Title: Assessing Earthquake Hazard from Relationships between Fault Zone Morphology and Rupture Characteristics

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Large earthquakes cause billions of dollars in damage and extensive loss of life and property, yet knowledge of when and where large earthquakes will strike remains elusive. Earthquakes occur from stick slip motion on faults driven from the far field by plate tectonic motions. NASA's geodetic imaging GPS and InSAR measurements provide crustal deformation observations that are invaluable to understanding active faults. Researchers are increasingly turning to sub-meter topographic measurements to characterize the morphology of earthquake fault zones. Fault zone morphology reflects the roughness of faults, which control rupture size, and tectonic stress orientations. NASA has a long history of measuring the present-day to decadal time scale deformation associated with fault zones. Earthquake ruptures permanently alter the land surface and repeated earthquakes cause integrated effects. NASA's 2002 Solid Earth Science Working Group Report asks two questions for understanding earthquake hazards, which remain relevant today:

1. *What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?*
2. *How do tectonics and climate interact to shape the Earth's surface and create natural hazards?*

Fault zones result from distributed deformation over repeated earthquakes between two blocks of crust (**Figure 1**). Gravity and weather drive surface processes to erode and alter fault zones further. Tectonic and erosion may operate together creating rock damage and landscape asymmetry across faults. It is necessary measure the permanent deformation and surface responses from many earthquakes along recently active faults. Space-based fixed-point observing provides a means of recovering topography for global active faults with opportunity for on-demand access. Geomorphic metrics computed from surface morphology and simulations allow scientists to compute relations with earthquake size and shaking hazard.

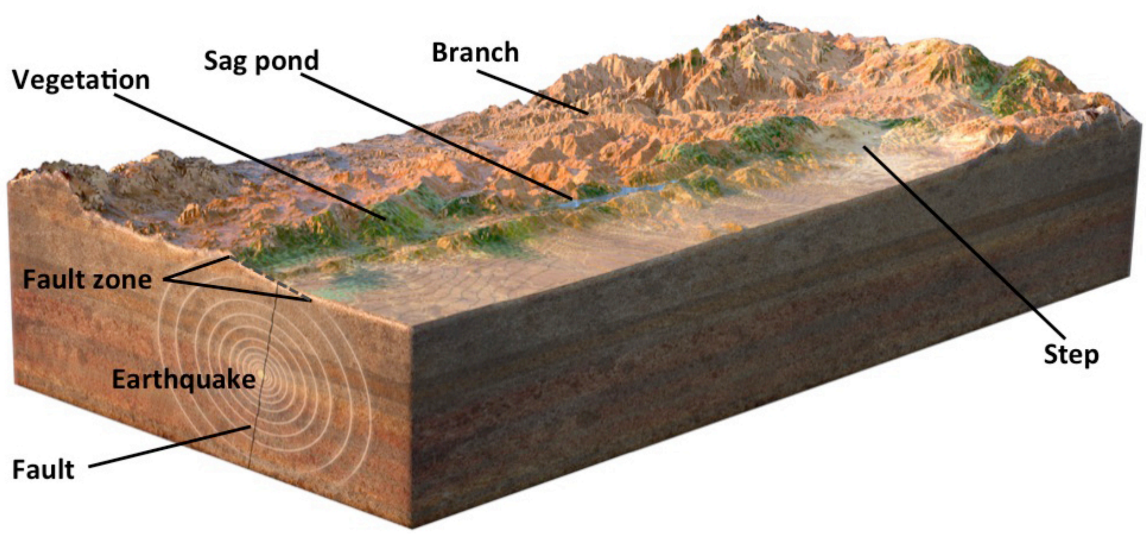

Figure 1. Faults are made up of a central core surrounded by a damage zone. Key topographic features observable at the surface provide information about the width of the fault zone, the roughness of the fault, and the orientation of the fault relative to tectonic motions (artwork Chuck Carter, Jet Propulsion Laboratory).

Understanding Earthquake Potential and Rupture Characteristics Remain Key Challenges in Earthquake System Science in the Coming Decade

A key challenge for earthquake science is to understand the earthquake potential of faults and segments. Landforms along a fault zone express the incremental and cumulative effects of displacements from earthquakes and the resultant surficial responses to rock damage. Fault zones are segmented and blocks of different strengths bound the segments. Geodetic imaging observations are transforming our understanding of earthquake processes by providing measurement of crustal deformation associated with strain accumulation and release. Seismicity provides the location and size of events, while geodetic imaging observations provide observations of surface deformation that reflect tectonic driving motions and response of the Earth's crust and earthquake faults. Measurement of fault zone morphology globally would reveal relationships between fault segment complexity and earthquake ruptures, filling a gap in measurements that would complement ongoing geodetic, geological, and seismological observations.

A variety of observational, theoretical and numerical evidence indicates that the roughness of a fault is directly related to the fault friction and to the control of how earthquakes stop once they begin to propagate along a fault. Rupture directivity has an impact on ensuing damage from earthquakes. Fault branches typically form on one side of a fault reflecting the stress field, which controls the direction of rupture propagation. If the southern San Andreas fault has its overdue large, M≥7.5 earthquake the basins in the Los Angeles area that form a chain will act as a waveguide and produce extensive damage. Less damage occurs for a rupture that propagates southward from the north. Asymmetry across a fault zone indicates rupture directivity, which is important then for damage assessment.

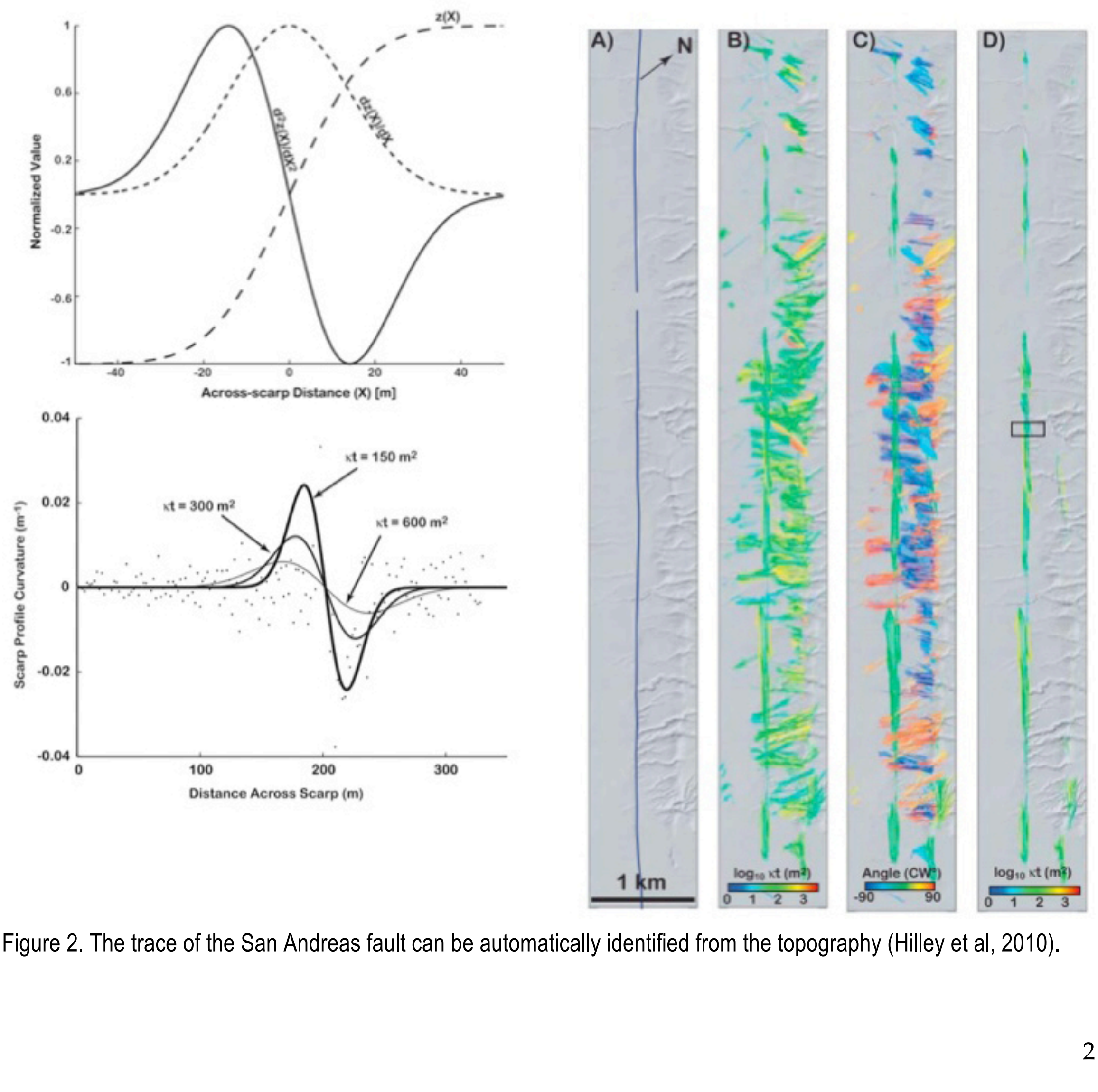

Figure 2. The trace of the San Andreas fault can be automatically identified from the topography (Hilley et al, 2010).

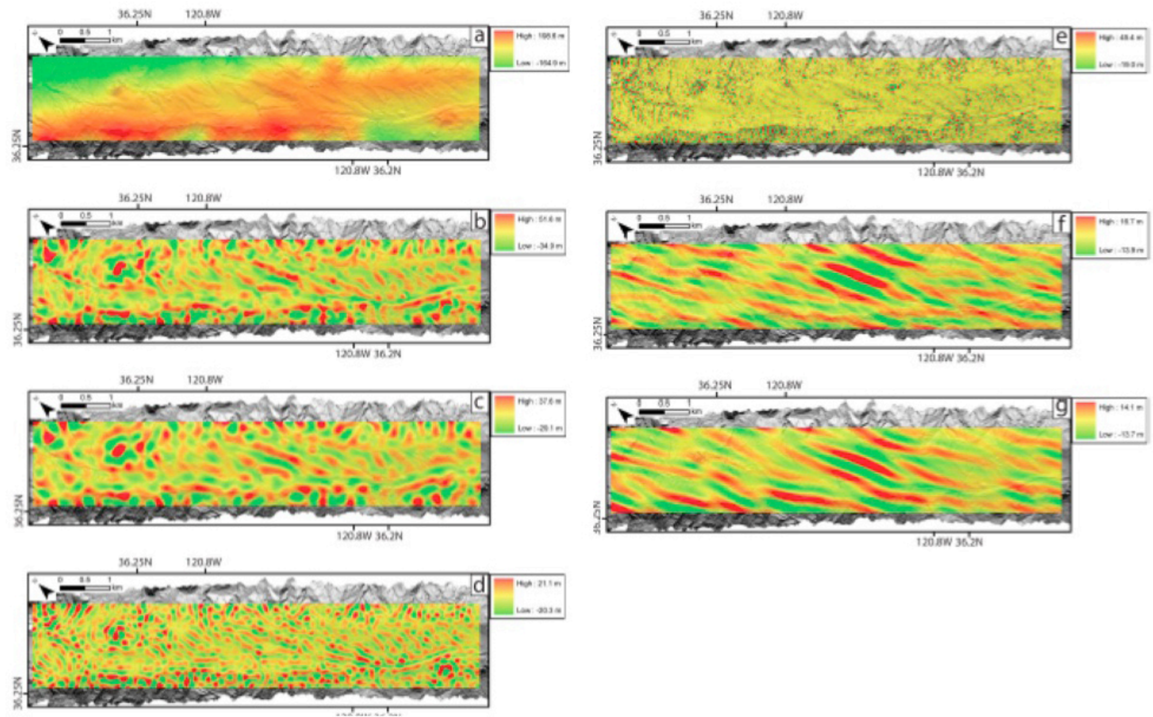

Figure 3. Spectral analysis of topography along the central San Andreas fault (Mustang Ridge) can detect fault zone structure and shear zone feature spacing and orientations (Delong et al, 2010). Surfaces constructed from fast Fourier transform filtering of lidar derived DEM draped on original shaded relief maps using different filters. Automatic anisotropic filtering shows asymmetries with the fault - parallel features removed.

Measurement of Fault Zone Morphology is Timely and Ready to Inform Earthquake Research

Researchers are automating methods to analyze digital elevation models for understanding tectonic activity and fault behavior (Figure 2 and Figure 3). Geomorphic metrics quantify characteristics of the landscape. A variety of geomorphic metrics can be computed and related to earthquakes. 1 m resolution digital elevation models from lidar along the well-studied San Jacinto fault show that fault damage can be inferred from changes in drainage patterns across the fault zone. Fault damage and fault zone complexities are indicators of fault strength. Asymmetry across the fault zone correlates with rupture propagation direction. Landscapes can be filtered for patterns and asymmetries.

The planned launch of NISAR in 2020 would allow fusion of deformation and fault zone morphologic measurements. Topographic measurement of fault zones would be used in the processing of NISAR data where available. Detailed topographic measurements in California and the Western United States from the OpenTopography Project serves as a proof-of-concept for global measurements and provides valuable calibration and validation data.

Space-Based Observations Provide Global, Systematic, and On-Demand Observations

Scientists are increasingly turning to lidar and airborne structure from motion (SfM) measurements to characterize the morphology of earthquake fault zones. Their essential value is that they measure topography and surface characteristics at the appropriate fine scale (meter) at which fault zone deformation processes operate. The measurements are difficult, expensive, and time consuming to make. While extremely useful, they are not systematic, can have long latency following earthquakes, and cover small areas. NASA has a long history developing new methods for studying earthquakes and related natural hazards. The focus has been on geology of fault zones from spectral imagers such as ASTER and crustal deformation from GPS and radar measurements. Geomorphic measurements represent the next opportunity for NASA's pioneering developments for earthquake research (Figure 4). No other spaceborne mission provides the capability of producing sub-meter measurement of fault zone morphology.

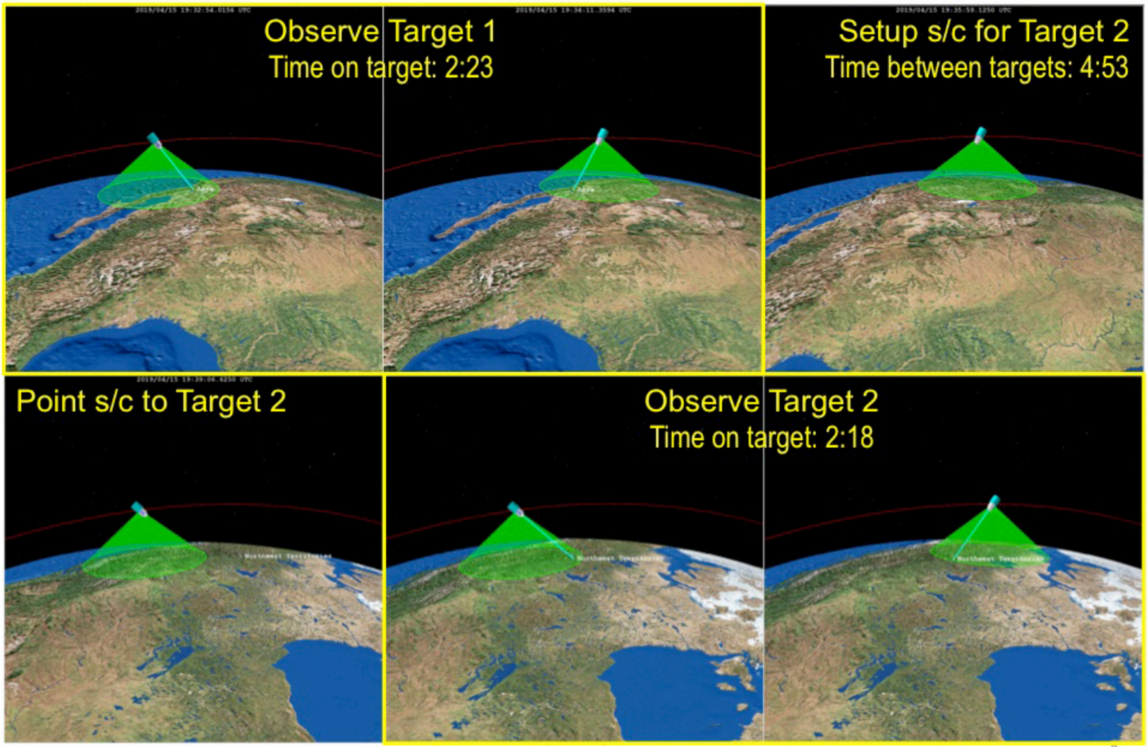

Figure 4. Measuring fault zone morphology requires multi-angle imaging of a target for 3D reconstruction of topography and determination surface cracking and fault zone damage. Such a system would dwell on a target for minutes during a pass before moving on to the next target.

Understanding Earthquake Characteristics Mitigates Hazard and Global Measurements Aid Response

Accurate earthquake probabilities can be computed if synthetic and actual earthquake histories are consistent. Earthquake simulations model long sequences of earthquakes taking as parameters fault geometry, crustal deformation velocities, friction along fault segments, and stress transfer relations. Friction is derived from the assumption that earthquakes rupture with repeating similar offset patterns called characteristic earthquakes. While this is a convenient simplifying assumption, observational support for characteristic earthquakes is debated. Uncertainty in knowledge of characteristic earthquakes for tuning the models and the simplification of imposing uniform friction along fault segments of tens of kilometers propagate through the models. Fault segment complexity computed from geomorphic metrics could serve as a normalized dimensionless proxy for fault friction removing the need to make assumptions about characteristic earthquakes. Improved assessment of earthquake potential (Figure 5) would served the estimated 283 million people exposed to major earthquake risk worldwide.

Spaceborne geomorphic measurements could be used to respond to earthquakes that cause loss of life or property from the earthquake, aftershocks, or induced hazards. Accurate geographically detailed estimation of damage and risk resulting from disasters is critical for pre-event emergency planning and post-event recovery. Information during the disaster is essential for emergency planners to allocate resources for response and recovery efforts. Scientifically the measurements would enable the monitoring of rapid post-seismic response and evolution of fault zone properties following large ruptures filling a key observational gap. The data will help to identify processes that occur in close time-space proximity to the occurrence of large earthquake ruptures.

A mission to measure fault zone morphology would be used by earthquake researchers. Other fields could also benefit from detailed topographic measurements.

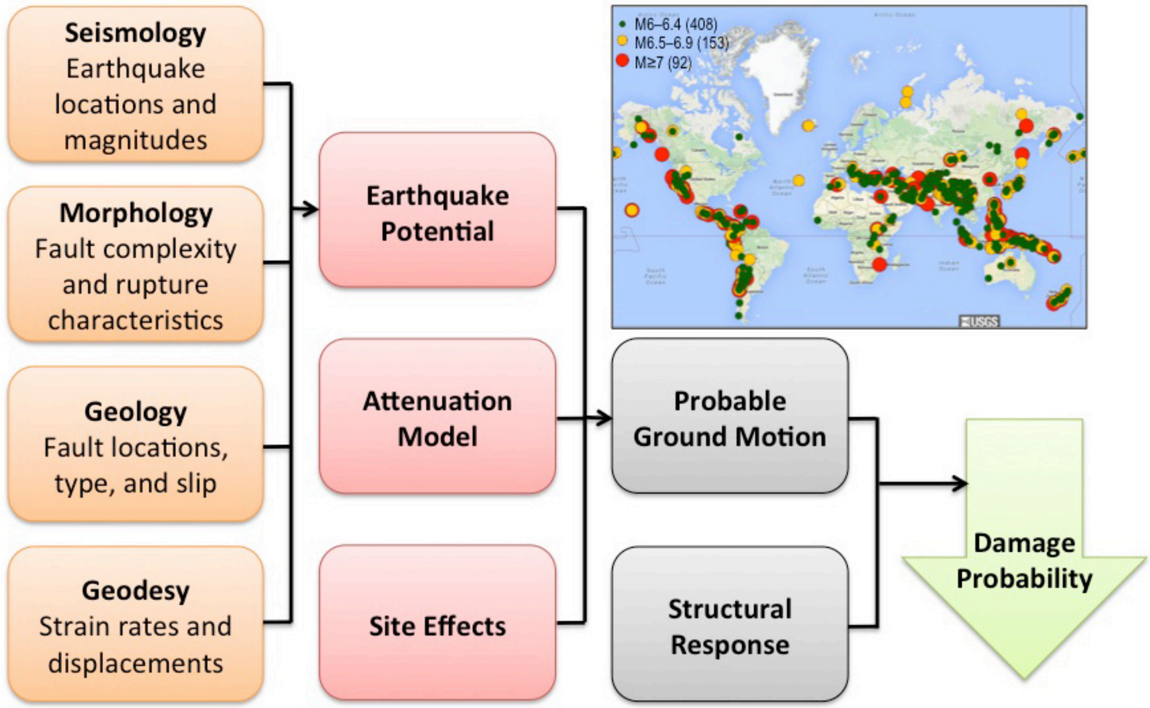

Figure 5. Fault zone morphology contributes to earthquake hazard estimation by relating surface patterns to rupture characteristics. Measurements (orange) couple with and regional and local seismic effects (red) to produce probable ground motion estimates (gray), which when combined with structural response can be used to estimate damage probability. Map: Land earthquakes ≥M6 1970 – present. Damaging earthquakes have occurred on every populated continent.