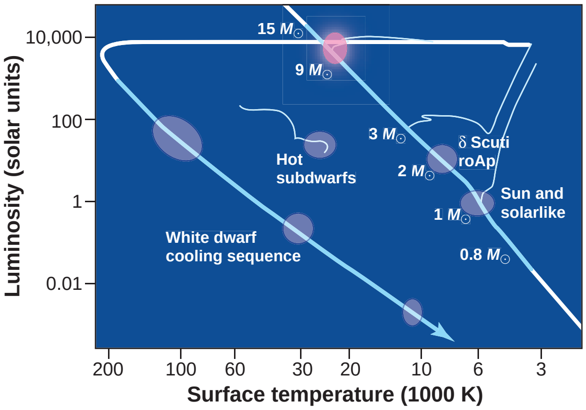

The fates of stars. In this Hertzsprung-Russel diagram, the main diagonal line denotes "main sequence" stars, which, like the Sun, burn hydrogen in their cores. Lines moving away from the main sequence are followed by stars after they have exhausted their hydrogen fuel supply. After a brief period of helium burning, most stars eventually reach the white dwarf cooling track—the last part of this evolution for stars of less than ~8 solar masses ($M_\odot$). Asteroseismology has produced insights into the interior and evolution of a growing variety of stars (see shaded areas). The latest stars to yield some of their secrets are the β-Cepheids (red area)—massive main-sequence stars that are destined to become supernovae.

With more than 90% of all stars sharing fates similar to that of the Sun, more massive stars (which will eventually explode as supernovae) escaped this detailed scrutiny—but not anymore.

Aerts *et al.* monitored the β-Cephei star HD 129929 (with a mass of 9.5 solar masses) for more than 21 years. Earlier studies identified some oscillation modes of this star, but gaps in data sampling precluded unambiguous assignments. Aerts *et al.* now show that HD 129929 is indeed a multiperiodic star. They resolve six independent oscillation modes in the star. From these periods and stellar models, they infer that the interior of the star rotates at different rates at different depths, and that the turbulent process of convection in its central nuclear furnace drives mixing of material beyond the "classical" limits of the convective core. Both of these results had been hinted at by earlier studies of the evolution of massive stars, but Aerts *et al.* (*1*) shed new light on these processes.

For their work to succeed, Aerts *et al.* required precision photometry, which was made possible by advances in instrumentation in the second half of the 20th century. But no instrument can remove the final constraint—time. Rewards for these past advances in instrumentation are now finally being realized. For us humans, 20 years may seem like a long time, yet to the universe it is but the blink of an eye. Thanks to the observers who collected data for future analysis since the 1980s, the next few years should see a rapid growth in the seismology of HD 129929 and other massive stars as the data continue to accumulate.

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GEOPHYSICS

Slow But Not Quite Silent

Timothy I. Melbourne and Frank H. Webb

Faults at subduction zones—regions where one tectonic plate dives beneath another—generate the world's largest earthquakes, which rapidly release strain over large areas of the plate interface. In recent years, a much slower form of strain release has been detected in many subduction zones throughout the world. It involves episodes of fault slip that resemble conventional earthquakes, except that faulting occurs slowly, often lasting weeks or months.

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Such sluggish faulting should not by itself produce shaking at frequencies or intensities that can be detected with seismometers. Hence, "slow earthquakes" were held to be seismically quiet, or aseismic. But on page 1942 of this issue, Rogers and Dragert (*1*) show that slow earthquakes in the Cascadia subduction zone are not silent. Their geodetic deformation signature correlates with a characteristic seismic tremor that bears the telltale signature of forced fluid flow. This correlation opens up a more facile avenue for studying slow earthquakes.

Isolated reports of slow earthquakes have been around for decades (*2*). But until a few years ago, the geophysical networks needed to resolve subtle signatures of slow earthquakes did not exist. It took the deployment of dense global positioning system (GPS) arrays around the world in the 1990s for transient slow faulting to be recognized as a widespread and fundamental phenomenon. Japan, with its state-of-the-art arrays of seismic and geodetic instrumentation, has led the way in identifying transient slow faulting events (*3*, *4*).

A common characteristic of slow earthquakes in subduction zones is that they are deep. They occur along the deeper reaches of the plate interface, below the seismogenic region that breaks every few hundred years to produce great earthquakes. Like tickling the dragon's belly, the slow faulting stress loads the seismogenic regions. Quantification of the stress caused by the deep, slow earthquakes requires knowledge of the precise location and amount of the slow slip. Herein lies a problem. Static surface deformation from deep faulting provides only a blurry image of creep at depth. Moreover, the vertical deformation that is most useful for locating the creep is the least resolvable with GPS. As a result, stress drops have remained largely unconstrained, and the loading of the seismogenic zone by slow earthquakes has not been well quantified.

Such was the state of affairs until last year, when Obara discovered nonvolcanic tremor associated with subduction of the Philippine sea plate beneath southeast Japan (*5*). With the ultralow noise, bore-hole Hi-Net array, Obara was able to detect long-period seismic tremor at levels that on any conventional network would have gone unnoticed or been attributed to anthropogenic or other nontectonic sources. The signals Obara recognized were previously only found within active volcanoes, where they are generated by flow-induced resonance in magma-carrying conduits (*6*). Obara's tremor, however, appeared to come from deep regions, at depths of at least 35 km, and well away from any known volcanic source.

Like their volcanic cousins, the signals described by Obara are emergent, that is, they mostly lack any isolated seismic *P* or *S* waves that can be used to locate their origin.

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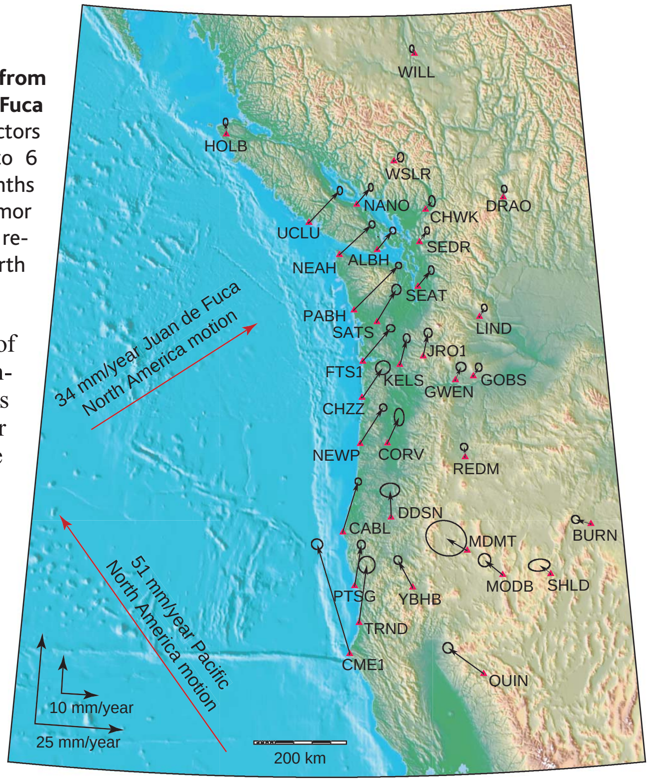

Interseismic deformation from subduction of the Juan de Fuca plate. The deformation vectors reverse themselves for 2 to 6 weeks every 14.5 ± 1 months during slow earthquakes. Tremor correlated with the vector reversals is detected to the north of the Olympic Peninsula.

Through cross-correlation of their filtered signal envelopes, however, Obara was able to estimate that their hypocenters fall along the 35- to 40-km depth contour within the subducting Philippine sea plate. At precisely this depth, the water-releasing dehydration from basalt to eclogite is expected to occur (*7*). It thus seems likely that the tremor originates from the forced flow of fluids that are released near the plate interface during metamorphic dehydration. But how is the tremor related to slow earthquakes?

Obara's data show clearly that tremor occurs in regions of known slow earthquakes, but is absent in areas where no slow earthquakes have been detected. However, he did not show that tremor and slow earthquakes occur simultaneously. As Julian has pointed out (*8*), the Cascadia subduction zone off the western coast of North America, with its periodic and predictable slow earthquakes (see the figure) (*9*), is ideal for addressing the relation between slow earthquakes and Obara-type tremor. After detailed analysis of 10 years of seismic recordings from Vancouver Island, Rogers and Dragert now conclude not only that slow earthquakes and tremor are highly correlated, but that one is the hallmark of the other. Cascadia slow earthquakes are not silent; rather, they are accompanied by tremor that is notably absent when slow faulting is not occurring.

The slow earthquakes in the Cascadia subduction zone, and by extension elsewhere around the world, thus seem to be moderated by fluid flow in or near the plate interface. As in southwest Japan, the Cascadia tremor peaks between 1 and 5 Hz, persists for days to weeks, migrates tens of km horizontally along the fault plane, and appears to both trigger and be triggered by adjacent conventional earthquakes. The tremor is not caused by near-simultaneous slip of large regions, as in conventional earthquakes, but probably by brine resonating the walls of the conduits through which it episodically bursts. The precise mechanism on how the fluid flow enables slow slip remains unclear, but may prove as simple as hydraulic pressure unclamping the fault walls that sandwich the fluid.

The correspondence established by Rogers and Dragert (*1*) provides an important new tool with which to study the slow earthquake process. Tremor can potentially be used to locate slow slip at depth more precisely than can static deformation measures at Earth's surface. With nearly 2000 new geophysical instruments coming online with EarthScope (*10*), the future promises better seismic locations, energy estimates, and source mechanisms, as well as tighter constraints on along-strike propagation of tremor and slip.

It may therefore be only a matter of time before the initiation of regular earthquakes is itself tied definitively to fault fluid flow, an idea that has been around for years. If this idea is proven to be correct, it probably applies to faults beyond those at subduction zones. Free-flowing brine has been detected in faults at depths below 10 km in the deepest boreholes on Earth (*11*). Like many other aspects of earthquake physics, discoveries first made in subduction-zone faults may prove to be applicable to all active faults—particularly those on which many of our cities are built.

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ECOLOGY AND EVOLUTION

Desperately Seeking Similarity

Janis L. Dickinson and Walter D. Koenig

Ever since W. D. Hamilton pointed out that cooperation is facilitated by genetic relatedness (*1*), "kin selection" has held a central place in the study of social behavior. Although most cooperative societies comprise close relatives (*2*), there has always been a caveat to the logical conclusion that kin selection is the driving force in their evolution. Consider cooperative breeders such as the meerkat (*Suricata suricatta*) that have "helpers" providing care to young that are not their own. Although helpers are usually a breeder's offspring from prior years, close genetic relatedness between the giver and recipient of aid is not necessarily crucial to the evolution of helping behavior. The importance of kinship relative to other more direct benefits of group living and cooperation is the subject of much debate. Two studies on pages 1947 and 1949 of this issue (*3, 4*) shed new light on this problem.

In support of kin selection, a preponderance of cooperative species have groups consisting of close relatives. One particularly notable experiment in a British bird species showed that returning helpers preferred to assist relatives over unrelated pairs at closer nests (*5*). Critics argue that cooperation among relatives arises as a side effect of delayed dispersal, which causes offspring to remain near kin. This viewpoint is advocated in recent reviews highlighting gains for helpers independent of aiding relatives (*6, 7*) and severe competition that reduces or eliminates kin-selected benefits

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binary systems in the near-Earth, main-belt, and Kuiper-belt populations, because they provide a wealth of information about physical properties, formation processes, and collisional environments (*38–40*).
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Episodic Tremor and Slip on the Cascadia Subduction Zone: The Chatter of Silent Slip

Garry Rogers* and Herb Dragert

We found that repeated slow slip events observed on the deeper interface of the northern Cascadia subduction zone, which were at first thought to be silent, have unique nonearthquake seismic signatures. Tremorlike seismic signals were found to correlate temporally and spatially with slip events identified from crustal motion data spanning the past 6 years. During the period between slips, tremor activity is minor or nonexistent. We call this associated tremor and slip phenomenon episodic tremor and slip (ETS) and propose that ETS activity can be used as a real-time indicator of stress loading of the Cascadia megathrust earthquake zone.

The Cascadia subduction zone is a region that has repeatedly ruptured in great thrust earthquakes of moment magnitude greater than 8 (*1*, *2*). Recently, slip events have been detected on the deeper (25- to 45-km) part of the northern Cascadia subduction zone interface by observation of transient surface deformation on a network of continuously recording Global Positioning System (GPS) sites (*3*). The slip events occur down-dip from the currently locked, seismogenic portion of the subduction zone (*4*), and, for the geographic region around Victoria, British Columbia, (Fig. 1), repeat at 13- to 16-month intervals (*5*). These slips were not accompanied by earthquakes and were thought to be seismically silent. However, unique nonearthquake signals that accompany the occurrence of slip have been identified using data from the regional digital seismic network. These pulsating, tremorlike seismic signals are similar to those reported in the forearc region of Japan (*6*, *7*), but the signals observed in Cascadia correlate temporally and spatially with six deep slip events that have occurred over the past 7 years. At other times, this tremor activity is minor or nonexistent. These tremors have a lower frequency content than nearby earthquakes, and they are uncorrelated with the deep or shallow earthquake patterns in the region. They have been observed only in the subduction zone region and specifically in the same region as the deep slip events. We refer to this associated tremor and slip phenomenon as episodic tremor and slip (ETS).

The seismic tremors described here are different from small earthquakes. The frequency content is mainly between 1 and 5 Hz, whereas most of the energy in small earthquakes is above 10 Hz. A tremor onset is usually emergent and the signal consists of pulses of energy, often about a minute in duration. A continuous signal may last from a few minutes to several days. Tremors are strongest on horizontal seismographs and move across the seismic network at shear wave velocities. A tremor on an individual seismograph is unremarkable and does not appear different from transient noise due to wind or cultural sources. It is only when a number of seismograph signals are viewed together that the similarity in the envelope of the seismic signal at each site identifies the signal as ETS (Fig. 1).

The tremor activity migrates along the strike of the subduction zone in conjunction with the deep slip events at rates ranging from about 5 to 15 km per day. Sometimes there is a gradual migration, but at other times there is a sudden jump from one region of the subduction fault to another. Tremors vary in amplitude, and the strongest can be detected as far as 300 km from the source region. During an ETS event, tremor activity lasts about 10 to 20 days in any one region and contains tremor sequences with amplitudes that are at least a factor of 10 larger

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than the minimum detectable tremor amplitude. Because of the emergent nature of the tremors, they are difficult to locate as precisely as nearby earthquakes using standard earthquake location procedures. Arrival times of coherent bursts detected across the network suggest source depths of 20 to 40 km, with uncertainties of several kilometers. Deeper solutions are to the northeast, and all solutions are near or just above the subduction interface. The fact that surface displacement patterns have been satisfactorily modeled using simple dislocations of 2 to 4 cm on the plate interface bounded by the 25- and 45-km depth contours (*3*) strongly suggests a spatial correlation with the source region of tremors.

To establish the temporal correlation between the slip events and the tremor activity (Fig. 2), we established the timing of six slip events observed on southern Vancouver Island since 1997 by cross-correlating changes in the east-west component of the Victoria GPS site (ALBH) with a symmetric 180-day sawtooth function, which replicated an average slip time series (*8*). This approach allowed the resolution of the midpoint of the slips to within 2 days. The duration of the slips, estimated from slope breaks in the ALBH time series, varied from 6 to 20 days. Seismic data were then examined at corresponding times to check for tremor activity. In each case, it was observed that sustained tremor activity on southern Vancouver Island coincided with the occurrence of slip (Fig. 2). For five of the slip events, tremors continued to migrate north along the axis of Vancouver Island, moving beyond the region of diagnostic GPS coverage.

To test a one-to-one correspondence, we examined continuous digital seismic data from the beginning of 1999 to the end of the 2003 tremor event to look for tremor activity outside the time windows of the slip events. No substantial activity was found for southern Vancouver Island, although a few periods with scattered low-amplitude tremor activity were observed in most months. Sustained large-amplitude tremor events have also been observed in northern and mid-Vancouver Island, as continuations of tremors migrating from the south and as independent tremor events. This implies that the ETS process occurs over the full length of the northern Cascadia subduction zone, but GPS coverage at the northern end is sparse, and surface displacements indicative of slip at depth have not been identified.

The cause of the tremor is not clear. Obara (*6*) has suggested fluids as a source for similar tremors in Japan. Because the tremor observed in Cascadia is mainly composed of shear waves, and because it correlates with slip that is relieving stress due to convergence (*3*), a shearing source seems most likely. However, because of the abundance of available fluids from the subducting plate in the subduction forearc (*9*), fluids may play an important role in the ETS process by regulating the shear strength of rock.

If the one-to-one correlation between transient slip and seismic signatures proves to be robust, then the tremorlike seismic signals can provide a real-time indicator of the occurrence of slip. Because slip events on the deep slab interface increase the stress across the locked plate interface located up-dip, it is conceivable that a slip event could trigger a large subduction thrust earthquake (*10*, *11*). Consequently, the onset of ETS activity could lead to recognized times of higher probability for the occurrence of megathrust earthquakes in the Cascadia subduction zone.

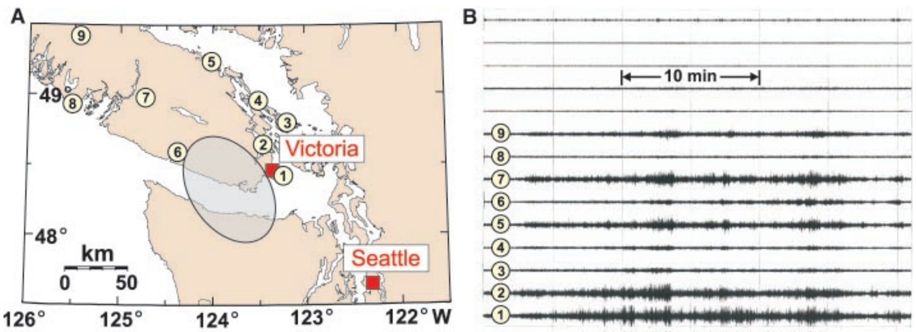

Fig. 1. (**A**) Map of seismic network sites (numbered circles) and approximate source region (shaded ellipse) for tremors used for correlation with observed slips. It has been observed that tremors and slip migrate parallel to the strike of the subduction zone to the north and south, as well as through this shaded region. (**B**) Sample seismic records of tremor activity at selected sites. It is the similarity of the envelope of the seismic signal on many seismographs that identifies ETS activity.

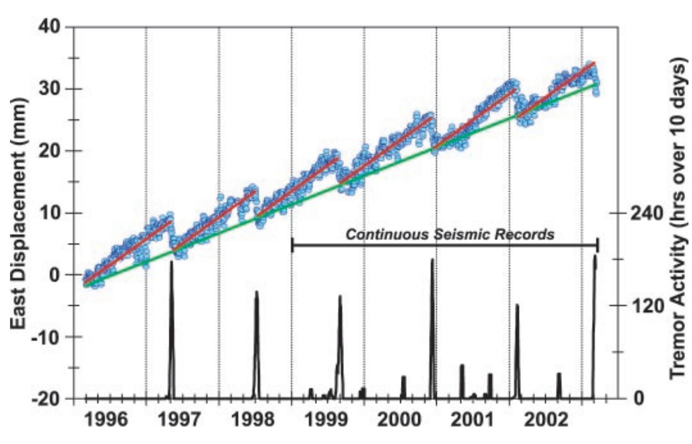

Fig. 2. Comparison of slip and tremor activity observed for the Victoria area. Blue circles show day-by-day changes in the east component of the GPS site ALBH (Victoria) with respect to the GPS site near Penticton, which is assumed to be fixed on the North America plate. The continuous green line shows the long-term (interseismic) eastward motion of the site. Red line segments show the mean elevated eastward trends between the slip events, which are marked by the reversals of motion every 13 to 16 months. The bottom graph shows the total number of hours of tremor activity observed for southern Vancouver Island within a sliding 10-day period (continuous seismic data were examined from 1999 onward). Ten days corresponds to the nominal duration of a slip event. The graph ends 10 March 2003, with the slip and tremor activity that was predicted for the spring of 2003.

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