2-4-2017

Super-Interseismic Periods: Redefining Earthquake Recurrence

John P. Loveless
Smith College, jloveles@smith.edu

Super-interseismic periods: Redefining earthquake recurrence

John P. Loveless[1]

[1]Department of Geosciences, Smith College, Northampton, MA 01063, USA.

Corresponding author: John P. Loveless (jloveless@smith.edu)

Key Points:

- Recent studies show temporal variation in interseismic strain patterns.
- Great earthquakes modify coupling on adjacent parts of fault.
- Earthquake clusters may arise from such fluctuations in coupling.

Abstract

Precise geodetic measurements made over broad swaths of tectonically active regions record patterns of interseismic strain accumulation, providing key insights into the locus and timing of pending earthquakes. Recent studies of geodetic position time series, including that of *Melnick et al.* [2017] in this issue, illustrate temporal variation in the pattern of interseismic deformation. These authors propose that the 2010 M_w=8.8 Maule, Chile earthquake enhanced coupling on the Andean subduction zone adjacent to the rupture, including on the portion of the megathrust that broke five years later in the M_w=8.3 Illapel event.

1 Introduction

The classical concept of an earthquake recurrence interval [*Shimazaki and Nakata*, 1980] is rooted in an assumption that spatial patterns of interseismic strain accumulation that precede seismic rupture are consistent through time. However, a growing body of evidence based on geodetic and geologic observations suggests fundamental deviations from this simple model, including spatially and temporally clustered earthquakes and short-term fluctuation in patterns of interseismic fault coupling preceding large earthquakes. Paleoseismic data provide long records of earthquake deformation, which are essential for providing insight into patterns of fault slip over multiple seismic cycles. However, these data can be complicated by imprecise temporal resolution and ambiguity in correlating multiple observations along a single seismogenic fault [*Biasi and Weldon*, 2009]. As a result, distinguishing, for example, a single large magnitude rupture along a great length of the fault from a temporally clustered sequence of smaller earthquakes can be difficult [*Gold et al.*, 2017]. On the other hand, modern satellite geodesy observations provide a more spatially complete picture of earthquake cycle deformation but thus far have only been capable of imaging single earthquakes and small fractions of the preceding and subsequent interseismic periods. In several instances, major subduction zone earthquakes have occurred in regions inferred from geodetic observations to be pre-seismically coupled [*Loveless and Meade*, 2011; *Moreno et al.*, 2010; *Protti et al.*, 2014], but the extent to which coupling patterns vary within an interseismic period or between sequential earthquake cycles is unclear owing to the short time duration of available observations. To improve our understanding of earthquake occurrence and recurrence, it is important to synthesize insights gained about fault system behavior throughout the earthquake cycle from both geologic and geodetic data.

The proliferation of geodetic data along subduction zone fore arcs has led to unprecedented insight into megathrust earthquake cycle processes. Specifically, geodetic observations can be used to constrain the distribution of interseismic coupling and coseismic slip, as well as aseismic slip and postseismic processes [*Wang et al.*, 2012]. Geodetic velocities near seismogenic faults are often taken to represent steady, secular motion in response to spatially variable but temporally constant interseismic fault coupling, even for data spanning major earthquakes and hence including portions of two sequential interseismic periods [*Ergintav et al.*, 2009]. This assumption may reflect, at least in part, the relatively short duration of geodetic observations compared to the length of a decades- to centuries-long earthquake cycle, which inhibits exploration of temporal variation in interseismic behavior beyond that attributed to postseismic processes.

However, in order to fully exploit the information that fault coupling maps provide about the potential for future damaging earthquakes, we must acknowledge the possibility that the distribution of coupling is heterogeneous in both space and time.

2 Temporal variation in earthquake cycle processes

In this issue, *Melnick et al.* [2017] underscore the importance of temporal variation in fault coupling patterns by suggesting that the 2010 M_W=8.8 Maule megathrust earthquake offshore south-central Chile resulted in a "super-interseismic phase" of the earthquake cycle to the north and south of the rupture area, enhancing coupling on these along-strike adjacent regions of the subduction interface. Five years later, the M_W=8.3 Illapel earthquake struck central Chile, ~200 km to the north of the Maule rupture in a region of interplate coupling increased by the Maule event. On December 25, 2016, while the *Melnick et al.* [2017] manuscript was under revision, a M_W=7.6 earthquake occurred south of the Maule rupture, also in a region that likely also showed increased coupling owing to the 2010 event. The authors note that the close temporal and spatial spacing of these large to great earthquakes is similar to five past great earthquake doublets along the central Chilean subduction zone dating back to 1570, with doublet spacing ranging 5–16 years separated by remarkably consistent interseismic periods of 71–88 years.

Melnick et al. [2017] suggest that the Maule earthquake induced bending in the upper and possibly lower plates of the subduction zone, geodetically imaged by examining patterns of vertical axis rotation extracted from spatial gradients in station velocities (Figure 1a). The distribution of rotation is symmetric along the strike of the subduction zone about the center of the Maule earthquake rupture area, with clockwise rotation to the north and counterclockwise to the south (Figure 1b). The decoupling of the rupture area during the earthquake, as well as following the event as a result of postseismic afterslip, can increase the degree of subduction coupling adjacent to the slipping region by bending the upper plate and "dragging" it against the interface (Figure 1c), thereby increasing shear stress at the periphery of slipping zones, which may trigger failure on these along-strike sections.

That the occurrence of one earthquake may influence the timing of nearby earthquakes is a commonly employed model in studies of earthquake sequences. Changes in static stress within the crust owing to finite fault slip [e.g., *King et al.*, 1994] and dynamic stress arising from the passage of seismic waves through the crust [e.g., *Kilb et al.*, 2000] have been invoked to explain the spatial and temporal relationships between a mainshock and the spatial and temporal patterns of its aftershock sequence. However, several recent studies, including *Melnick et al.* [2017], suggest that coseismically induced changes in earthquake cycle behavior can occur over spatial and temporal scales beyond that of a triggered event or aftershock sequence. Based on analysis of GPS position time series, *Heki and Mitsui* [2013] suggest accelerated subduction of the Pacific Plate following two major earthquakes offshore Japan — the 2003 M_W=8.1 Tokachi-oki and 2011 M_W=9.1 Tohoku-oki events. *Loveless and Meade* [2016] propose that, despite accounting for postseismic deformation from major earthquakes and assuming that nominally interseismic geodetic velocities vary minimally through time, spatial patterns of coupling on the Japanese subduction interfaces shift on time scales as short as a few years, influenced primarily but not exclusively by megathrust earthquakes. Such abrupt fluctuation in interseismic deformation has substantial implication for earthquake hazard assessment, as it indicates that identifying likely sites of future seismicity is not as simple as integrating a static image of fault coupling over time. Rather, continued geodetic observations throughout interseismic phases of global subduction zone earthquake cycles will shed light on the degree to which temporal changes in the patterns of coupling influence the location, timing, and recurrence of great earthquakes.

Ongoing geodetic observation will complement several recent studies that have highlighted temporal variations in earthquake recurrence over historical (~100-yr) to paleoseismic (~10-kyr) time scales on continental strike slip faults [*Dolan et al.*, 2007; *Dolan et al.*, 2016; *Gold et al.*, 2017] and subduction zones [*Nocquet et al.*, 2016; *Philibosian et al.*, 2016; *Sieh et al.*, 2008]. Combining the satellite geodetic record with a paleogeodetic record from uplifted fossil coral microatolls, studies has enabled documentation of spatiotemporal variation in earthquake cycle processes on the Sumatra subduction zone over hundred- to thousand-year timescales [*Meltzner et al.*, 2015; *Philibosian et al.*, 2016; *Sieh et al.*, 2008]. Most recently, *Philibosian et al.* [2016] used fossil corals recording vertical deformation since the year 1500 to estimate great earthquake rupture patterns, as well as coupling patterns during the intervening interseismic periods. In general, they find spatial anti-correlation between the locus of coseismic slip and concentrations of coupling in the subsequent interseismic phase, with earthquake slip apparently enhancing interplate coupling on adjacent along-strike segments of the subduction interface. These zones of enhanced coupling are then often the sites of the next great earthquakes on the subduction zone. This pattern is consistent with the interpretations of *Melnick et al.* [2017] but extends their plate bending hypothesis beyond a portion of a single earthquake cycle to a repeatable pattern that may be pervasive over many seismic cycles along global subduction zones. Notably, the concept of a super-interseismic phase has been inferred from two very different datasets: horizontal GPS observations recording variations in coupling over 5 years [*Melnick et al.*, 2017], and vertical fossil coral data that suggest coupling fluctuations over 10–50 year intervals [*Philibosian et al.*, 2016].

Over longer time scales, and in a continental strike-slip setting, *Dolan et al.* [2007] noted that several-thousand-year periods of faster-than-average seismic activity in the Los Angeles basin region of southern California have coincided with relative quiescence on faults of the Eastern California Shear Zone and vice versa. Furthermore, temporal variations in slip rate on the Garlock fault apparently coincide with those on the Mojave segment of the San Andreas fault [*Dolan et al.*, 2016], suggesting that when the Garlock and San Andreas faults show faster than average slip rates, they suppress activity on Eastern California Shear Zone faults, potentially by ejecting a Mojave Desert crustal block eastward, which clamps faults to the east [*Dolan et al.*, 2007]. To achieve these coordinated changes in fault slip rates across hundreds of kilometers of a fault system on millennial time scales, *Dolan et al.* [2016] propose that mechanical changes in the deep roots of active faults alternate between strain hardening during bursts of seismic activity and annealing during periods of comparative quiescence, and whichever portions of the fault system are annealed at a given time are most likely to slip at faster-than-average rates in order to accommodate relative plate motion.

The above-mentioned temporal variations in slip rates and coupling patterns necessarily complicate use of these metrics in seismic hazard assessment. Estimating earthquake recurrence intervals in the face of time-varying rates of interseismic strain accumulation presents a challenge in conveying the very concept of earthquake recurrence to the public. Brian Tucker, director of GeoHazards International, a nonprofit organization that helps communities prepare for natural hazards, relayed in the *Washington Post* an anecdote following the 2015 Gorkha, Nepal earthquake in which he was told by a government official in the late 1990s that, because of the occurrence of a major earthquake in 1934, Nepal need not worry about future seismic hazard [*Achenbach*, 2015]. Recognition and understanding of the concept of earthquake recurrence is necessary for building seismic resilience. Continued collection and analysis of geodetic data will ideally clarify this concept, but as studies such as that of *Melnick et al.* [2017] show, these data will also reveal additional complexities in earthquake cycle deformation.

Acknowledgments

I thank editor Andrew Newman for his invitation to write this commentary as well as suggestions to clarify the presentation.

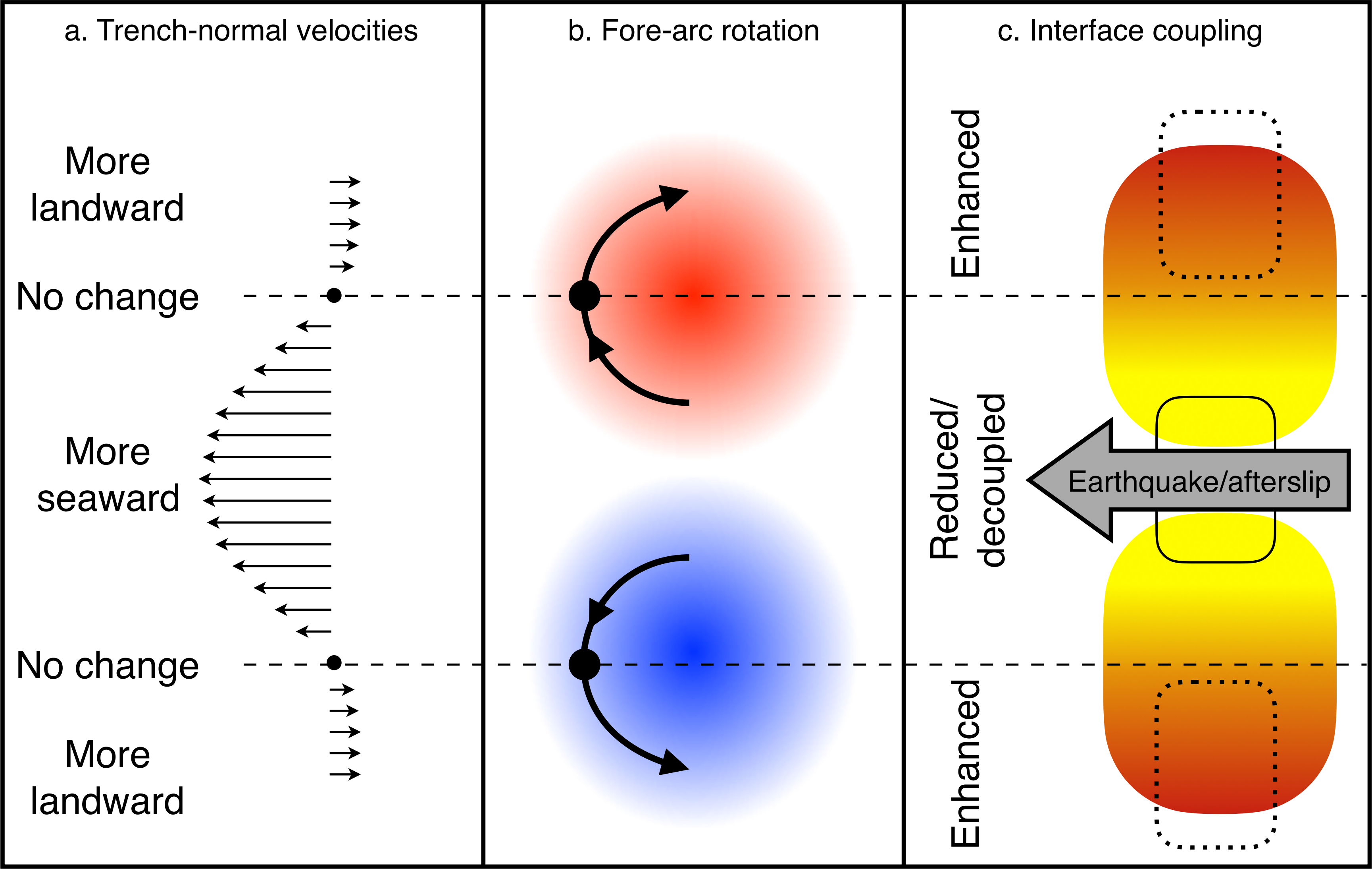
References

Achenbach, J. (2015), Experts had warned for decades that Nepal was vulnerable to a killer quake, in *Washington Post*, edited.
Biasi, G. P., and R. J. Weldon (2009), San Andreas Fault Rupture Scenarios from Multiple Paleoseismic Records: Stringing Pearls, Bull. Seis. Soc. Am., 99(2A), 471-498, doi: 10.1785/0120080287.
Dolan, J. F., D. D. Bowman, and C. G. Sammis (2007), Long-range and long-term fault interactions in Southern California, Geology, 35(9), 855--858, doi: 10.1130/G23789A.1.
Dolan, J. F., L. J. McAuliffe, E. J. Rhodes, S. F. McGill, and R. Zinke (2016), Extreme multi-millennial slip rate variations on the Garlock fault, California: Strain super-cycles, potentially time-variable fault strength, and implications for system-level earthquake occurrence, E&PSL, 446, 123–136, doi: 10.1016/j.epsl.2016.04.011.
Ergintav, S., S. McClusky, E. Hearn, R. Reilinger, R. Cakmak, T. Herring, H. Ozener, O. Lenk, and E. Tari (2009), Seven years of postseismic deformation following the 1999, M = 7.4 and M = 7.2, Izmit-Düzce, Turkey earthquake sequence, J. Geophys. Res., 114(B7), doi: 10.1029/2008JB006021.
Gold, R. D., E. Cowgill, J. R. Arrowsmith, and A. M. Friedrich (2017), Pulsed strain release on the Altyn Tagh fault, northwest China, E&PSL, 459, 291 - 300, doi: 10.1016/j.epsl.2016.11.024.
Heki, K., and Y. Mitsui (2013), Accelerated pacific plate subduction following interplate thrust earthquakes at the Japan trench, E&PSL, 363, 44-49, doi: 10.1016/j.epsl.2012.12.031.
Kilb, D., J. Gomberg, and P. Bodin (2000), Triggering of earthquake aftershocks by dynamic stresses, Nature, 408(6812), 570–574.
King, G. C. P., R. S. Stein, and J. Lin (1994), Static stress changes and the triggering of earthquakes, Bull. Seis. Soc. Am., 84(3), 935-953.
Loveless, J. P., and B. J. Meade (2011), Spatial correlation of interseismic coupling and coseismic rupture extent of the 2011 M_W = 9.0 Tohoku-oki earthquake, Geophys. Res. Lett., 38(17), L17306, doi: 10.1029/2011GL048561.
Loveless, J. P., and B. J. Meade (2016), Two decades of spatiotemporal variations in subduction zone coupling offshore Japan, E&PSL, 436, 19-30, doi: 10.1016/j.epsl.2015.12.033.
Melnick, D., M. Moreno, J. Quinteros, J. C. Baez, Z. Deng, S. Li, and O. Oncken (2017), The super-interseismic phase of the megathrust earthquake cycle in Chile, Geophys. Res. Lett.

Meltzner, A. J., et al. (2015), Time-varying interseismic strain rates and similar seismic ruptures on the Nias–Simeulue patch of the Sunda megathrust, QSRv, 122, 258 - 281, doi: 10.1016/j.quascirev.2015.06.003.
Moreno, M., M. Rosenau, and O. Oncken (2010), 2010 Maule earthquake slip correlates with pre-seismic locking of Andean subduction zone, Nature, 467, 198-202, doi: 10.1038/nature09349.
Nocquet, J.-M., et al. (2016), Supercycle at the Ecuadorian subduction zone revealed after the 2016 Pedernales earthquake, Nature Geoscience, doi: 10.1038/ngeo2864.
Philibosian, B., et al. (2016), Earthquake Supercycles on the Mentawai Segment of the Sunda Megathrust in the 17th Century and Earlier, J. Geophys. Res., doi: 10.1002/2016JB013560.
Protti, M., V. Gonzalez, A. V. Newman, T. H. Dixon, S. Y. Schwartz, J. S. Marshall, L. Feng, J. I. Walter, R. Malservisi, and S. E. Owen (2014), Nicoya earthquake rupture anticipated by geodetic measurement of the locked plate interface, Nature Geoscience, 7(2), 117-121, doi: 10.1038/ngeo2038.
Shimazaki, K., and T. Nakata (1980), Time-predictable recurrence model for large earthquakes, Geophys. Res. Lett., 7(4), 279-282.
Sieh, K., D. H. Natawidjaja, A. J. Meltzner, C.-C. Shen, H. Cheng, K.-S. Li, B. W. Suwargadi, J. Galetzka, B. Philibosian, and R. L. Edwards (2008), Earthquake Supercycles Inferred from Sea-Level Changes Recorded in the Corals of West Sumatra, Science, 322(5908), 1674–1678, doi: 10.1126/science.1163589.
Wang, K., Y. Hu, and J. He (2012), Deformation cycles of subduction earthquakes in a viscoelastic Earth, Nature, 484(7394), 327–332.

Figure 1. Schematic model of post-earthquake changes in a) trench-normal fore-arc velocities, b) fore-arc vertical axis rotation, and c) coupling on the subduction interface. Decoupling occurs in the earthquake rupture zone (solid contour in c.) and continues with afterslip. This induces clockwise fore-arc rotation north of the rupture area and counterclockwise rotation to the south; the red and blue color scheme follows that of *Melnick et al.* [2017]. Rotation of the upper plate increases landward velocity adjacent to the rupture zone, consistent with enhanced coupling on the interface beneath these regions. Loci of enhanced coupling (shaded red in c.) may be the site of subsequent earthquakes (dotted contours in c.), facilitated by the “super-interseismic” coupling.

Figure 1.


a. Trench-normal velocities
More landward
No change
More seaward
No change
More landward
b. Fore-arc rotation
c. Interface coupling
Enhanced
Reduced/ decoupled
Earthquake/afterslip
Enhanced