Progress in Seismic Recording and Analysis

London. At a meeting of the Royal Society held in London on 28 and 29 January, seismologists from many parts of the world described technical progress in their field which a sponsor of the meeting said had "resulted in a complete transformation of seismology." There was no participant from the Soviet Union.

Much of the progress derives from efforts over the past 6 years to improve techniques for detecting underground nuclear explosions. Although a great deal of this research, apparently including significant aspects, is still covered by security, developers of new seismic equipment were eager to have the new techniques put to work on classical problems of seismology. Hence, participants felt, there was an unusually comprehensive review of seismology at the meeting.

The meeting aroused unusual interest because of the forthcoming resumption of negotiations directed toward extending the 1963 nuclear test-ban treaty to cover underground testing. And it was interesting for another reason: it signified that seismologists, previously divided into groups either covered or not covered by security regulations, are somewhat more free to talk openly. Observers in the United States point out, however, that dissatisfaction with security curtains was not a prime reason for the meeting, and that the majority of seismologists do not seem to be dissatisfied with the flow of information between scientists working on nuclear detection and those not involved.

Sponsorship of the meeting was shared by Sir William Penney, chairman of the United Kingdom Atomic Energy Authority, and Sir Edward Bullard, professor of geophysics at the University of Cambridge. Representatives of academic and governmental research groups of the United States and the United Kingdom played a leading part in the proceedings.

The background events are complex. Since 1958, seismologists, benefiting from advances in instrumentation and data-processing in all branches of physics and from their own studies, have enormously increased the sensitivity of their instruments for studying elastic waves sent through the earth by earthquakes and explosions. These recent advances are expected to add much to the seismologist's fundamental knowledge of the earth's interior. But more than an interest in basic research was behind the drive to improve seismic instrumentation. There was also a need to provide more warning of the approach of tsunamis (ocean waves produced by earthquakes) and to find reliable ways of detecting underground explosions. Here the urgency was political. In 1963 the United States, in discussing a test-ban treaty, was insisting on a minimum of seven international inspections of suspected test sites a year, while the Soviet Union would accept only three. In 1964, confidence in the increasing sensitivity of seismic instrumentation had risen to the point where the U.S. government was reportedly modifying its insistence on seven inspections a year.

British and American experiments with large arrays of seismographs had shown that some characteristics of a seismic event can be measured at sites between 3000 and 9000 kilometers (30 and 90 degrees) from the central point more accurately than at closer sites. Signals received between 3000 and 9000 kilometers from the central point apparently pass chiefly through the seemingly homogeneous mantle, rather than through the variegated structures closer to the surface which must be traversed by the waves received at less than 3000 kilometers. It is important to understand that these results by no means indicate that all characteristics of seismic events can be measured better at long range than at short range. Some features emerge more clearly at short distances from the events.

At the London meeting Bullard noted that recent experiments have emphasized the difficulties arising from local variations in structure. Signals from the Gnome explosion of 10 December 1961 in a salt dome near Carlsbad, New Mexico, indicated that the area around the Nevada test site provides peculiarly poor local transmission of seismic signals. Signals from the explosion, on 22 October 1964, of a 5-kiloton device nearly 1 kilometer below ground in the Tatum Salt Dome near Baxterville, Mississippi, showed that transmission eastward was better than transmission in the vicinity of the Nevada test site.

Bullard noted that the British and Americans have increased the accuracy of their detection systems by a factor of 10 by the simple but expensive expedient of moving their arrays of seismographs to quiet sites in the heart of continents, away from the random earth tremors associated with large towns and the sea, near which many of the classical networks of seismometers are located. Another participant at the meeting noted that this factor of improvement may have been achieved by the British, but that Americans had operated seismographs well away from noisy areas before 1958. Now, Bullard continued, seismologists are concerned with what they have come to call "signal-generated noise," produced by scattering along the propagation path and by local noise at the source and at the receiving instruments. Such noise shows up even when the received signals have passed through the mantle. An attack on this problem is being made by means of sophisticated filtering.

Bullard's comment on the improvement of signal-to-noise ratios drew strong disagreement from Frank Press, head of the Seismological Laboratory of the California Institute of Technology. One of Press's colleagues,

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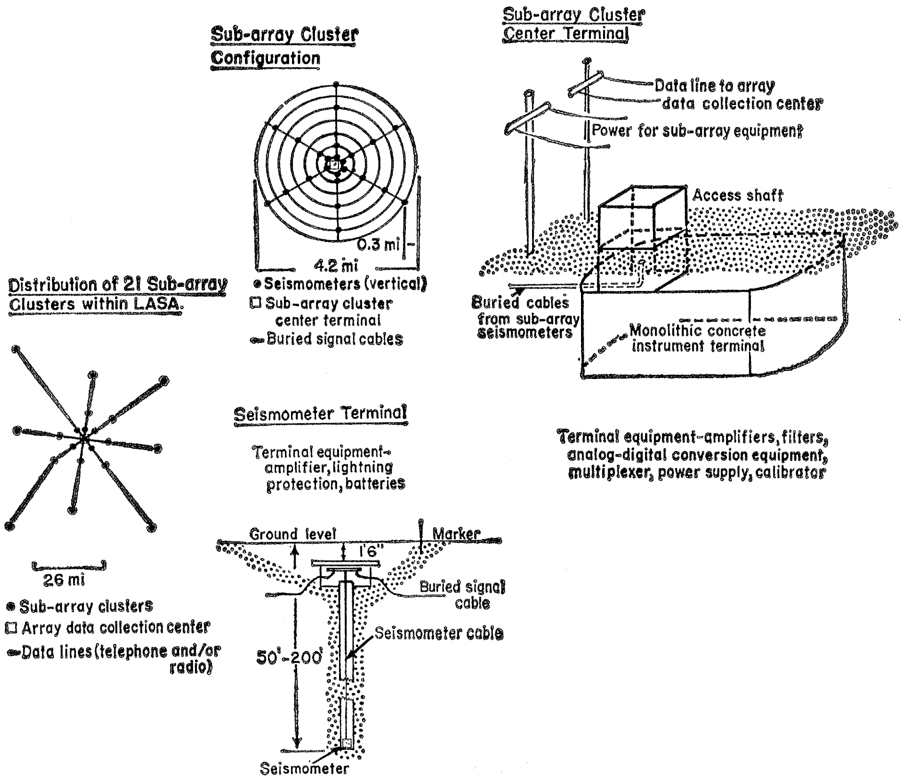

Plan of large aperture seismic array being set up by ARPA.

Stewart Smith, spoke at the meeting. Press stated after the meeting that Bullard's comment was "simply not correct." He did not elaborate. Another participant, objecting to the statement about the increased accuracy that was obtained by placing instruments in quiet locations, said that increase by a factor of 50 was nearer the mark.

According to British researchers, techniques of adding the signals from the individual instruments in an array (with appropriate time delays) have resulted in better discrimination between waves of different velocities and seem to show rather sharp distinctions between the wave patterns from bomb explosions and from earthquakes. Data from several British arrays widely separated on the earth's surface have indicated that wave outputs from explosions are generally symmetrical; those from earthquakes are less symmetrical.

Success with U.S. arrays in Tennessee, Oklahoma, Arizona, Utah, and Oregon and with British arrays in Wyoming, the Canadian Northwest, and Scotland has encouraged the Advanced Research Projects Agency (ARPA) of the U.S. Department of Defense to start building a $10-million array near Miles City, Montana. There will be 21 clusters of instruments, each with 25 seismometers, arranged in a squares-within-squares pattern inside a circle of 200-kilometer diameter.

The seismometer sensors will be placed in holes 200 feet deep, an ARPA representative reported at the meeting. Two clusters of instruments have been completed, and construction of the other clusters has begun. A field test, in which data from all instruments in one array will be telemetered to the data-handling center, is scheduled for June.

The increases in sensitivity already achieved and the prospect of further increases have led seismologists to conceive of a system of 20 to 30 large arrays distributed over the earth's surface to monitor earthquakes and explosions. All the arrays could be outside the Soviet Union. Presumably the system would be calibrated by test explosions.

Many of the developments discussed at the Royal Society meeting had already reached the public in outline. At the Massachusetts Institute of Technology last fall, Press mentioned the progress made with "velocity filtering" in large arrays. In the spring of 1963, H. I. S. Thirlaway, leader of the seismology group of the United Kingdom Atomic Energy Authority, reported on the distinctive characteristics of the first compressional waves, or P waves, arriving from underground nuclear explosions (*New Scientist*, 9 May 1963). E. W. Carpenter of the same British group has just reviewed the limitations and capabilities of the systems developed so far (*Science*, 22 Jan.).

Some seismologists, however, have been dissatisfied with the way in which information about new developments has been disclosed to the scientific world. For a number of years some American and British seismologists worked behind a security curtain while others remained outside. Even after security regulations had been relaxed, important communications were made in the form of special pamphlets, newsletters, and duplicated reports. Those concerned with university teaching in seismology have often found that such procedures make it difficult to ensure that important innovations are included in the development of student course work and research.

Obviously, some features of a proposed seismological monitoring system were not made public at the Royal Society meeting; they will be discussed in the revised technical brief which scientists are preparing for presentation at the renewed Geneva talks, to be held within the next few months. The wide range of papers at the London meeting covered not only short-period, early-arriving waves, of most interest to the detector of nuclear explosions, but also long-period waves. G. Jobert of the Institut de Physique du Globe (Paris) described a type of ultralong-period seismometer which has been used for calculating the spectra of the free vibrations of the earth.

On behalf of workers at the California Institute of Technology Seismological Laboratory, Stewart W. Smith reported that a new three-component pendulum system, together with previously existing strain seismographs, has been measuring waves with a period longer than 1 minute. The new pendulum system and a broad-band digital seismograph have been used to study phase velocities, seismic attenuation, and source characteristics of large earthquakes. One of the earthquakes studied was that at Niigata, Japan, in 1964. Data from studies of long-period waves, Smith said, are requiring the group at the California Institute of Technology to postulate discontinuities in the upper mantle that were not indicated by the short-period waves. This statement stirred debate. C. L. Pekeris of the Weizmann Institute asserted that seismologists must seek to postulate as few discontinuities as possible, not invoke new ones to fit travel-time data. Bullard commented that it was hard to account for the observed constant velocity of certain P waves out to distances 14 to 16 degrees from an event unless there were some kind of decreased-velocity layer below the Mohorovičić discontinuity.

G. H. Sutton of Columbia University's Lamont Geological Laboratory reported success in installing and operating long-period seismographs on the ocean bottom near Bermuda. The Bermuda installation is the forerunner of a larger instrument off California which will be connected to the shore by cables.

P. L. Willmore described seismometers he and his colleagues at the International Seismological Center in Edinburgh have designed, and D. M. McGregor discussed the center's proposed system of collecting and processing data relevant to epicenter determinations. The collection begins with January 1964, and data have already been received from 126 stations, McGregor said.

There were papers on seismic noise. B. J. Hinde of the National Institute of Oceanography in Wormley, Surrey, described a pair of three-component stations which respond to microseismic ground displacements. J. A. Hudson of Jesus College, Cambridge, described the theoretical studies he and L. Knopoff have been making on the scattering of waves in various postulated media. R. A. Haubrich of the University of California's Institute of Geophysics and Planetary Physics discussed sources of noise at frequencies of 5 to 500 millicycles per second.

J. M. de Noyer of the University of Michigan's Institute of Science and Technology reported that proper arrays will result in improvement of the signal-to-noise ratio for shear waves (S waves) from relatively near, small earthquakes that is similar in degree to the improvement reported for P waves. De Noyer and his colleagues have been using arrays of three-component seismometers to work out an additional method of identifying small seismic events.

N. A. Anstey of Seismograph Service Ltd. (Holwood, Kent) described two analog correlators of the integration-over-distance type (as opposed to the integration-over-time type). These instruments can provide correlation between wave forms in real time, when that is desired.

Several speakers discussed arrays and the handling of their data.

R. E. Long of the University of Durham described the design principles of a digital "delay computer" for handling seismic data from experiments conducted by the university's department of geology. The computer is designed to handle computations of the "velocity filtering" type.

Milo M. Backus of the Texas Instruments Company discussed ways of using small surface arrays, vertical arrays, large-aperture surface arrays, and signal processing to reduce signal-generated noise.

F. E. Whiteway described the advantages and disadvantages of the arrays of the United Kingdom Atomic Energy Authority (UKAEA), as developed in Eskdalemuir, Scotland; Pole Mountain, Wyoming; and Yellowknife, Northern Territories, Canada. He was summarizing from a much longer paper written with J. W. Birtill of the UKAEA seismology group. The United Kingdom program began with tests of a small array on Salisbury plain in February 1961. The station at Pole Mountain was opened to gather data from the Gnome shot; the array was considerably altered in an effort to reduce the great variation in noise levels from instrument to instrument, but the variation was not reduced greatly and the array was dismantled in September 1963. Construction of the installation at Eskdalemuir was begun in June 1962, and of that at Yellowknife, in December 1962. The full Yellowknife array, with its two 22.5-kilometer chains of seismometers, was completed in December 1963.

R. A. Frosch of ARPA and P. E. Green, Jr., of M.I.T.'s Lincoln Laboratory described the concept of the Large Aperture Seismic Array near Miles City, Montana. Data from this array will be processed in Billings, Montana, and then reduced at the Lincoln Laboratory, near Boston. It is hoped, Frosch said, that this array will be able to detect individual events down to magnitudes of about 3.0 to 3.3 on the Richter scale. The design of the array was based on the performance of the five circular arrays built under the U.S. Vela-Uniform program and of the British cross-arrays.

Speakers who described results from various arrays were P. N. S. O'Brien of British Petroleum, who worked with a chain of sensors in the Italian Alps, reading signals from lake-bottom explosions; S. J. Duda of the Seismological Institute in Uppsala, Sweden, who described regional seismicities indicated by data from one of the Vela-Uniform arrays, at Tonto Forest near Payson, Arizona; Thirlaway and Carpenter of the Atomic Energy Authority; F. Holzer of the University of California's Lawrence Radiation Laboratory; and Bruce Bolt of the University of California.

Bolt described the central-California net of ten telemetered stations (built with Vela-Uniform money), which began operating 1 January 1962. Byerly and Tocher of the University of California had decided in 1960 to use local seismicity data to study the characteristics of earthquake aftershocks, especially those of small magnitude, and to gain more insight into the mechanism operating at the earthquake source. The array has been used to study local shocks, Nevada test explosions and earthquakes, and such events as the Soviet nuclear explosion of 14 January near Semipalatinsk. In observing central California shocks, the station network appears to have missed no shocks of magnitude greater than 1. Examination of two main earthquakes in August and September 1963, and of 40 associated shocks, showed an average focal depth of about 6.3 kilometers.

Earlier observers had reported a concentration of earthquake focal depths at about 15 kilometers. The polarity of P waves from the shocks "supports the hypothesis of release of strain along constant directions," Bolt said (see H. Benioff, *Science*, 27 Mar. 1964). Observations of a main earthquake of magnitude 5.1 on 16 November 1964 and of 40 aftershocks over 26 days showed an "extraordinary" closeness of location, Bolt reported. "Ninety percent of the epicenters lie within a circle of radius 2 kilometers; the depths lie between 6 and 10 km. We must speculate therefore on possible rock deformations which will release energy in discrete quanta for 26 days from a volume of linear dimensions of order 2 kms."—VICTOR K. MCELHENY