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United States Department of the Interior

U.S. GEOLOGICAL SURVEY

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April 8, 2010

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Reference: *Central and Eastern United States Seismic Source Characterization for Nuclear Facilities - USGS review of earthquake catalog and feedback on datasets, methods, and models*

Dear Mr. Salomone:

This letter is in response to your request to the USGS that they provide feedback on the datasets, methods, and models pertaining to the Central and Eastern U.S. Seismic Source Characterization (CEUS-SSC).

We received a preliminary earthquake catalog during 2009 and the preliminary HID (source model description) during March 2010. USGS scientists Charles Mueller and Margaret Hopper reviewed the catalog and provided feedback to the TI team during January 2010. Several other scientists including Russell Wheeler, Anthony Crone, Robert Williams, and Bill Stephenson from USGS - Golden, CO as well as Arthur Frankel and Tom Pratt from USGS - Seattle, WA have looked over various portions of the available information in the data summary and evaluation tables, and the seismic sources contained in the HID. We sent a series of emails to you over the past couple of months regarding our suggestions. I have summarized the main conclusions of these reviews and emails below. In addition, I will also include hard copies of these documents along with this letter. In general the USGS scientists are impressed by the tremendous effort the TI team has put into improving the seismic source model for the CEUS.

The USGS group recommends that the TI team consider the following reviews and datasets.

1. Catalog reviews of Mueller and Hopper were sent to Dr. Robert Youngs of the TI team. We are including a one-page summary of the conclusions from Mueller's extensive review as well as Hopper's review of the seismicity catalog. The review by Mueller

compares the declustered USGS and CEUS-SSC catalogs and reveals significant differences due to methodologies and source catalogs. It is recommended that the TI team consider alternative approaches to declustering in the final version of the CEUS-SSC model.

2. An email from Mark Petersen to Larry Salomone contains comments and informational material from Russ Wheeler and Art Frankel. We recommended that the TI team consider the following datasets and models: the Nemaha Ridge zone, Eastern Tennessee zone, a background source zone (providing a floor to the hazard), an Eastern Arkansas zone, and a Charlevoix b-value zone.
3. An email from Russ Wheeler to Larry Salomone discussed potential magnitudes across the CEUS and structural relationships in the Rome Trough and Rough Creek Graben.
4. An email from Rob Williams to Mark Petersen provides additional references for the New Madrid Seismic Zone – some of these references may have already been incorporated into the current model.
5. An email from Tony Crone to Mark Petersen provides a statement that the information on the Cheraw and Meers faults seems to be complete.

We look forward to reviewing the final model that is expected to be received on August 2, 2010. If you have further questions please feel free to contact me or other USGS scientists responsible for the item of interest.

Sincerely,

Mark D. Petersen
U.S. Geological Survey -
National Seismic Hazard Mapping Project Chief

ATTACHMENTS:

1. Catalog review (a) Charles Mueller one-page conclusions from catalog review and (b) Margaret Hopper's catalog review
2. E-mail from Mark Petersen to Larry Salomone
3. E-mail from Russ Wheeler to Larry Salomone
4. E-mail from Rob Williams to Mark Petersen
5. E-mail from Tony Crone to Mark Petersen

1. Catalog Review

a. Charles Mueller review conclusions sent to Robert Youngs January, 2010

Review of the CEUS-SSC Seismicity Catalog: Recommendations and Conclusions

1) The report would benefit overall from more discussion/explanation, especially regarding the purpose and uses of the catalog, source catalog choices and preference order, and processing procedures (especially Sections 4.0 and 7.0).

2) There are 318 "final" differences in the CEUS-SSC catalog (entries in the CEUS-SSC catalog but not in the USGS catalog: magnitude >= 3, declustered, accounting for completeness––about 10% of the total catalog). As expected most of these are contributed by source catalogs not explicitly used by USGS, notably ISC, GSC, SUSN, WES, MUN, METZ, and RANDJ. The reliability of some of the ISC data is questionable based on the analysis above. The authors should try to determine if there truly are problems with the ISC data, and, if so, whether they are limited to the Oklahoma region or are more general. Should some or all of the ISC data be deleted from the source catalog mix? Most of the other "new" contributions are based on special studies, which are usually assumed to be carefully done even though they may not be published or formally vetted. Is it possible/reasonable to provide more information about some of these source catalogs?

3) There are 55 "final" differences in the USGS catalog (entries in the USGS catalog but not in the CEUS-SSC catalog: magnitude >= 3, declustered, accounting for completeness—about 2% of the total catalog). Even though CEUS-SSC uses USGS as one of its source catalogs, these differences are well understood: events declustered as aftershocks by CEUS-SSC but not by USGS, or events declared non-tectonic by CEUS-SSC but not by USGS.

4) The catalog of non-tectonic events is a valuable by-product of this work. It should be provided as a separate file.

5) The moment magnitude analysis (Section 6) seems straightforward, but its success relies on accurate, uniform moment magnitude determinations from diverse sources. Is it possible/realistic to provide more information about the reliability and uniformity of the moment magnitude dataset?

b. Margaret Hopper's catalog review sent Dec, 2009:

Margaret Hopper
2009 Dec 31

Catalogs

The first two catalogs below should be included.

1. PDE

The National Earthquake Information Center's (NEIC) primary earthquake catalog is the Preliminary Determination of Epicenters (PDE). The PDE catalog, at this web site called "USGS/NEIC (PDE) 1973 – Present", can be downloaded or searched via a Latitude/Longitude rectangle at
http://neic.usgs.gov/neis/epic/
In the output list, the left-most column shows one of these three:
PDE-Q – initial locations and magnitudes for recent events
PDE-W – locations and magnitudes reviewed and published in the weekly PDE listings
PDE – NEIC's best and final locations and magnitudes. These solutions have been re-worked incorporating all the best available data; they are published in the monthly PDE listings about ten months in arrears.
In fact, most of the PDE earthquakes do seem to be included in the EPRI catalog from other sources, but they should be listed with the explicit source citation "PDE" so that parameters obtained from the PDE catalog may be distinguished from others.
The search above will return only basic information, but the same earthquakes are listed in much more detail in the Monthly Listing files:
ftp://hazards.cr.usgs.gov/pde/manuscript/

and in the Monthly Bulletins (EDR):
http://earthquake.usgs.gov/research/data/?areaID=13
A comprehensive catalog should include the relevant earthquakes and parameters from the PDE catalog.

2. USHIS and
Stover, Carl W., and Coffman, Jerry L., 1993, Seismicity of the United States, 1568-1989 (Revised): U.S. Geological Survey Professional Paper 1527, 418 p.
This is NEIC's primary catalog of historical earthquakes in the United States.
The USHIS catalog, at this web site called "Significant U.S. Earthquakes (1568 – 1989)," can be downloaded or searched at
http://neic.usgs.gov/neis/epic/

The basic data in the USHIS catalog come from the paper publication, Stover and Coffman (1993). Stover and Coffman (1993) contains additional data, such as earthquake summaries and felt areas, that are not available in the condensed digital version, "USHIS."
A comprehensive catalog should include the relevant earthquakes and parameters from the USHIS catalog.

3. Centennial Catalog
http://earthquake.usgs.gov/research/data/centennial.php
Engdahl, E.R., and A. Villaseñor, Global Seismicity: 1900–1999, in W.H.K. Lee, H. Kanamori, P.C. Jennings, and C. Kisslinger (editors), International Handbook of Earthquake and Engineering Seismology, Part A, Chapter 41, pp. 665–690, Academic Press, 2002.

The Centennial Catalog includes only large earthquakes, but those earthquakes have been relocated and their magnitudes corrected. This catalog is available in digital format.

4. NOAA Global Significant Earthquakes Database – supplementary data
http://www.ngdc.noaa.gov/hazard/earthqk.shtml
This catalog provides additional digital data about the most significant earthquakes, information about deaths, injuries, damage ($ million), numbers of houses destroyed or damaged, photographs, tsunami, etc. A comprehensive catalog might include relevant information from this supplementary file.

5. Hopper listing – supplementary data
This listing that you already have provides additional digital data (e.g., summaries, felt areas) for many of the earthquakes in the USHIS catalog. The summaries and felt areas were typed from the paper Stover and Coffman (1993) catalog.
The felt areas had caveats attached to them (e.g., "land area only"). The felt-area caveats must always be taken into consideration in any calculations using those felt areas.
A comprehensive catalog might include relevant supplementary information from this file, but the preferred listings should come directly from the original sources, USHIS and PDE, and cite those sources.

Comparison of catalogs

An event-by-event comparison of the earthquakes in my listings that lie within the EPRI study area revealed no significant differences --- not surprising since my listings were included in the EPRI catalog. My listings included only larger events, reflecting my interest in site effects and earthquakes large enough to produce them.
A comparison of the EPRI catalog with the PDE catalog on the web found these additional earthquakes:

```
PDE   1981 1207200110.47V  37.288 -82.915  0  G                                    491009...
.0.P.....E..
PDE   2008 0404183306.58*B 33.687 -87.363  1  G  1.08                              507008...
.0.P........
PDE   2008 1218000507   K  36.050 -83.591 10                    2.90LgGS           5060103F.
.3.P........
PDE   2008 1224102201   T  44.650 -69.510  0                    2.50LgOTT  2.10LgWES  475011.F.
.3.P........
PDE   2008 1227050434.60L  40.114 -76.403  4                    3.40MDPAL          4730394F.
.3.P........
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PDE   2008 1228205659.99*B 30.440-103.362  5  G  1.26           2.60MLGS              498008...
.3.P........
PDE   2008 1231053408.80L  40.107 -77.003  1                                          4730093F. .
.P........
PDE   2008 1231065448.47O  46.137 -75.427 18  G                 3.20MDPAL  2.90LgOTT  447021.F.
.3.P........
PDE   2009 0107203255   K  35.567 -92.573  0                    2.70MDCERI            502005.F.
.3.P........
PDE   2009 0109192626   K  37.341 -90.002  8                    2.50MDCERI            485008.F.
.3.P........
PDE   2009 0116210944   K  35.645 -89.694  8                    2.80MDCERI            5060123F.
.3.P........
PDE   2009 0126065528   L  43.255 -78.723  7                    2.30LgOTT  2.10MDPAL  4720154F.
.3.P........
PDE   2009 0126105232   K  36.081 -90.989  0                    2.90LgCERI            4860213F.
.3.P........
PDE   2009 0127112012   K  36.777 -84.132 25                    3.10MDCERI            5060132F.
.3.P........
PDE   2009 0128111909.47 A 35.163 -97.871  5  G  1.14           3.40LgGS              4990153F.
.3.P........
PDE   2009 0129211127   K  33.015 -80.172  5  G                 2.50MDCERI            5110072F.
.3.P........
PDE   2009 0130005752.38?C 35.724 -96.920  5  G  1.45           2.40LgGS              4990052F.
.3.P........
PDE   2009 0130014121.66 A 32.501-104.607  5  G  0.99           2.70LgGS              496015...
.3.P........
PDE   2009 0130203238.24?C 33.663 -87.351  1  G  1.43           2.90LgGS              507005...
.3.P........
PDE   2009 0203033419.10L  40.870 -74.522  5  G                 3.00MDPAL             4940314F.
.3.P........
PDE   2009 0203102310.01 A 34.589 -96.340  5  G  1.27           3.10LgGS              499016.F.
.3.P........
PDE   2009 0203232710.33 A 36.992-104.884  5  G  1.22           3.00LgGS              496017...
.3.P........
PDE   2009 0213110231.71 A 37.133-104.870  5  G  1.23           2.70MLGS              479015...
.3.P........
PDE   2009 0214131627.24OH 41.840 -81.000  5  G                 2.60LgOGSO 2.60LgOTT  471016.F.
.3.P........
PDE   2009 0214222222   L  40.948 -74.392  2                    2.40MDPAL             4940233F.
.3.P........
PDE   2009 0217080948   K  35.922 -89.927 12                    2.60MDCERI            5060062F.
.3.P........
PDE   2009 0218034150.72L  42.570 -74.103  9                    2.70MDPAL             4720122F.
.3.P........
PDE   2009 0218064235.60L  40.868 -74.551  4                    2.30MDPAL             4940102F.
.3.P........
PDE   2009 0218162023   L  42.572 -74.101 10  G                 2.40MDPAL             472004.F.
.3.P........
PDE   2009 0220180419.70L  42.573 -74.096  8                    2.70MDPAL             472020...
.3.P........
PDE   2009 0222094306.75 A 36.369 -98.087  5  G  1.28           3.20LgGS              499025.F.
.3.P........
PDE   2009 0223154620.29L  42.574 -74.095  7                    2.10MDPAL             472006.F.
.3.P........
PDE   2009 0225041415.33 A 34.735 -96.036  5  G  1.39           3.30LgGS              4990123F.
.3.P........
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The first two, in Alabama and West Virginia, are apparently quite small and lack magnitudes. The rest are from monthly PDE's that were published after the EPRI catalog had been compiled. So this comparison, too, found no significant earthquakes that are missing from the EPRI catalog.

Comments, typos, etc., by sections

1.1 "The USGS catalog." The USGS has many catalogs. What is THE catalog for earthquakes by the USGS? For most purposes, that would be the monthly PDE catalog. The catalog discussed here should be "the Mueller catalog," or whatever Chuck Mueller names it. There

needs to be some discussion of what's in it. In fact, there needs to be more discussion of what's in most of the catalogs.
1.3 Seeber and Armbruster, 2002 is cited but not in reference lists.
1.12 Did a section get left out?
1.14 "NEBD" should be "NEDB"
1.17 Line 6. "Two additional lists contain respectively the earthquakes (that) occurred in Ohio's border regions…"
1.19 Line 3. "but those for earthquakes (that) occurred prior to 1930 have been disregarded because (they) are (were) likely obtained from…"
2.1 Bechtel, 2006, is cited but not in reference lists.
3.1 Line 4. "All the earthquakes (non-tectonic events) received a unique ID…"
3.4 Line 1. "Bulletin" not "Bulleting"
3.5 Seeber and Armbruster, 2002 is cited but not in reference lists.
3.8 "NEBD" should be "NEDB"
3.12 This URL doesn't work. Try http://www.geol.vt.edu/outreach/vtso/
4.0 Paragraph 2. How were the catalogs merged? How were duplicates identified? What "variable time windows" were used? What criteria were used to decide that apparent duplicates should be assigned the same TMP ID? How far apart in time and space might be considered duplicates? Weren't there a few earthquakes at the same place exactly 12 hours off or off by the difference between local time and UTC? How did you resolve such puzzles?
5.0 Paragraph 2. "A list of earthquakes with Io and FA was provided by Margaret Hopper." It should be noted that the felt areas were all from Stover and Coffman (1993) except for a few, as noted, that came from Coffman and others (1982).

Coffman, J.L., von Hake, C.A., and Stover, C.W., 1982, Earthquake history of the United States: U.S. National Oceanic and Atmospheric Administration and U.S. Geological Survey, Publication No. 41-1, revised edition, [through 1980], 258p.

Stover, Carl W., and Coffman, Jerry L., 1993, Seismicity of the United States, 1568-1989 (Revised): U.S. Geological Survey Professional Paper 1527, 418 p.

Note: Coffman and others (1982) was the predecessor U.S. historical earthquake catalog to Stover and Coffman (1993). Coffman and others (1982) is still sometimes used (1) because it has a lower size cutoff and thus contains earthquakes that are too small to be included in the later publication and (2) because it contains information about the U.S. effects of earthquakes with epicenters outside the borders of the U.S. (e.g., St. Lawrence shocks). Coffman and others (1982) is not available in digital format.
5.1 Atkinson (1993) is cited but not in reference list.
Figures 6.2 and 6.6 and 6.7 key. EPRI (1993) is cited but not in reference list.
Figure 6.11 key. Miao and Langston (2007) is cited but not in reference list.
6.10 Table 6.1 Ebel (2000) is cited but not in reference lists.
6.10 Paragraph 5. Ebel (2000) is cited but not in reference lists.
6.10 Paragraph 5. Using lnFA=12.6 instead of 11.23 is perhaps still not enough to yield a reasonable magnitude for the 1727 Nov 10 Cape Ann earthquake.

The Stover and Coffman (1993) felt area of 296,000 km sq [lnFA = ln(296,000)=12.6] is listed with a caveat: "LAND AREA ONLY." Such caveats are shown in the column to the right of the felt-area column in the Hopper listing. The total "felt area" might be as much as double that, since the epicenter is just offshore.

Moreover, Stover and Coffman (1993) lists the maximum reported intensity, not the epicentral intensity. These would normally be the same, but the 1727 epicenter is a little offshore, so its epicentral intensity could be a little higher than the VII listed.

Thus an estimated magnitude based on these two parameters is probably a little too low.

Have the felt-area caveats been ignored in other calculations?

9.0 Paragraph 2. EPRI (1993) is cited but not in reference lists.

2. E-mail from Mark Petersen to Larry Salomone sent February, 2010

List of questions for the TI team on additional sources for the CEUS-SSC model –compilation from Mark Petersen, Art Frankel, Russ Wheeler, Chuck Mueller, Steve Harmsen. – January, 2010

The current model seems to have most of the major sources that are included in the U.S. National Seismic Hazard Maps. However, there are some regions where we have considered separate treatment that the TI team might want to consider. We still do not have complete information on the models but will review this information as it becomes available.

1. The Nemaha Ridge area has experienced two M 5 earthquakes. The Kansas Geological Survey http://www.kgs.ku.edu/Publications/pic3/pic3_2.html indicated that the Nemaha Ridge-Humboldt Fault Zone is the site of moderate risk potential. They report that "the largest recorded Kansas earthquake hit the Manhattan area in 1867. It toppled chimneys and cracked foundations and was felt as far away as Dubuque, Iowa". The TI team should discuss putting a zone to account for earthquakes in this region.
2. The 1996-2008 USGS models included a separate source zone for eastern TN. The purpose of this zone is to reduce the clustered hazard patterns obtained from smooth seismicity. Gridded seismicity alone may not capture the trend of the zone and the areal zones they have that encompass eastern Tennessee will dilute the hazard there (see note from Art Frankel below).
3. The USGS maps have a floor of hazard to account for the short seismicity catalog. Uniform seismicity zones allow for some level of hazard in areas where no earthquakes have occurred.
4. Tish Tuttle has identified liquefaction features in East Central Arkansas (see notes below). These features would be similar to those that define the ALM source zone.
5. The USGS considers a Charlevoix b-value zone.

Here are some comments from the National Seismic Hazard Group:

Tish Tuttle: Marianna, AR, large sand blows formed Near Marianna, AR, large sand blows formed between 5-7 ka, and possibly as early as 10 ka.

 Ages of sand blows do not match NM chronology and no large sand blows have been found in Marianna that formed during NM events in 1811-1812, 1450 AD, or 900 AD.

 Therefore, Marianna sand blows formed as result of very large local paleoearthquakes.

- ERMFZ and WRFZ are likely sources of events; numerous sand blows occur along lineaments parallel to these fault zones.
- Recent trenching of sand blows along one such lineament revealed unusual fracture that cross cuts older sand blow

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Art Frankel: There does not seem to be a distinct Eastern TN zone. Gridded seismicity may not capture the trend of the zone and the areal zones they have that encompass ET will dilute the hazard there.

Their Gulf coast source zone will ensure there is virtually no hazard in the zone, since the seismicity in their zone is very low. Our extended margin zone provided a floor of hazard for the Gulf coast.

Russ Wheeler: I sent you and the other five of us my review of the HID document on 11/23/09. I can't think of any zones that they should add. However, as far as I know their NAPP (Northern Appalachian) zone should be deleted and the review explains why. SSC considers NAPP nonextended. That interpretation is contradicted by an influential published cross section of Maine and adjacent Quebec that blends seismic reflection, gravity, aeromag, and geologic data. The profile is a source of information that SSC appears to have missed. The review provides the reference for the profile, and summarizes some of what it shows and is interpreted to show.

Whether any source zones should be added or removed depends partly on what SSC's "kernel density" method is. From the way it is used at several places in the document, it appears to be similar to Art's smoothed seismicity method. If that's the case, then I am puzzled by the inclusion of most of their seismotectonic zones. Some of the zone boundaries divide seismically more active areas from less active areas. Smoothed seismicity represents the spatial variation of seismicity. If that's what kernel density does, then if local seismicity was also used to define any seismotectonic zones that would seem to be double counting. If SSC did not use seismicity to define zones, then probably the zones would be based on subjective extensions of known geology. Such extensions appear to be inconsistent from one seismotectonic zone to another.

However, the SSC document provides no explanation of why they should have defined most of their zones in the first place. This omission makes the SSC seem like a rejuvenation of EPRI-SOG, which SSC was intended to replace. If that's the case, then SSC represents an improvement in having larger zones and, therefore, larger Mmax values. However, because the HID document is descriptive instead of explanatory, it's not clear whether the underlying zonation methodology differs much from EPRI-SOG's.

Given all this, I'd agree with Art about adding the Nemaha Ridge. It couldn't hurt the other SSC zones, and it would allow those two M 5's to have more influence than they do in our maps. That, of course, requires a subjective assumption that the Ridge is likely to differ from the surrounding craton. We don't have to make such an assumption. SSC could argue that they should make it, because they have to be conservative to protect critical structures against low-probability events.

Fundamentally, I think that a zone ought to earn its way onto a hazard map. Very few parts of the CEUS have done that.

3. E-mail from Russ Wheeler to Larry Salomone sent April 2010

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Lakewood, Colorado 80225

Central Geologic Hazards Team

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April 6, 2010

Mr. Lawrence Salomone:

The SSC project members have done a thorough job of collecting the data, models, and tools that are needed for their work. As far as we know, they have not missed any except the few listed below, and others that Mark Petersen has sent to you separately. Below we include explanations of why we consider each item to be important to consider as possible new aspects of the SSC model. Some of these items may already have been considered by project members without our knowing of it.

(1) Sarah Gassman (Dept. of Civil and Environmental Engineering, University of South Carolina) has recently used geotechnical data to obtain preliminary estimates of M (moment magnitude) of the large prehistoric earthquakes in the South Carolina Coastal Plain. She summarized the work in a poster at a meeting on the CEUS that took place on October 31, 2009 in Memphis. You and at least some other project members attended. However, because Gassman's work is new, all project members might not have encountered it yet.

(2) Three structure-contour maps of the Rome Trough in eastern Kentucky and West Virginia, and of the Rough Creek Graben in western Kentucky, show that both grabens have large structural relief (Drahovzal and Noger, 1995; Shumaker, 1996; Wheeler and others, 1997). The elevation differences between the deepest basement tops within the grabens and the basement tops adjacent to the grabens are almost wholly of Cambrian age and measured in kilometers. The Rome Trough is much larger in map view than the coeval Birmingham graben and of comparable depth. Across the north border fault of the Rough Creek Graben, basement deepens more than 5 km over a map distance smaller than 3 km. All three grabens are much deeper and younger than any grabens that we know of in cratons, except the Precambrian Mid-continent Rift with its crustal-scale filling of syn-rifting igneous rocks. To our knowledge, the Rough Creek, Rome, and Birmingham structures have no or negligible syn-rifting igneous rocks. Accordingly, the three maps cited below may impact the modeled location of the cratonward boundary of the IRM-N seismotectonic zone.

(3) Some recent estimates of the sizes of the very large New Madrid earthquakes are around M7, much smaller than other estimates. During SSC Workshop 2 Martitia Tuttle drew

attention to the similarity of the areas of the liquefaction fields and the distance to the farthest liquefaction features of the 2001 Bhuj, India earthquake and one of the very large 1811-12 New Madrid earthquakes (Tuttle and others, 2002). The similarity may be useful in estimating weights that are assigned to the lower estimates of the New Madrid M.

(4) We cannot determine whether the SSC procedure for estimating Mmax has missed any important data, models, or tools because we have not yet seen the complete details of the procedure, including a full derivation of the bias correction.

(5) We recommend that the probability distributions with which Mmax is modeled for the seismotectonic source zones include the M of the 2001 earthquake in Bhuj, northwest India. Bhuj is the largest modern instrumental earthquake in any of Earth's SCRs. The following arguments suggest that the credibility of the SSC analysis might be undercut if the upper tails of the distributions do not include the Bhuj M.

First, some people have argued that Bhuj occurred in a plate boundary instead of within the Indian stable continental region (SCR). If the argument is correct, then Bhuj would not be pertinent to the SSC. However, measured map distances and close consideration of the plate-tectonic setting of the earthquake do not support the argument. The very large Kachchh earthquake in 1819 occurred roughly 200-250 km southeast of the outcrop of the edge of the India-Eurasia plate boundary that is in Afghanistan and Pakistan. Bhuj occurred approximately 150 km southeast of Kachchh. Johnston and others (1994) set aside for special consideration the SCR earthquakes within about 40 km of boundaries between SCRs and active continental crust, thereby including the Kachchh and Bhuj earthquakes in the Indian SCR. The digital database of Johnston and others lists 124 of these transitional earthquakes and their distances from the nearest boundaries with active continental crust. Eighty-five percent of the distances are 100 km or smaller. In an update of the Johnston and others catalog of SCR earthquakes, Schulte and Mooney (2005) considered only earthquakes 200 km or more from the nearest SCR boundary. At the 2008 workshop on Mmax we heard that the Geological Survey of Canada also uses a 200 km distance. Thus, three groups that have extensively considered the effect of plate boundaries on SCR earthquakes would consider Bhuj to be an SCR earthquake.

Second, the fault system that probably generated Bhuj has cumulative movements more typical of SCR faults than plate-boundary faults. Bhuj occurred in a Mesozoic graben whose trend makes a large angle with the likely orientation of maximum shortening that is caused by the strike-slip plate boundary northwest of Bhuj. The large angle implies that the normal faults of the graben are being reactivated in nearly pure reverse slip. The main shock focal mechanism supports the implication (Antolik and Dreger, 2003). Yet the structural relief on the graben is only a few kilometers instead of the tens or hundreds of kilometers that are common in plate boundaries. Again, Bhuj is likely an SCR earthquake. It occurred in domain 114 of Johnston and others (1994) and probably it is already in one of the superdomains of the prior distribution for SSC's Bayesian estimation of Mmax.

Third, a Bhuj-sized earthquake could have occurred prehistorically anywhere in the CEUS without us knowing it. The upper end of the aftershock zone was at depths of 5-10 km (Bodin and Horton, 2004). Therefore, a Bhuj sized earthquake might not produce a recognizable scarp or warp of the ground surface. The Bhuj liquefaction field was large, but Bhuj occurred where the water table is shallow. If such an earthquake had occurred in the Great Plains of the central U.S., the liquefaction field might have been more subdued. Additionally, very few parts of the CEUS have been searched for liquefaction features, particularly in glaciated or forested areas such as those in the northern and eastern parts of the CEUS.

Fourth, the rupture zone of Bhuj was short enough and wide enough to suggest that an earthquake like Bhuj might occur anywhere in the CEUS, particularly in the Cambrian and younger seismotectonic zones that rim the craton. The rupture zone was approximately a dipping trapezoid with a shallow edge 55 km long, a deep edge 25 km long, a vertical distance between the edges of 30 km, and a dip of approximately 42 degrees (Bodin and Horton, 2004). Thus, the rupture area was 1,792 square kilometers and the subsurface rupture length was 55 km. Geologic and structure-contour maps show that a similarly short rupture zone could fit on faults short enough that they are known or likely in most or all parts of the CEUS. Several parts of the CEUS have such short faults striking in several orientations. The most widely-used regression equations do not predict such a small rupture zone for such a large earthquake. The length, width, and rupture area are considerably smaller than predicted for all earthquakes treated together, including those in both SCRs and plate boundaries (Wells and Coppersmith, 1994). The rupture area is also smaller than predicted for SCR earthquakes alone (Somerville and others, 2001).

In conclusion, if any of the Bayesian Mmax posterior distributions do not have a bin that includes the M7.6 size of the Bhuj earthquake, we recommend explanation of the reason for exclusion of the Bhuj value. A potentially simpler alternative would be to include M-frequency graphs for all seismotectonic zones, and to observe which graphs show an annual probability of a Bhuj-sized or larger earthquake that is too small to matter to the SSC analysis. The zones for which Bhuj does not matter would not need to have their Mmax treatment changed. Because there are few seismotectonic zones, all the graphs could be included in one or two diagrams and remain legible.

Cordially,

Russell L. Wheeler

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4. References from e-mail from Rob Williams to Mark Petersen sent March, 2010

Mark,

Jack Odum, Bill Stephenson, Tom Pratt, and I have added some (in blue text and before the original NRC list) to this file. Pretty sure that it is not complete. Haven't checked your 2008 NSHM reference list.
File attached here.

Seems like a fairly complete list of references on faulting - . One article that is missing from the **Word doc on Information pertinent to seismic sources:**

Reelfoot rift zone Reelfoot rift RLMEs (Central New Madrid fault zone, Eastern Rift Margin North, Eastern Rift Margin South, Commerce Fault

ftp://CEUS-PPRP@amftp.amec.com/Data%20Tables%203-9-10/Seismotectonic/Reelfoot_Rift-NMSZ_Data_Summary_Hanson_03-01-10%20KJC.doc

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This article is listed, however, in the Word doc specific to eastern margin faults. Slightly confusing.

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5. E-mail from Tony Crone to Mark Petersen sent April, 2010

Mark,

I've read the SSC Project data sheets and summaries for the Meers and Cheraw faults, the two structures that I'm most familiar with. The information contained in those documents appears to be complete and thoroughly analyzed. I didn't note any glaring misrepresentations or omissions of important references. Overall, it appears that the SSC Project members have done a fine job of reviewing the published information and accurately representing it in the project's compilation.

Tony

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