GEOPHYSICS

Silent Heralds of Megathrust Earthquakes?

Alfred Hirn and Mireille Laigle

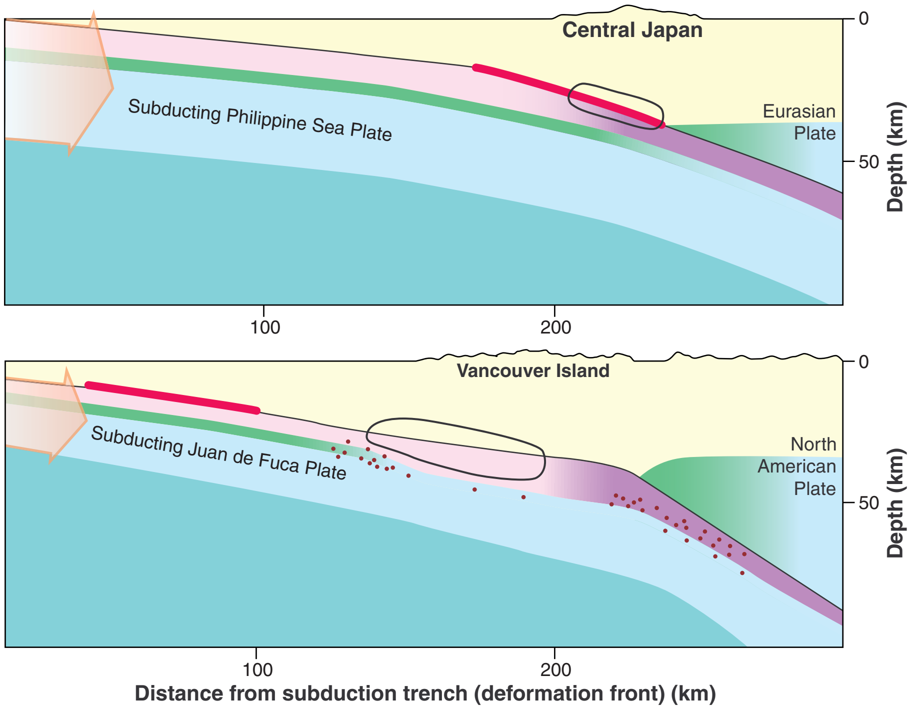
During an earthquake, rupture propagates along the fault plane within a few tens of seconds. Much slower rupture, lasting for weeks or months, has recently been observed in slip transients or slow earthquakes (*1*, *2*). These events are also dubbed "silent earthquakes," because seismometers cannot sense any seismic waves during rupture. Silent earthquakes share their source region with that of low-frequency seismic waves (*3–5*), akin to the seismic tremor known to occur in volcanoes where it is attributed to fluids trapped in cracks or conduits.

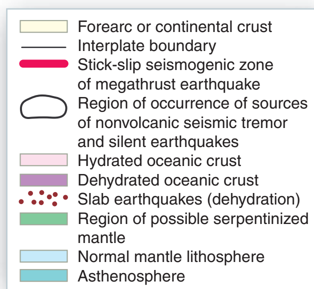
Silent earthquakes and seismic tremor do not cause strong, sudden ground motion, and are hence not considered hazardous. However, they occur in subduction zones where 90% of Earth's destructive seismic energy is released in large-magnitude ($M >$ 7.0) megathrust earthquakes. Monitoring and interpreting such events may improve our understanding of the stress build-up in subduction zones and help in forecasting large future earthquakes (*6*). The documented examples of this activity are in regions where megathrust events are expected: the Nankai subduction zone in Japan and, most recently, the Cascadia subduction zone in the Pacific, off Washington state and western Canada (*7*).

In Japan, low-noise seismometer arrays have discovered deep nonvolcanic seismic tremor in the Nankai subduction zone, where at least nine great ($M >$ 8.0) earthquake sequences have occurred in the historical record at intervals of one or two centuries, with devastating consequences. The tremor is attributed to water that has been liberated by metamorphism of the subducting Philippine sea plate and is trapped under the forearc crust (*3*). Intraslab earthquakes have been linked to such metamorphism (*8*). Seismic exploration has also elucidated the interplate fault region and its possible water content (*9*, *10*). For example, high pore-fluid pressure has been imaged in the Tokai segment (*6*) and suggested as a cause of the silent earthquake detected there.

In the Cascadia subduction zone, a silent earthquake was detected (*1*) with space-geodetic, Global Positioning System (GPS) arrays, which sense the slow motion of Earth's surface over several hundred kilometers. Seismic tremor occurred in the same time span, from sources in the region where the silent earthquake slip occurred. This activity, called episodic tremor and slip (ETS), was predicted to recur in Cascadia every 14 months, with the latest event predicted for July 2004 (*11*). The expected ETS event was observed from 8 to 24 July, with the slip migrating northward from Puget Sound, Washington, to Vancouver Island at the northern end of the Cascadia subduction zone. Two significant (M = 5.8 and 6.4) earthquakes were also detected off Vancouver Island. The event was preceded by another, unexpected episode of tremor and slip beginning in late April; this event may have moved southward into northern California and terminated at the southern end of the subducting slab (*7*).

The belt of tremor sources associated with the Nankai subduction zone (see the





Cross sections of the Nankai and Cascadia subduction zones. The two panels show the forearc regions between the subduction trench and volcanic arc, which are 50 km on either side of the figure. Megathrust earthquakes are thought to occur on the seismogenic part of the dipping interplate boundary (red lines). Silent earthquakes and nonvolcanic seismic tremor sources are thought to occur in the circled regions. In the Cascadia subduction zone, these events occur downdip of the megathrust seismogenic zone (**bottom**), whereas in the Tokai part of the Nankai subduction zone, they occur on the megathrust seismogenic zone (**top**). They are likely related to water fed under the forearc crust by dehydration of the subducting plate. No such events are recorded in the Kanto part of the Nankai subduction zone, as discussed in the text.

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CREDIT: ALFRED HIRN AND PRESTON HUEY/SCIENCE figure, top panel) also terminates abruptly to the northeast of Tokai, consistent with a lateral edge to the subducting slab. The slab itself appears to be split apart widely downstream of Mount Fuji. No seismic tremor is detected in the region east of Mount Fuji to the outskirts of Tokyo, the site of the 1923 Kanto ($M = 7.9$) earthquake, where the other part of the slab is subducting. In the latter area, water thus appears not to be trapped under the forearc crust, but originates in a deeper section of the slab and reacts with the forearc mantle to form serpentinite (*12*). The liberation of water at larger depth than in the other cases cited may be explained by the cold Pacific plate that rapidly subducts beneath the slab and cools the overlying mantle. Water thus moderates the size of the megathrust earthquake by limiting the extent of rupture to above the stably gliding serpentinized arc mantle (*13*).

When seismic tremor signals the presence of water beneath the forearc crust, water may also contribute to the development of silent earthquakes. Along the Nankai belt of tremor sources, silent earthquakes occur only on the Tokai segment (see the figure, top panel), in the same region where a megathrust earthquake is believed to be overdue. Megathrust earthquakes result from a stick-slip frictional instability on the interplate fault (*14*). A stick-slip segment can be unclamped by lowering the effective compressive normal stress. It can then still participate in the megathrust earthquake rupture, but the latter cannot nucleate on it. Such a scenario has been suggested to occur in the upperpart of the Hellenic subduction zone, due to the extra weight of a slab that is rolling back (*15*).

The deeper part of the Tokai megathrust rupture zone could be similarly unclamped, here by an increase of pore-fluid pressure on the interplate fault, as imaged by Kodaira *et al*. (*6*). In their simple earthquake-slip model, the block unclamped by pore-fluid pressure under the forearc crust would experience silent earthquakes before the megathrust earthquake. The absence of silent earthquakes on the other segments of Nankai is then consistent with more recent rupture on these segments. Silent earthquakes could herald their evolution to preseismic stage, because the seismic tremor indicates water availability, although this may be modulated by local structure.

In the Cascadia subduction zone, seismic tremor and silent earthquakes occur downdip of where the interplate is presently locked (see the figure, bottom panel). This is very different from Nankai, as is the specific one-to-one coincidence of their occurrence as events on the order of a week or more with migration or propagation over hundreds of kilometers along the unlocked interplate where it is not in stick-slip condition. They appear to be confined to the forearc crust, consistent with water being trapped here from the slab beneath, and the long-term slip could comprise here a succession of transient episodes of fluid flow at the interplate boundary. Further down, water enters the arc mantle instead, and the resulting serpentinite above the interplate enables smooth, continuous gliding (*13*).

These newly discovered seismic phenomena and inferred structural signatures provide an unprecedented opportunity to understand subduction and elucidate the processes that lead to major earthquakes. The search for silent earthquakes and seismic tremor should now be extended to other subduction zones, while the unexpected episode of tremor and slip mentioned above illustrates the need for more in-depth studies in Nankai and Cascadia. New continuous GPS arrays and low-noise seismometer arrays extending to the ocean-bottom are required. Furthermore, seismic exploration should be used to further elucidate the architecture and water content of interplates and their walls.

References and Notes

1. H. Dragert, K. Wang, T. S. James, *Science* **292**, 1525 (2001).
2. S. Osawa *et al.*, *Science* **298**, 1009 (2002).
3. K. Obara, *Science* **296**, 1679 (2002).
4. A. Katsumata, N. Kamaya, *Geophys. Res. Lett.* 10.1029/2002GL015981 (2003).
5. G. Rogers, H. Dragert, *Science* **300**, 1942 (2003).
6. S. Kodaira *et al.*, *Science* **304**, 1295 (2004).
7. See www.pnsn.org.
8. L. P. Preston *et al.*, *Science* **302**, 1197 (2003).
9. M. R. Nedimovic, R. H. Hyndman, K. Ramachandran, G. D. Spence, *Nature* **424**, 416 (2003).
10. A. J. Calvert, *Nature* **428**, 163 (2004).
11. M. M. Miller, T. Melbourne, D. J. Johnson, W. Q. Sumner, *Science* **295**, 2423 (2002).
12. S. Kamiya, Y. Kobayashi, *Geophys. Res. Lett.* **27**, 819 (2000).
13. R. D. Hyndman, M. Yamano, D. A. Oleskevitch, *Island Arc* **6**, 244 (1997).
14. C. H. Scholz, *Nature* **391**, 37 (1998).
15. M. Laigle, M. Sachpazi, A. Hirn, *Tectonophysics*, 10.1016/j.tecto.2004.07.009 (2004).

BIOMEDICINE

A Fresh Look at BSE

Bruce Chesebro

Mad cow disease, or bovine spongiform encephalopathy (BSE), is the cattle form of a family of progressive brain diseases. These diseases include scrapie in sheep, Creutzfeldt-Jakob disease (CJD) in humans, and chronic wasting disease (CWD) in deer and elk. They are also known as either “prion diseases” because of the association of a misfolded cellular prion protein in pathogenesis or “transmissible spongiform encephalopathies” (TSEs) because of the spongelike nature of the damaged brain tissue (*1*).

The recent discovery of two BSE-infected cows, one in Canada and one in the United States, has dramatically increased concern in North America among meat producers and consumers alike over the extent to which BSE poses a threat to humans as well as to domestic and wild animals. The European BSE epidemic of the late-1980s seems to have been initiated a decade earlier in the United Kingdom by changes in the production of meat and bone meal (MBM) from rendered livestock, which led to contamination of MBM with the BSE infectious agent. Furthermore, the fact that UK farmers fed this rendered MBM to younger animals and that this MBM was distributed to many countries may have contributed to the ensuing BSE epidemic in the United Kingdom and internationally (*2*).

Despite extensive knowledge about the spread of BSE through contaminated MBM, the source of BSE in Europe remains an unsolved mystery (*2*). It has been proposed that BSE could be derived from a cross-species infection, perhaps through contamination of MBM by scrapie-infected sheep tissues (see the figure). Alternatively, BSE may have been an endemic disease in cattle that went unnoticed because of its low level of horizontal transmission. Lastly, BSE might have originated by “spontaneous” misfolding of the normal cellular prion protein into the disease-associated abnormal isoform (*3*), which is postulated to be the infectious agent or “prion.”

Spontaneous protein misfolding is not a new phenomenon as proteins are known to sometimes misfold after synthesis. Cells in turn have devised ingenious ways to deal with this problem. These include molecular chaperone proteins that bind to misfolded proteins and help them to unfold, and organelles called proteosomes that degrade misfolded or unwanted proteins. However, although misfolded prion proteins have been generated in test tubes as well as in cultured cells, it has been difficult to

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