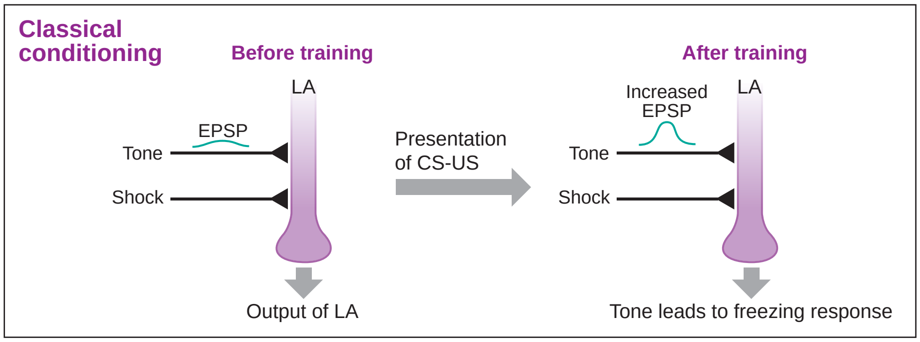

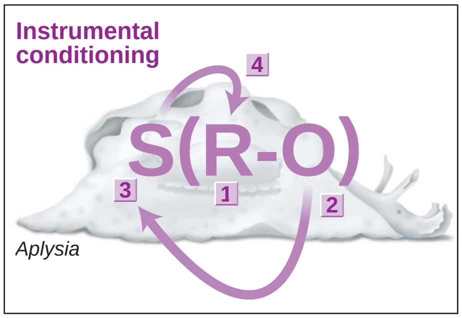

Classical and instrumental conditioning. (Top) One form of classical conditioning involves conditioning animals to fear a stimulus (*7*). In the example shown, animals are conditioned to expect an electric shock (unconditioned stimulus, US) when they hear an auditory tone (conditioned stimulus, CS). The neurons involved in learning this connection are situated in the lateral amygdala (LA), which instigates a conditioned freezing response when the tone is heard. The cellular mechanism underlying this learned behavior is a change in the activity of NMDA receptors at specific synapses (long-term potentiation) that then increase AMPA-type glutamate receptor currents in lateral amygdala neurons. (**Bottom**) Instrumental conditioning in the sea slug *Aplysia* (*4*). During instrumental conditioning, a stimulus (S) results in a response (R) that leads to an expected outcome (O), usually a reward. (1) The sea slug exhibits spontaneous biting behavior. (2) Stimulation of the esophageal nerve responsible for ingestion leads to dopamine release onto the B51 sensory neuron. (3) If dopamine is applied to B51 contingent on esophageal nerve activity and biting behavior, there is a change in the resting potential and excitability of B51. (4) This change increases the probability that a biting response will occur.

ward-seeking behaviors trained by this type of conditioning. Dopamine may mediate approach behaviors activated by stimuli that are associated with biologically relevant events. The Brembs *et al.* work adds a new dimension to this research by presenting a simple system in which the effects of dopamine on single neurons, and on the behavior produced by those neurons, can be studied.

In the rat, release of dopamine in the nucleus accumbens can be selectively gated by the sensory properties of food, which in turn are gated by hunger and novelty (*11*). This suggests that food reinforcement delivered to a hungry rat leads to the release of dopamine, which provides the incentive motivating repetition of the behavior that produced the food (*10, 11*). In *Aplysia*, it is B51 that influences the buccal motor system to carry out ingestion (*8*). Repeated application of dopamine to B51 after it fires with an ingestion-like pattern alters the excitability of this neuron, leading to a higher probability of ingestion-like patterns. It is noteworthy that Brembs *et al.* artificially delivered dopamine to B51 every time it fired with an ingestion-like pattern. It will be important to further investigate the neural pathway that connects food intake, the esophageal nerve, and B51 to determine which stimuli are necessary and sufficient for stimulating natural release of dopamine contingent on biting, and to analyze the types of neural plasticity that dopamine induces.

Mechanisms of classical conditioning are highly conserved across a broad range of species (*5, 7*). Now, thanks to the work of Brembs and colleagues, it is clear that the mechanisms underlying instrumental conditioning may also be highly conserved. The next step will be to see whether any common cellular mechanisms underlie classical and instrumental conditioning.

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PERSPECTIVES: PLATE TECTONICS

Seismological Detection of Slab Metamorphism

Bruce Julian

Seismology is concerned primarily with the study of earthquakes, sudden, transient disturbances that radiate elastic waves in the Earth. There are also nontransient seismic processes, however, some of which are of great interest and practical importance. At volcanoes, more or less continuous ground vibrations often occur. Called "volcanic tremor," they are thought to be excited by the subterranean flow of magmatic fluids. Their detection is an important indicator of volcanic activity (*1*).

But major improvements in instrumental capability often lead to unexpected discoveries. On page 1679 of this issue, Obara (*2*) reports the detection of continuous ground vibrations far away from any volcanic activity. The vibrations are probably caused by metamorphic processes related to the subduction of lithosphere beneath southwestern Japan.

Obara has analyzed data from Hi-net, a new network of about 600 digital seismometers situated in bore holes with depth of 200 to 300 m across Japan. The station density and sensitivity of the network, which began operation in late 2000, far surpass those of any comparable seismographic network. In the United States, some two or three dozen similar instruments of nonuniform types are spread unevenly over a much larger area.

The Hi-net data show vibrations that persist for minutes to weeks and originate in the lower crust in the Nankai subduction zone. Here, the Philippine Sea plate subducts beneath Shikoku and southwestern Honshu in Japan. Without a dense network and centralized processing, these vibrations would probably have gone unnoticed, or been interpreted as meteorological or cultural noise. The fact that rapid temporal variations in the Hi-net signals are spatially coherent over large regions rules out such explanations.

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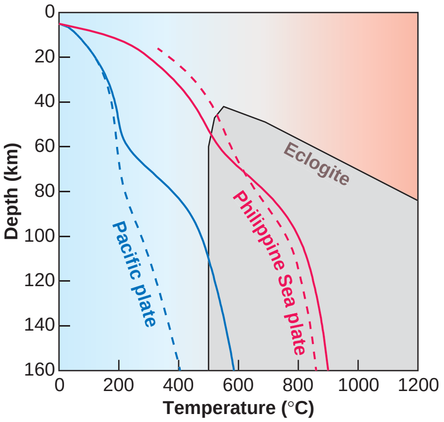
Applying cross-correlation techniques to these signals, Obara has located the sources of the vibrations at depths of 35 to 45 km. The impressive agreement of these locations with the shape and position of the seismic zone at these depths in the subduction zone [see fig. 1 in (*2*)] demonstrates clearly that the vibrations are of tectonic origin.

Obara likens the vibrations to volcanic tremor and suggests that they are caused by flow of water liberated by dehydration of the subducting Philippine Sea plate. This suggestion accords well with the behavior of hydrous minerals in the subducting basalts, which are expected to dehydrate at a temperature of about 500°C to form eclogite (see the figure). Inferred temperatures in the Nankai subduction zone (see the figure) reach this value about 45 to 55 km beneath southwestern Japan.

The "metamorphic tremor" varies spatially as well as temporally. These variations are sometimes correlated, with the source locations migrating along the strike of the subduction zone for distances of about 100 km at speeds as low as 9 km/day [see fig. 4 in (*2*)]. This migration is much slower than the redistribution of stress by elastic waves and much faster than the conduction of heat in rocks. It may represent the migration of fluids released by metamorphism, or perhaps a kinematic wave resulting from the interaction of fluid flow, temperature, chemical reactions, and rheology.

There is evidence that small- to moderate-sized earthquakes may also trigger metamorphic tremor. Three earthquakes with magnitudes from 4.8 to 6.7 occurred near the tremor active zone during 2001; all were followed by tremor episodes lasting several days (in one case after a delay of 7 days) and occurring 40 to 50 km away. More such observations are required to establish the statistical significance of this correlation, but a connection is plausible: Strain changes caused by earthquakes can alter pore-fluid pressures in rocks at a distance from the source (*3*).

Almost as striking as the correlation of the source locations with the position and shape of the subducting Philippine Sea plate is the apparent absence of similar vibrations in northeastern Japan, where the Pacific Plate subducts beneath northern Honshu at the Japan Trench. The most obvious difference between the two zones is in the ages of the subducting plates and thus their temperatures. The Philippine Sea plate is 15 to 30 million years old, whereas the Pacific plate is about 130 million years old and about 300° to 500°C colder (*4*). The Pacific plate is also subducting faster (83 mm/year compared with 40 mm/year) and therefore has less time to heat up before reaching a given depth.



Conditions for dehydration of minerals in subduction zones. When basalt enters the eclogite stability field (shaded), dehydration reactions begin to liberate water (although some hydrous minerals remain stable). The relevant phase boundary is at about 500°C and depends only weakly on depth. Also shown are theoretical temperatures versus depth at the top (solid line) and base (dashed line) of the subducted crust in Japan. In the subducted Philippine Sea plate in southwestern Japan (red), dehydration is expected to begin at depths of about 45 to 55 km. In the colder subducted Pacific plate in northeast Japan (blue), the depth of dehydration exceeds 100 km. [Adapted from (*4*)]

Dehydration of the Pacific plate beneath northeastern Japan should occur at depths of 100 km or more, where it finally reaches the temperature at which the dehydrated eclogite is stable (see the figure). It will be interesting to see if more sophisticated processing techniques can detect tremor from such depths in the Hi-net data.

Does metamorphic tremor occur elsewhere in the world? Places where young, warm lithosphere subducts include southern Mexico and western South America. But the region with the densest seismological instrumentation is the Cascadia subduction zone, from southern British Columbia to northern California, where universities and government agencies operate networks of hundreds of seismometers. The Farallon and Gorda plates, which subduct there, were formed at the Gorda and Juan de Fuca ridges a few hundred kilometers offshore and are only about 4 to 10 million years old.

Most seismometers in Cascadia are, however, of lower quality than those of Hi-net. They lack horizontal components, are not deployed in bore holes, and use relatively noisy analog telemetry techniques. Tremor signals like those from southwestern Japan would therefore go unnoticed, even if they were present. Furthermore, because of operational practices (programming computers to discard data that lack obvious earthquake signals), it is probably not possible to conduct an intensive search for metamorphic tremor in existing data archives. The search for metamorphic tremor in future seismic data from Cascadia should have high priority.

The recent discovery of "slow earthquakes" in Cascadia may, however, be relevant. Dragert *et al.* (*5*) and Miller *et al.* (*6*) have analyzed ground deformation in western Washington and British Columbia measured with the Global Positioning System (GPS), and found that during the 1990s, the region between the trench and the Cascade volcanoes experienced eight such events, with equivalent slip magnitudes of about 6.7 but durations of 2 to 8 weeks, too slow for conventional seismometers to detect. The events appear to repeat at intervals of about 14.5 months, and involve slip of a few centimeters on faults that are 30 to 50 kilometers deep and hundreds of km long. The approximate agreement of the source depths and event durations with the metamorphic tremor episodes beneath Japan and their occurrence in similar tectonic settings suggest that the phenomena may be related.

What might we learn from seismological observations of metamorphic tremor? Probably the closest analog is volcanic tremor, but we do not yet understand its excitation quantitatively (*7*). Volcanic tremor is closely associated with evidence of magma motion, suggesting that fluid flow excites tremor by a process that resembles the excitation of animal vocal cords and many wind musical instruments. Theoretical models are, however, still unrealistic—for example, treating the fluid as incompressible (ignoring acoustic resonance) and modeling the channel-wall rocks with lumped masses, springs, and dashpots (*1*). With better models of flow-induced vibration, it may be possible to use seismic data to infer volumetric flow rates, fluid densities, and viscosities for both volcanic and metamorphic tremor.

Seismologists and petrologists have a long history of fruitful interaction, using each other's data to understand the structure and state of Earth's interior. Nevertheless, the direct seismological detection and measurement of active metamorphic processes will surely take both groups by surprise. Seismologists and petrologists have more to tell each other than either group imagined.

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