Session No. 2

Course Title: **Earthquake Hazard and Emergency Management**

Session Title: **Causes of Earthquakes**

Author: **James R. Martin, II**

Time: 120 minutes

Objectives:

2.1 Describe the basic structure of the earth's interior.

2.2 Explain the dynamic processes that shape the earth's surface and cause the majority of the world's earthquakes, and identify the world's major plates and plate boundaries.

2.3 Distinguish between plate-boundary and intraplate earthquakes and identify regions in the U.S. where plate-boundary, intraplate, and subduction zone earthquakes tend to occur.

2.4 Explain the major types of faults and the basic behavior that produces earthquakes.

Scope:

During this session, the instructor will present the major geological concepts responsible for the occurrence of earthquakes. The instructor should briefly cover the historical development of the understanding of earthquakes, and spend the bulk of the time discussing current theories (plate tectonics) and the relevancy of these concepts to earthquake hazards in the U.S. The notes for these sessions were developed to emphasize only those basic aspects of geology relevant to the overall goals of this course. That is, the material in this section is to be presented with the understanding that the students will have a wide range of backgrounds, many of which are non-scientific in nature. It is recommended that supplemental reading and/or videos be used where necessary. The lecture format will be mostly conventional lecture with the use of visual aids in the form of slides and/or computer animations, etc. Depending upon the background of the students, the instructor is encouraged to organize a brief group discussion where the students are broken up into teams of two or three to answer questions posed. A suggested classroom exercise is presented in this session, as well as a homework assignment that covers the entire session. The classroom exercise can be presented following Objective 2.3 or 2.4. The homework assignment should be presented at the end of the entire session.

The concepts presented in this session are designed to provide an in-depth understanding and appreciation of the fundamental causes of earthquakes. The highly erratic and unpredictable nature of the causative geological processes is of particular relevance. A better understanding of these processes provides an improved ability to anticipate and communicate the unique aspects of earthquake hazards. Also, the information in this session is important for improved communication with scientists, engineers, government officials, and the public.

Electronic visuals presented in these notes, plus other useful visual aids such as computer animations, are included in the accompanying file: “Session 2 – Electronic Visuals.ppt.”

Readings:

Required student reading:

Highlighted links on the following URL related to the interior of the earth and plate tectonics
http://earthquake.usgs.gov/bytopic/plates.html

Suggested instructor reading and resources:

Highlighted links on the following URL related to the interior of the earth and plate tectonics
http://earthquake.usgs.gov/bytopic/plates.html

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

Reiter, L., *Earthquake Hazard Analysis*, 1990, Columbia University. Press.

Supplemental background reading material provided in the accompanying MS Word file:
“Session 2 - Causes of Earthquakes Background Reading.doc.”

Visual aids provided in the accompanying file: “Session 2- Electronic Visuals.ppt”

Other useful Internet web pages:

http://wwwneic.cr.usgs.gov/neis/plate_tectonics/rift_man.html

http://pubs.usgs.gov/publications/text/dynamic.html#anchor10790904

http://wrgis.wr.usgs.gov/docs/usgsnps/animate/pltecan.html

Handouts:

Handout 2.1 Classroom Discussion Exercise 2.1

Handout 2.2 Homework Assignment 2.1. The homework assignment should be distributed after Objective 2.4. Approximately one week is adequate time to allow for completion of this assignment.

Electronic visuals included: [*see Session 2 – Electronic Visuals.ppt*]

2.1 Earth's Interior
2.2 Oceanic and Crustal Plates
2.3 Convection Drives the Plates
2.4 Locations of Earthquakes
2.5 Earth's Major Plates
2.6 Plate Tectonics Animation
2.7 San Andreas Fault – Well-Known Plate Boundary
2.8 Map of Plates in the Western US
2.9 Subduction Zone
2.10 Elastic Rebound Theory
2.11 Elastic Rebound Theory
2.12 Elastic Rebound Theory
2.13 San Andreas Fault Offset – 1906 SF EQ
2.14 Table Showing Magnitude vs. Ruptured Fault Length
2.15 Types of Faults

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

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General Requirements:

The information presented in this session is technical in nature and additional background study will be required by instructors with non-scientific backgrounds. Accordingly, the instructor should thoroughly review the background reading material developed for this session (Session 2 – Causes of Earthquakes Background Reading.doc). 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. The instructor is therefore encouraged to cover as much of this material as feasible, and to make adaptations where appropriate as the makeup of the class and availability of outside resources dictate. The instructor should review the in-class discussion handout in the attached file, "Handout 2-1 Classroom Exercise.doc," and the students should be told at the end of the first 60-minute session to be prepared for this in-class assignment at the beginning of the second 60-minute session on this topic. Notes are provided to remind the instructor at the end of Objective 2.3 to prompt the students to prepare for the discussion in the second lecture period.

Additional requirements:

Computer and projector.

Objective 2.1 Describe the basic structure of the earth's interior.

Requirements:

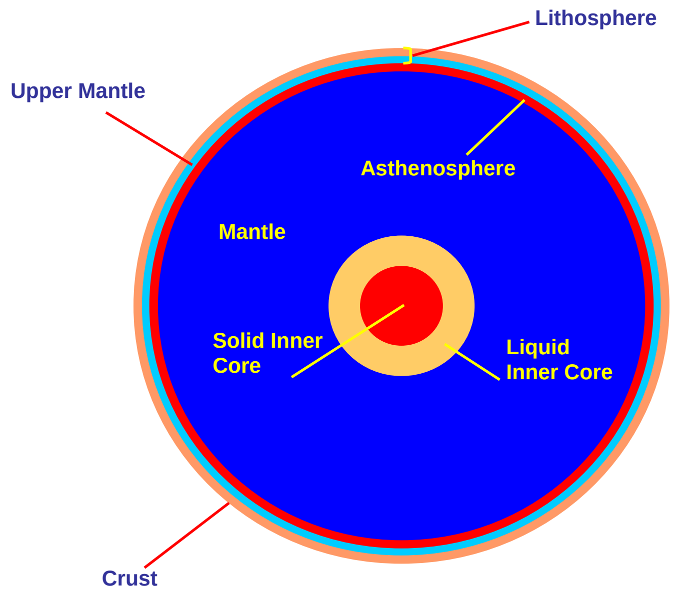
The content should be presented as lecture. The lecture will be enhanced if the instructor presents electronic slides or overheads of the visuals below. The instructor is cued as to when the graphics from the accompanying electronic visual files should be presented.

Electronic Visuals Included:

Electronic Visual 2.1 Earth's Interior
Electronic Visual 2.2 Oceanic and Crustal Plates
Electronic Visual 2.3 Convection Drives the Plates

Remarks:

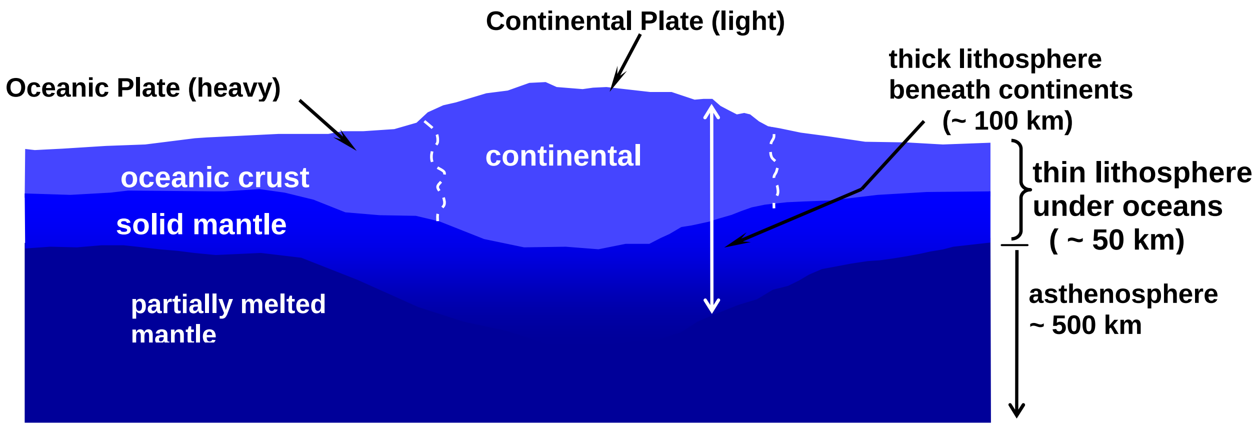
I. **The basic internal structure of the earth is as shown below:** [*Electronic Visual 2.1*]



Visual 2.1: Sketch depicting the internal structure of the earth. Of primary importance is the Lithosphere (brown, blue) and Asthenosphere (red) interface. Movement of brittle lithospheric plates across the underlying soft, warm Asthenosphere is the basic driving force that produces most earthquakes.

II. **Lithosphere: the rigid crust and part of the upper mantel that is comprised of a number of Plates.** [*Electronic Visual 2.2*]

A. The lithosphere is thick under the continents (≈100 km) and thin under young ocean basins (≈10 km) at spreading centers along mid-ocean ridges.



Visual 2.2: Sketch showing the relationship between the lithosphere and asthenosphere, as well as the greater thickness of continental crust relative to oceanic crust.

B. The lithosphere consists of crust and upper mantle; exhibits brittle behavior.

C. Lithospheric plates essentially "float" atop the soft, warm aesthenosphere.

D. The lithosphere/asthenosphere boundary is delineated based on temperature.

E. Earthquakes occur only in the lithosphere (or in lithospheric material in subduction zones). Only lithosphere has the strength and the brittle behavior to fracture in an earthquake.

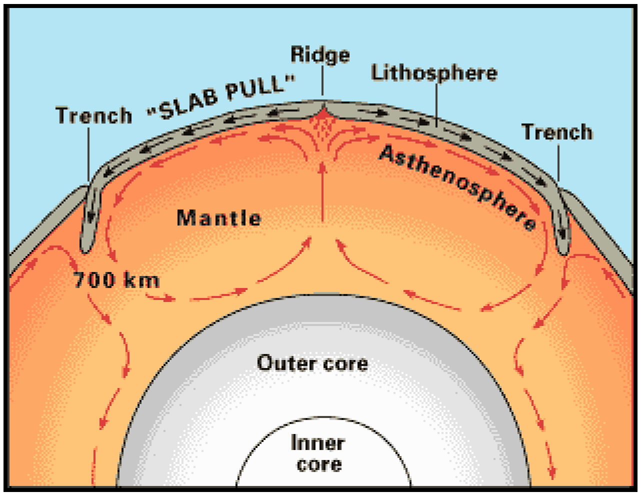
III. Crust: The hard, outermost region of the earth (forms upper part of lithosphere).

IV. Asthenosphere: A weaker zone of the upper mantle that underlies the Lithosphere.

A. The Asthenosphere is solid, but is warm and ductile and can "flow" like a very dense liquid over long periods of time.

B. The existence of the Asthenosphere is due to a combination of mineral composition, pressure and temperatures that permit flow-type behavior.

C. Heat in the earth produces circular thermal gradients (convection currents) that cause continuous slow flow of asthenospheric materials as shown: [*Electronic Visual 2.3]*



Visual 2.3: Conceptual drawing of assumed convection cells in the mantle. Lithosphere is dragged along as Asthenoshpere materials flow. Where plates subduct and begin to sink into the Asthenosphere, the descending slab begins to soften and flow at a depth of about 700 km. Credit: USGS.

D. As asthenospheric materials flow, the overlying lithospheric plates are dragged along –the interactions between neighboring lithospheric plates (sliding past, subducting beneath, colliding, etc.) is what produces most earthquakes.

Objective 2.2 Explain the dynamic processes that shape the earth's surface and cause the majority of the world's earthquakes, and identify the world's major plate boundaries.

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 2.4 Locations of Earthquakes
Electronic Visual 2.5 Earth's Major Plates
Electronic Visual 2.6 Plate Tectonics Animation

Remarks:

I. **Plate Tectonics**

A. **Tectonics**: Branch of Geology dealing with structural or deformational features of the outer part of the Earth. The word ***tectonics*** is derived from the Greek root "to build."

B. **Plate:** In geologic terms, a large, rigid slab of solid rock.

C. **Plate Tectonics**: A theory of tectonics in which the outer part of the Earth (Lithosphere) is comprised of rigid plates that interact (collide, translate, rift apart, subduct). The term refers to how the earth is built of plates, and the theory explains the interaction among these plates.

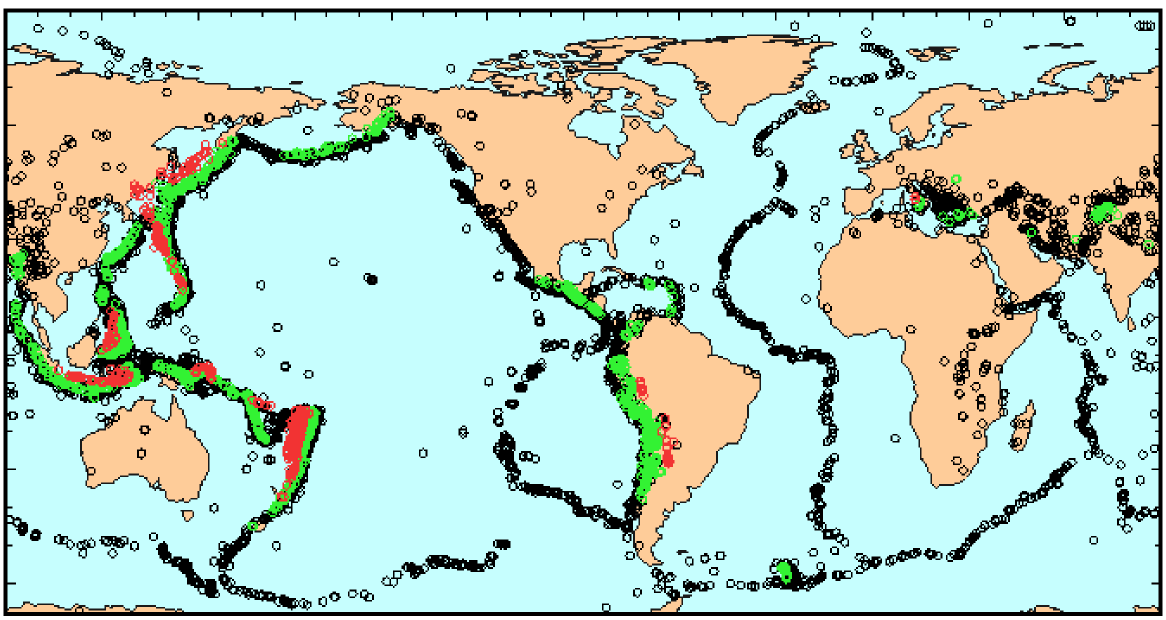
1. Basic concept of plate tectonics theory first proposed in early 1900s by Alfred Wegener, but idea not widely accepted at the time.

2. The theory was more fully developed during the 1960s; by 1970s, concept became the basic theoretical underpinning of the earth sciences.

3. The tendency of earthquakes to occur in narrow belts around the world was first established in the 1940s and 50s. Trend was one of the primary bits of evidence supporting Plate Tectonics Theory.

4. Now it is common knowledge that the location of earthquakes delineates the earth's tectonic plates, as earthquakes occur mainly along the boundaries of plates.

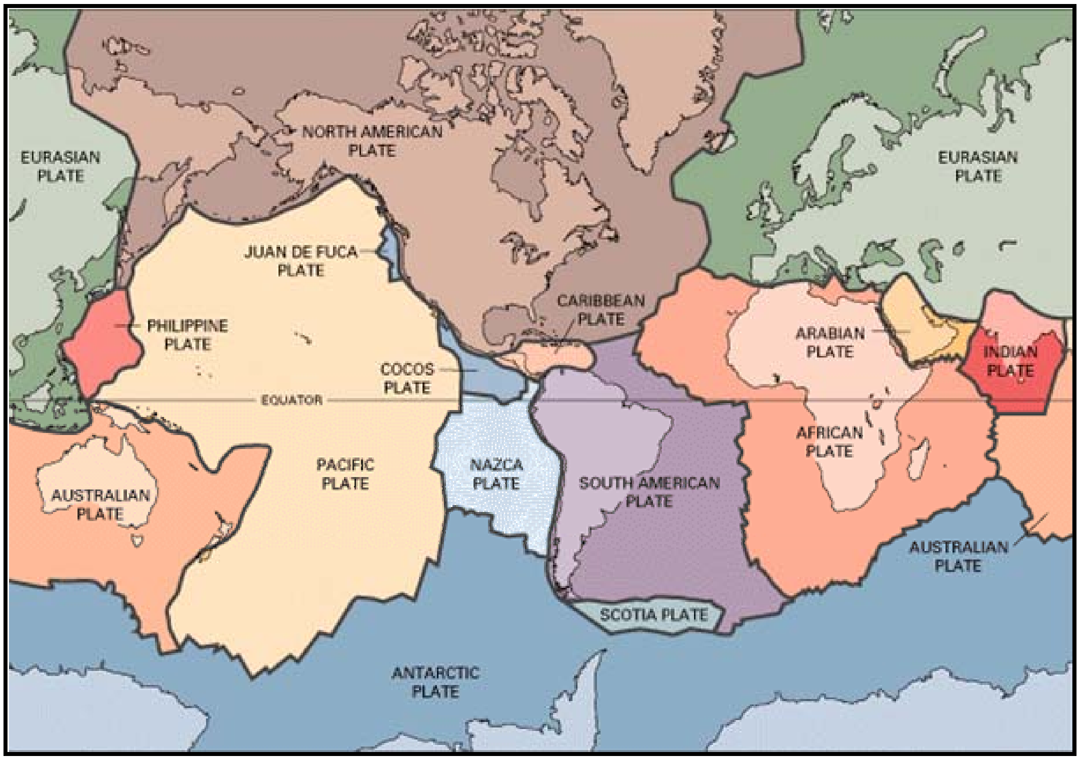
5. Approximately 90% of the world's earthquakes occur in areas along plate boundaries. [*Electronic Visual 2.4]*



Visual 2.4: Map showing locations (dots) of earthquakes since 1980 greater than Magnitude 5. The basic trend that earthquakes tend to occur in narrow zones around the world was first established in the 1940s and 1950s. Credit: USGS.

6. The earth consists of seven major plates, each divided into smaller plates:

[*Electronic Visual 2.5 and animation from Visual 2.6*]



Visual 2.5: Map showing locations of earth's major plates. While comparing this map to the previous visual, it can be seen that the locations of most of the world's earthquakes correspond to plate boundaries. Credit: USGS.

Objective 2.3 Distinguish between plate-boundary and intra-plate earthquakes and identify regions in the U.S. where plate-boundary, intra-plate, and subduction zone earthquakes tend to occur.

Requirements:

The content should be presented as lecture, supplemented with electronic visuals. The instructor is cued as to when the graphics from the accompanying electronic visual files should be presented. Following the completion of this objective, the instructor is encouraged to present the in-class discussion assignment.

Electronic Visuals Included:

Electronic Visual 2.7 San Andreas Fault – Well-Known Plate Boundary
Electronic Visual 2.8 Map of Plates in the Western U.S. Earth's Major Plates
Electronic Visual 2.9 Subduction Zone

Handout Included:

Handout 2.1 Classroom Discussion Exercise 2.1

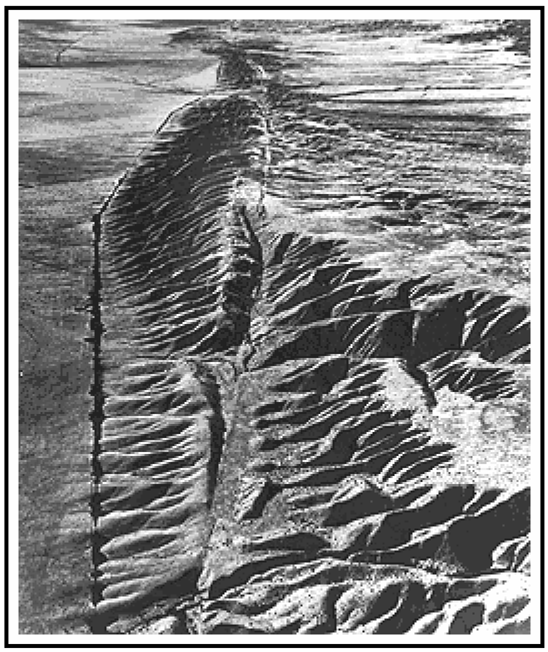
Remarks:

I. Types of Earthquakes

A. ***Plate-boundary earthquake*** **—** Earthquake that occurs along a fault associated with an active plate boundary.

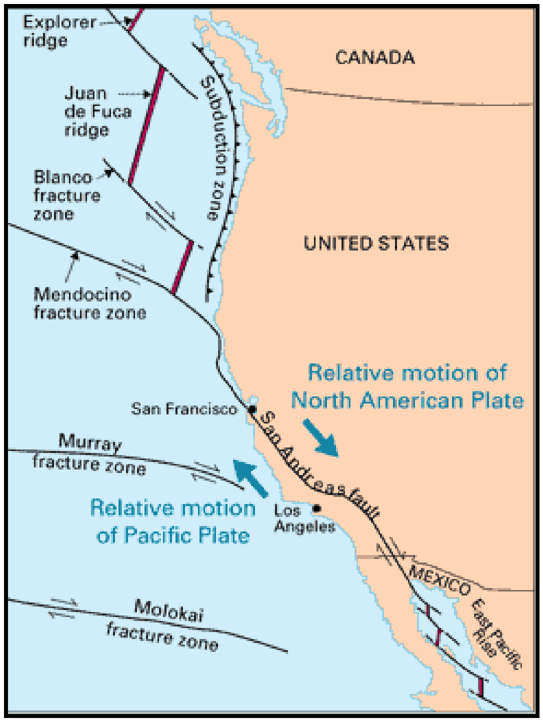
1. An example of this type of boundary is the **San Andreas Fault** in California. Ninety pecent of the world's earthquakes occur along plate boundaries. *[Electronic Visual 2.7]*

2. These events occur frequently and are relatively well understood, as per plate tectonic theory.



Visual 2.7: Aerial photograph showing the San Andreas Fault, the plate boundary between the North American and Pacific Plate. This fault system is responsible for much of the seismicity in California. Credit: USGS.

3. A more general example of plate boundaries in the U.S. is shown in the following visual: [*Electronic Visual 2.8*]



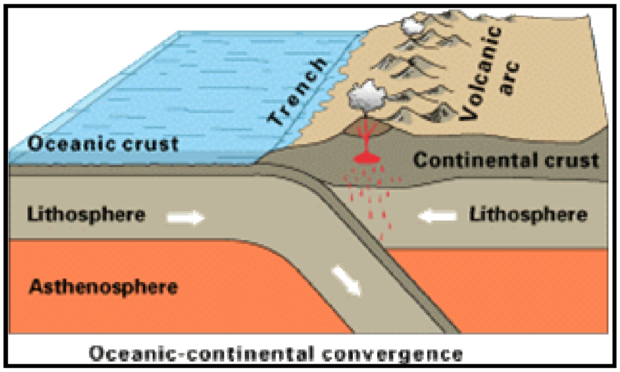
Visual 2.8: Map showing major western North American plate boundaries, and directions of plate movement. Credit: USGS

B. ***Subduction zone earthquake* —** Type of plate-boundary earthquake where one plate is subducting beneath the other. [*Electronic Visual 2.9*]

1. These earthquakes typically located very deep (up to 600 km depth recorded). Some of world's largest earthquakes are of this type.

2. The 1985 Mexico City Earthquake was of this type.

3. The Cascadia Subduction Zone, located off the coast of the Puget Sound region in the Pacific Northwest is of this type.



Visual 2.9: Sketch depicting a subduction zone, where one plate is sinking beneath another (or being "subducted"). Because oceanic crust is colder and heavier than continental crust, oceanic crust subducts beneath continental crust when they collide. The Cascadia Subduction Zone, located off the coast of the Puget Sound region in the Pacific Northwest is of this type. Credit: USGS.

C. ***Intraplate earthquake*** — Earthquake that occurs along a fault within the stable region of a plate's interior, away from plate boundaries, in the interior of plates.

1. Only 10% of the world's earthquakes are of this type.

2. Intra-plate earthquakes can occur near plate boundaries margins – the distinction between the two being whether the earthquake occurs on a fault forming the interface between two plates.

3. These events occur relatively infrequently, and are usually poorly understood; there are many uncertainties about their cause.

4. Examples of this type of earthquake occurring in the U.S. include the New Madrid, MO earthquakes of 1811-12 (> magnitude 8) and the 1886 Charleston, SC earthquake (> magnitude 7). Several other active faults of this type are located in the central and eastern portions of North America.

5. The causative faults for historical intraplate earthquakes in the central and eastern US are typically at depths of less than about 25 km, and involve shear failure of brittle rocks. The specific mechanisms for these earthquakes are poorly understood.

[***Instructor note:*** *this is a good point at which to end the first half of this 120 minute session. Following the discussion of intra-plate earthquakes, the students should be asked to very briefly research (i.e., the Internet) possible causes and mechanisms for intraplate earthquakes and come to the next class prepared to discuss this in a group setting. In addition to the causes of these events, the students should be asked to think about what special challenges might be involved with earthquake hazard management in intra-plate regions such as the eastern U.S. The instructor should review the in-class handout and make sure students have some basic* *preparation before they arrive in class the next session. The purpose of this exercise is to foster interactions of the students with each other and the instructor, pique their interest, and have them develop an appreciation for the relative uncertainty involved with intraplate earthquakes (and thus our difficulty in assessing seismic risks in these regions). It is not important that they understand all of the finer details of the scientific processes, etc. Therefore, the next session should begin with the classroom discussion exercise and then follow with remainder of lecture material].*

[*Handout 2.1 Classroom Discussion Exercise 2.1; conduct in-class discussion]*

Objective 2.4 Explain the major types of faults and the behavior that produces earthquakes.

Requirements:

The content should be presented as lecture. The lecture will be enhanced if the instructor provides electronic versions of the visuals and photographs below. Following the completion of this objective, the instructor should present the in-class discussion assignment if this was not presented following Objective 2.3.

Electronic Visuals Included:

Electronic Visual 2.10	Elastic Rebound Theory
Electronic Visual 2.11	Elastic Rebound Theory
Electronic Visual 2.12	Elastic Rebound Theory
Electronic Visual 2.13	San Andreas Fault Offset – 1906 SF EQ
Electronic Visual 2.14	Table Showing Magnitude vs. Ruptured Fault Length
Electronic Visual 2.15	Types of Faults

Handouts Included:

Handout 2.2 Homework Assignment 2.1

Remarks:

I. Faults and Earthquake Motion.

A. Earthquakes result from abrupt slippages along faults in rock.

1. The slippage produces heat and seismic waves that we feel as an earthquake; the mechanical energy associated with the fault rupture is converted into heat and seismic waves; similar to process of clapping hands that transformed mechanical energy into heat and sound waves.

2. Earthquake waves travel throughout the earth (propagate) from where they are generated at the fault.

3. Earthquake waves lose energy with distance; similar to ripples in a pond struck by a stone or sound waves in air – the farther away the sound, the lower the volume.

4. The process of energy decay with distance from the source is called attenuation.

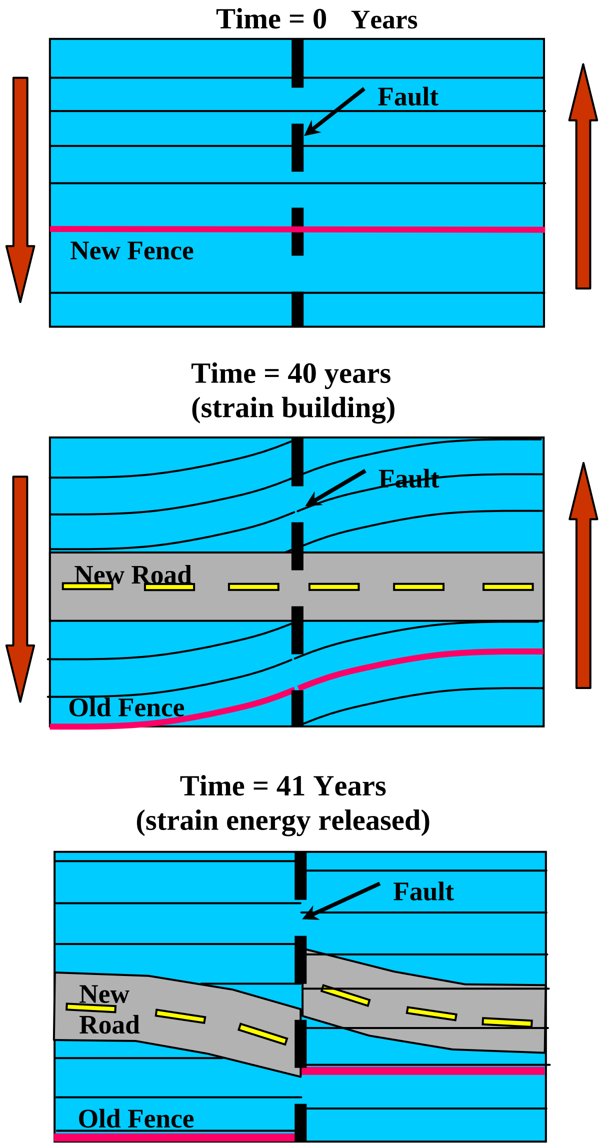
B. Fault rupture is explained by “elastic rebound theory” first proposed by H. Reid in the early 190’s, following the 1906 San Francisco Earthquake.

1. The rocks that generate earthquakes have elastic properties that cause them to deform when subjected to tectonic forces and to “snap back” and vibrate when energy is suddenly released. The deformation behavior is similar to that of gelatin.

2. During the rupture, the rough sides of the fault rub against each other. Energy is used up by crushing of rock and by sliding friction. Earthquake waves are generated by both the rubbing and crushing of rock as well as the elastic rebounding of the rocks along the ruptured fault.

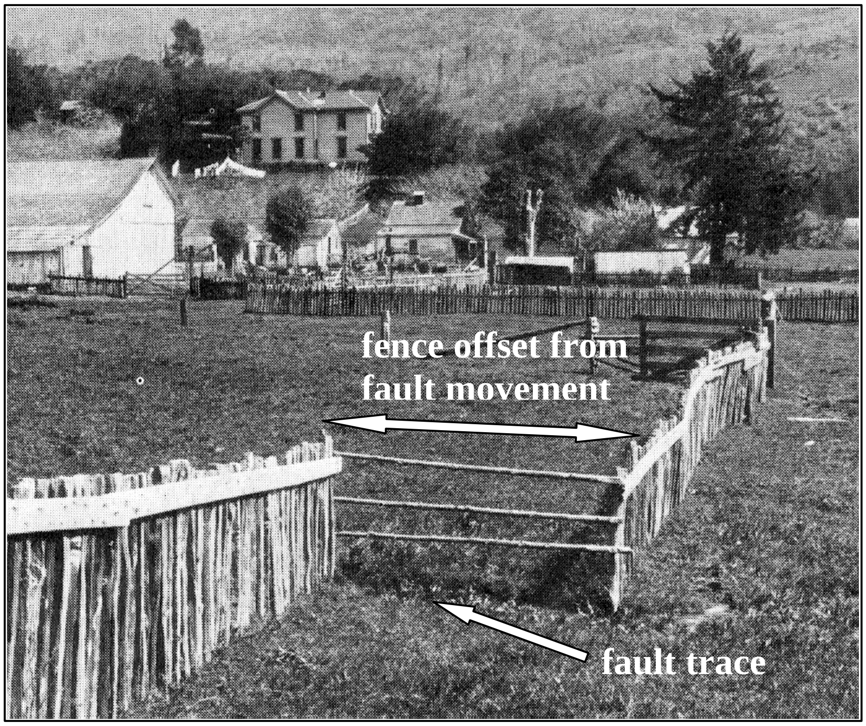
3. Strains on opposing sides of a fault build due to tectonic forces. The strain continues to build until the stresses overcome the frictional resistance along the fault and slippage suddenly occurs releasing the strain energy stored in the rock.

4. Process is much like bending a stick until it breaks – the fibers strain and crack under the force applied until some critical point is reached when the stick suddenly snaps. In a similar manner, the three-part time-sequenced schematic below illustrates the building of strain in the earth and the occurrence of an earthquake: [*Electronic Visuals 2.10, 2.11, & 2.12*]



Visuals 2.10, 2.11, 2.12: Three-part figure depicting the build-up of strain due to tectonic forces and sudden slippage that releases strain energy in an earthquake. Tectonic forces (red arrows) are typically associated.

5. A good example of evidence for the type of fault movement depicted in the visual above is illustrated in the photograph below. The photo shows a fence offset by movement that occurred along the San Andreas Fault during the 1906 San Francisco Earthquake. *[Electronic Visual 2.13]*



Visual 2.13: Photograph showing evidence of fault movement along the San Andreas Fault during the 1906 San Francisco Earthquake. Photo credit: USGS.

6. The length of ruptured fault associated with a large earthquake is typically on the order of tens of kilometers, as shown in the table below. As expected, the longer the fault, the more energy released and the larger the earthquake. It also can be seen that duration of ground shaking also increases as a function of fault length, as more time is required for longer faults to slip. The average amount of fault displacement for a large earthquake (> magnitude 7) is on the order of a few meters.

[*Electronic Visual 14*]

Magnitude (Mw)	***Date***	***California Location***	***Ruptured Fault Length (km)***	***Duration (secs.)***
7.5	July 21, 1952	Kern County	75	27
7.3	June 28, 1992	Landers	70	24
7.0	October 17, 1989	Loma Prieta	40	7
6.9	May 18, 1940	Imperial Valley	50	-
6.7	January 17, 1994	Northridge	14	7
5.9	October 1, 1987	Whittier Narrows	6	3

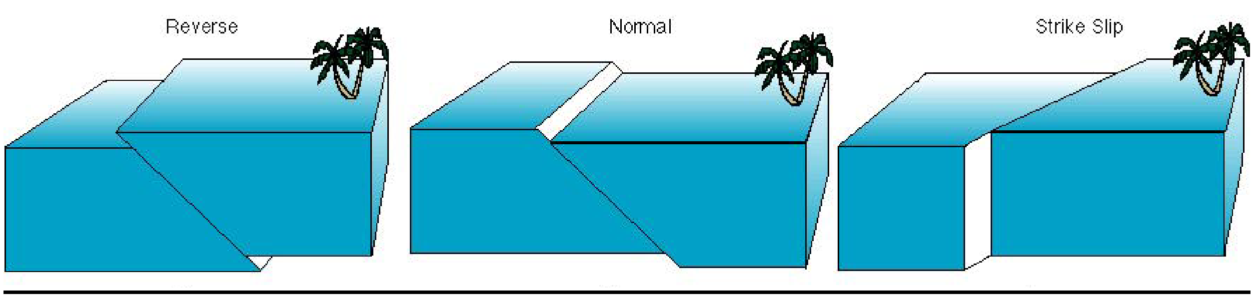
Visual 2.14: Table showing magnitude versus length of ruptured fault. Data source: USGS.

II. Types of faults: There are three basic types of faults; the type of fault depends upon the direction of regional tectonic stresses and other factors. [*Electronic Visual 15*]

A. Strike-Slip (i.e., San Andreas).

B. Normal.

C. Reverse (and thrust).



Visual 2.15: Sketch illustrating three types; from the left: reverse fault; normal fault and strike-slip fault. Credit: USGS.

[*Handout 2.2: Homework Assignment 2.1; discuss homework assignment answers in a following session or post answers on-line*]

References Utilized:

http://earthquake.usgs.gov/bytopic/plates.html

http://www.neic.cr.usgs.gov/neis/plate_tectonics/rift_man.html

Reiter, L.. 1990. *Earthquake Hazard Analysis*..Columbia University Press..

http://pubs.usgs.gov/publications/text/dynamic.html#anchor10790904

http://wrgis.wr.usgs.gov/docs/usgsnps/animate/pltecan.html

Yeats, R. S., Sieh, K., and C. R. Allen. 1997. *The Geology of Earthquakes*. Oxford University Press.