground-motion records at ten different shaking levels (0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0g) at specific periods (PGA, 0.1 s SA, 0.2 s SA, 0.3 s SA, 0.5 s SA, 1.0 s SA, and 2.0 s SA) to obtain input, or base rock ground-motions. The Shake91 program was run for each of these shaking levels and the predicted site amplifications were determined for each level. In this study we used the shear modulus and damping ratio relations published by EPRI (1993) with an uncertainty of 0.30 natural log units.

*Technical Seismic Hazard Maps*

Technical seismic hazard maps were generated for both probabilistic and scenario (deterministic) cases. The probabilistic maps are for 2%, 5%, and 10% in 50 years. The scenario seismic hazard maps are for five scenarios: M7.5 on the NE segment of the New Madrid seismic zone, a M6.0 south of St. Louis near St. Genevieve, a M6.0 east of St. Louis near the Shoal Creek paleoseismic site, a M5.8 beneath St. Louis, and a M7.1 near Vincennes, IN at the location of a large paleoseismic earthquake in the Wabash Valley seismic zone (Figure A). The scenario hazard maps are for median ground motion hazard for the specified earthquake. All technical seismic hazard maps were generated at seven periods, including PGA.

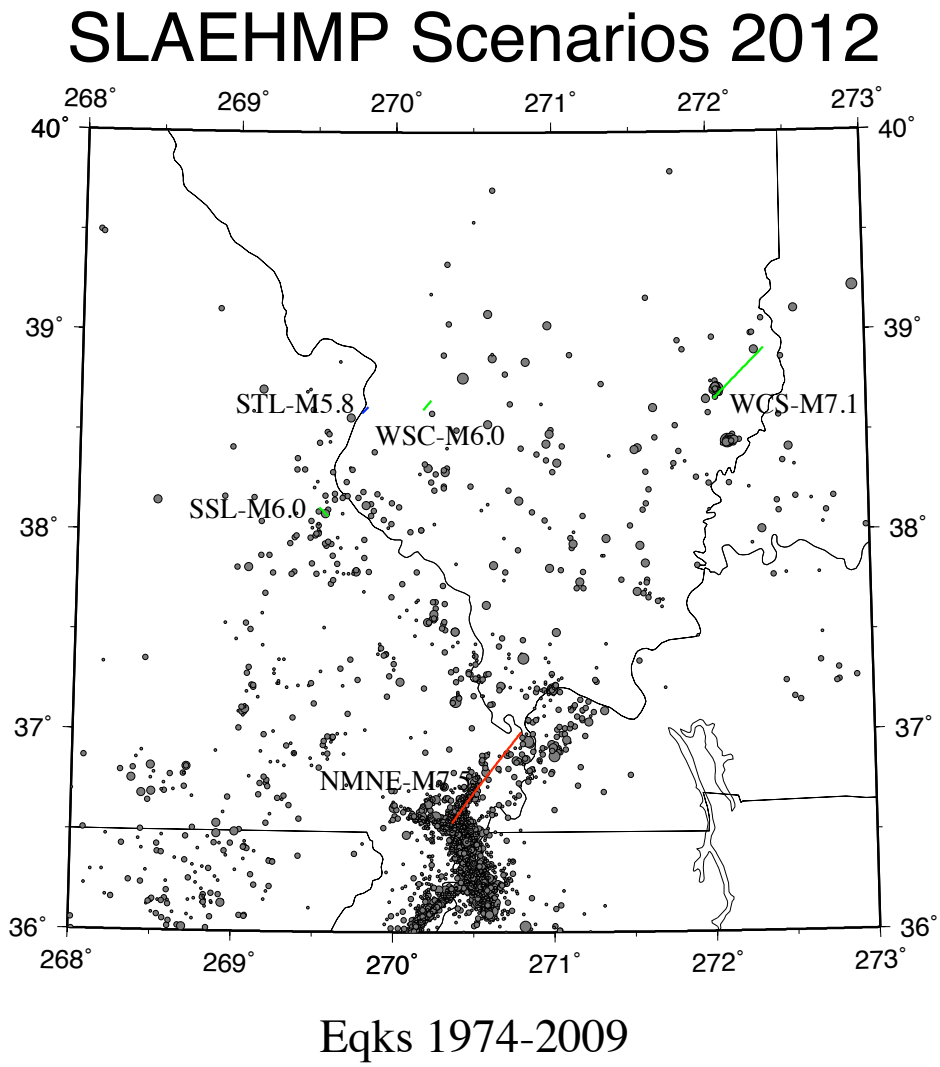



Figure A: Location map for the five SLAEHMP earthquake scenarios. The grey dots are earthquakes in the region between 1974 and 2009. The line segments (red, green, and blue) are the locations of the ruptures for the scenarios.

The probabilistic seismic hazard maps are shown in figures B-G. Figures B, D, and F are

PGA hazard maps for 2%, 5%, and 10% in 50 year ground motion hazard, respectively. Figures C, E, and G show probabilistic seismic hazard maps at six periods of spectral amplification again for 2%, 5%, and 10% in 50 year ground motion hazard, respectively.

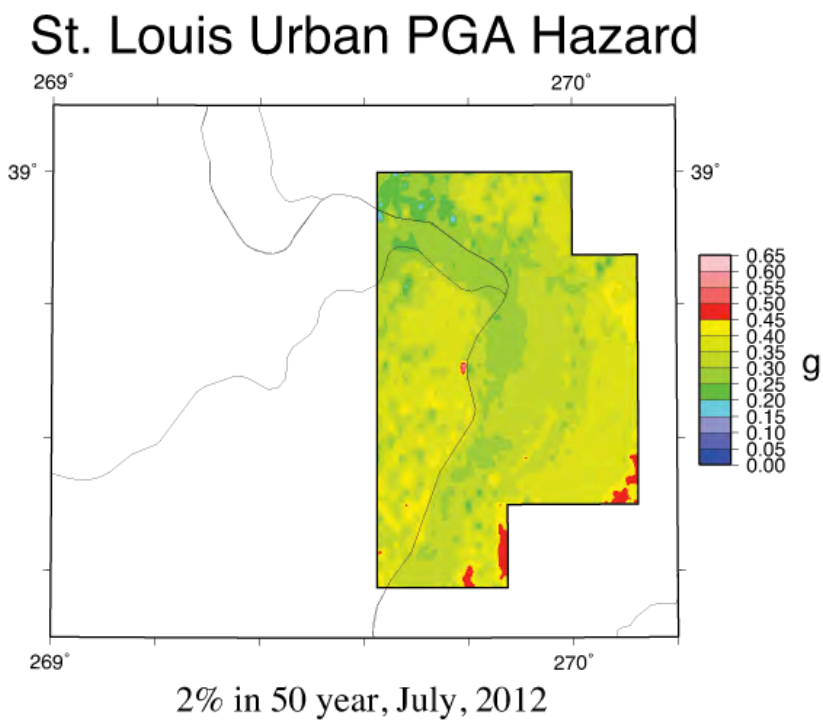



Figure B: 2% in 50-year peak ground acceleration hazard map.

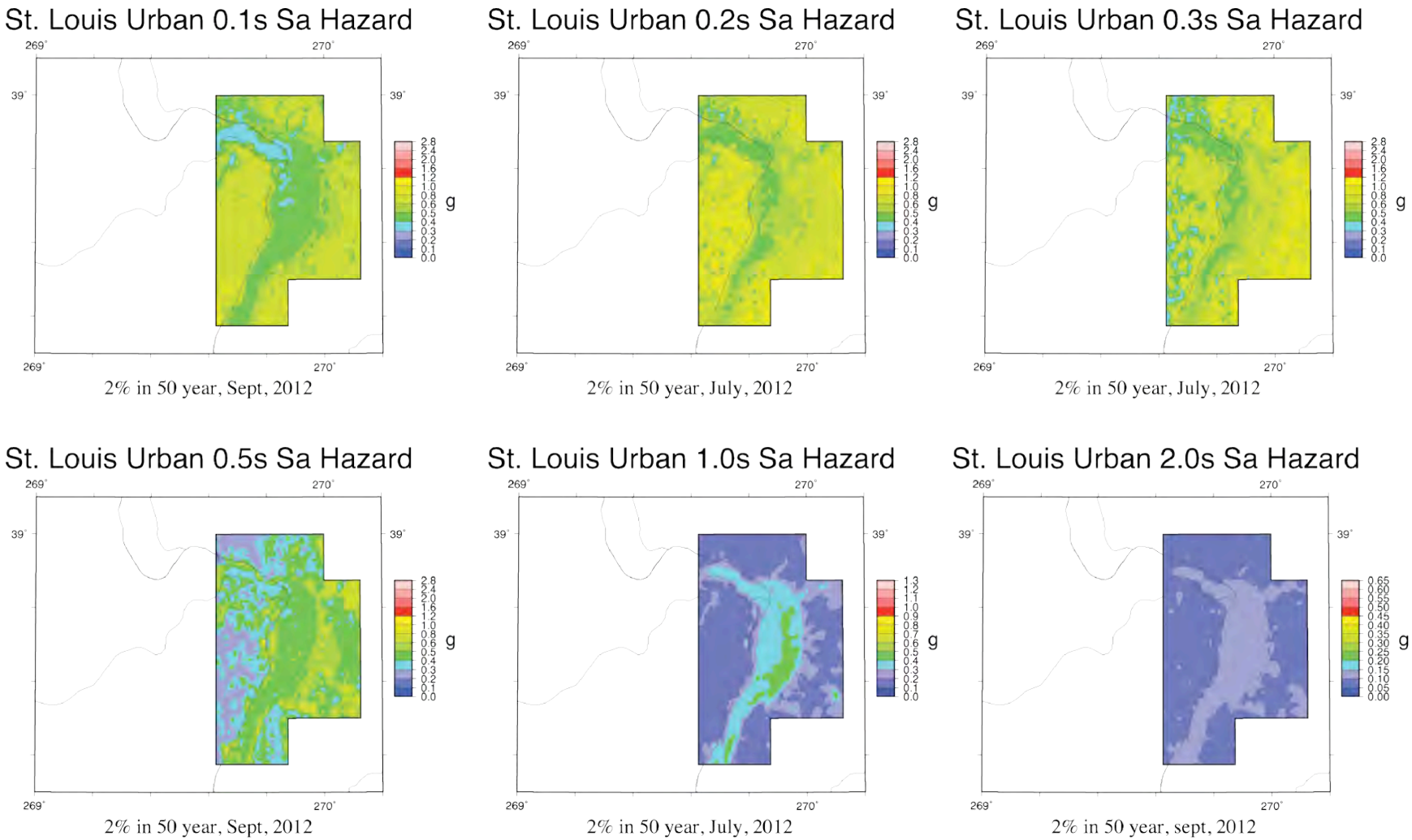



Figure C: 2% in 50 year seismic hazard maps at six spectral acceleration (Sa) periods.

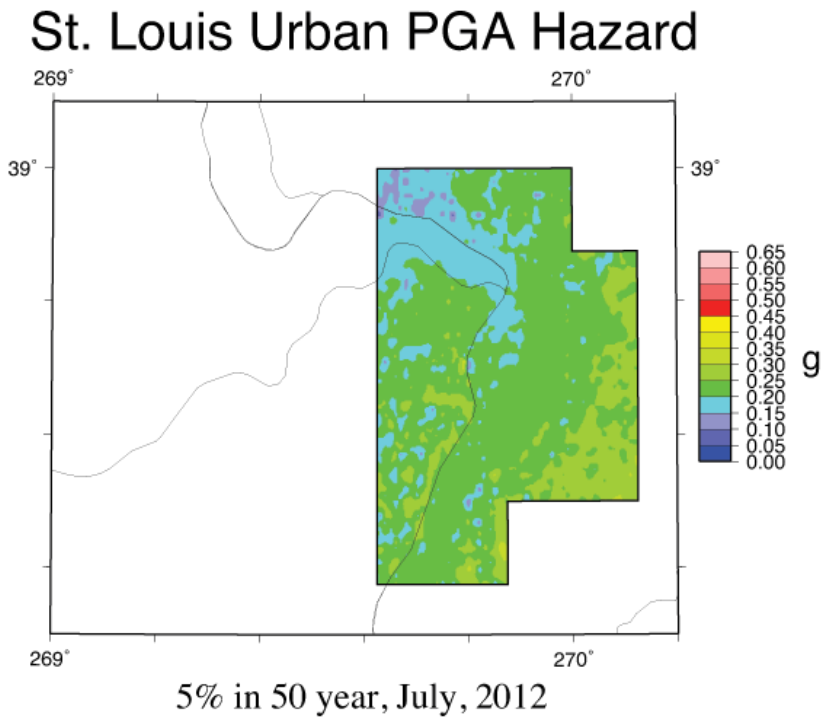



Figure D: 5% in 50-year peak ground acceleration hazard map.

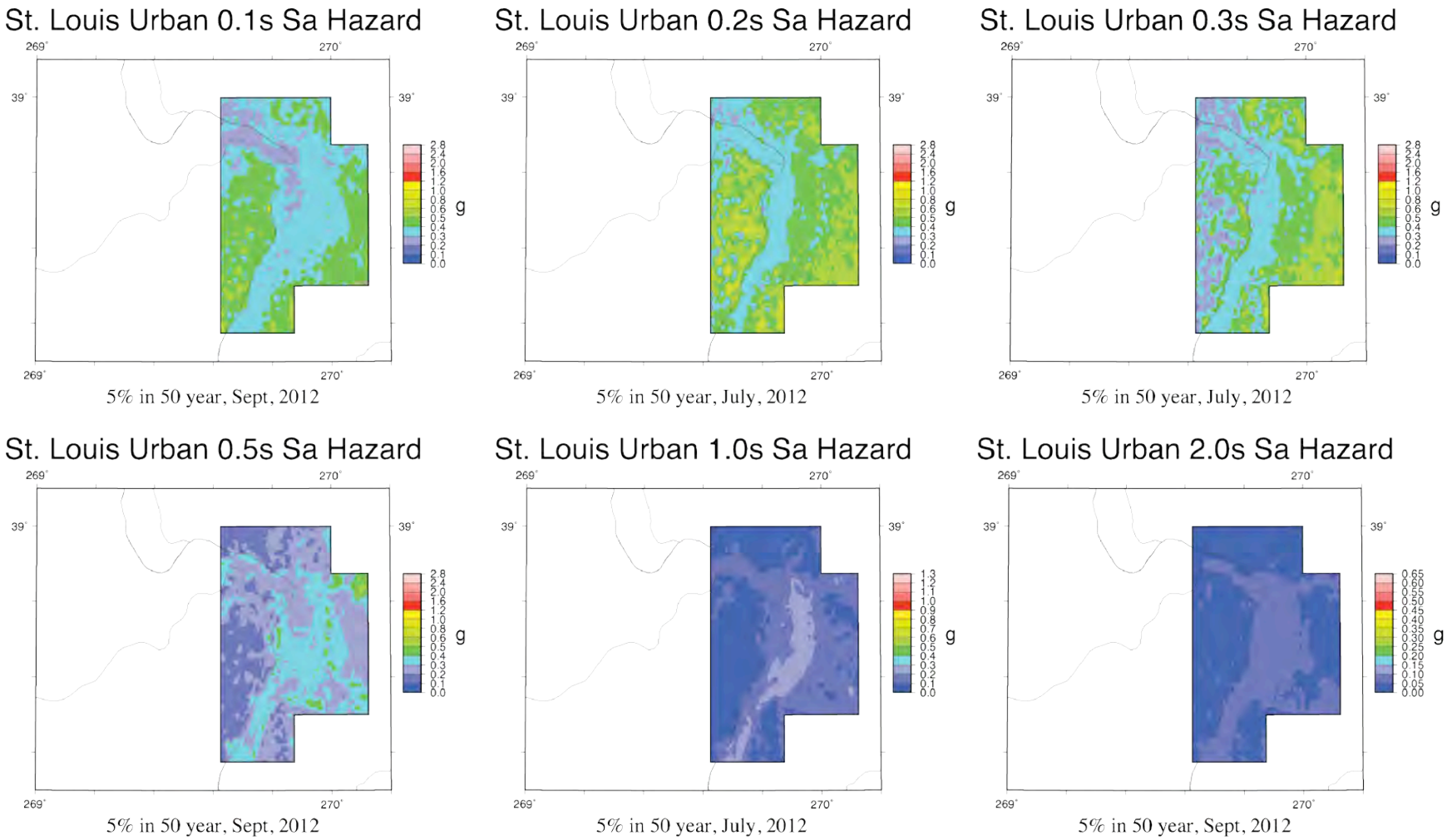



Figure E: 5% in 50 year seismic hazard maps at six spectral acceleration (Sa) periods.

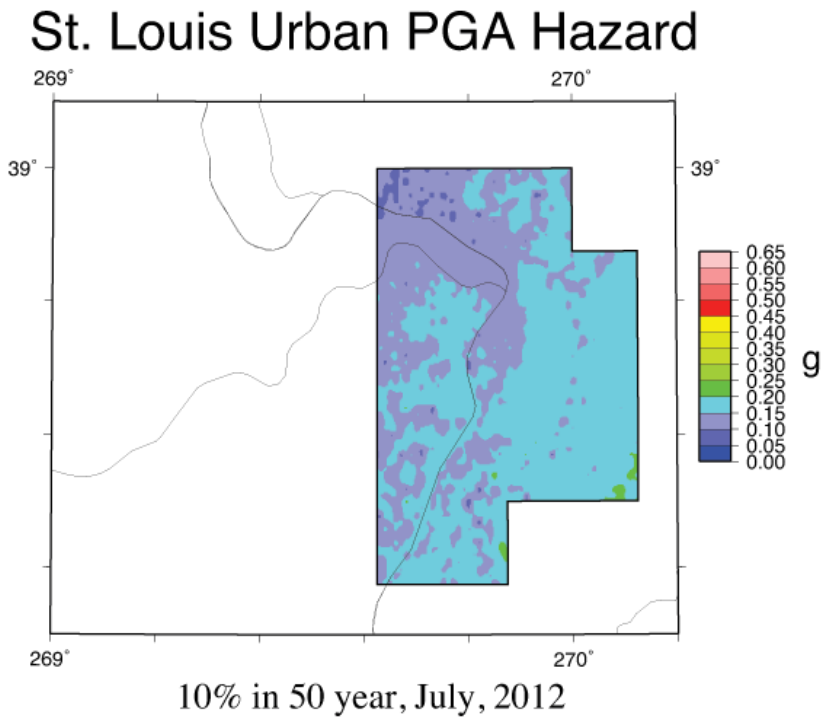



Figure F: 10% in 50-year peak ground acceleration hazard map.

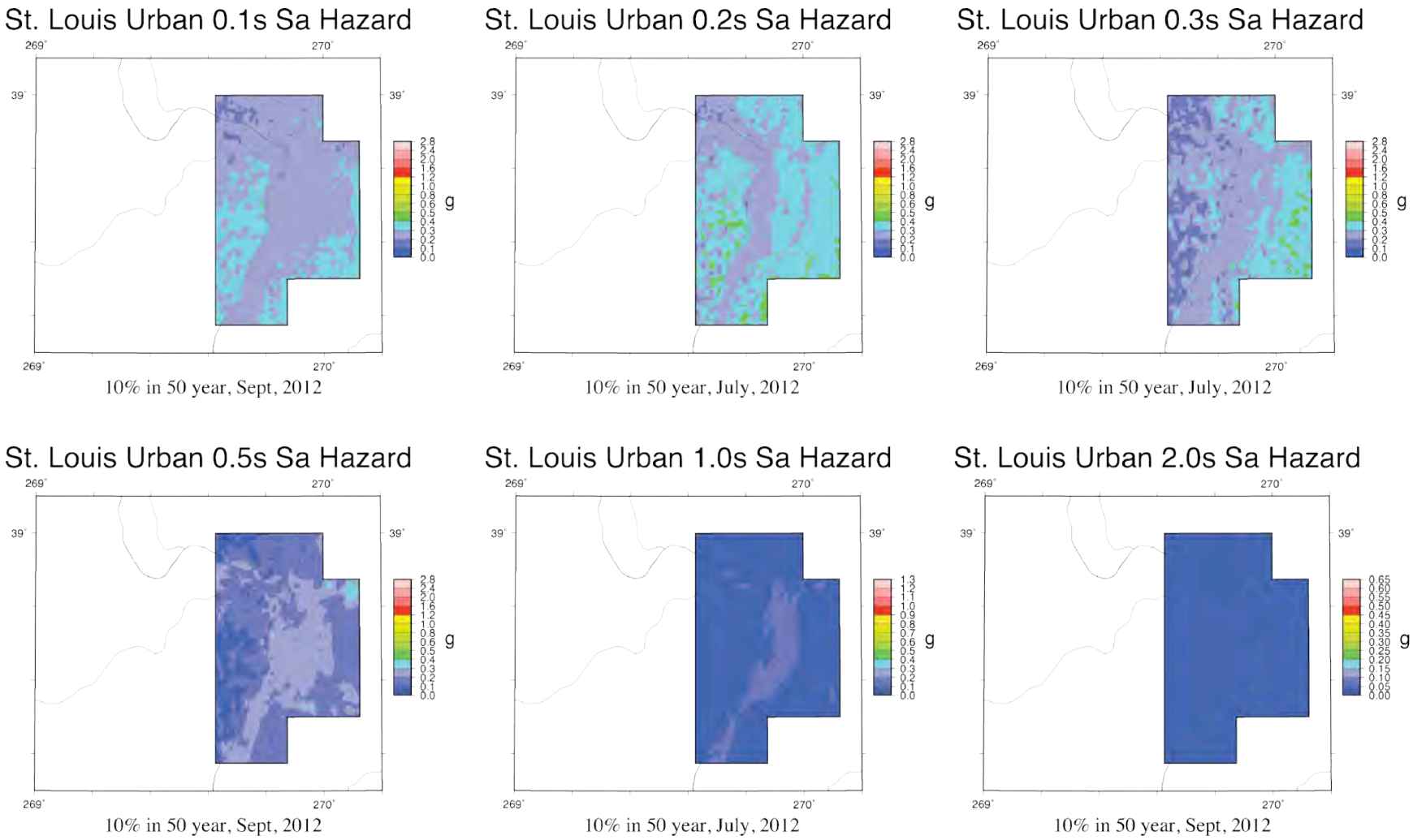



Figure G: 10% in 50 year seismic hazard maps at six spectral acceleration (Sa) periods.

Figures H-Q present the five scenario technical seismic hazard maps. Figures H, J, L, N, and P are PGA scenario maps for the five scenarios listed above, respectively. Figures I, K, M, O, and Q are scenario maps for six spectral periods for the five scenarios, respectively. The most likely earthquake scenario is the M7.5 on the NE segment of the New Madrid seismic zone and corresponds to a probability of occurring of 0.002 (1 in 500 years). The other scenarios are extremely rare earthquake scenarios with much lower likelihoods of occurring.

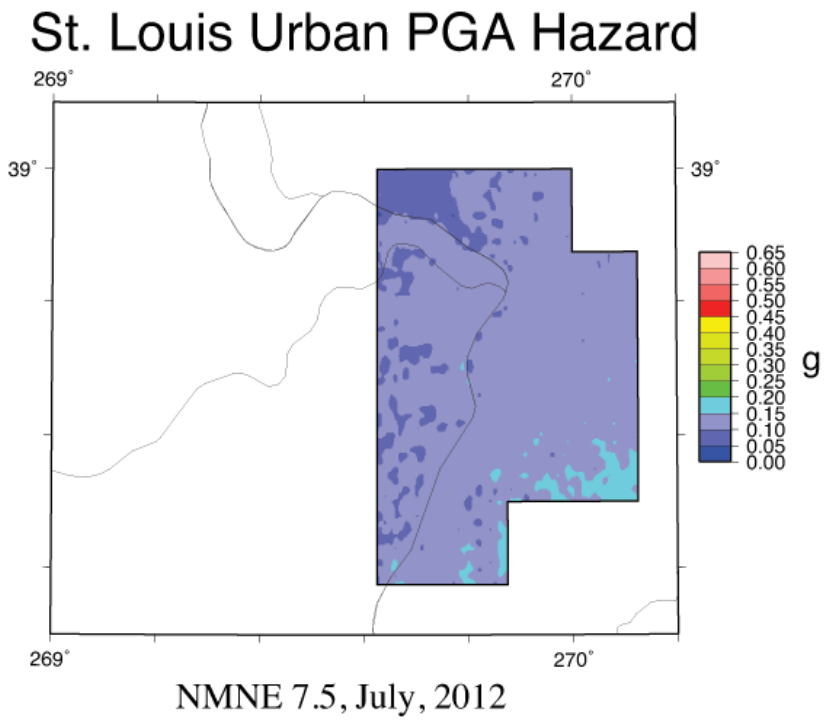



Figure H: Scenario peak ground acceleration hazard map for the NE segment of the New Madrid seismic zone.

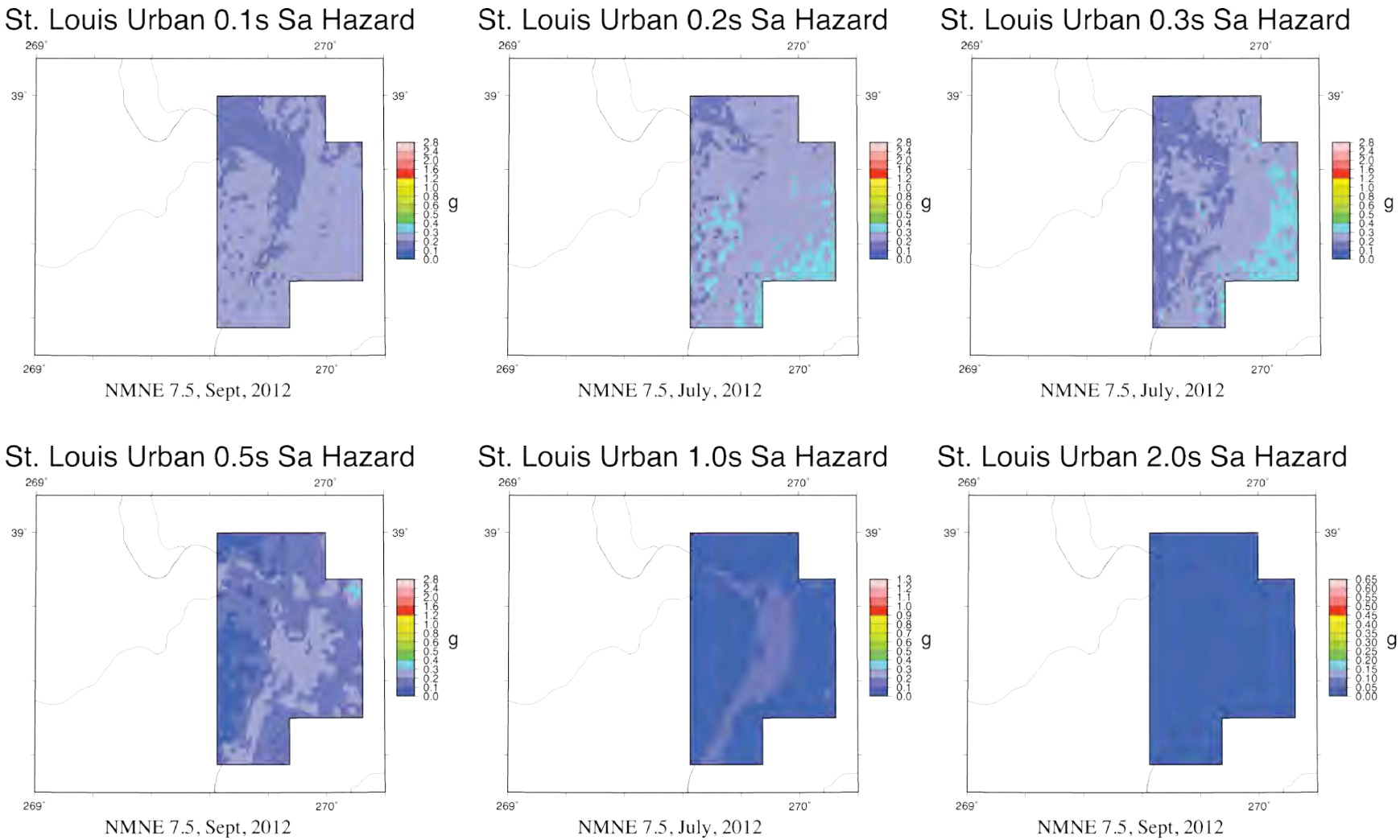



Figure I: Scenario seismic hazard maps for the NE segment of the New Madrid seismic zone at six spectral acceleration (Sa) periods.

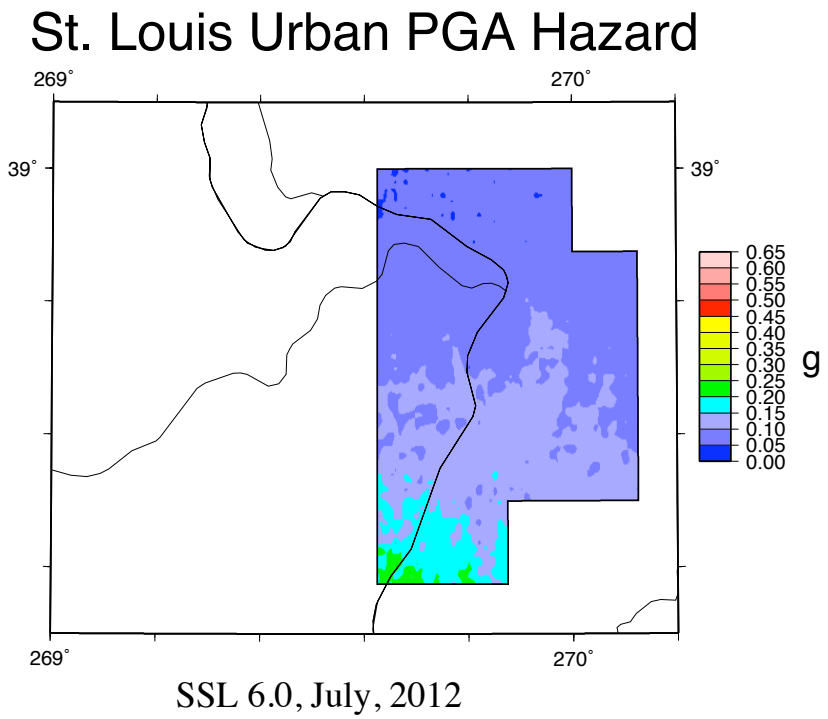



Figure J: Scenario peak ground acceleration hazard map for a M6.0 earthquake near St. Genevieve, MO.

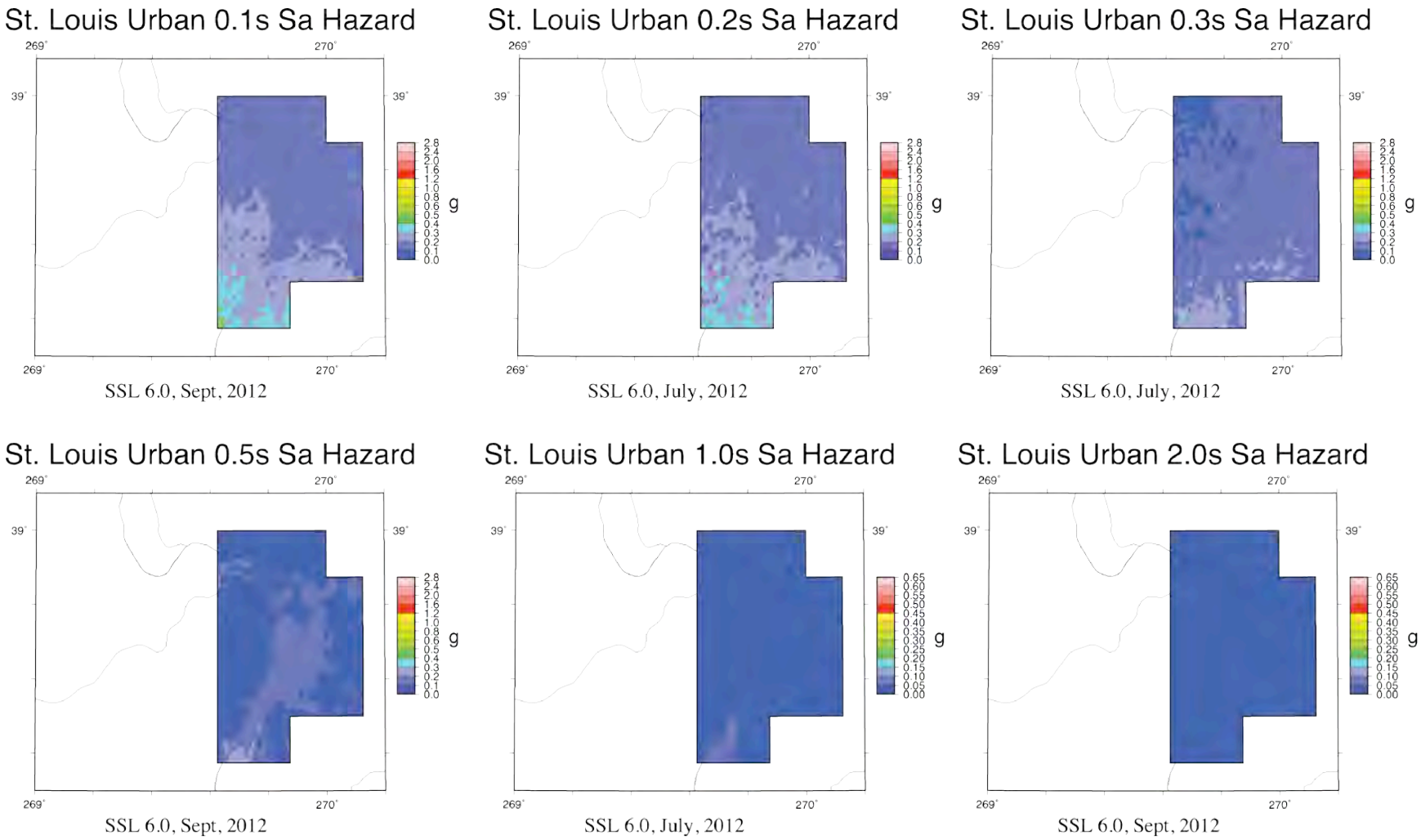



Figure K: Scenario seismic hazard maps for a M6.0 earthquake near St. Genevieve, MO at six spectral acceleration (Sa) periods.

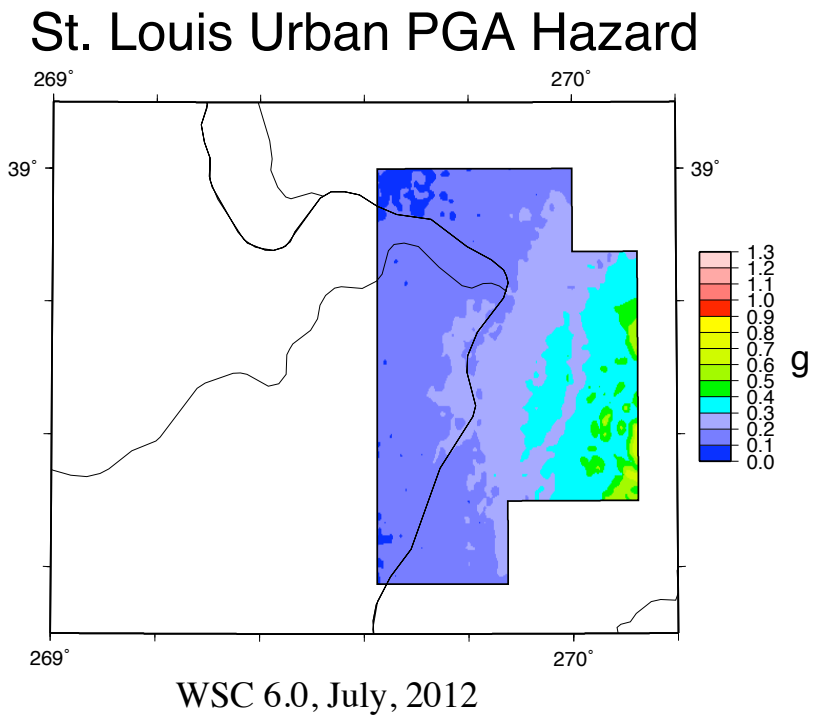



Figure L: Scenario peak ground acceleration seismic hazard map for a M6.0 earthquake near the Shoal Creek, IL paleoseismic location.

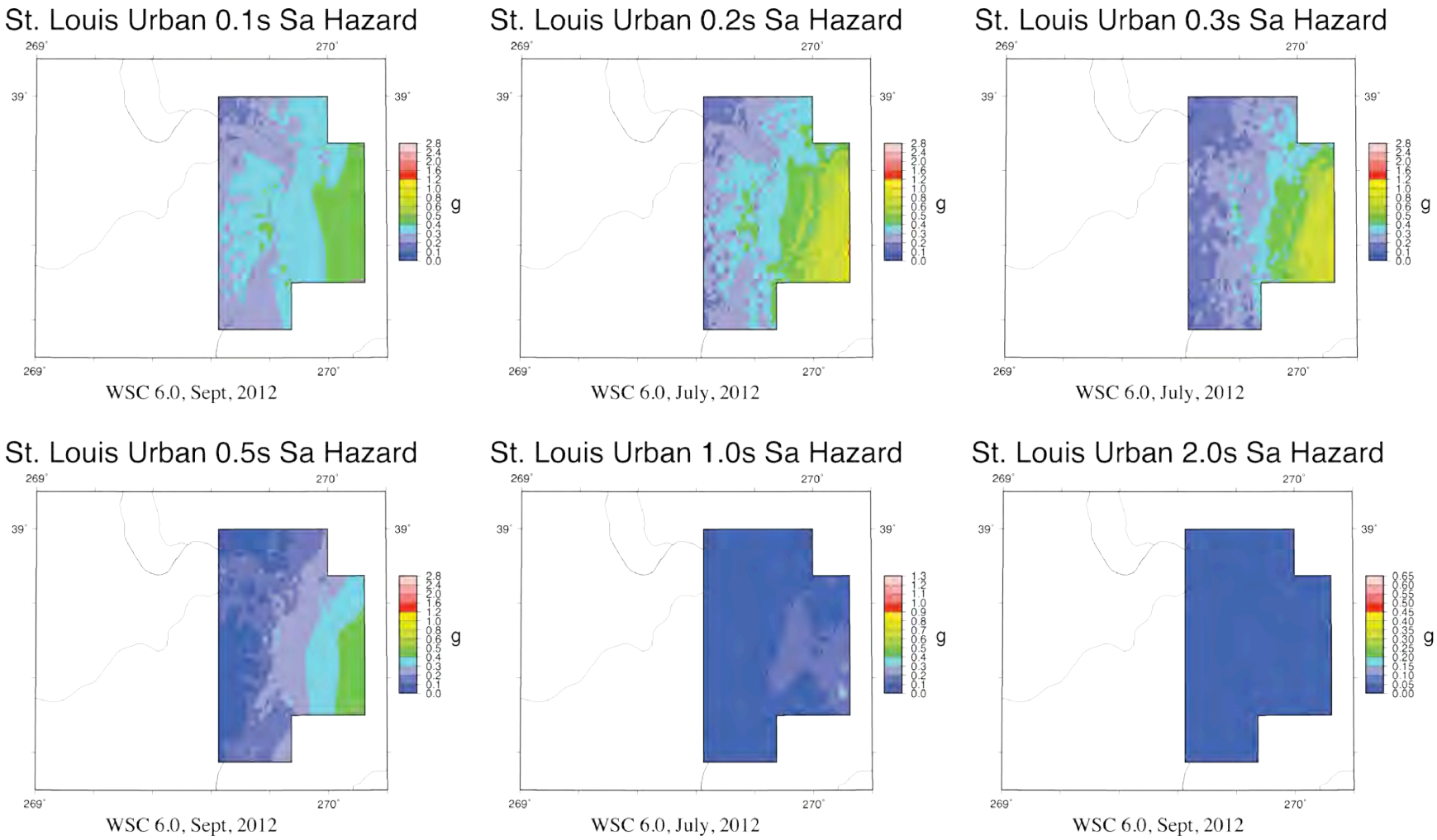



Figure M: Scenario seismic hazard maps for a M6.0 earthquake near the Shoal Creek, IL paleoseismic location at six spectral accelration (Sa) periods.

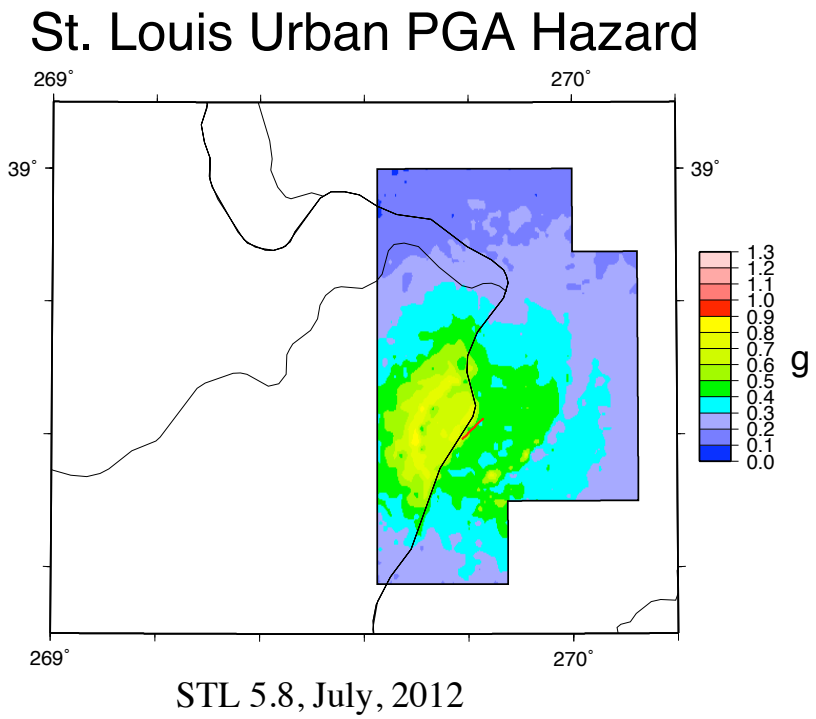



Figure N: Scenario peak ground acceleration seismic hazard map for a M5.8 beneath St. Louis. The red line is the modeled fault rupture.

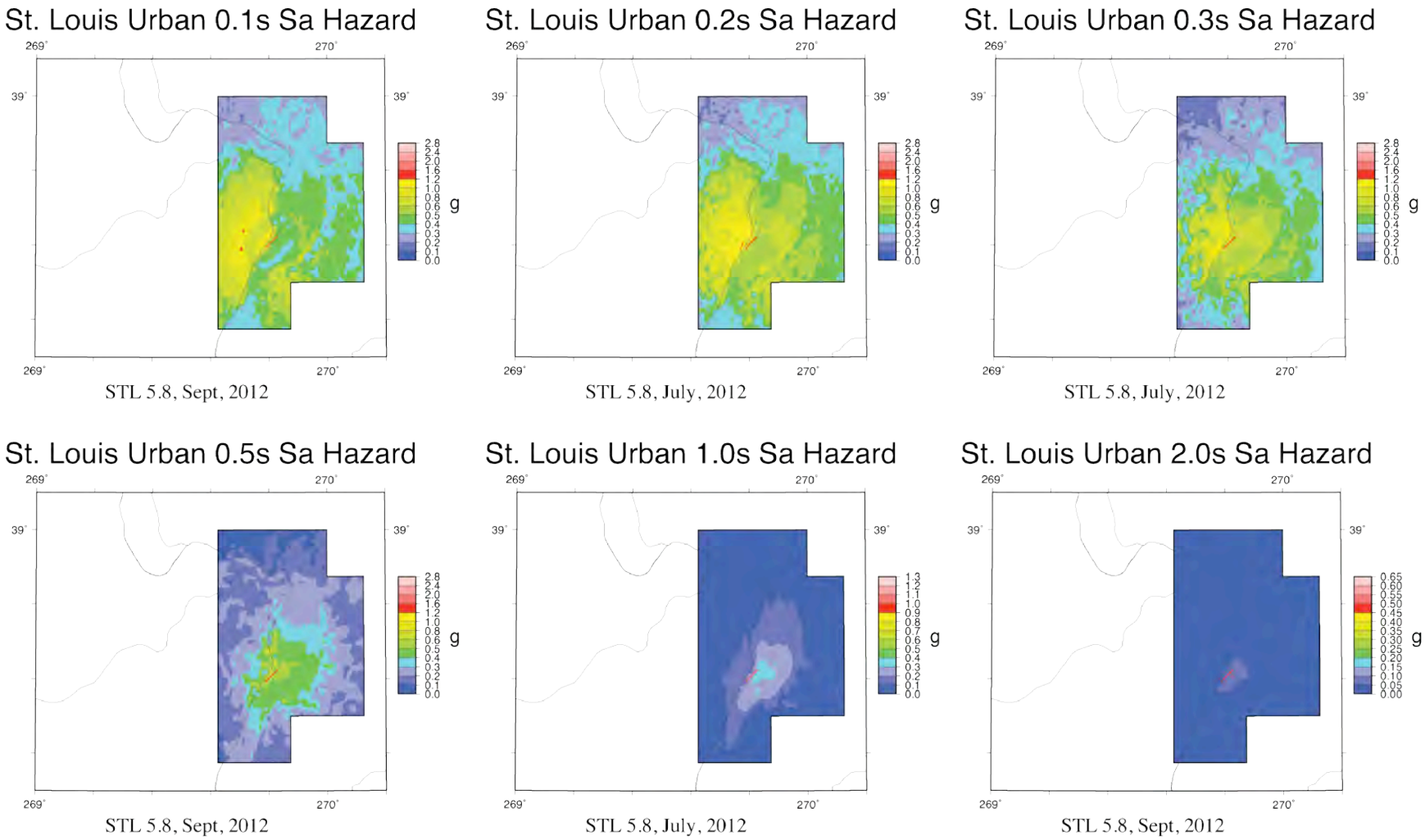



Figure O: Scenario seismic hazard maps for a M5.8 earthquake beneath St. Louis at six spectral acceleration (Sa) periods. Red line is the fault rupture.

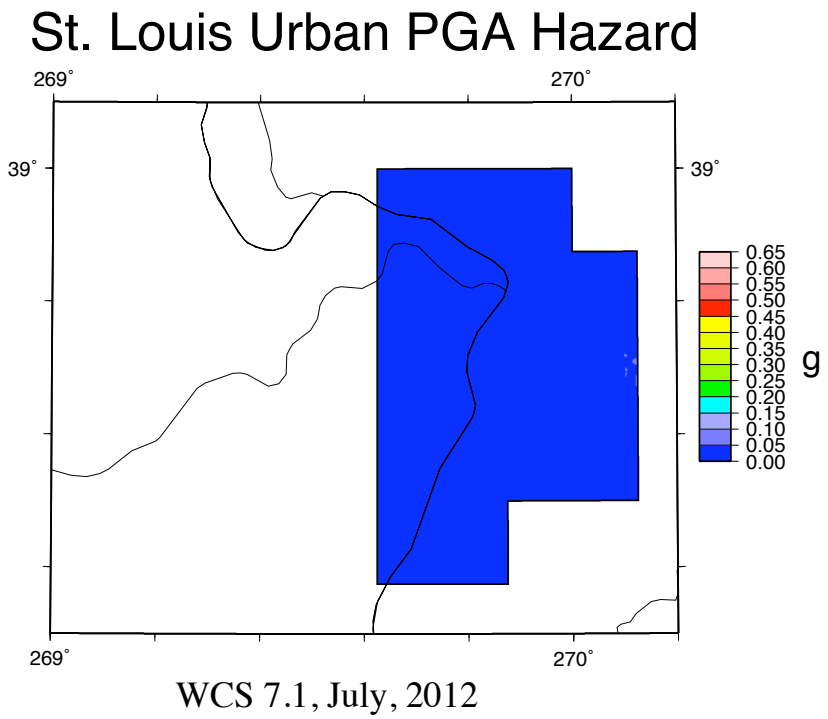



Figure P: Scenario peak ground acceleration seismic hazard map for a M7.1 near Vincennes, IN.

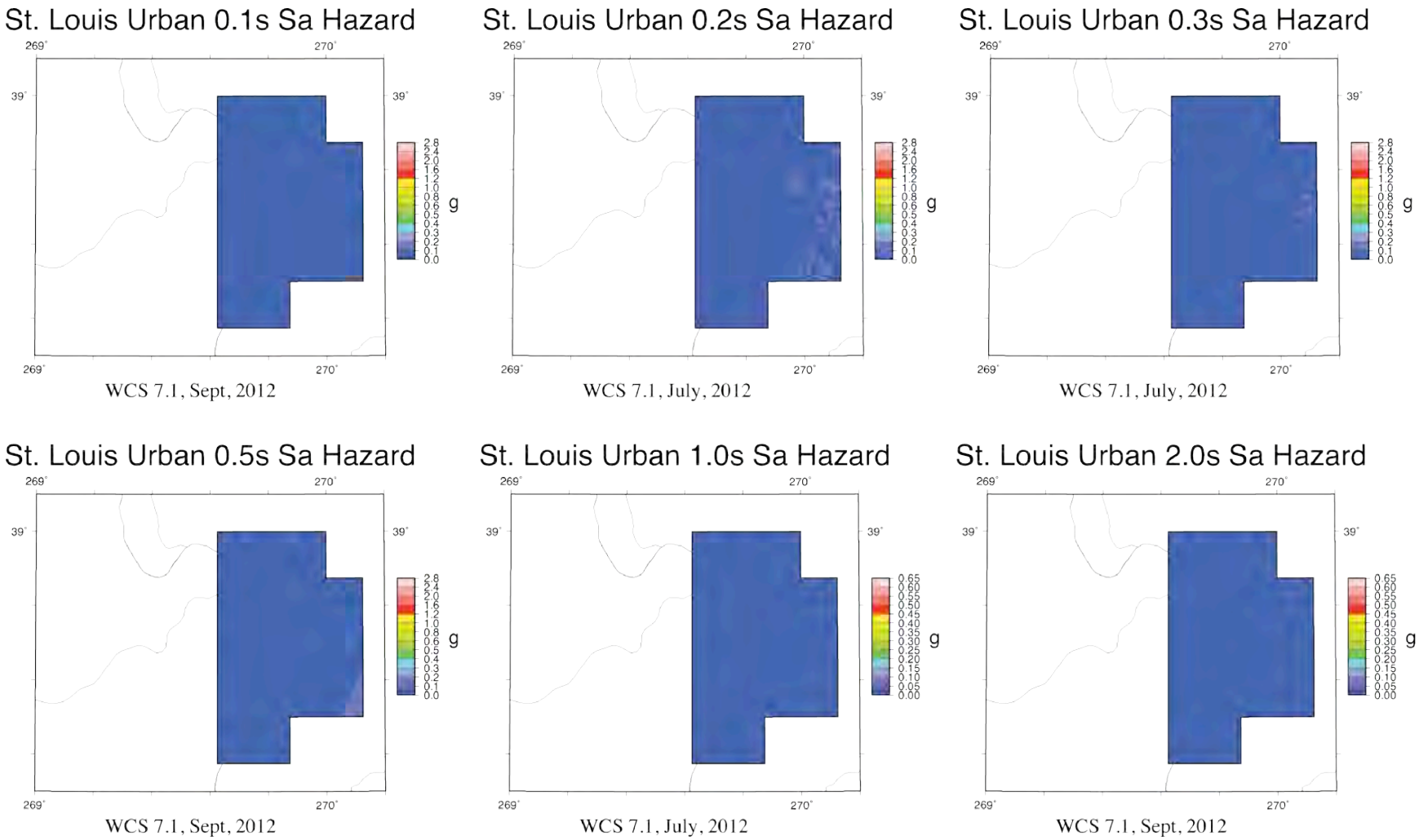



Figure Q: Scenario seismic hazard maps for a M7.1 earthquake near Vincennes, IN at six spectral acceleration (Sa) periods.

*Simplified Shaking Hazard Map*

A simplified shaking hazard map for the non-technical user community has been generated from the most-likely earthquake scenario PGA hazard map (M7.5 on the NE segment of the New Madrid seismic zone). It corresponds to the hazard from the 500-year earthquake. Because the ground motions in the scenario are median ground motions (half the expected ground motions for this earthquake are below the value on the scenario map and half above), the simplified shaking hazard map represents the 1000-year ground motion levels from the 500-year earthquake.

The technical scenario seismic hazard maps was simplified by specifying that a low seismic hazard is for median PGAs below 0.1 g, moderate seismic hazard is for median PGAs from 0.1 g to 0.3 g, and severe seismic hazard is for median PGAs above 0.3 g. Figure R presents the simplified shaking hazard map.

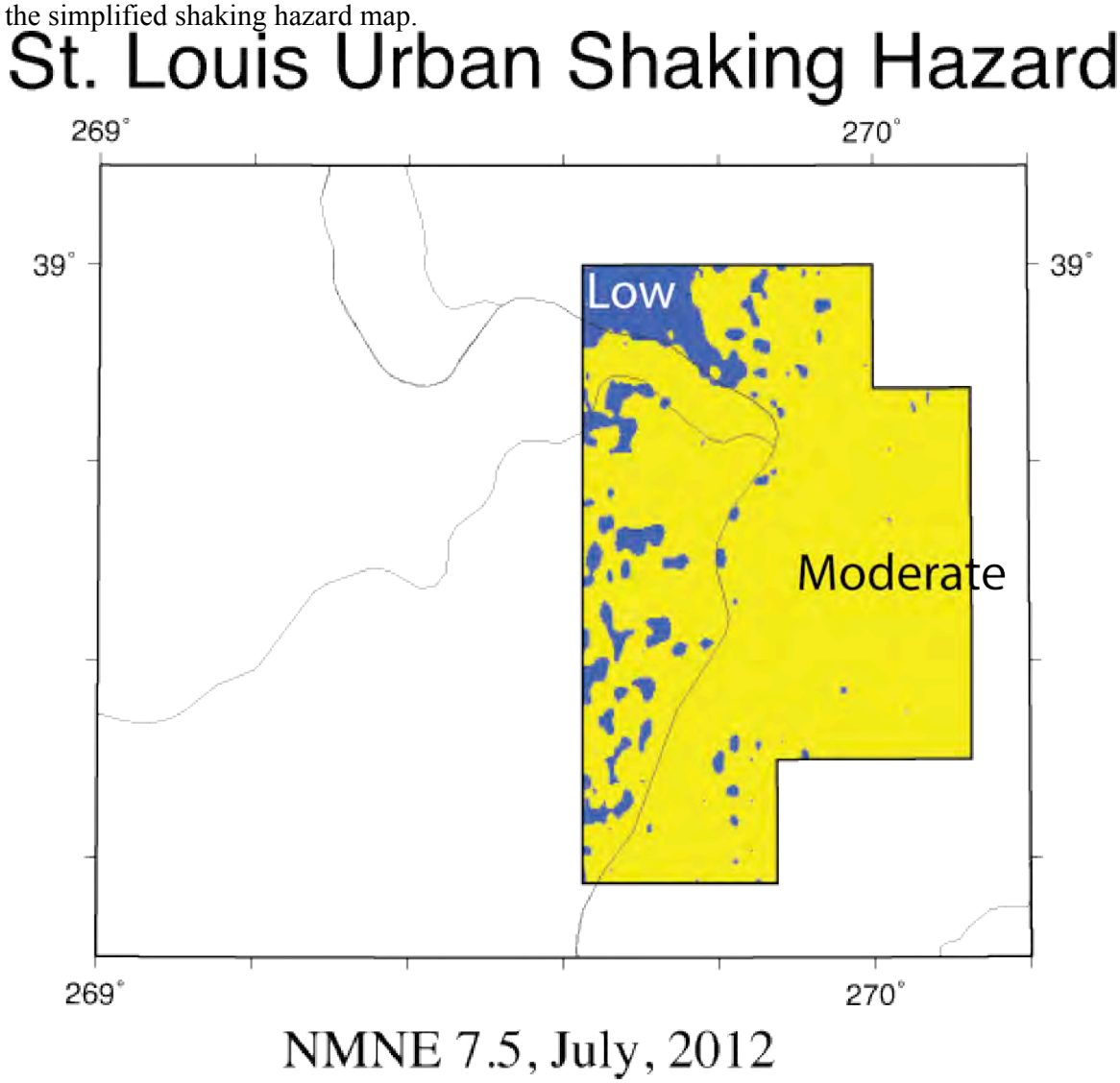



Figure R: Simplified earthquake shaking hazard map for St. Louis.

References for Seismic Hazard Map section:

Cramer, C.H., 2003, Site-specific seismic-hazard analysis that is completely probabilistic, *Bull. Seism. Soc. Am.* **93**, 1841-1846.

Cramer, C.H., J.S. Gomberg, E.S. Scheig, B. A. Waldron, and K. Tucker, 2004, *Memphis, Shelby County, Tennessee, seismic hazard maps*, U.S. Geological Survey, Open-File Report 04-1294, 41pp.

EPRI, 1993, Guidelines for determining design basis ground motions, Palo Alto, Calif: Electric Power Research Institute, v. 1-5, EPRI TR-102293.

## Publications to Date

There are no publications on this work to date, but a draft open-file report (OFR) has been prepared. The OFR is in the initial process of USGS review. The draft OFR is a product and deliverable of this contract.

## Appendix A.
## Defined Uncertainty of Illinois borehole locations and bedrock elevations

THE UNCERTAINTY OF POINT LOCATIONS AND ELEVATIONS, AND THE IMPLICATIONS FOR THE DETERMINATION OF SEDIMENT THICKNESS AND BEDROCK TOPOGRAPHY

The primary data for bedrock elevation are boring descriptions compiled from archives at the ISGS Geological Records Unit. The original boring records vary widely in the accuracy and precision of their locations and elevations. The related geologic descriptions also vary widely in reliability and detail. These attributes are partly classifiable by boring type ("Status"), such as water well, geotechnical boring, petroleum boring, etc., but there is variation within each Status category as well. After compiling the historic data, we perform quality assurance and control by checking well locations, assigning elevations when none were originally given, and interpreting the log descriptions. The quality of the result of the location verification depends upon supporting data found in the original records, supporting data added from other sources such as plat or tax maps, and the local topographic or geologic variability. The supporting data also vary in quality by the date of their acquisition and by their locale (especially county-county variability). A further complication in describing the entire data set is that these data were compiled by quadrangle over 12 years of mapping. The available supporting data, verification rubric, and effort expended varied with time.

To the data compiled from archived records were added new observations from our mapping, including outcrop descriptions, stratigraphic borings, and geophysical studies. These are relatively few compared to the historic information. Finally, synthetic data including points extrapolated from borings that do not reach bedrock, and contours and streamlines added by judgment are added to the data set.

**Uncertainty of Location**

Point locations were verified by examining all available locational information including GPS coordinates, driller's logs, water well permits, address matching, air photos, and conversations with drillers. Points were moved within a GIS environment, and the new locational information and coordinates were updated in the ISGS GRU Oracle database. The most accurate locations were obtained in the field using GPS devices or air photos. Water wells could be verified to several degrees of accuracy. The least accurate locations could only be matched to property boundaries shown on plat maps or to quarter-quarter-quarter PLSS descriptions. These may thus be only within 250 feet of the actual location. Where a house could be identified for a particular property by examination of air photos, DOQs or a known street address and no additional information was available, the well was placed on the driveway. Such a point is probably within 150 ft of the actual water well. Water wells drilled since about 1975 usually have a Water Permit. Some Water Permits in GRU include driving directions from which street addresses could be obtained, or large scale maps of drilling locations with distances to features observable on air photos such as house corners or property boundaries. These points are probably accurate to within several 10's of feet. Other locations were described by the driller in telephone conversations. These may also be accurate to within several 10's of feet. Bridge boring records from the Illinois Department of Transportation could be matched to bridge locations on DOQs. Boring locations were placed relative to the bridge center based upon Station Number (footages) or accompanying technical drawings, when available. These locations are thus accurate from approximately 5 to 50 ft. Stratigraphic borings and field observations were located by an ISGS geologist on a topographic map, air photo, or with differentially corrected GPS coordinates. These locations are probably accurate from within 1 to 50 ft. The only records generally available for Coal borings are driller's logs. Locations described by PLSS and other descriptive information are assumed to be correct because the coal companies have a presumed interest in the accuracy of their data. Points were deleted from the analysis, however, when log descriptions conflicted strongly with, e.g., elevations on topographic maps, or reported bedrock elevations were much different than neighboring data points. The accuracy of coal borings used may thus vary from 10's to 250 ft. Classes of locational information and supplementary notes can be found in the SOURCE, VERIFIED_BY, VERIFIED_NOTES, VERIFIED_DATE, and COMMENTS fields. SOURCE codes are: APH – Air photograph verified DOQ -- Digital orthophotograph verified PLT -- Platbook or street address verified TAX -- Location from tax records GPS -- Global Positioning System verified PMT -- Permit verified TOP -- Topographic map verified DRL -- Location from driller LOG -- Location from log FLD -- Field verified Other source codes that do not appear in the bedrock points dataset but do appear in its parent data set are: UNV -- Unverified location BAD -- Questionable location or no supporting information available.

**Uncertainty of Elevation**

- If not surveyed or obtained by differentially corrected GPS, assigned elevation determined by quality of spatial determination, topographic variability, and topographic map accuracy

- Topographic variability: low on American Bottoms, till plains; high on transitional areas, incised uplands, and ridged uplands
- Topographic map accuracy: nominally ~10 ft, but age of map and source of data have small effect (c.f. Cahokia, Collinsville)
- Range of uncertainty is 1 to ~25 ft, though we certainly tried to use more of the former than the latter

**Use of Synthetic points**

Synthetic points can be created to constrain the bedrock surface where insufficient actual observations occurred. An initial map of predicted bedrock outcrop is constructed by digitally comparing an early draft of the bedrock topography map to the surficial digital elevation model. Where predicted outcrop is known to not occur, the surface is forced down by 10 ft, and where outcrop is expected but not predicted by the model the surface is raised by 5 ft. Similarly, where early models of the bedrock surface intersected well-known borings that did not reach bedrock, the surface is depressed by 10 ft. Synthetic points are added to bedrock valley axes to remove interior depressions.

**Log interpretation**

The interpretation of water well, geotechnical, and coal borings is not straightforward because of varying nomenclature, a tendency for various practitioners to value materials selectively, and variable care taken in log descriptions. Although the occurrence of limestone seems to be well recognized by most practitioners, weathered shale is often misidentified as till, and till can also be misidentified as shale. For corroborating evidence to descriptions of bedrock in geotechnical borings, blow counts typically rise abruptly to 100 blows per 6 in, and unconfined compressive strengths (Qu) also rise abruptly. Reevaluation of lithologies incorrectly described in logs requires familiarity with nearby geology and best professional judgment. Till misidentified as shale may be described as "blue shale", "soft gray slate", "clayey shale", and "soft shale". Shale can be also lumped into the "overburden" with till in coal borings. Weathered shale misidentified as till might be described as having "abundant soft pebbles", which are actually lenses of less weathered rock. Complicating that interpretation is the fact that some tills, especially the Omphghent member of the Banner Formation, contain abundant weathered shale clasts.

**Uncertainty of Bedrock Elevation and Sediment Thickness**

The net result of all of the above plus estimates of the bedrock topographic roughness.