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1 **Super-interseismic periods: Redefining earthquake recurrence**

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5 **Key Points:**

- 6 • Recent studies show temporal variation in interseismic strain patterns.
- 7 • Great earthquakes modify coupling on adjacent parts of fault.
- 8 • Earthquake clusters may arise from such fluctuations in coupling.
- 9

10 Abstract

11 Precise geodetic measurements made over broad swaths of tectonically active regions
12 record patterns of interseismic strain accumulation, providing key insights into the locus
13 and timing of pending earthquakes. Recent studies of geodetic position time series,
14 including that of *Melnick et al.* [2017] in this issue, illustrate temporal variation in the
15 pattern of interseismic deformation. These authors propose that the 2010 $M_w=8.8$ Maule,
16 Chile earthquake enhanced coupling on the Andean subduction zone adjacent to the
17 rupture, including on the portion of the megathrust that broke five years later in the
18 $M_w=8.3$ Illapel event.

19 1 Introduction

20 The classical concept of an earthquake recurrence interval [*Shimazaki and*
21 *Nakata*, 1980] is rooted in an assumption that spatial patterns of interseismic strain
22 accumulation that precede seismic rupture are consistent through time. However, a
23 growing body of evidence based on geodetic and geologic observations suggests
24 fundamental deviations from this simple model, including spatially and temporally
25 clustered earthquakes and short-term fluctuation in patterns of interseismic fault coupling
26 preceding large earthquakes. Paleoseismic data provide long records of earthquake
27 deformation, which are essential for providing insight into patterns of fault slip over
28 multiple seismic cycles. However, these data can be complicated by imprecise temporal
29 resolution and ambiguity in correlating multiple observations along a single seismogenic
30 fault [*Biasi and Weldon*, 2009]. As a result, distinguishing, for example, a single large
31 magnitude rupture along a great length of the fault from a temporally clustered sequence
32 of smaller earthquakes can be difficult [*Gold et al.*, 2017]. On the other hand, modern
33 satellite geodesy observations provide a more spatially complete picture of earthquake
34 cycle deformation but thus far have only been capable of imaging single earthquakes and
35 small fractions of the preceding and subsequent interseismic periods. In several instances,
36 major subduction zone earthquakes have occurred in regions inferred from geodetic
37 observations to be pre-seismically coupled [*Loveless and Meade*, 2011; *Moreno et al.*,
38 2010; *Protti et al.*, 2014], but the extent to which coupling patterns vary within an
39 interseismic period or between sequential earthquake cycles is unclear owing to the short
40 time duration of available observations. To improve our understanding of earthquake
41 occurrence and recurrence, it is important to synthesize insights gained about fault system
42 behavior throughout the earthquake cycle from both geologic and geodetic data.

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

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

57 **2 Temporal variation in earthquake cycle processes**

58 In this issue, *Melnick et al.* [2017] underscore the importance of temporal
59 variation in fault coupling patterns by suggesting that the 2010 $M_W=8.8$ Maule
60 megathrust earthquake offshore south-central Chile resulted in a “super-interseismic
61 phase” of the earthquake cycle to the north and south of the rupture area, enhancing
62 coupling on these along-strike adjacent regions of the subduction interface. Five years
63 later, the $M_W=8.3$ Illapel earthquake struck central Chile, ~200 km to the north of the
64 Maule rupture in a region of interplate coupling increased by the Maule event. On
65 December 25, 2016, while the *Melnick et al.* [2017] manuscript was under revision, a
66 $M_W=7.6$ earthquake occurred south of the Maule rupture, also in a region that likely also
67 showed increased coupling owing to the 2010 event. The authors note that the close
68 temporal and spatial spacing of these large to great earthquakes is similar to five past
69 great earthquake doublets along the central Chilean subduction zone dating back to 1570,
70 with doublet spacing ranging 5–16 years separated by remarkably consistent interseismic
71 periods of 71–88 years.

72 *Melnick et al.* [2017] suggest that the Maule earthquake induced bending in the
73 upper and possibly lower plates of the subduction zone, geodetically imaged by
74 examining patterns of vertical axis rotation extracted from spatial gradients in station
75 velocities (Figure 1a). The distribution of rotation is symmetric along the strike of the
76 subduction zone about the center of the Maule earthquake rupture area, with clockwise
77 rotation to the north and counterclockwise to the south (Figure 1b). The decoupling of the
78 rupture area during the earthquake, as well as following the event as a result of
79 postseismic afterslip, can increase the degree of subduction coupling adjacent to the
80 slipping region by bending the upper plate and “dragging” it against the interface (Figure
81 1c), thereby increasing shear stress at the periphery of slipping zones, which may trigger
82 failure on these along-strike sections.

83 That the occurrence of one earthquake may influence the timing of nearby
84 earthquakes is a commonly employed model in studies of earthquake sequences. Changes
85 in static stress within the crust owing to finite fault slip [e.g., *King et al.*, 1994] and
86 dynamic stress arising from the passage of seismic waves through the crust [e.g., *Kilb et al.*,
87 2000] have been invoked to explain the spatial and temporal relationships between a
88 mainshock and the spatial and temporal patterns of its aftershock sequence. However,
89 several recent studies, including *Melnick et al.* [2017], suggest that coseismically induced
90 changes in earthquake cycle behavior can occur over spatial and temporal scales beyond
91 that of a triggered event or aftershock sequence. Based on analysis of GPS position time
92 series, *Heki and Mitsui* [2013] suggest accelerated subduction of the Pacific Plate
93 following two major earthquakes offshore Japan — the 2003 $M_W=8.1$ Tokachi-oki and
94 2011 $M_W=9.1$ Tohoku-oki events. *Loveless and Meade* [2016] propose that, despite
95 accounting for postseismic deformation from major earthquakes and assuming that
96 nominally interseismic geodetic velocities vary minimally through time, spatial patterns

97 of coupling on the Japanese subduction interfaces shift on time scales as short as a few
98 years, influenced primarily but not exclusively by megathrust earthquakes. Such abrupt
99 fluctuation in interseismic deformation has substantial implication for earthquake hazard
100 assessment, as it indicates that identifying likely sites of future seismicity is not as simple
101 as integrating a static image of fault coupling over time. Rather, continued geodetic
102 observations throughout interseismic phases of global subduction zone earthquake cycles
103 will shed light on the degree to which temporal changes in the patterns of coupling
104 influence the location, timing, and recurrence of great earthquakes.

105 Ongoing geodetic observation will complement several recent studies that have
106 highlighted temporal variations in earthquake recurrence over historical (~100-yr) to
107 paleoseismic (~10-kyr) time scales on continental strike slip faults [*Dolan et al.*, 2007;
108 *Dolan et al.*, 2016; *Gold et al.*, 2017] and subduction zones [*Nocquet et al.*, 2016;
109 *Philibosian et al.*, 2016; *Sieh et al.*, 2008]. Combining the satellite geodetic record with a
110 paleogeodetic record from uplifted fossil coral microatolls, studies has enabled
111 documentation of spatiotemporal variation in earthquake cycle processes on the Sumatra
112 subduction zone over hundred- to thousand-year timescales [*Meltzner et al.*, 2015;
113 *Philibosian et al.*, 2016; *Sieh et al.*, 2008]. Most recently, *Philibosian et al.* [2016] used
114 fossil corals recording vertical deformation since the year 1500 to estimate great
115 earthquake rupture patterns, as well as coupling patterns during the intervening
116 interseismic periods. In general, they find spatial anti-correlation between the locus of
117 coseismic slip and concentrations of coupling in the subsequent interseismic phase, with
118 earthquake slip apparently enhancing interplate coupling on adjacent along-strike
119 segments of the subduction interface. These zones of enhanced coupling are then often
120 the sites of the next great earthquakes on the subduction zone. This pattern is consistent
121 with the interpretations of *Melnick et al.* [2017] but extends their plate bending
122 hypothesis beyond a portion of a single earthquake cycle to a repeatable pattern that may
123 be pervasive over many seismic cycles along global subduction zones. Notably, the
124 concept of a super-interseismic phase has been inferred from two very different datasets:
125 horizontal GPS observations recording variations in coupling over 5 years [*Melnick et al.*,
126 2017], and vertical fossil coral data that suggest coupling fluctuations over 10–50 year
127 intervals [*Philibosian et al.*, 2016].

128 Over longer time scales, and in a continental strike-slip setting, *Dolan et al.*
129 [2007] noted that several-thousand-year periods of faster-than-average seismic activity in
130 the Los Angeles basin region of southern California have coincided with relative
131 quiescence on faults of the Eastern California Shear Zone and vice versa. Furthermore,
132 temporal variations in slip rate on the Garlock fault apparently coincide with those on the
133 Mojave segment of the San Andreas fault [*Dolan et al.*, 2016], suggesting that when the
134 Garlock and San Andreas faults show faster than average slip rates, they suppress activity
135 on Eastern California Shear Zone faults, potentially by ejecting a Mojave Desert crustal
136 block eastward, which clamps faults to the east [*Dolan et al.*, 2007]. To achieve these
137 coordinated changes in fault slip rates across hundreds of kilometers of a fault system on
138 millennial time scales, *Dolan et al.* [2016] propose that mechanical changes in the deep
139 roots of active faults alternate between strain hardening during bursts of seismic activity
140 and annealing during periods of comparative quiescence, and whichever portions of the

141 fault system are annealed at a given time are most likely to slip at faster-than-average
 142 rates in order to accommodate relative plate motion.

143 The above-mentioned temporal variations in slip rates and coupling patterns
 144 necessarily complicate use of these metrics in seismic hazard assessment. Estimating
 145 earthquake recurrence intervals in the face of time-varying rates of interseismic strain
 146 accumulation presents a challenge in conveying the very concept of earthquake
 147 recurrence to the public. Brian Tucker, director of GeoHazards International, a nonprofit
 148 organization that helps communities prepare for natural hazards, relayed in the
 149 *Washington Post* an anecdote following the 2015 Gorkha, Nepal earthquake in which he
 150 was told by a government official in the late 1990s that, because of the occurrence of a
 151 major earthquake in 1934, Nepal need not worry about future seismic hazard [Achenbach,
 152 2015]. Recognition and understanding of the concept of earthquake recurrence is
 153 necessary for building seismic resilience. Continued collection and analysis of geodetic
 154 data will ideally clarify this concept, but as studies such as that of Melnick *et al.* [2017]
 155 show, these data will also reveal additional complexities in earthquake cycle deformation.

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159 References

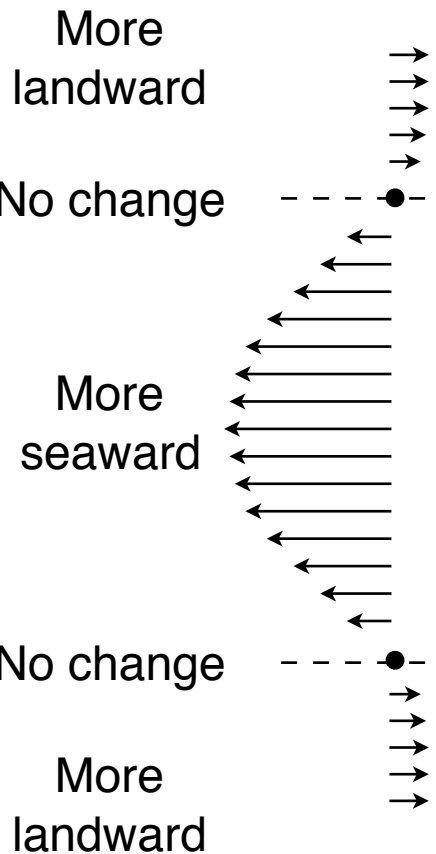
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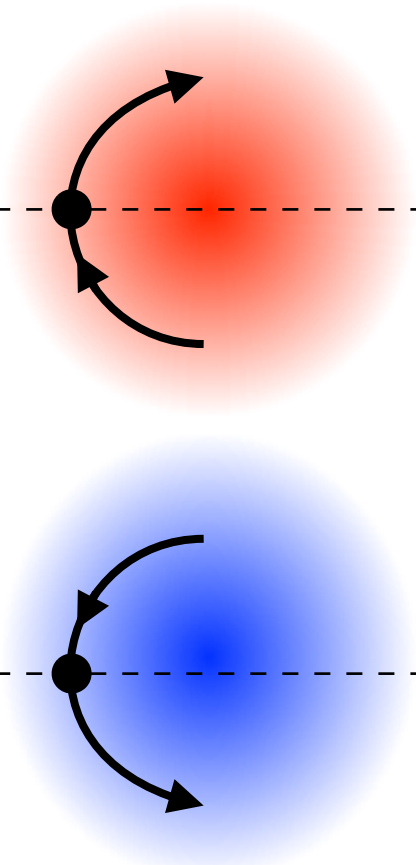
208 **Figure 1.** Schematic model of post-earthquake changes in a) trench-normal fore-arc
209 velocities, b) fore-arc vertical axis rotation, and c) coupling on the subduction interface.
210 Decoupling occurs in the earthquake rupture zone (solid contour in c.) and continues with
211 afterslip. This induces clockwise fore-arc rotation north of the rupture area and
212 counterclockwise rotation to the south; the red and blue color scheme follows that of
213 *Melnick et al.* [2017]. Rotation of the upper plate increases landward velocity adjacent to
214 the rupture zone, consistent with enhanced coupling on the interface beneath these
215 regions. Loci of enhanced coupling (shaded red in c.) may be the site of subsequent
216 earthquakes (dotted contours in c.), facilitated by the “super-interseismic” coupling.
217
218

Figure 1.

a. Trench-normal velocities



b. Fore-arc rotation



c. Interface coupling

