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Imaging the Deep Earth

German A. Prieto

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GEOPHYSICS

Imaging the Deep Earth

Improved processing of seismic noise data enables detailed imaging of deep Earth structures.

German A. Prieto

Insights into Earth's thermal and chemical structure, from the inner core to the crust, have historically been gained from analyzing seismic waves excited by earthquakes (*1*). However, the resolution of these methods is limited because nearly all earthquakes occur along tectonic plate boundaries, leaving large areas that are seismically quiet. Recent developments in seismic noise tomography have shown great potential for high-resolution imaging of Earth's interior structure (*2*). This approach yields data wherever a seismic instrument can be deployed, but the seismic noise signals (*3*) used to image the crustal and upper mantle structures often lack resolution for most of the remaining mantle. On page 1063 of this issue, Poli *et al*. (*4*) overcome some of these limitations, enabling the imaging of deep-Earth structures.

Ambient seismic noise is a ubiquitous signal that is recorded at seismic stations globally, even in the interior of continents. At periods below 30 s, microseismic noise is generated by pressure fluctuations on the ocean bottom in coastal waters and by nonlinear interactions of ocean waves traveling in opposite directions (*5*, *6*) (see the figure, panel A). Microseismic noise is dominated by surface waves, which travel in the top 10 to 100 km of Earth's interior. However, storms over the oceans can also generate global body waves (*7*), which propagate through Earth's mantle and can be reflected from major interfaces (see the figure, panel B).

More than 50 years ago, Aki (*8*) showed how the ambient seismic noise can be used to estimate the propagation speed of surface waves underneath a seismic array. Soon after, Claerbout (*9*) suggested that Earth's reflection response (that is, the imaging of interfaces at depth) could be extracted from carefully treated seismic signals. But it was not until the advent of continuously recorded high-density seismic networks that these proposals could be put in practice.

In 2005, Shapiro *et al*. presented a tomographic model of the velocity structure of Earth's crust and upper mantle, based on ambient seismic noise records (*2*). The main idea behind this approach (*10*) is that a coherent signal can be extracted from apparently random noise by cross-correlation between multiple seismic stations. The signal extracted is used to calculate the propagation speed of surface waves between each pair of stations (see the figure, panel A). Since then, several seismic noise imaging methods have been developed, most of them based on surface-wave measurements (*11*–*13*). Because of the ubiquitous nature of the ambient seismic noise, continuous monitoring of the subsurface is possible (*14*).

Body waves have also been observed in the ambient seismic noise (*7*), but only in a limited number of cases have station-to-station body wave arrivals been reported (*3*). Most reported noise-derived body waves have been related to reflections from the Moho (the discontinuity between Earth's crust and mantle) or other shallow crustal interfaces. A substantial portion of Earth's mantle thus remained out of reach for noise imaging.

Poli *et al*. are now able to extract global station-to-station body-waves from the noise and to determine the thickness of the transition zone and the fine structure of its interfaces in the area of study. The authors carefully processed the ambient seismic field of a yearlong continuously recording seismic experiment (POLENET/LAPNET) in northern Finland. They removed earthquake signals and other glitches in the data (for example, when stations were offline or reported large spikes), using shorter signals for cross-correlation and stacking (averaging) over the entire time span of the experiment. As in many other seismic noise studies, the cross-correlations of the signals show clear surface waves but no evident body waves. Only after "muting" these surface waves (that is, setting their amplitudes to zero) and summing the cross-correlations over the entire network, did evidence for vertically propagating body waves from the mantle transition interfaces emerge (see the figure, panel B). The authors further corroborated this interpretation with theoretical predictions based on a standard Earth model.

The results are a major advance in seismic noise tomography. There have been multiple seismic deployments in the past 10 to 20 years over continents; analysis of these data with Poli *et al*.'s technique should reveal further evidence for body waves from the deep Earth. The combined results may help to resolve the topography of the mantle transition zone at the global scale and place

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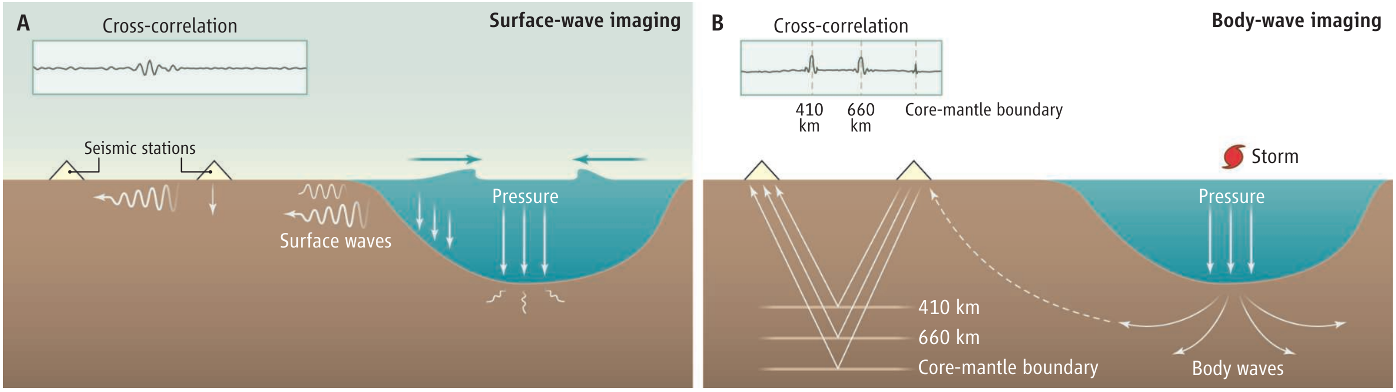

Surface and body waves in ambient noise tomography. **(A)** Microseismic noise is mostly generated in the ocean basins by wave-wave interactions and occasionally during strong storm activity. The resulting microseismic surface waves are recorded at seismic stations and cross-correlated for surface-wave tomography. **(B)** Signals from body waves generated in the ocean basins are recorded at one seismic station, travel back into the deep Earth, are reflected from any interfaces encountered, and are registered at a second seismic station. Poli *et al*. use this approach to image the thickness and structure of the mantle transition zone.

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constraints on the thermodynamics of mantle transition minerals (*15*).

With improved signal processing and data from seismic networks with high station density, it may become possible to obtain detailed information not only about the lithosphere and the mantle transition zone, but also about the core-mantle boundary (*16*). Seismic noise will likely become a key ingredient in imaging efforts to discern Earth's structures, independent of the presence of earthquakes.

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DEVELOPMENT

Plant Gametes Do Fertilization with a Twist

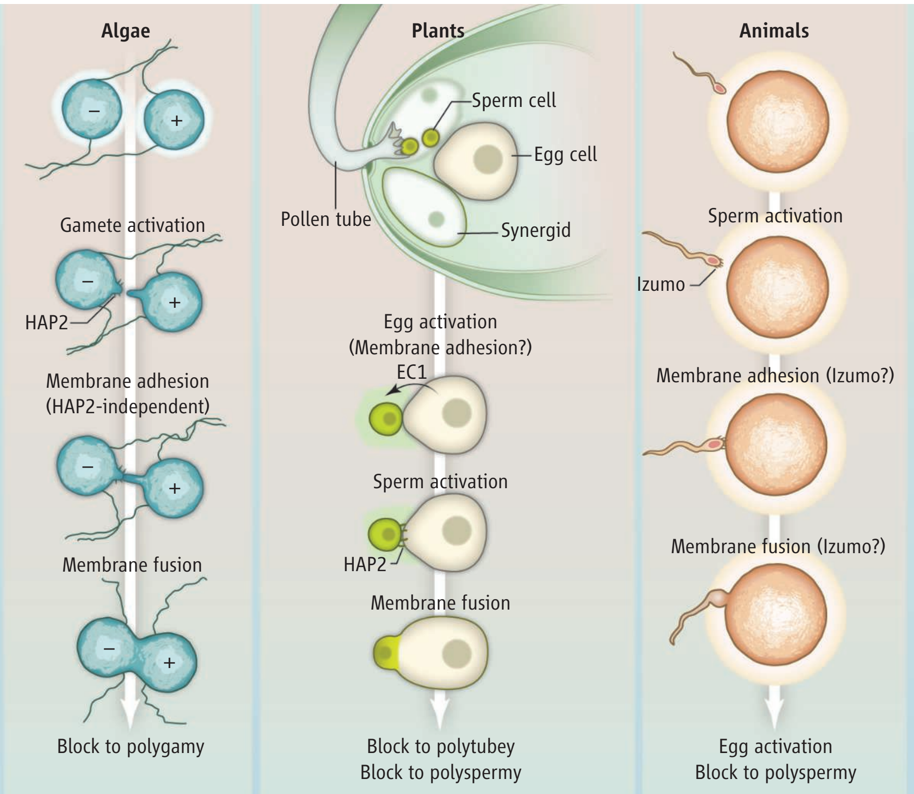
Identification of key regulatory mechanisms of higher plant gametes advances our understanding of fertilization.

William J. Snell

A new generation in eukaryotes begins with fusion between sperm and egg, but we know little about the mechanisms involved. Sperm-egg interactions have been studied most thoroughly in animals, but on page 1093 of this issue, Sprunck *et al.* (*1*) have pushed our understanding of gamete interactions in plants to the head of the model organisms class. They discovered that plants do the fertilization dance similarly to animals, but with a twist. In animals, the egg remains quiescent until fused with the sperm, but in *Arabidopsis* the egg leads. The egg cell responds to sperm discharged from a newly arrived pollen tube by secreting a cloud of sperm-activating proteins. The aroused sperm redistributes a previously cryptic putative membrane fusogen to its plasma membrane to prepare for fusion.

In most animals, the sperm is activated for fusion after binding to the outer vestments of the egg (the zona pellucida in mammals) (*2*, *3*). After penetrating the zona, the sperm fuses with the egg plasma membrane, which triggers the egg to release contents of secretory vesicles and undergo surface modifications (blocks to polyspermy) to prevent fusion of additional sperm (*4*). Animal fertilization is particularly resistant to genetic studies (*2*). In mammals, only the sperm protein Izumo-1 is exclusive to gametes and shown by gene disruption to be essential for an unknown step in membrane fusion (*5*, *6*).

Studying higher plant fertilization is challenging because the female gametophyte is inaccessible and more players are involved: the pollen cell with two sperm and two dimorphic eggs with adjacent synergid cells (see the figure). The most thorough understanding of fertilization is in the model plant *Arabidopsis*. The pollen tube is drawn to an embryo sac within an ovule by attractants produced by the synergids (*7*). Upon pollen tube arrival at a synergid, the synergid degenerates and two sperm are discharged, which then travel to the egg cell. After a brief pause, one sperm fuses with the egg cell to form the zygote, and the other fuses with the central cell to form the endosperm (*8*). Fusion activates a block to



Fertilization across phyla. As in algae and animals, *Arabidopsis* gametes undergo mutual activation. Upon sperm arrival, the egg cell secretes EC1 proteins that trigger sperm to display previously cryptic HAP2. Adhesion between *Chlamydomonas* gametes also triggers exposure of cryptic HAP2, and in mammals, sperm binding to egg triggers exposure of Izumo-1. Only in the two plant systems are both gametes activated before fusion.

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