RESEARCH: SEISMOLOGY

Shaking Without Quaking

Hiroo Kanamori

After a large earthquake, seismic waves travel around the planet many times and eventually set up oscillations with typical periods of 3 to 54 min (see figure). Recently, several reports, including that by Suda *et al.* (*1*) on page 2089 of this issue, show that Earth appears to be oscillating all the time, even without earthquakes.

The idea that Earth can ring like a bell was suggested more than 80 years ago (*2*), but when seismologists actually "saw" its oscillations after the 1960 Chilean earthquake (magnitude M_w = 9.5), the largest earthquake to occur in this century, they were really excited. Bullen, who attended the 1960 meeting of the International Union of Geodesy and Geophysics held in Helsinki, where the first observations of Earth's free oscillations were presented by several groups of investigators, wrote "there occurred one of the most dramatic scientific sessions this author has witnessed" [(*3*), p. 260].

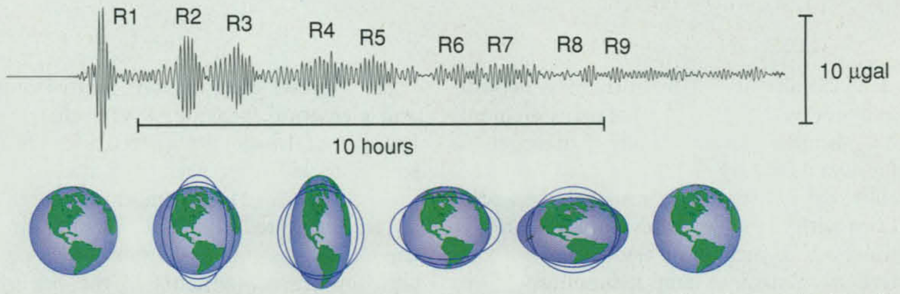
Do such oscillations occur without earthquakes? In 1959, Benioff *et al.* (*4*) searched for such oscillations over a period range longer than 10 min, but found none. Now, nearly 40 years later, Nawa *et al.* (*5*) have detected, from the record of a superconducting gravity meter at Showa station, Antarctica, almost continuous oscillations of Earth over a period range of 4 min to 1 hour. The successful detection was probably a result of a combination of a good performance of the superconducting gravity meter, a seismically quiet Antarctic site, a long, uninterrupted recording, and especially, a modern data analysis technique that made use of graphic spectral analysis.

Suda *et al.* (*1*) and Kobayashi and Nishida (*6*) investigated the records of gravity meters and seismometers, respectively, at several stations around the world and found clear evidence of continuous oscillations over a period range of 3 to 8 min. These peaks are also evident in the similar spectra presented by Tanimoto (*7*). The amplitudes of these oscillations are small. For the 54-min spheroid-shaped oscillation excited by the M_w = 9.5 Chilean earthquake, the vertical amplitude on Earth's surface was about 1 cm, or about 3 μgal (1 Galileo = 10^{-2} m s^{-2}) in acceleration. With the improvement in the signal-to-noise ratio and digital recording system of seismic and gravity instruments over the last two decades, we can now detect free oscillations for earthquakes with M_w = 8 with acceleration amplitudes of about 30 ngal. The amplitudes of the background oscillations recently detected in the absence of earthquakes were on the order of 1 ngal. This measurement reflects the notable improvement of signal detection capability, including stable digital recording systems and data stacking and analysis techniques, over the past decades.

Possible source mechanisms for the oscillations include (i) atmospheric disturbance, (ii) variations in loading pressure on the sea floor resulting from ocean tides and currents, and (iii) slow deformation in Earth's interior, including the fluid core. Most of the authors of the recent reports favor an atmospheric source for these background oscillations (*6, 7*). The situation may be somewhat similar to that of solar oscillations (*8*), although the detailed mechanism is still under investigation. Tanimoto (*7*) showed that turbulent convective motion in the atmosphere with an average velocity of about 6.5 m s^{-1} can explain the observed background signal at periods longer than 6 min. Kobayashi and Nishida (*6*) showed that dynamic pressure caused by atmospheric disturbances can excite oscillations with an amplitude of 1 ngal over a period range of 2 to 5 min. The record of the Antarctic gravity meter indicates enhanced excitation during the winter seasons and at periods of about 4 min, which coincide with those of atmospheric acoustic oscillations (*5*). These observations support the conclusion that the main cause of the observed oscillations is the atmospheric perturbations. However, other causes are not excluded. It would be exciting if these observations lead to the discovery of some slow, deep processes (for example, episodic plate motion, slow movement associated with shallow and deep earthquakes, large-scale magmatic processes, or slow processes associated with Earth's core). In fact, several spectral peaks at periods longer than 15 min observed in the Antarctica records cannot be attributed to the oscillations that can be excited by sources near Earth's surface, such as the atmosphere and oceans (*5*). Deep sources could excite oscillations that cannot be excited by shallow sources. Although these spectral peaks at very long periods could be caused by some instrumental effects, further studies are needed.

These findings may have several implications. Kobayashi and Nishida (*6*) and Fukao *et al.* (*9*) suggest that atmospheric excitations can be used to explore the internal structure of terrestrial planets with atmospheres, that is, Mars and Venus. Kobayashi and Nishida (*6*) estimated that the atmospheres of Mars and Venus can produce oscillations with an amplitude of several nanogals. Such oscillations, if detected from just a single instrument deployed on these planets, could provide information on the radial variations of elastic properties in the planets.

These observations underscore the importance of energy coupling among the lithosphere, hydrosphere, and atmosphere. In most traditional seismological studies, waves in the solid Earth (seismic waves), the ocean (tsunami, or long-wavelength ocean waves), and the atmosphere (acoustic-gravity waves) are treated separately. However, several studies demonstrated significant energy coupling. For example, at-



Ringing changes. (**Top**) Seismogram showing the ground motion acceleration excited by the 1994 Bolivian earthquake (M_w = 8.3), recorded at Pasadena 7500 km away. R indicates surface Rayleigh wave trains; R1 is the direct wave, and R2 is the wave propagating backwards from Bolivia along the major arc. When R1 and R2 make another round trip, they become R3 and R4, which in turn become R5 and R6, and so on. (**Bottom**) These waves, after circling around Earth many times, produce oscillatory motions, as shown schematically. Successive deformation patterns during one cycle of oscillation of the fundamental mode are shown from left to right. The waves in the top panel would actually produce a more complex pattern.

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mospheric waves excited by the 1991 Pinatubo eruption were coupled to the solid Earth, and detailed studies of these coupled waves with the global seismic network provided a means for estimating the total thermal energy emitted by the eruption (*10*). The deformation associated with the 1994 Northridge earthquake caused significant perturbation to the ionosphere (*11*). The tsunami excited by the 1968 Tokachi-Oki, Japan, earthquake caused ionospheric disturbances, which suggest the use of ionospheric measurements for mapping the tsunami wave field in the ocean, which in turn could be used for tsunami warning purposes (*12*).

The observations reported in these recent papers encourage enhanced efforts toward understanding the geophysical processes involving both the atmosphere and solid Earth. Reports on disturbances in the ionosphere before large earthquakes are numerous (*13*), but the physics is poorly understood and skepticism prevails. A better understanding of the physics of the lithosphere-atmosphere energy coupling will be a key to resolving these mysterious observations.

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GEOCHEMISTRY

Origins of Hydrothermal Ores

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The dominance of hydrothermal deposits as major industrial sources of many elements has stimulated intense study of their genesis for over a century. Their origin is unequivocally by precipitation from aqueous solutions within the upper several kilometers of the crust. Typical close association with active magmatism or deep sedimentary basins implies that these are the heat sources that warm the transporting fluids (see figure). Ore deposition takes place from rising hot solutions at a range of temperatures that extends above 600°C. The challenge has been to unravel the complex chemical and physical processes, including interaction with complicated and varied geology, during extraction of the ore components from source rocks, component transport, and then precipitation of the ores. The fragmentary evidence of these processes is characteristically ancient, perhaps several billion years old, and has been damaged by subsequent geologic events. Our objective continues to be to create ever more accurate models of ore formation not only as an intellectual exercise but also to guide mineral exploration. On page 2091 of this issue, Audétat *et al.* (*1*) report experimental results that increase our confidence in such models. Several types of information provide the principal bases for current genetic models.

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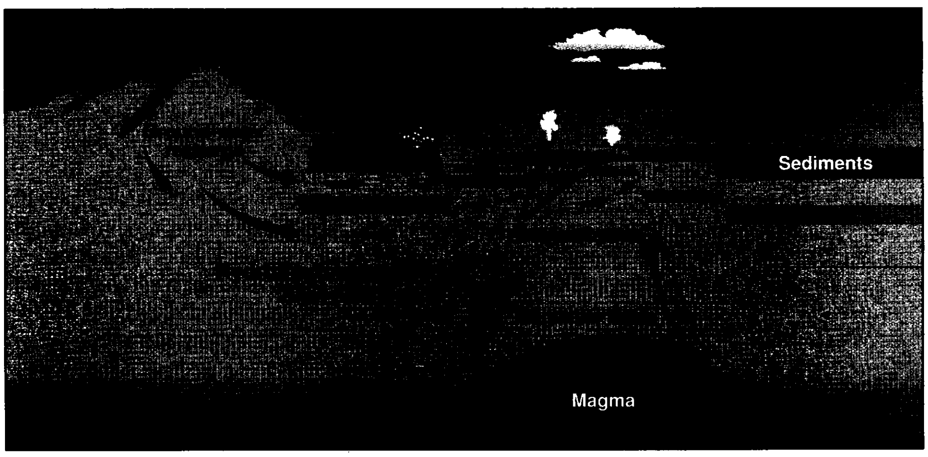
1) Mineral compositions, both isotopic and elemental, provide several clues. The isotopes of 15 elements often identify the source rocks, their ages, and the time of mineralization (*2*). Thermodynamic stability and measured or calculated solubility of the mineral assemblages limit the processes contributing components to the ore solution, the chemistry of transport, and the conditions and causes of deposition (*3*).

Many heavy metals occur in ores as sulfides or oxides that are insoluble under most conditions. Laboratory experiments at hydrothermal temperatures, in combination with chemical modeling, show that chemical complexing with Cl and S and favorable pH and redox state are the main controls on solubility. Solubilities can now be calculated thermodynamically for most important ore metals at most depositing and transporting conditions to at least 350°C (*4*).

Solubility behavior indicates the possible physical and chemical processes that could cause precipitation from the fluid, including cooling, reaction with wall rocks (such as neutralization of an acid solution encountering limestone, or an oxidized solution encountering reducing organic matter), exsolution of gases such as H_2S or CO_2 because of decreased pressure, and mixing with cooler water of different chemistry.

2) Fluid inclusions offer samples of the fluids passing through the deposit and, often, approximations of the associated tem-



Valuable deposits. Schematic section of a geothermal system and associated ores. Magmatic and heated ground waters flow upward, possibly depositing ore as a result of cooling or reaction with wall rock. It mixes with heated ground water and boils, causing ore deposition as a result of cooling, chemical change, and loss of volatiles. The ground-water circulation system may occupy 20 to 30 km^2, with a discharge of 10^6 to 10^8 m^3 per year. The system may be active for 10,000 to 30,000 years, or longer if additional magma is intruded. [Adapted from figure 14.2 of (*9*)]