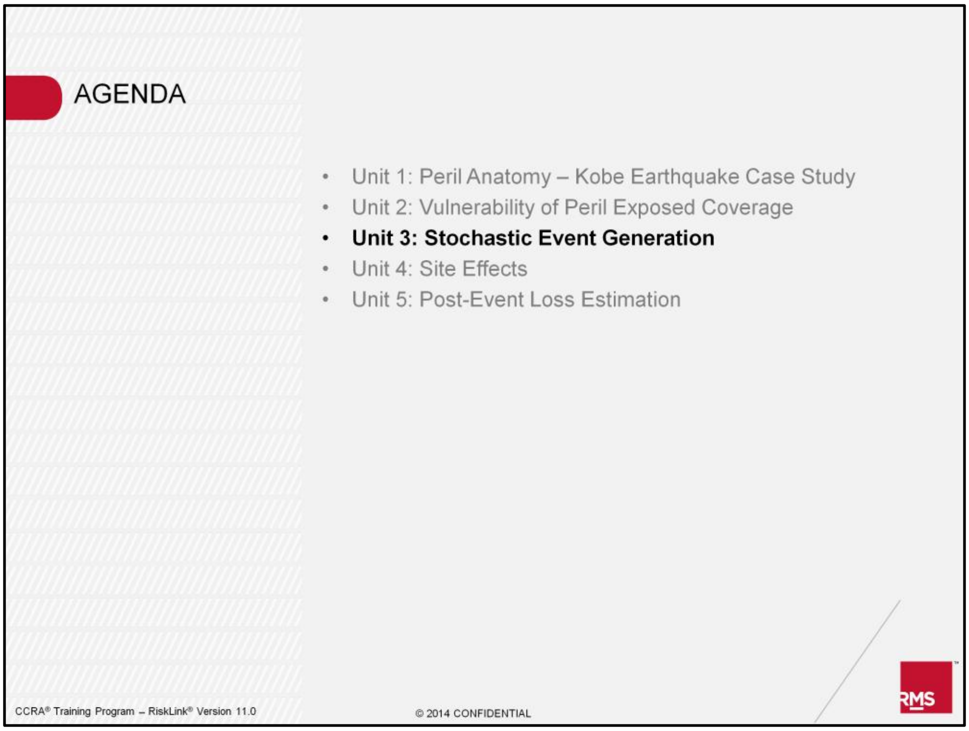
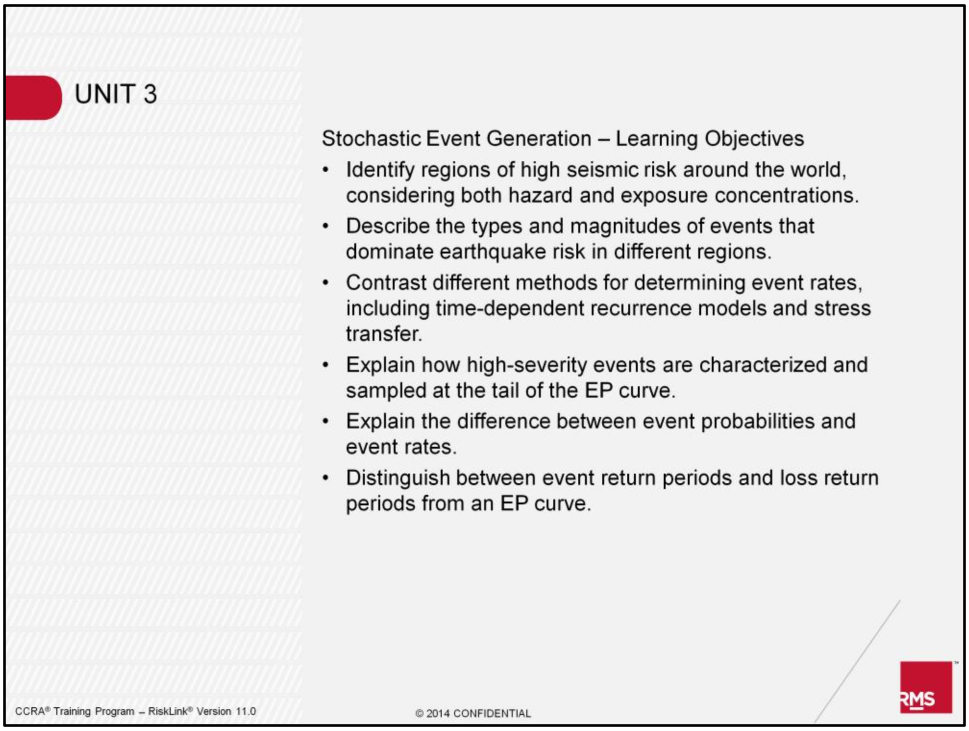
EARTHQUAKE MODELING UNIT 3

RMS® CCRA® Training Program

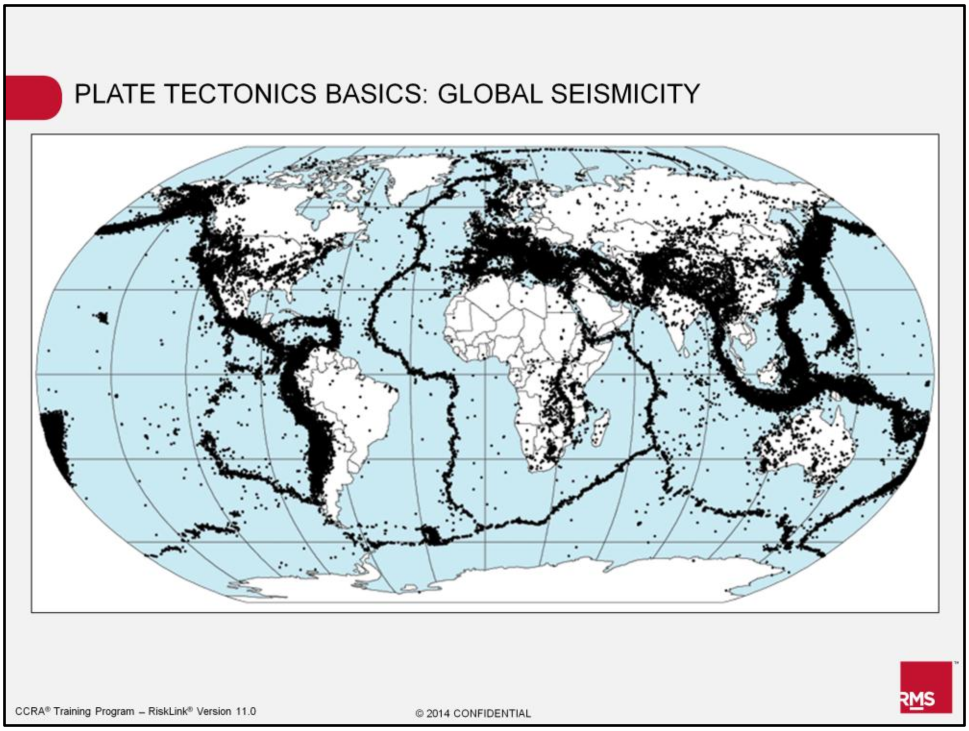
Certified Catastrophe Risk Analyst



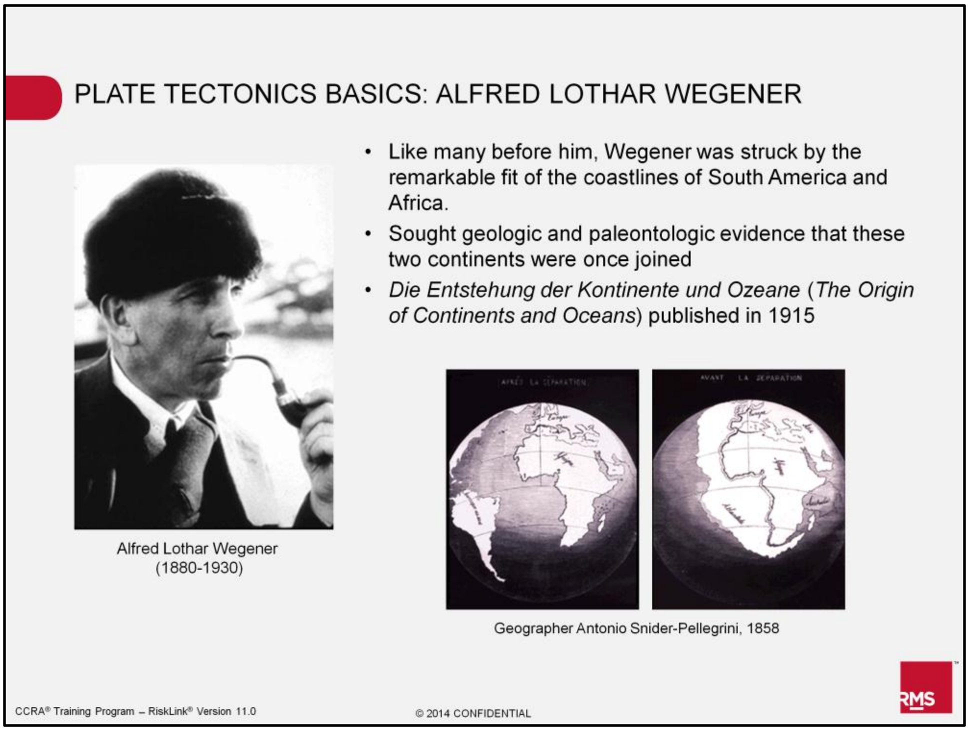
This unit will discuss stochastic event set generation and explore how events are characterized.



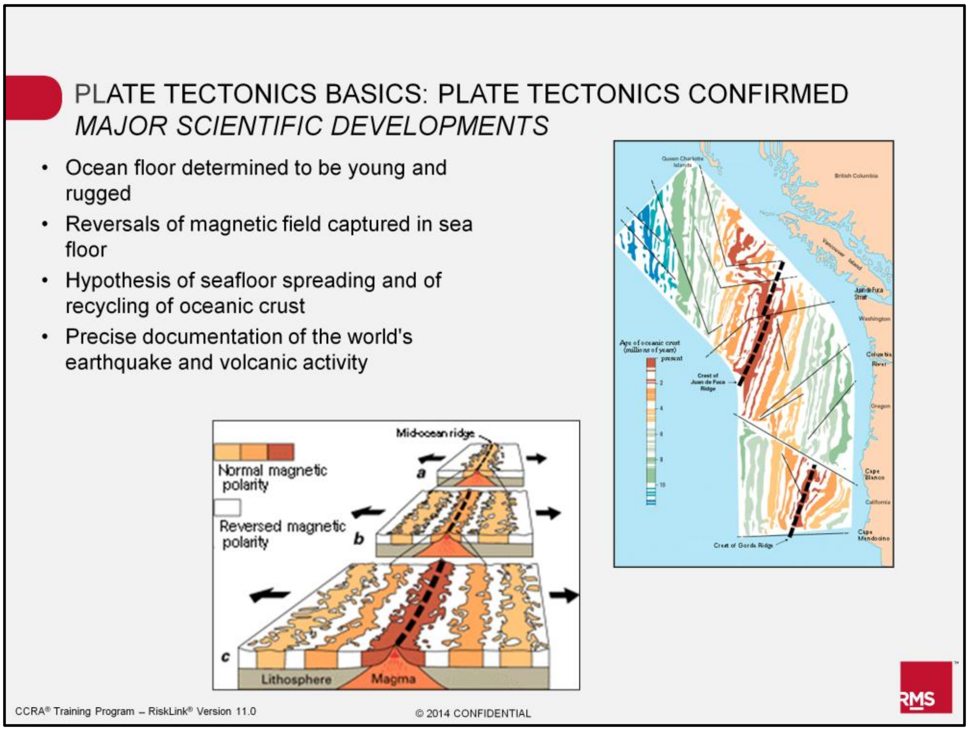
At the end of this unit you should have a good understanding of each of the six learning objectives listed on this slide.



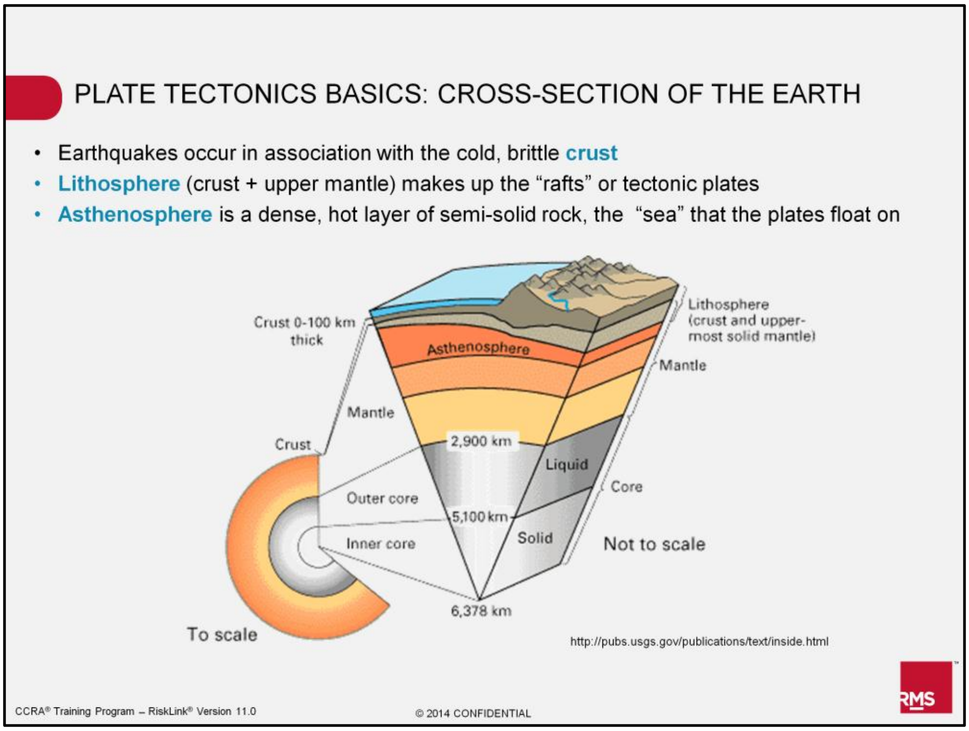
You may already be familiar with plate tectonics but we will start by giving you some background on the subject. This map shows more than 350,000 earthquake events that occurred over a 35 year period. You can see that the earthquakes are showing clear boundaries with large plates that are on the Earth's surface. Most of these plates have continents within them. A few of them, like the Pacific, are all oceanic crust. We will talk about the differences between oceanic crust and continental crust in terms of earthquakes shortly.



What is the origin of plate tectonics? About 150 years ago, a number of researchers noticed how the South America plate and the African plate looked like they would fit together, but there were a lot of questions about how these plates might have moved apart. At the time there was no understanding about what was happening on the ocean floor. There was no imaging and very little information about where earthquakes were occurring. Around the turn of the 20th century, Alfred Lothar Wegener was very interested in this issue and sought out geologic and paleontologic information. In 1915 he published a hypothesis of this plate tectonics idea. Because his hypothesis lacked an explanation for why the tectonic plates would be moving, Wegener's ideas where not well received by the scientific community. It was not until several decades later that scientific observations were able to confirm his ideas.



But then in the 1950s and 1960s researchers became more aware of what was happening on the ocean floor. Imaging of the ocean floor showed it was very young and very rugged. It was also noticed that the magnetic field on the earth switches direction and striping could be seen on the ocean floor, which indicated that the crust was progressively older away from the risk zones that were now identified. Through this process of collecting more data in the 1950s and the 1960s, it was realized there really is a mechanism explaining plate tectonics and it has gone from being a theory to being a well understood mechanism for earthquake generation on the planet.



This slide shows an image of a cross section of the earth from the inner core. You can see that at the very top surface we have what is called the crust. The crust is very cold and brittle and within the crust is where earthquakes occur. The lithosphere is a combination of the brittle crustal material with hotter, softer material referred to as the upper mantle, and forms the tectonic plates. The tectonic plates, or rafts, float on the very hot asthenosphere. It is possible that convection within the asthenosphere drives plate tectonics, but the mechanism by which the plates themselves move is still very poorly understood and there is still a lot of research to be done in this area.

PLATE TECTONICS BASICS: CONTINENTAL VS. OCEANIC CRUST

Continental Plates

- Composed of granitic rocks that are made up of relatively lightweight minerals such as quartz and feldspar.
- Crust under the continents is much thicker, as much as 100 km.
- Like icebergs, continents have deep "roots" to support their elevations.

Oceanic Plates

- Composed of basaltic rocks that are much denser and heavier.
- Crust under the oceans is generally only about 5 km thick.

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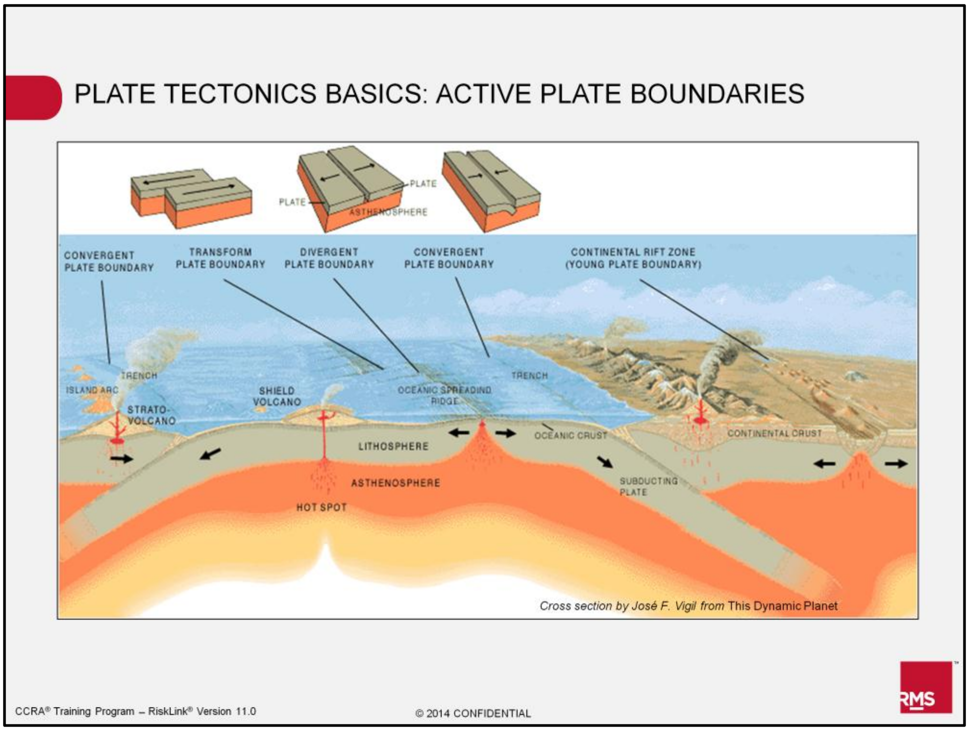
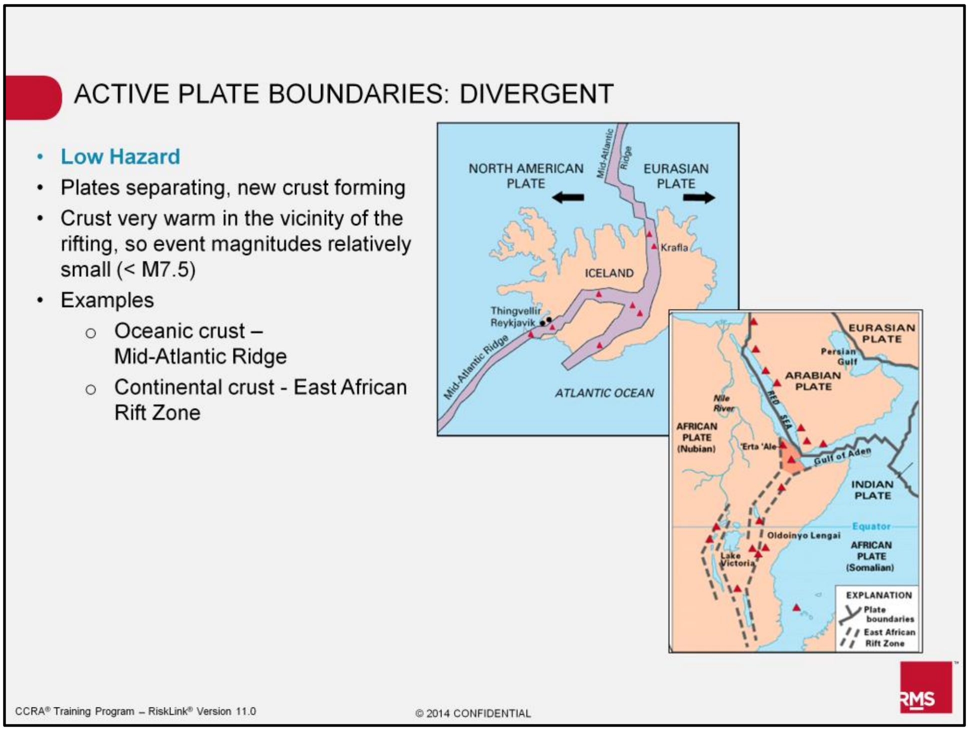
There are essentially two types of crust on the planet; continental crust and oceanic crust. Continental crust is very thick, at times as much as 100 kilometers thick. It is made of granitic rock, which is the lighter minerals quartz and feldspar, and is relatively lightweight so it floats very well. These pieces of continental crust float like icebergs and have deep roots that support their high elevation.

Oceanic crust is very young. It is very dense and heavy, and tends to be very thin.



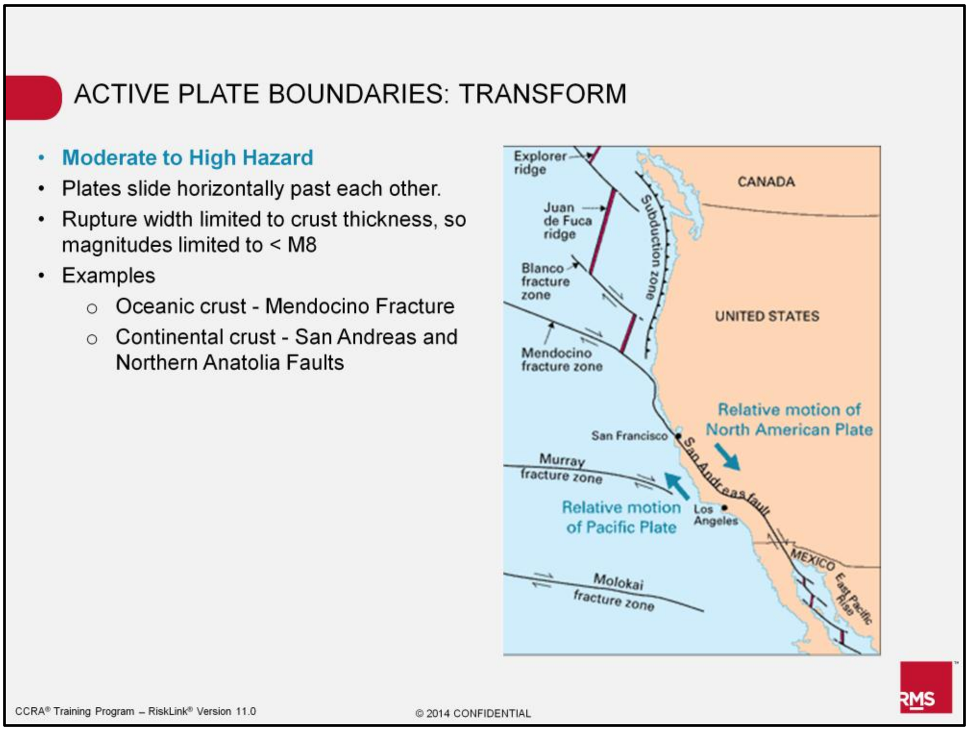
Looking at the roles of these two types of crust in plate tectonics, there are essentially three kinds of active plate boundaries. A transform plate boundary is where plates are sliding past each other. Divergent plate boundaries are places where the plates are moving apart from each other. And then there are convergent plate boundaries, where two plates are colliding together.

The cross section on this slide shows all of the plate boundaries in proximity to each other. In general, we do not see this many active plate boundaries together but you can see that when a convergent plate is pushed beneath another, this creates a critical component to generating very large earthquakes. We will now walk through each of these active plate boundaries in more detail so we understand how earthquake are generated within them.



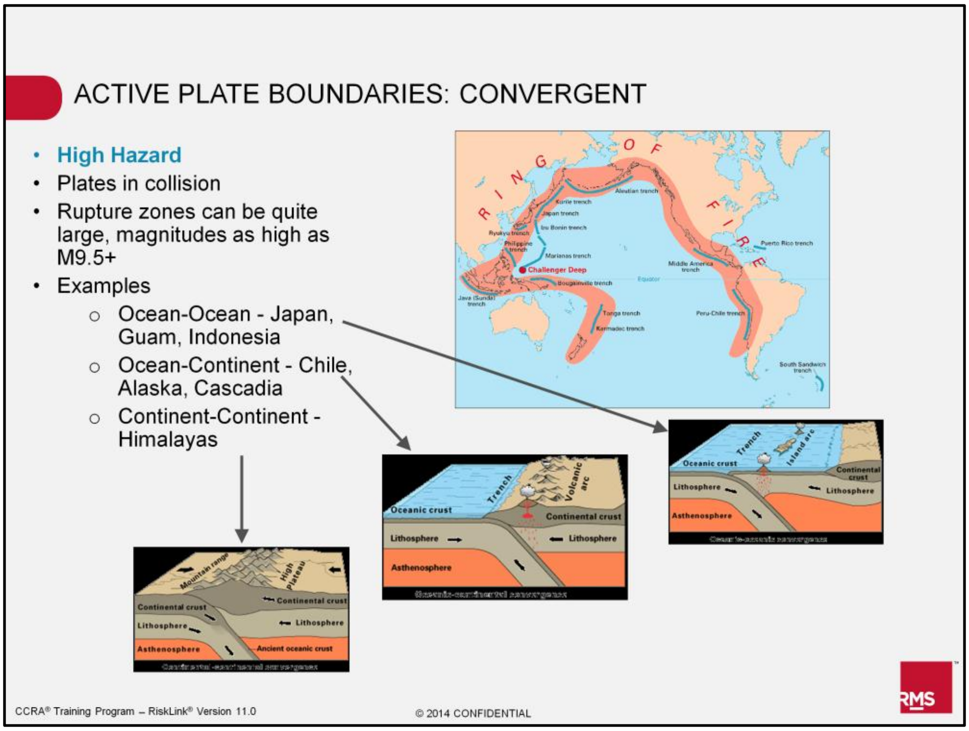
The divergent boundary is the boundary with the lowest hazard. In the divergent boundary, two plates are slowly moving away from each other and new crust is being formed. Think of plate motions on the order of how fast your fingernails grow. So the plates are moving apart at a very slow rate. Oceans open on the order of hundreds of millions of years with the plate movement. There are two places with divergent plate boundaries with which you may be familiar. In the Atlantic is the Mid-Atlantic Ridge. The upper map of Iceland shows that Iceland lies on the Mid-Atlantic Ridge. It is an island formed from this rifting where a large amount of magmatic material comes up.

The other example of rifting is the East Africa Rift Zone. In this area the eastern part of Africa is slowly moving away from the rest of the continent and forming a large rift zone where there is a lot of volcanic activity and new plate development. In general these environments are very warm. There is a lot of hot material coming up. This warm material warms up the crust. As a result the crust is not as brittle and cannot generate as large an earthquake as would be seen in a colder environment. This is also true in volcanic areas such as Hawaii. Generally the magnitude of earthquakes associated specifically with volcanic activity will be relatively low, less than M7.5, limited by the fact that materials are very warm in that area.



This slide shows a transform plate boundary. This has a moderate to high hazard depending on how long the system has existed. The plates in a transform plate boundary are sliding past each other horizontally. The San Andreas Fault is a well known example of this, as is the northern Anatolia Fault in Turkey. The magnitude of events associated with this type of environment depends on the length of the major boundary. The San Andreas is a system that has existed for over five million years. It is a long system that can generate events that rupture large segments or long lengths of the fault; the longer the length of the fault that ruptures, the larger the magnitude. These well deformed older strikes of systems can generate events up into the low magnitude eights but in general we do not expect magnitude events quite this large from transform boundaries. The M7.0 event in 2010 that severely impacted Port-au-Prince, Haiti occurred on the transform boundary between the Caribbean and North American tectonic plates.

There are transform boundaries that are not on continents but within the oceanic plate. In general they are off-shore and are not known as major sources of earthquakes. While they certainly can generate earthquakes, they do not generate earthquakes that cause financial losses. A particularly well-known example in the California area is the Mendocino fracture zone, which extends off the northern coast of California off into the Pacific.



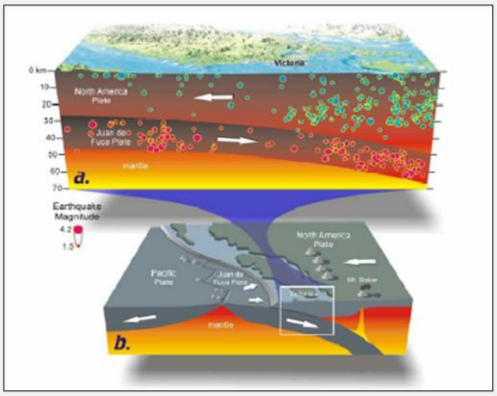
The most important plate boundary from a hazard perspective is the convergent boundary. These are very high hazard because there are two plates in collision. There are three ways plates can collide. First, an oceanic plate can collide with another oceanic plate. In this environment, shown in the first image on the far right, one oceanic plate is going underneath the other. Typically when plates collide, one will be pushed beneath the other. Often these generate volcanoes. The volcanoes in Japan were created by an oceanic plate pushing beneath another oceanic plate.

Secondly, a continental collision occurs when one continental plate collides with another. This is common in the Himalayas where India is colliding with the rest of Asia and pushing up very large mountain ranges.

Finally, the most common convergent boundary, in terms of generating very large earthquakes, is when a continental plate collides with an oceanic plate. This is happening around most of the Pacific Rim. The earthquakes generated can be up into the magnitude 9.5 or higher. The 2004 Indonesian, 2010 Chile, and 2011 Japan earthquakes were convergent boundary events and show how devastating they can be. These earthquakes are generated along the interface between two plates; the contact between these two plates is what generates these large earthquakes.

CONVERGENT PLATE BOUNDARIES AND EARTHQUAKES

- Subduction zones occur when an oceanic plate is pushed beneath either an oceanic or continental plate.



http://www.seismo.nrcan.gc.ca/hazards/13wcee/13WCEEp1065Onur_Seemann.pdf

- Subduction interface events occur along the surface of contact between the two plates (up to M9.5+).
- Subduction intraslab events occur within the subducting slab (up to M7.25).
- Crustal earthquakes occur within the over-riding continental plate (up to M8).

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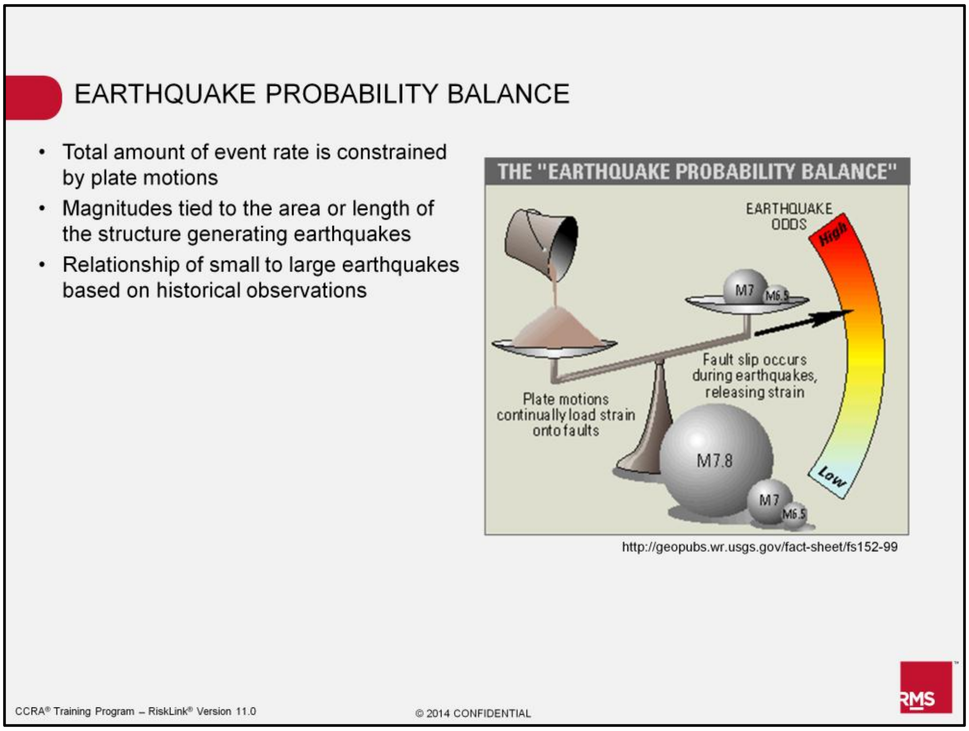
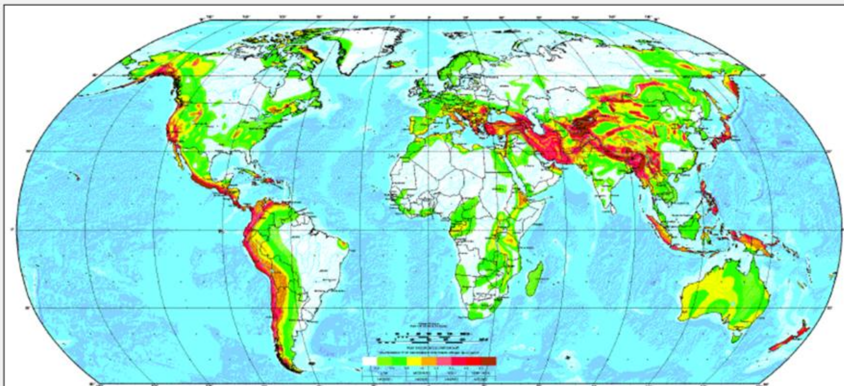
We will look at the convergent plate boundary in a little more detail to understand the different types of earthquakes associated with them. Typically an oceanic plate is being pushed underneath a continental plate. Interface events, events that occur along the surface where the two plates are in contact, can be very large. But there is a whole suite of other events that occur in these environments. Because there are so many stresses being placed on the plates being pushed together, there are also events within the overriding plate and events in the plate being pushed beneath another. The plate that is pushed beneath another is not only being forced down beneath the other plate but it is also typically being bent as it is forced down into the earth. This results in what are called intraslab earthquakes. Intraslab earthquakes can be quite large, up to a magnitude 7.25. The Nisqually earthquake in the Pacific Northwest is an example of an instraslab earthquake. Crustal earthquakes occur above the subducting slab in the plate above the interface. The image on this slide shows a zoomed in look at the interaction between these two plates. The arrows indicate the direction of motion. The plates are moving in opposite directions. The earthquakes shown in blue are in the shallow crust and are the result of stretching in this part of the crust. The earthquakes shown in red are intraslab earthquakes where the plate is being bent and pushed beneath another plate.



We have looked at the different kinds of earthquakes that can be generated in these different environments. The main process that defines how often earthquakes occur is constrained by plate tectonic motions. The image on this slide shows the earthquake probability balance. The plate motion is a continuous load on the fault and then the earthquake releases these stresses. The size of the earthquake determines the amount of stress released. How often earthquakes occur depends on what size earthquakes can happen on a particular fault and how much of the plate motion is constrained to that structure. In general, small earthquakes are much more likely to occur than large earthquakes and the relationship of small to large earthquakes and how often they occur is based primarily on historic observation.

GLOBAL SEISMIC HAZARD MAP



Global Seismic Hazard Assessment Program (GSHAP): http://www.seismo.ethz.ch/gshap/

- Landscape dominated by convergent plate boundaries
- Secondary in importance is major strike-slip fault systems

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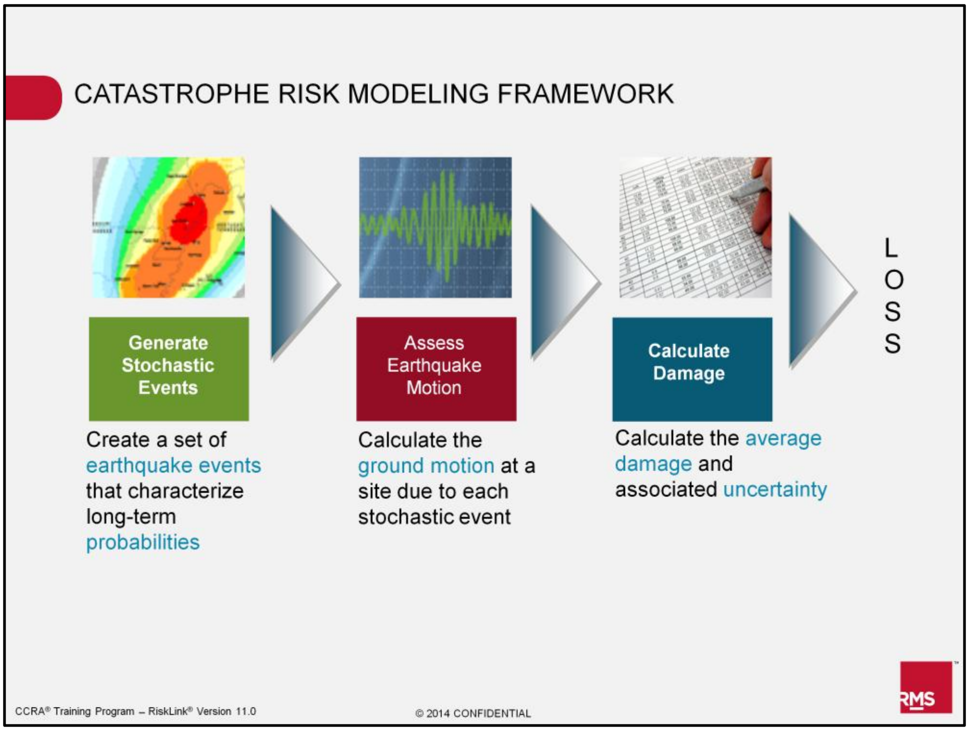
Now that we have looked at the different types of earthquakes that can be generated, let's take a look at a hazard map of the globe. This map shows all of the current understanding of seismic activity around the world. Experts from different parts of the world have put together their own regional seismic maps. A few years ago these were all brought together to create a comprehensive look at global seismic risk.

The first thing that becomes obvious is that all of the continents around the Pacific, in other words the Pacific Rim, have very high hazard. There is a major subduction zone in Alaska, there is a subduction zone off the coast of the Pacific Northwest, there is a major transform zone in California, and off of Mexico and in all of South America there is a major subduction zone. In the east on the Asian boundaries, there is a subduction zone in New Zealand as well as in Papua New Guinea, the Philippines, Taiwan, Japan, the Kurils, and Kamchatka. The Pacific Rim is ringed by very large subduction forces and that is why this area is particularly sensitive to earthquakes. The map also shows that central Asia is under a lot of stress. India is colliding with Asia resulting in extensive deformation and pushing up in the Himalayas. There are also some major strike slip faults in China and Mongolia that have developed over millions and millions of years that can generate events into the high magnitude eights.

Strike slip faults are also important as there are many major population centers on major strike slip faults. Turkey is a good example. The subduction zones along the coastlines and the major strike slip faults in the crusts within continents are the main drivers of seismic risk around the world.



Next we will talk about how stochastic events are generated. The first step in creating a catastrophe risk model is the stochastic event generation. We need to determine how often, how big, and where earthquakes are likely to happen. Once we have that information, we then determine the impact for an individual event. We look at its ground motions and, for individual locations, we look at the site effects. Then we need to calculate the damage and take into account the uncertainty to determine the loss.

STOCHASTIC EVENT SET GENERATION

- Definition:
  - A stochastic event set is a set of uniquely defined simulated earthquakes incorporating probabilistic assessments of events over long periods of time.
- Based on, but not purely representative, of the historical record.
- Elements of earthquake stochastic event set creation:
  - Geometric characterization of earthquake source
  - Parametric characterization of earthquake source
    - Magnitude
    - Rate
    - Parameter uncertainty

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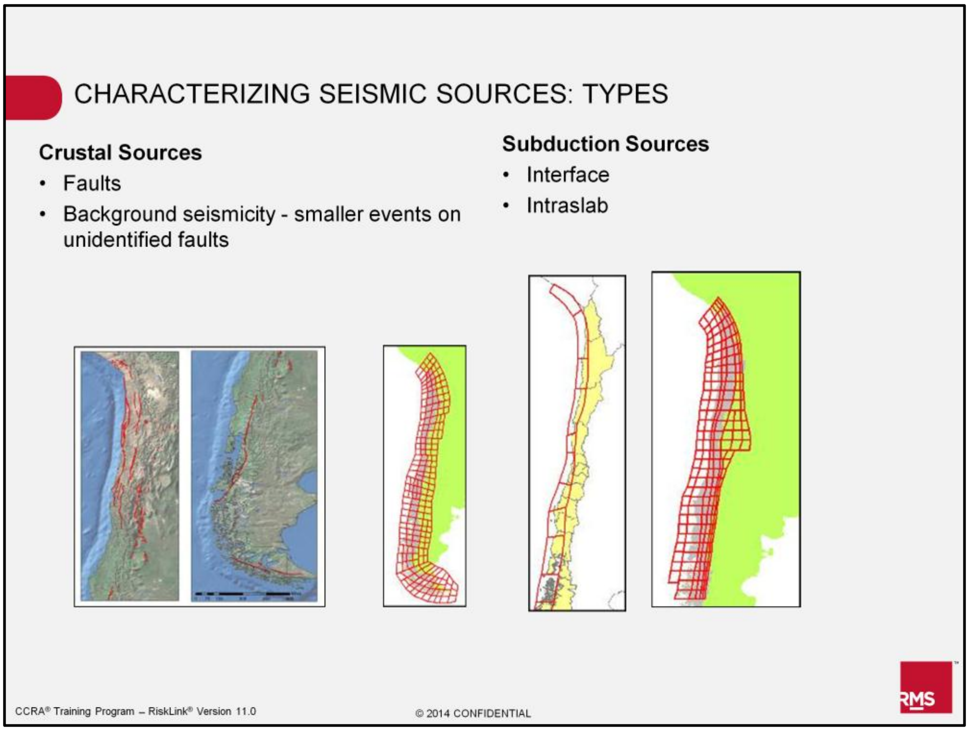
It is important to remember that the stochastic event set does not represent the historic record. It is based on the historic record but is a representation of the events we feel are likely to occur in that region. It is a unique set of events that cover all the possibilities and look at very long term records. We need to determine the geometry of the sources as well as the parameters for them. In the next few slides we will walk through the steps of this process.



There are four types of sources that are included within a seismic hazard model. You will look at these distinctions when you do the exercise for this course. We will start with crustal faults. You have seen that within the continental crust there are major fault systems and there are also minor fault systems. These have not been studied in a consistent way across the globe. In the U.S. we have a good sense of where the major fault systems are but this is not necessarily the case in other parts of the world. To accommodate for this, we have generated the background seismicity sources. The images on the left show the background sources used to model crustal events not associated with known faults. All of these images are from Chile. We have one set of crustal sources that are faults and we have one set of crustal sources that are area zones that take into account the events that are not attributed to faults. We also use them to model smaller magnitude events that might be associated with faults.

Not every source model is going to need subduction zones but in many cases these are necessary. For example, there are no subduction zones in the California earthquake model but in Chile there are subduction zone sources. For regions that have subduction zones, we always include two types of sources; the interface zone and the intraslab zone. The interface source is for the events that happen between the two tectonic plates and the instraslab source is used to model events where one plate is being forced beneath another.

CHARACTERIZING SEISMIC SOURCES: GEOMETRY

Types of sources in RMS models

Interface, Intraslab and Non-Vertical Fault Sources

- Dipping plane sources
  - Seismicity associated with defined dipping plane or broad zone of faults

Vertical Faults

- Line sources
  - Seismicity associated with well-defined vertical structure usually strike-slip faults (no processing advantage to including as vertical plane)

Background Seismicity Zones

- Area sources
  - Accounts for seismicity not associated with known faults over a broad region

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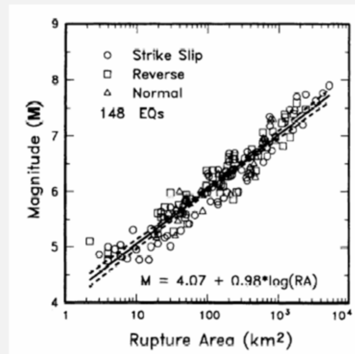
How exactly are these modeled? Because the interface, intraslab, and non-vertical faults are all dipping sources, we model these in three dimensions. There are a number of strike-slip faults, however, that are vertical faults and there is no processing advantage to modeling the vertical faults in three dimensions. It actually simplifies the calculations to model them as line sources.

Then there is background seismicity. These are modeled as areas that do not dip. They are broad zones and they are modeled using a series of sub-parallel line sources that are oriented according to the primary stress orientations of the region.

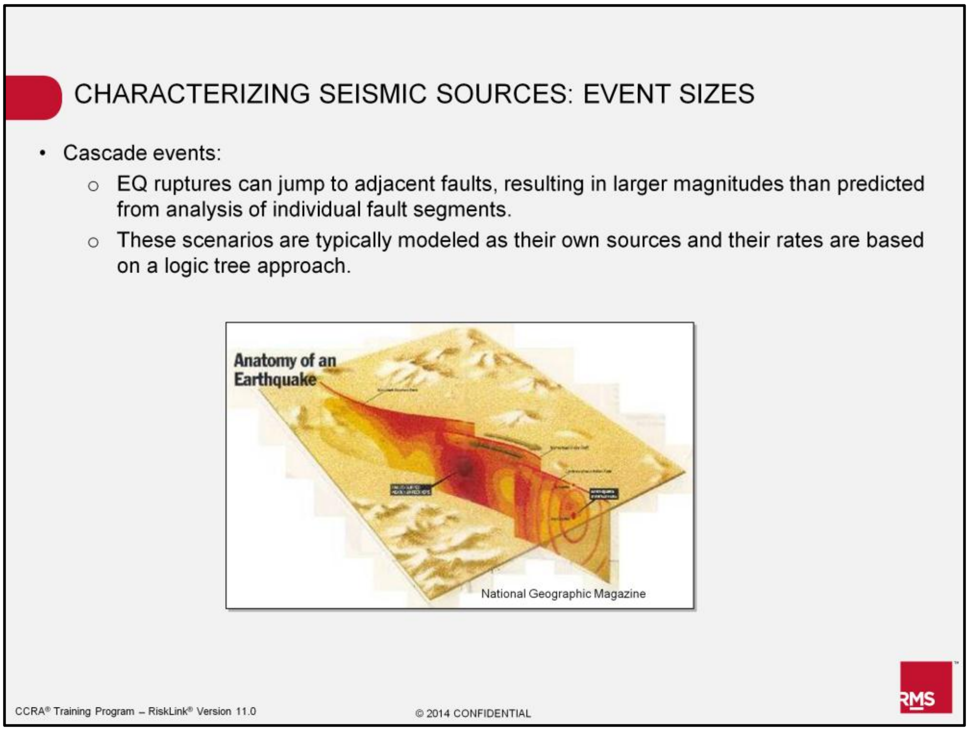
CHARACTERIZING SEISMIC SOURCES: EVENT SIZES

- The upper bounds for events on a given structure are estimated from fault dimensions (area or length).
- Characteristic Magnitude:
  - The largest expected event on a fault based on fault dimensions.
- Maximum Magnitude:
  - Largest credible earthquake taking into account uncertainty in characteristic magnitude.
- Typically the maximum magnitude will be 0.2 to 0.5 magnitude units greater than the characteristic event but is attributed very little to rate.



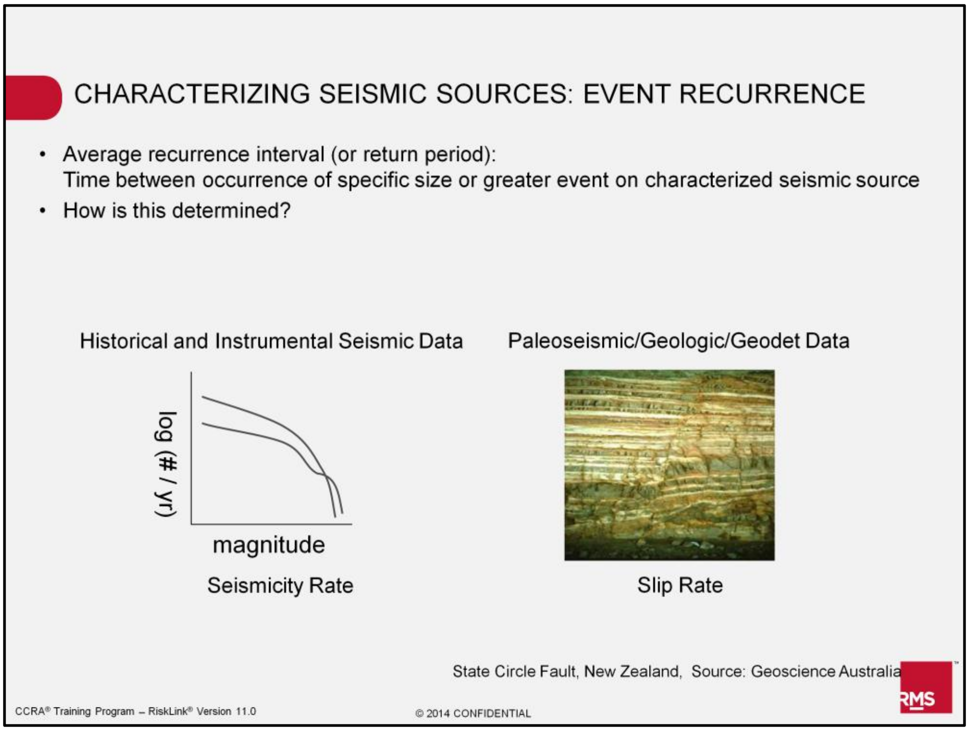
Wells and Coppersmith, 1994
Magnitude – Rupture Area Relationship

We have talked about how we characterize the location of source zones now lets talk about how we characterize event size. There are two important definitions when looking at event size; the characteristic magnitude and the maximum magnitude. The characteristic magnitude is the expected largest event that the source can produce based on its dimensions. The plot on this slide shows the magnitude rupture area relationship from Wells and Coppersmith. This is a well-known relationship that is used in many different studies. You can see that while there is a linear relationship that falls down the middle of this scatter of information that is based on historic events, we have a rupture area not plotted against magnitude. There is quite a bit of scatter. The relationship helps us determine what the characteristic magnitude would be but there is still quite a bit of uncertainty about what that magnitude is. And that is why we have the concept of maximum magnitude. We allow for events larger than the characteristic magnitude by taking into account the uncertainty in that characteristic magnitude determination. The maximum magnitude is the largest possible earthquake that we take into account on that source. Typically the maximum magnitude is going to be between 0.2 and 0.5 magnitude units higher than the characteristic magnitude. But it is important to understand that we are taking uncertainty into account and that these larger magnitude events actually are much less likely. They require much more seismic moment or flip rate to be generated so they are not going to happen very often. They are included in the event set but are given very little weight.

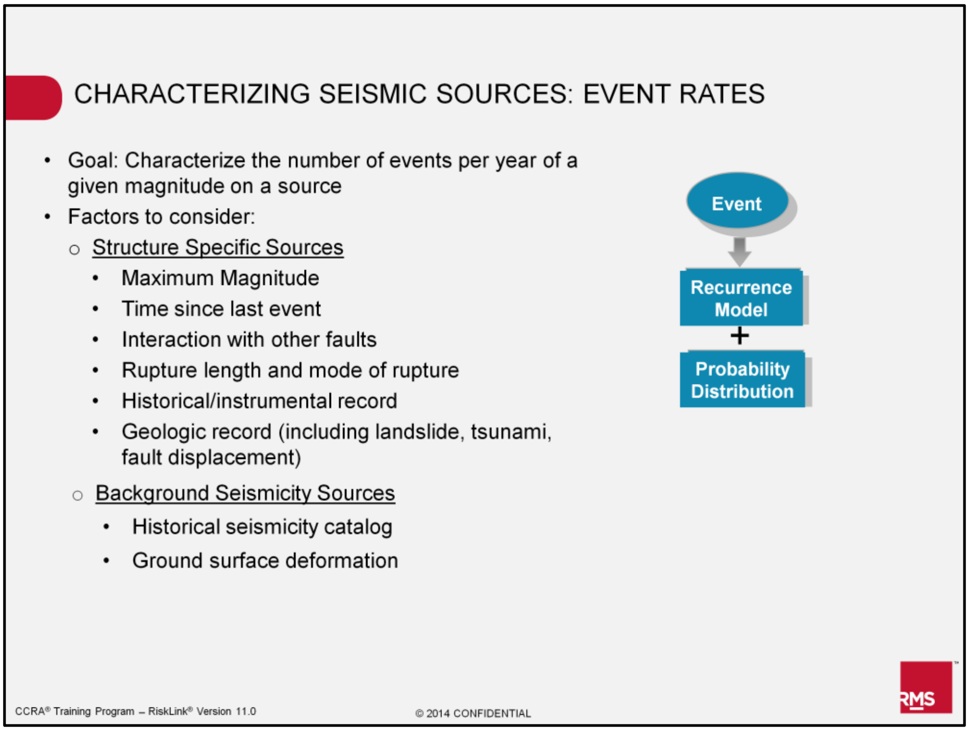


Another thing to consider when looking at event size is that in some cases these events will propagate from one source to another. These events are called cascade events. Cascade events only occur in an environment where there are faults end-to-end, such as major strike slip systems. Recent examples of this include the Landers earthquake and the Hector Mine earthquake in California where multiple end-to-end faults were ruptured. A more well-known example is the 1906 earthquake that ruptured many segments of the San Andreas Fault in California. Because we know these types of events can occur, they are typically included within the event set as their own structures. The image shows three faults rupturing together in the Landers earthquake. These would be included in the event set as individual structures with their own event rate probabilities and event distribution.

When looking at modeling cascades on a system with three fault segments (A, B, and C) like the one shown, all the possible combinations of rupture are considered. This includes the possibility of the individual segments going alone, the two-segment pairs (AB and BC), and finally all three segments combined (ABC). They are weighted through a logic tree approach. We look at all the different examples of possible outcomes and we distribute the amount of slip across the fault to the different options to come up with event rate.



Next we will talk about event rate. The goal in looking at event recurrence is to determine the time between different events so we can characterize risk on that source. There are a couple of different ways to look at how often earthquakes happen on particular sources. When we look at faults in particular, we can look at seismic data or we can actually look at the ground in a trench to view slip rates. The first approach is very numerical, looking at the statistics of the seismic data. We look at small events to infer how often the big events happen because generally the big events do not happen very often. When looking in a trench or at the geology, we are only looking at the very big events so we will have to infer from them how often the small events occur. We have information about small events and we have information about big events but often when we try to infer back the same information for a single source they do not always link up. There are still clearly developing areas within the science of how often earthquakes occur.



Once we have defined how large the events on a source can be, we need to determine the rate for the events that the source can produce. To determine the final event rates, we combine the recurrence of events on a source with a particular probability model.

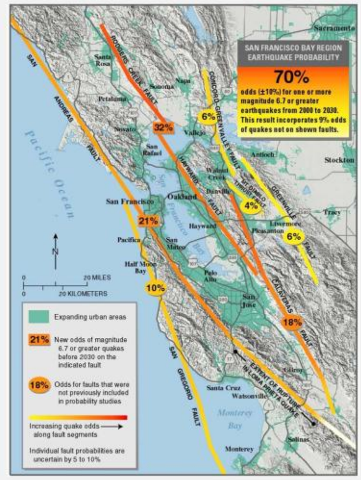
To determine the recurrence on specific structures, very detailed information about past events may be available in the historical and geological record. The geological record can be examined by deposits directly over the fault to see how and when it has been impacted by earthquakes. In many cases, these types of studies can produce chronologies of a few to a dozen events. This particular field of science is called paleoseismology. Mapping and areal photography of the fault can also be used to determine the length of rupture of past events and the mode of rupture (e.g., strike slip vs normal).

In some cases, and typically for background seismicity sources, very little information will be available to help define event recurrence so rates of smaller events may be used to infer rates of bigger events. Alternatively, ground deformation studies may point to slip rates on faults that can be used to determine how often events occur.

The next step is to combine a recurrence model of how often earthquakes happen with a probability distribution. The choice of probability distribution depends on the data available and the type of approach to be used. For example, do the events happen without interaction between them? Do they happen randomly in time? Is there some time dependence, or is there some sort of stress interaction?

COMMON MISCONCEPTION
PROBABILITIES VS. RATES

- Not interchangeable
- Rates represent the long-term (100k to millions of years) occurrence frequency for an event of a particular magnitude or greater.
  - The inverse of the rate is the return period of an event of that magnitude or greater.
- Probabilities are the chances of an event happening for a particular time window and distribution (e.g., normal or skewed).



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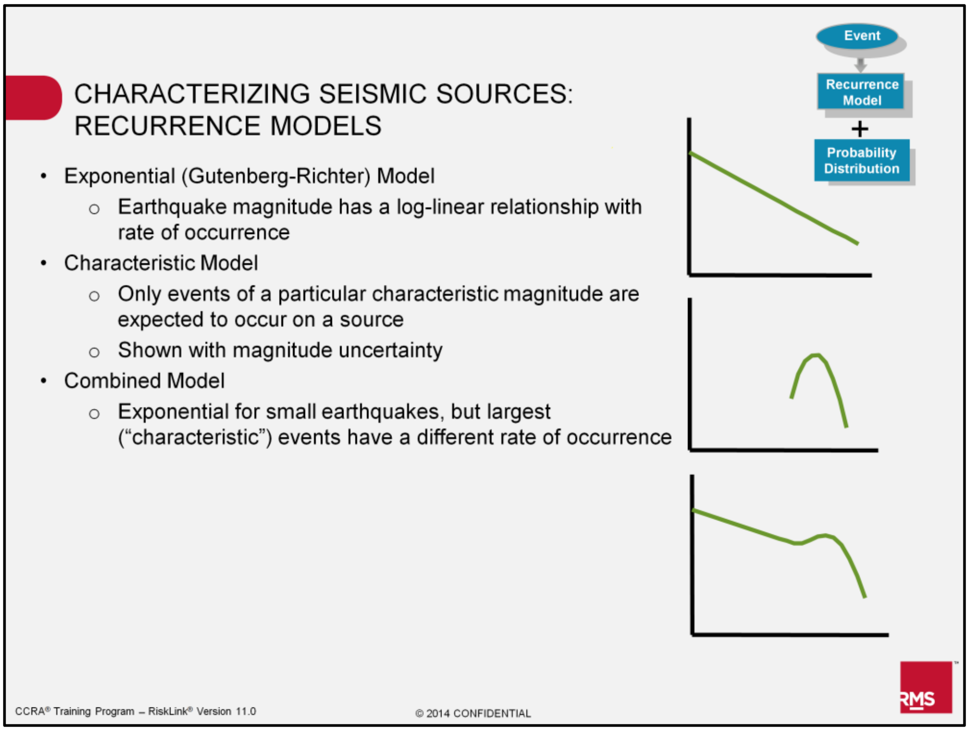
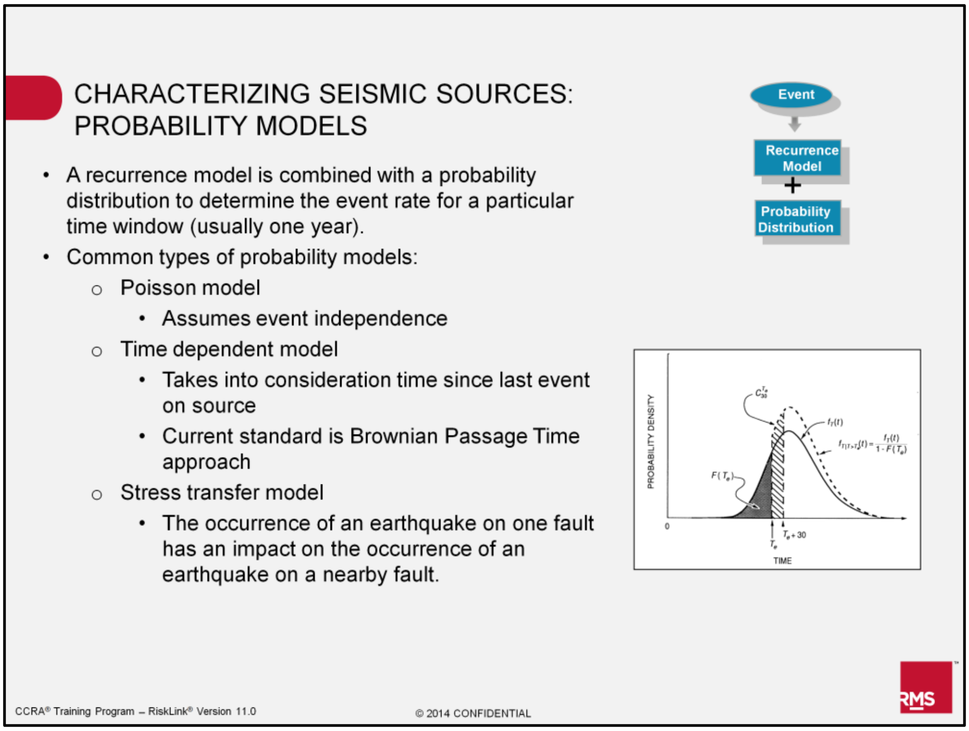
Next we will look at a common misconception regarding probabilities and rates. We often get questions that make it apparent people are confusing probabilities and rates, which cannot be used interchangeably. Rates represent the long term recurrence in terms of tens of thousands to millions of years for the occurrence of an event of a particular magnitude or greater. For example, the San Andreas Fault, which was the source of the 1906 earthquake, generally has an earthquake about every 250 to 300 years. So the San Andreas Fault in the Bay Area has a rate of having a magnitude 7.8 or greater event on the order of one every 300 years. Probabilities, however, take more information into account. Specifically, probabilities look at the chances of an earthquake happening in a particular time window; one year or 30 years, for example. Probabilities also take into account whether we are using information about past events. To reiterate, probabilities look at the chances of an earthquake occurring in a particular time window while rates look at long term recurrence.



There are several different ways to look at how often earthquakes happen on an individual source. When we look at earthquakes globally, there is a log linear relationship between magnitudes of earthquakes. There is essentially a ten-fold higher increase in occurrence when the magnitude is decreased. In other words, there are ten times as many threes as there are fours and ten times as many fours as there are fives. This is why there are not magnitude eight or nine earthquakes very often. This applies across large regions and is the exponential Gutenberg-Richter Model. This assumption is also used to model recurrence for the background seismicity regions.

We also know that individual fault structures often have a characteristic event, which was mentioned earlier in this presentation. There is an event of a typical magnitude that occurs or repeats on that structure and we have to take into account the possibility of uncertainty around that. Because of this, the characteristic model assumes that recurrence on a structure primarily occurs, or events primarily occur, in just one range of magnitude so there is no rate associated with smaller magnitude events. This is a restrictive approach to recurrence and is often used for major subduction zones, which typically do not generate smaller events.

For less well defined fault systems with smaller characteristic magnitudes and low slip rates, we often combine these two models into what is shown at the bottom of the slide. A combination of the smaller events occurring in a log linear way but the larger events having a higher chance of occurring with a larger amount of rate being distributed at the higher magnitudes.

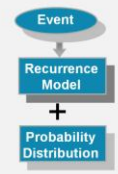


Once a recurrence model has been determined it needs to be combined with a probability distribution. For many sources there is often not enough information to determine when the last event occurred. This is particularly true outside of the U.S. When we look at fault systems, it is either unclear when the last event occurred, or the characteristic magnitude is unknown. So an assumption needs to be made that all events on that structure are time independent and we do not know when the next one will occur.

When we do have this information, we like to use time dependent recurrence. This makes the assumption that since we know when the last event occurred, we can say something about when the next event will occur. There have been a lot of developments in this field of looking at how often earthquakes happen and how they repeat. There is now a current standard within the scientific community called the Brownian Passage Time approach. This is simply a way of redistributing the rate based on when the last event occurred and how often these events are expected to occur.

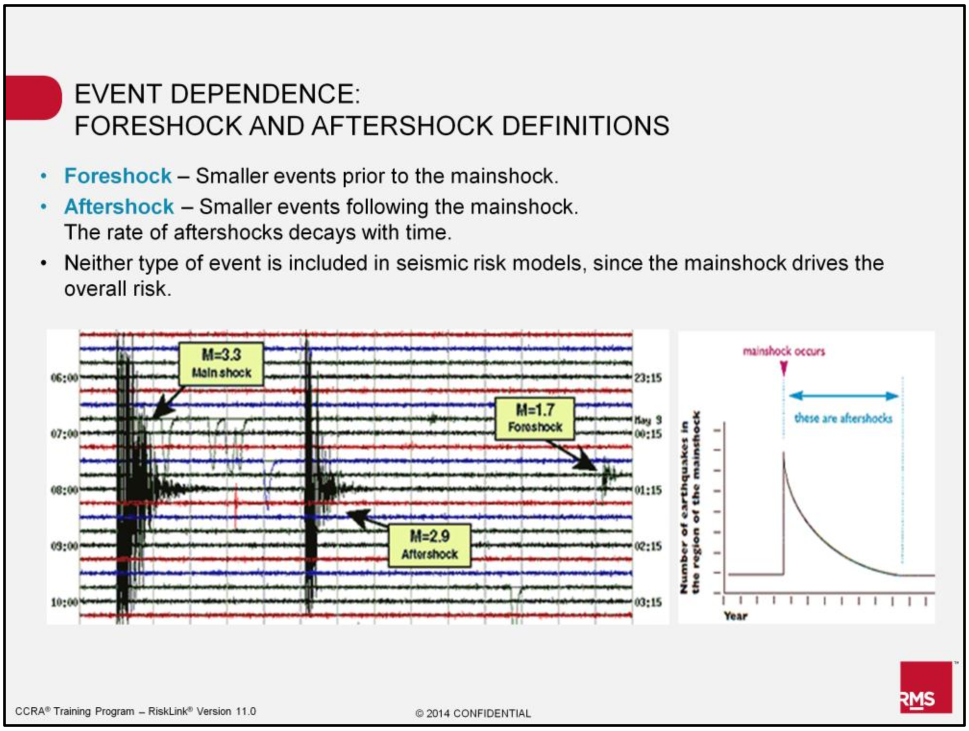
Stress transfer is also something new within seismic hazard modeling. It takes into account that when earthquakes happen on a particular fault, the stresses in the region will be impacted by that earthquake. For some structures there will be an increase in the stresses on them making the next earthquake more likely to happen. Other structures will be relaxed by the event so that the next earthquake will take more time to occur than it would have without this event.

EVENT INDEPENDENCE VS. DEPENDENCE



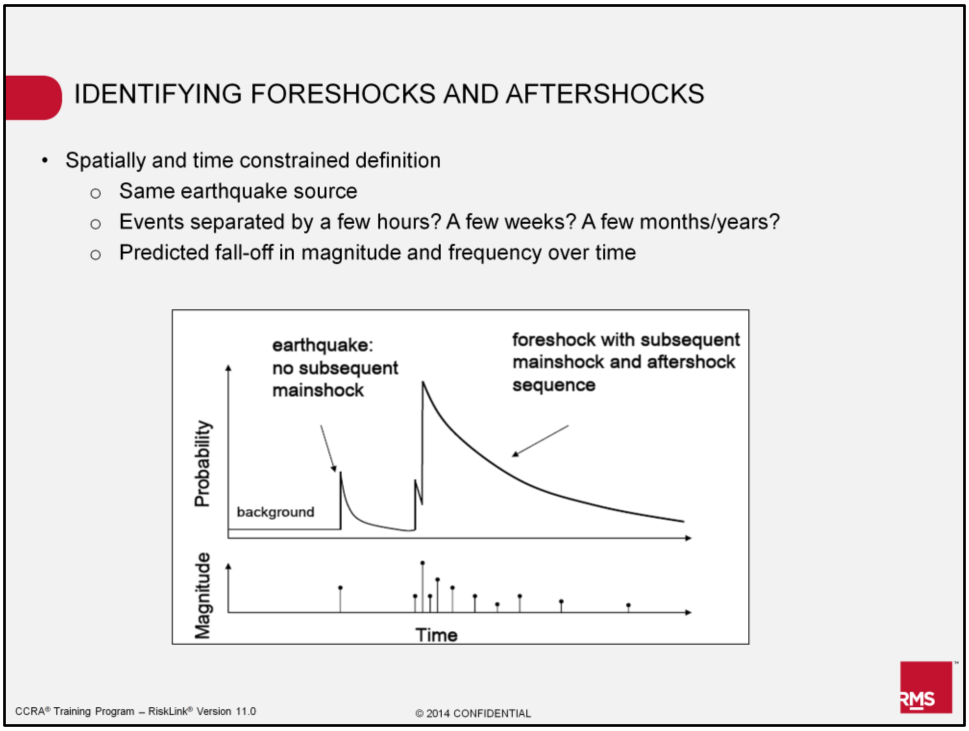
- Poisson probability distribution assumes event independence: What does this mean?
    - Each earthquake is not the precursor to, nor the result of, another larger magnitude earthquake.
    - Time consistent intervals between events of similar sizes
    - Assumptions:
        - Slip along faults is nearly constant over time
        - Other forces (e.g., stress in the crust) do not impact fault slip over time
        - It is possible to identify which events are dependent
- Incomplete historical earthquake record makes event independence a valid assumption.

What does the assumption of event independence mean? This slide provides a definition as well as a list of assumptions for event independence. Given more complete seismic information over hundreds of years, these assumptions will quite often no longer apply. Given that smaller magnitude events are not completely recorded the further back in time the historical record progresses, the less likely it is possible to identify dependent events. Thus, it is very likely that most events recorded prior to the advent of instrumental recordings are independent events not related to other smaller recorded events. Another valid generalization is that dependent events are much smaller, and thus do not significantly impact the modeling of catastrophic risk analysis results.



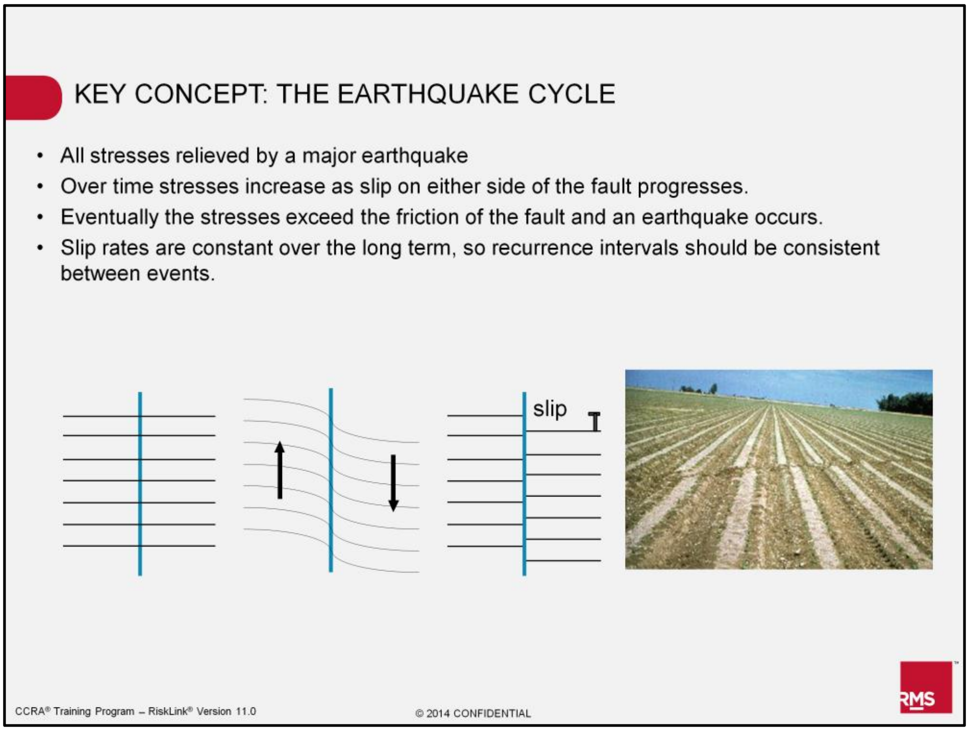
There are two types of dependent events; foreshock and aftershock events, as defined on this slide. Shown in the figure on the left is a seismogram, or recording of earth tremors. Note that there is a relative larger magnitude earthquake (mainshock) followed by a smaller magnitude earthquake (aftershock). It is also preceded by a small 1.7 magnitude earthquake identified as a foreshock. Foreshocks can often not be identified as such until after the mainshock event has occurred.

In addition to an observed fall-off of aftershock magnitude over time, the graph on the right shows that the number of aftershocks after a mainshock fall off in frequency over time as well.

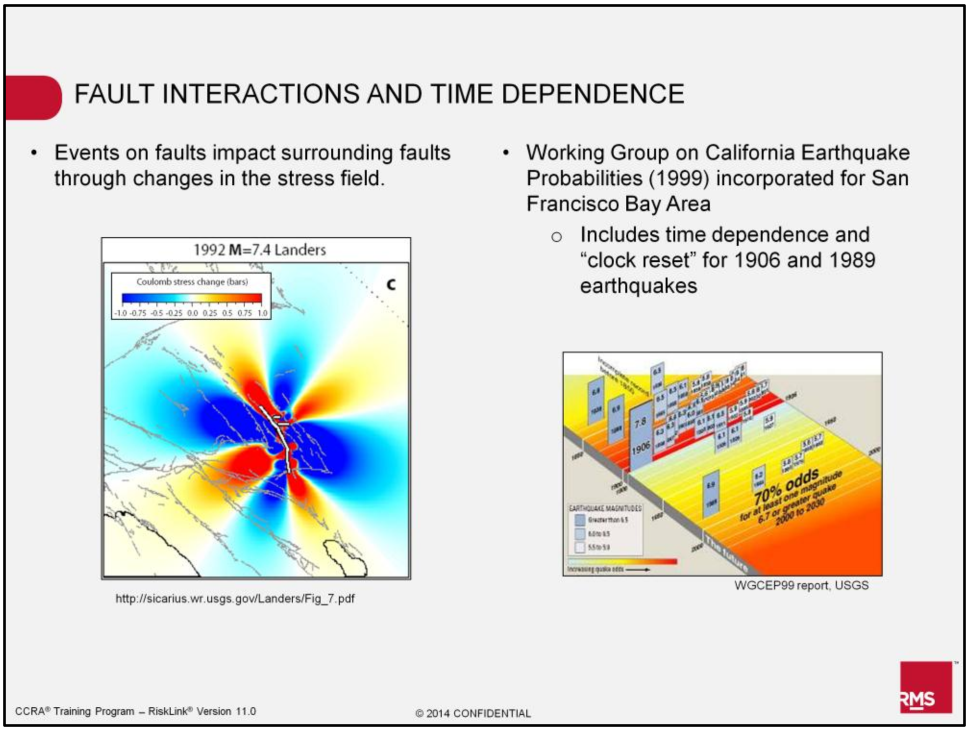


If the Poisson probability distribution and associated assumption of event independence is applied, then it is important to pick out foreshock and aftershock events where instrumentally recorded earthquake catalogs are used in the calculation. The task is then to define the spatial and temporal distribution of these events around a mainshock event. This requires the use of several methodologies to determine whether one event is the direct offspring of another event, or whether it is simply a "background event", low magnitude events related to constant movement along a fault zone.

Shown in this figure is the recording of earthquakes by magnitude over time, as well as by event probability over time. Statistical relationships can be used to mathematically characterize the spatial, temporal, and magnitude relationships of events. This has led to relatively recent investigations into providing the probabilities of aftershock events after large mainshock events.

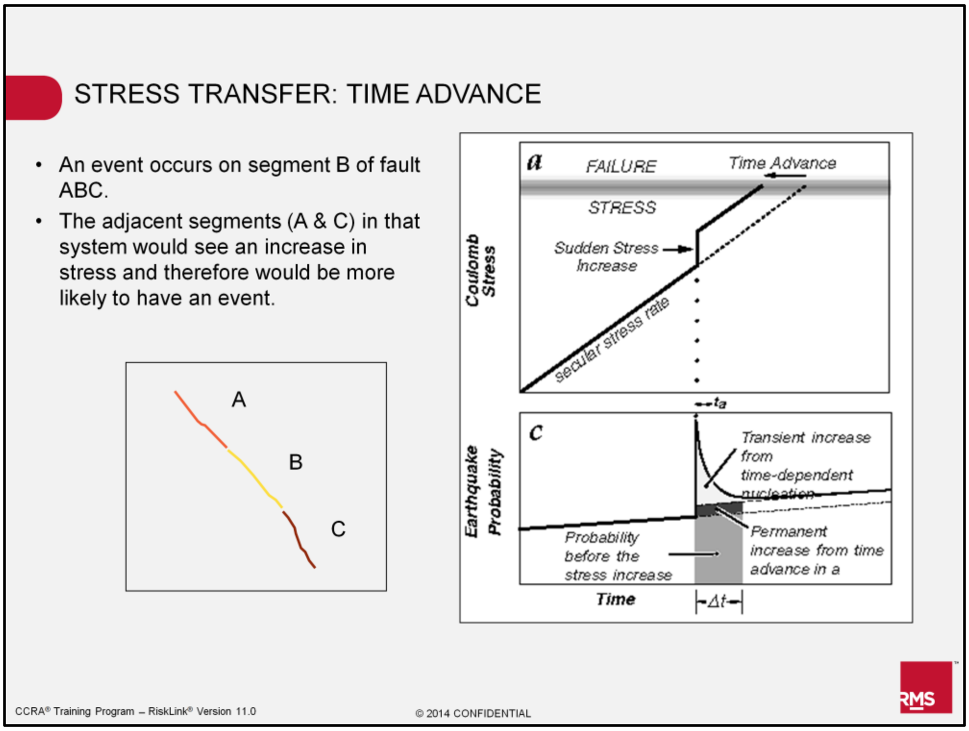


We next explore the concept of earthquake time dependence, which is based on the assumption of the earthquake cycle. The earthquake cycle assumes that when an earthquake occurs, the fault is completely relaxed and is sitting there relaxed waiting for stress to build up. Over time there is an increase of slips at a distance from the fault which progressively increases stress on the fault. The stresses are resisted by the friction along that interface and once the stresses exceed how strong the fault is sealed, you will get an earthquake. Another piece of the earthquake cycle is an assumption that the overall slip rates are constant over the long term, on the order of tens of thousands to millions of years, and that we can get a consistent interval between the earthquakes through this process. This is the basis for time dependent recurrence modeling, which is the assumption that once an earthquake occurs it will take a significant period of time for stress to build up before the likelihood of another event occurring.

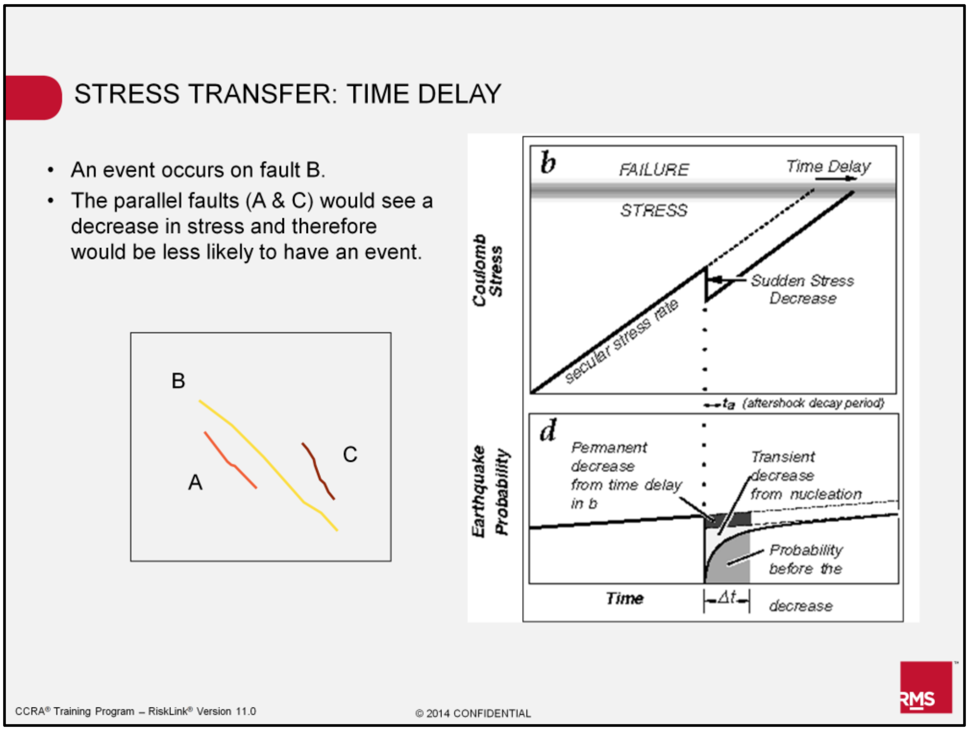


Fault interaction is something relatively new. It has been understood that when an earthquake happens the stresses are changed in the immediate area but recently this has been incorporated into hazard assessments for the San Francisco Bay area. The image on the lower right shows earthquakes with time. Think of it as moving along a conveyor belt from the past toward the future. The little boxes represent earthquakes that happened in the past and you can see there was an extensive suite of earthquakes in the Bay Area prior to 1906. Then the 1906 earthquake occurred. It was a very large event and essentially relaxed all the structures in the Bay Area. There was not another large earthquake until 1989. Scientists looked at this and realized the large 1906 event had relaxed all of the structures in the Bay Area, and that at some point in the future we are likely to come out of what is termed a stress shadow and earthquakes may start occurring with more frequency in the San Francisco Bay area. They included this information in their assessment in 1999 of the chances of an earthquake in the Bay Area. They have now said there is a 70% chance of a magnitude 6.7 or greater earthquake happening before 2030.

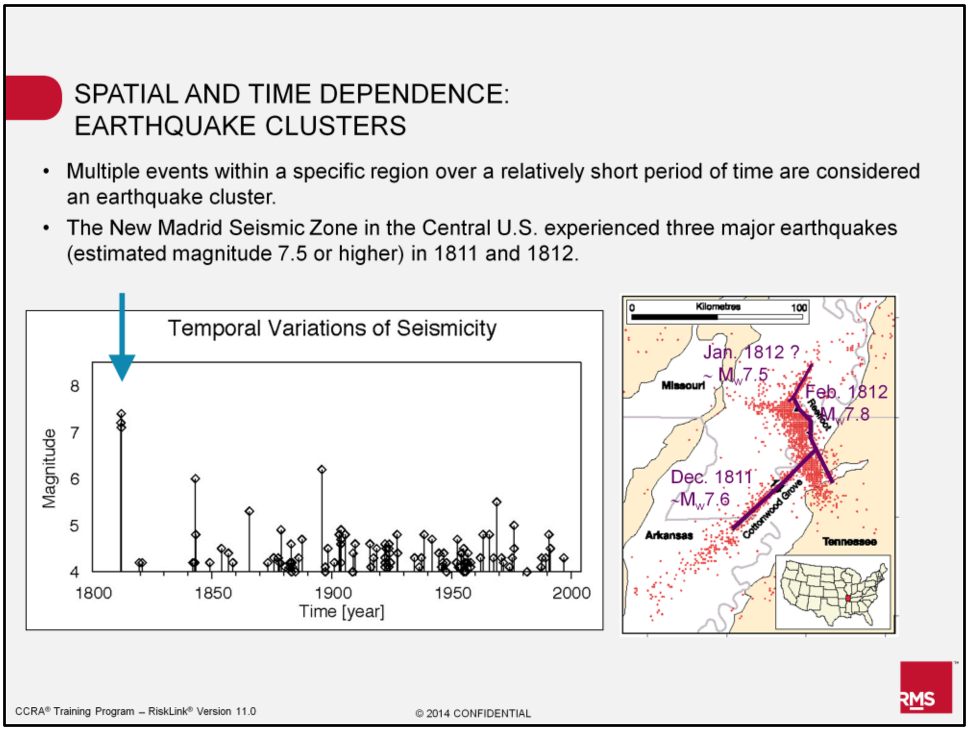
The image on the left shows how the Landers earthquake affected the stress fields in southern California. The blue zones are the zones that are relaxed; the red zones are the zones where stress has been increased. You can see that the ends of the fault zone are where the stresses are particularly high.



Here are a couple of examples of stress transfer. This is a very simplified picture but it will provide some understanding of how stress transfer works. Looking at the schematic drawing at the bottom, if an event occurs on fault B, fault B will then be relaxed but it will transfer stresses to fault A and fault C. Without interaction between faults, the stresses slowly build up and eventually a fault will get to the point where the stresses exceed the friction of the fault and an earthquake occurs. So faults A and C were in a steady state of increasing stress and the earthquake on fault B has caused a sudden large increase of stress. After that increase they continue along in their steady state of increasing stress but that large increase has caused an advance in time. This means that there will be less time between earthquakes on faults A and C. This has a large impact, particularly immediately after the earthquake, and is why there is often concern of large aftershocks or another event being triggered by the initial event. These major stress changes are slowly relaxed with time and then the distant slip rates take over the stress field.

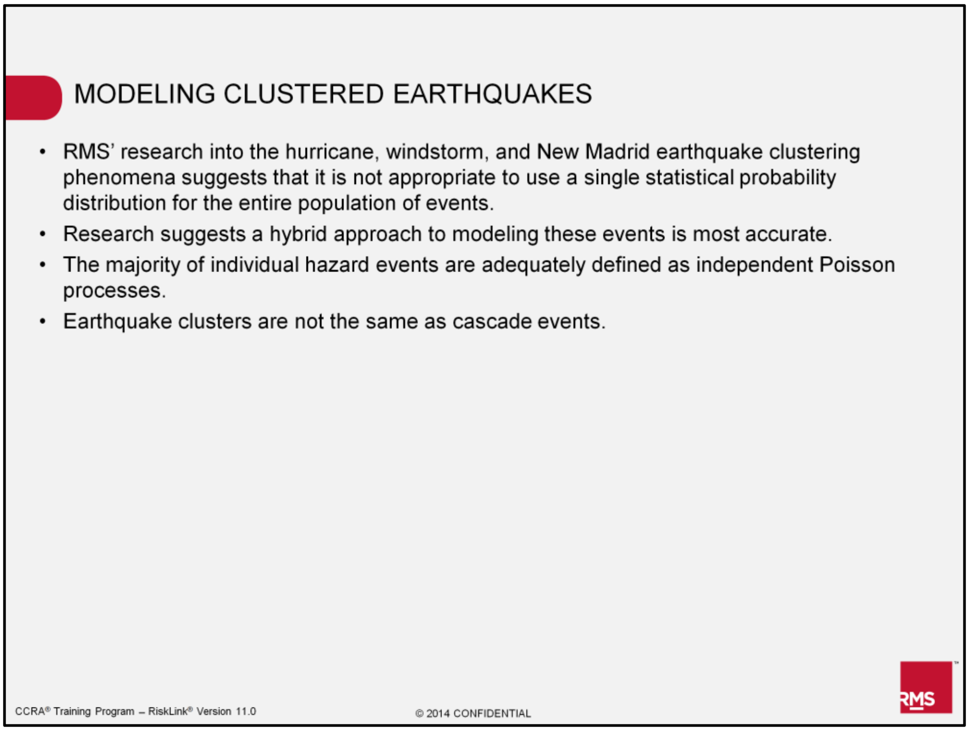


There can also be the converse. In this, case fault B has had a large earthquake. The large event on fault B relaxed any structures immediately parallel. This is essentially what happened in 1906 to the major faults parallel to the San Andreas, such as the Hayward and the Calaveras; these two faults were relaxed by the 1906 earthquake. In this case, faults A and C were increasing their stresses at a slow steady rate but now because they have been relaxed their state has dropped and they will continue along this steady state with a bit of a time delay, meaning it will take longer until the next earthquake on those structures.



Any combination of events that occur on a fault or a fault zone within a time span of a few weeks, or even less than a few years, are considered earthquake clusters. These include swarms where no one event is distinguished by its size as a mainshock. Strictly speaking, earthquake clusters include mainshocks as well as foreshocks and aftershocks. The initiation of rupture on several fault segments or other faults in a fault zone are caused by stress transfer from one fault structure to surrounding structures in the same region. It is important to note here that earthquake clusters are differentiated from cascade events. A cascade event can be identified as <u>one</u> damaging event caused by rupture along multiple fault segments over a period of seconds or minutes, whereas earthquake clusters are <u>many</u> damaging events occurring on single or multiple earthquake sources (including volcanic sources) over longer periods of time.

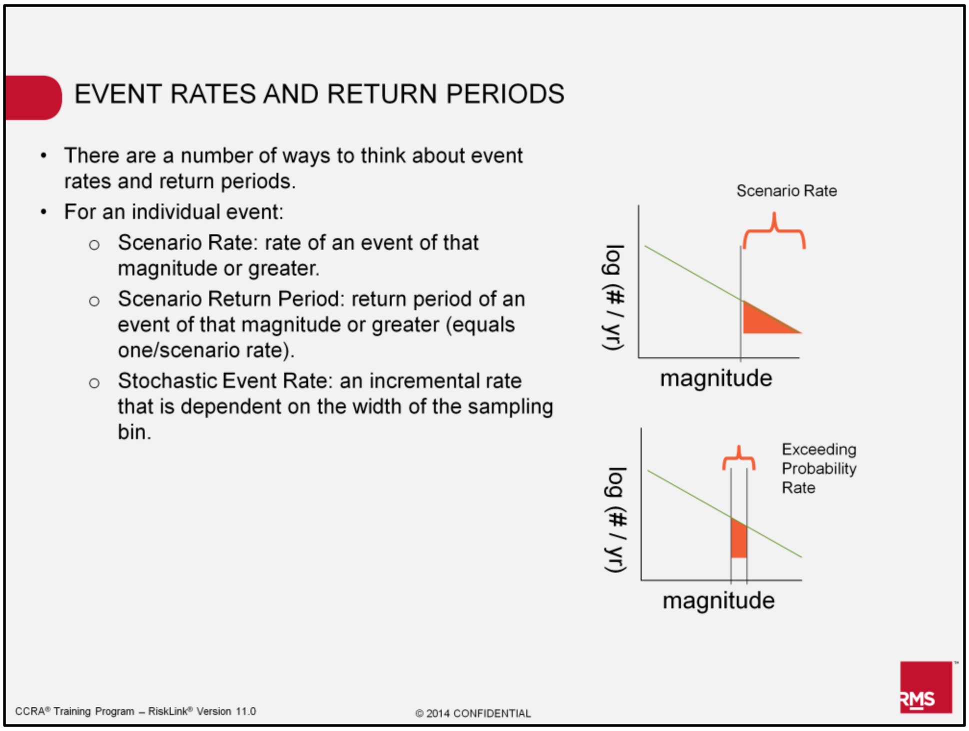
The New Madrid fault zone experienced a large magnitude earthquake cluster during 1811 and 1812. These events occurred on three separate fault structures within the New Madrid fault zone shown in the figure on the right. The figure also shows the recorded low-level seismicity over the past few decade as red dots. Most of this activity is non-damaging “background seismicity.” Note that these events were not only spatially constrained to the same fault zone, but that the temporal clustering of three magnitude 7.5 and higher events is constrained to a period of three months. No other historically recorded events greater than 6.5 have been recorded since in that region.



So how does one model clustered events? To begin with, there is no single event probability distribution. It is more likely that there is more than one that may be appropriate. Because the available historical record in some regions and for some magnitude ranges readily fits the assumption of event independence, the Poisson distribution is appropriate. However, for other regions or magnitude ranges, this may be an incorrect assumption because the tectonic environment causes the region to be "prone" to large magnitude events that are clustered in space and time. A negative binomial distribution is one distribution that might be more appropriate for this population of events.

Thus a hybrid approach to modeling these events is more accurate. That being said, given the current scientific understanding, individual damaging events are adequately modeled as independent Poisson processes. RMS has recently started some new and promising research on this subject and hopes to include this in the near future.

Finally, it is important to reiterate the point made on the last slide that earthquake clusters are not the same as cascade events; however, cascade events can be included in an earthquake cluster.



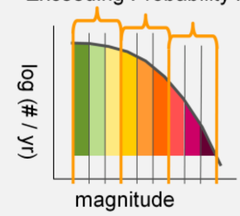
Next we will look at some definitions about how rates are used within a catastrophe model. There are a number of different ways to think about return periods and rates. Typically we talk about rates for individual events when thinking about scenarios. This is a simple Gutenberg-Richter relationship.

Looking at the graphs on this slide; if we have a magnitude seven, the area under the curve is the rate of an event of that magnitude or greater. So the scenario rate for a source of magnitude eight would be referred to as the rate of that magnitude or greater. The return period of a scenario is the inverse, or taking one over the scenario rate. There is often some confusion about how the scenario rate relates to the stochastic event rate. The stochastic event rate is not the entire rate from that magnitude and greater but is actually just a sliver of the recurrence model and the amount of rate in that sliver is dependent upon the sampling widths.

STOCHASTIC EVENT RATES

- Rates are determined by slicing up the frequency magnitude relationship for an individual source.
- The slices are centered around the magnitude to be associated with the rate.
- The bin widths can vary from source to source and from magnitude to magnitude for an individual source.
- Individual stochastic event rates are purely a construction of the bin width and are not reflective of the rate for an event outside of the stochastic event set.

Exceeding Probability Rates



Magnitude	Scenario Rate	Incremental Rate	Stochastic Rate
6.9	0.000001	0.000001	-
6.8	0.000011	0.000010	0.000069
6.7	0.000069	0.000058	-
6.6	0.000233	0.000164	-
6.5	0.000456	0.000232	0.000560
6.4	0.000629	0.000164	-
6.3	0.000686	0.000058	-
6.2	0.000697	0.000010	0.000069
6.1	0.000697	0.000001	-

When we look at the full sampling of stochastic events for a source, we take the full distribution. In this case it is a characteristic distribution. We carve it into small pieces and then use those to come up with rates for the stochastic events. It is important to understand that we are not looking at the rate of that magnitude or greater. We are actually looking at the rate of that particular magnitude in a slice.

To help clarify this point, the chart shows a distribution divided up into slices. The table shows the scenario rate by magnitude, in other words, the rate of that magnitude and greater. Then we can divide it into little pieces so this is the amount of rate in the bin, which is color coded. The dark pink shows the amount of rate in the dark pink bin. The rate of each bin is then put into the table. To come up with the stochastic event rate we accumulate these little incremental pieces. In this case we are just going to run three stochastic events. We are going to run 6.8, 6.5, and 6.2 and you can see on the table the rate associated with each of those stochastic events. The rate for 6.8 and 6.2 is actually very small because the 6.5 magnitude is a characteristic event and the 6.8 and 6.2 are taking into account uncertainty around the characteristic magnitude. It is the characteristic magnitude that gets the most rate.

It is important to clarify that the inverse of these numbers to try to get a return period is not really a useful calculation. You have just taken a little piece of the rate from this distribution so it is not appropriate to try to determine return periods for these events just as their own little pieces of information.

RETURN PERIOD LOSSES

- Events are analyzed and sorted from highest loss.
- Rates are accumulated to create the exceedance probability curve, taking into account secondary uncertainty.
- Return period losses are the loss level that can be expected at that return period.
- Specific events associated with that loss are not that return period event.
- ELT reports mean losses and rates without secondary uncertainty.

Critical Probability	Return Period	Results with Secondary Uncertainty
0.02%	5,000	$26,189,870
0.10%	1,000	$18,629,839
0.20%	500	$15,437,495
0.40%	250	$12,295,236
1.00%	100	$8,282,797
2.00%	50	$5,450,369
	Pure Premium	$384,995
	Standard Deviation	$1,624,756
	CV	4.2202

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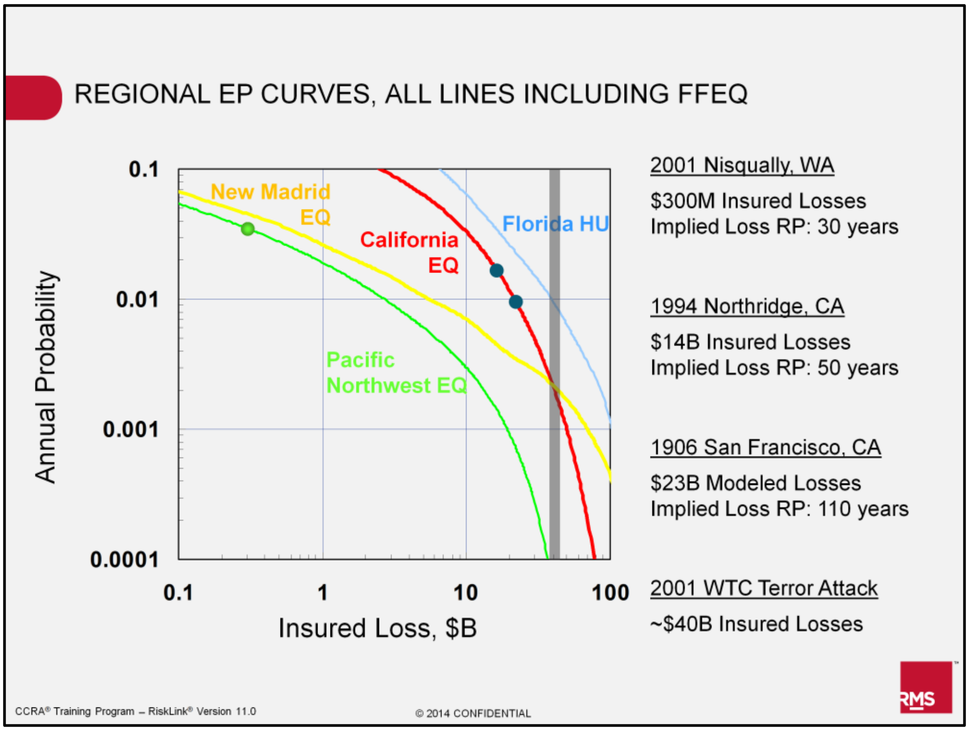
RMS

When we want to look at return periods, we want to look at return periods within the entire stochastic event set. You need to combine all the events, sorting them from highest losses to lowest, accumulating the rate to generate the exceedance probability curve, taking into account secondary uncertainty. So for example, $12.3 million is the return period loss for 250 years. This means that at the 250-year return period level, this is the level of loss we would expect. Specific events associated within the ELT with this loss level are not necessarily a good representation of that return period type of event. This is a common misconception made when looking at the ELT; trying to pull out events specifically associated with a return period. While they may be helpful in looking at accumulation, it is very important to take into account where those events are and where the exposures are and not to get too tied into the return period with which they are associated. The output on this slide is from RiskLink, taking into account secondary uncertainty. When you look at the ELT you do not get secondary uncertainty but you will get the mean losses and the rates without secondary uncertainty.

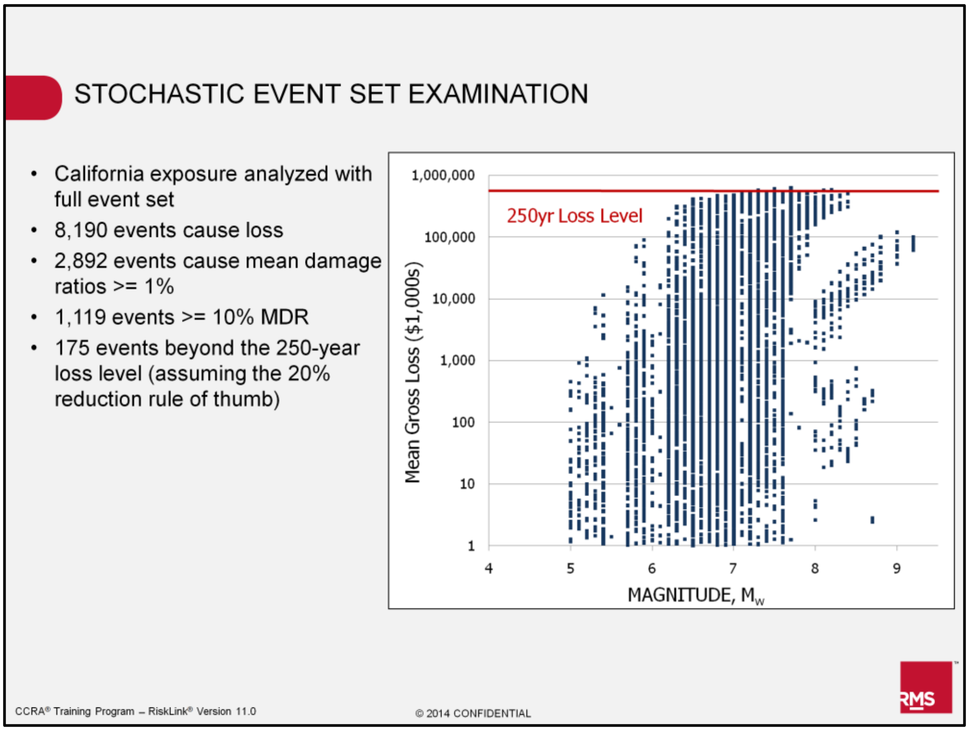


Let's look at a couple of examples of how we can think about return period losses. Here are some EP curves plotted for several models including other perils. Note that this graph uses log scales on both axis. In terms of insured loss, you can see we are going from one billion to ten billion to 100 billion. Annual probability is also increasing ten-fold.

We will start by looking at the Pacific Northwest shown in green. The Pacific Northwest has the lowest hazard compared to New Madrid in yellow, California in red, and Florida in pale blue. When you run the Nisqually earthquake event parameters you get around a $300 million insured loss. When we look up $300 million on the EP, we get a return period of about 30 years. So the Nisqually type event has a 30-year return period.

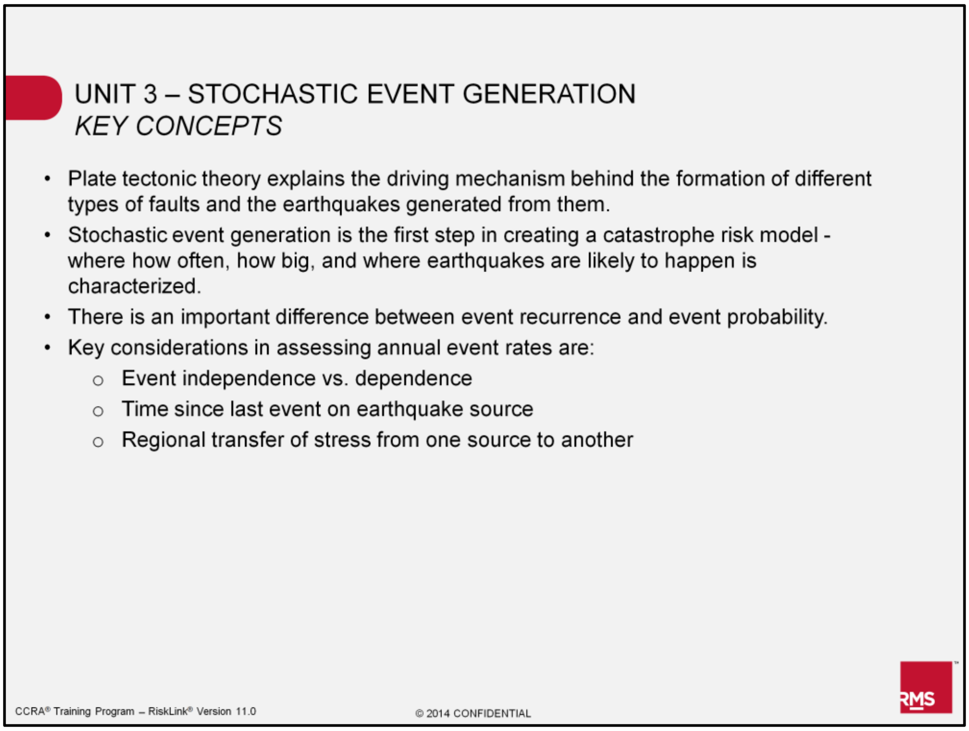
We can also do this with Northridge, which is a $14 billion loss and has about a 50-year return period on the California EP. The 1906 event has a $23 billion modeled loss which implies a 110-year return period for that level.

To give some context for other perils, Hurricane Charlie in Florida generated about a $9 billion loss in the pale blue curve. The World Trade Center attack resulted in about $40 billion worth of loss but we do not know a return period for it so it is shown as the grey vertical line. This gives you some understanding of how you can think about individual events and their loss return periods.



This is a plot of magnitude versus losses for the full suite of events for a California exposure. In all the stochastic events, which include 8,190 events that cause loss, about 2,900 events cause mean damage ratios of more than 1% across all buildings exposed. There are 1,119 events that cause mean damage ratio averages above 10%.

Next, we are going to give you a hint about how to work on the exercise. We have talked about looking back at the results from RiskLink. The output gives you return period losses that include secondary uncertainty. Because the ELT does not include secondary uncertainty, it is a little difficult to think about how to go from a particular loss level, for say a 250-year loss, with secondary uncertainty to then know how to look at the events in the ELT. To do this you should use the 20% rule of thumb. For example, if we went in and looked at the 250-year loss level with secondary uncertainty and then we reduced that by 20%, we take that loss level and we look at all the events greater than that loss level to understand all the events beyond that 250-year loss. In this case in California, there are 175 events beyond that 250-year loss.



This slide highlights the key points from Unit 3 of this course. We encourage you to review these topics to ensure that you have a good understanding of each bulleted item before proceeding to Unit 4.