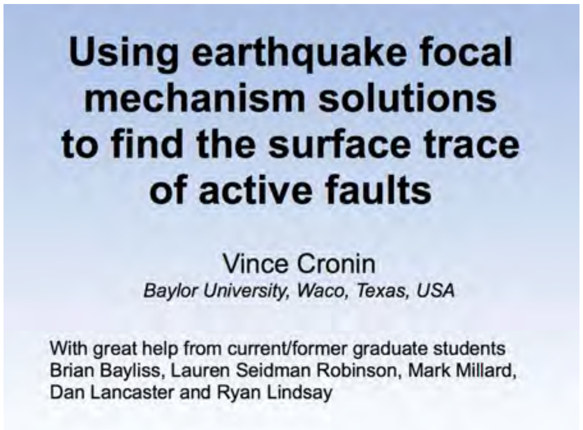
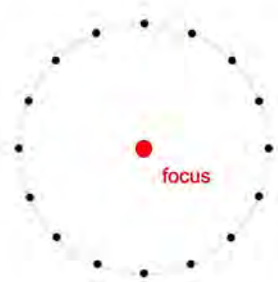


I would like to thank Hector Mora, Franck Audemard and the other organizers for inviting me to come to the Latin American Geological Congress.

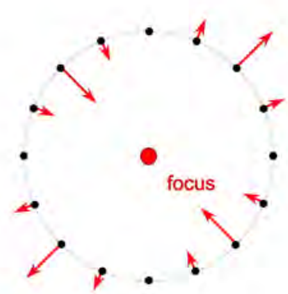
I grew up in Los Angeles, California, and have survived earthquakes that have killed other, less fortunate people in my hometown. The homes of my parents and some of my friends have been damaged or destroyed by earthquakes. I share that experience with far too many people in Latin America and the Caribbean.

Today, I want to give a brief introduction to a relatively simple and inexpensive method for finding where the fault that produced a given earthquake intersects the ground surface. This is an essential piece of information needed by earthquake engineers who perform the probabilistic assessment of seismic risk that is used to design earthquake-resistant structures. Knowing the location of seismogenic faults is also important to public planners and others involved in promoting public safety.

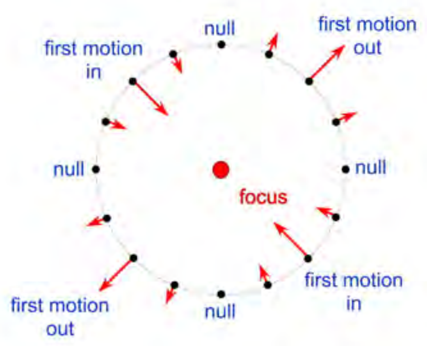
I am here because I want to help you identify seismogenic faults. I also want to teach anyone interested how to use the method that has been developed and tested by my students and me. The software I have written to assist in this analysis is available for free online, through the web address shown. Write it down, and contact me if you think this method can help you to identify seismogenic faults.



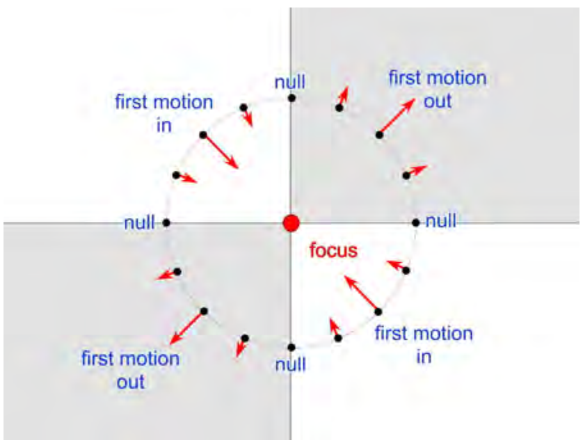
Let me give you a quick primer on earthquake focal mechanisms. Imagine a set of points around the focus of an earthquake in the upper 30 km of the continental crust.



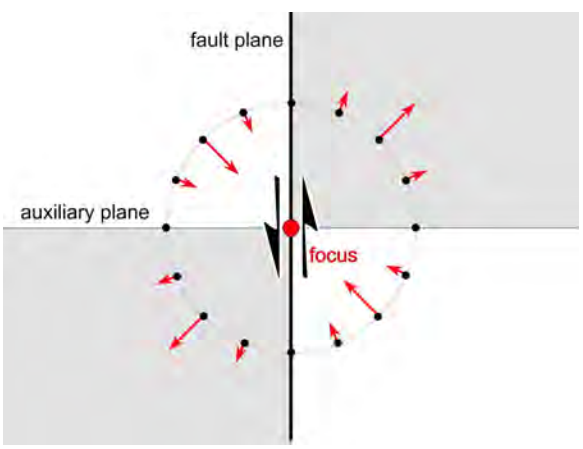
When the earthquake occurs, the first motions of these points will vary systematically around the focus.



Some points move in, some out, and some do not move at all as the initial energy propagates away from the focus.

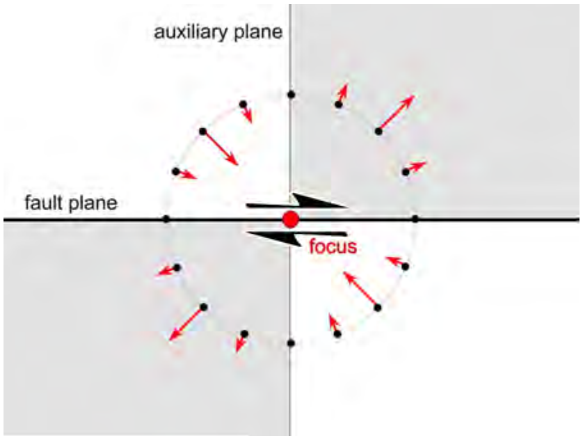


These different motions can be grouped into quadrants, with the boundaries of the quadrants constituting nodal planes along which the first motion is null. The nodal planes are at right angles to one another.

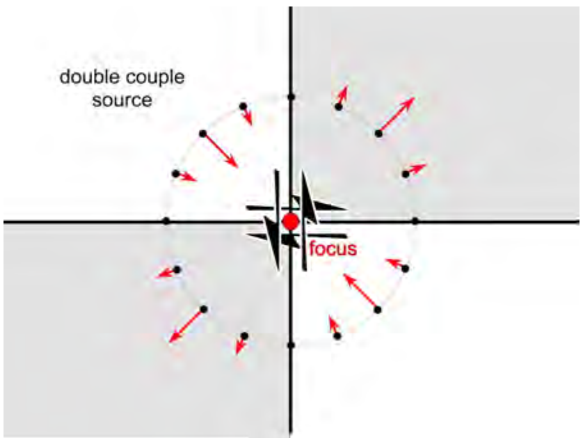


The observed radiation pattern, which can be discerned by studying the records of multiple seismograph stations*, is typically generated by frictional slip on a fault plane that is coincident with either ***one*** of the nodal planes...

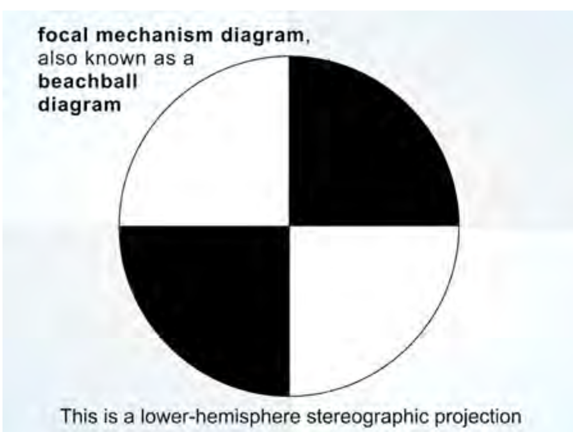
*Traditionally, the first motion of the P-wave along the vertical axis of the seismometer is studied: either up, down or null. Consult your local seismologist for more.



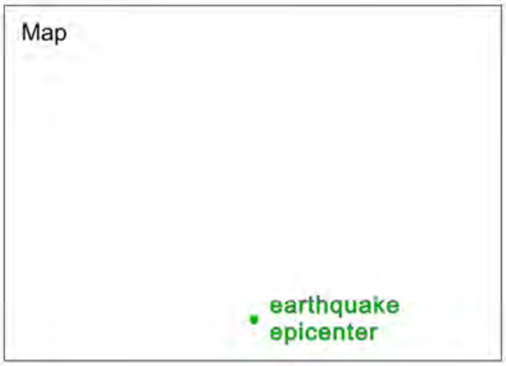
...or the ***other*** nodal plane. The nodal plane that is perpendicular to the fault plane is called the auxiliary plane, and no fault slip occurs along the auxiliary plane.



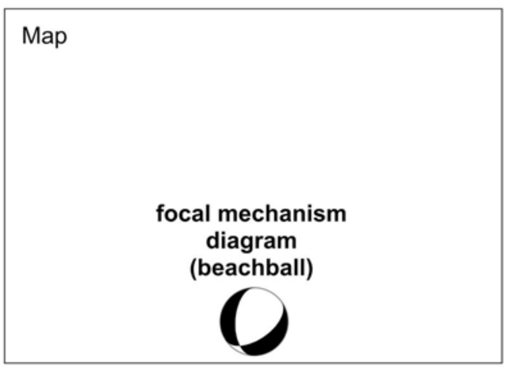
Seismologists can tell us the orientation of the nodal planes and the corresponding direction of dip, but they cannot tell us which of the two nodal planes coincides with the fault based on the radiation pattern alone, without considering additional geological information.



The double-couple radiation pattern is represented by a focal mechanism diagram, also known as a ***beachball*** diagram. The diagram shown here corresponds to strike-slip displacement on vertical faults.

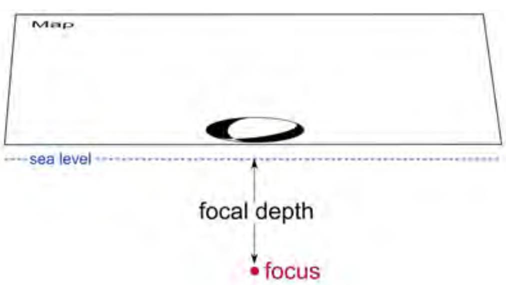


The horizontal location of an earthquake in map view is represented by the earthquake epicenter.

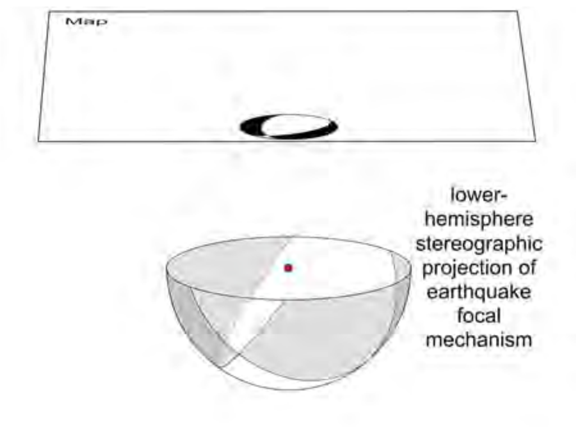


The focal mechanism diagram for a given earthquake is usually plotted at the epicenter. Maps of focal mechanism diagrams generated by seismologists are quite common.

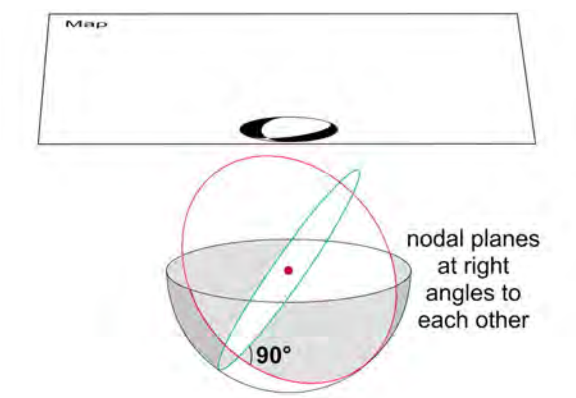
We take this information one step further and attempt to spatially correlate the earthquake with the fault that generated it. So if we take that horizontal map surface and tilt it up so we can look beneath...



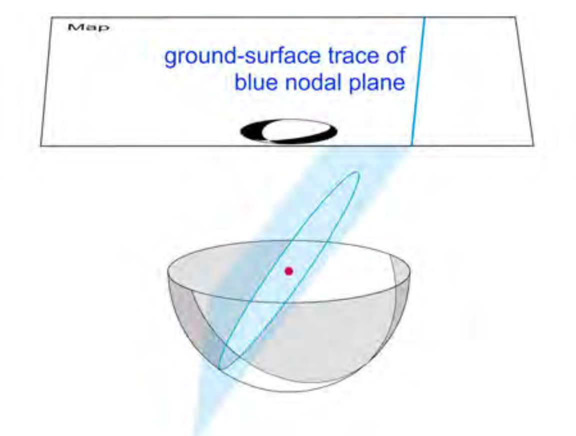
...we see the earthquake focus directly under the epicenter and the focal mechanism diagram.



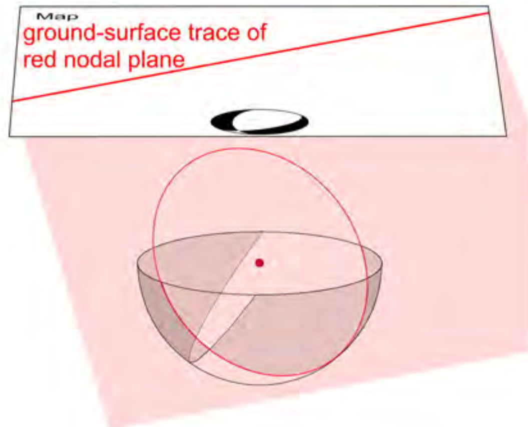
The focal mechanism diagram is a lower hemisphere stereographic projection. We can envision it as the bottom of a focal sphere around the earthquake focus.



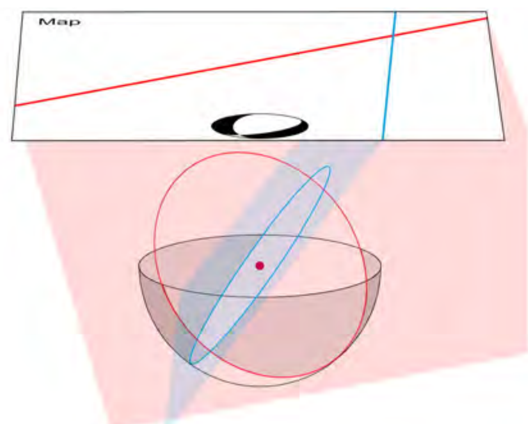
The two nodal planes intersect the focal sphere along great circles that are 90° apart from one another.



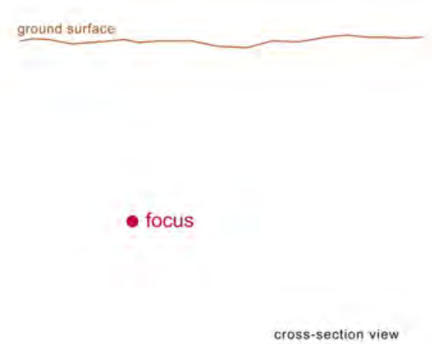
We can project either nodal plane from the focus upward to define the ground-surface trace of the nodal plane, shown as the blue line on the map surface.



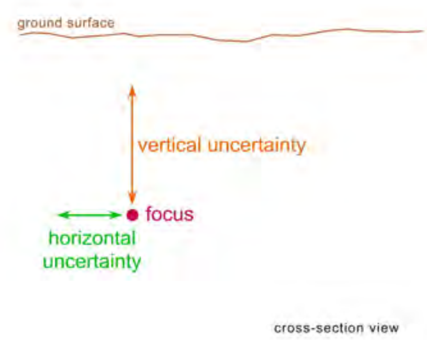
The ground-surface trace of the other nodal plane is the red line on the map surface.



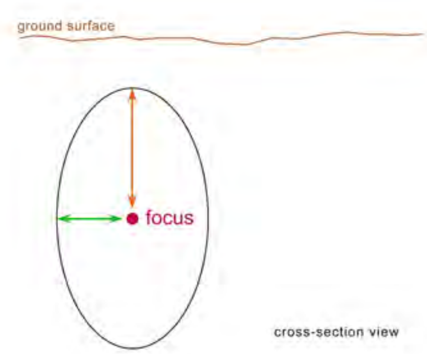
So any focal mechanism provides two traces, one of which is parallel to the seismogenic fault surface at the focus.



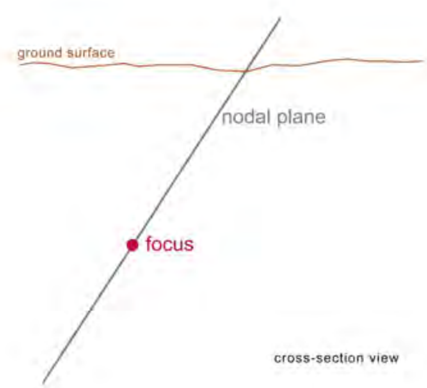
Of course, we do not know the location of the earthquake focus perfectly.



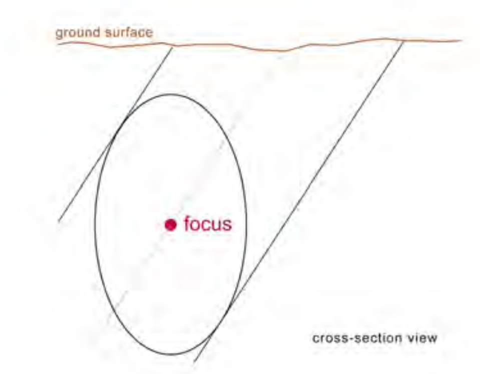
Any focal location has a vertical and horizontal uncertainty associated with it.



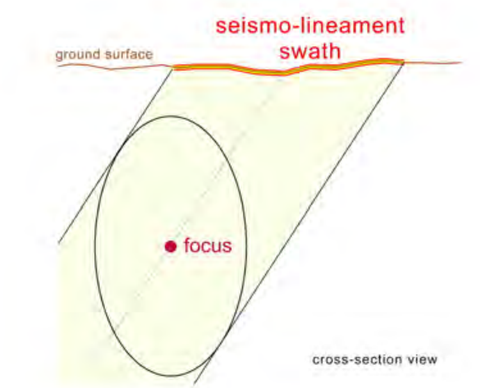
We can assume that the vertical and horizontal uncertainties define an uncertainty ellipsoid around the focus.



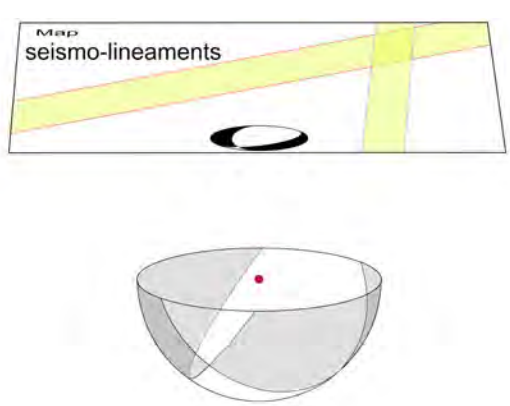
So if we start with a nodal plane projected from the earthquake focus...



...and incorporate the uncertainties in the focal location, we can establish an uncertainty volume for the nodal plane.

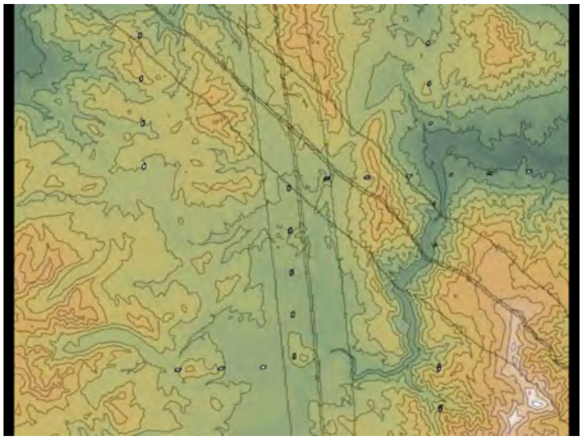


The intersection of that uncertainty volume with the ground surface defines the seismo-lineament swath for that nodal plane.



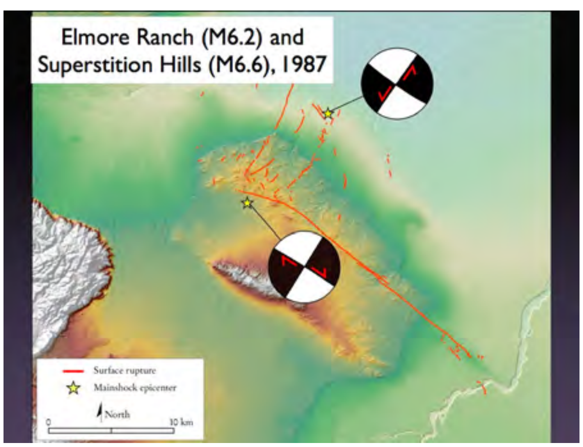
And so for any earthquake, there are two seismo-lineaments: one associated with the fault plane, and the other associated with the auxiliary plane. If the fault is approximately planar and extends to the ground surface, and if the focal mechanism and location are good, the surface trace of the fault should be within one of the seismo-lineaments.

This slide explains the meaning of the seismo-lineament swaths that you will see on slides for the rest of the presentation. The seismo-lineaments are the surface trace of the nodal planes, plus or minus the uncertainties in focal location.



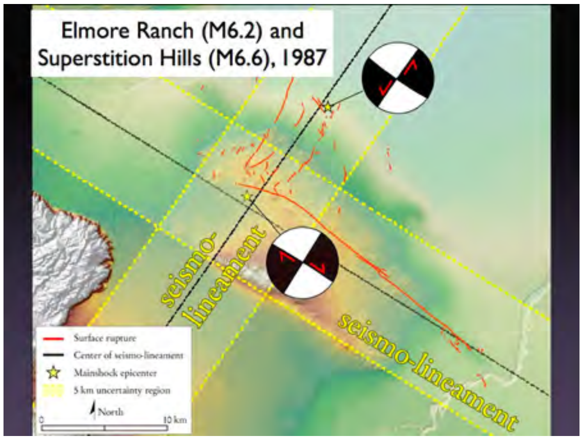
This is an example of the raw output of my seismo-lineament code, which produces a topographic map with the boundaries of the seismo-lineaments. Like a pirate's treasure map, this is a map of where to look for the fault that caused the earthquake.

Does this method of finding seismogenic faults actually work? We have tested the method using data from several earthquakes that produced surface rupture, so we knew that fault produced the earthquake. Could we "find" the fault that caused the earthquake using the published focal mechanism solution? Let me show you some examples.



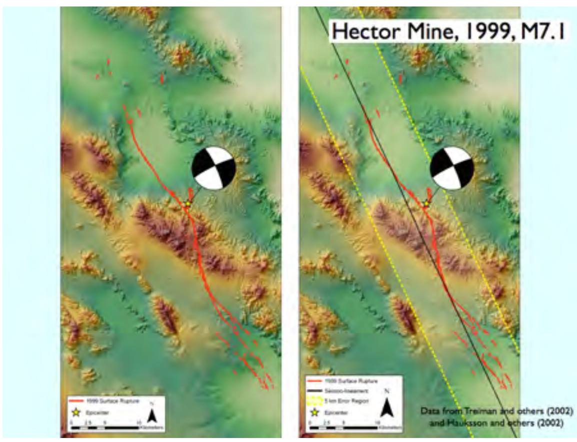
Two strike-slip earthquakes occurred one day apart, with the smaller event first. The mapped surface rupture along the active faults is shown by the red curves in this and in the following slides.

(Millard, 2007)



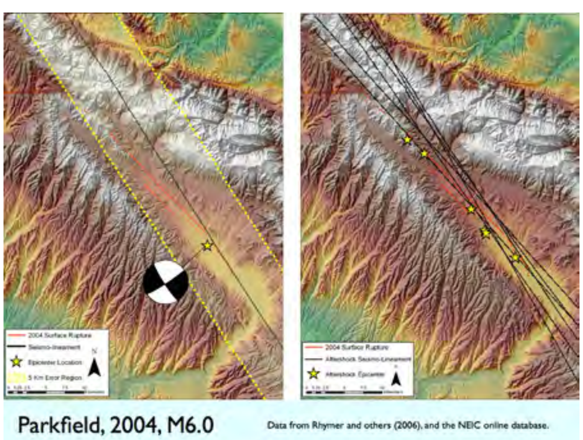
The resulting seismo-lineaments include the surface traces of orthogonal fault systems that generated the two events. A geologist looking within these seismo-lineaments would find the traces of the active faults.

(Millard, 2007)



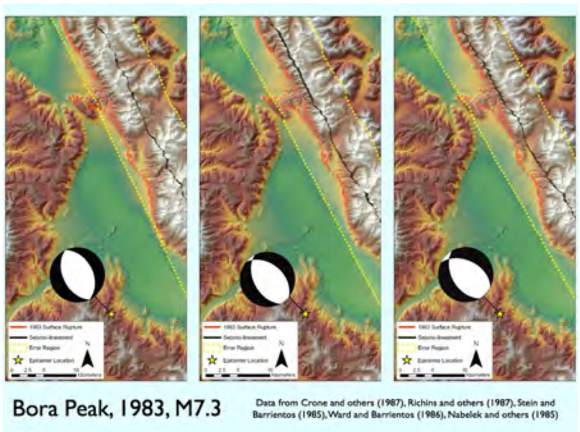
Here is another strike-slip earthquake. A geologist looking within the northwest-trending seismo-lineament would find the seismogenic fault.

(Millard, 2007)



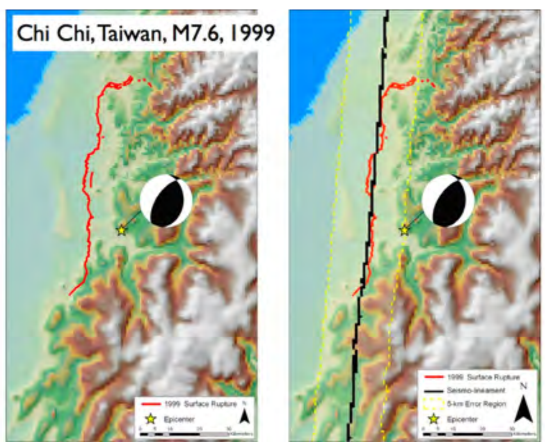
Here is yet another strike-slip earthquake. A geologist looking within the northwest-trending seismo-lineament from the main shock (left panel) would find the seismogenic fault. The panel on the right shows the trace of the nodal planes for several aftershocks, so we could have used aftershocks to find the active fault, too.

(Millard, 2007)



Here is a normal-slip earthquake, for which different seismologists have supplied three slightly different focal mechanism solutions. A geologist looking within the northwest-trending seismo-lineament generated by any of these solutions would find the seismogenic fault.

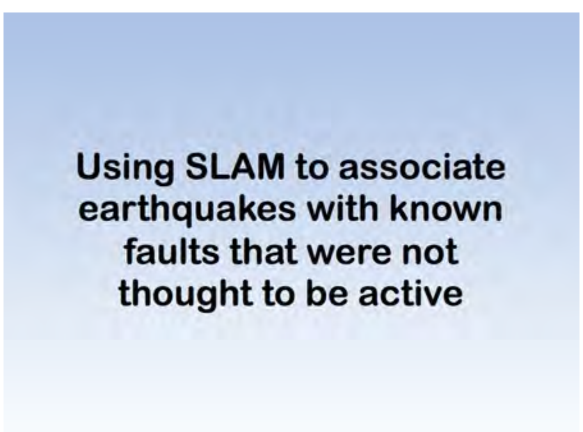
(Millard, 2007)



Here is a reverse-slip earthquake. A geologist looking within the corresponding seismo-lineaments would find the trace of the active fault.

So we have tested this method using strike-slip, normal, reverse and oblique earthquake focal mechanisms, and have successfully found the known surface traces of the seismogenic faults.

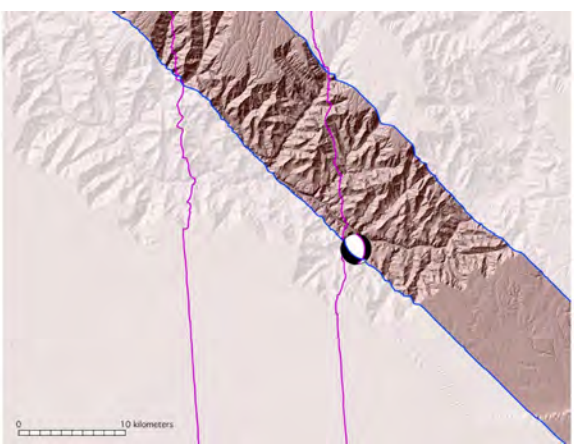
(Millard, 2007)



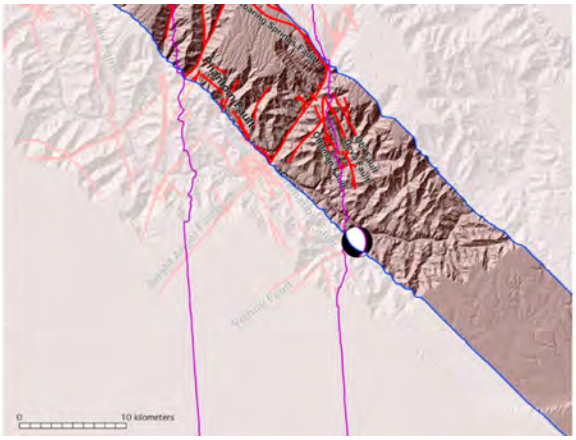
Here are some examples of earthquakes in an area with no known active faults.

There are many distinctive geomorphic lineaments in this landscape...

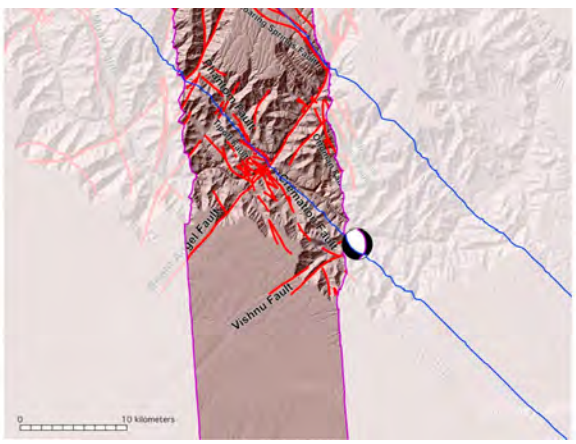
...and many if not all of these lineaments are associated with mapped faults. None of these faults have been considered to have Recent activity. But there are earthquakes here, so something must be active!



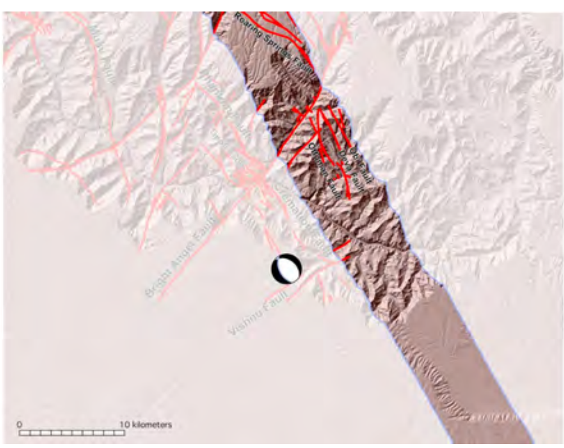
Here are the two seismo-lineaments associated with one of the recent earthquakes.



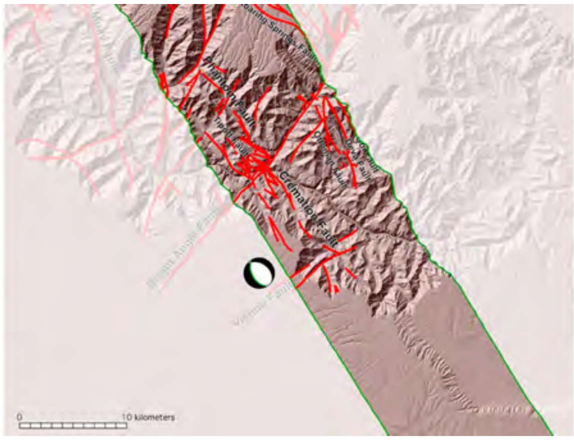
The northwest-trending seismo-lineament includes several known faults that are parallel to the nodal plane.



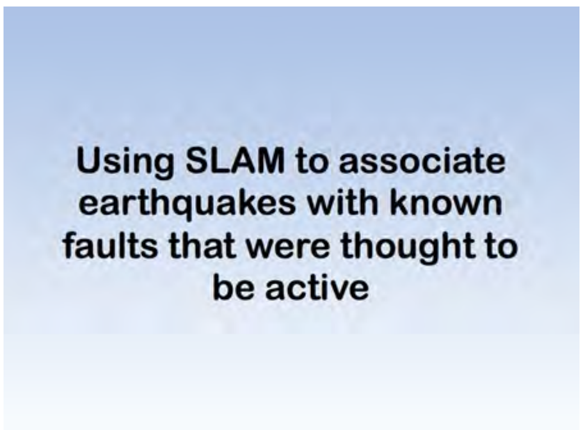
The other seismo-lineament is not parallel to any of the mapped faults or geomorphic lineaments. We infer that this is the auxiliary plane, and the more northwest-trending seismo-lineament is along the fault plane for this earthquake.



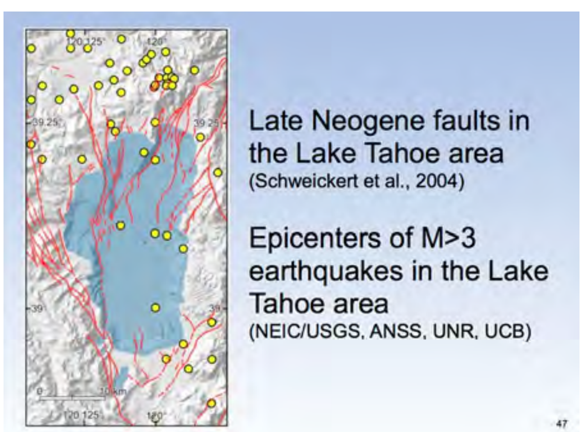
One of the seismo-lineaments of another earthquake covers the same trend, from which we might infer that not only is one or more of these faults seismogenic, but we might have recorded multiple earthquakes along the same fault.



And a third earthquake has a coincident seismo-lineament. Again, we infer that one or more of these faults is seismogenic, and we might have recorded multiple earthquakes along the same trend.

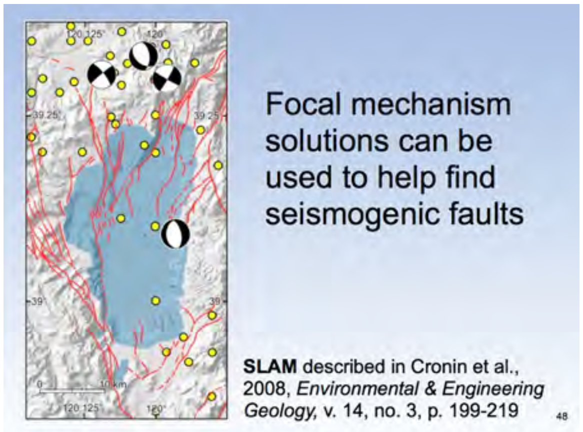


We have used this method to correlate earthquakes with faults that were thought to have had late Neogene activity, but for which no Holocene material at the ground surface.



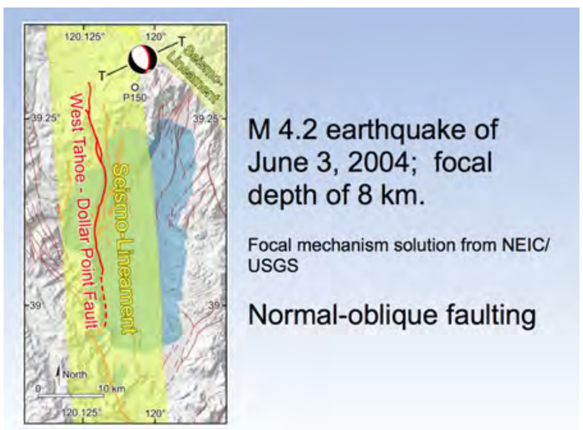
The area around Lake Tahoe in the western US has had a number of earthquakes, and paleoseismologists have mapped several faults (shown in red) that have had Quaternary activity.

(Ryan Lindsay M.S. thesis, in review 2011)



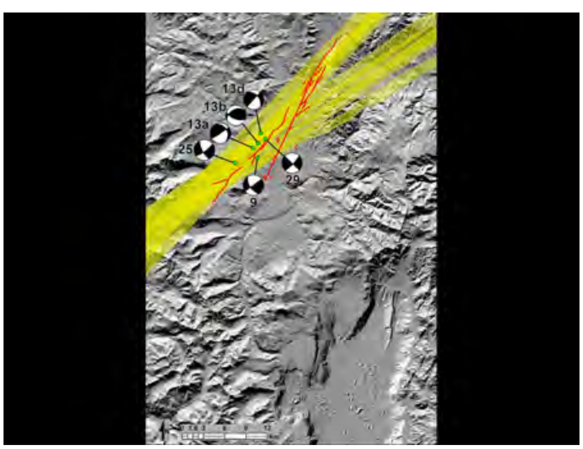
None of the Quaternary faults have demonstrated Holocene activity, generally because there is little or no static Holocene material where these faults intersect the ground surface. No earthquake has been correlated to any specific fault in the area.

(Ryan Lindsay M.S. thesis, in review 2011)



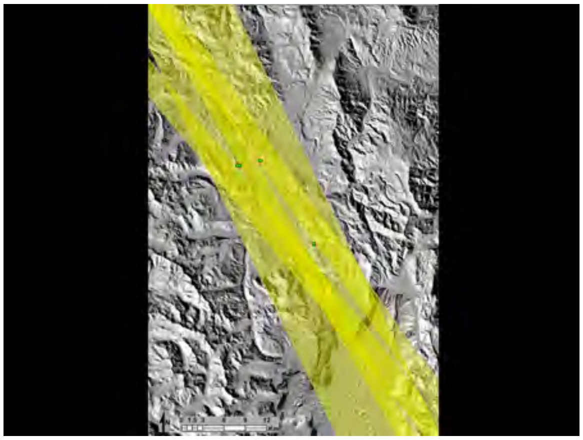
That is, until now. We have used the Seismo-Lineament Analysis Method to spatially correlate this earthquake with the West Tahoe-Dollar Point fault zone. The trace of this fault is within the seismo-lineament, and the fault has the same strike, dip, sense of displacement, and slip vector as the earthquake focal mechanism solution. So we have effectively demonstrated that this fault is currently producing earthquakes.

(Ryan Lindsay M.S. thesis, in review 2011)



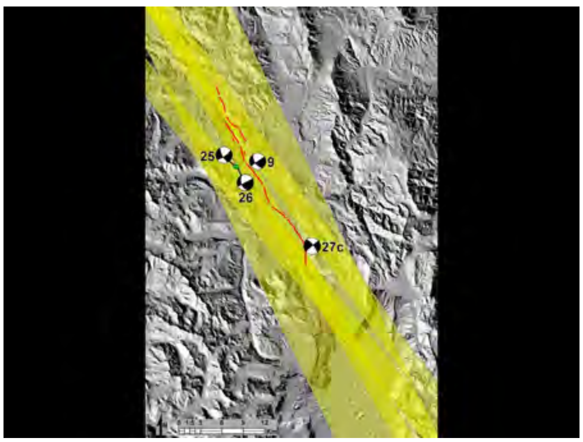
Several kilometers north of the Lake Tahoe Basin (shown in the lower right part of this hillshade map), we have correlated six earthquakes with strands of the Dog Valley fault zone, shown in red.

(Ryan Lindsay M.S. thesis, in review 2011)



Several seismo-lineaments overlap in this image, indicating that this might be a place to look for a fault that has produced several earthquakes recently. When we started our work in this area, there were no faults mapped along this trned...

(Ryan Lindsay M.S. thesis, in review 2011)



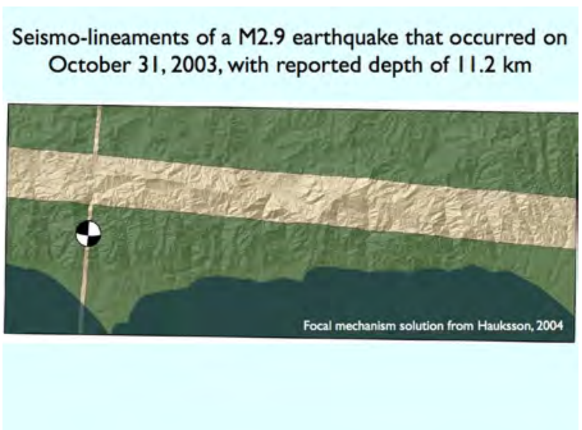
...but we almost immediately learned of a newly recognized structure called the Polaris fault, shown in red. Paleoseismic work on this fault demonstrates that it has had displacement in the Holocene. Our work indicates that it has produced earthquakes in the last half century.

(Ryan Lindsay M.S. thesis, in review 2011)

The Polaris fault has a clear geomorphic signature, once you know where to look. For example, the fault controls part of the channel of the Truckee River.

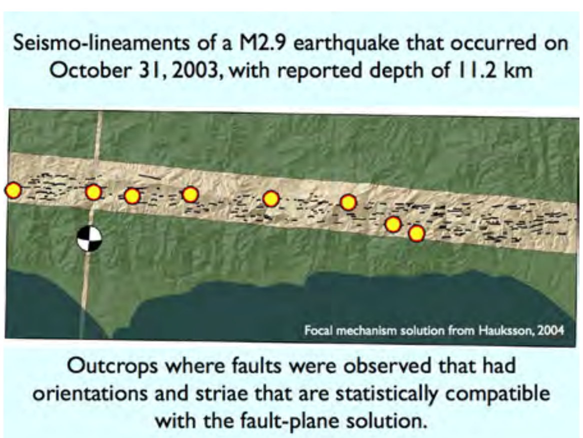
(Ryan Lindsay M.S. thesis, in review 2011)

The SLAM method has not only allowed us to correlate earthquakes with known faults, but it has helped us to find new seismogenic faults.



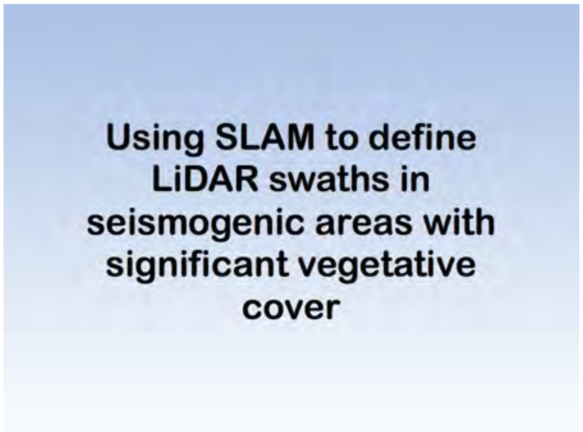
A small strike-slip earthquake near Los Angeles was associated with the seismo-lineaments shown. We did not find faults along the narrow north-trending swath, but...

(Cronin, Millard, Seidman and Bayliss, 2008)

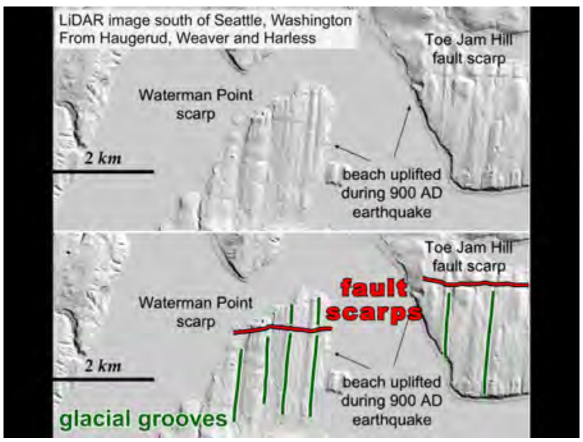


...along the east-west swath we found geomorphic features and a number of fault surfaces with horizontal shear striae indicating a fault exists in this swath. The yellow dots indicates sites where strike-slip faults were observed that are parallel to the nodal plane. We have interpreted these faults to be part of a previously unmapped seismogenic fault zone.

(Cronin, Millard, Seidman and Bayliss, 2008)



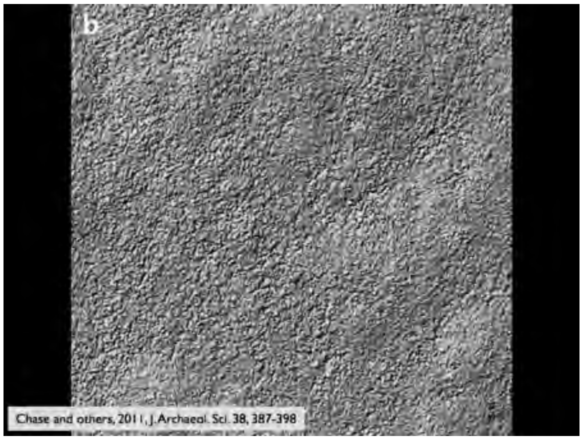
We think SLAM might be useful in designing aerial LiDAR surveys to find new seismogenic faults.



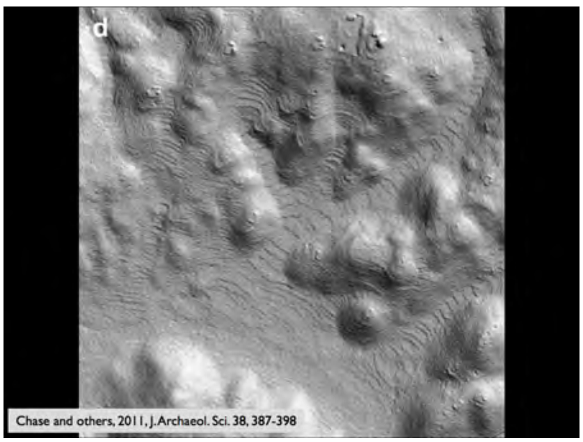
Here is the classic image by Ralph Hagerud and others showing bare-earth LiDAR data of the Puget Sound area. When the trees were removed from the data, previously unmapped active faults were discovered that cross-cut glacial grooves.

In areas where the ground surface is obscured by vegetation, as in the rain forests of Central and South America, seismo-lineaments can be used to guide the design of aerial LiDAR surveys that can penetrate the forest canopy to image the ground surface.

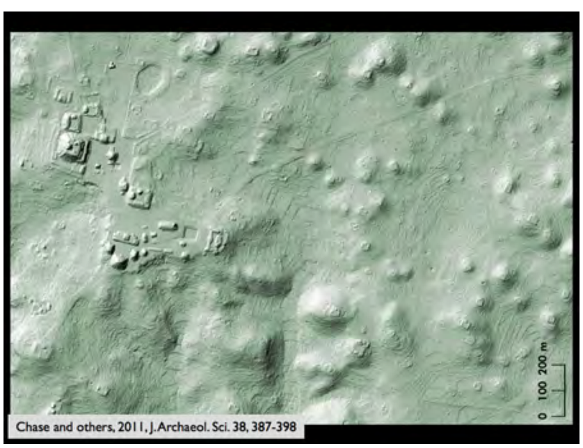
This is an aerial photograph of the rain forest at Caracol, Belize. Whatever might be on the forest floor is completely obscured. Let me point out a prominent drainage in the image so you can correlate with the next two images <<point to drinage on slide>>



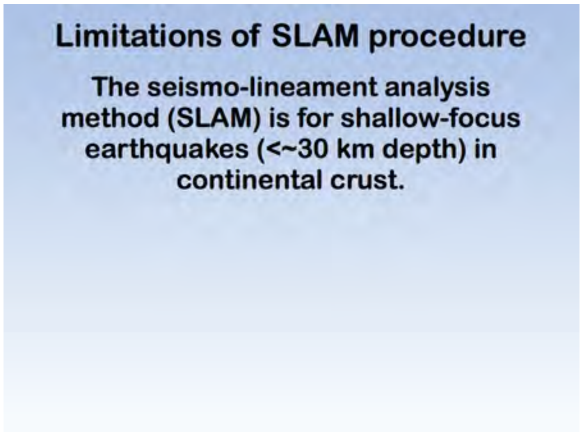
This is exactly the same map area, and here is the same drainage. <<point to drainage on slide.>> The first-return LiDAR data shows the top of the forest canopy, but when the later returns are processed and the forest is removed...



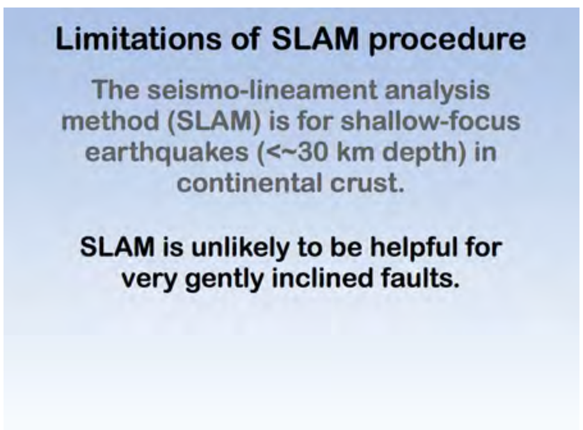
...amazing detail emerges, including buildings, roadways, drainage courses <<point to drainage on slide>>...



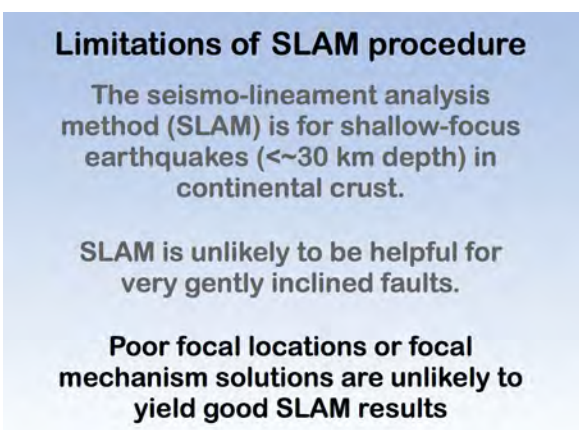
...pyramids, terraces, and cenotes. We think that using seismo-lineaments to focus aerial LiDAR data acquisition will help us find previously unmapped seismogenic faults, even in areas with significant vegetative cover.



The seismo-lineament analysis method (or SLAM) is not a silver bullet. It certainly has its limitations, as does any method. SLAM is for shallow-focus earthquakes (less than around 30 km depth) in continental crust.



SLAM is unlikely to be helpful for very gently inclined faults. As fault dip flattens to the horizontal, the width of a seismo-lineament on the ground surface widens to the point that it becomes useless. Still, we have used this method successfully on reverse-slip faults dipping 30° or so.



Poor focal locations or inaccurate focal mechanism solutions are unlikely to yield good SLAM results. This is no surprise, because the accuracy of results from any method is limited by the quality of the input data.

The purpose of my work is to correlate recorded earthquakes with the faults that generated them. I want to identify faults that can produce earthquakes that can cause damage, injury or death, so that these can be avoided.

I have presented our work at this meeting to teach you about SLAM and to offer to collaborate with you in your search for seismogenic faults in Latin America or elsewhere. Please contact me if you would like to use this method, either on your own or in collaboration with me.

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Additional references and resources related to SLAM are available online at http://bearspace.baylor.edu/Vince_Cronin/www/SLAM

