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Seismo-Lineament Analysis Method (SLAM), Using Earthquake Focal Mechanisms to Help Recognize Seismogenic Faults

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Abstract: The Seismo-Lineament Analysis Method (SLAM) uses an earthquake focal mechanism in a process intended to spatially correlate a shallow-focus earthquake with the ground-surface trace of the fault that generated the earthquake. The nodal planes (NP) derived from the focal mechanism are projected upward to the ground surface, represented by a topographic/hillshade map based on a digital elevation model. The intersection of a NP and the ground is called a seismo-lineament. When uncertainties in hypocenter location and NP orientation are incorporated, the seismo-lineament is a swath on the ground surface. If the NP is the fault-plane solution (i.e., coincides with the causative fault), the fault that generated the earthquake is likely to be found within the seismo-lineament if the fault is emergent and approximately planar from the hypocenter to the ground. Faults that are spatially correlated with earthquakes as small as M 2.9 have been located using SLAM.

Key words: earthquake, focal mechanism, active faulting, paleoseismology, fault geomorphology

INTRODUCTION

The fundamental goal of the paleoseismology community is to identify and usefully characterize seismogenic faults that can generate damaging earthquakes, so that the risks associated with these hazards can be avoided or mitigated. Faults that have ruptured the ground surface and that have generated moderate or larger (M>5) earthquakes are generally good targets for trench studies. Some faults capable of generating significant earthquakes are inaccessible to trenching because they are not emergent (*i.e.*, they are "buried" or "blind"). Some seismogenic faults have not caused co-seismic ground-surface rupture during historic times, and have remained unrecognized. There are many examples of faults that had not been recognized as seismogenic (or that were not mapped at all) before they produced damaging earthquakes. The quality, completeness, and coverage of active-fault mapping is still highly variable worldwide.

Most earthquakes along a typical fault do not rupture the entire fault surface -- large faults do not generate only large earthquakes, and small earthquakes do not occur only along small faults (Cronin et al., 2008). Active faults that can produce major earthquakes also produce myriad smaller earthquakes that spatially correlate with the primary fault surface. We can use small earthquakes to help us identify seismogenic faults that are capable of producing large earthquakes.

The Seismo-Lineament Analysis Method, or SLAM, uses earthquake hypocenter and focal mechanism data, hillshade maps derived from digital elevation models (DEM), geomorphic analysis and geologic field work to help identify the ground-surface trace of faults that produce earthquakes (Cronin et al., 2008). The current version of SLAM can accommodate a triaxial-ellipsoidal

uncertainty region around the hypocenter, and incorporates reported uncertainties in nodal-plane orientation (Cronin & Cronin, 2014). SLAM has been used to spatially correlate faults and well-located earthquakes with reported magnitudes as low as 2.9. SLAM has also been used to discover new faults and to spatially correlate earthquakes with mapped faults that were not thought to be seismogenic, faults that were thought to have Neogene displacement but that were not known to have been seismogenic in historic times, and faults that had been associated with historic earthquakes (Cronin et al., 2008; Millard, 2007; Lindsay, 2012; Reed, 2013). I will use the pronoun "we" throughout this single-author paper because the development and initial applications of SLAM have been collaborative efforts involving several co-workers, acknowledged at the end of this paper.

GENERAL DESCRIPTION OF SLAM

Details about focal mechanism solutions and their derivation are available elsewhere (*e.g.*, Dziewonski et al., 1981; Reasenberg & Oppenheimer, 1985; Hardebeck & Shearer, 2002; Stein & Wysession, 2003; Shearer, 2009; Cronin, 2010). Some comments about focal mechanisms are appropriate here in the interest of clarity. The focal mechanism for an earthquake with a double-couple mechanism includes two nodal planes, oriented perpendicular to one another. The fault that generated the earthquake is coincident with one of the nodal planes (called the *fault-plane solution*), while the other plane is a symmetry plane called the *auxiliary plane* that does not (necessarily) have any displacement along it. The slip vector on the fault plane is parallel with the vector normal to the auxiliary plane. The geometry of a focal mechanism solution is often graphically represented using a focal mechanism (or beach ball) diagram.

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The *minimal* data required for a SLAM analysis are a hypocenter location (latitude, longitude, depth), the corresponding earthquake focal mechanism (dip azimuth or strike, dip angle, and rake of the hanging-wall slip vector for one of the nodal planes), and a map of the epicentral area. It is better, but not necessary, if the map is a topographic map. The *ideal* input data for a SLAM analysis are the hypocenter location with associated uncertainties, the corresponding focal mechanism with uncertainties, and a DEM of the epicentral area that is of sufficient resolution to capture significant geomorphic features related to fault displacement of the ground surface. Hypocenter locations that result from multiple-event relocation studies of the epicentral region are preferred to single-event locations (*e.g.*, Waldhauser & Ellsworth, 2000; Waldhauser, 2001).
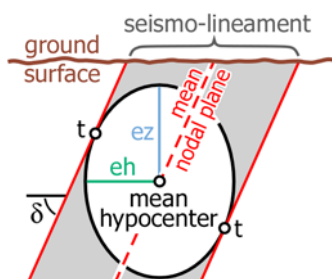

Fig 1. Vertical cross section of a seismo-lineament, shown perpendicular to the strike of the mean nodal plane. =dip angle of mean nodal plane, t=tangent point, eh=horizontal uncertainty, ez=vertical uncertainty.

A key element of SLAM is a procedure to project a nodal plane from the hypocenter upward, defining the intersection of the nodal plane and the ground surface (Figure 1). We call this intersection a *seismo-lineament* (Cronin et al., 2008).
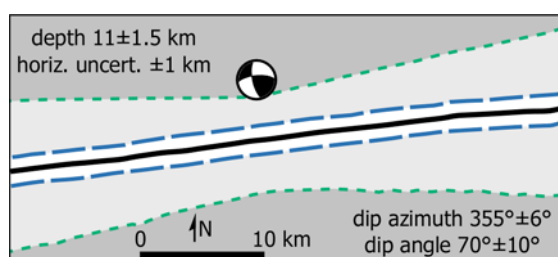

Fig 2. Examples of seismo-lineaments (SL) for an inclined nodal plane projected onto an irregular ground surface. Solid curve is the SL for the mean nodal plane alone, with no uncertainties reported or used. Area between long-dashed curves is the SL for a case when only the hypocenter uncertainty estimates are used. Area between short-dashed curves is the SL when uncertainties for both the hypocenter and nodal plane are used. Focal mechanism diagram plotted at the epicenter.

If the uncertainties in hypocenter location and nodal-plane orientation are not specified, the seismo-lineament will be a line or curve on a ground-surface map (Fig. 2). If the hypocenter location uncertainty is known, two planes that are tangent to the hypocenter uncertainty ellipsoid and that are parallel to the mean

nodal plane are projected to the ground surface, defining the seismo-lineament as a linear swath as seen in map view. If uncertainties are known for both the hypocenter location and nodal plane orientation, the resulting seismo-lineament has the appearance of a bow tie, with the epicenter located near the narrowest part of the swath (*i.e.,* near the "knot" of the bow tie). An open-source code written in *Mathematica* (available via http://bearspace.baylor.edu/Vince_Cronin/www/SLAM/) is used to define the boundaries of a seismo-lineament, using a DEM to represent the ground surface.

The seismo-lineament for a given nodal plane defines the area where the trace of the fault is likely to be found if the causative fault is emergent and approximately planar from the hypocenter to the ground surface, and if the given nodal plane is coincident with the fault.

There are two seismo-lineaments for each earthquake, each corresponding to one of the two nodal planes. We create a hillshade map of the DEM in the area of each seismo-lineament, with low-angle illumination directed parallel to the mean dip direction of the corresponding nodal plane. Fault-related features on the landscape are likely to be oriented perpendicular to this illumination direction. We conduct a geomorphic analysis using the hillshade maps of seismo-lineaments, intending to identify possible fault-related features. We also consult published geologic maps and compile the traces of known faults in our study area. The geomorphic analysis and fault-trace compilation generate hypotheses about the possible causative fault that can be tested during subsequent geologic fieldwork, and help us to differentiate between the fault-plane solution and the auxiliary plane.

An additional aide in differentiating the fault-plane solution from the auxiliary plane involves mapping earthquakes that occurred in the epicentral region perhaps six months before and six months after the main event. Plainly, this would include the aftershock sequence of a large earthquake (Figure 3), but mapping temporally related earthquakes can help us interpret the fault plane solution for smaller events as well.

EXAMPLES

The largest recorded earthquake in the North Tahoe-Truckee area of east-central California is the M_L 6 event of September 12, 1966, at an estimated depth of 10 km (Ryall et al., 1968). This earthquake caused damage throughout the epicentral area, but caused no reported injuries (Kachadoorian et al., 1967). The Dog Valley Fault Zone (DVFZ) was recognized as a result of the 1966 Truckee earthquake, based on geomorphic lineaments that are sub-parallel to the long axis of the aftershock cluster, and also sub-parallel to the strike of the inferred fault-plane solution (Hawkins et al., 1986). Minor, discontinuous ground rupture was mapped in ~7 locations between Prosser Reservoir and Hoke Valley, in a zone that was ~3 km wide (Figure 3). Ground cracking occurred mostly in the area where aftershocks were

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concentrated (Kachadoorian et al., 1967; Greensfelder, 1968). Hawkins et al. (1986) described the DVFZ as "concealed" after digging two exploratory trenches across geomorphic lineaments without exposing any faults.

We used the hypocenter location of Ryall et al. (1968) and the focal mechanism of Tsai and Aki (1970) in the SLAM analysis of the 1966 Truckee earthquake (Figure 3). Neither published source provided formal uncertainties for their data. We used horizontal and vertical uncertainties of 2 km to define the seismo-lineament, based on an informal assessment noted by Ryall et al. (1968). Greensfelder (1968) and Ryall et al. (1968) determined the locations of aftershocks.
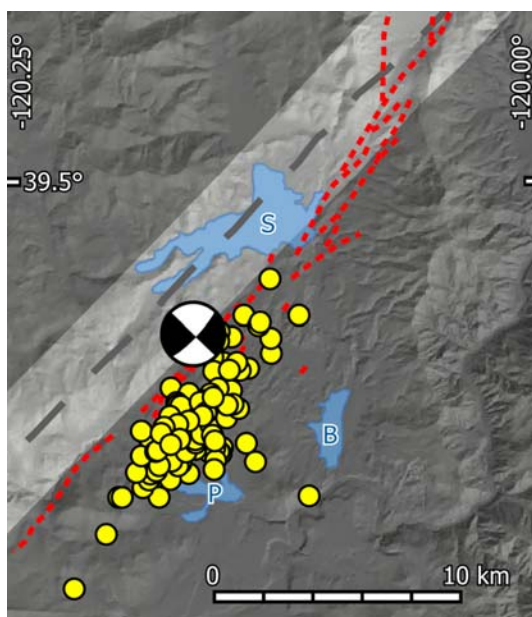

Fig 3. Focal mechanism, seismo-lineament (light gray swath), and trace of the mean nodal plane for inferred fault-plane solutions (dark gray dashed curve) of the M_L 6 Truckee earthquake of 12 September 1966. Red dashed curves are inferred strands of the DVFZ (US Geological Survey, 2014). Small circles are aftershock epicenters, from Greensfelder (1968). S=Stampede Reservoir, P=Prosser Creek Reservoir, B=Boca Reservoir.

Hawkins et al. (1986) indicated that the M_L 6 Verdi earthquake of 29 December 1948 and an earthquake sequence from January to September 1983 also occurred along the DVFZ. Lindsay (2012) and Reed (2013) applied SLAM to several earthquakes with epicenters in the vicinity of the DVFZ, including the M 4.0 event of 3 July 1983 and the M 3.2 event of 30 August 1992 (Figure 4). Hypocenter location data for the 1983 event are from the Northern California Earthquake Data Center (NCEDC, 2013), and the relocated hypocenter data for the 1992 event are from Waldhauser (2013). Horizontal uncertainties for both events are <0.54 km, and vertical uncertainties are ≤0.8 km. Focal mechanism solutions used to define the seismo-lineaments are from the NCEDC catalog (2013).

No ground deformation was reported for either of these minor events, although both were felt locally. Seismo-lineaments associated with both earthquakes correlate spatially with the DVFZ, as well as with the trend of aftershocks and ground deformation noted from the much larger M_L 6 earthquake of 1966 (Figure 4). SLAM provides the tools to recognize that the DVFZ is seismogenic based on data from recent magnitude 3.2 and 4.0 events, even without knowledge of the M_L 6.0 events of 1948 and 1966 along the same fault zone.
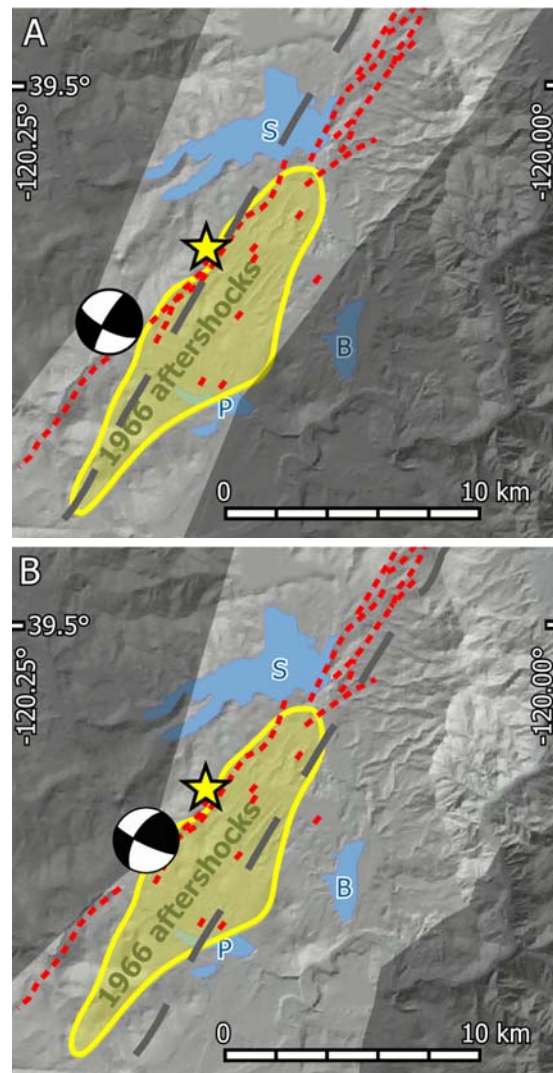

Fig 4. Focal mechanisms, seismo-lineaments (light gray), and traces of the mean nodal planes for inferred fault-plane solutions (dark gray dashed curves) for two minor earthquakes. [A] M 4 earthquake at 11.05 km depth on 3 July 1983. [B] M 3.2 earthquake at 5.344 km depth on 30 August 1992. The star marks the epicenter for the 1966 Truckee earthquake. Other symbols are the same as in Figure 3.

DISCUSSION

When well-located earthquake hypocenters coincide with a fault, and the slip characteristics defined by the corresponding earthquake focal mechanisms are compatible with slip indicators along the fault, it is

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reasonable to conclude that the fault is seismogenic. SLAM provides several potential benefits for those who need to identify seismogenic faults. As seen in the DVFZ example, SLAM can utilize data from small earthquakes to help identify seismogenic faults capable of large earthquakes. SLAM can be used along with traditional methods to help identify places where trench studies might produce useful information about suspected active faults. Seismo-lineament swaths might also be used to define survey tracks for airborne laser swath mapping (ALSM) along suspected fault trends. The combination of SLAM with ALSM to create bare-earth surface maps should be particularly useful in seismically active areas where forest cover has inhibited traditional geologic mapping, as is common in tropical and temperate rain forests.

The primary limitations in the application of SLAM to identify seismogenic faults are the availability and accuracy of hypocenter and focal mechanism data. The earthquake-seismology community should continue to create and routinely update searchable catalogues of relocated earthquakes (*e.g.,* Waldhauser, 2013) and high-quality focal mechanism solutions, along with their uncertainty estimates. These data are only as good as the seismograph networks that collect them. The geoscience community should continue to stress the importance of building, maintaining, and improving seismograph networks in seismogenic areas worldwide, with appropriate shared/open-data policies, so that we can recognize earthquake hazards more effectively and assess the corresponding risks.

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