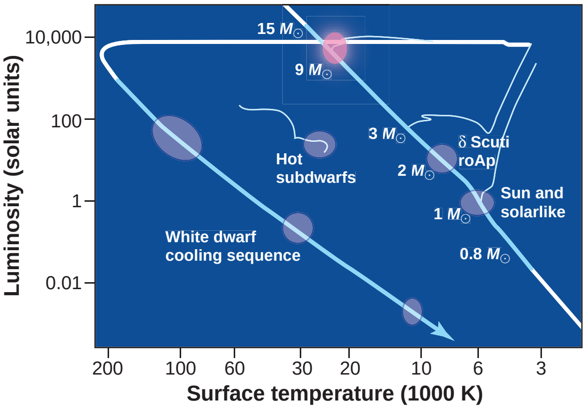

The fates of stars. In this Hertzsprung-Russel diagram, the main diagonal line denotes "main sequence" stars, which, like the Sun, burn hydrogen in their cores. Lines moving away from the main sequence are followed by stars after they have exhausted their hydrogen fuel supply. After a brief period of 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

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content/full/300/5627/1886

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.

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.

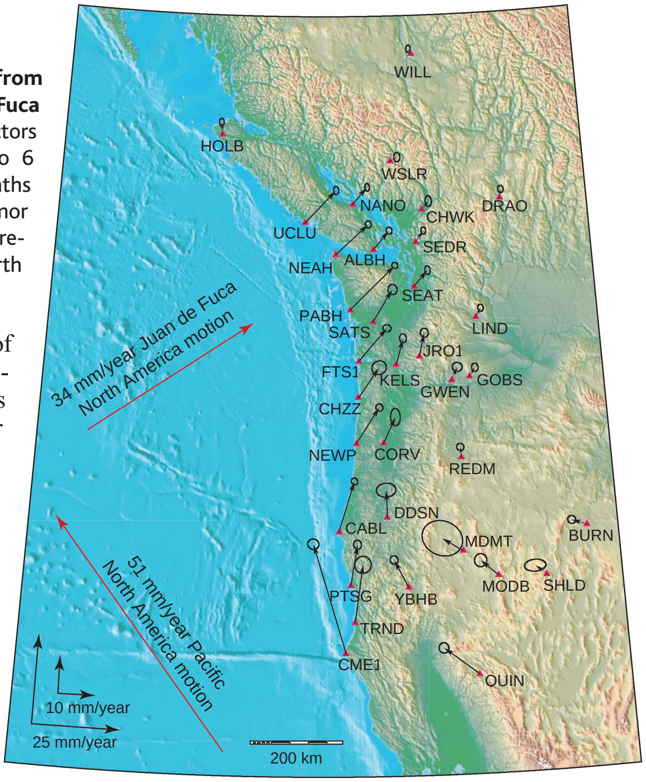
Isolated reports of slow earthquakes have been around for decades (*2*). But until a few years ago, the geophysical networks needed to resolve subtle signatures of slow earthquakes did not exist. It took the deployment of dense global positioning system (GPS) arrays around the world in the 1990s for 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.

T. I. Melbourne is in the Department of Geological Sciences, Central Washington University, Ellensburg, WA 98926, USA. E-mail: tim@geophysics.cwu.edu F. H. Webb is in the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91125, USA.



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

The authors are at the Hastings Reservation and Museum of Vertebrate Zoology, University of California, Berkeley, CA 93924, USA. E-mail: sialia@uclink.berkeley.edu, wicker@uclink.berkeley.edu