Southern Cascadia Episodic Slow Earthquakes

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Southern Cascadia episodic slow earthquakes

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[1] Continuous GPS and seismic data from northern California show that slow earthquakes periodically rupture the Gorda-North America plate interface within southern Cascadia. On average, these creep events have occurred every 10.9 ± 1.2 months since at least 1998. Appearing as week-long GPS extensional transients that reverse secular forearc contraction, the data show a recurrence interval 22% shorter than slow events recognized to the north. Seismic tremor here accompanies the GPS reversals, correlated across as many as 5 northern California seismometers. Tremor occurs sporadically throughout the year, but increases in duration and intensity by a factor of about 10 simultaneous with the GPS reversals. Beneath west-central Oregon, three reversals are also apparent, but more stations are needed to confirm sporadic slip on the plate interface here. Together, these measurements suggest that slow earthquakes likely occur throughout the Cascadia subduction zone and add further evidence for the role of fault-fluid migration in controlling transient slow-slip events here. INDEX TERMS: 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 1243 Geodesy and Gravity: Space geodetic surveys; 7230 Seismology: Seismicity and seismotectonics. Citation: Szeliga, W., T. I. Melbourne, M. M. Miller, and V. M. Santillan (2004), Southern Cascadia episodic slow earthquakes, Geophys. Res. Lett. 31, L16602, doi:10.1029/2004GL020824.

1. Introduction

[2] Slow faulting events recently recognized along convergent margins globally are now understood to constitute a fundamental mode of moment release that both trigger and are triggered by regular earthquakes [Dragert et al., 2001; Heki et al., 1997; Hirose et al., 1999; Kawasaki et al., 1995; Kostoglodov et al., 2003; Larson et al., 2004; Linde and Silver, 1989; Lowry et al., 2001; Miller et al., 2002; Obara, 2002; Ozawa et al., 2002; Rogers and Dragert, 2003; Sagiya and Ozawa, 2002]. In the Pacific Northwest, continuous GPS has detected nine slow earthquakes occurring at 13.9 ± 0.9 month intervals within the northern Cascadia plate interface [Dragert et al., 2001; Miller et al., 2002] accompanied by harmonic tremor largely absent when slow earthquakes are not occurring [Obara, 2002; Rogers and Dragert, 2003]. To date, no observations of Cascadia transients, also called slow earthquakes, silent earthquakes, or episodic tremor and slip events, have been made outside of the northern Puget basin, suggesting either that the unique bend in the Juan de Fuca plate here is somehow conducive to slow slip or that instrument density is insufficient outside this region for confident detection. Since slow earthquakes may modulate seismogenic rupture either by reducing the size of a future earthquake, delaying its recurrence, or acting as a trigger, along-strike variability in the existence of slow faulting yields important clues about partitioning, particularly seismogenic segmentation, of the Cascadia subduction zone. In this report we present continuous GPS and seismic data from northern California and Oregon that indicates periodic slow earthquakes occur throughout Cascadia, and with quite variable recurrence rates.

2. GPS Data

[3] Continuous GPS data from the Pacific Northwest Geodetic Array and the Bay Area Regional Deformation Array [Miller et al., 2001; Murray et al., 1998] were processed with the Gipsy-Oasis II software [Lichten and Border, 1987] (Figure 1). Precise point positioning and precise orbits and clocks were used to analyze the phase data with ambiguity resolution applied [Heflin et al., 1992; Zumberge et al., 1997]. Daily solutions for station positions and corresponding matrices of the covariance among the three position components were determined within the International Terrestrial Reference Frame (ITRF 2000) [Altamimi et al., 2002] using daily frame data products provided by the International Geodynamics Service [Zumberge et al., 1997]. A regional stabilization was subsequently applied to each daily position, using a reference set of 42 stations from the North America plate region; 23 of these are concentrated in the Pacific Northwest, the remainder are distributed on the stable plate interior or in other regional networks in western North America. Of the 42 stations, 33 have published positions and velocities in ITRF 2000. This stabilization transformation minimizes network-wide position discrepancies, or common-mode errors. Final time series were simultaneously detrended and corrected for known artifacts that include offsets due to hardware upgrades, earthquakes, and annual and semi-annual sinusoidal signals introduced by mismodeled tropospheric delays and other seasonal effects [Blewitt and Lavallée, 2002; Nikolaidis, 2002].

3. Seismic Tremor Data

[4] Continuous horizontal component 100-hz seismic data from Guralp 40T’s and 20-hz seismic data from a combination of both STS-1’s and STS-2’s spanning four years from 2000 through 2003 were downloaded from the Northern California Seismic Network (Figure 1). Eight stations are available with minor outages that together span northernmost California, with average spacing of 136 km. Four stations lie within 150 km of the trench, one of which (YBH and WDC) are among the quietest of stations in northern California based on our examination of four years...
of continuous seismic data from all available stations. Four additional stations lie sufficiently west and south of where tremor is expected to be visible and can be used to assess background noise when picking tremor. Due to the distances between instruments, signals correlated across stations must have their genesis in deep-earth processes and cannot be attributed to anthropogenic, meteorologic or other local noise sources. Tremor signals are readily correlated by eye (Figure 2), and their spectra show predominant frequencies in the 1–5 Hz band, similar to that reported in Japan and northern Cascadia [Obara, 2002; Rogers and Dragert, 2003]. All seismic data in this study were band-passed between 1 and 5 Hz frequencies and gain-normalized to enhance tremor identification. The data record a multitude of signals that include local non-tectonic noise, teleseismic and local earthquakes; tremor signals are distinguished by waveform and coda correlation across adjacent stations. However, due to the emergent nature of the signal [Rogers and Dragert, 2003], and the lack of accurately identifiable phases, constraining event onset time with the precision required to determine source depth and location becomes highly assumption-dependent and was not performed in this study.

Identification of tremor entailed plotting all gain-removed, horizontal seismic traces in spatial and temporal proximity, similar to historical drum recordings. Tremor was then identified as signals correlated both temporally and spatially across at least three stations. Periods during which no correlated tremor is evident have background seismic velocities typically less than 0.07 micrometers per second. We therefore summed the rate of visibly correlated tremor whose maximum velocities exceed 0.5 micrometers per second, or roughly 10-times background noise. Figure 2 shows a typical example, approximately 21 minutes of tremor recorded on 5 seismic stations. This window was taken from a much longer burst recorded on 12/10/2002, two days after the onset of transient westward movement of the GPS station YBHB that began on 12/08/2002. During the time of this GPS reversal, correlated tremor activity increased to approximately 90 hours per week.

4. Northern California and Central Oregon Transients

[6] Purely from the standpoint of deformation, westerly resets at YBHB are expected for slow earthquakes along the deeper Gorda-North American plate interface. Surface deformation from such events results from a sum of contraction from shallow plate locking and extension from the slow faulting itself. Since secular deformation in

Figure 1. Topographic/bathymetric map of Northern California. Red circles represent continuous GPS stations, blue diamonds represent seismic stations used in this study. Note the sparse distribution of continuous GPS stations in Northern California and Coastal Oregon. Vectors represent motion of each station relative to stable North America. Note the northwesterward movement of station YBHB. This is due to a summation of east-west oriented compression from subduction, westerly compression from Basin and Range expansion, and northwesterly translation of the Sierra Nevada microplate. During slow earthquakes, fault fluid migration along the plate interface allows the upper plate (North America) to move west. This is demonstrated in Figure 3a where westerly resets are observed at station YBHB.

Figure 2. Approximately 20 minutes of tremor recorded on stations from the Northern California seismic network. Vertical axis is in cm/s and horizontal axis is in hundreds of seconds after 09:00 UTM on 12/10/2002. Note the overall waveform correlation between the top 5 seismic stations. The bottom 3 seismic stations are located on the coast and do not show evidence of tremor. Obvious digitization errors in the form of step functions were manually digitized manually removed.
Figure 3. GPS eastings from Yreka, CA, Newport, OR and Alberthead, BC, and seismic tremor histogram from Yreka. a.) Blue points are daily GPS station positions in mm of the longitudinal component of station YBHB. Solid red line is a plot of the hours of tremor per week at seismic station YBHB. Note the similarity of shape displayed by ALBH (Figure 3c) and YBHB. The correlation between GPS offsets and increased tremor activity indicates that slow faulting occurs beneath Northern California. b.) Purple points represent daily solutions of station position for the longitudinal component of GPS station NEWP from Newport, Oregon. Note the similarity of NEWP offsets (dashed black lines) to those at ALBH. The lack of seismic and continuous GPS stations near NEWP precludes the definitive identification of slow earthquakes here at the present time. c.) Green points represent daily position solutions of the longitudinal component of ALBH. Note the characteristic sawtooth reset shape of the timeseries due to slow faulting events. For correlation between increased tremor and GPS offsets at station ALBH, see Rogers and Dragert [2003]. Solid black lines denote times of known slow earthquakes at ALBH.

5. Discussion

The northern California data demonstrate that slow Cascadia earthquakes are not confined to the structural bight in the Juan de Fuca plate beneath the northern Puget Basin, and argue that they occur throughout Cascadia and many other subduction zones. More importantly, these results follow Obara [2002] and Rogers and Dragert [2003] in linking seismic tremor and slow faulting to an underlying cause, most likely fault fluid transport [Melbourne and Webb, 2003]. Analysis of tremor alone for source processes that might constrain such transport is complex, since the lack of discernible phases prohibits discrimination between path and source contributions to tremor coda. For example, delta-function sources, propagated through complex crustal media, have been shown to cause harmonic volcano tremor originally attributed to resonance at the source [Chouet et al., 1987; Kedar et al., 1998; Koyanagi et al., 1987]. Moreover, if Cascadia tremor does indeed result from a harmonic source at depth, a host of distinct driving mechanisms could produce source resonance and identical surface observations, again obfuscating the underlying physics [Chouet et al., 1987; Koyanagi et al., 1987].
If both tremor and slow slip are manifestations of hydraulic transport resonating and unclamping fault walls that sandwich pore fluids, an important next step will be to implement experiments that can constrain near-field (static), non-double couple components of moment release. These, in turn, will likely be of great use in constraining slow earthquake physics at a resolution higher than that afforded by either GPS or tremor.

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