Subduction Zone—Plate Interaction

Background to accompany the animations & videos on: **IRIS Education and Outreach Animations**

Link to Vocabulary (Page 5)

Introduction

Subduction zones are broad areas where two plates are moving in opposite directions. The oceanic plate descends beneath a continental plate in this example. [See **Divergent and Convergent Plate Boundaries** for more-detailed depictions].

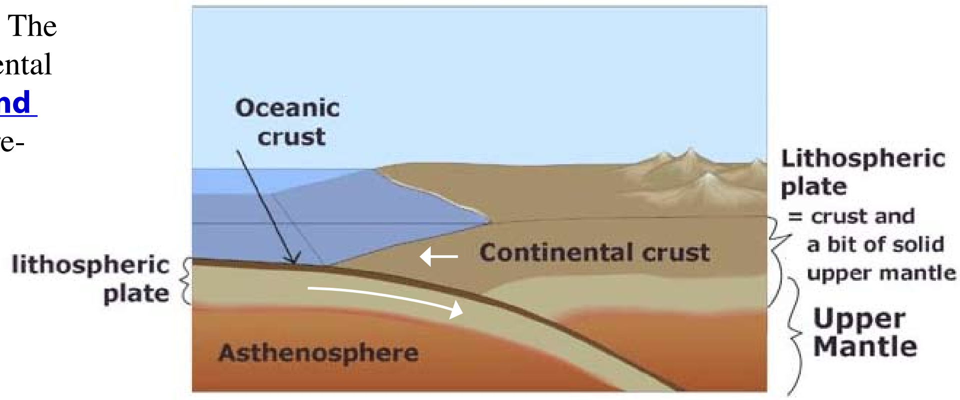

Figure 1—Ocean-continent subduction zone. The lithospheric plate (aka tectonic plate) is comprised of the crust and upper mantle. Steep dip of the down-going plate is greatly exaggerated.

The contact between the plates is sometimes called an interplate thrust or megathrust fault. Where the plates are locked together, frictional stress builds. When that stress exceeds a critical value, a sudden failure occurs along the fault plane that can result in a "mega-thrust" earthquake releasing strain energy and radiating seismic waves. In this configuration, it is common for the leading edge to lock under high friction. The locked fault can hold for hundreds of years, building up enormous stress before releasing.

The reason the thinner plate dives beneath the thicker plate is because the oceanic plate is composed of iron-rich basalt rock that is denser (heavier per unit area) than the rock layers that form the continent. A combination of forces acting on the lithospheric plates include the circulation of heat rising in the mantle, and the pull of gravity.

As frictional stress builds along the fault boundaries, it is accompanied by an increase in strain in the adjacent rocks. When the frictional stress exceeds a critical value, a sudden failure occurs along the fault plane that can result in a violent displacement of the Earth's crust. When this happens, the ensuing earthquake releases elastic strain energy and seismic waves are radiated. The process of strain, stress, and failure is referred to as the elastic-rebound theory. (See page 6 for more on this topic.)

Earthquakes generated in this setting are called Great Subduction Zone earthquakes. They are the largest earthquakes in the world and can exceed magnitude 9.0. The devastating Sumatra-Andaman earthquake of December 26, 2004 (star on Figure 2) had a magnitude of 9.3.

Figure 2—The oceanic plate is moving towards and diving beneath Sumatra (red barbs show direction of down-going plate). An interactive Flash animation comparing the Sumatra-Andaman subduction zone with the Cascadia subduction zone: www.iris.edu/hq/programs/education_and_outreach/animations

The earthquake occurred on the interface between the India and Burma tectonic plates where the India plate is subducting beneath the overriding Burma plate. Earthquake size is proportional to fault area which was was about 1200 km long and as much as 200 km wide (See Figure 3 for a comparison of the area of the Sumatra-Andaman earthquake with the size of California.)
The uplift caused by the elastic rebound of the overlying plate is what caused the deadly tsunami that killed over 225, 000 people.
For more detail on Sumatra: **http://neic.usgs.gov/neis/eq_depot/2004/eq_041226/neic_slav_ts.html**

In 1960 and 1964, destructive magnitude-9 earthquakes occurred in Chile and Alaska respectively.

A similar configuration of plates can be found along the Cascadia Subduction Zone (Figure 4). This is a very long sloping fault that separates the Juan de Fuca and North America plates and stretches from mid-Vancouver Island to Northern California. The contact between the two plates, the area of the subduction zone fault, could also produce a magnitude 9.0 earthquake, if rupture occurred over its whole area. It last ruptured on January 26, 1700 (for details see **Orphan Tsunami**.)

As a result of the compression between these plates, the overlying continental plate is actively deforming. And although a M9 earthquake is a looming threat, it isn't the only earthquake source in the area. Smaller earthquakes are common in two other parts of the subduction zone:

1. Within the deforming part of the North American plate; and
2. within the brittle down-going slab of the Juan de Fuca Plate as the brittle slab bends in its dive beneath the North American Plate.

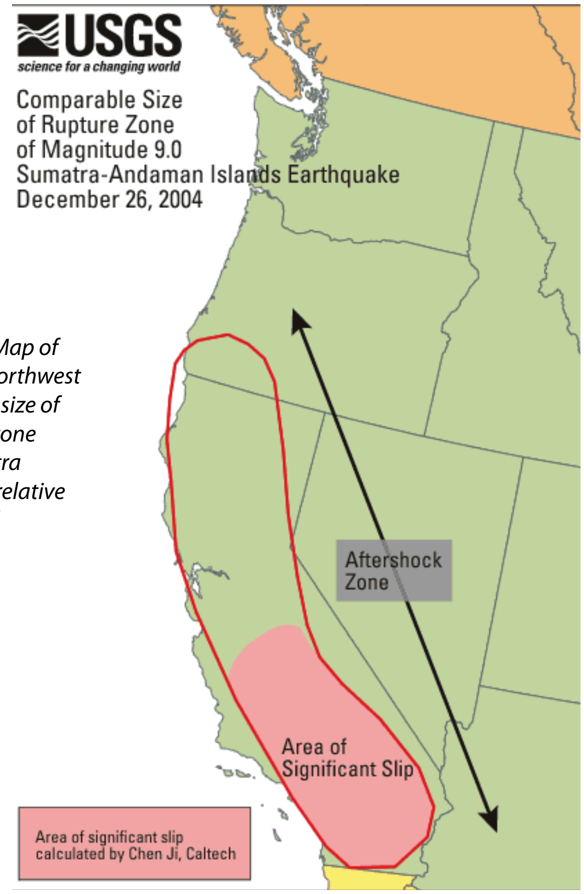

Figure 3— *Map of the Pacific Northwest showing the size of the rupture zone of the Sumatra earthquake relative to the size of California .*

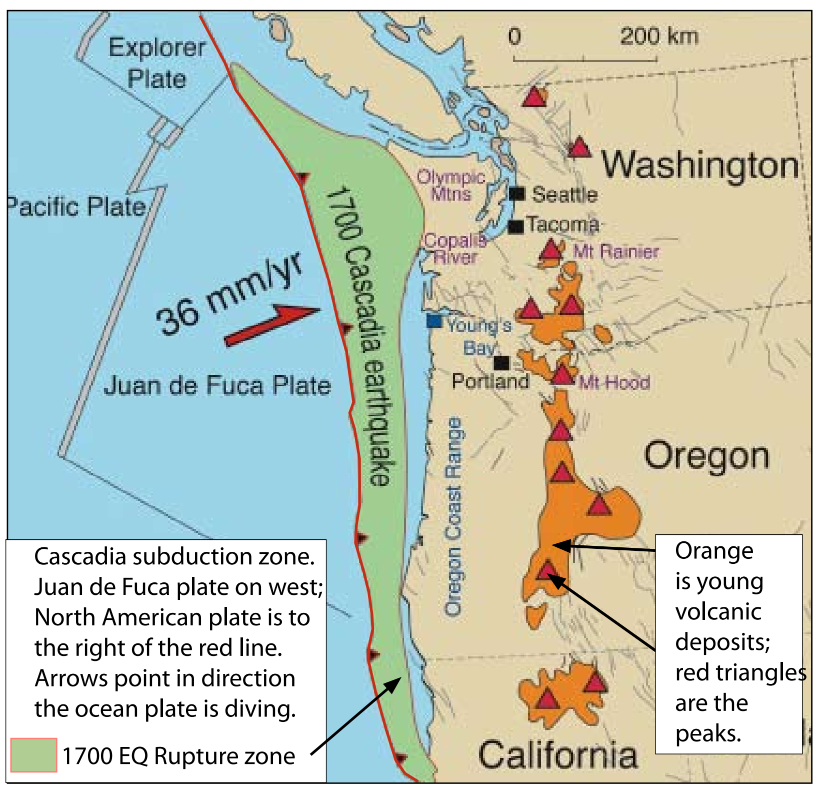

Figure 4—*Map of the Pacific Northwest geologic setting. The area is the subduction zone that ruptured during the great earthquake of 1700. The line of contact between the Juan de Fuca and North American plates on the surface is on the western edge of the green area.*

Complicated deformation of a subduction zone

The deforming part of the North American plate has been the focus of much attention by scientists since they recognized that the Juan de Fuca Plate is diving beneath the North American Plate at 36 mm (1.4 in) per year. Furthermore, the coastal areas appear to be moving backwards, apparently shoved by the diving plate. Solid evidence for this is seen in the movement of GPS stations relative to the stable North American continent. See notes on the animation depicted in Figure 2.

Since the advent of GPS, a subduction zone behavior known as "episodic tremor and slip" (ETS) has been reported. Recent increased monitoring by GPS and seismometers has revealed that not all of the subduction zone is stuck. ETS consists of repeated slow slip events on the mid portion of the subduction fault, accompanied by unique non-earthquake tremor-like seismic signals that emanate from the same region during slip back. If the area were moving steadily in one direction the slope would mimic graph #1 in the graphic, with no sawtooth pattern.

Learn more about ETS on **page 4** of this document.

Figure 5—*USGS map from Hyndman and Wang, 1995, shows the shallow locked portion of the Cascadia Subduction Zone fault and the deeper transitional zone where small earthquake clusters sometimes occur.*

Animation of "episodic tremor and slip" in a subduction zone

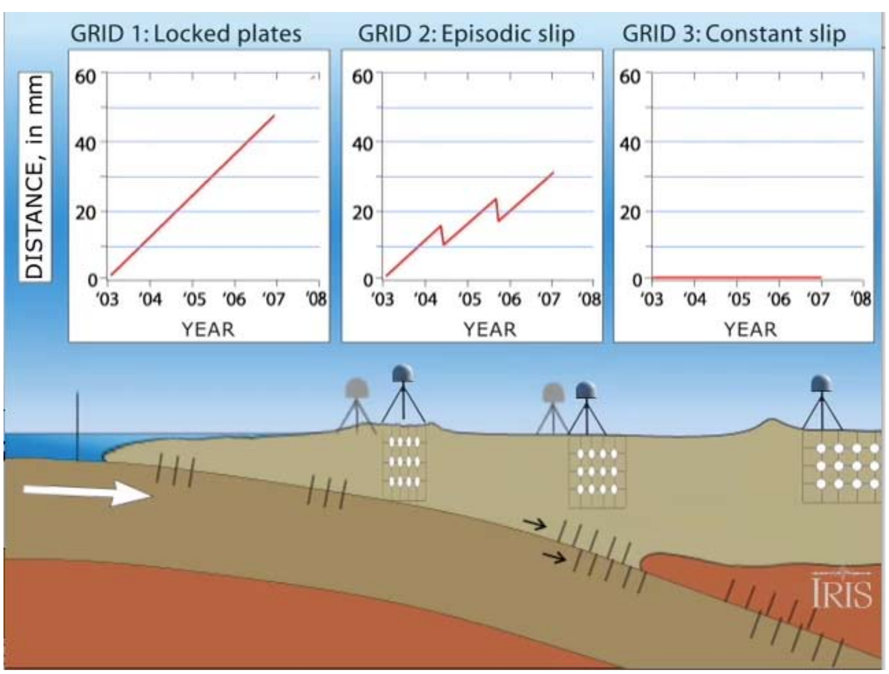

Figure 6—*There are a lot of things going on in this animation. The 3 grids portray deformation in three zones of a subduction region. Three things to focus on are:*

1) The leading edge of the continental plate is locked with the subducting slab, thus gets shortened, building up energy as in the previous animation. The graph shows steady change in distance as the land the GPS is mounted to is being forced landward.

2) The center grid is the focus of "Episodic Tremor and Slip" as it is being forced landward by the affects of subduction, but it occasionally backslides, apparently releasing some energy. This backslide is accompanied by earthquake tremors. The small GPS station sitting above the grid reflects the forward-backward motion. (This GPS is the focus of the next animation: 3A.GPS-graph-CU.mov Watch the sawtooth pattern on the graph. (see "What is Episodic Tremor and Slip? next page.)

3) The furthest inland station shows no deformation, thus the graph is flat: no change over time.

* From **EarthScope's OnSite Newsletter** winter/spring 2007

Episodic Tremor and Slip in the Pacific Northwest

Every 14 months the Pacific Northwest experiences slow slip on a fault that is the equivalent of about a magnitude 6.5 earthquake. While a typical earthquake of this magnitude happens in less than 10 seconds, the duration of these slip events is two to several weeks. The most recent event occurred from January 14 through February 1, 2007.

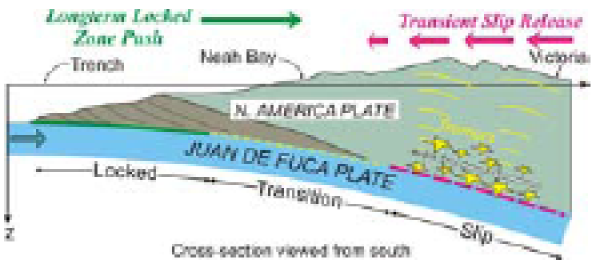

Figure 1. Courtesy of H. Dragert. Geological Survey of Canada

In the Pacific Northwest, the Juan de Fuca plate is subducting (or dipping) beneath the North American plate from northern California to Vancouver Island. These plates slide past each other along the solid green, dashed yellow and dashed red lines in Figure 1. The Cascadia subduction zone, as it is called, experiences large earthquakes, perhaps as large as the 2004 Sumatra earthquake, once every 500 years on average. The last one was about 300 years ago in January 1700. The slip during these earthquakes, occurring on the "locked" zone in the figure, is thought to accommodate most, if not all, of the relative motion between the North American plate and the Juan de Fuca plate. Down dip of this locked zone (red dashed lines), the plates must still slide past each other. However, instead of rupturing in devastating earthquakes, much of that slip appears to be occurring during the Episodic Tremor and Slip (ETS) events (labeled "slip" in the figure).

EarthScope and other research projects have installed Global Positioning System (GPS) stations near the Northwest Pacific coast to record ETS events. These instruments are continuously moving to the northeast relative to the stable interior of North America because the Juan de Fuca plate is pushing on the North American plate (green arrow in Figure 1). During an ETS event, the stations above the ETS zone slip backwards (the red arrows in the figure). Seismometers also record the slip. These signals initially were considered to be noise from wind or other sources, however, by filtering and analyzing the seismograms, it was discovered that tremor produces signals that are similar on many seismometers and that the signals move across a network of seismometers at the speed of waves generated by earthquakes. Tremors typically originate where the two plates meet at depths of 30-45 km. These tremors may be related to high fluid pore pressure in the rock resulting from dehydration reactions as the subducting plate heats up and undergoes increasing pressure.

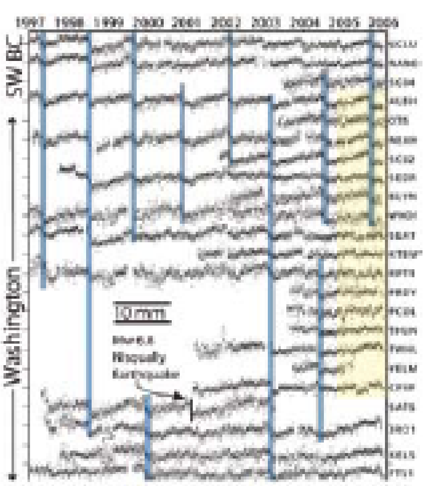

Figure 2. Plot of East-West position vs time for 2? GPS sites (eastward motions are positive). The blue vertical lines mark ETS events where multiple stations temporarily move westward.

One of the most exciting areas of research to emerge from joint GPS and seismic monitoring is the discovery of ETS. Japanese researchers were the first to identify periodic slip events, however, with the installation of more GPS stations, this phenomena has been detected in Cascadia and many other subduction zones around the world. In Cascadia, initial recognition of slow faulting led to the identification of eight additional events with a regular 14-month periodicity and the forecasting of future events. Since then, five predicted events have occurred with the same periodicity. Further study has shown that ETS events likely occur all along the Cascadia subduction zone but with different periodicity (see Figure 2.). For example, ETS events occur beneath Northern California every 11 months and off the coast of central Oregon approximately every 18 months. The 2007 ETS event began under the southern Puget Sound area to the southwest of Seattle and propagated north northwest into Vancouver Island, Canada at a rate of 10 km per day (Figure 3). Over a three-week period, it is estimated that there was 3 cm of slip and that the amount of energy released was equivalent to a magnitude 6.6 earthquake. An account of this event and two previous ETS events as they unfolded can be found at http://www. pnsn.org/WEBICORDER/ DEEPTREM/ fall2006.html. These ETS events can effect the magnitude and timing of future large earthquakes within the subduction zone and thus are important in advancing our understanding of the seismic hazards in the region. As more GPS, strainmeters and seismometers are installed in Cascadia and near other subduction zones, it is hoped that answers to many more questions about these events will be found.

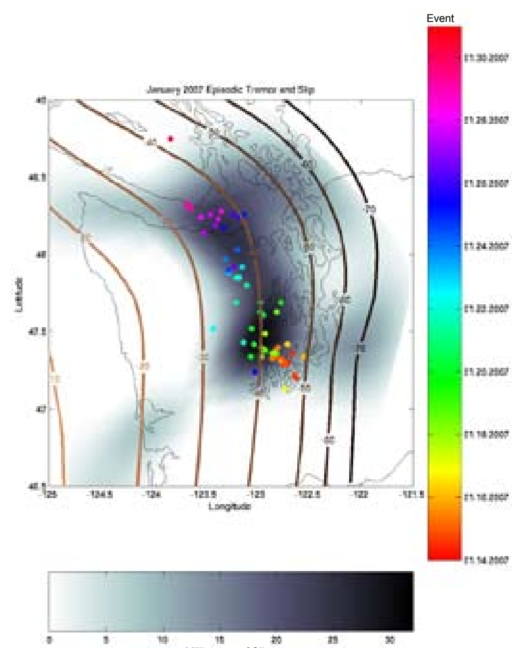

Figure 3. From January 14, 2007 until February 2, 2007, tremor migrated from the south Puget Sound region to southern Vancouver Island at about 10 km per day (colored dots). Amount of slip is inferred from GPS data.

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Vocabulary

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Asperity—literally "roughness. It is an area on a fault that is stuck or locked. A type of surface roughness appearing along the interface of two faults. Physics the elastically compressed region of contact between two surfaces caused by the normal force

Asthenosphere—the ductile part of the earth just below the lithosphere, including the lower mantle. The asthenosphere is about 180 km thick.

Crust—the outermost major layer of the earth, ranging from about 10 to 65 km in thickness worldwide. The uppermost 15-35 km of crust is brittle enough to produce earthquakes. Oceanic crust is thinnest; continental crust is thickest.

Elastic strain—Earthquakes are caused by the sudden release of energy within some limited region of the rocks of the Earth. The energy can be released by elastic strain, gravity, chemical reactions, or even the motion of massive bodies. Of all these the release of elastic strain is the most important cause, because this form of energy is the only kind...

Fault plane—The plane along which the break or shear of a fault occurs. It is a plane of differential movement, that can be vertical as in a strike slip fault or inclined like a subduction zone fault.

Fault zone—Since faults do not usually consist of a single, clean fracture, the term fault zone is used when referring to the zone of complex deformation that is associated with the fault plane.

Lithosphere—the outer solid part of the earth, including the crust and uppermost mantle. The lithosphere is about 100 km thick, although its thickness is age dependent (older lithosphere is thicker).The lithosphere below the crust is brittle enough at some locations to produce earthquakes by faulting, such as within a subducted oceanic plate.

Locked fault—a fault that is not slipping because frictional resistance on the fault is greater than the shear stress across the fault (it is stuck). Such faults may store strain for extended periods that is eventually released in an earthquake when frictional resistance is overcome.

Mantle—the part of the earth's interior between the metallic outer core and the crust.

Strain—Strain is defined as the amount of deformation an object experiences compared to its original size and shape. For example, if a block 10 cm on a side is deformed so that it becomes 9 cm long, the strain is (10-9)/10 or 0.1 (sometimes expressed in percent, in this case 10 percent.) Note that strain is dimensionless. Learn more: http://www.uwgb.edu/DutchS/structge/stress.htm

Stress—Stress is defined as force per unit area. It has the same units as pressure, and in fact pressure is one special variety of stress. However, stress is a much more complex quantity than pressure because it varies both with direction and with the surface it acts on. Learn more: http://www.uwgb.edu/DutchS/structge/stress.htm

Subduction— the process of the oceanic lithosphere colliding with and descending beneath the continental lithosphere.

Subduction zone—the place where two lithospheric plates come together, one riding over the other. Most volcanoes on land occur parallel to and inland from the boundary between the two plates.

Tectonic earthquake—an earthquake that is due to the movement of the tectonic plates. Tectonic earthquakes will occur anywhere within the earth where there is sufficient stored elastic strain energy to drive fracture propagation along a fault plane. Other earthquakes can be caused by blasts.

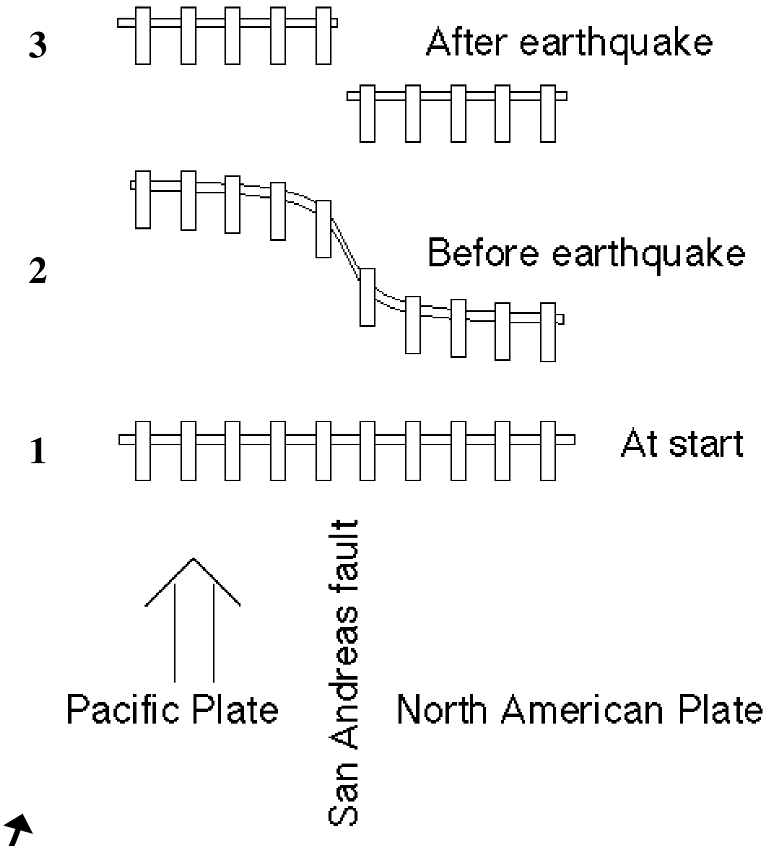
Tectonic plates— the large, thin, relatively rigid plates that move relative to one another on the outer surface of the Earth.

Elastic Rebound Theory

(from USGS' Reid's Elastic Rebound Theory)

From an examination of the displacement of the ground surface which accompanied the 1906 earthquake, Henry Fielding Reid, Professor of Geology at Johns Hopkins University, concluded that the earthquake must have involved an "elastic rebound" of previously stored elastic stress.

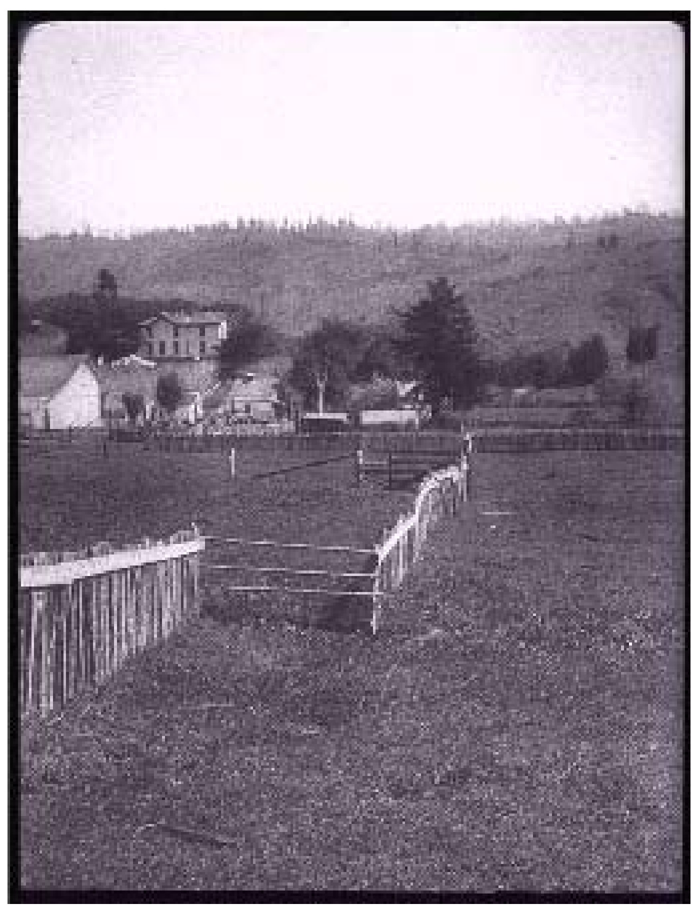
If a stretched rubber band is broken or cut, elastic energy stored in the rubber band during the stretching will suddenly be released. Similarly, the crust of the earth can gradually store elastic stress that is released suddenly during an earthquake.



This gradual accumulation and release of stress and strain is now referred to as the "elastic rebound theory" of earthquakes. Most earthquakes are the result of the sudden elastic rebound of previously stored energy.

The diagram upper right illustrates the process. Start at the bottom. A straight fence is built across the San Andreas fault. As the Pacific plate moves northwest, it gradually distorts the fence. Just before an earthquake, the fence has an "S" shape. When the earthquake occurs the distortion is released and the two parts of the fence are again straight; but now there is an offset.

This diagram greatly exaggerates the distortion. Actually, the distortion is spread over many miles and can only be seen with precise instrumentation (e.g. GPS).



This picture, taken near Bolinas in Marin County by G.K. Gilbert, shows a fence that was offset about 8.5 feet along the trace of the fault (from Steinbrugge Collection of the UC Berkeley Earthquake Engineering Research Center ***Larger Image****).*