Relay Ramp Deformation and Throw Patterns Applied to Mechanics-Based Interpretations of Normal Faults: The Hat Creek Fault as a Case Example*

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Abstract

Normal fault evolution is commonly analyzed in terms of the patterns of throw measured across the fault, whether along the fault trace in the form of throw profiles or across the fault surface as interpreted from offsets of prominent reflectors in 3D seismic data. This approach to fault analysis is possible because faults behave in mechanically predictable ways so that field data can inform perceptions of fault evolution and 3D structural architecture. Faults are initiated in brittle rocks when the frictional strength is overcome, with subsequent fault propagation as slip accrues over time. The surrounding rock volume is approximated as behaving in an elastic manner during interseismic periods, but with irrecoverable deformation in response to fault slip events. The elastic rheology results in general relationships between fault size and fault throw, as well as controlling the manner in which throw is distributed across the fault surface. Theoretical relationships deduced from the field of linear elastic fracture mechanics as well as empirical data obtained from field observations, analog models, and 3D seismic interpretation, all provide strong support for an approximately elliptical distribution of fault throw. This pattern is maintained through time (i.e., fault growth is self-similar) such that the point of maximum throw is commonly representative of the oldest portion of the fault. Accordingly, fault throw profiles along the surface trace (i.e., along fault strike) can be used to deduce fault growth history.

Segmented normal faults are comprised of a number of initially isolated segments that follow these growth characteristics; however, the eventual interaction and linkage of adjacent segments produces predictable changes in throw profiles that relate to the 3D geometry and spatial arrangement of such segments. For example, throw maxima may become skewed toward non-elliptical shapes because of mechanical interactions between segments. As these segments become mutually closer, the throw profile evolves toward that of a single segment of equivalent combined length in a phenomenon referred to as kinematic coherence.

Problems with Conventional Throw Analysis Techniques

In situations where the segments overlap each other (ultimately leading to physical linkage of the segments in many instances), a common analysis technique is to add the individual throws of each segment at mutually adjacent points along strike to determine a cumulative throw representative of that location along the fault. The logic used is that adjacent fault segments partition the total strain between them; therefore, combining their throw amounts will produce an accurate representation of total throw (and thus strain) across the fault. However, cumulative throw profiles produced in this way often show anomalously high or low throw amounts in regions of segment overlap. A common reason for these anomalous cumulative throw values is that a portion of the strain is taken up by deformation of the wedge of rock between the fault segments (i.e., the relay zone). This contribution to the strain is not conventionally included in throw analyses; however, our theoretical and field analyses show that the contribution of the relay zone to total throw is significant and can provide important insights into the evolution of the fault system.

Relay zones are intersegment deformed zones that are typically tilted at the Earth's surface. Our analysis of field examples at the Hat Creek fault (California), the Bishop Tuff volcanic tableland (California), the Canyonlands grabens (Utah), and the Lake Mead region (Nevada) has revealed that a range of relay zone geometries and tilt directions are possible depending on the nature of segment interaction through time and 3D geometry. Some relay zones tilt in the direction of fault dip (i.e., from the rear fault segment toward the front fault segment), referred to as forward-tilting ramps. In such cases, the change in elevation across the relay zone should be added to the throw accommodated along the faults themselves in order to obtain an accurate estimate of cumulative throw. More commonly in evolved fault systems, the relay zone tilts backward, against the direction of fault dip (Figure 1). In such cases, the change in elevation across the relay zone should be subtracted from the fault throw to produce a cumulative throw plot.

Inferences About Fault Evolution From Ramp Geometry

This inconsistency in relay ramp tilt characteristics can be used to make inferences about fault evolution. Our elastic models indicate that forward-tilting ramps tend to develop early in the fault evolution, when segments are underlapping. This tilt is progressively removed as extensional strain increases and the fault segments propagate past each other until, ultimately, the ramp starts to tilt backward. Static elastic models that only consider a single geometric configuration of fault segments may show backward tilting ramps developing before the segments have even overlapped; however, it is necessary to consider both the 3D geometry of the fault segments and the progressive deformation history within the relay ramp to develop accurate relationships between segment geometry and ramp tilt. Taking both of these factors into account, we show that forward tilting ramps may persist until as much as ~10% overlap of the segments (relative to their lengths). Furthermore, forward tilting ramps do not accommodate more than 15% of the maximum throw along the fault scarp, whereas backward tilting ramps can accommodate about a third of the total throw by 30% overlap. This percentage is further increased in instances where the back fault segment is longer than the front fault segment. Therefore, conventional techniques for estimating cumulative throw become increasingly inaccurate as the amount of segment overlap increases.

The Hat Creek Fault Case Example

The Hat Creek fault in northern California is a 47-km long segmented normal fault system along the western edge of the Modoc plateau. Relay ramps are common between segments, such as the example in Figure 1. Much of the fault has remained seemingly inactive since the Late Pleistocene; however, a portion of the fault is currently active with numerous lines of evidence for Holocene activity (e.g., up to 56 m of throw offset within ~24 kyr Hat Creek lavas). The active portion of the fault has been previously documented to involve a 23.5 km length of scarp south of the volcanic edifice Cinder Butte. Our analysis of the tectonic geomorphology along the scarp, particularly the development of fault trace monoclines in young lavas that are progressively disaggregated during repeated earthquake events, provides evidence that the active scarp continues north of Cinder Butte and is at least 30 km long in total, capable of ~M6.7 earthquakes every 500-800 years. Although these conclusions were based on field mapping and observations, the throw profiles along different segments of the fault provide supporting evidence for this conclusion. The previously documented portion of the active scarp shows throw profiles with mechanically interacting segments that experienced kinematic coherence. Nonetheless, the maximum throw along these combined segments is strongly skewed toward the north end of the fault. The addition of newly mapped segments north of Cinder Butte produces a more centralized peak in the throw profiles (Figure 2), indicating a longer kinematically coherent fault. Hence, throw profiles can be used to guide intuition regarding which fault segments evolved together and are likely to rupture in tandem.

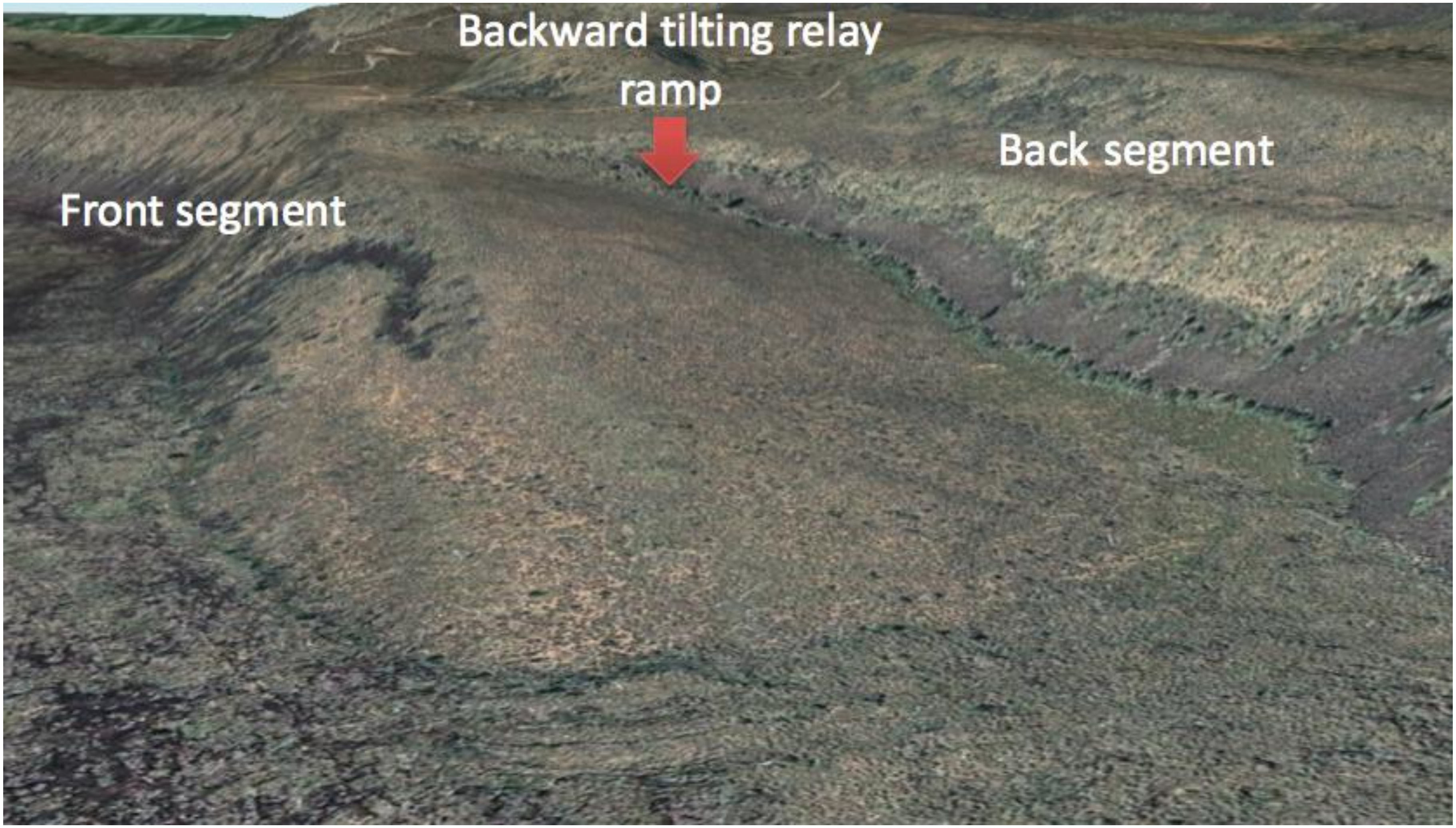

Figure 1. Google Earth image of a backward tilting relay ramp along the Hat Creek fault, California. The change in elevation of the ramp from the front segment to the back segment should be subtracted from the combined throw from each segment to obtain the correct cumulative throw across the fault near the relay ramp.

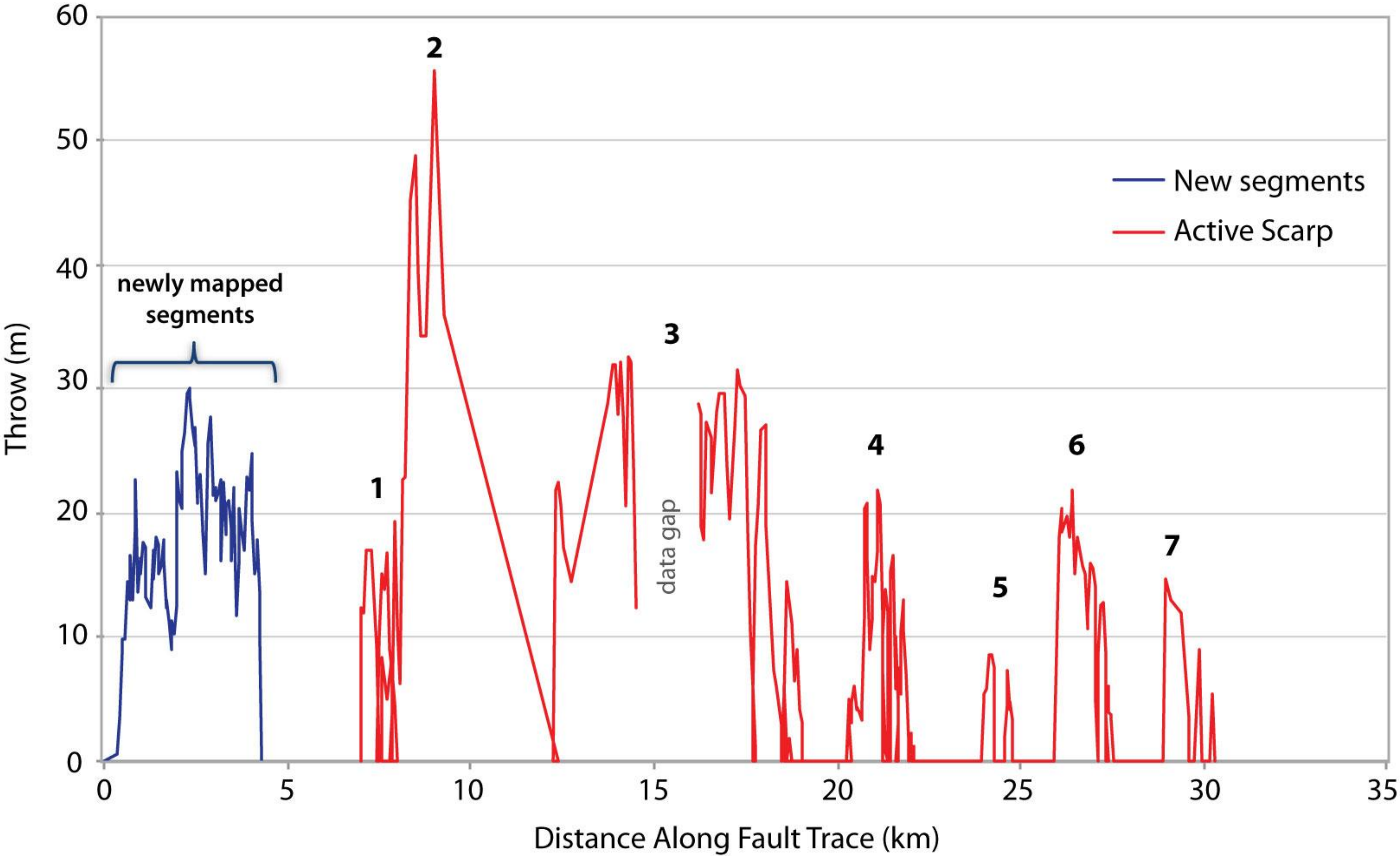

Figure 2. Throw profile along the Hat Creek fault, California. The seven segments in red represent the previously documented active portion of the fault. Each segment has an approximately elliptical throw distribution. However, the throw maximum is not centered, as would be expected along a kinematically coherent system. The addition of newly mapped segments (in blue) produces a more mechanically feasible throw distribution and implies the active portion of the fault is longer than was previously inferred, increasing the regional seismic hazard.