

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

Karl Mueller

Department of Geological Sciences, University of Colorado, Boulder, Colorado 80309, USA

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.

## REFERENCES CITED

- Amos, C.B., Audet, P., Hammond, W.C., Burgmann, R., Johanson, I.A., and Blewitt, G., 2014, Uplift and seismicity driven by groundwater depletion in central California: *Nature*, v. 509, p. 483–486, doi:10.1038/nature13275.
- Bergen, K., Shaw, J., Leon, L., Dolan, J., Pratt, T., Ponti, D., Morrow, E., Barrera, W., Rhodes, E., Murari, M., and Owen, L., 2017, Accelerating slip rates on the Puente Hills blind thrust fault system beneath metropolitan Los Angeles, California, USA: *Geology*, v. 45, p. 227–230, doi:10.1130/G38520.1.
- Biswas, D.K., Hyodo, M., Taniguchi, Y., Kaneko, M., Katoh, S., Sato, H., Kinugasa, Y., and Mizuno, K., 1999, Magnetostratigraphy of Plio-Pleistocene sediments in a 1700-m core from Osaka Bay, southwestern Japan and short geomagnetic events in the middle Matuyama and early Brunhes chrons: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 148, p. 233–248, doi:10.1016/S0031-0182(98)00185-0.
- Brothers, D., Kilb, D., Luttrell, K., Driscoll, N., and Kent, G., 2011, Loading of the San Andreas fault by flood-induced rupture of faults beneath the Salton Sea: *Nature Geoscience*, v. 4, p. 486–492, doi:10.1038/ngeo1184.
- Bull, J.M., Barnes, P.M., Lamarche, G., Sanderson, D.J., Cowie, P.A., Taylor, S.K., and Dix, J.K., 2006, High-resolution record of displacement accumulation on an active normal fault: Implications for models of slip accumulation during

- repeated earthquakes: *Journal of Structural Geology*, v. 28, p. 1146–1166, doi:10.1016/j.jsg.2006.03.006.
- Calais, E., Freed, A.M., Van Arsdale, R., and Stein, S., 2010, Triggering of New Madrid seismicity by late-Pleistocene erosion: *Nature*, v. 466, p. 608–611, doi:10.1038/nature09258.
- Dolan, J.F., Christofferson, S.A., and Shaw, J.H., 2003, Recognition of paleoearthquakes on the Puente Hills blind thrust fault, California: *Science*, v. 300, p. 115–118, doi:10.1126/science.1080593.
- DuRoss, C.B., Personius, S.F., Crone, A.J., Olig, S.S., Hylland, M.D., Lund, W.R., and Schwartz, D.P., 2016, Fault segmentation: New concepts from the Wasatch Fault Zone, Utah, USA: *Journal of Geophysical Research: Solid Earth*, v. 121, p. 1131–1157, doi:10.1002/2015JB012519.
- Ellsworth, W.L., 2013, Injection-induced earthquakes: *Science*, v. 341, doi:10.1126/science.1225942.
- Freed, A., 2005, Earthquake triggering by static, dynamic and postseismic stress transfer: *Annual Review of Earth and Planetary Sciences*, v. 33, p. 335–367, doi:10.1146/annurev.earth.33.092203.122505.
- Grothe, P.M., 2012, A precise time-displacement-length growth history of the Osaka-wan blind thrust: Evidence for long-term unstable slip [Masters thesis]: Boulder, University of Colorado, 73 p.
- Grothe, P.R., Cardozo, N., Mueller, K., and Ishiyama, T., 2014, Propagation history of the Osaka-wan blind thrust, Japan, from trishear modeling: *Journal of Structural Geology*, v. 58, p. 79–94, doi:10.1016/j.jsg.2013.10.014.
- Hoth, S., Adam, J., Kukowski, N., and Oncken, O., 2006, Influence of erosion on the kinematics of bivergent orogens: Results from scaled sandbox simulations, in Willett, S.D., et al., eds., *Tectonics, Climate and Landscape Evolution: Geological Society of America Special Paper 398*, p. 201–225, doi:10.1130/2006.2398(12).
- Keranen, K., Weingarten, M., Abers, G.A., Bekins, B., and Ge, S., 2014, Sharp increase since 2008 induced by massive wastewater injection: *Science*, v. 345, p. 448–451, doi:10.1126/science.1255802.
- Kim, Y.S., and Sanderson, D.J., 2005, The relationship between displacement and length of faults: a review: *Earth-Science Reviews*, v. 68, p. 317–334, doi:10.1016/j.earscirev.2004.06.003.
- Leon, L.A., Christofferson, S.A., Dolan, J.F., Shaw, J.H., and Pratt, T.L., 2007, Earthquake-by-earthquake fold growth above the Puente Hills blind thrust fault, Los Angeles, California: Implications for fold kinematics and seismic hazard: *Journal of Geophysical Research*, v. 112, B03S03, doi:10.1029/2006JB004461.
- Luttrell, K., and D. Sandwell, 2010, Ocean loading effects on stress at near shore plate boundary fault systems: *Journal of Geophysical Research*, v. 115, B08411, doi:10.1029JB0006541.
- Meyer, V., Nicol, A., Childs, C., Walsh, J.J., and Watterson, J., 2002, Progressive localization of strain during the evolution of a normal fault population: *Journal of Structural Geology*, v. 24, p. 1215–1231, doi:10.1016/S0191-8141(01)00104-3.
- Mouslopoulou, V., Nicol, A., Walsh, J.J., Begg, J.G., Townsend, D.B., and Hristopulods, D.T., 2012, Fault-slip accumulation in an active rift over thousands to millions of years and the importance of paleoearthquake sampling: *Journal of Structural Geology*, v. 36, p. 71–80, doi:10.1016/j.jsg.2011.11.010.
- Nicol, A., Walsh, J., Berryman, K., and Nodder, S., 2005, Growth of a normal fault by the accumulation of slip over millions of years: *Journal of Structural Geology*, v. 27, p. 327–342, doi:10.1016/j.jsg.2004.09.002.
- Rockwell, T.K., Dawson, T.E., Young Ben Horin, J., and Seitz, G., 2015, A 21-event, 4,000-year history of surface ruptures in the Anza Seismic Gap, San Jacinto Fault, and implications for long-term earthquake production on a major plate boundary fault: *Pure and Applied Geophysics*, v. 172, p. 1143–1165, doi:10.1007/s00024-014-0955-z.
- Schlagenhauf, A., Manighetti, I., Benedetti, L., Gaudemer, Y., Finkel, R., Mala-vieille, J., and Pou, K., 2011, Earthquake supercycles in Central Italy, inferred from <sup>36</sup>Cl exposure dating: *Earth and Planetary Science Letters*, v. 307, p. 487–500, doi:10.1016/j.epsl.2011.05.022.
- Steer, P., Simoes, M., Cattin, R., and Shyu, B., 2014, Erosion influences the seismicity of active thrust faults: *Nature Communications*, v. 5, p. 1–7, doi:10.1038/ncomms6564.
- Walsh, J.J., Nicol, A., and Childs, C., 2002, An alternative model for the growth of faults: *Journal of Structural Geology*, v. 24, p. 1669–1675, doi:10.1016/S0191-8141(01)00165-1.
- Walls, C., Rockwell, T., Mueller, K., Bock, Y., Williams, S., Pfanner, J., Dolan, J., and Fang, P., 1998, Escape tectonics in the Los Angeles metropolitan region and implications for seismic risk: *Nature*, v. 394, p. 356–360, doi:10.1038/28590.
- Weingarten, M., Ge, S., Godt, J.W., Bekins, B.A., and Rubinstein, J.L., 2015, High-rate injection is associated with the increase in U.S. mid-continent seismicity: *Science*, v. 348, p. 1336–1340, doi:10.1126/science.aab1345.
- Wu, P., and Johnston, P., 2000, Can deglaciation trigger earthquakes in North America: *Geophysical Research Letters*, v. 27, p. 1323–1326, doi:10.1029/1999GL011070.

Printed in USA