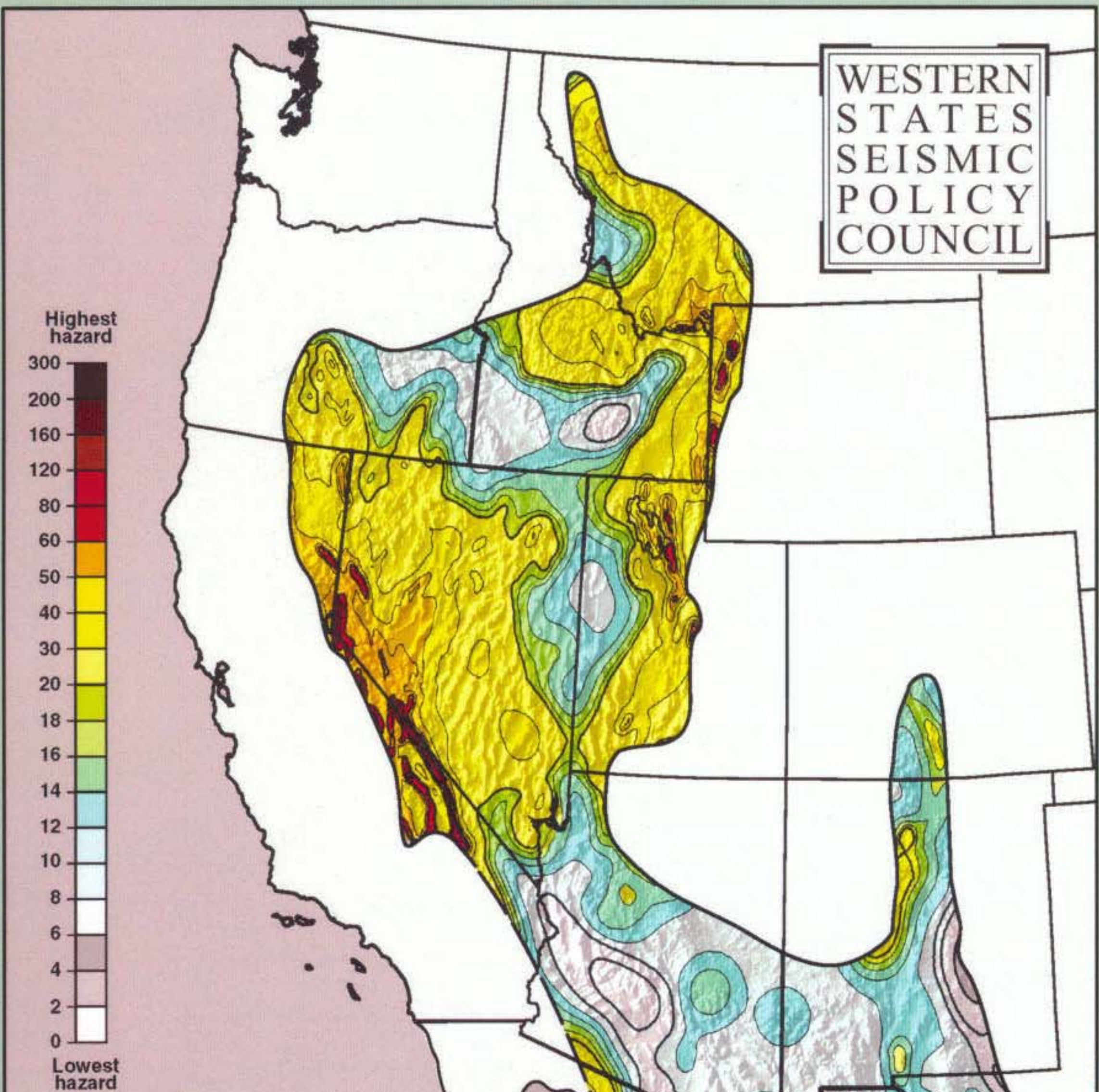
# WESTERN STATES SEISMIC POLICY COUNCIL

# *BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP SEISMIC-HAZARD RECOMMENDATIONS TO THE U.S. GEOLOGICAL SURVEY NATIONAL SEISMIC HAZARD MAPPING PROGRAM*

EDITED BY WILLIAM R. LUND

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2006

# BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP SEISMIC-HAZARD RECOMMENDATIONS TO THE U.S. GEOLOGICAL SURVEY NATIONAL SEISMIC HAZARD MAPPING PROGRAM

Prepared by the
Basin and Range Province Earthquake Working Group
in cooperation with the
Basin and Range Province Committee
of the
Western States Seismic Policy Council

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*Edited by*
*William R. Lund, Utah Geological Survey*

***May 2006***

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# BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP SEISMIC-HAZARD RECOMMENDATIONS TO THE U.S. GEOLOGICAL SURVEY NATIONAL SEISMIC HAZARD MAPPING PROGRAM

*Edited by William R. Lund*

## INTRODUCTION

This report presents consensus recommendations of the Basin and Range Province Earthquake Working Group (BRPEWG) on five seismic-hazard issues in the Basin and Range Province (BRP) important to the U.S. Geological Survey's (USGS) 2007 update of the National Seismic Hazard Maps (NSHMs). Scientists attending the Western States Seismic Policy Council (WSSPC)-sponsored Basin and Range Province Seismic Hazard Summit II (BRPSHSII) held in Reno, Nevada, in May 2004 first identified the five issues. Following BRPSHSII, WSSPC incorporated the issues into their Policy Recommendation (PR) 04-5, which advocated convening a broad-based group of technical experts to evaluate each of the issues and advise the USGS regarding the 2007 NSHM update. In response to PR 04-5, the WSSPC Basin and Range Province Committee (BRPC) and the Utah Geological Survey (UGS) convened the BRPEWG under the auspices of WSSPC and the USGS NSHM Project. The BRPEWG was charged with reviewing information regarding the five issues, and developing consensus recommendations for the 2007 NSHM update. The BRPEWG drew its members from several BRP state geological surveys, federal government agencies, academic institutions and seismological laboratories, and geotechnical consulting firms. The BRPEWG met on March 8-10, 2006, in Salt Lake City, Utah.

## BRPEWG RECOMMENDATIONS

The BRPEWG arrived at the following consensus recommendations through a deliberative process. The Working Group relied on the broad technical expertise and experience of its members when considering how the issues should be accommodated in the 2007 update of the NSHMs. Where appropriate, the Working Group also made recommendations for long-term research that will permit further refinement of the NSHMs beyond the 2007 update.

### Issue 1

### Use and Relative Weighting of Time-Dependent, Poisson, and Clustering Models in Characterizing Fault Behavior

#### Short-Term Recommendation for the 2007 NSHMs

1. The USGS should incorporate uncertainties in slip rates and recurrence intervals for the more significant BRP faults.
    a. Most studies giving slip rates and recurrence intervals identify the range of uncertainties.
    b. In Utah, use the slip-rate/recurrence distributions developed by the Utah Quaternary Fault Parameters Working Group (Lund, 2005a).

#### Long-Term Recommendations

1. Regional working groups are needed to develop consensus slip-rate and/or recurrence-interval distributions for significant faults.
    a. These rate distributions should represent temporal variation of the rates, if any, and other uncertainties.
    b. A high-level working group needs to recommend guidelines for establishing these distributions.
    c. Each regional group needs a "champion" who will take "ownership" to lead the group and secure results.
    d. Regions will not necessarily be by state. Some organizations (e.g., USGS or WSSPC) need to take responsibility to assure complete geographic coverage.

2. The USGS should continue to develop time-dependent maps as a research product.
    a. In general, research needs to focus more on the timing of the most recent earthquake, average recurrence, and determining coefficients of variation for recurrence.

## Issue 2

## Proper Magnitude-Frequency Distributions (Gutenberg-Richter versus Characteristic Earthquake Models) for BRP Faults

### Short-Term Recommendations for the 2007 NSHMs

1. The USGS "floating exponential" model should be validated to the extent possible, or at least made consistent with the paleoseismic and historical earthquake record in the BRP. The USGS model should also be compared with traditional magnitude-frequency models currently used in state-of-the-practice PSHAs.

2. The USGS should use the same recurrence model and weights for all BRP faults unless there is a technical basis for deviating from this characterization.

3. Weights assigned to the maximum magnitude and "floating exponential" models used for the 2007 NSHMs should, at a minimum, have the same weights as those used in California (2/3 - 1/3) unless there is a technical basis for deviating from this characterization.

4. To avoid double-counting earthquakes in the range of M 6.5 to the characteristic earthquake magnitude, zones surrounding BRP faults should be removed from the areas included in the Gaussian smoothing of background seismicity.

5. The methodology used for constructing the NSHMs must be fully transparent. The USGS is urged to publish, if only as a short note, how recurrence modeling is performed for the NSHMs, especially for fault-specific sources.

## Issue 3

## Use of Length versus Displacement Relations to Estimate Earthquake Magnitude

### Short-Term Recommendations for the 2007 NSHMs

**Estimating Displacement and Length:**

1. Include uncertainty in surface rupture length (SRL) and its consequences for magnitude.

2. Constrain the minimum magnitude assigned to surface-faulting earthquakes to M 6.5 to be consistent with the hazard set by background seismicity.

3. Use magnitude-displacement regressions to improve magnitude estimates where the magnitude from SRL appears inconsistent.

4. Have a working group look at the faults for which displacement data are available (thought to be ~20 in Nevada), and suggest a weighting between displacement and SRL estimates of magnitude to achieve a combined fault magnitude estimate.

### Long-Term Recommendations

**Regressions:**

1. Revisit the Wells and Coppersmith (1994) regressions to update the database and evaluate the need to censor short rupture lengths and small magnitudes.

2. Develop a $M_W$ versus SRL*displacement scaling as a tool for improving use of displacement in making magnitude estimates.

3. Develop a multivariate regression for magnitude, given SRL and displacement, to improve magnitude estimates on faults for which both are available.

4. Invest in determining whether regional regressions materially improve ground motion predictions; for long strike-slip faults (western BRP) consider using the Hanks and Bakun (2002) $M_W$ versus area regression relation.

5. For short faults, consider whether Wells and Coppersmith (1994) is appropriate considering the results of Stirling and others (2002).

6. Evaluate whether an estimate of magnitude based on area (with an assumed width) is more appropriate than magnitude based on SRL.

**Displacement:**

1. There should be a concerted effort to assess:
    a. the variability of displacement along rupture strike for historical surface ruptures for the entire range of magnitude (e.g., a follow up to McCalpin and Slemmons, 1998), and
    b. whether surface-faulting data for the BRP support regional (BRP-specific) regressions.

## Issue 4

## Probabilities and Magnitudes of Multi-Segment Ruptures

### Short-Term Recommendations for the 2007 NSHMs

1. Hazard calculations for the NSHMs should consider the possibility of multi-segment ruptures on BRP faults.

2. For BRP faults for which single-segment-rupture models are being used to compute the hazard, the 2007 NSHMs should also use an unsegmented rupture model which accounts for the possibility of ruptures extending beyond segment boundaries. The unsegmented model should be given a relatively low weight.

3. The two faults that ruptured together in the 1959 Hebgen Lake earthquake should be treated as a single seismic source for the purpose of the 2007 NSHM hazard calculations.

### Short-Term/Long-Term Recommendation

1. Where available, displacement data should be used to provide a consistency check for segmentation models – especially to identify segments on which ruptures longer than the mapped length could occur.

### Long-Term Recommendations

1. Newly developed methods for probabilistically constructing rupture scenarios from paleoearthquake timing and displacements should be applied to the Wasatch fault.

2. Research needs to be conducted on the following topics to facilitate segmentation modeling in the BRP:
   a. how to recognize and characterize fault-rupture segments,
   b. the quality and quantity of paleoseismic data needed to support segmented earthquake models along BRP faults, and
   c. construction of earthquake-segmentation models for important BRP faults.

## Issue 5

## Resolving Discrepancies between Geodetic Extension Rates and Geologic Slip Rates

### Short-Term Recommendations for the 2007 NSHMs

1. Convert vertical slip rates to extensional rates for consistency with GPS data. This involves resolving the question of dip of normal faults. The NSHMs currently use a dip of 60°; the BRPEWG recommends using a dip of 50°±10°.

2. For the BRP, use the province-wide kinematic (GPS) boundary condition (12-14 mm/yr) as a constraint on the sum of geologic slip rates. Enhance the fault catalog used in the NSHMs if necessary to achieve the far-field rates.

3. Modify the boundaries of the geodetic zones in the western Great Basin used in the 1996 NSHMs to better reflect the areas of high strain depicted on the GPS-based strain-rate map.

4. Use the geodetic data as the total strain budget. Ideally, the moment rates from the faults, areal source zones, and GPS zones should add up to the full geodetic budget. This total should be comparable to the seismicity, which is a separate estimate of moment rate. Differences that exist between these individual moment sources should be fully accounted for in the 2007 NSHMs.

5. The USGS should test models to evaluate the effect of releasing geodetic strain as 80% coseismic and 20% aseismic.

6. The USGS should evaluate the impact on the NSHMs of partitioning geodetic strain on individual faults within a zone (assigning default slip rates) versus distributing the geodetic strain uniformly across the zone.

### Long-Term Recommendations

1. Move toward assigning minimum slip rates to specific faults. To this end, develop a strategy of how to assign slip rates based on combined geodetic and geologic criteria; this could be a charge for a future working group.

2. Develop a consistent-resolution fault map for the western margin of the Great Basin as a first step toward an integrated geodetic/geologic model.

3. Develop robust, geologically based (paleoseismic) slip rates in the source zones where geodesy shows significant strain accumulation, giving priority to urban and rapidly urbanizing areas.

4. The geoscience community should work toward the goal of determining if geodesy can identify specific faults where strain is being localized (i.e., indicator of higher hazard).

5. Where adequate data exist, develop an integrated model that incorporates geodetic, seismicity, and fault data.
6. The USGS should fully explain in an easily

accessible publication or Web page the methodology behind the NSHMs, including the properties of each version of the maps so that changes in the maps over time can be completely understood.

## BACKGROUND

The BRPEWG and the recommendations presented here are the outcome of a process begun in May 1997, when WSSPC, the USGS, the Federal Emergency Management Agency, and several BRP state geological surveys jointly sponsored the Basin and Range Province Seismic-Hazard Summit (BRPSHS) in Reno, Nevada. The purpose of BRPSHS was to bring together technical experts, emergency planners, and policy makers to review important technical issues in characterizing seismic hazards in the BRP and to consider their public-policy implications (Lund, 1998). Seven years later in May 2004, the same organizations sponsored a second seismic-hazard summit, BRPSHSII, in Sparks, Nevada. The purpose of BRPSHSII was to convene a group similar to that in 1997, to present and discuss advances in BRP earthquake-hazard research since the first summit, and to evaluate the implications of the new research for hazard reduction and public policy in the BRP (Lund, 2005b).

### Seismic-Hazard Issues

The scientists attending BRPSHSII identified six seismic-hazard issues in the BRP that they considered important to the 2007 NSHM update. The six issues are:

1. Use and relative weighting of time-dependent, Poisson, and clustering models in characterizing fault behavior.
2. Appropriate attenuation relations, stress drop, and kappa in modeling ground motions, including consideration of evidence from precarious rock studies.
3. Proper magnitude-frequency distributions (Gutenberg-Richter versus characteristic earthquake models) for BRP faults.
4. Use of length versus displacement relations to estimate earthquake magnitude.
5. Probabilities and magnitudes of multi-segment ruptures.
6. Resolving discrepancies between geodetic extension rates and geologic slip rates.

### WSSPC Policy Recommendation

The BRPC reviewed the above issues following BRPSHSII, and prepared a draft WSSPC policy statement that recommended convening a broad-based technical working group to develop scientific consensus regarding fault behavior, ground shaking, ground-failure modeling, and research priorities relevant to seismic policy and the USGS NSHMs in the BRP. After review and discussion by the WSSPC Board, the draft policy was adopted as *WSSPC Policy Recommendation 04-5: Basin and Range Province Earthquake Working Group* (the full text of the policy may be viewed at http://www.wsspc.org/PublicPolicy/PolicyRecs/2004/policy04-5.html). The BRPC and the UGS took responsibility for implementing PR 04-5 under the auspices of the USGS NSHM Project.

## BASIN AND RANGE PROVINCE EARTHQUAKE WORKING GROUP

Various seismic-hazard-evaluation initiatives in California (Working Groups on California Earthquake Probabilities, 1988, 1990, 1995, 1999, 2003), as well as the Utah Quaternary Fault Parameters Working Group (Lund, 2005a) have successfully employed working groups composed of technical experts to critically evaluate datasets or issues and arrive at consensus decisions regarding data values/reliability and seismic-policy recommendations/decisions. The BRPC and the UGS employed a similar strategy when convening the BRPEWG, which consisted of subject-matter experts in the fields of geology, paleoseismology, seismology, and geodetics with experience in the BRP (table 1).

### BRPEWG Process

The BRPEWG met for three days (March 8-10, 2006) in Salt Lake City to consider five of the six seismic-policy issues identified at BRPSHSII and incorporated in WSSPC PR 04-5. The sixth issue (number 2 above), "*Appropriate attenuation relations, stress drop, and kappa in modeling ground motions, including consideration of evidence from precarious rock studies,*" is being addressed through a separate USGS-sponsored process (Next Generation of Attenuation Models), and therefore was not considered by the BRPEWG. The three-day meeting was divided into six four-hour sessions. The BRPEWG devoted the first five sessions to considering the five seismic-policy issues. The Working Group used the sixth session, on the afternoon of the final day, to review the recommendations generated during the meeting.

For each session, the BRPC and UGS identified two subject-matter experts to serve as session leaders (table 2). Session leaders were charged with framing their issue succinctly for the BRPEWG as a whole, facilitating discussion during their session, and guiding the BRPEWG toward consensus recommendations to the USGS for the 2007 NSHMs. Where appropriate, the BRPEWG also made longer term recommendations that the USGS could use to set research priorities for both their own internal studies and for their National Earthquake Hazards Reduction Program (NEHRP) external grants to better resolve these issues for future (beyond 2007) NSHM updates.

Each pair of leaders organized their session as they thought appropriate; the BRPC and UGS did not mandate a consistent session format. However, all of the meeting sessions followed a generally similar pattern, with the session leaders and invited speakers making a series of technical presentations to help define and provide information about the issue under consideration. The presentations were followed

***Table 1.*** *Members of the BRPEWG*

| | |
|---|---|
| John Anderson | University of Nevada Reno Seismological Laboratory |
| Walter Arabasz | University of Utah Seismograph Stations |
| Glenn Biasi | University of Nevada Reno Seismological Laboratory |
| Tony Crone | U.S. Geological Survey, Denver |
| Craig dePolo | Nevada Bureau of Mines & Geology |
| Chris DuRoss | Utah Geological Survey |
| Kathy Haller | U.S. Geological Survey, Denver |
| Bill Hammond | Nevada Bureau of Mines & Geology |
| Suzanne Hecker | U.S. Geological Survey, Menlo Park |
| Mark Hemphill-Haley | Humboldt State University |
| David Love | New Mexico Bureau of Geology & Mineral Resources |
| William Lund | Utah Geological Survey |
| Vince Matthews | Colorado Geological Survey |
| Jim McCalpin | GEOHAZ, Inc. |
| Susan Olig | URS Corp. |
| Dean Ostenaa | U.S. Bureau of Reclamation, Denver |
| Phil Pearthree | Arizona Geological Survey |
| Jim Pechmann | University of Utah Seismograph Stations |
| Mark Petersen | U.S. Geological Survey, Denver |
| Robert Smith | University of Utah Department of Geology and Geophysics |
| Bill Phillips | Idaho Geological Survey |
| David Schwartz | U.S. Geological Survey, Menlo Park |
| Burt Slemmons | University of Nevada Reno, emeritus |
| Mike Stickney | Montana Bureau of Mines & Geology |
| Wayne Thatcher | U.S. Geological Survey, Menlo Park |
| Chris Wills | California Geological Survey |
| Ivan Wong | URS Corp. |

***Table 2.*** *BRPEWG session leaders.*

| **Session Leader** | **Seismic-Policy Issue** |
|---|---|
| John Anderson/Susan Olig | Use and relative weighting of time-dependent, Poisson, and clustering models in characterizing fault behavior |
| David Schwartz/Ivan Wong | Proper magnitude-frequency distributions (Gutenberg-Richter versus characteristic earthquake models) for BRP faults |
| Glenn Biasi/Mark Hemphill-Haley | Use of length versus displacement relations to estimate earthquake magnitude |
| Craig dePolo/Jim Pechmann | Probabilities and magnitudes of multi-segment ruptures |
| Robert Smith/Wayne Thatcher | Resolving discrepancies between geodetic extension rates and geologic slip rates |

by open discussion to elicit consensus recommendations from the BRPEWG. The UGS took careful notes during the sessions, and prepared draft summaries of the sessions and the resulting recommendations. The UGS distributed the draft summaries to the BRPEWG members for review and comment. The members commented directly to the session leaders, who then revised the UGS drafts and created a final session summary (see "Session Summaries" below) and set of recommendations for their session.

## SUMMARY

The BRPEWG recommendations contained in this document provide guidance to the USGS regarding five critical seismic-hazard issues in the BRP that are relevant to the next update of the NSHMs. The short-term recommendations reflect the BRPEWG's consensus on best professional practice at this time for the 2007 NSHM update. Recognizing that these critical issues can only be accommodated, not resolved, in the 2007 NSHMs, the BRPEWG also made recommendations for long-term research priorities and goals that will help both the USGS and other research institutions eventually resolve the issues to better refine the NSHMs in the future. The BRPEWG hopes that the USGS will find their recommendations both timely and useful, and that the BRPEWG process will result in improvements to the NSHMs and a reduction in seismic risk in the BRP.

## ACKNOWLEDGMENTS

William Lund (UGS) organized and convened the meeting with assistance from the BRPC BRPEWG Organizing Committee (Ivan Wong [URS Corp.], Gary Christenson [UGS], Craig dePolo [NBM&G], and Bill Phillips [IGS]). On behalf of WSSPC and the UGS, we thank all of the members of the BRPEWG who gave generously of their time to make this effort a success. We especially thank the session leaders who organized and conducted their sessions, the members of BRPEWG who made presentations during the meeting, and the UGS (William Lund, Gary Christenson, Chris DuRoss, and Mike Hylland) for preparing the session summaries. William Lund compiled and edited the final report. Funding for the BRPEWG was provided by the UGS and through USGS NEHRP grant 03HQAG0008.

## REFERENCES

Hanks, T.C., and Bakun, W.H., 2002, A bilinear source-scaling model for M-log A observations of continental earthquakes: Bulletin of the Seismological Society of America, v. 92, no. 5, p. 1841-1846.

Lund, W.R., editor, 1998, Proceedings volume – Basin and Range Province Seismic-Hazard Summit: Utah Geological Survey Miscellaneous Publication 98-2, 204 p.

—2005a, Consensus preferred recurrence-interval and vertical slip-rate estimates – A review of Utah paleoseismic-trenching data by the Utah Quaternary Fault Parameters Working Group: Utah Geological Survey Bulletin 134, compact disk.

—editor, 2005b, Proceedings volume – Basin and Range Province Seismic-Hazard Summit II: Utah Geological Survey Miscellaneous Publication 05-2, compact disk.

McCalpin, J.P., and Slemmons, D.B., 1998, Statistics of paleoseismic data: Final Technical Report to the U.S. Geological Survey, contract 1434-HQ-96-GR-02752, National Earthquake Hazards Reduction Program, 62 p.

Stirling, M., Rhoades, D., and Berryman, K., 2002, Comparison of earthquake scaling relations derived from data of the instrumental and preinstrumental era: Bulletin of the Seismological Society of America, v. 92, no. 2, p. 812-830.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.

Working Group on California Earthquake Probabilities (WGCEP), 1988, Probabilities of large earthquakes occurring in California on the San Andreas fault: U.S. Geological Survey Open-File Report 88-398, 62 p.

—1990, Probabilities of large earthquakes in the San Francisco Bay region, California: U.S. Geological Survey Circular 1053, 51 p.

—1995, Seismic hazards in southern California - probable earthquakes, 1994-2024: Bulletin of the Seismological Society of America, v. 85, p. 379-439.

—1999, Earthquake probabilities in the San Francisco Bay region - 2000 to 2030 – A summary of findings: U.S. Geological Survey Open-File Report 99-517, 36 p.

—2003, Earthquake probabilities in the San Francisco Bay Region: 2002-2031 - U.S. Geological Survey Open-File Report 03-214, variously paginated.

# SESSION SUMMARIES

# SESSION 1

# USE AND RELATIVE WEIGHTING OF TIME-DEPENDENT, POISSON, AND CLUSTERING MODELS IN CHARACTERIZING FAULT BEHAVIOR

## Session Leaders

John Anderson, University of Nevada Reno Seismological Laboratory, Reno, Nevada

Susan Olig, URS Corporation, Oakland, California

## Presentations

*BRPEWG morning session, March 8, 2006*

| | |
|---|---|
| **Olig** | Earthquake clustering and time-dependent models |
| **dePolo** | Behavior of the Genoa fault, Monte Cristo fault, and Warm Springs fault system, Nevada |
| **Schwartz** | Time dependence and historical earthquakes – Hebgen Lake faults |
| **Petersen** | Process for the 2007 maps and time-dependent hazard analysis |
| **Olig** | Time-dependent probabilistic seismic hazard analyses along the Wasatch Front, Utah: The need for longer and more complete paleoseismic records |

## Session Summary

Susan Olig began the session by noting that slip rates drive seismic hazard, and then centered initial discussions on temporal clustering and slip variability. She and Craig dePolo gave examples of paleoseismic data indicating clustering behavior on several Basin and Range Province (BRP) faults. Important points regarding clustering behavior included:

- BRP faults, particularly those for which we've obtained long paleoseismic records, commonly demonstrate clustering behavior (e.g., Canyon Ferry fault, Montana; Lost River fault, Idaho; Pajarito fault, New Mexico).
- The National Seismic Hazards Maps (NSHMs) presently use long-term average slip rates, and do not consider clustering behavior.
- Where temporal clusters occur, slip-rate distributions incorporating slip-rate variability (e.g., including inter- and intra-cluster rates) and uncertainty would be an improvement over just considering long-term average slip rates.
- We need to understand why clustering occurs if we wish to use only an intra- or inter-cluster slip rate in a probabilistic seismic hazard analysis (PSHA).
- Paleoseismic records for BRP faults should be compiled and compared/contrasted to understand the timing and causes of clustering.
- Lower slip-rate faults seem to have less regular recurrence and are more subject to clustering than are high slip-rate faults.
- Weighted mean slip rates for slip-rate distributions that consider clusters are generally higher (increasing the hazard) than long-term average slip rates, but are needed to better incorporate uncertainty.
- Slip-rate distributions typically are not symmetrical.

Discussion turned to the use of time-dependent models in PSHAs. David Schwartz highlighted the Hebgen Lake fault paleoseismic record and issues related to time-dependent models for faults with historical earthquakes. Mark Petersen indicated that time-dependent models are a research product of the NSHM Project, but outside of California, are not being considered for incorporation into the 2007 NSHM update. He then discussed the various time-dependent models (Poisson, time-predictable, Brownian passage time, empirical). Important points from the discussion of time-dependent models included:

- We need complete paleoseismic records with well-established average recurrence (2-3 intervals), coefficients of variation for recurrence, and elapsed time since the most recent earthquake before applying a time-dependent model. Only a few faults in the BRP have been studied well enough for time dependence to be applied.
- To determine recurrence, we need to include variability in slip rates and recurrence intervals and not just rely on long-term average slip rates.
- Time dependence should theoretically raise the probabilities of earthquakes on some faults.
- Faults will yield different long-term slip rates depending on how far back (how many earthquakes) we are able to extend the paleoseismic record.
- BRP faults having low slip rates (and long recurrence) may not be suitable for time-dependent modeling due to the difficulty in determining average recurrence over multiple earthquake cycles.
- Faults with historical earthquakes pose a challenge because time-dependent models yield a greatly reduced hazard (depending on stress drop, a potential for subsequent rupture in the near-term may remain), whereas the hazard is unchanged following a historical earthquake using a Poisson model.
- We need to collect/analyze data on recurrence for faults with historical earthquakes to look for time-dependent behavior.
- It is difficult to use Coulomb stress changes caused by historical earthquakes in time-dependent models because, although a historical earthquake may cause stresses to increase on certain neighboring faults, we do not know each fault's state of stress prior to the historical event.

## Recommendations

The BRPEWG reached consensus on the following recommendations regarding the NSHMs:

### Short-term Recommendation for the 2007 NSHMs

1. The USGS should incorporate uncertainties in slip rates and recurrence intervals for the more significant BRP faults.
   a. Most studies giving slip rates and recurrence intervals identify the range of uncertainties.
   b. In Utah, use the slip-rate/recurrence distributions developed by the Utah Quaternary Fault Parameters Working Group (Lund, 2005).

### Long-term Recommendations

1 Regional working groups are needed to develop consensus slip-rate and/or recurrence-interval distributions for significant faults.
   a. These rate distributions should represent temporal variation of the rates, if any, and other uncertainties.
   b. A high-level working group needs to recommend guidelines for establishing these distributions.
   c. Each regional group needs a "champion" who will take "ownership" to lead the group and secure results.
   d. Regions will not necessarily be by state. Some organizations (e.g., USGS or WSSPC) need to take responsibility to assure complete geographic coverage.

2. USGS should continue to develop time-dependent maps as a research product.
   a. In general, research needs to focus more on the timing of the most recent earthquake, average recurrence, and determining coefficients of variation for recurrence.

## References

Lund, W.R., 2005, Consensus preferred recurrence-interval and vertical slip-rate estimates - A review of Utah paleoseismic-trenching data by the Utah Quaternary Fault Parameters Working Group: Utah Geological Survey Bulletin 134, compact disk.

# SESSION 2

# PROPER MAGNITUDE-FREQUENCY DISTRIBUTIONS (GUTENBERG-RICHTER VERSUS CHARACTERISTIC EARTHQUAKE MODELS) FOR BASIN AND RANGE PROVINCE FAULTS

## Session Leaders

David Schwartz, U.S. Geological Survey, Menlo Park, California

Ivan Wong, URS Corporation, Oakland, California

## Presentations

*BRPEWG afternoon session, March 8, 2006*

| | |
|---|---|
| **Wong and Schwartz** | Introduction of issue and specific questions |
| **Schwartz** | Recurrence models and their physical and observational basis |
| **Wong** | Impact on hazard from choice of recurrence model |
| **Petersen** | Models and weights used in USGS National Seismic Hazard Maps |
| **Hecker** | Analysis of paleoseismic displacements and implications to recurrence models |
| **Olig** | Example of non-characteristic behavior in the Rio Grande Rift: Hubbell Spring fault, New Mexico |
| **Arabasz** | Analysis of Wasatch Front historical seismicity |
| **Wong** | Models and their weights considered in other PSHAs and rationale |

## Session Summary

Ivan Wong began the session by outlining outstanding issues and questions related to the proper magnitude-frequency (recurrence) distribution for Basin and Range Province (BRP) faults. David Schwartz then characterized the three magnitude-frequency distributions (characteristic, maximum magnitude, and truncated exponential [modified Gutenberg-Richter]) currently used to model the recurrence (size and frequency) of earthquakes on faults.

Ivan then discussed how the choice of a recurrence model can impact hazard. The highest probabilistic hazard results from use of the truncated exponential model because it allows for frequent moderate-sized earthquakes. The limited exponential portion of the recurrence in the characteristic model and the lack of an exponential portion in the maximum magnitude model results in lower to lowest hazard, respectively.

Mark Petersen presented the recurrence models used for the 2002 National Seismic Hazard Maps (NSHMs). The NSHMs employ a weighted combination of maximum magnitude (referred to as characteristic in Frankel and others, 2002), and "floating exponential" (referred to as truncated Gutenberg-Richter in Frankel and others, 2002) models weighted at 50/50 for all BRP faults except for the Wasatch fault, which is weighted at 80/20. A discussion ensued during which Mark Petersen described in greater detail the 2002 NSHM recurrence model: the maximum magnitude model is similar to that developed by Wesnousky (1986), but includes a distribution of possible magnitudes based on epistemic and aleatory uncertainties, whereas the floating exponential model essentially "floats" a M 6.5 to ~$M_{max}$ earthquake along the fault. Additional discussion focused on whether or not large faults in the BRP are a major source of moderate-size (M ≤ 6.5) earthquakes, and the effect on the NSHMs of modifying the current USGS magnitude-frequency models.

Suzanne Hecker reported on the work that she and Norm Abrahamson are doing to evaluate slip-at-a-point variability on active faults and the resulting implications for earthquake-size distributions. Results to date, which incorporate thresholds of detection for earthquake displacements, do not support a truncated exponential model for earthquake distributions on large faults. The variability in displacements from multiple events on a fault at a given location indicates a relatively narrow range suggesting the characteristic model best fits the paleoseismic data.

Conversely, the next presentation by Susan Olig on the Hubbell Springs fault in New Mexico reported on large variability in displacement among the four to five surface-faulting earthquakes on that fault since about 84 ± 6 ka. Her conclusion was that at least in the case of the Hubbell Springs fault, neither the characteristic nor maximum-magnitude earthquake models seem to apply. During the follow-up discussion, it was pointed out that the characteristic-earthquake model does not require that all earthquakes be of the same magnitude (there is a bell-shaped distribution around the mean characteristic magnitude), that a complex upward propagation of the rupture through thick unconsolidated sediments may help account for the variability, and that not all traces of the very complex Hubbell Springs fault were trenched, allowing for additional, as-yet unrecognized displacement during the apparent low-slip earthquakes.

Walter Arabasz discussed observed seismicity and recurrence modeling for the Wasatch fault (WF). He concluded that observed historical seismicity is consistent with a characteristic model, but that the association of sampled seismicity with the WF is uncertain (if the instrumental seismicity is not on the WF, then its behavior is even more likely to be characteristic). With regard to a magnitude-frequency model, a maximum-magnitude model is viable for the WF provided that smaller earthquakes are incorporated in a background seismic zone.

Ivan Wong discussed the rationale for the various recurrence models and their weights used in current state-of-the-practice probabilistic seismic hazard analyses (PSHAs) in the BRP such as that done for Yucca Mountain. In all these analyses, the characteristic model was heavily favored.

The discussion following the presentations was wide ranging and covered differences in the 2002 NSHM frequency-magnitude model compared to those used in most PSHAs, whether or not the WF is a suitable analogue for other BRP faults, and whether the current 50/50 application of maximum magnitude and floating exponential models used for BRP faults on the 2002 NSHMs is appropriate. Of particular concern was the 80/20 weighting for the WF in the 2002 NSHMs, which drives the hazard down (fewer moderate-size earthquakes) relative to other BRP faults weighted at 50/50. The BRPEWG discussed the possibility of using a single distribution (for example, the current California 67/33 model for unsegmented faults) for the entire BRP, and acknowledged that whatever magnitude-frequency model is adopted for the BRP, it must account for historical seismicity (i.e., a lack of small- and moderate-size earthquakes on most BRP faults) and be consistent with the paleoseismic record.

## Short-Term Recommendations for the 2007 NSHMs

The BRPEWG reached consensus on five recommendations regarding the magnitude-frequency relations used for the NSHMs:

1. The USGS "floating exponential" model should be validated to the extent possible, or at least made consistent with the paleoseismic and historical earthquake record in the BRP. The USGS model should also be compared with traditional magnitude-frequency models currently used in state-of-the-practice PSHAs.

2. The USGS should use the same recurrence model and weights for all BRP faults unless there is a technical basis for deviating from this characterization.

3. Weights assigned to the maximum magnitude and "floating exponential" models used for the 2007 NSHMs should, at a minimum, have the same weights as those used in California (2/3 - 1/3) unless there is a technical basis for deviating from this characterization.

4. To avoid double-counting earthquakes in the range of M 6.5 to the characteristic earthquake magnitude, zones surrounding BRP faults should be removed from the areas included in the Gaussian smoothing of background seismicity.

5. The methodology used for constructing the NSHMs must be fully transparent. The USGS is urged to publish, if only as a short note, how recurrence modeling is performed for the NSHMs, especially for fault-specific sources.

## References

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 update of the National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 02-420, 33 p.

Wesnousky, S.G., 1986, Earthquakes, Quaternary faults, and seismic hazard in California: Journal of Geophysical Research, v. 91, p. 12,587-12631.

# SESSION 3

# USE OF LENGTH VERSUS DISPLACEMENT RELATIONS TO ESTIMATE EARTHQUAKE MAGNITUDE

## Session Leaders

Glenn Biasi, University of Nevada Reno Seismological Laboratory, Reno, Nevada

Mark Hemphill-Haley, Department of Geology, Humboldt State University, Arcata, California

## Presentations

*BRPEWG morning session, March 9, 2006*

| | |
|---|---|
| **Hemphill-Haley** | Length and displacement inferences about magnitude |
| **Hemphill-Haley** | Using prehistoric coseismic surface displacements to estimate earthquake magnitude: Hemphill-Haley and Weldon (1999) |
| **Biasi and Hemphill-Haley** | Average displacement estimation in “Integrated hazard analysis of the Wasatch Front, Utah:” Chang and Smith (2002) |
| **Biasi** | Probabilities of magnitude and surface rupture length from a displacement observation: Biasi and Weldon (in press) |
| **Slemmons** | Linear regressions of magnitude and the Denali earthquake |
| **Biasi and Hemphill-Haley** | Wells and Coppersmith (1994) magnitude regressions |
| **Hemphill-Haley and Biasi** | Instrumental versus preinstrumental earthquake scaling relations: Stirling and others (2002) |
| **Biasi and Hemphill-Haley** | Bilinear source scaling: Hanks and Bakun (2002) |
| **Anderson** | Moment magnitude equations |

## Session Summary

Glenn Biasi and Mark Hemphill-Haley structured the magnitude-regression session around the estimation of seismic moment ($M_O$), where $M_O$ = shear modulus *average displacement* rupture length *down-dip rupture width. The session leaders posed two questions regarding updating the National Seismic Hazard Maps (NSHMs) for the Basin and Range Province (BRP):

1. What primary data are needed to improve estimates of average displacement and length?

2. What data are needed to reliably infer magnitude from displacement and/or length?

### Estimating Fault Displacement, Surface Rupture Length, and Width

Mark Hemphill-Haley started the session by outlining the advantages and disadvantages of using surface rupture length (SRL) and displacement to estimate earthquake magnitude, citing both historic and prehistoric examples of anomalous displacement and SRL measurements (e.g., the 1959 M 7.5 Hebgen Lake earthquake, which had a short SRL but large displacement and magnitude). Mark and Glenn Biasi then summarized methods developed by Hemphill-Haley and Weldon (1999), Chang and Smith (2002), and Biasi and Weldon (in press) to estimate average displacement and paleoearthquake magnitude given observed point displacements. The Hemphill-Haley and Weldon (1999) work shows how average displacement estimates improve when multiple measurements are made of a rupture, and using the Landers example, how even a single displacement measurement can improve the magnitude estimate. The Chang and Smith (2002) method develops an average displacement estimate by assuming segment bounds and an elliptical rupture shape, then using paleoseismic displacements to adjust the height of the rupture. For short segments their method tends to predict large average and maximum displacements. For multi-segment ruptures, average rupture displacements can be smaller than for the individual contributing segments, but the lower displacement estimates brought paleomagnitude estimates more in line with expectations. The Biasi and Weldon (in press) method uses individual displacement measurements to develop a probability distribution for magnitude and length. Burt Slemmons presented information from the Alaska pipeline, which accommodated 4.9 meters of right-lateral displacement on the Denali fault during the 2002 M 7.9 Denali earthquake. The Denali fault rupture is a good analog for strike-slip surface faulting in the Walker Lane fault zone in the western BRP.

Working Group members discussed issues related to displacement measurements, including (1) differences in average, maximum, and modal displacement values, (2) estimating displacement uncertainties (related to the number of measurements and difficulties in obtaining accurate measurements), and (3) measurement (and geologic) biases due to paleoseismic site selection, scarp preservation, and the difficulty in recognizing single- versus multiple-event displacements. Discussions regarding SRL estimates focused on (1) the importance of including length uncertainties, (2) the effect of segmentation, multi-segment rupture (e.g., 1915 M 7.3 Pleasant Valley), multi-fault rupture (e.g., 1992 M 7.4 Landers), and spatial clustering (e.g., Central Nevada seismic belt) on SRL estimates, and (3) measurement biases due to fault-scarp preservation. Working Group members also discussed estimates of fault width (as a function of fault geometry and dip angle) and considered potential scaling relations between width, displacement, and length for BRP faults. The BRPEWG considered potential variations in shear modulus, but agreed that a lack of data precluded defining regional shear-modulus boundaries, and that incorporating estimated uncertainties (e.g., ±10%) into the NSHMs was not appropriate due to the resulting insignificant changes in hazard. A better understanding of the values and uncertainties in shear modulus in the BRP is needed.

### Magnitude Regressions

Glenn and Mark organized a review and discussion of early magnitude-SRL regressions (e.g., Slemmons, 1977; Bonilla and others, 1984), and recent SRL, displacement, width, and area regressions in Wells and Coppersmith (1994). Wells and Coppersmith regressions show that SRL tends to systematically underestimate the subsurface rupture length. They then presented and discussed the results of Hanks and Bakun (2002), who included improved (bilinear) regressions for large-magnitude (M >7) strike-slip earthquakes, and Stirling and others (2002), who relied on a censored instrumental dataset (i.e., removing earthquakes with SRL <10 km, area <200 $km^2$, average displacement <2 m, and moment magnitude [$M_W$] <6.5) to form SRL and area regressions that fit preinstrumental large earthquakes. John Anderson presented three equations for determining moment magnitude from seismic moment, static stress drop, and a constant defined by fault type, and discussed the application of each equation to short versus long SRL faults.

Mark Petersen stated that the NSHMs cap the magnitude of BRP earthquakes at 7.5. Craig dePolo noted that the longest historical surface ruptures (of about 100 km) in the BRP occurred during the 1872 M 7.4 Owens Valley and 1887 M 7.4 Pitaychachi earthquakes. Working Group members discussed the current practice of using a single SRL regression (from Wells and Coppersmith, 1994) to determine earthquake magnitudes for the 2002 NSHMs, which likely underestimates the hazard (as suggested by short faults having large displacements). Working Group members agreed that displacement information should be used with SRL to estimate magnitude for faults having anomalously short ruptures and large displacements. Working Group members also discussed the use of a minimum magnitude estimate (e.g., M ~6.5) for faults having surface rupture, a short SRL, but poor displacement-per-event information. Discussions also considered (1) using additional fault-parameter regressions (e.g., based on displacement*SRL, width, or area), (2) the possibility of developing multivariate regressions using SRL and displacement, and (3) the method of predicting SRL given observed displacement (Biasi and Weldon, in press). The BRPEWG considered the suitability of global, all-fault-type magnitude regressions for BRP faults and the prospect of developing BRP-specific regressions (after Dowrick and Rhoades, 2004), but most agreed that limited historical surface faulting in the BRP precluded developing region-specific regressions.

## Recommendations

The BRPEWG reached consensus on the following recommendations regarding the magnitude-frequency relations used for the NSHMs:

### Short-Term Recommendations for the 2007 NSHMs

#### Estimating Displacement and Length:

1. Include uncertainty in SRL and its consequences for magnitude.

2. Constrain the minimum magnitude assigned to surface-faulting earthquakes to M 6.5 to be consistent with the hazard set by background seismicity.

3. Use magnitude-displacement regressions to improve magnitude estimates where the magnitude from SRL appears inconsistent.

4. Have a working group look at the faults for which displacement data are available (thought to be ~20 in Nevada), and suggest a weighting between displacement and SRL estimates of magnitude to achieve a combined fault magnitude estimate.

## Long-Term Recommendations

### Regressions:

1. Revisit the Wells and Coppersmith (1994) regressions to update the database and evaluate the need to censor short rupture lengths and small magnitudes.

2. Develop a $M_W$ versus SRL*displacement scaling as a tool for improving use of displacement in making magnitude estimates.

3. Develop a multivariate regression for magnitude, given SRL and displacement, to improve magnitude estimates on faults for which both are available.

4. Invest in determining whether regional regressions materially improve ground motion predictions; for long strike-slip faults (western BRP) consider using the Hanks and Bakun (2002) $M_W$ versus area regression relation.

5. For short faults, consider whether Wells and Coppersmith (1994) is appropriate considering the results of Stirling and others (2002).

6. Evaluate whether an estimate of magnitude based on area (with an assumed width) is more appropriate than a magnitude based on SRL.

### Displacement:

1. There should be a concerted effort to assess:

a. the variability of displacement along rupture strike for historical surface ruptures for the entire range of magnitude (e.g., a follow-up to McCalpin and Slemmons, 1998), and

b. whether surface-faulting data for the BRP support regional (BRP-specific) regressions.

## References

Biasi, G.P., and Weldon, R.J., in press, Estimating surface rupture length and magnitude of paleoearthquakes from point measurements of rupture displacement: Bulletin of the Seismological Society of America.

Bonilla, M.G., Mark, R.K., and Lienkaemper, J.J., 1984, Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement: Bulletin of the Seismological Society of America, v. 74, p. 2379-2411.

Chang, W.L., and Smith, R.B., 2002, Integrated seismic–hazard analysis of the Wasatch Front, Utah: Bulletin of the Seismological Society of America, v. 92, no. 5, p. 1904-1922.

Dowrick, D.J., and Rhoades, D.A., 2004, Relations between earthquake magnitude and fault rupture dimensions; how regionally variable are they?: Bulletin of the Seismological Society of America, v. 94, no. 3, p. 776-788.

Hanks, T.C., and Bakun, W.H., 2002, A bilinear source-scaling model for M-log A observations of continental earthquakes: Bulletin of the Seismological Society of America, v. 92, no. 5, p. 1841-1846.

Hemphill-Haley, M.A., and Weldon, R.J., 1999, Estimating prehistoric earthquake magnitude from point measurements of surface rupture: Bulletin of the Seismological Society of America, v. 89, no. 5, p. 1264-1279.

McCalpin, J.P., and Slemmons, D.B., 1998, Statistics of paleoseismic data: Final Technical Report prepared for the U.S. Geological Survey, contract 1434-HQ-96-GR-02752, National Earthquake Hazards Reduction Program, 62 p.

Slemmons, D.B., 1977, Faults and earthquake magnitude: U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, Miscellaneous Paper S-73-1, Report 6, 129 p.

Stirling, M., Rhoades, D., and Berryman, K., 2002, Comparison of earthquake scaling relations derived from data of the instrumental and preinstrumental era: Bulletin of the Seismological Society of America, v. 92, no. 2, p. 812-830.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974-1002.

# SESSION 4

# PROBABILITIES AND MAGNITUDES OF MULTI-SEGMENT RUPTURES

## Session Leaders

Craig dePolo, Nevada Bureau of Mines and Geology, Reno, Nevada

James Pechmann, University of Utah Seismograph Stations, Salt Lake City, Utah

## Presentations

*BRPEWG afternoon session, March 9, 2006*

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|---|---|
| **Pechmann** | Probabilities and magnitudes of multi-segment ruptures: specific questions |
| **Haller** | Fault segmentation models in probabilistic seismic hazard analyses and an example for the Wasatch fault |
| **dePolo** | The fault segmentation model and maximum earthquake magnitudes for the Basin and Range Province |
| **DuRoss** | Addressing the potential for multi-segment ruptures on the Wasatch fault |
| **Pechmann** | Use of multi-segment rupture models in the National Seismic Hazard Maps: options and effects |

## Session Summary

Jim Pechmann began the session by pointing out that the 2002 National Seismic Hazard Maps (NSHMs) use multi-segment rupture (MSR) models for the San Andreas and Hayward faults in California. He then posed three fundamental questions regarding the use of MSR models for Basin and Range Province (BRP) faults:

1. Should the NSHMs use MSR models for BRP faults?

2. If so, what general types of models should be used, and how should they be weighted relative to single-segment rupture (SSR) models?

3. Should rupture "spill-over" and triggered earthquakes be considered in the models as well?

Kathy Haller stated that characteristic earthquake magnitudes for faults on the NSHMs are determined from surface rupture length only. She presented examples of three comparatively well-studied BRP faults (Lost River, Hebgen Lake, and Pleasant Valley) where the use of magnitudes from segmentation (fault length) models, plus slip rates, to calculate the average rate of surface-faulting earthquakes results in a significant over-estimation of the expected number of such earthquakes compared to the paleoseismic record. Kathy noted that the two fault strands that ruptured together during the 1959 Hebgen Lake earthquake are modeled separately on the 2002 NSHMs. She then discussed the Ruby Mountain fault, which is one of only three segmented BRP faults on the NSHMs (the others being the Wasatch fault [WF] and the Hurricane fault). Earthquake occurrence for individual segments of the Ruby Mountains fault is in general agreement with the observed paleoseismic record. Finally, Kathy discussed the WF. For the segments of the WF, the NSHMs use average rates of surface-faulting earthquakes, which are estimated directly from paleoearthquake timing instead of from slip rates. Kathy pointed out that the treatment of characteristic magnitude uncertainty in the NSHMs effectively gives some weight to MSRs along the WF because the assumed epistemic uncertainty of ±0.2 M produces rupture lengths which are up to 15-20 kilometers longer than the single-segment rupture (SSR) lengths. Application of a simple two-segment rupture model to the WF showed that the differences in the 2% in 50 years peak ground accelerations calculated using this model and the NSHM SSR model are small (between -4% and +7% g). Lessons learned from Kathy's presentation include:

- The need to carefully evaluate both the quality and quantity of data supporting segmentation prior to constructing a segmentation model for a fault.

- The need to define a minimum data standard (type, quantity, and quality) for fault segmentation in the BRP.
- The need to be aware of possible outcomes when choosing a segmentation model.

Craig dePolo then discussed the history and present practice of defining fault segments on long faults. He defined earthquake segmentation as "using physical features of a fault, including historical and paleoseismic data, to define potential earthquake segments for approximating future earthquake ruptures." The basis for earthquake segmentation includes (1) historical surface ruptures, (2) paleoseismic information (trenching data), and (3) tectonic geomorphology (chiefly young fault scarps). However, Craig noted that earthquake segmentation theory only predicted about half of the end points of historical BRP surface-faulting ruptures. Regarding a threshold for MSRs, Craig believes that overall fault lengths must exceed 15-20 kilometers. Craig concluded by saying that the division of long faults into earthquake segments makes physical sense and likely does model future earthquakes; however, echoing Kathy, he stated that the process of determining defensible segmentation models and likelihoods is difficult, especially where good paleoearthquake data are lacking.

Chris DuRoss presented the results of his recent work on evaluating the potential for MSRs on the WF. To examine that possibility, Chris updated and revised the WF paleoearthquake space-time diagram, evaluated paleoseismic data quality/confidence, and generated a variety of MSR models for the fault. His work is ongoing, but preliminary results for the central four (Brigham City to Provo) segments indicate that six to eight two-segment ruptures, combined from 16 single-segment paleoearthquakes in the past 6000 years, are possible. Chris displayed a displacement versus rupture-length diagram for the WF, which shows that 47% of individual paleoearthquake displacements for the WF segments are larger than the maximum displacements predicted by the segment lengths (using Wells and Coppersmith [1994] all-fault regression), thus again indicating that MSRs are a possibility on the WF.

Jim Pechmann concluded the session presentations by reviewing the five principal types of MSR models presently in use, and the effects of MSR models on seismic-hazard analyses. The MSR models include an unsegmented model (e.g., Youngs and others, 2000; Wong and others, 2002), weighted sets of MSR scenarios based on expert judgment (e.g., Frankel and others, 2002), weighted sets of MSR scenarios based on "stringing" ruptures together probabilistically using paleoearthquake timing and displacements (Biasi and Weldon, under development), and two versions of cascade models (e.g., WGCEP, 1995; Andrews and Schwerer, 2000; Field and others, 1999). Jim concluded that "overall, MSR models give lower probabilistic seismic hazard than SSR models if the models are moment balanced," (i.e., the slip rate is the same for both). The hazard is lower because MSRs produce larger earthquakes, which result in longer recurrence intervals, which translate into fewer earthquakes over a given time period, and consequently, lower seismic hazard. Jim also commented on Kathy Haller's two-segment rupture model for the WF, which was not moment balanced, but showed only a small change in hazard compared to a SSR model. Jim finished by stating that while MSRs may have only a small effect on overall hazard, MSR scenarios, where credible, are important for emergency planning purposes due to the potential for longer period and duration ground shaking and greater geographical extent of damage (along two segments rather than one).

Discussion following the presentations considered whether or not long faults on the NSHMs should be segmented (the BRPEWG consensus was yes), and whether or not current information for most BRP faults is sufficient to allow them to be segmented (the consensus was generally no). Working Group members agreed that acquiring the new data necessary to permit fault segmentation would be a long-term undertaking. A suggestion was made to focus data-gathering activities on urban faults where the risk is the greatest. An objection to this suggestion was raised on the grounds that most opportunities to study urban faults have been lost to development, while more remote faults are still largely available for study and may teach us important lessons. Discussion then moved on to whether or not a MSR model should be applied to BRP faults once they are segmented, and if so what kind of model it should be. Working Group members agreed that the method of probabilistically using earthquake timing and displacement to create MSR scenarios should be applied to the WF. They also agreed that cascade models are not appropriate for the BRP because these models assume that MSRs occur on two or more complete segments, but even two-segment ruptures along the WF were considered unlikely. The BRPEWG concluded that it is important to consider the possibility of MSRs on presently segmented BRP faults when doing the NSHM hazard calculations. Given our present understanding of fault segmentation in the BRP, it was decided that the best way to account for MSRs is by using an unsegmented model with a maximum rupture length greater than the average segment length.

## Recommendations

The Working Group reached consensus on six recommendations regarding SSR versus MSR models for BRP faults. Three are short-term recommendations and should be included in the 2007 NSHMs update. One recommendation is both short- and long-term, and the final two recommendations are long-term and are intended to guide future research.

### Short-Term Recommendations for the 2007 NSHMs

1. Hazard calculations for the NSHMs should consider the possibility of MSRs on BRP faults.

2. For BRP faults for which SSR models are being used to compute the hazard, the 2007 NSHMs should also use an unsegmented rupture model which accounts for the possibility of ruptures extending beyond segment boundaries. The unsegmented model should be given a relatively low weight.

3. The two faults that ruptured together in the 1959 Hebgen Lake earthquake should be treated as a single seismic source for the purpose of the 2007 NSHM hazard calculations.

### Short-Term/Long-Term Recommendation

1. Where available, displacement data should be used to provide a consistency check for segmentation models – especially to identify segments on which ruptures longer than the mapped length could occur.

### Long-Term Recommendations

1. Newly developed methods for probabilistically constructing rupture scenarios from paleoearthquake timing and displacements should be applied to the WF.

2. Research needs to be conducted on the following topics to facilitate segmentation modeling in the BRP:
   a. how to recognize and characterize fault-rupture segments,
   b. the quality and quantity of paleoseismic data needed to support segmented earthquake models along BRP faults, and
   c. construction of earthquake-segmentation models for important BRP faults.

## References

Andrews, D.J., and Schwerer, E., 2000, Probability of rupture of multiple fault segments: Bulletin of the Seismological Society of America, v. 90, no. 6, p. 1498-1506.

Field, E.H., Jackson, D.D., and Dolan, J.F., 1999, A mutually consistent seismic-hazard source model for southern California: Bulletin of the Seismological Society of America, v. 89, no. 3, p. 559-578.

Frankel, A.D., Petersen, M.D., Mueller, C.S., Haller, K.M., Wheeler, R.L., Leyendecker, E.V., Wesson, R.L., Harmsen, S.C., Cramer, C.H., Perkins, D.M., and Rukstales, K.S., 2002, Documentation for the 2002 update of the National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 02-420, 33 p.

Wells, D.L., and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, no. 4, p. 974–1002.

Wong, I., Silva, W., Olig, S., Thomas, P., Wright, D., Ashland, F., Gregor, N., Pechmann, J., Dober, M., Christenson, G., and Gerth, R., 2002, Earthquake scenario and probabilistic ground shaking maps for the Salt Lake City, Utah, metropolitan area: Utah Geological Survey Miscellaneous Publication 02-5, 50 p.

Working Group on California Earthquake Probabilities (WGCEP), 1995, Seismic hazards in southern California - probable earthquakes, 1994-2024: Bulletin of the Seismological Society of America, v. 85, p. 379-439.

Youngs, R.R., Swan, F.H., Power, M.S., Schwartz, D.P., and Green, R.K., 2000, Probabilistic analysis of earthquake ground shaking hazard along the Wasatch Front, Utah, *in* Gori, P. L., and Hays, W. W., editors, Assessment of regional earthquake hazards and risk along the Wasatch Front, Utah: U.S. Geological Survey Professional Paper 1500 K-R, p. M1-M67.

# SESSION 5

# RESOLVING DISCREPANCIES BETWEEN GEODETIC EXTENSION RATES AND GEOLOGIC SLIP RATES

## Session Leaders

Robert Smith, University of Utah, Salt Lake City, Utah

Wayne Thatcher, U.S. Geological Survey, Menlo Park, California

## Presentations

*BRPEWG morning session, March 10, 2006*

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|---|---|
| **Thatcher** | Introduction and objectives |
| **Crone** | Geological perspective on contemporary deformation in the Basin and Range Province |
| **Hammond** | Kinematic overview of active Basin and Range deformation measured with GPS |
| **Smith and Chang** | Integrated earthquake hazard assessment, eastern Basin and Range |
| **Thatcher** | Summary and discussion |

## Session Summary

Wayne Thatcher began the session by summarizing the issues related to integrating geodetic extension rates and geologic slip rates in models of seismic hazard. The geodetic data indicate a total strain budget of 12-14 mm/yr across the Basin and Range Province (BRP), of which modern seismicity and paleoseismically determined fault slip rates are individual components. Tony Crone then summarized the spatial and temporal patterns of Quaternary faulting across the BRP using the geologically determined earthquake-timing and slip-rate data compiled in the Quaternary Fault and Fold Database of the United States, and highlighted the limitations of geologic data (both from a regional perspective and from site-specific trench studies) in determining the timing of surface-faulting earthquakes. Tony also noted that historical earthquake activity in the Central Nevada seismic belt (CNSB) (six surface-faulting earthquakes since 1915) is anomalous in the BRP paleoseismic record, and raised the question as to whether the locations and rates of GPS-determined deformation might fluctuate greatly over time spans that are relevant to seismic-hazard assessment.

The next two presentations dealt with geodetic constraints on horizontal strain. Bill Hammond discussed province-wide data and issues, and Robert Smith and WuLung Chang focused on the eastern margin of the BRP, in particular the Yellowstone-Snake River Plain and Wasatch Front regions. Bill illustrated the spatial variability of GPS-measured extension across the BRP (with respect to stable North America), ranging from ~3 mm/yr across western Utah and central Nevada to ~10 mm/yr across western Nevada and eastern California. He noted the concentration of contemporary deformation at the province margins, the large component of dextral shear at the western margin, and the anomalously high GPS-measured rates of dilatation across the CNSB, where the geodetic moment rate is nearly six times higher than the moment rate inferred from paleoseismic studies. According to Bill, recent modeling by several groups strongly suggests that the geodetic velocities across the CNSB are temporarily enhanced by post-seismic relaxation following the historical surface-faulting earthquakes. Bob Smith discussed data from campaign and continuous GPS networks in the Yellowstone-Snake River Plain region, models of post-rupture stress contagion on adjacent segments of the Wasatch fault (WF), and use of GPS-measured interseismic loading rates as proxies for geologically determined fault slip rates. As part of this discussion, WuLung presented models he has been developing, using data from the WF, for strain loading, converting geologic (vertical) displacement to geodetic (horizontal) extension, multi-segment ruptures, and integrated probabilistic seismic-hazard assessment.

Prior to ending the session with open discussion of the issues, Mark Petersen summarized how geodetic data were used in the 1996 and 2002 NSHMs. Mark said that GPS-measured relative velocities were applied in zones in the high-strain-rate region of western Nevada and eastern California. In each zone, 50% of the geodetic rate is accounted for by coseismic strain release, and deformation is distributed uniformly across the zone rather than partitioned on individual faults. The BRPEWG recommended that, in the future, the rates in these zones need to be increased (e.g., by increasing the percentage of coseismic strain release), and the eastern limit of the zones needs to extend farther east to include the Walker Lane fault zone. Mark also indicated that geodetic data could be used in other areas where there is little geologic slip-rate data. Finally, John Anderson reiterated that models of strain rate need to faithfully account for seismic moment, and that for the BRP as a whole, the geologic moment rate is less than the seismicity- and geodesy-based rates by a factor of 2 to 3.

The closing discussion revisited the issues raised during the presentations that are important in incorporating geodetic data in the NSHMs. Key issues include the following:

- Uncertainty in fault dip; the dip of normal faults is critical in relating vertical slip rates and horizontal extension rates.
- Model-dependency of slip rates (e.g., corrections for post-seismic relaxation effects).
- Coseismic versus aseismic strain release; although evidence is generally lacking for aseismic creep, its existence cannot be completely dismissed. However, should the 50% weight presently given to aseismic strain release be lowered to 20%, or even 10%?
- Geodetic moment rate applied such that the rate of faults is not double-counted.
- How best to assign the geodetic slip-rate "residual" (i.e., the rate remaining after historical seismicity and paleoseismic data are accounted for): to known faults individually, or as a smoothed rate across a broad area?
- Areas having a large component of strike-slip faulting where accurate measurement of fault slip is difficult.
- The relatively short geodetic record; is it representative of the total long-term moment rate?
- Strain-rate gradients need to be preserved at the higher strain-rate eastern and western margins of the BRP.

## Recommendations

The BRPEWG reached consensus on a number of both short-term and long-term recommendations related to geodetic extension rates/geologic slip rates in the BRP. In general, the BRPEWG believes that the geodetic and geologic data need to be combined into a single integrated model, rather than used separately, for effective incorporation in the NSHMs.

### Short-Term Recommendations for the 2007 NSHMs

1. Convert vertical slip rates to extensional rates for consistency with GPS data. This involves resolving the question of dip of normal faults. The NSHMs currently use a dip of 60°; the Working Group recommends using a dip of 50°±10°.

2. For the BRP, use the province-wide kinematic (GPS) boundary condition (12-14 mm/yr) as a constraint on the sum of geologic slip rates. Enhance the fault catalog used in the NSHMs as necessary to achieve the far-field rates.

3. Modify the boundaries of the geodetic zones in the western Great Basin used in the 1996 NSHMs to better reflect the areas of high strain depicted on the GPS-based strain-rate map.

4. Use the geodetic data as the total strain budget. Ideally, the moment rates from the faults, areal source zones, and GPS zones should add up to the full geodetic budget. This total should be comparable to the seismicity, which is a separate estimate of moment rate. Differences that exist between these individual moment sources should be fully accounted for in the 2007 NSHMs.

5. The USGS should test models to evaluate the effect of releasing geodetic strain as 80% coseismic and 20% aseismic.

6. The USGS should evaluate the impact on the NSHMs of partitioning geodetic strain on individual faults within a zone (assigning default slip rates) versus distributing the geodetic strain uniformly across the zone.

### Long-Term Recommendations

1. Move toward assigning minimum slip rates to specific faults. To this end, develop a strategy of how to assign slip rates based on combined geodetic and geologic criteria; this could be a charge for a future working group.

2. Develop a consistent-resolution fault map for the western margin of the Great Basin as a first step toward an integrated geodetic/geologic model.

3. Develop robust, geologically based (paleoseismic) slip rates in the source zones where geodesy shows significant strain accumulation, giving priority to urban and rapidly urbanizing areas.

4. The geoscience community should work toward the goal of determining if geodesy can identify specific faults where strain is being localized (i.e., indicator of higher hazard).

5. Where adequate data exist, develop an integrated model that incorporates geodetic, seismicity, and fault data.

6. The USGS should fully explain in an easily accessible publication or Web page the methodology behind the NSHMs, including the properties of each version of the maps so that changes in the maps over time can be completely understood.