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RESEARCH **FOCUS**

Variation in slip rates on active faults: Natural growth or stress transients?

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Bergen et al. (2017) present evidence in this issue of *Geology* for a marked, fivefold acceleration in slip rate on the Puente Hills blind thrust system, a fault network that directly underlies the Los Angeles metropolitan area (California, USA). Their work thus has considerable implications for the challenge of assessing seismic hazards in this densely populated megacity. Assessing seismic hazard relies in part on measurements of slip rate, itself used as a proxy for moment release over time along a fault. This is then merged with records of earthquake magnitude and recurrence as defined by paleoseismic investigations (Schlagenhauf et al., 2011; DuRoss et al., 2016).

Characterization of the slip rate at multiple sites along the length of a fault provides a basis for understanding how single faults might evolve naturally as a result of lateral propagation (Nicol et al., 2005), and how segmented faults evolve with increasing displacement (Kim and Sanderson, 2005). As Late Quaternary stratigraphy in sedimentary basins deformed by active faults becomes more tightly defined at time scales of 10^4–10^5 yr, the more likely the stratigraphy will be to identify transient changes in slip rates (Nicol et al., 2005; Bull et al., 2006; Mouslopoulou et al., 2012; Grothe, 2012; Grothe et al., 2014). While detailed records of Late Holocene recurrence of slip events are increasingly available from some ideal paleoseismic sites along strike slip faults (Rockwell et al., 2015), records of fault behavior at longer time scales of 10^4–10^5 yr hold additional promise for identifying the processes that might drive transient changes in slip and rate.

So what governs fault slip rates? Plate motions are the first-order control on where and why faults start and stop and how fast they move, probably followed by fault maturity and strength characteristics. As slip on complex arrays of faults occurs with greater amounts of strain, displacement typically become localized into fewer, through-going, more rapidly moving structures that accommodate the majority of plate motion (Meyer et al., 2002); an extreme case includes long-lived subduction zones. For isolated structures, in particular dip slip faults, displacement-length scaling provides a visual representation of the outer (i.e., total slip) envelope for how slip rates might vary naturally in three dimensions as increasing strain is accommodated (Kim and Sanderson, 2005; Nicol et al., 2005; Bull et al., 2006). Work in Japan and New Zealand (Nicol et al., 2005; Bull et al., 2006; Grothe, 2012; Grothe et al., 2014) suggests that triangular-shaped displacement to fault length profiles defined by multiple deformed stratigraphic horizons arises by more rapid slip in the centers of reactivated dip slip faults. Given this relationship, slip rate may naturally increase with time where displacement is measured at a single point along the fault that propagates laterally away from the site. Faults that reactivate older, more mature slip surfaces may exhibit more rapid initial lateral propagation histories, and may alternatively produce a different history of fault slip and lateral propagation (Walsh et al., 2002).

Well-characterized slip histories thus require multiple sites where progressive fault displacement is defined by well-constrained stratigraphic sequences. Some of the best opportunities include dip slip faults that deform basins containing strata correlated with high-frequency late Quaternary sea-level changes, or volcanic arcs where dated tephra are abundant (Biswas et al., 1999). Paradoxically, hidden or blind thrusts may offer the best records for intermediate-timescale fault behavior because they are typically continuously buried in rapidly subsiding basins (Leon et al., 2007).

Although the natural three-dimensional growth of active faults may lead to variation in the rate of slip along them, other external processes may affect local (non-tectonic) stress that drives shorter-term, transient changes in displacement rate. These include unloading or loading associated with erosion (Calais et al., 2010; Steer et al., 2014), melting of an ice cap (Wu and Johnston, 2000) and ground water withdrawal (Amos et al., 2014), sea-level rise (Luttrell and Sandwell, 2010), lake filling (Brothers et al., 2011,) and natural or man-made changes in pore fluid pressure (Ellsworth, 2013; Keranen et al., 2014; Weingarten et al., 2015). Viscoelastic stress triggering from earthquakes may advance or retard slip at earthquake recurrence time scales (Freed, 2005), but is unlikely to change the rate of fault slip at longer time scales. An additional and poorly understood process that might affect the slip rate on faults is toggling, where nearby faults alternatively accommodate variation in moment release, presumably through short-term transient changes in fault strength or variations in orogen dynamics (Hoth et al., 2006).

So where do all these possibilities leave us with regard to the results presented by Bergen et al. (2017)? Their measurement site lies at nearly the westernmost endpoint of three thrust ramps interpreted to rupture together during large earthquakes, based on paleoseismic evidence (Dolan et al., 2003). The age of strata offset by the Puente Hills thrust records a progressive fivefold increase in slip rate, which appears to be accelerating over the past ~250 k.y. If the increase in slip rate at the west end of the blind thrust is a natural consequence of lateral propagation, additional data gathered from along the fault system might elucidate exactly how much this process matters for the amount of rate increase. Alternatively, a comparison of slip rates on other nearby thrusts and strike slip faults that accommodate north-south shortening in the northern Los Angeles Basin over the same time period (Walls et al., 1998) may yield insight into whether toggling is a possible explanation.

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