pressure to stake seabed mining claims as fast as possible, which Rusk warned could produce a "direct rivalry among those with the technological capacity to exploit the seabeds and . . . the large majority of nations without such capability," has a substantive side. The most obvious is the economic threat which unilateral claims by the United States or Japan would pose to developing nations. A U.N. report, which was cited by Levering in testimony, said that the developing countries produced in 1971 half the world's 5.4 million metric tons of copper, one-fourth of its 0.5 million metric tons of nickel, one-third of its manganese, and three-fourths of its cobalt. Thus, nations like Zaire, which are mineral-rich and mineral-exporting, have an economic stake in preventing new minerals—to which they cannot have access—from entering world metals markets. The looming diplomatic thunderclouds, then, seem to have monetary linings.

Unilateral action could also hinder U.S. leadership in the Law of the Sea Conference on other issues such as defense and fishing rights. According to the Federation of American Scientists (FAS) which opposes the Metcalf bill, the draft international treaty President Nixon issued in 1970 embodied "an enlightened compromise between internationalist and nationalist interests"—including the proposed international body for regulating the deep seabed. Any unilateral moves by the mining companies would be provocative, like Peru's proclaimed 200-mile tuna fishing limit which nearly caused a military confrontation with the United States a few years back, or Iceland's extension of her fishing limits last year which touched off the cod war with England and Germany (*Science*, 1 Dec. 1972). According to FAS, the Metcalf-Downing bill, and the threat it poses, "has become a symbol to many countries of defiance of the multilateral negotiating process." Should the mining companies proceed, FAS fears, the U.S. position as an enlightened international negotiator will cave in.

The third problem posed by the mining interests' barging ahead with their new technology is that their claim to the ocean resources may be illegal. Laylin has written* that legally, "any person may now carry on activities on the deep ocean floor without a license provided that he conducts these activities 'with reasonable regard' to the equal right of others." This is possible, he says, under the customary law of the freedom of the seas, which has evolved since it was first pronounced by Hugo Grotius, a Dutchman, in 1609, to include fishing rights, military maneuvers, and shipping jurisdiction.

But Wolfgang Friedmann of the Columbia Law School has pointed out that the legal issue may work the other way: If the seas belong to everybody, then no one can take anything without everyone's permission that is, without an international organ to approve the taking. Friedmann said in a prepared statement:

> Under classical international law it was a contested question whether the deep sea was nobody's property (Res Nullius), and therefore in principle subject to national appropriation, or everybody's property (Res Communes), and therefore not subject to any state's appropriation or sovereignty.

Sohn said that under the "res communes" principle, and in the view of the U.N. moratorium resolution and related declarations, some legal experts would regard the appropriation of seabed minerals as unlawful. "To implement this bill would probably be doing something illegal."

With so many foes—from Johnson and Rusk right down to the smallest developing country—it could seem that an unfettered race to lay claim to the seabed would be out of the question. But on the contrary, the mining com-

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* John G. Laylin, "Past, present and future development of the customary international law of the sea and deep seabed," *International Lawyer*, 5 (No. 3) (July 1971).

RESEARCH NEWS

Earthquake Predictions: Breakthrough in Theoretical Insight?

Earthquake prediction, an old and elusive goal of seismologists and astrologers alike, appears to be on the verge of practical reality as a result of recent advances in the earth and material sciences.—C. H. SCHOLZ, Lamont Geological Observatory, speaking before the American Geophysical Union, 18 April, 1973, in Washington, D.C.

No one is routinely predicting earthquakes yet. Japanese seismologists, however, have been able to forecast intermediate-sized quakes in one region with some accuracy. In the U.S.S.R., three relatively large quakes have been successfully predicted on an experimental basis. But the real news about earthquake prediction and the motivation for the optimistic assessment above concern the discovery of what seem to be changes in the properties of rocks surrounding a fault which occur prior to earthquakes and the development of an explicit physical model that appears to account for these premonitory signals.

Verification of the proposed model would put earthquake prediction on a scientific basis, removing this kind of forecast from the province of astrologers and other seers. Indeed, nonscientific prophecies of major earthquakes still attract considerable attention in California, where the devastating quakes of 1857 and 1906 have not been forgotten and where smaller quakes serve to remind the inhabitants of the presence of active faults.

Less well remembered are the possibly more destructive quakes known to have occurred in the Mississippi Valley near Memphis, in Boston, Massachusetts, and in Charleston, South Carolina. Concern over possible seismic activity is becoming more widespread in the United States, however, with debates over the siting of nuclear power plants and other land use plans. (Proposed nuclear plants in Northern California have twice been canceled because of uncertainties regarding the seismic risk of the selected sites). Reports of major earthquakes in Nicaragua and Turkey in recent years and of the moderate-sized 1971 event in San Fernando, California, have increased awareness that a major earthquake in the United States could cause catastrophic damage. Estimates of the potential damage in Southern California alone run as high as $20 billion. Development of the capability to forecast earthquakes reliably, because of the accompanying opportunity to reduce damage and save lives, would thus provide some measure of protection against one of the most devastating of all natural disasters.

Many countries—among them Japan, which has been conducting major efforts to predict earthquakes for some time—face even greater earthquake hazards than the United States. Japan is located at the boundary of two crustal plates, one of which is being thrust under the other; nearly the entire country is criss-crossed by active faults. Repeated geodetic surveys have enabled Japanese earth scientists to detect vertical and horizontal movements of the earth's surface and to forecast a major quake in 1964 near Niigata. Tiltmeters that measure local surface deformations were used to give warnings during a swarm of smaller quakes that occurred from 1965 to 1967 near Matsushiro in central Japan. Investigators also found that microearthquake activity increased prior to large quakes. Predictions have been based largely on a combination of experience and empirical formulas rather than on any explicit physical theory of earthquake origins.

Earthquakes are also a hazard in several parts of the U.S.S.R. Soviet scientists have identified a number of geophysical precursors to earthquakes:

- Mechanical deformations of the earth's surface similar to those found in Japan.
- Increases in the electrical conductivity of the ground. This method was successfully used to predict a strong earthquake in the Kamchatka region, along the Bering coast.
- Changes in the chemical composition of groundwater sampled in deep wells, in particular an increase in the radon emitted. This method gave several weeks' warning before two different earthquakes in the Tashkent region (south-central Asia just north of the Himalayas).
- Seismological indicators, including an increase in microseismic activity, a change in the orientation of the stress axis in a region, and a shift in the frequency composition of seismic waves from small quakes toward higher frequencies.

What may prove to be the most significant discovery, however, is an anomaly in the observed velocities of seismic waves prior to an earthquake. Studies in the Garm region of the Tadzhik Republic by A. N. Semenov and I. L. Nersesov, of the Institute of Physics of the Earth in Moscow, showed variations in the ratio of the velocity of the compressional wave, V_p, to that of the shear wave, V_s. This ratio decreased from its normal value some weeks or months before a quake, then gradually increased, reaching approximately its normal value just before the event. The magnitude of the decrease in the ratio was about the same for all the quakes studied, but the timing was closely related to the size of the subsequent earthquake—the larger the quake, the earlier the anomalous seismic signals were observed.

Theoretical Explanations

These results have stimulated seismologists in other countries to look for similar precursors and to try to explain the Soviet results theoretically. U.S. seismologists, although relative late-comers to work on earthquake prediction, have now reported similar anomalies in V_p/V_s and have been first to suggest what mechanical processes might give rise to the phenomenon. An advantage in developing explanatory models has been the familiarity of the U.S. workers with extensive experimental studies of how rocks fracture; these studies were carried out at several laboratories in this country in the mid-1960's. W. F. Brace of the Massachusetts Institute of Technology and others showed that definite changes take place in the properties of rocks stressed almost to the point of rupture. In particular, microcracks and voids appear and the rocks increase in volume, a phenomenon known as dilatancy. Another factor was the chance discovery at the Denver Arsenal and later in a controlled experiment near Rangely, Colorado, that earthquakes could be triggered by injecting water into wells along a fault. The higher fluid pressures caused by injection are thought to have reduced the effective friction along the fault.

Dilatancy is well known in the laboratory, but direct evidence for its occurrence in the ground is inconclusive. That dilatancy is the mechanism responsible for the precursor seismic signals, however, is the hypothesis proposed in differing forms by Amos Nur of Stanford, Chris Scholz of Lamont Geological Observatory, and James Whitcomb of the California Institute of Technology. In essence the model suggests that when rocks along a fault are stressed almost to their breaking point (by relative motions between two crustal plates), the rocks dilate and underground cracks open up. Then, as groundwater flows in from surrounding regions and fluid pressures in the rock increase, the shear strength of the rock gradually decreases to the point where failure (resulting in an earthquake) occurs.

Nur proposes that the cracks initially open in dry brittle rock, in which increasing volume is associated (in laboratory experiments) with decreasing V_p/V_s. As water diffuses into the dilated region, however, the V_p/V_s ratio gradually increases because V_p is higher in saturated rock than in unsaturated rock. Other investigators doubt the validity of assuming that the rocks are initially dry, although they agree that diffusion of water into the dilated region is the key process.

Whitcomb and his colleagues argue that the velocity anomaly can be more easily explained if dilatancy occurs in fluid-filled, porous rocks. In this case the increased volume reduces the pore pressure in the rocks as fluid is drained off into new cracks. Because of lower pore pressures, the rock is more resistant to fracture—in effect, dilatancy delays the impending earthquake until enough water can flow into the region to return pressures to their earlier values. During this period, the presence of cracks large enough that the rock is unsaturated with fluid will greatly reduce the bulk modulus of elasticity for the media, causing a sharp drop in V_p, but leaving V_s relatively unaffected. As more and more of the dilatant region becomes saturated, the V_p/V_s ratio will gradually increase.

Scholz and his colleagues also propose that dilatancy occurs in fluid-filled rock and causes the rock to become undersaturated, thus reducing V_p. Moreover, they suggest, dilatancy is the principal phenomenon behind a wide variety of precursor effects that may occur in many or perhaps all shallow earthquakes. Thus, for example, increases in the number of microearthquakes shortly before a large or intermediate quake may be a consequence of increasing pore pressure as fluid flows into the dilatant region. The increase in volume during dilatancy could produce upward vertical movements of the crust at the surface, the investigators calculate, of several centimeters—large enough to be detectable. The electrical conductivity of rock depends mainly on the amount of water it contains, so that the model predicts large increases in conductivity during dilatancy—an effect already found in the laboratory. Finally the rate of flow of water in the rocks of the dilatant zone will be increased, leading to more active transport and release of short-lived isotopes such as radon.

The dilatancy model appears to agree in many respects with the published data from the U.S.S.R. and Japan. More recently, Y. P. Aggarwal and his colleagues at Lamont monitored a swarm of small earthquakes that occurred in 1971 in the Blue Mountain Lake region of New York. They found evidence that, even for quakes as small as magnitude 1 to 3 on the Richter scale, the V_p/V_s ratio first decreased, then gradually increased prior to the quakes. The pattern and the size of the V_p/V_s anomalies are similar to those observed by Soviet seismologists in the Garm region for quakes of magnitude 3 to 5.

Evidence that the same phenomena occurs with larger (and potentially hazardous) quakes was obtained from seismic records of the 1971 San Fernando, California, event (magnitude 6.4) by Whitcomb. Two seismic stations maintained by the Caltech group were fortuitously positioned near the quake region, and a search of their records showed an apparent decrease in V_p/V_s about 3½ years prior to the quake, followed by a gradual increase. The records also showed that changes in V_p alone accounted for most of the anomaly, in agreement with the dilatancy model. The size of the decrease does not appear to be related to the magnitude of the subsequent quake, which is consistent with the explanation that the observed seismic velocities depend on whether or not the rock is saturated with water rather than on the volume of the dilatant region (or on the magnitude of the quake).

The time interval between the onset of the seismic anomaly and the quake, however, increases with increasing magnitude. Indeed, the relation (Fig. 1) between the length of the fault (L) (a measure of the quake magnitude) and the precursor time interval (t) is strikingly constant over a large range with t approximately proportional to L^2, a characteristic relation for phenomena involving diffusion processes. Thus the data are consistent with the explanation that the duration of the anomaly depends on the length of time it takes water to diffuse into the dilatant volume from neighboring regions. The relation between size of the quake and the length of the warning period also appears to hold for precursors other than seismic anomalies (Fig. 2). If the formula can be extrapolated to still larger events, then precursor signals might occur as much as 25 to 40 years in advance of a quake of magnitude 8.

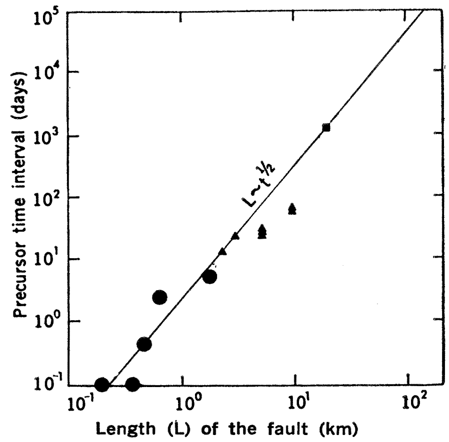

Fig. 1. Precursor time interval for the anomalous seismic velocity ratio as a function of earthquake dimension. Data shown are from San Fernando, California (square), Tadzhik, U.S.S.R. (triangles), and Blue Mountain Lake, New York (circles). [Source: California Institute of Technology]

However attractive, the dilatancy model is based on limited data, and many earth scientists are not yet willing to credit dilatancy as the primary cause of earthquake precursors. The V_p/V_s anomaly has only been observed on thrust faults (where one crustal block is pushing under another), and has not yet been observed along strike-slip faults such as the San Andreas in California. In seismic data, moreover, the arrival of the shear wave (from which V_s is computed) is often ambiguous—leaving ample room for error. The most serious objection to the dilatancy models, however, is that they require physical changes to take place throughout a huge region—spanning 100 km for the San Fernando earthquake. No direct evidence of dilatancy on such a large scale has been reported, and many geophysicists are skeptical. In the words of one observer, dilatancy remains a "provocative hypothesis," and other explanations for the precursory phenomena are being sought.

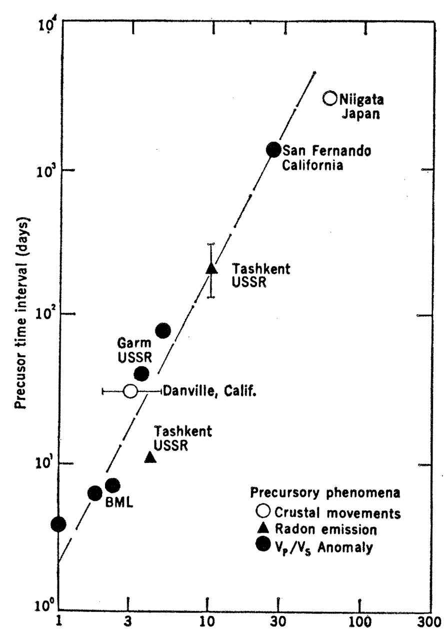

Fig. 2. Precursor time interval for several different phenomena as a function of earthquake dimension. [Source: Lamont Geological Observatory]

Practical prediction of earthquakes is in any case not likely to be possible overnight. Very few faults in this country are instrumented well enough to be able to detect precursor signals at all, let alone provide the intensive monitoring needed to confirm the dilatancy model. More refinements will be necessary to reduce the uncertainty with which the dilatancy model could predict quakes—an uncertainty that for a major earthquake is measured in years. Nonetheless, predictions that are deterministic rather than statistical may well be possible. The proposed link between fluid pressures and the initiation of earthquakes also raises the possibility that the timing and perhaps the magnitude of these destructive events might eventually be controlled by means of a network of deep wells. The problems of practical prediction and attempts to instrument one portion of the San Andreas fault in California will be reported in a second article.

The United States and the U.S.S.R. have begun formal collaboration on earthquake prediction work as part of the Moscow agreement reached last year. Soviet scientists headed by M. A. Sadovsky toured U.S. laboratories earlier this month, and an exchange of scientists between the two countries is expected next year, all of which may further increase the rapid rate of progress in earthquake prediction. But in a sense collaboration had already begun with the development of the dilatancy model by U.S. investigators to explain Soviet data, a development that may bode well for disaster-prone areas of the world.—Allen L. Hammond

Additional Reading

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4. C. H. Scholz, L. R. Sykes, Y. P. Aggarwal, in preparation.