19 December 1969, Volume 166, Number 3912 SCIENCE

Earthquake Prediction and Control

Scientists look beyond prediction to controlled release of stored strain energy in active fault zones.

L. C. Pakiser, J. P. Eaton, J. H. Healy, C. B. Raleigh

The great Alaska earthquake (Richter magnitude, 8.4 to 8.6) of 27 March 1964 awakened earth scientists and public officials to the need for intensified research on earthquakes, their effects on man and his works, and possible means of reducing their hazards. Although the loss of life in Alaska (115) and property damage ($300 million) were small for such a great earthquake, the realization that an earthquake of similar magnitude could occur in densely populated coastal California, where loss of life would almost certainly be in the thousands and property damage in the billions of dollars, dramatized the urgent need for remedial action.

Following the 1964 Alaska earthquake, an Ad Hoc Panel on Earthquake Prediction was organized by Frank Press of the Massachusetts Institute of Technology at the request of the President's Science Advisor, Donald Hornig, to study the opportunities for research on earthquake prediction. The report of the panel (*1*) was completed in September 1965 and released by Hornig in October. The 10-year program recommended by the panel calls for a new generation of instruments for monitoring earthquake faults in California and Alaska, extensive geological and geophysical surveys of fault zones, laboratory and theoretical studies of mechanisms of rock failure, research in prediction theory, and strongly augmented research in earthquake engineering. The panel estimated the cost of the program at $137 million.

Although the Press Panel report has not been adopted as a national program, many of its recommendations are being carried out on a modest scale by government agencies and universities. The Ad Hoc Interagency Working Group for Earthquake Research (*2*) reported that six federal government agencies spent $7.4 million on earthquake research in fiscal year 1967. Both the Environmental Science Services Administration and the U.S. Geological Survey have established new earthquake-research laboratories in California. The research programs they have established are guided to a significant degree by the recommendations of the Press Panel, but they fall far short of providing the information needed for safe development of coastal California and other U.S. areas subject to earthquakes. The magnitude of the problem can be seen from the Urban Land Institute's estimate (*2*) that, by the year 2000, the population of California will have increased from one-tenth to one-seventh of the national total, or to about 40 million in a national population of 300 million.

In 1962, the Earthquake Prediction Research Group in Japan outlined a plan for research on the prediction of earthquakes (*3*). In 1965, following the destructive Niigata earthquake of 1964, the Japanese government sponsored and provided financial support for a 5-year plan for research on earthquake prediction (*4*). The program is now well advanced (*5*).

Earthquakes are a cause of common concern to Japan and the United States. The National Science Foundation and the Japan Society for Promotion of Science have jointly sponsored three conferences on research related to earthquake prediction (*6*). The most recent of these, held at the U.S. Geological Survey's National Center for Earthquake Research, in October and November 1968, reviewed the latest progress in Japan and the United States on studies of premonitory phenomena associated with earthquakes, and related problems (*7*).

The discovery (*8, 9*) that injection of waste fluids in a well drilled into the Precambrian rocks beneath the Rocky Mountain Arsenal near Denver, Colorado, had triggered a series of earthquakes, and evidence that earthquakes are triggered by the impounding of water in reservoirs (*10, 11*) and by large underground nuclear explosions (*12, 12a*), have raised the possibility that earthquake hazards can be reduced by the controlled release of stored strain energy in active fault zones.

Earthquakes in California

There has been no major breakthrough in earthquake prediction since the reviews by Press (*13*) and Rikitake (*5*), but steady progress has been made toward understanding the nature of earthquakes along the continental margins, including coastal California. An enormous amount of evidence has been marshaled in support of Hess's concept of sea-floor spreading, Wilson's transform faults, and the later ideas of Vine, Le Pichon, Isacks, Oliv-

The authors are affiliated with the U.S. Geological Survey's National Center for Earthquake Research in Menlo Park, California.

er, Sykes, and others, on the motions of large, rigid plates of the lithosphere that plunge downward under the island arcs and continental margins to form the major earthquake belts of the globe (*14, 15*). These revolutionary new concepts provide a global tectonic framework in which we can envision, for the first time, the kinematic processes that operate to generate earthquakes at depths ranging from the shallow crust to 700 kilometers.

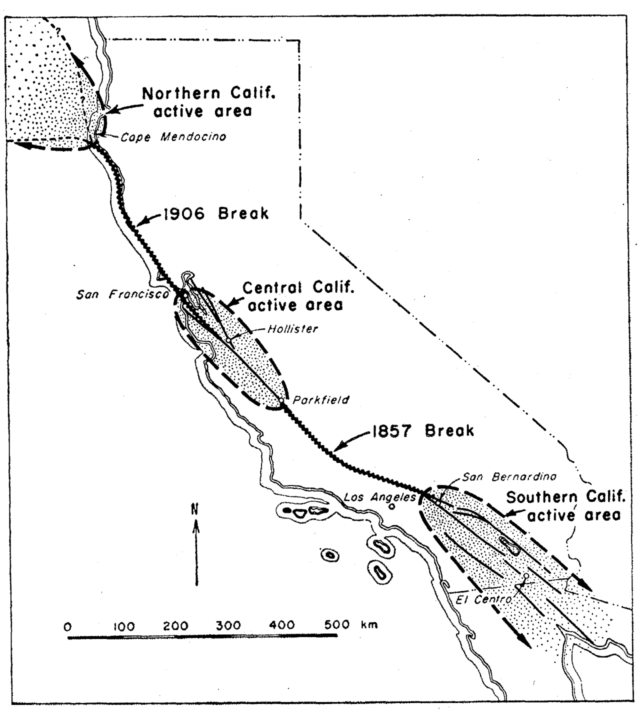
In this framework, the San Andreas fault system of California is seen as a transform fault associated with spreading from the East Pacific Rise and with northwestward motion of a large, rigid plate of oceanic lithosphere toward the Aleutian Islands, where it descends into the earth's mantle at a rate of about 5 centimeters per year.

Allen and others have identified areas of contrasting seismic behavior along different segments of the San Andreas fault zone in California (*16*). The segments corresponding to the surface breaks of the great 1906 San Francisco and 1857 Fort Tejon earthquakes (Fig. 1) seem to be "locked" and characterized by infrequent but very severe earthquakes. At present, the seismic activity is extremely low in the locked zones, and no fault creep—the quiet, steady-to-episodic slippage along the fault—has been discovered in these segments. These segments are likely candidates for great earthquakes in the future, perhaps within the next few decades, because the crust there is capable of storing large amounts of strain energy which can be released suddenly and violently. The "active" areas between San Francisco and Parkfield, southeast of San Bernardino, and also probably northwest of Cape Mendocino seem to be characterized by fault creep, accompanied by frequent minor-to-severe (but not great) earthquakes; thus the accumulation of large amounts of stored strain energy is inhibited. In our judgment, the segment of the San Andreas fault on the San Francisco Peninsula northwest of Hollister should be considered locked, although the Hayward and Calaveras faults east of San Francisco Bay are active. The San Andreas may be locked over much of its length because of the pronounced curvature of the fault near the north end of the 1906 break at Cape Mendocino and near the center of the 1857 break (Fig. 1). If this pattern of contrasting seismic behavior is valid, it is clear that both Los Angeles and San Francisco are vulnerable to severe earthquake damage in the future.

The San Andreas fault zone also exhibits markedly differing patterns of seismic behavior when viewed in detail. Aftershocks of the June 1966 Parkfield-Cholame (*17*) earthquake lie along a narrow, near-vertical zone about 15 kilometers deep which nearly coincides at the surface with the mapped fault break (Fig. 2). Cumulative fault creep of about 20 centimeters has been measured in this segment since 1966.

On the other hand, most of the aftershocks of a moderate earthquake that occurred southeast of Hollister at Bear Valley in 1967 were tightly clustered in a more or less spherical zone 3 kilometers in diameter and centered, just west of the San Andreas fault, at a depth of 3 kilometers (Fig. 3). Bear Valley is near the inferred junction of the San Andreas and Calaveras faults. The center of the hypocentral zone at Bear Valley is within easy range of conventional drilling techniques and is thus available for direct observation and experimentation.

The results in the Parkfield-Cholame area and at Bear Valley were obtained from networks of portable seismographs. Seismic activity in California is also being continuously monitored by telemetered nets of short-period seismographs operated by the University of California at Berkeley, the California Institute of Technology, and the U.S. Geological Survey. In the vicinity of Hollister and Gilroy, micro-earth-



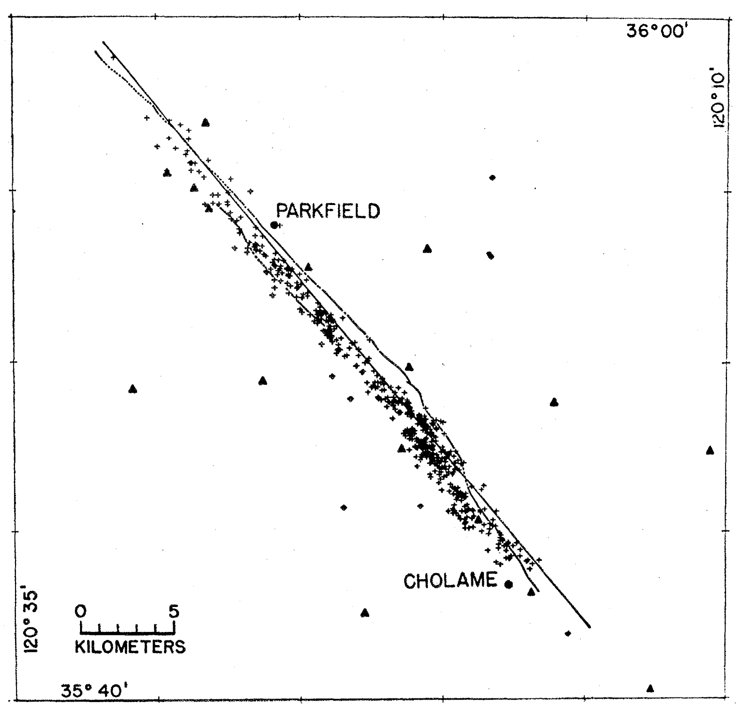


Fig. 1 (left). Areas of contrasting seismic behavior along the San Andreas fault zone in California. [From C. R. Allen (*16*), with permission] Fig. 2 (right). Aftershocks of the Parkfield-Cholame, California, earthquake of 27 June 1966. (Triangles) Seismographs of the U.S. Geological Survey and Environmental Science Services Administration portable networks; (crosses) aftershock epicenters. Zones of surface fracturing that accompanied the main shock (primarily) are shown by the heavy, interrupted curves. The surface outcrop of a reference plane fitted by least squares to the hypocenters is shown by the unbroken heavy line. The standard deviation of hypocenters from the reference plane (which dips 86 degrees southwestward) is 0.5 kilometer.

quakes recorded on the Geological Survey's telemetered net exhibit well-defined epicenter trends along, or near, the Sargent, San Andreas, and Calaveras faults (Fig. 4).

In this area, as elsewhere in California, focal depths of micro-earthquakes do not exceed 15 kilometers. Crustal thickness averages about 25 kilometers. Thus, brittle behavior of the rocks in the San Andreas fault system seems to be confined to the upper crust; this implies some form of smooth slippage or flow along the faults in the lower crust and upper mantle.

Fault movements along the San Andreas system are being monitored by several federal, state, and local governmental agencies, and by universities. The most extensive fault-movement studies are the Geodimeter measurements of the State of California Department of Water Resources (now being continued by the State Division of Mines and Geology). These studies reveal a fault-movement rate that averages about 4 centimeters per year. The movement between Hollister and Cholame seems to be primarily in the form of fault creep (*18*). North of Hollister, in the San Francisco Bay area, the movement is distributed primarily between the Calaveras and Hayward faults, and prominent creep has been noted at several places along the Hayward fault. No local fault movement was detected south of Cholame in the segment of the San Andreas fault that broke in 1857. These observations are compatible with the contrasting seismic behavior along different segments of the San Andreas fault zone.

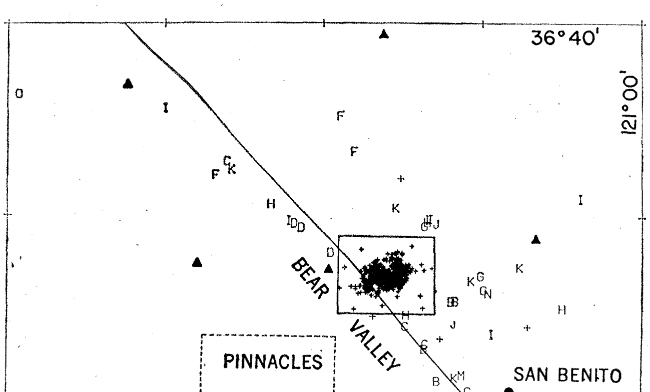
Significantly, the Department of Water Resources found that earthquakes are often preceded by changes, and even reversals, in the rates of movement of the faults along which they occur (*18*). Breiner and Kovach (*19*) have found evidence that fault-creep episodes are frequently preceded by local fluctuations in the earth's magnetic field (Fig. 5).

Laboratory Investigations

Laboratory investigations related to the mechanism of earthquakes and the physical properties of rocks in earthquake source regions have been intensified recently in several governmental and university research institutions. Some results relevant to the problem of earthquake prediction were recently reviewed by Brace (*20*). He particularly drew attention to the discovery by Raleigh and Paterson (*21*) that serpentine, under pressures at which it normally is ductile, becomes embrittled at high temperatures because of dehydration. Brittle fracture may, therefore, occur at depths extending into the upper mantle where hydrous phases in the mantle reach temperatures at which they dehydrate. This discovery seems to provide a mechanism for intermediate and perhaps deep-focus earthquakes as the rigid lithosphere descends into the mantle beneath island arcs and continental margins.

Byerlee and Brace (*22*) have shown that when two surfaces of granite or unaltered gabbro slide past one another under high confining pressure, the motion occurs through stick slip that is qualitatively similar to the shallow-focus earthquakes of the San Andreas fault system, but the confining pressures and stress drops are larger than those inferred for California (Fig. 6). On the other hand, motion for gabbro and dunite in which olivine has been altered to serpentine occurs by stable sliding (Fig. 7) similar to the behavior of the San Andreas fault system in the deep crust and upper mantle.

It is well known that seismic velocity, electrical resistivity, and magnetic susceptibility of rocks are strongly dependent on stress. Brace and Orange (*23*) have shown in particular that rocks under confining pressure undergo large decreases in resistivity as they become dilatant at stresses near that for fracture (Fig. 8). Resistivity decreased following an initial increase with stress for all rocks except marble



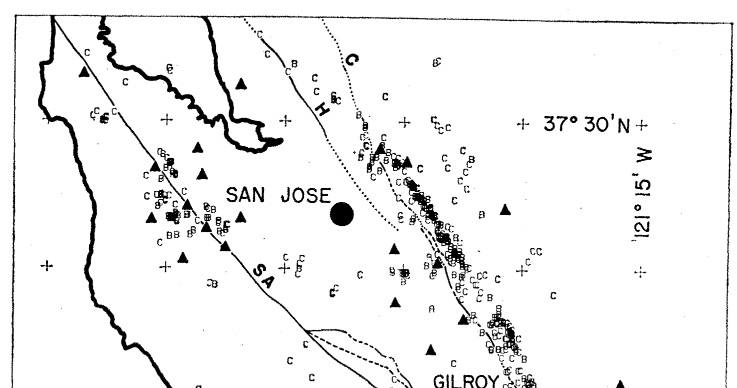


Fig. 3 (left). Micro-earthquakes along the actively creeping strand of the San Andreas fault (solid line) near Bear Valley during July and August 1967. (Triangles) Seismograph stations (the network extended outside the map area); (crosses inside the small rectangle) the Bear Valley earthquake of 22 July 1967 and its aftershocks. Most of these events occurred at depths of 2 to 4 kilometers. Other micro-earthquakes are represented by letters indicating depth of focus: A, 0 to 1 kilometer; B, 1 to 2 kilometers; C, 2 to 3 kilometers; and so on. Crosses outside the small rectangle indicate events with poorly determined focal depths. Fig. 4 (right). Micro-earthquakes along the San Andreas and related faults between San Francisco Bay and Hollister, March 1968 to April 1969. Seismographs are shown as solid triangles and epicenters by letters indicating the precision of location: A, excellent; B, good; C, fair. Events with poorly established epicenters are not shown. (SA) San Andreas fault; (S) Sargent fault; (H) Hayward fault; (C) Calaveras fault.

as new cracks formed in water-saturated rocks; the decrease was accompanied by a small increase in volume. This observation suggests the possibility of monitoring stress variations in fault zones by resistivity measurements obtained with surface or in-hole electrode arrays.

Man-Made Earthquakes

Man-made earthquakes have been known since Carder (*10*) documented the occurrence of about 600 local tremors during the 10 years following the formation of Lake Mead, in Arizona and Nevada, by Hoover Dam in 1935. Most of these tremors were micro-earthquakes, but one had a magnitude of about 5, and two had magnitudes of about 4. Carder concluded that the seismic activity was caused by the load of water in Lake Mead that reactivated faults in the area.

Carder's discovery remained of academic interest until Evans (*8*) dramatically demonstrated a correlation between the rate of injection of waste fluids and the frequency of earthquakes in the vicinity of the Rocky Mountain Arsenal well near Denver, Colorado, following the first injection of fluids in March 1962. The U.S. Geological Survey recorded the seismic activity in the vicinity of the Rocky Mountain Arsenal well, and Healy and his co-workers demonstrated (*9*) that the epicenters of the earthquakes occurred in a narrow, nearly linear zone about 8 kilometers long and trending northwestward (Fig. 9), with the well near the center of the zone. Focal depths of the earthquakes ranged from 4 to 6 kilometers, just below the bottom of the 3.8-kilometer-deep Arsenal well. Following termination of fluid injection in February 1966, the frequency of the earthquakes declined, as had been expected, but in late 1966 seismic activity began again, unexpectedly, and it continued through most of 1967. The largest earthquakes, of magnitudes up to 5.5, occurred during this period and caused minor damage. The seismic activity declined again in 1968 and has continued at a low level into 1969.

Seismic radiation patterns of the first motion on seismograms recorded at the Arsenal indicate right-lateral strike-slip movement along fractures oriented parallel to the trend of the seismic zone. This led Healy and his co-workers to conclude (*9*) that the earthquakes were triggered by reduction of frictional resistance to faulting with increasing pore pressure, a conclusion which was supported by an analysis, according to the theory of Hubbert and Rubey (*24*), of the conditions in the hypocentral zone of the earthquakes.

Stimulated by the occurrence of the earthquakes near Denver, a search for similar phenomena elsewhere led to the recognition that the Unita Basin Seismological Observatory, in Utah, had recorded a series of minor earthquakes with epicenters near the Rangely oil field in northwestern Colorado. The Rangely oil field is the site of a secondary-recovery operation involving the injection of water under pressure. To verify the location of the earthquakes, four portable seismographs were installed by the U.S. Geological Survey near the oil field in 1967 and operated for 10 days. A high level of seismic activity was recorded. At all four stations, about 20 micro-earthquakes were recorded strongly enough to be located (*25*). These earthquakes occurred near parts of the oil field where the fluid-injection operation has produced the largest recent increases in fluid pressures (Fig. 10).

Recently Rothé (*11*) reviewed the association of earthquakes with the filling of reservoirs. Several examples were found, the most significant being the Koyna, India, earthquake of 10

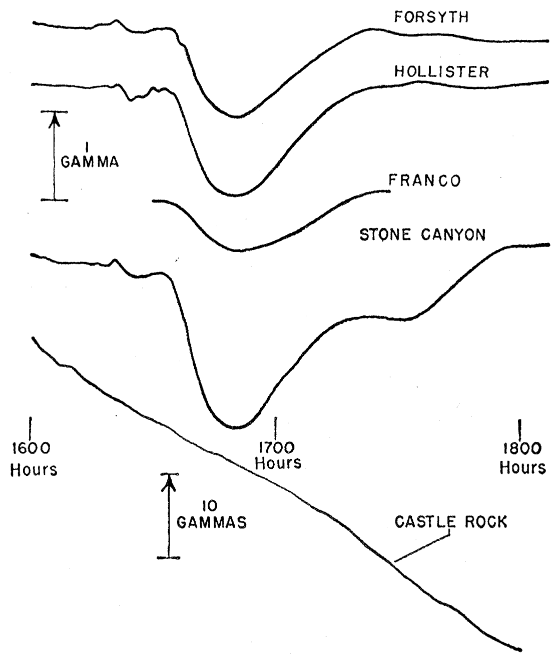
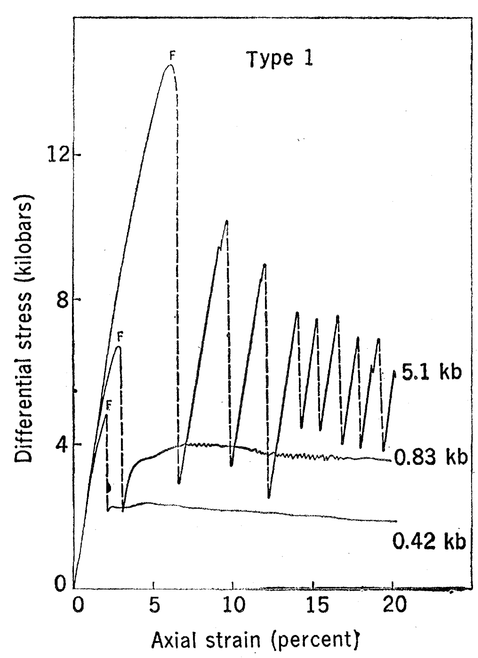
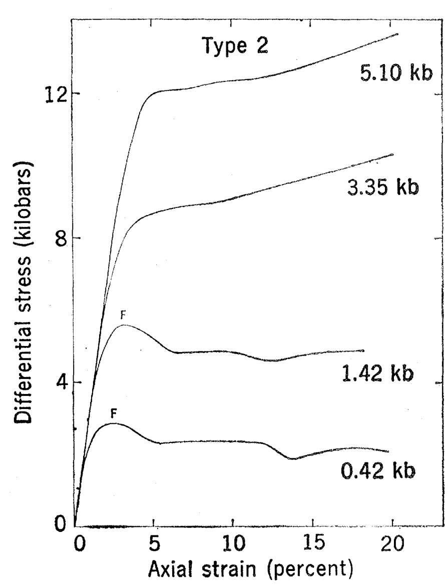


Fig. 5 (left). Local magnetic event in the vicinity of Hollister, California, as it appeared on four magnetometers on 18 April 1967. Creep displacement of 4 millimeters followed 16 hours later (times are given in Greenwich Mean Time.) [From S. Breiner and R. L. Kovach (*19*), with permission]

Fig. 6 (below left). Differential stress plotted against axial strain for San Marcos gabbro. The value at the end of each curve gives the confining pressure. [From J. D. Byerlee and W. F. Brace (*22*), with permission]

Fig. 7 (below right). Differential stress plotted against axial strain for Spruce Pine dunite. The value at the end of each curve gives the confining pressure. [From J. D. Byerlee and W. F. Brace (*22*), with permission]





December 1967, which had a magnitude of about 6½ and resulted in the deaths of about 200 people and in widespread destruction. The epicenter was estimated to have been within 10 kilometers of the Koyna dam, about 150 kilometers southeast of Bombay, which created a reservoir of 2 billion cubic meters in 1962 and 1963. Minor tremors had been previously recorded in the Koyna reservoir area, beginning in 1963. These events led Indian scientists to convene a special meeting in New Delhi on 19 December 1967 to consider the Koyna earthquake and its implications; the proceedings were published in a special number of the *Journal of the Indian Geophysical Union* (*26*). Lee and Raleigh (*27*) made a fault-plane solution of the 10 December earthquake; their solution indicates that the mechanism was strike-slip faulting. From this study they concluded that tectonic strain stored in the rocks of the Koyna region was the source of the energy that released the earthquake.

Rothé (*11*) and Gough and Gough (*28*) have called attention to the earthquakes at Lake Kariba in the Kariba Gorge of the Zambezi River, Zambia. Thousands of earthquakes were recorded on a seismograph net installed after the lake was impounded by a hydroelectric dam in 1958. Gough and Gough concluded that normal faults in the area were reactivated by the reservoir load, by fault lubrication, or by both (*28*). The largest of the earthquakes had a magnitude of 5.8.

Ryall and his co-workers (*29*) have noted numerous instances in which earthquakes were triggered by underground nuclear explosions at the Atomic Energy Commission's Nevada Test Site. In particular, they studied the Boxcar explosion of April 1968 and demonstrated that the blast triggered thousands of aftershocks in a northeast-trending zone 12 kilometers long and 4 kilometers wide.

Prior to the Benham underground nuclear explosion (yield, 1.1 megatons) of 19 December 1968, the U.S. Geological Survey installed a network of 27 seismographs in the vicinity of the Nevada Test Site (*12*). Aftershocks of the explosion recorded by the network occurred as far as 13 kilometers from ground zero. Focal depths computed for the shocks ranged from the surface to a depth of about 7 kilometers. The magnitudes of the thousands of aftershocks recorded were generally small and did not exceed 5.0, as compared to the Benham magnitude of 6.3. The epicenters of the shocks migrated with time. Most were within 7 kilometers of ground zero during the first week following the explosion. After about 3 weeks the fracture zone was extended about 3 to 4 kilometers southward, and there was an accompanying increase in seismic activity. The aftershocks occurred west of ground zero, however, rather than along the zone of prominent surface fracturing to the east that developed after the Benham explosion and several earlier explosions. Analysis of the first motions of seismograms recorded from the Benham aftershocks suggest that they were triggered primarily by release of natural tectonic stress (Fig. 11).

It is becoming increasingly evident that man can inadvertently trigger earthquakes by building dams, inject-

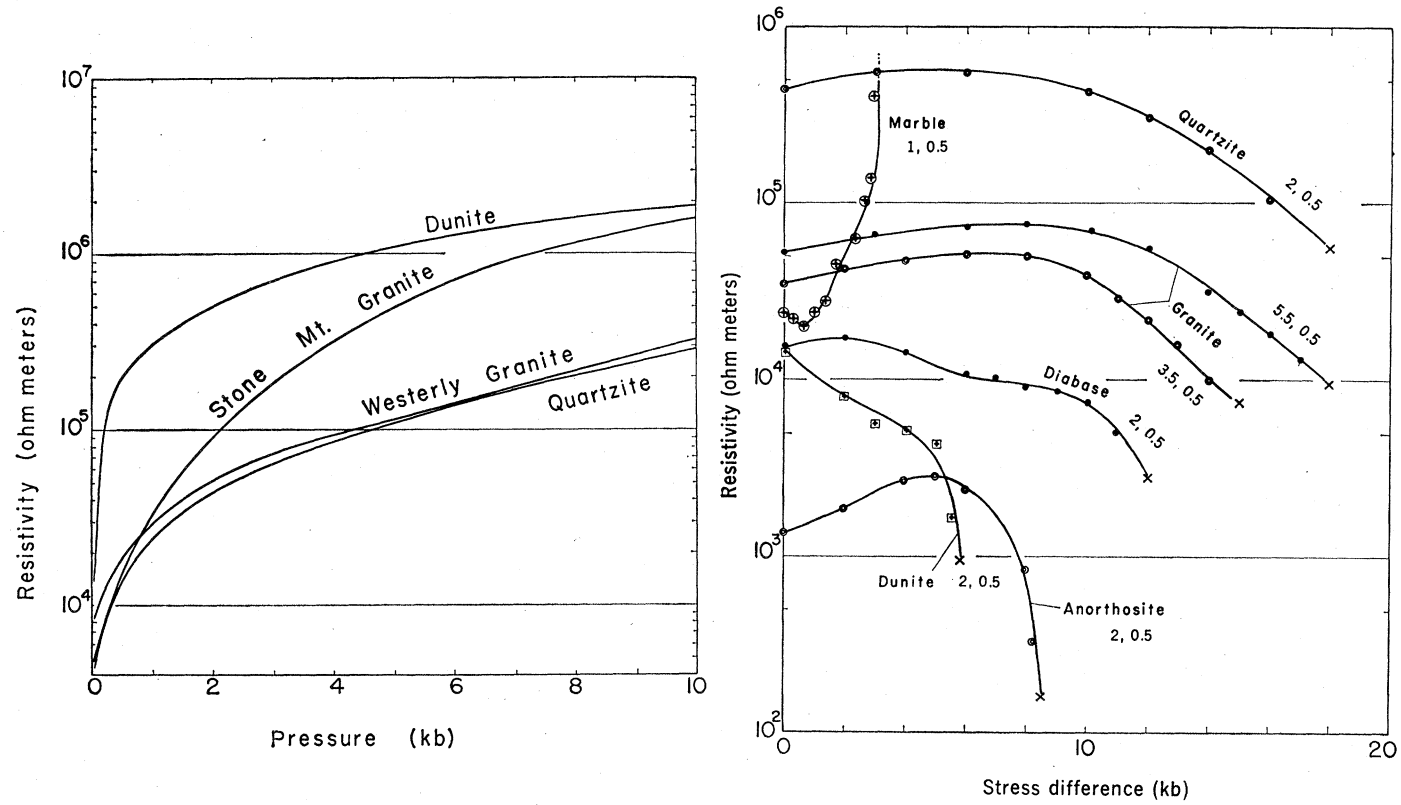
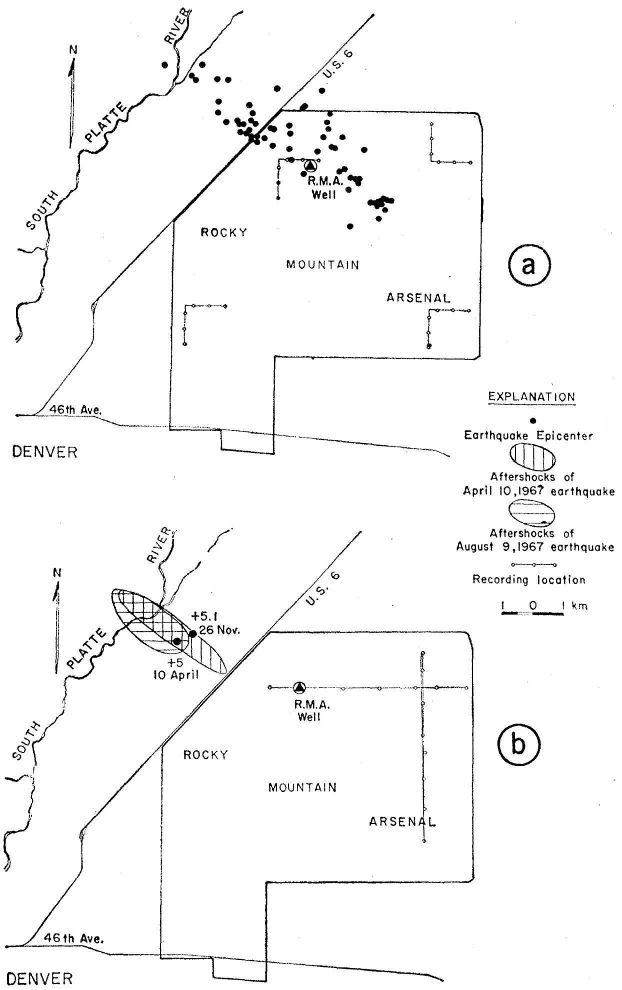
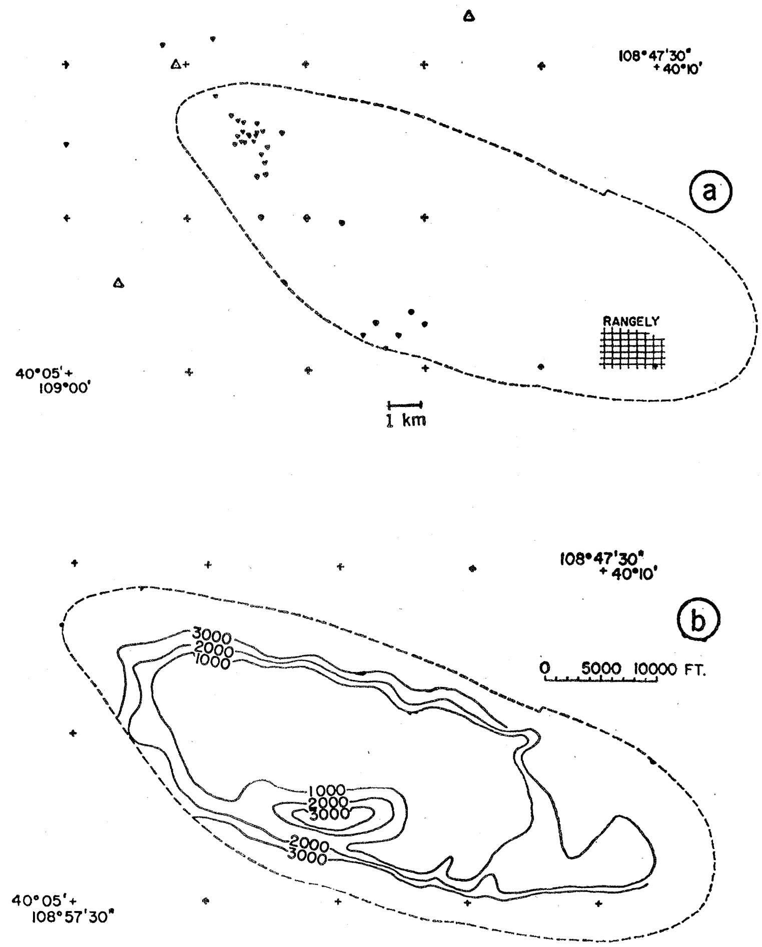


Fig. 8. Effects of hydrostatic pressure (left) and stress (right) on electrical resistivity of rocks saturated with tap water. The numbers after the names of the rocks subjected to stress give, respectively, the total pressure and the pore pressure, in kilobars. Fracture occurred at point X, except in the case of the marble, which did not fracture and for which the resistivity increased with stress, instead of decreasing as that of the other specimens did. To obtain the actual resistivity from the values indicated in the graph, certain corrections must be made: for quartz, the indicated value must be multiplied by 0.01; for granite (3.5 kilobars), by 0.5; for diabase, by 10; for dunite, by 10; and for anorthosite, by 100. These corrections are necessary because the curves have been shifted vertically to separate them for greater clarity. The temperature of the stressed rocks was 50°C. [From W. F. Brace and A. S. Orange (*23*), with permission]

ing fluids into the rocks of the earth's crust, and exploding nuclear devices underground. Earthquakes triggered by reservoirs and fluid injection have been destructive, some (as at Koyna) severely so, but, so far, seismic activity associated with explosions has occurred in the immediate vicinity of ground zero and has been less severe than the direct seismic effects of the explosions. It thus seems necessary for engineers of dams, and of fluid-injection projects in particular, to give heed to the possibility that their works may trigger destructive and even death-dealing earthquakes. These discoveries also suggest the possibility of using fluid injection and perhaps explosions beneficially to control the release of stored tectonic stress and thus reduce earthquake hazards.





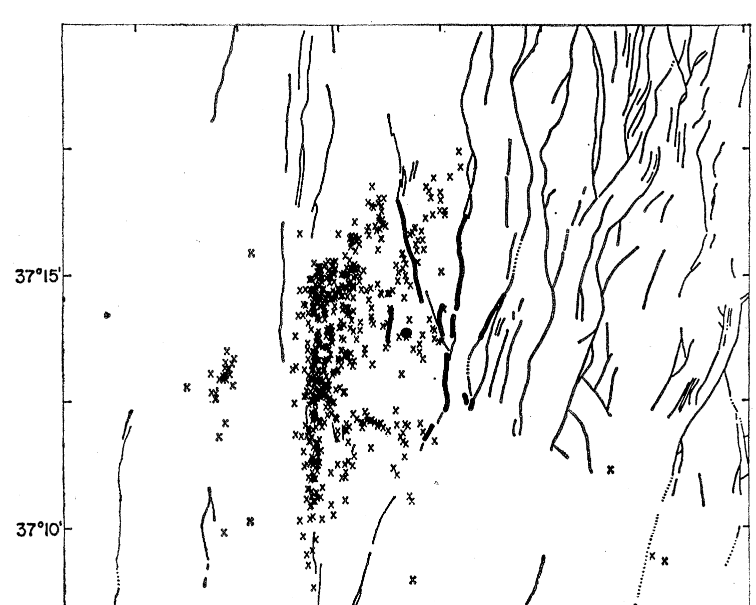


Fig. 9 (above left). (a) Epicenters of earthquakes located in the vicinity of the Rocky Mountain Arsenal (R.M.A.) well near Denver, Colorado, in January and February 1966 by means of a dense network of temporary seismograph stations. (b) Locations of the earthquakes of 10 April and 26 November 1967, and of their aftershocks. The magnitudes of these two earthquakes were estimated to be 5.0 and 5.1, respectively. [From J. H. Healy, W. W. Rubey, D. T. Griggs, and C. B. Raleigh (*9*), with permission]

Fig. 10 (above right). Micro-earthquakes at the Rangely oil field, in Colorado. (a) Epicenters of 32 micro-earthquakes located by means of four stations. (Small inverted triangles) Epicenters; (larger triangles) stations. (b) Fluid pressures in the oil-producing horizon, the Weber sand, September 1967. Injection wells are near the perimeter of the field. Bottom hole pressure contour interval, 1000 pounds per square inch. [Pressure contours published with permission of the Chevron Oil Company]

Fig. 11 (right). Aftershocks and ground fracturing caused by the 1.1-megaton Benham underground nuclear explosion in southern Nevada. (Solid circle) Location of the explosion; (crosses) epicenters; (lighter lines) surface trace mapped before Benham was detonated; (heavier lines) ground fracturing. [From R. M. Hamilton, F. A. McKeown, and J. H. Healy (*12a*), with permission]

Outlook for Prediction and Control

Since 1964, most earth scientists have concluded that earthquake prediction is a legitimate subject for research, but they differ widely in their estimates of the prospects for success. Several developments of the 1960's lead us to conclude that the prospects for success during the next 10 years are good.

In 1965, at Matsushiro in the Nagano prefecture of Japan, swarms of earthquakes began which were so intense that as many as 600 were felt on some days. Some of the earthquakes were destructive, with magnitudes of about 5. By the time the Matsushiro seismic activity declined, in 1967, Japanese scientists had issued the first warnings of future earthquake hazards, in the form of estimates of the location and probable maximum magnitude of potentially damaging earthquakes expected over a period of a few months (*5*). The warnings were based on an intensive program of leveling and Geodimeter surveys, micro-earthquake recordings, tiltmeter measurements, and geomagnetic observations. The Japanese scientists found that, without exception, swarms of very small shocks occurred in the epicentral regions of shocks that came several months later. Ground tilt was found to correlate strongly with the growth and decay of the seismic activity, and anomalous tilt was observed shortly before the occurrence of some earthquakes of magnitude about 5. Anomalous magnetic fluctuations were also observed. By continuously correlating the various changes that were occurring, the Japanese scientists were able to forecast periods of danger and to issue their warnings.

Rikitake (*5*) considers the Matsushiro warnings to have been a scientific success and "helpful for local governments," but notes that "those engaged in the sightseeing and hotel business were not really pleased. . . . Great care must be taken to find an adequate way of issuing a warning. . . . It is also of importance to train people . . . to properly behave in case of an earthquake warning."

In our judgment, long-range forecasting (of the order of a year) of general locations and approximate magnitudes of earthquakes, based on observed changes in the rates of vertical and horizontal motions and on seismic activity in fault zones, is attainable in the near future. In 1955, prior to the 1964 Niigata earthquake in Japan, the rate of uplift of bench marks north of the epicenter increased to about 5 times that of the preceding years. The rate of uplift began to decrease in 1959, and later there was a tendency toward subsidence. Considerable subsidence had been observed before the earthquake occurred (*5*). This suggests that an earthquake-warning system might be provided in part by leveling surveys repeated every few months or so.

The rate of movement along different segments of the San Andreas fault in seismically active areas was observed to change before the occurrence of moderate earthquakes (*18*). The change was manifested as changes in the length of Geodimeter lines crossing faults: the lines lengthen or shorten depending on their orientation with respect to the fault. If a fault in a zone characterized by creep becomes locally locked, we would expect the lengthening or shortening of lines crossing the fault to slow down or stop. If the movement should be transferred to an adjacent fault, we might expect the direction of movement even to reverse. Locking or transfer of fault movement would tend to create the conditions favoring a moderate earthquake. Such locking and transfer appear to have occurred repeatedly in California (*18*), and this suggests that a partial earthquake-warning system might also be provided by Geodimeter surveys repeated every few months.

Combined leveling and Geodimeter surveying, accompanied by continuous monitoring of seismic activity, appears, therefore, to offer a promising basis for a long-range earthquake-warning system.

It seems reasonable to hope that short-range prediction of earthquakes (on the order of hours or days) may be achieved through *continuous* monitoring of ground tilt, strain, seismic activity, and possibly fluctuations in the earth's magnetic field. Such monitoring should be accompanied by periodic measurement of rock stress in drill holes and by periodic or continuous observation of physical properties (for example, electrical resistivity or seismic velocity) that are stress-dependent. Short-range prediction capability cannot be achieved, however, in the absence of accelerating research on earthquake prediction along the general lines of the Press (*1*) and Pecora (*2*) reports (see *30*).

It has been demonstrated that earthquakes can be artificially triggered by fluid injection, impounding of water in reservoirs, and explosion of nuclear devices underground, and also that many earthquakes in California and Nevada occur at depths accessible to the drill. We can soberly conclude from these observations that it may be possible to develop a practical method for artificially dislodging locked sections of a major fault and to induce steady creep or periodic release of accumulating elastic strain energy along the fault to inhibit the natural accumulation of sufficient energy to produce a disastrous earthquake (*31*). It is also clear that our current knowledge of the processes involved in the generation of earthquakes is insufficient to guide an engineering program for earthquake control. We suggest that an intensified program of field, laboratory, and theoretical studies aimed at improving our understanding of earthquakes will not only advance the prospects for earthquake prediction but also provide an adequate basis for planning and implementing earthquake-control experiments that might ultimately provide the basis for a system of earthquake control.

References and Notes

1. *Earthquake Prediction: a Proposal for a Ten-Year Program of Research* (Office of Science and Technology, Washington, D.C., 1965).
2. *Proposal for a Ten-Year National Earthquake Hazards Program: a Partnership of Science and the Community* (Federal Council for Science and Technology, Washington, D.C., 1968). The members of the Working Group were L. Alldredge, W. E. Benson, W. Heitman, S. J. Lukasik, T. W. Mermel, L. C. Pakiser, A. J. Pressesky, W. A. Raney, H. B. Schechter, C. F. Scheffey, V. R. Willmarth, W. E. Hall (executive secretary), and W. T. Pecora (chairman). The report recommended implementation of a 10-year national earthquake hazards program along the general lines of the Press Panel report, but with less emphasis on earthquake prediction, greater emphasis on earthquake engineering, and estimated costs increased to $220 million.
3. *Prediction of Earthquakes: Progress to Date and Plans for Further Development* (Earthquake Research Institute, University of Tokyo, Tokyo, 1962).
4. T. Hagiwara and T. Rikitake, *Science* **157**, 761 (1967).
5. T. Rikitake, *Earth-Sci. Rev.* **4**, 245 (1968).
6. Proceedings of the 1st (1964) and 2nd (1966) United States–Japan Conferences on Research Related to Earthquake Prediction Problems, held, respectively, at the University of Tokyo and the Lamont Geological Observatory (available from the Earthquake Research Institute, University of Tokyo, or the Lamont Geological Observatory, Palisades, N.Y.)
7. J. Oliver, *Science* **164**, 92 (1969); see also a series of papers presented at the conference (L. Alsop and J. Oliver, Eds.), *Trans. Amer. Geophys. Union* **50**, 376 (1969).
8. D. Evans, *Mountain Geol.* **3**, 23 (1966).
9. J. H. Healy, W. W. Rubey, D. T. Griggs, C. B. Raleigh, *Science* **161**, 1301 (1968).
10. D. S. Carder, *Bull. Seismol. Soc. Amer.* **35**, 175 (1945).
11. J. P. Rothé, *New Sci.* **39**, 75 (1968).
12. *Trans. Amer. Geophys. Union* **50**, 247 (1969) (abstracts of the symposium on Seismic Effects of Large Underground Nuclear Explosions, Golden Anniversary Meeting of the American Geophysical Union). See especially

abstracts by J. H. Healy and R. M. Hamilton; A. Ryall, G. Boucher, W. V. Savage, and A. E. Jones; F. A. McKeown, D. D. Dickey, and G. E. Brethauer; S. W. Smith; J. Evernden; and E. R. Engdahl, W. V. Mickey, S. R. Brockman, and K. W. King.
12a. R. M. Hamilton, F. A. McKeown, J. H. Healy, *Science* **166**, 604 (1969).
13. F. Press and W. F. Brace, *Science* **152**, 1575 (1966).
14. B. Isacks, J. Oliver, L. R. Sykes, *J. Geophys. Res.* **73**, 5855 (1968).
15. H. H. Hess, in *Petrological Studies: A Volume in Honor of A. F. Buddington*, A. E. J. Engels, H. L. James, B. F. Leonard, Eds., (Geological Society of America, New York, 1962), p. 599; J. T. Wilson, *Science* **150**, 482 (196 F. J. Vine and J. T. Wilson, *ibid.*, p. 4 X. Le Pichon, *J. Geophys. Res.* **73**, 3661 (1968); see a R. S. Dietz, *Nature* **190**, 854 (1961).
16. C. R. Allen, in "Proceedings, Conference on the Geologic Problems of the San Andreas Fault System," *Stanford Univ. Pub. Univ. Ser. Geol. Sci. No. 11* (1968), p. 70.
17. J. P. Eaton, in "The Parkfield-Cholame, California, Earthquakes of June–August 1966: Surface Geologic Effects, Water-Resources Aspects, and Preliminary Seismic Data," *U.S. Geol. Surv. Prof. Pap. No. 579* (1967), p. 57.
18. "Geodimeter Fault Movement Investigations in California," *Calif. Dep. Water Resour. Bull. No. 116–6* (1968).
19. S. Breiner and R. L. Kovach, in "Proceedings, Conference on the Geologic Problems of the San Andreas Fault System, *Stanford Univ. Pub. Univ. Ser. Geol. Sci. No. 11* (1968), p. 70.
20. W. F. Brace, *Tectonophys.* **6**, 75 (1968).
21. C. B. Raleigh and M. S. Paterson, *J. Geophys. Res.* **67**, 4956 (1964).
22. J. D. Byerlee and W. F. Brace, *ibid.* **73**, 6031 (1968).
23. W. F. Brace and A. S. Orange, *Science* **153**, 1525 (1966).
24. M. K. Hubbert and W. W. Rubey, *Bull. Geol. Soc. Amer.* **70**, 115 (1959).
25. J. H. Healy, C. B. Raleigh, J. M. Coakley, paper presented before the 64th Annual Meeting of the Cordilleran Section of the Geological Society of America, the Seismological Society of America, and the Paleontological Society of America, Tucson, Ariz., April 1968.
26. *J. Indian Geophys. Union* **5** (1968).
27. W. H. K. Lee and C. B. Raleigh, *Nature* **223**, 172 (1969).
28. D. I. Gough and W. I. Gough, *Trans. Amer. Geophys. Union* **50**, 236 (1969).
29. A. Ryall, G. Boncher, W. V. Savage, A. E. Jones, *ibid.*, p. 236.
30. A fairly comprehensive review of the status of research on earthquake prediction is contained in a special issue of *Tectonophysics* [**6**, No. 1 (1968)].
31. C. Y. King [*J. Geophys. Res.* **74**, 1702 (1969)] has suggested that the fraction of stress energy released at the source of an earthquake radiated as seismic-wave energy decreases with decreasing magnitude, and is zero for fault creep. Therefore the number of small earthquakes needed to release dangerous crustal stresses should be much smaller than the number estimated on the basis of magnitude alone.
32. Publication of this article is authorized by the director of the U.S. Geological Survey. We thank the Chevron Oil Company for its cooperation in carrying out the investigation at the Rangely Oil Field, in Colorado, and for permission to publish the pressure contours of Fig. 10; the Division of Nuclear Reactor Development and Technology of the U.S. Atomic Energy Commission for partial support of the investigations of microearthquakes in California; the Earthquake Mechanism Laboratory of the Environmental Science Services Administration for some of the data used to locate the epicenters shown in Fig. 2; and the Nevada Operations Office of the U.S. Atomic Energy Commission for its cooperation in carrying out the investigation of the aftershocks of the Benham underground nuclear explosion illustrated in Fig. 11.

Control of Specific Gene Expression in Higher Organisms

Expression of mammalian genes may be controlled by repressors acting on the translation of messenger RNA.

Gordon M. Tomkins, Thomas D. Gelehrter, Daryl Granner
David Martin, Jr., Herbert H. Samuels, E. Brad Thompson

It is generally acknowledged that the genetic information in most complete cells of a complex metazoan organism is identical with that of every other cell. Within a given organism the tremendous diversity of cell phenotypes must therefore derive from the fact that each cell expresses only a limited amount of its full genetic potential and that different cell types express different portions of their genome. A complete theory of metazoan cell biology must account not only for this differentiation of cell function, but also for the development of an adult organism from a single cell, a process which requires an orderly progression (and repression) of gene activities until the highly structured end state is reached.

Faced with complexity on this scale, biologists have turned to simpler nonnuclear systems—bacteria and their viruses—in which the control of individual genetic elements can be understood more easily. With these organisms, it has been established that DNA is the primary genetic material and that genetic information is expressed through an intermediate, messenger RNA, which acts as the direct template for protein synthesis.

A bacterial gene is "active" only when its corresponding messenger is produced. Therefore, regulation of gene function depends on controlling the synthesis of specific messenger RNA's. In bacteriophage λ and the group of genes controlling lactose metabolism in *Escherichia coli*, the formation of the messenger is inhibited by the attachment of specific protein repressors to specific regulatory sites on the chromosome. The genes controlling lactose metabolism are activated by a specific "inducer" that combines with the repressor, causing the latter to detach from the DNA and permitting the messenger RNA to be synthesized (*1*, *2*).

The elegance of these ideas and the clarity with which they have subsequently been verified in microorganisms have led to their widespread acceptance as an explanation for gene regulation of higher organisms as well. This acceptance has been bolstered by the demonstration that the fundamental mechanisms of information flow in higher organisms are virtually identical with those in bacteria. Thus, in both cases, DNA is the primary genetic material; in both cases genetic information is expressed by transcription into RNA; and in both cases the codes assigning specific RNA triplets to specific amino acids are essentially identical (*3*).

However, certain features of the structure and function of the genetic apparatus of eukaryotic cells are very different from their bacterial counterparts; these differences raise the possi-

Dr. Tomkins is from the Department of Biochemistry and Biophysics, University of California, San Francisco Medical Center; Dr. Gelehrter is from the Division of Medical Genetics, at the University of Washington; Dr. Granner is from the Department of Medicine at the University of Wisconsin; Dr. Martin is from the Department of Medicine at the San Francisco Medical Center; Dr. Samuels is from the Department of Medicine at the New York University Medical Center; and Dr. Thompson is from the National Cancer Institute.