Session No. 3

Course Title: Earthquake Hazard and Emergency Management

Session 3: Distribution of Earthquakes

Author: James R. Martin, II

Time: 90 minutes

Objectives:

3.1 Identify the three primary "belts" where most earthquakes occur worldwide.

3.2 Identify regions of the United States where earthquakes tend to occur and explain the primary fault systems/mechanisms for earthquakes in each region.

3.3 Recognize the national seismic hazard maps, identify where they can be obtained, and explain what information is presented on these maps.

Scope:

During this session, the instructor will present the major plate boundary systems, and discuss the locations of earthquakes worldwide. The instructor will then focus on specific regions of the U.S. where earthquakes are prone to occur. The instructor should present and discuss the national seismic hazard maps and tie in the fact that the hazard maps reflect in scientific terms the information presented in the first part of the lecture. The instructor should explain the maps in general terms and discuss how they were developed, but the technical details of how the maps were developed and how the various maps are specifically used in engineering design is beyond the scope of this class.

A suggested student exercise involves an in-class discussion (about 10 -15 minutes) on the concepts of probability and risk and the U.S. seismic hazard maps. This information is important to cover in this class because the basis of seismic hazard assessment in the U.S., including all building codes, is based on the government's probabilistic seismic hazard assessments displayed on these maps. The class discussion should be conducted at the end of the session. Also, a homework assignment for this session is included in the attached handouts for this session and should be handed out at the end of this session. Electronic visual images of the figures presented in these notes, plus other useful visual aids, are included in the accompanying file: Session 3 Electronic Visuals.ppt.

Reading:

Required student reading:

Highlighted links related to earthquake processes shown at http://earthquake.usgs.gov/bytopic/plates.html, especially “When the Earth Moves: Seafloor Spreading & Plate Tectonics” and “Where Do Earthquakes Happen?”

Required instructor reading and resources:

Highlighted links related to earthquake processes shown at” http://earthquake.usgs.gov/bytopic/plates.html, especially “When the Earth Moves: Seafloor Spreading & Plate Tectonics” and “Where Do Earthquakes Happen?”

Yeats, R. S., Sieh, K., and C. R. Allen. 1997. *The Geology of Earthquakes*, Oxford University Press, ISBN 0-19-507827-6,Chapters. 1-4.

Bolt, Bruce.1993. *Earthquakes*. W.H. Freeman Company, ISBN 0-7167-2236-4 Chapter. 2, “Where Earthquakes Occur,” pp. 25-40.

1. Visual aids provided in the accompanying file: “Session 3- Electronic Visuals.ppt”

2. Other useful Internet web pages: http://earthquake.usgs.gov/bytopic/

Electronic visuals included: *[see Session 3 Electronic Visuals.ppt]*

3.1 World’s three major belts
3.2 Locations of earthquakes
3.3 Seismicity in southern California
3.4 Major fault system in northern California
3.5 Cascadia Subduction Zone
3.6 Wasatch Fault
3.7 Seismic zone in Central US
3.8 Reelfoot Rift
3.9 Charlevoix Seismic Zone in northeastern North America
3.10 Epicenters of earthquakes in the southeastern US
3.11 Generalized USGS seismic hazard maps
3.12 Detailed USGS seismic hazard map for US
3.13 Detailed USGS seismic hazard map for California and Nevada

Note that many of the graphics used for this material were obtained from the United States Geological Survey (USGS) and are in the public domain and not subject to copyright. Appropriate credit is given for USGS-produced graphics. For information on their use policy see: http://sfbay.wr.usgs.gov/access/copyright.html.

Handouts included:

3.1 Handout 3.1: Class Discussion Assignment (handout is for instructor only)
3.2 Handout 3.2: Homework Assignment 3.1

General Requirements:

The information presented in this section is technical in nature, and additional background study will be required by instructors with non-scientific backgrounds. Accordingly, the instructor should thoroughly review the recommended reading material for this session. In some cases, the instructor may wish to enlist the aid of an outside expert, such as faculty from a geological sciences or engineering department, to teach this material,. While some instructors may alternatively elect to reduce the technical content presented, the concepts are important for a complete understanding of earthquakes and the nature of the hazard they pose. Therefore,the instructor should cover as much of this material as feasible, and make adaptations where appropriate as the makeup of the class and availability of outside resources dictate.

Points to be emphasized strongly are: the fact that earthquakes are due to geological processes that can be understood and thus their locations predicted in most cases (plate boundaries); earthquakes occur in many areas throughout the world where urban centers are located (and growing); earthquakes occur in many areas in the U.S., including areas outside of the western US; in fact, most regions of the country are susceptible to damaging earthquakes.

Additional requirements:

Computer and projector for electronic visuals.

Objective 3.1 Identify the three primary "belts" where most earthquakes occur worldwide

Requirements:

The content should be presented as lecture, supplemented with electronic visuals. The instructor is cued as to when the graphics from the electronic visual files should be presented.

Electronic Visuals Included:

Electronic Visual 3.1 World's three major belts

Remarks:

I. Dr. Richter noted in his famous book published in 1958: "It is probable that no large area of the world is permanently unaffected by earthquakes."

A. The USGS typically reports about 2,000 earthquakes per month, for an average of about 70 earthquakes per day. There actually are many more quakes than this, but we are limited in our ability to detect small earthquakes that occur far away from seismic observing stations. (See http://earthquake.usgs.gov/recenteqs/)

B. Earthquakes can strike any location at any time, but history shows they occur in the same general patterns year after year, principally in three large zones of the earth. **See Visual below.**

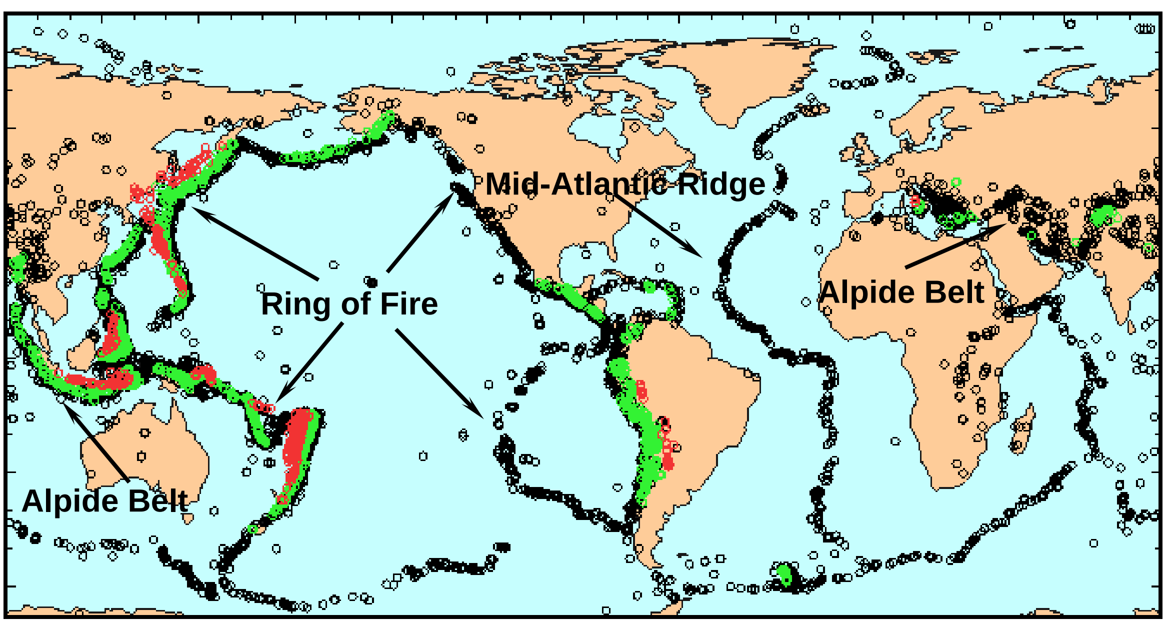
C. The basic idea that earthquakes tend to occur in narrow zones or "belts" around the world was first established in the 1940s and 1950s. This led to the development of plate boundary theory discussed earlier.

II. The world's three major seismic belts [*Electronic Visual 3.1*]

A. The world's greatest earthquake belt, the circum-Pacific seismic belt (also called "The Ring of Fire"), is found along the rim of the Pacific Ocean, where about 81 percent of the world's largest earthquakes occur.

B. The second important belt, the Alpide, extends from Java to Sumatra through the Himalayas, the Mediterranean, and out into the Atlantic. This belt accounts for about 17 percent of the world's largest earthquakes.

C. The third prominent belt follows the submerged mid-Atlantic Ridge. The remaining shocks are scattered in various areas of the world.



Visual 3.1: Map showing world's three major "belts" (major plate boundaries) where the majority of the world's earthquakes occur. Credit: USGS.

Objective 3.2 Identify regions of the United States where earthquakes tend to occur and explain the primary fault systems/mechanisms for earthquakes in each region.

Requirements:

The content should be presented as lecture, supplemented with electronic visuals. The instructor is cued as to when the graphics from the electronic visual files should be presented.

Electronic Visuals Included:

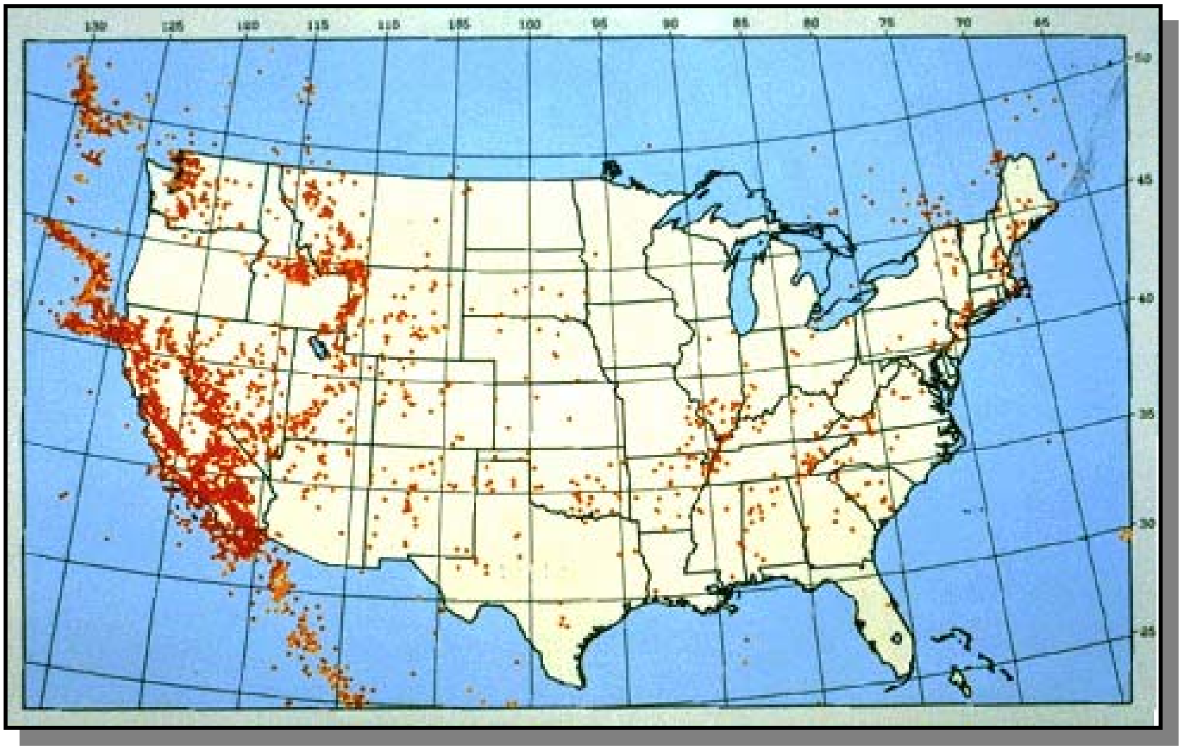
Electronic Visual 3.2	Seismicity in North America
Electronic Visual 3.3	Seismicity in southern California
Electronic Visual 3.4	Northern California seismicity
Electronic Visual 3.5	Cascadia Subduction Zone
Electronic Visual 3.6	Idaho, Utah, Wyoming (Wasatch Fault)
Electronic Visual 3.7	Seismic zones in Central US
Electronic Visual 3.8	Reelfoot Rift
Electronic Visual 3.9	Charlevoix Seismic Zone
Electronic Visual 3.10	Southeastern U.S. seismicity

Remarks:

I. Most seismicity in the continental U.S .is associated with western states, as shown in Visual 3.2. [*Electronic Visual 3.2*]

A. Two major western U.S. plate boundaries include the San Andreas Fault in California and the Cascadia Subduction Zone off the coast of Oregon and Washington

B. It is important to note that although most earthquakes occur in the western region, earthquakes are found in most other regions of the U.S., including many areas located within the stable portion of the continent far away from plate boundaries.



Visual 3.2: Map showing locations of earthquakes (red dots) seismic activity in the United States. Credit: USGS.

II. Pacific Coast Region -- California, Nevada, Oregon, Washington

A. Southern California [*Electronic Visual 3.3]*

1. This is one of most active seismic regions in the U.S.; Alaska probably only U.S. area as seismically active.

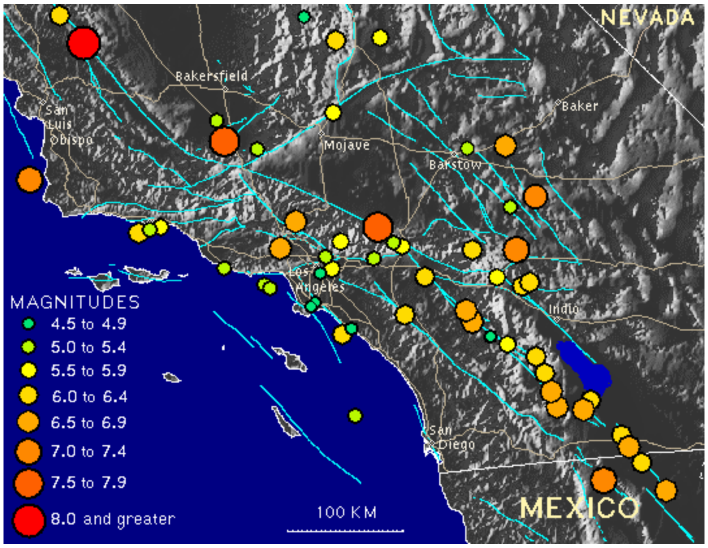
2. Most recent damaging earthquake was 1994 Northridge earthquake near Los Angeles.

3. Source of seismicity generally associated with North American & Pacific plate boundary (San Andreas system).

4. Recent probability studies predict that somewhere in southern California should experience a magnitude 7.0 or greater earthquake about seven times each century (USGS). About half of these will be on the San Andreas "system" (the San Andreas, San Jacinto, Imperial, and Elsinore Faults) and half will be on other faults. The equivalent probability in the next 30 years is about 85%.

5. USGS studies suggest that six major fault systems are responsible for most of the seismicity in the metropolitan Los Angeles area. The studies also suggest that the majority of seismic strain in Los Angeles region is released in large, M = 7.2 to 7.6 earthquakes that occur, on average, every 140 years. Last earthquake of this size in metropolitan Los Angeles area was more than 200 years ago. Smaller, damaging earthquakes (i.e., 1994 Northridge) occur in the region much more frequently.

6. Parkfield, CA has experienced a significant earthquake (M_L= 5.5 to 6 range) about every 22 years for the last 132+ years (1857, 1881, 1901, 1922, 1934 and 1966). The last earthquake occurred in 1966, and was "due" in 1988-- earthquake is currently "overdue" according to characteristic behavior. The area was very heavily instrumented in the early 1980s in anticipation of the next earthquake. It is expensive to keep a continuous monitoring program going.



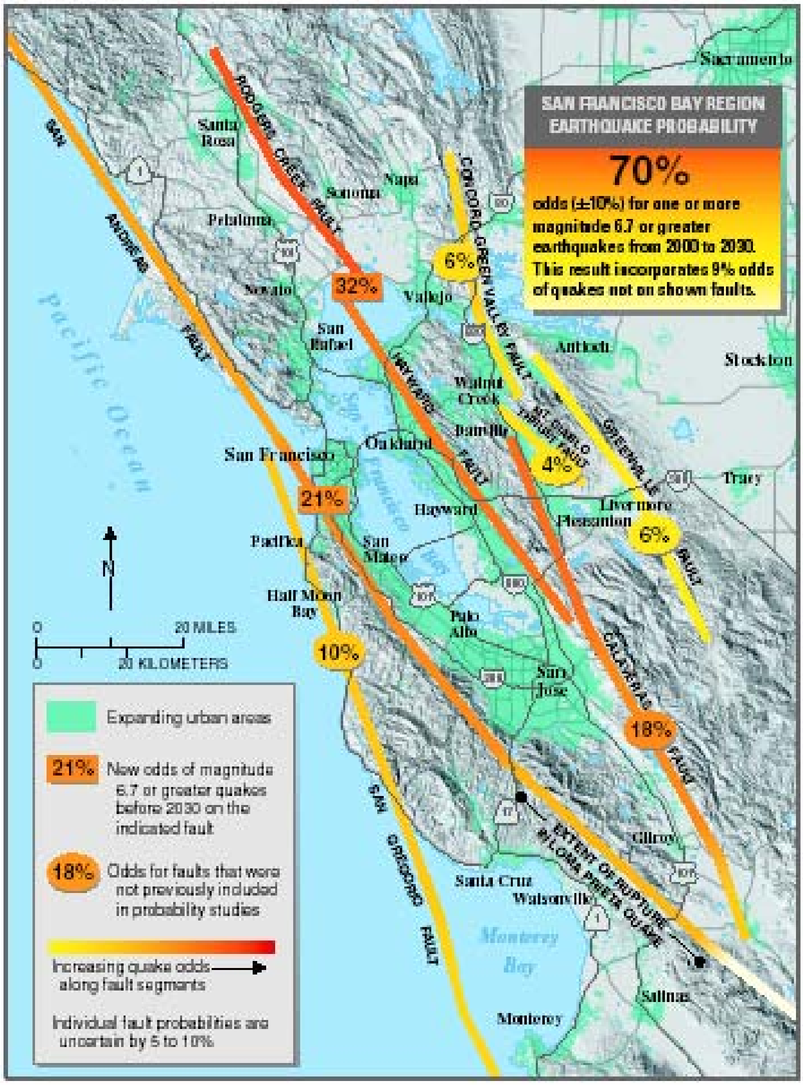
Visual 3.3: Map showing seismicity in southern California. Credit: USGS.

B. Northern California [*Electronic Visual 3.4*]

1. Last major damaging earthquake was the 1989 Loma Prieta Earthquake.

2. Northern California has a high seismicity rate. On the basis of research conducted since the 1989 Loma Prieta earthquake, USGS researchers and other scientists conclude that there is a 70% probability of at least one magnitude 6.7 or greater quake, capable of causing widespread damage, striking the San Francisco Bay region before 2030. Major quakes may occur in any part of this rapidly growing region. This emphasizes the

urgency for all communities in the Bay region to continue preparing for earthquakes.



Visual 3.4: Map showing major fault systems in northern CA with associated probability of earthquakes. Credit: USGS

C. Oregon & Washington: [*Electronic Visual 3.5*]

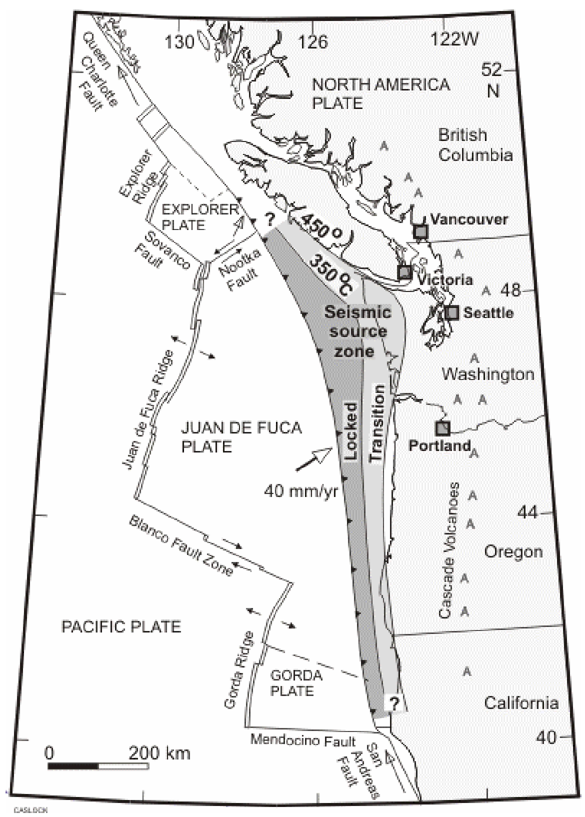
1. This region has a lower rate of seismicity relative to California region

2. Although region is near plate boundary, not associated with the San Andreas Fault system (this system ends in northern California); seismicity in this region is chiefly associated with boundary of the Juan De Fuca and

Pacific plates that form the Cascadia Subduction Zone, as shown in Visual 3.5.

3. Three major historical quakes in the Puget Sound region (M = 7.1 in 1949; M=6.5 in 1965; and, M=6.9 in 2001)

4. Some recent geologic studies suggest that “great” earthquakes (M= 8 to 9) have occurred there in the prehistoric past (USGS). Other, studies suggest many prehistoric earthquakes were no larger than those that have occurred in historic times; this is the current subject of debate. Traditionally, important facilities in this region have been designed for M=7 earthquakes.



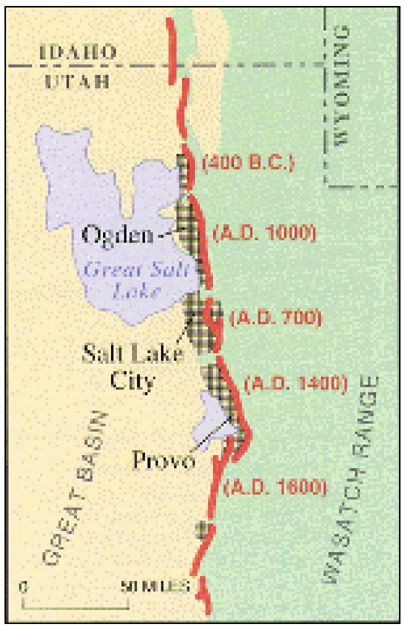
Visual 3.5: Map showing Cascadia Subduction Zone located off the coast of the Pacific Northwest region. Credit: USGS.

III. Rocky Mountain Region

A. Most active area includes Montana, Wyoming, Idaho, and Utah. [*Electronic Visual 3.6*]

B. Two historical events include Hegben-Yellowstone earthquake of 1959, (M=7.1) and Borah Peak, Idaho Earthquake of 1983 (M=7.3)

C. Seismic sources vary, due to both near-surface and deeply-buried fault systems. Wasatch fault is a large, well-known earthquake-producing fault system in this region. The 180-mile long Wasatch Fault Zone is broken into several segments. Each segment, about 20 to 30 miles long, may produce its own earthquake independent of other segments. A moderate, potentially damaging earthquake (magnitude 5.5 to 6.5) occurs somewhere in Utah about every seven years (USGS).



Visual 3.6: Map illustrating Wasatch Fault and dates of prehistoric earthquakes. Credit: USGS.

IV. Central Region

A. Major historical earthquakes in the New Madrid, Missouri area: [*Electronic Visual 3.7*]

Mon.	Year	M
Dec	1811	8.6
Jan	1812	8.4
Feb	1812	8.7

also, five aftershocks of M = 7 to 8, and 10 aftershocks of M = 6 to 7.

1. These M = 8+ events are largest known earthquakes in contiguous U.S.

2. One of the 8+ events caused the Mississippi River to temporarily change course, creating Reelfoot Lake.

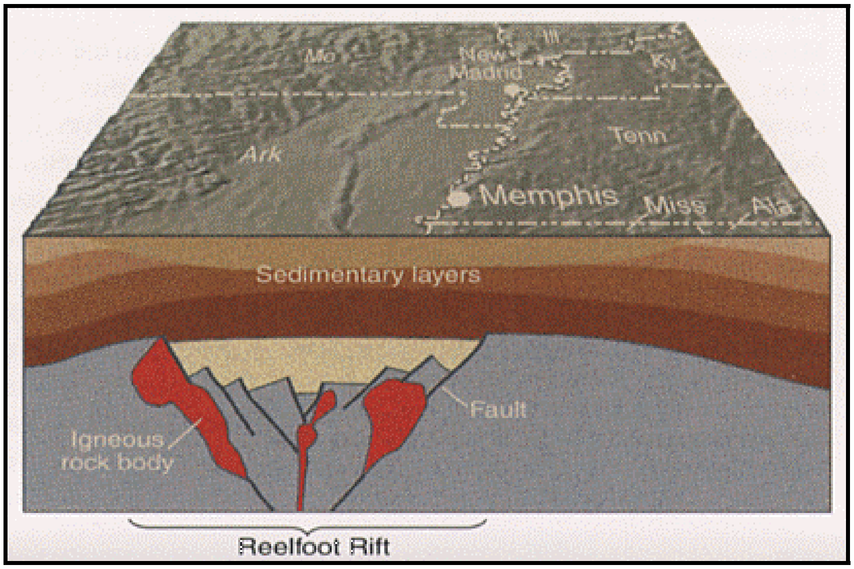
3. Widespread liquefaction and landslides in these events.

4. Recurrence interval not accurately known, but is believed to be in range of 500-1000 years based on recent paleoseismological studies.

5. Source believed to be associated with ancient rift zone (Reelfoot Rift) that roughly parallels Mississippi, Ohio, and Wabash Rivers. [*Electronic Visual 3.8*]

B. Recent paleoseismic work (i.e., Obermeier et al 1992; Martin and Pond, 1993) indicates that six prehistoric earthquakes of magnitude 6.5 and larger also have occurred in the Wabash Valley Seismic Zone, north of the New Madrid region in southern Illinois and Indiana. The largest of these events, a M7.5+ earthquake centered near Vincennes, IN, appears to have occurred about 6,500 years ago. Several events in the range of M6+ range have occurred within the last 4,500 years or so. Other work in this region has uncovered evidence for fault movements that occurred within the last 40,000 years. Together, these findings have important implications for seismic hazard assessments of this region.

Visual 3.7: Map showing seismic zones in the Central U.S. Credit: USGS.



Visual 3.8: Schematic of Reelfoot Rift associated with earthquakes in the New Madrid region.

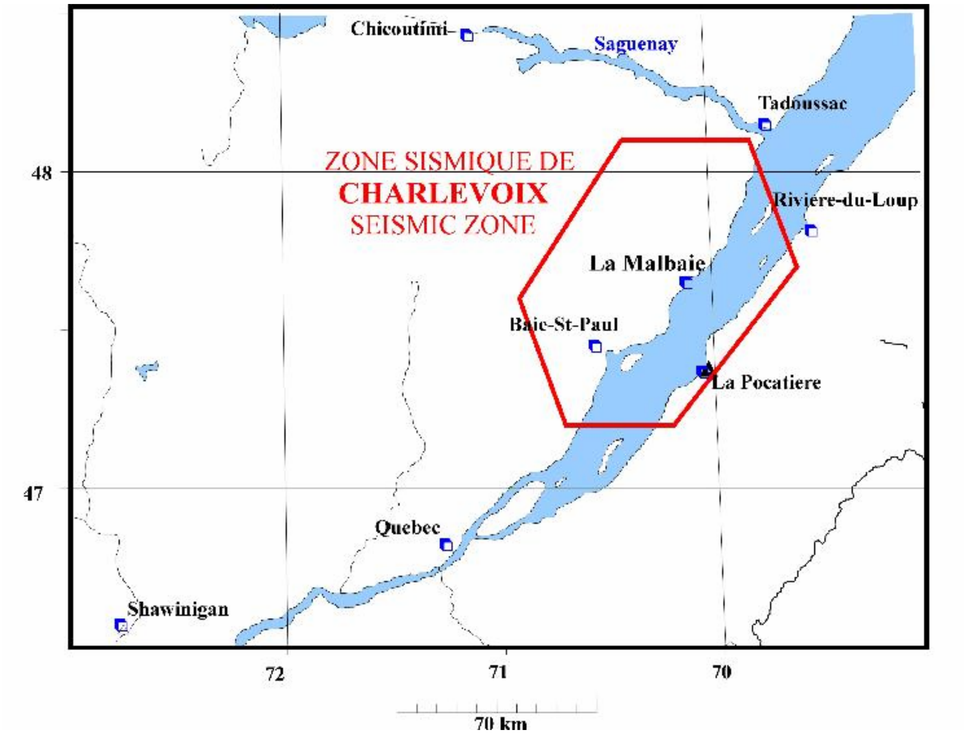
V. **Northeastern Region** [*Electronic Visual 3.9*]

A. Earthquakes in this region probably associated with ancient rift zones

B. Most active area is near St. Lawrence Seaway in Southern Canada, especially near Atlantic Ocean - some seismicity focused around Charlevoix Impact Crater from prehistoric meteor impact. (Faults initially formed during the rifting of the proto-North American continent (Laurasia) during the formation of an ancient ocean called Iapetus, approximately 700 million years ago).

C. Last major earthquake was in 1988 in Saguenay, Quebec (M=5.9). This was first large eastern earthquake with recorded ground motions and observed liquefaction. Said by some seismologists to be "unusual" with respect to certain characteristics, such as frequency content (source spectrum had unusual shape), but “unusual” is difficult to prove, since this is the only instrumentally recorded large eastern North America earthquake.

D. New York and Boston have had a number of historical earthquakes in range of magnitude 5+. Probably associated with faults formed during rifting of Pangaea about 200 million years ago.



Visual 3.9: Map showing Charlevoix Seismic Zone in the northeastern North America. Credit: Natural Resources Canada.

VI. Southeastern Region [*Electronic Visual 3.10*]

A. Most active area currently, in terms of rate of recorded seismicity, is eastern Tennessee; however, no large historical earthquakes have occurred there.

B. Charleston, SC earthquake of 1886 (M=7.5) was site of largest historical earthquake on the eastern seaboard. Very large felt area (> 2 million square miles). Felt in NY, Cuba, Illinois. Major building damage, liquefaction. Original earthquake size estimated from earthquake intensities. Magnitude may have been overestimated partly due to liquefaction-induced damages.

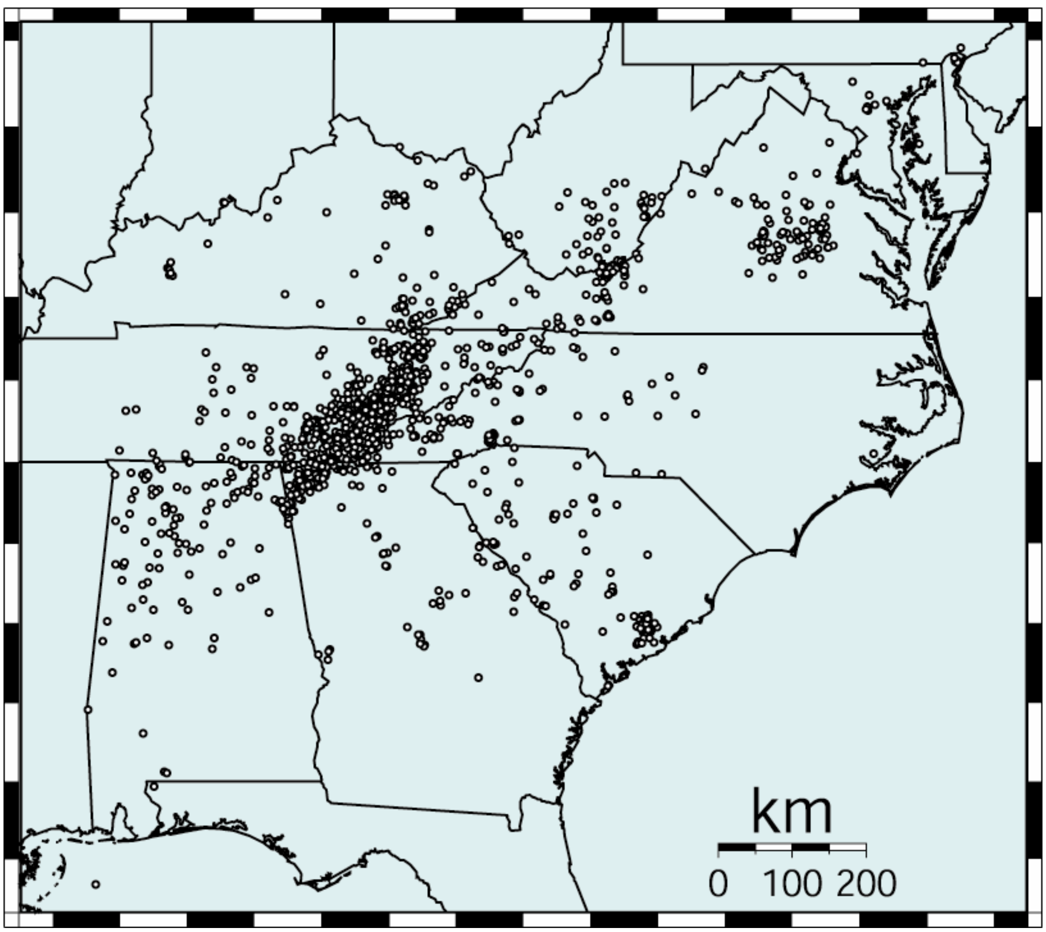
1. Source for Charleston, SC earthquake(s) believed to be due to one or more deeply buried faults. Probably associated with faults that formed in the mid-Mesozoic Era during rifting of Pangaea accompanying the formation of the modern Atlantic Ocean (Mesozoic faulting 100-200 million yrs. ago). It has been postulated that the thick (~1 km) deposit of Coastal Plain sediments underlying Charleston reduced peak ground motions beneath the city during the 1886 event (Martin and Clough, 1994).

2. Paleoliquefaction studies by researchers from USGS, Virginia Tech, and more recently, the University of South Carolina, indicate that large earthquakes have occurred every 400 to 1000 years for the last 6000 years

or so in the area (Talwani and Schaeffer, 2001; Obermeier et al, 1987; Martin and Clough, 1994). Weaker evidence indicates earthquake(s) occurring as far back as 30,000 years ago. Return period of about 450 years is used for seismic hazard calculations in the region. All evidence to date indicates epicenters of all events have remained close to Charleston. This recent evidence has greatly increased the calculated seismic hazard in the region.

C. Piedmont – Union, SC had M ≈ 6 earthquake in 1913.

D. Southwestern Virginia -- Pearisburg, VA; earthquake of magnitude ≈ 6 occurred there in 1897. Small earthquakes continue to occur in this area. Fault is located near the New River.



Visual 3.10: Map showing epicenters of earthquakes (M>0.0) in the southeastern U.S. from 1977 through 1999. Note relatively high rate of activity in eastern TN. Credit: Virginia Tech Seismological Observatory

VII. Other U.S. regions of high seismicity include Alaska, Hawaii, and Puerto Rico. All of these regions have conditions appropriate for very large ground shaking.

VIII. As can be seen, all regions (Western, Pacific Northwest, Southeast, Northeast, Midwest) of the U.S. are susceptible to earthquakes.

Objective 3.3 Recognize the national seismic hazard maps, identify where they can be obtained, and explain what information is presented on these maps

Requirements:

The content should be presented as lecture, supplemented with electronic visuals. The instructor is cued as to when the graphics from the electronic visual files should be presented. The class discussion should be conducted following the end of this objective and the homework assigned handed out following that. One week should be allowed for completion of this assignment.

Electronic Visuals Included:

Electronic Visual 3.11 Generalized USGS seismic hazard map
Electronic Visual 3.12 Detailed USGS seismic hazard map
Electronic Visual 3.13 Detailed USGS seismic hazard map for CA and NV

Handouts Included:

Handout 3.1: Class Discussion Assignment
Handout 3.2: Homework Assignment 3.1

Remarks:

I. National seismic hazard maps developed by USGS.

A. Most recent versions of the maps were developed in 2002 and revised in 2003.

B. Maps are available on the web at: *http://eqhazmaps.usgs.gov/*

II. Maps are based on probabilistic studies of seismicity in all regions of the U.S.

A. Maps are plotted in terms of accelerations with an associated probability that indicates the likelihood of these values being exceeded in 50 years (typical design life span of most infrastructure, such as buildings and bridges).

B. Maps illustrate the relative probability of a given level of earthquake ground motion in one part of the U.S. relative to another.

C. Also, the maps illustrate the relative earthquake "demand" on structures in one region relative to another, at a given probability level.

D. The maps are plotted for three different probability levels: 2%, 5%, and 10% probability of non-exceedance in 50 years. For instance, the 2%/50-year map shows accelerations values that have a 2% chance of being exceeded in 50 years.

E. Similar to the occurrence of floods, the probability levels are often referred to by probabilistic return period associated with each event; that is, the 2%/50-year probability level is referred to as the "2,500-year earthquake." Similarly, the 5%- and 10%/50-year probability levels are referred to as the "1,000-year" and "500-year earthquakes," respectively.*

F. The specific basis for originally selecting these three specific probability levels for mapping and use in engineering design is somewhat moot and is probably a remnant of the first series of seismic safety analyses performed for nuclear power facilities in the late 1960s and 1970s when probabilistic seismic hazard analysis techniques were being originally developed. These probabilities have become the "standard" probability levels frequently referred to and used in seismic design. The 2%/50-year map is used, more or less, as the basis for structural design of buildings in most regions, although systematic modifications and adjustments allowed by building codes (i.e., factoring by 2/3 due to conservative 1.5 margin of safety against collapse of well-constructed buildings) are often made to the mapped acceleration values before they are used in design.

III. The maps have been adopted by U.S. building codes and reference standards (IBC2003, UBC, NEHRP, etc.) for use in structural engineering design (although slight modifications are sometimes made for specific regions, such as California). ***Thus, the national seismic hazard maps from the USGS form the basis of the level of protection provided to structures in various regions.***

[*Electronic Visuals 3.11, 3.12 and 3.13*]

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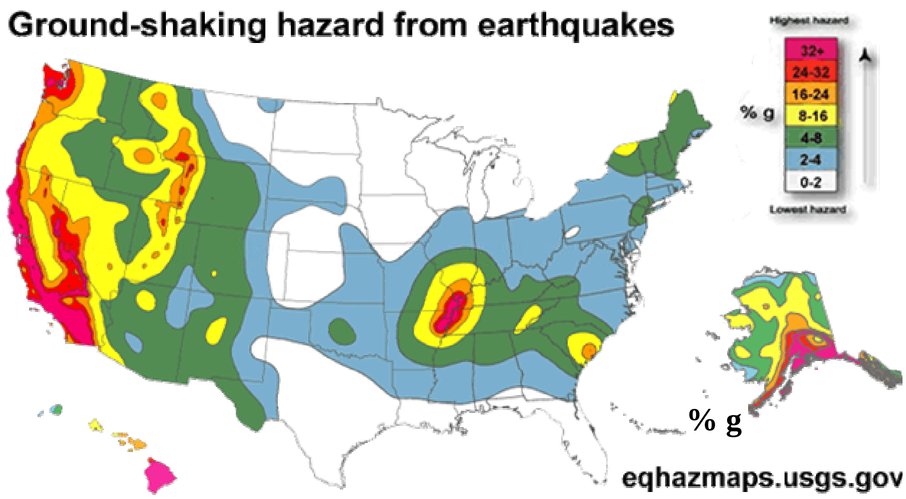
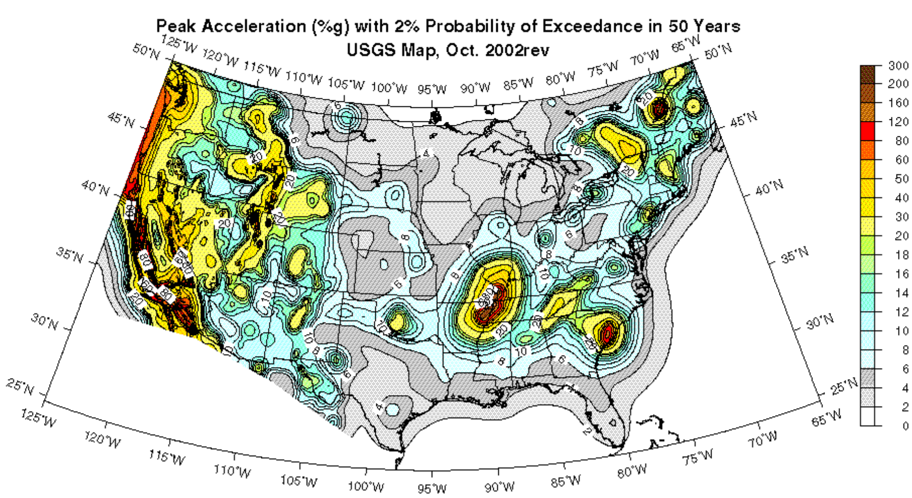
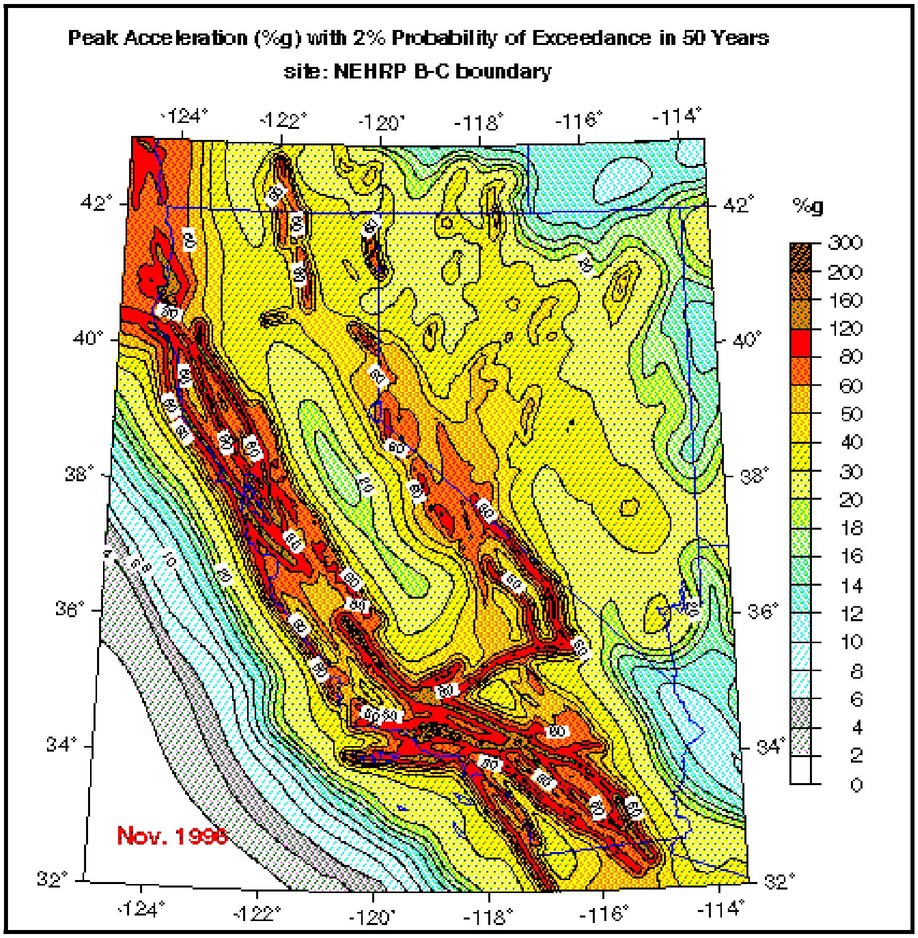
* This term is commonly misunderstood and misinterpreted. The term "2,500 year earthquake" does not indicate that an event that occurs once every 2,500 years! Rather, this term reflects a **<u>probability</u>**, that is, the earthquake event that has a probability of 1 in 2,500 of occurring in one year. For instance, the "100-year flood" can actually occur several years in a row or even several times in one year (as occurred in the 1990s in Virginia). The Poisson model is used to predict the probability of earthquakes based on the average rate of earthquakes of a given size that occur in a region, hence the importance of seismic monitoring networks that record earthquakes, including the frequent small events that are not felt. A statically representative data catalog of the number of earthquakes of various size forms the basis for estimating the likelihood of future events, including large damaging earthquakes. The more data available, the better the predictions (at least statistically). For more on the discussion of probability associated with the maps, see **FAQs** at: **http://geohazards.cr.usgs.gov/eq/html/faq.html** and/or: **"Info for the Layman" at http://geohazards.cr.usgs.gov/eq/**



Visual 3.11: Generalized USGS seismic hazard map for the United States (2002). Map shows peak ground accelerations (in % gravity) with a 10% probability of being exceeded in 50 years ("500-year earthquake").



Visual 3.12: Detailed USGS seismic hazard map for the United States (2002). Map shows peak ground accelerations (in % gravity) with a 2% probability of being exceeded in 50 years ("2,500-year earthquake").



Visual 3.13: Detailed USGS seismic hazard map for California and Nevada (1996). Map shows peak ground accelerations (in % gravity) with a 2% probability of being exceeded in 50 years ("2,500-year earthquake").

[*Conduct class discussion now using Handout 3.1; handout homework assignment*]

References Utilized:

Bolt, Bruce. 1993. *Earthquakes.* W.H. Freeman Company. Chapter 2, Where Earthquakes Occur, pp. 25-40.

International Building Code (IBC). 2003. International Code Council (ICC). See ICC website: *http://www.iccsafe.org/*

Martin, J.R., and G.W. Clough.1994. "Seismic Parameters from Liquefaction Evidence." *Journal of Geotechnical Engineering*, *ASCE*, August, 1994, pp. 1345-1361, Martin, J.R., and E.C. Pond, 1993. "Seismic Analysis of Relict Liquefaction Features in Regions of Infrequent Seismicity." *Transportation Research Board Record No. 1411*. National Research Council, January, 1993, pp. 53-60.

Natural Resources Canada (2004), data and figure from website at: http://www.seismo.nrcan.gc.ca/historic_eq/imageschar/charlocmap.jpg

Obermeier, S. F. 1998. "Seismic Liquefaction Features: Examples from Paleoseismic Investigations in the Continental United States." *Open-File Report 98-488*, U.S. Geological Survey, Reston, VA.

Obermeier, S. F., Weems, R. E. and R. B. Jacobson. 1987. "Earthquake-Induced Liquefaction Features in the Coastal South Carolina Region." *Open File Report 87-504*. U.S. Geol. Survey, Reston, VA.

Obermeier, S. F., Martin, J.R., Frankel, A.D., Youd, T.L., Munson, P.J., Munson, C.A., and E.C. Pond.,1992. "Liquefaction Evidence for Strong Holocene Earthquake(s) in the Wabash Valley of Southern Indiana-Illinois, with a Preliminary Estimate of Magnitude." *U.S. Geological Survey Professional Paper 1536*, May, 1992, pp. 1-27.

Obermeier, S.F., Munson, P.J., Munson, C.A., Martin, J.R., Youd, T.L., and N.K Bluer. "Liquefaction Evidence for a Strong Holocene Earthquake in the Wabash Valley of Indiana-Illinois." *Seismological Research Letters, Journal of the Eastern Section of the Seismological Society of America*, Vol. 63, No. 3, July-September, 1992, pp. 321-335.

Pond, E. and J. R. Martin.1997. "Estimated Magnitudes and Ground Motions Characteristics Associated with Prehistoric Earthquakes in the Wabash Valley Region of the Central United States." *Journal of Seismological Research Letters*, Seismological Society of America (Eastern and Central U.S.) Vol. 68, No. 4, pp. 611-623.

Talwani, P., and W. Schaeffer.2001. "Recurrence Rates of Large Earthquakes in the South Carolina Coastal Plain Based on Paleoliquefaction Data." *Journal of Geophysical Research (JGR)*, 106, pp. 621-642.

US Geological Survey, data and figures from websites at: http://geohazards.cr.usgs.gov/eq/ and http://earthquake.usgs.gov/bytopic/

Yeats, R. S., Sieh, K., and C. R. Allen. 1997. *The Geology of Earthquakes*, Oxford University Press, Chapter. 1, p. 165, and pp. 369-370.