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TALES OF THE EARTH

Paroxysms and Perturbations of the Blue Planet

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CHAPTER TWO

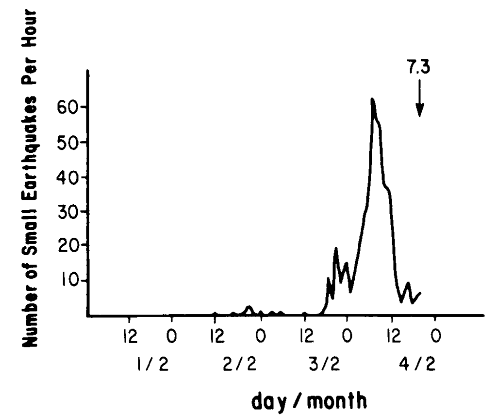
. . . *And from Time to Time Its Surface Moves Around*

Well water grew turbid and hibernating snakes took up their warm-weather rounds. Groundwater levels rose and fell. Radon levels changed radically and sensors showed that the ground was tilting. Domestic animals behaved strangely. A report notes that "pigs bit each other and tried to run up walls, cows fought each other and pawed the ground, deer ran away, turtles were seen to jump out of the water and to make noise, and a hen was seen to fly to a tree top."

This took place in Liaoning Province in northeastern China in early February 1975. Earlier, in January, the Earthquake Research Branch of the provincial government had predicted that a major earthquake would occur in the region that month or the following month. A massive quake had occurred in nearby Bo Hai in 1969, and Liaoning Province had been laced with monitoring devices in the intervening years.

By late January, the signs were growing more intense. Some wells stopped flowing altogether; others spouted water. The electrical conductivity of the ground itself changed. All of these signs were considered earthquake "precursor anomalies." The most important of them all was a swarm of small tremors, or foreshocks, that were first sensed on February 1, and continued with increasing frequency and magnitude over the next three days, reaching a peak on February 4.

At 10:30 that morning, the Liaoning provincial government



Graph of microseismic activity preceding the Haicheng earthquake of 1975. The arrow marks the time of occurrence of the earthquake of magnitude of 7.3. Note the increase in microseismic activity, which reached a peak just prior to the earthquake. From Yong et al., 1988.

issued an earthquake warning and began an emergency evacuation of the city of Haicheng. At 7:36 that evening, the Haicheng earthquake struck the area—a major one measuring 7.3 on the Richter scale. Thanks to the evacuation and other precautions that had been taken, an immeasurable amount of damage and loss of life was averted. It was the first time in history that an earthquake had been forecast with such precision.

It was also the last time, so far.

No earthquake that we know of has changed the course of civilization, as the volcanic eruption at Thera evidently did, but it is safe to say that no geologic phenomenon has taken a greater toll of human lives than earthquakes. They are common, almost daily events at relatively low magnitudes as measured on the Richter scale.

Most of us are familiar with the Richter scale numerology; the newspapers will announce that a quake of magnitude 6.3 was recordeed in, say, Peru, or maybe 7.3, which sounds worse. How much worse? The Richter scale, named for Charles Richter (1900–1985), a seismologist who worked at the California Institute of Technology, can be a bit deceptive. It provides a measure of the energy released in an earthquake, determined from seismographic readings taken in local and distant stations, but on an exponential scale rather than a linear one. A magnitude 7.3 earthquake is not just slightly larger than a 6.3 quake; it is *fifty* times larger. In turn, an 8.3 earthquake is fifty times larger than a 7.3

quake, which means that it is *twenty-five hundred* times stronger than a "small" 6.3-magnitude quake.

Even a 6.3-magnitude earthquake is something to be reckoned with. In terms of the energy released, it is the equivalent of a one-megaton nuclear explosion, or about fifty times larger than the Hiroshima bomb. Such quakes are not uncommon (around 100 per year with magnitudes between 6.0 and 6.9), and there are vast numbers of quakes with magnitudes of about 5.3 and less. Most of the global earthquake energy released in any given year, however, is the result of the few earthquakes that register 7.3 and greater.

Obviously, the amount of havoc an earthquake causes depends on where its energy is released. A quake of magnitude 7.3 that occurs at a depth of four miles below the Earth's crust will bring about substantial destruction. On the other hand, a deep-focus quake of the same magnitude—one that occurs at, for instance, a depth of 400 miles—may result in little if any damage on the surface. The damage, for the most part, is caused by the motion of the Earth's surface, or ground motion, which will vary considerably depending on the transmissive and dissipative properties of the rocks and geologic formations that lie between the earthquake location, or *focus*, and the surface.

While it has been determined that so far as earthquake (and tornado) damage are concerned, the safest place to live in the United States is near a tiny town called Crossroads in southeastern New Mexico, earthquakes can occur virtually anywhere. Their geographic distribution is generally categorized in the terms of plate tectonics. Thus we have either *interplate* or *intraplate* earthquakes.

Most quakes are of the *interplate* variety, occurring along the boundaries of the Earth's great plates where they grind against each other. The mechanisms of such quakes are fairly well understood in a general way. As one plate moves slowly past its neighbor, enormous strain builds up, not unlike the way in which strain builds up when you try to open a firmly closed jar. Eventually, the strain placed on the lid is enough, and it opens with a pop. Similarly, the strain built up by the plates eventually results in its quick release in the form of earthquake movement, and the plates return to a relatively unstrained state.

The process is more complicated than that, of course, depending on the type of boundary between plates, of which there are

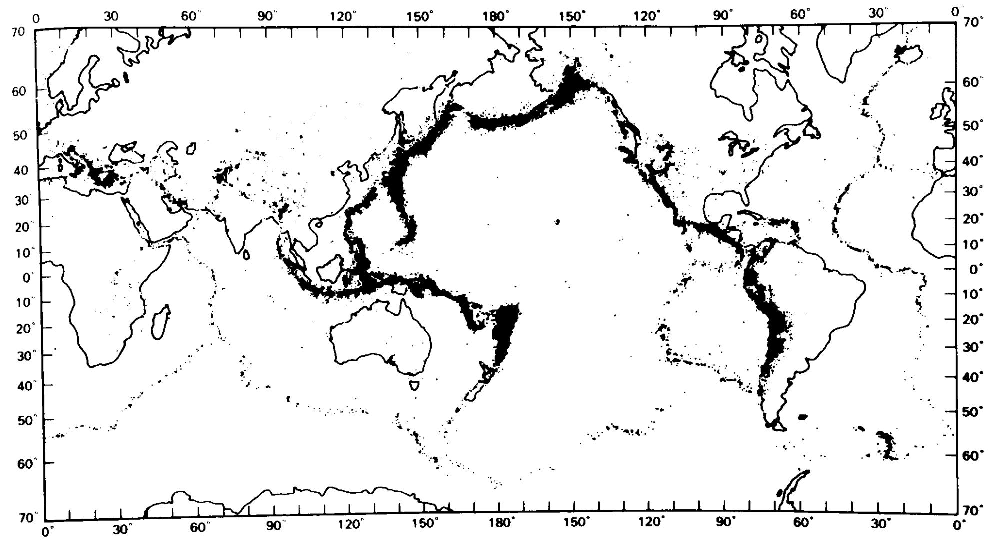
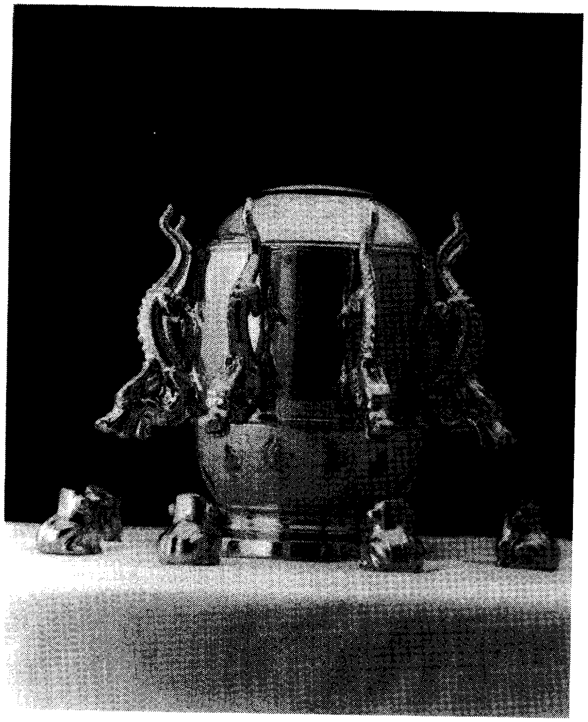


Diagram showing the distribution of earthquake foci. Notice that those in the oceans are concentrated along the mid-ocean ridges and those on the continental borders of the Pacific Ocean along the subduction zones. From Uyeda, 1971.

three kinds. At mid-ocean ridges, the plates form with the upwelling of magmatic material, and their lateral movement is away from the ridge in opposite directions. This is what is happening at the mid-Atlantic ridge, for example. On the other hand, there are places where two adjoining plates move horizontally relative to each other, usually at different velocities, along what are called *transform* faults (as is the case with the San Andreas fault and others in California). The third boundary type is when one plate is subducted under its neighbor and back into the deep interior of the Earth. Quakes along the mid-ocean ridges are relatively few in number and are usually small. Transform-fault quakes can be either small or large in magnitude. The subduction-zone quakes are the most numerous and are often among the largest; their focal zones (that is, where the energy is released) can extend to depths greater than 400 miles. In contrast, the focal zones at the other two boundary types are typically shallow.

The least-understood earthquakes are those that occur within a plate—the intraplate quakes. Though far less common than



Model of the earliest seismograph developed by Zhang Heng in A.D. 132. It consists of a closed bronze urn with a ring of eight dragons holding balls between their jaws. If the earth is tilted by an earth tremor, a pendulum moves inside it and opens the jaws of the dragon facing the source of the tremor. The ball drops into the mouth of the frog sitting below. From Young et al., 1988.

quakes that occur along the boundaries of plates, the intraplate quakes account for about half of the high-magnitude, shallow-depth earthquakes that rattle into human consciousness and wreak havoc on humankind's works. The Haicheng quake, the only one to have been so successfully predicted that the community could be evacuated, was an intraplate earthquake.

That the first such prediction took place in China seems fitting, since seismology as a science had its origins there with the development in A.D. 132 of the first instrument to record ground motion from earthquakes. Chinese concern with earthquakes is understandable, even at so early a time in history. These violent upheavals are common there and have taken a tremendous toll on the Middle Kingdom's huge population. The State Seismological Bureau of the People's Republic reported that in the thirty-seven years from 1949 to 1976, some 27 million people died and 76 million more were injured as a result of 100 earthquakes. If these

figures are correct, the toll is nearly unimaginable. By comparison, the total number of Americans killed in the American Civil War has been estimated at 364,000; those in World War II, at 407,000. The greatest hazard to life in the United States, it is generally agreed, is the automobile, which accounts for 50,000 deaths each year (or in a 37-year period, by way of comparison 1,850,000)—not even a tenth of China's earthquake toll.

In March 1966, two devastating quakes struck China: a 6.8-magnitude quake at Xingtai on March 6, and one of 7.2 at Ningjin on March 22. Premier Zhou Enlai promptly instituted a comprehensive earthquake prediction program and, under this edict and the central control associated with it, China has developed the most extensive earthquake-monitoring system in the world. Though not so advanced in instrumentation as those in the United States and Japan, the Chinese program involves many more people, and more diverse types of potential earthquake precursor signals are tracked.

The science of earthquake prediction it still largely empirical. Scientists measure various properties over time and then examine them *after* a quake to see if any one of them, or several, seems to have been a significant precursor. The hypothesis is that strain will build up over an extended time in a given region and then, during a period of a few months or even years, small cracks (and accompanying tremors) will develop in the underlying rocks. The consequent physical changes in the material properties of the rocks are presumed to extend upward to depths sufficiently shallow that they can be detected by sensitive instruments at the surface.

Most efforts at prediction—in China as elsewhere in the world—concentrate on seismic observations of small earthquake tremors, or foreshocks, which may (or may not) show a recognizable pattern before the main quake. Ground tilting can give some warning over the long term that strain is building up within the earth. As cracks form, changes in groundwater levels will result, as observed in wells. Even the electrical conductivity of the Earth itself changes. There have been reports of sounds and of light, or lightning, just seconds before major earthquakes, but they are poorly documented and the phenomenon is little understood.

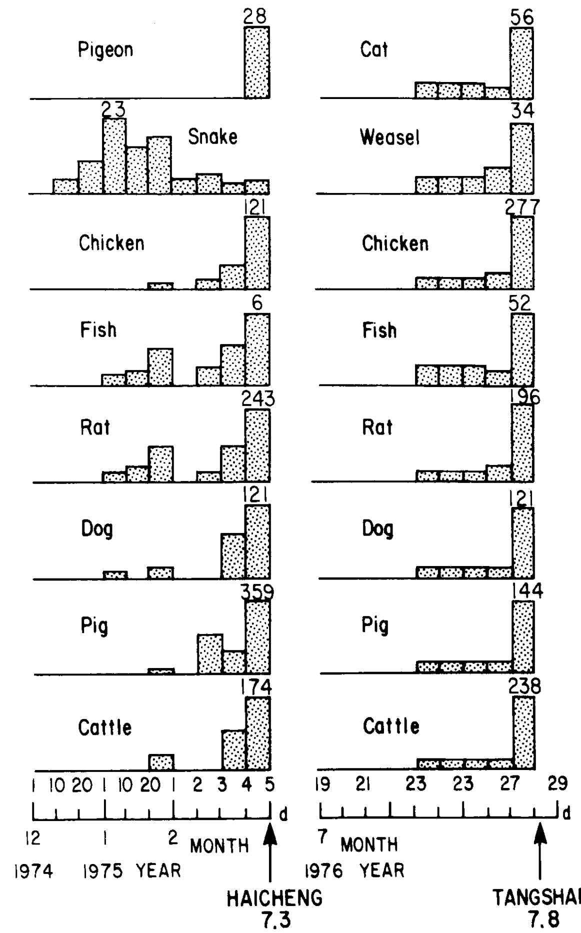
The oddest precursor signal, but one that is well documented, is the anomalous behavior of animals, usually occurring over a short time of a few days to a few hours before an earthquake.

Most such reports arise in China, where looking for weird behavior among animals is an integral part of the monitoring program (though comparable reports have come from Italy, Japan, and elsewhere in the world). These reports include entries such as this one: "Rats ran away, pandas held their heads and screamed, cattle refused to enter barns or eat grass, dogs became noisy, horses stampeded and neighed, many earthworms came out, fish jumped on shore, mackerel jumped on the sea surface, eels went upstream in many rivers [etc]."

For a good many scientists, such reports are anathema, and they dismiss them out of hand as anecdotal. Among other things, it would be embarrassing to some scientists if the likes of earthworms and eels could pick up precursor signals that sophisticated instruments do not. But the records are arresting and the cause of erratic behavior is not understood. What is one to make of it? Perhaps the best advice is that given by an eminent geophysicist, Harold Jeffreys, some years ago regarding another subject: "If the data speak rot, let the data speak rot." And then set out to understand what phenomena do, in fact, cause such strange behaviors.

After the Haicheng earthquake, it was unclear whether another would soon occur in the general area of northeastern China or whether the strains along the faults were now relaxed. In fact, the Haicheng quake was the last of three great quakes—each above magnitude 7.0 and all local record-breakers in magnitude and intensity—that had struck the region over several years. In June and July, scientists detected a few random precursor anomalies over the nearby area, but they were too inconclusive to issue a warning. There was no swarm of foreshocks of the sort that had been the major tip-off for the Haicheng quake. And, as with responsible earthquake prediction anywhere in populated and industrialized areas, the Chinese seismologists had an additional consideration. As the State Seismological Bureau of China has stated: "Most important of all, because of the political and economic significance of the area, any posting of a warning had to be carefully considered in light of its great social consequences." Who is to take responsibility for evacuating everyone from Los Angeles or Tokyo or Beijing, sending everyone into the countryside and halting all urban activity?

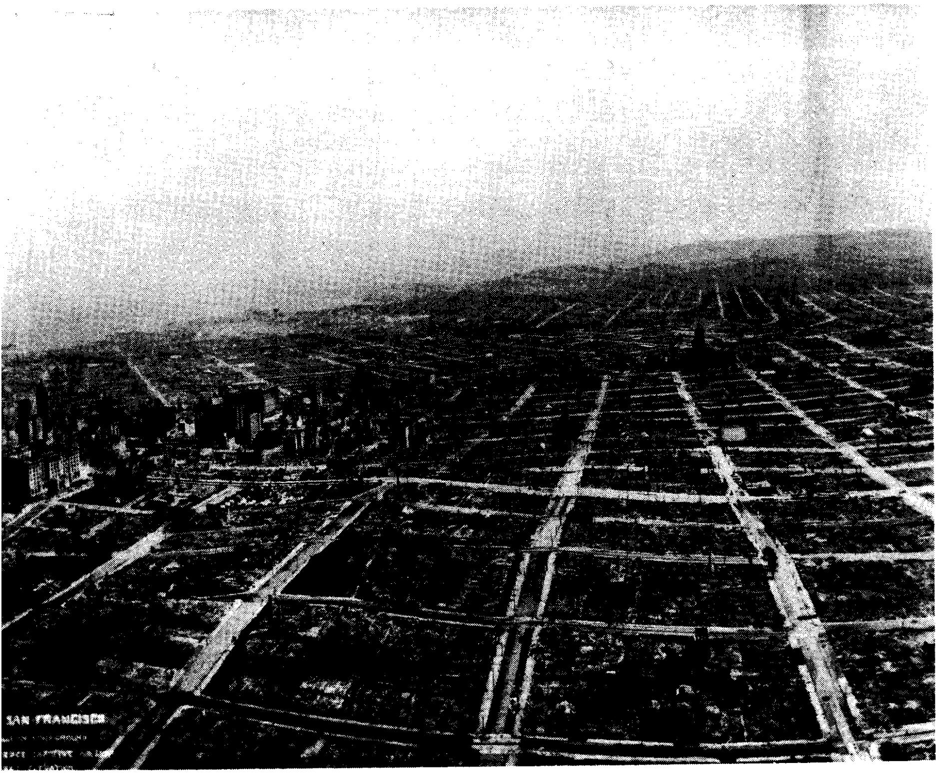
But, in Tangshan, another city in northeastern China, on July 28, 1976, seventeen months after the Chinese had triumphantly predicted the Haicheng quake, lightning flashed across the sky



Comparison of reports of anomalous animal behavior before the Haicheng and Tangshan earthquakes. The data for Haicheng are for the period December 1, 1974, to February 5, 1975, and those for Tangshan for the period July 19 to 26, 1975. Note the anomalies in the former occurring as early as one to two months before the shock, whereas there were appreciable anomalies in the latter only a few days before the main shock. From Yong et al., 1988.

and the Earth rumbled seconds before 3:42 in the morning. And in a matter of seconds, Tangshan, an industrial city of one million people, was reduced to rubble. Almost one-fourth of the city's people perished in the disaster.

Before long, Chinese scientists reviewed their monitoring records. As noted, there had been no swarm of foreshock tremors as in the Haicheng pattern, probably in itself dooming any prediction at Tangshan. But a few precursors had occurred in relative abundance before the earthquake. Groundwater levels had changed and unusual sound and light had been noted, along with



n Francisco after the earthquake and fire of 1906. United States Geological Survey, Menlo rk, California.

electromagnetic anomalies. And animals had acted strangely, indeed in almost exactly the pattern that had shown up at Haicheng. Of all the Tangshan precursors, this is the most enigmatic.

By comparison with the loss of life in Chinese earthquakes, the toll from America's most famous earthquake was minor: 700. The San Francisco earthquake of 1906, which occurred just before dawn at 5:12 on April 18, was by no means the nation's largest (it is estimated to have been about 7.6 in magnitude) but property losses were enormous: $500 million in current U.S. dollars from the effects of the quake itself, and another $3 billion from the fires that ensued.

Among the results were at least two movies about the quake. In the final scene of one of these, Jeannette MacDonald (an opera

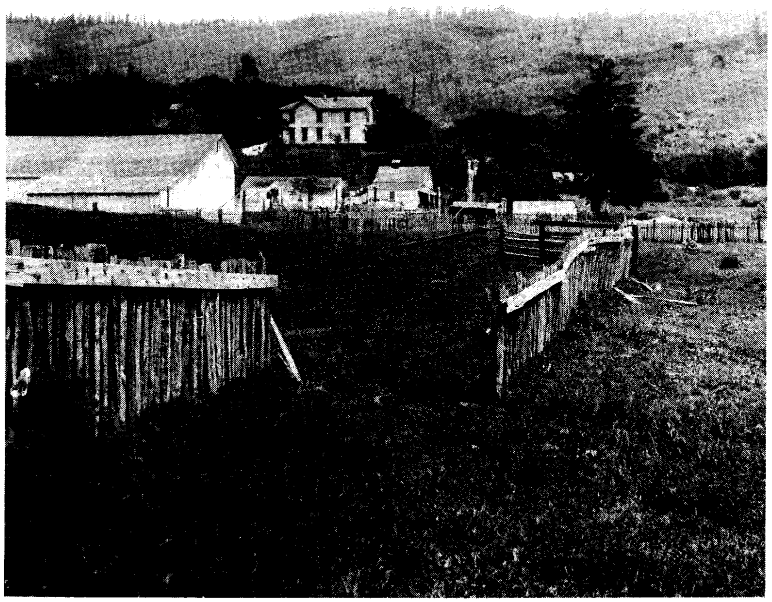
singer), Clark Gable (a gambler), and Spencer Tracy (a priest) march into the sunset with the rest of the cast, singing "San Francisco," firmly resolved to rebuild the city—an admirable if silly expression of the American pioneer spirit. The great operatic tenor Enrico Caruso was in fact in the city at the time, having arrived to sing *Carmen*. When the quake struck, he ran out of the St. Francis Hotel, one of the few buildings that withstood the earthquake, with a towel wrapped around his neck for protection and cradling a signed portrait of Theodore Roosevelt, evidently for spiritual sustenance. Caruso is reported to have cried out, "Give me Vesuvius!" Upon checking out of the hotel, he vowed never to return to San Francisco, and he never did.

Soon after the earthquake, California set up a State Earthquake Investigation Commission, much the same as the Royal Society had after the Krakatoa eruption, and its report was issued in 1908. Among its findings were a few comments on anomalous animal behavior and earthquake sounds—effects that occurred immediately before the ground motion was felt. In view of the recent Chinese experience, we recite some of them here.

> Horses whinnied or snorted before the shock and stampeded when the latter was felt, some falling owing to the commotion of the ground.
>
> A farmer in the same neighborhood observed his horses moving about, whinnying and snorting, and called to his boy, who was with them, but before the boy could answer he felt the shock.
>
> Several instances were reported where cows stampeded before the shock was felt by the observer.
>
> Dogs generally became alert before the aftershocks, and barked, whined, or ran to cover.

Whether or not domestic animals sensed what was happening at the time, the quake is well understood in plate tectonic terms. It was the result of a break along the San Andreas fault over a distance of 270 miles, centered on San Francisco, at the time a boom city that had been built up rapidly and in a manner of construction that was hardly earthquake resistant. The displacement along the break in the fault was mainly horizontal, in at least one place as much as twenty-one feet.

The San Andreas and its associated fault system extend along much of the length of California from Baja California to Cape Mendocino, north of San Francisco, where it continues out under the sea. It is a plate boundary, a transform-fault system, between



Fence offset by fault from the San Francisco earthquake of 1906. United States Geological Survey, Denver.

the North American plate to the east and the Pacific plate to the west. Relative to the North American plate, the Pacific plate moves toward the northwest at a rate ranging from a fraction of an inch to an inch or so each year. Strain builds up between the plates and, at various locations along the fault system, is released in the form of an earthquake, returning the affected fault to a relatively unstrained state. A quiescent period ensues, followed eventually by more strain and another "adjustment." Throughout

history, some portions of the San Andreas fault system have experienced many strain releases in the form of minor tremors, and such regions are considered relatively safe from a large, damaging earthquake. Other areas, like San Francisco, are fated to see quiet periods interrupted by major quakes.

About the time that the Chinese initiated their earthquake-prediction studies (and at a time when the Soviet Union and Japan were enlarging theirs), the United States embarked on its own extensive prediction research program. The direction of other countries' research often has an important impact on decisions about U.S. programs and vice versa. The procedures whereby a new, large-scale scientific study is started in this country follow a set pattern, and the earthquake prediction study was no exception.

First, it is important to have an imprimatur from an august scientific body, more often than not a report from a committee of the National Academy of Sciences, detailing the need for research. Then, the negotiating begins over who will do the work, or lead it: a university, a university consortium, a government agency, or a private corporation? In this case, the decision came down to the United States Geological Survey (USGS) or the Environmental Sciences Service Administration, which subsequently became the National Oceanic and Atmospheric Administration (NOAA). Historically the USGS has been one of the more respected scientific agencies within the government, originally with the primary responsibility of mapping the country. NOAA is a conglomerate of agencies, including the United States Weather Bureau. The final decision for earthquake prediction was made in favor of the Geological Survey.

In the initial stages of such new enterprises, grandiose projections are typically made; in this case, one regularly heard that a prediction scheme was "imminent," though a successful scheme has yet to be developed. Since then, the Geological Survey has made more modest projections. Funding began with about $1 million a year and is now at a level of $20 million. Decisions about funding for this and other such programs are internal, made by the Geological Survey and its parent organization, the Department of Interior. As with research programs cloaked in secrecy in the Department of Defense, it can be difficult for the interested public, or even Congress, to navigate the scientific bureaucracy in order to understand how the levels of funding are determined—

and justified. The final result is presented to the public, who can take it or leave it. This is not to say that the system doesn't work. It often works well. But there is little interplay with and review from extenal sources, which can lead to trouble. Sometimes opportunities for innovative research are avoided, or even prohibited. There is an American tendency to believe that if enough money is put into a program, eventually a solution will be found. But this is not always so, nor is it necessarily the best or only approach. In fact, it is often preferable to build a better mouse trap than simply a bigger one.

Like other such studies throughout the world, the U.S. program has sought identifiable precursors to major earthquakes, chiefly in measurements of seismicity and crustal movement and strain. Along the San Andreas fault system, hundreds of highly sensitive instruments feed elaborate data-processing facilities with microseismic information, detecting, counting, and determining the location of every tremor, however slight, and looking for the swarms of small earthquakes that sometimes precede a big one. Lasers on both sides of the faults effectively stare at each other, attuned to detect any relative crustal movement of the Pacific and North American plates. Yet other instruments measure large-scale subsidence and uplift of the Earth's surface. Between the 1960s and 1970s, the surface rose slightly along the San Andreas fault near the city of Palmdale, northeast of Los Angeles. Called the Palmdale Bulge, it is some 130 miles long and is clearly related to the buildup of strain in the underlying rock. Does it presage a major earthquake? It might reasonably, but there has been none so far.

In addition, tiltmeters measure local changes in ground surface, strain meters in drill holes measure vertical strain, and other instruments track water levels in wells, radon gas emissions, and changes in such things as geomagnetism and geoelectricity.

From trenches cut into the land near the fault system, "paleoseismologists" have laid bare the signs of major quakes that have occurred in the past, visible in the way rock strata are displaced. Radiocarbon dating of organic remains in the rock strata provides dates of the ancient major earthquakes, which, they have found, recurred at an average interval of 150 years, with a range from 50 to 300 years.

As the U.S. Earthquake Prediction Program, still in the research phase, is about twenty-five years old, it is not unreasonable

to ask how it is doing. A test case is provided by the Loma Prieta earthquake, a 7.1-magnitude quake that struck northern California on October 17, 1989, collapsing the elevated highway in Oakland and a section of the San Francisco Bay Bridge and stunning not only the people of the region but everyone who was watching the World Series between Oakland and San Francisco. The elaborate monitoring system of thousands of instruments busily collecting data all along the San Andreas fault produced no precursors, no foreshock swarms, no anomalous strains or crustal movements. As one scientist put it, "We did not see anything. It is fair to say that it was not encouraging."

But there was an element of serendipity, which often plays an important role in the advancement of science. A few weeks before the earthquake, an independent group of physicists at Stanford University were studying radio noise signals (specifically, low-frequency electromagnetic radiation) using radio receivers located only five miles from the epicenter of the earthquake. About twelve days before the quake, the background radio noise rose, and then, during the three days before the quake, it shot up by a factor of thirty, a level the scientists had never seen in two years of monitoring.

Are these findings happenstance or a real precursor? Why low-frequency electromagnetic radiation would have anything to do with earthquakes is a mystery. But, it should be added, very little is known about the mechanisms involved in the release of earthquake energy, even though it is measured in the range of megaton nuclear bombs.

A few earthquakes have been successfully predicted in the United States, but they have all been small ones, not calling for warnings of any public action. In 1973, scientists at Columbia University began measuring seismic velocities in the Adirondack Mountains of New York. They set off small explosives and watched to see how long it took for seismic waves to reach a nearby receiver. Russian seismologists had reported that anomalous changes in seismic velocities had occurred before some earthquakes, and when the Columbia scientists saw such changes on August 1, they predicted a quake of magnitude 2.5 to 3.0 in the next three days. And it happened on August 3, magnitude 2.6.

Two years later, across the continent in California, a seismograph network was installed to monitor the effects of the additional weight on the Earth's crust resulting from the construction of a large dam and the filling of the reservoir behind it. (As the reservoir fills, the extra weight of water puts a strain on the Earth's crust that is relieved by land subsidence and, in some cases, more abruptly by earthquakes.) In June, microseismic activity increased significantly and the scientists warned the Department of Water Resources to expect an earthquake. On August 1, a magnitude 5.9 quake shook the area. Then, the following year, in June 1976, the Geological Survey noted an increase in creep along the Calaveras fault east of San Jose, California, and predicted that a quake would occur within a three-month span of time centered on January 1, 1977. The quake, magnitude 3.2, occurred December 6.

Other than these, predictions—especially of major quakes—have not been successful, happily in every instance for the public involved. In 1976, two government scientists (one from the Geological Survey and one from the Bureau of Mines) made a private and unofficial prediction that three major earthquakes of magnitude 8.5, 9.4, and then 9.9 would strike near the coast of Peru in 1981. They based their prediction on unusual criteria. (This is, in fact, one way in which scientific advances can come about: by someone daring to head into the unknown, with the clear risk of being wrong.) Their method involved making gross extrapolations of the effects observed from rock bursts in mines to earthquake magnitude effects. The scientific community not only disapproved of the method, it noted certain problems with the predicters' mathematical equations, and also simply couldn't swallow the idea that two of the earthquakes predicted would be larger than anything observed in historical time. The American scientific community essentially dismissed the predictions out of hand.

But the forecast simply did not go away. Peru, along a plate subduction boundary, is a region subject to many major earthquakes. Some Peruvian scientists kept the pot boiling, seeing in these predictions a chance to obtain added funds to enlarge and improve the country's network of seismographic stations. In the United States, the Peruvian predictions were largely forgotten until November 1980, when, at an informal dinner following a meeting on earthquake prediction, one scientist made an offhand comment about them. Reporters present at the dinner pricked up their ears and the predictions went public. The media gobbled them up and the two scientists originally involved made confirm-

ing comments. Once such reports hit the newspapers, they tend to gain a nearly unshakable credibility in the eyes of the public. Not surprisingly, people in Peru were alarmed, and the Peruvian government asked the United States to evaluate the predictions.

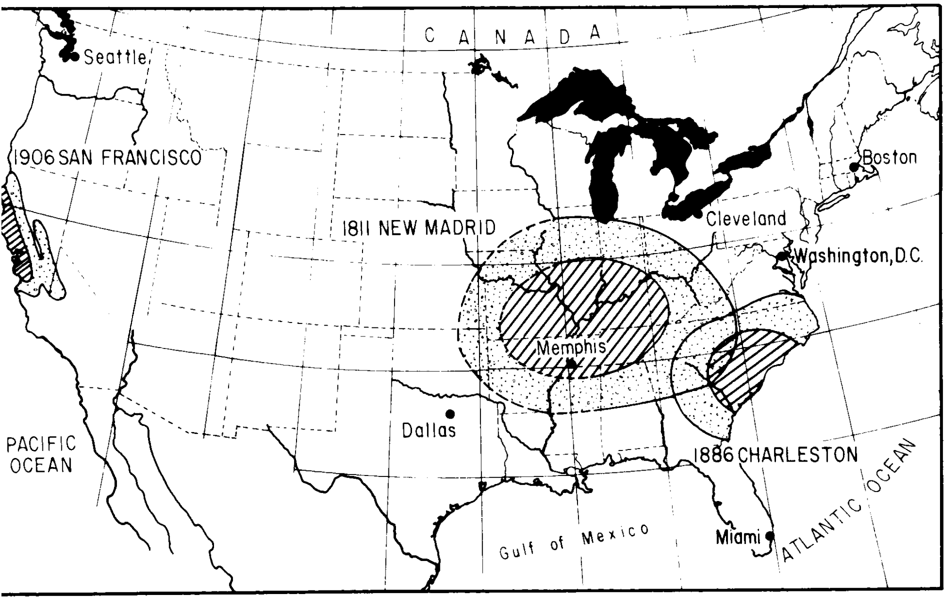
A panel of twelve scientists from the academic world and the U.S. Geological Survey, along with expert witnesses, convened in January 1981, a kangaroo court acting as prosecutor, judge, and jury, and for two days cross-examined the two scientists. They concluded, as expected, that there was no scientific basis for the predictions. Still, it was not until the predicted time of the quakes had passed without incident that the Peruvian populace was able to calm down.

The hazards of unwarranted earthquake predictions can be considerable, and understandably so, causing unjustified concern among the public. In 1989, a Reuters report appeared under the headline: "Geologist who forecast quake placed on leave." The story, which appeared shortly after the Loma Prieta quake of October 17, read as follows:

> A geologist for Santa Clara County may lose his job even though he became a media star by predicting the earthquake that hit Northern California last week.
>
> Jim Berkland was put on indefinite administrative leave after a county supervisor said he was not able to separate his "hobby" of predicting quakes and his daily work as a staff geologist.
>
> Berkland predicted in a local newspaper Oct. 13 that an earthquake between 3.5 and 6.0 on the Richter scale would rock Northern California between Oct. 14 and Oct. 21.
>
> He now says that between Nov. 11 and Nov. 18 a quake measuring about 5.5 will hit Northern California.
>
> County supervisor Sally Reed charged that Berkland is "creating fear in the public," by publicizing his predictions.
>
> Berkland says he thinks that totalling up the number of cats and dogs that run away from home in advance of a quake along with measuring the gravitational pull of the sun and moon help forecast the tremors. He claims an accuracy of 78 percent.

There are so many earthquakes of very small magnitude in California that any kind of guessing game will make you right a great deal of the time.

The pull of the Sun and the Moon also figured in the 1990 prediction that made a name (or more appropriate, notoriety) for a New Mexico meteorologist and business consultant, Iben Brown-



omparison of isoseismal contours for the New Madrid earthquakes of 1811–1812, the Charles-
n earthquakes of 1886, and the San Francisco earthquake of 1906. The hachured area repre-
nts the zone of most severe ground shaking and damage. The dotted area represents the zone
here the damage is less severe but ground shaking is felt by all. From U.S. Geological Survey,
ofessional paper 1240-B, 1981.

ing, before his death. He predicted a major earthquake on December 3, 1990, in the town of New Madrid, Missouri, causing a local furor of understandable alarm, for it was here that some of the nation's largest earthquakes took place in 1811–12. The other record-setters were the Charleston, South Carolina, quakes of 1886.

The town of New Madrid (locally pronounced *Mad*-rid) is located in the southeastern corner of Missouri on the banks of the Mississippi. When it was founded in 1789 by Colonel George Mason, a patriot of the American Revolution, and a handful of mercenaries, this was a sparsely populated part of the world. The empty lands to the west of the river were under the dominion of Spain, and Mason's notion was to establish a colony under Spanish authority (hence the town's name), which would control traffic along the Mississippi and exact tariffs. But the Spanish ceded

the land to the French, who in turn sold it to the United States in the Louisiana Purchase in 1803. New Madrid, its commercial venture foiled, nevertheless prospered as a farming community.

After midnight on December 16, 1811, a church bell pealed in Boston, Massachusetts. It was no pre-Christmas celebration or signal, but the result of an earthquake that rocked New Madrid, 1,100 miles away. The quake occurred at around 2:00 A.M. Another followed on January 23, and yet another on February 7. Their magnitudes have since been estimated at 8.6, 8.4, and 8.7, each one releasing energy equivalent to about 2,500 one-megaton nuclear bombs. Had these quakes occurred a century later, when the entire midsection of the country was far more densely populated, our general consideration of major earthquake hazard regions in the United States might well be different than it is today. (It should be pointed out, however, that earthquakes of this type—major intraplate quakes—tend to recur at intervals of about 600 to 800 years, unlike the 150-year average interval for the San Andreas fault system.)

What is it like when an 8.6 magnitude earthquake hits? The region of extensive damage included parts of Missouri, Illinois, Indiana, Kentucky, Tennessee, Mississippi, and Arkansas. All three quakes were felt throughout the populated areas of the eastern United States. They threw down chimneys in Cincinnati 400 miles away, rattled doors and windows in Washington, D.C., 800 miles away, and, as noted, rang a chuch bell in Boston. Eyewitnesses described the scene at New Madrid as follows:

> The earth was observed to roll in waves a few feet high with visible depressions between. By and by these swells burst throwing up large volumes of water, sand, and coal.
>
> . . . Undulations of the earth resembling waves, increasing in elevations as they advanced, and when they attained a certain fearful height the earth would burst.
>
> The shocks were clearly distinguishable into two classes, those in which the motion was horizontal and those in which it was perpendicular. The latter were attended with explosions and the terrible mixture of noises, . . . but they were by no means as destructive as the former.
>
> Cpt. Sarpy tied up at this [small] island on the evening of the 15th of December, 1811. In looking around they found that a party of river pirates occupied part of the island and were expecting Sarpy with the intention of robbing him. As soon as Sarpy found that out

he quietly dropped lower down the river. In the night the earthquake came and next morning when the accompanying haziness disappeared the island could no longer be seen. It had been utterly destroyed as well as its pirate inhabitants.

Two waterfalls with drops of about six feet were created in the Mississippi River. Sulfurous or other noxious odors and vapors were noted by virtually every observer in the vicinity. The third (and largest) shock came with a noise so tremendous it was heard as far away as Richmond, Virginia, and the nation's capital. Today, the most conspicuous result of these quakes is still visible: a region of "sunken lands" 160 by 40 miles in southeastern Missouri, western Tennesse, and northeastern Arkansas. There are sloughs, or bottom lands, with depressions of three to five feet; river swamps with depressions of five to ten feet; and lakes of fifteen to twenty feet, including Tennessee's Reelfoot Lake. Here and there in these sunken lands are isolated regions of uplift, circular bulges five to ten miles in diameter.

In Louisville, Kentucky, at the time of the New Madrid quakes, an inventor named Jared Brooks had built a number of pendulums and springs. Curious about earth tremors and vibrations, Brooks had designed the pendulums to detect minor horizontal movements of the Earth, the springs to detect vertical movements. Thanks to his curiosity and his primitive instruments, he was able to record a number of vibrations not generally felt, noting that between December 15 and March 15 there were an astonishing 1,874 aftershocks. The totals varied from a low of 58 for the penultimate week to a high of 292 for the week ending February 23.

A wholly different kind of vibration followed Iben Browning's 1990 prediction of a major quake in the same area. At the time it was forecast, December 3 or 4, schools in Arkansas and Missouri dismissed students, and factories told their employees to stay home. An earth scientist at Washington University in St. Louis later said, "The public was needlessly scared. It was very irresponsible." On the other hand, the media attention accorded to New Madrid by this hare-brained prediction led to an increase in tourism of between 30 and 40 percent. The New Madrid Historical Museum issued T-shirts that read "Visit Historic New Madrid (While It's Still There)" and realized so much money from selling them and other souvenirs that the museum was able

to build a $110,000 addition, and began producing New Madrid Fault Line wine.

The series of earthquakes that shook Charleston, South Carolina, in 1886 came in rapid succession, not spread out over almost two months like the New Madrid quakes. The first hit at 9:51 A.M. on August 31 with an estimated magnitude of 8.2. The shock, accompanied by a loud roar and ground motion in the form of waves up to two feet high, was felt in Boston 800 miles away; the upper Mississippi valley, 950 miles off; Cuba, 700 miles to the south; and Bermuda, 950 miles out in the Atlantic. The second shock, of lesser magnitude, followed eight minutes later, and in another ten minutes the third shock occurred, evidently comparable in magnitude to the first. There were two epicentral regions of principal damage—one sixteen miles northwest of the city, the other thirteen miles west of it—each presumably corresponding to one of the two main shocks.

The quakes caused numerous small craters to form, "sandblows," or "earthquake fountains," as they are sometimes called, which spewed sand ten to twenty feet into the air, covering much of the epicentral region with it. But the damage was not what might be expected from shocks of such magnitude. Relatively few buildings in Charleston were demolished; some suffered only minor damage. How could this be? Probably it was owing to the fact that the ground motion was mostly vertical, rather than horizontal. Horizontal motion causes the greatest damage to structures.

Except that they are all termed earthquakes, the shocks in California and those that occurred in Charleston and New Madrid could hardly be more unalike. California quakes are of the interplate type and are the result of a sudden release of accumulated strain energy. The ground motion in the 1906 earthquake in San Francisco was essentially horizontal. Typically, in California, a single major earthquake is followed by a modest sequence of much smaller aftershocks. In contrast, the Missouri and South Carolina quakes came in sequences of three major shocks of comparable magnitude, accompanied by an extended sequence of aftershocks. In these intraplate quakes, the motion of the ground was essentially vertical.

In both the New Madrid and Charleston earthquakes, loud roars were heard over about as much distance as the shocks themselves were felt. In New Madrid, at least, a sulfurous odor filled

A large craterlet formed by the Charleston earthquake, 1886. United States Geological Survey, Denver.

the air. We don't know why. We know very little about the mechanisms involved in such intraplate earthquakes, but the two described here illustrate effects that one might expect from a gigantic internal explosion, odd as such a concept may appear.

Far larger in magnitude—and perhaps in its effects on the process of human civilization—was a mammoth seizure of the Earth that took place outside the harbor of Lisbon, Portugal, in the year 1755. Three major shocks struck in rapid succession, at 9:50 A.M. on November 1, and ten minutes later at 10:00 A.M. The third came at noon. The first shock, estimated to have been at magnitude 9.0, was the greatest and lasted for six or seven minutes. It was also the greatest earthquake in recorded history.

At this time, Lisbon was a wealthy capital and the principal city of the Inquisition. It was essentially demolished in the shocks and their aftermath. All of its finest buildings—churches and palaces—were destroyed or severely damaged. Most shops and

View of Lisbon following the earthquake of 1755. New York Public Library, New York.

houses were razed, extensive damage being caused by the resultant fires. In all, 50,000 to 60,000 people were killed. Severe damage occurred throughout the Iberian Peninsula, including Seville, Cordova, and Granada, Spain, and there was damage in North Africa at Fez and Mequinez. Tremors from the Lisbon earthquake were felt in France, Switzerland, Italy, the Netherlands, Germany, and Great Britain and as far north as Fahlun, Sweden, 1,850 miles away—in all, over a territory of two million square miles. And besides the shocks and the fires, a tsunami struck. The sea first retreated in the harbor, then swept back, engulfing much of the city with waves up to fifty feet high. The tsunami reached several places in the North Atlantic: twelve-foot waves broke on the shores of Antigua in the West Indies, 3,540 miles across the ocean.

As at New Madrid and Charleston, this was an intraplate earthquake, and for this vicinity it was one of a kind. Nothing of this magnitude has been recorded before or since. The fact that the rapid sequence of shocks occurred on All Saints' Day was by no means lost on the populace; indeed, the toll might have been less had not so many people been at Mass. However great the physical damage it caused, the shock was perhaps greater in the realm of ideas, notably to the religious concept of God as a benevolent deity and to the philosophical notion of humanity and nature being at peace together. Was this divine retribution? Was all lost? This devastating event soon pitted two of the era's greatest thinkers against each other: François Marie Arouet (Voltaire) and Jean Jacques Rousseau.

In the first place, it was clear to many that God in His anger had destroyed Lisbon. With the earthquake occurring during Mass on a solemn church festival, God must have been condemning the irreverent attitude to His services and holy days. Indeed, God had to be saying that the very saints themselves had asked Him to bring His wrath down on Lisbon and its inhabitants. Like Sodom and Gomorrah, the city had to be destroyed. Many of the devout felt that all was lost and that they were powerless in a broken and sinful world. The wrathful God of the Old Testament had replaced the loving Father of the New Testament. Throughout Europe, clergy from all churches echoed the dismay. "There is no divine visitation which is likely to have so general an influence on sinners as an earthquake," said John Wesley, and the Bishop of Chichester dourly commented, "When the Almighty speaks in such tremendous language, he must not speak in vain.

The Jesuit Gabriel Malagrida, saintly, brave, sometimes erratic, and an intimate at one time to the Portuguese royalty, was one of the more outspoken. He wrote:

> Learn, O Lisbon, that the destroyers of our houses, palaces, churches, and convents, the cause of the death of so many people and of the flames that devoured such vast treasures, are your abominable sins, and not comets, stars, vapours and exhalations, and similar natural phenomena. Tragic Lisbon is now a mound of ruins. Would that it were less difficult to think of some method of restoring the place; but it has been abandoned, and the refugees from the city live in despair. As for the dead, what a great harvest of sinful souls such disasters send to Hell! It is scandalous to pretend the earthquake was just a natural event, for if that be true, there is no need to repent and try to avert the wrath of God, and not even the Devil himself could invent a false idea more likely to lead us all to irreparable ruin. Holy people had prophesied the earthquake was coming, yet the city continued in its sinful ways without a care for the future. Now, indeed, the case of Lisbon is desperate. It is necessary to devote all our strength and purpose to the task of repentance. Would to God we could see as much determination and fervour for this necessary exercise as are devoted to the erection of huts and new buildings! Does being billeted in the country outside the city areas put us outside the jurisdiction of God? God undoubtedly wishes to exercise His love and mercy, but be sure that wherever we are, He is watching, scourge in hand.

Such pronouncements by Gabriel Malagrida were anathema to the Marques de Pombal, the man responsible for reestablishing

Lisbon, and he asked the Papal Nuncio to banish Malagrida. The Jesuit was jailed and then brought before the Inquisition, that least-civilized aspect of Christianity, who found him guilty as a heretic and put him to death by strangulation in a horrid public display at the torchlight end of an *auto-da-fé*.

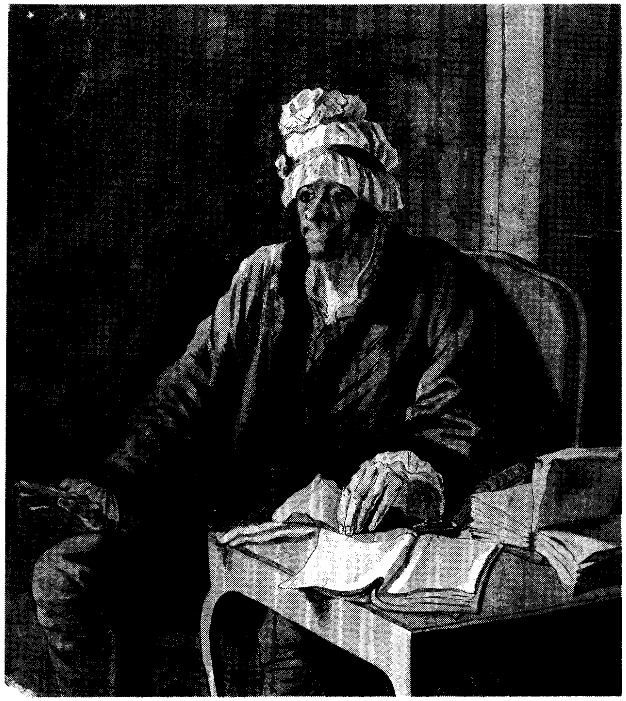
Elsewhere, in what had been called Europe's Enlightenment, many were turning away from orthodox Christianity (and its excess baggage, like the Inquisition) and filling the resultant vacuum with a search for God in Nature. The philosopher of divine Nature was Rousseau; its artists were Turner and Constable; its poets, Coleridge and Wordsworth. Nature was given divine stature, and the more simply and the closer Man lived to Nature, the more virtuous he became. Man and Nature were seen at peace with each other. In "The Tables Turned," Wordsworth could write:

> One impulse from a vernal wood
> May teach you more of man,
> Of moral evil and of good,
> Than all the sages can.
>
> Sweet is the lore which Nature brings;
> Our meddling intellect
> Misshapes the beauteous form of things—
> We murder to dissect.

This sort of beatific philosophizing was too much for the hard-nosed thinker Voltaire. He would have none of it. To Rousseau's philosophy, as expounded in his *Discourse on the Origin of Inequality*, Voltaire replied, "No one has ever used so much intelligence to persuade us to be stupid. After reading your book one feels that one ought to walk on all fours. Unfortunately during the last sixty years I have lost the habit."

With the Lisbon earthquake, Voltaire had a means for scuttling the "*tout est bien*" philosophy. In 1756, he wrote and published his *Poem upon the Lisbon Disaster*, arguing that we have to admit the existence of physical evil in this world. We should henceforth contemplate ruined Lisbon and stop deluding ourselves that Man and Nature are at peace with one another. Instead of the silly cliché "*tout est bien*," the truth was otherwise: "*Le mal est sur la terre.*"

Voltaire went even further in his poem. Everyone, he said, would now have to admit that mankind dare not hope for a safe

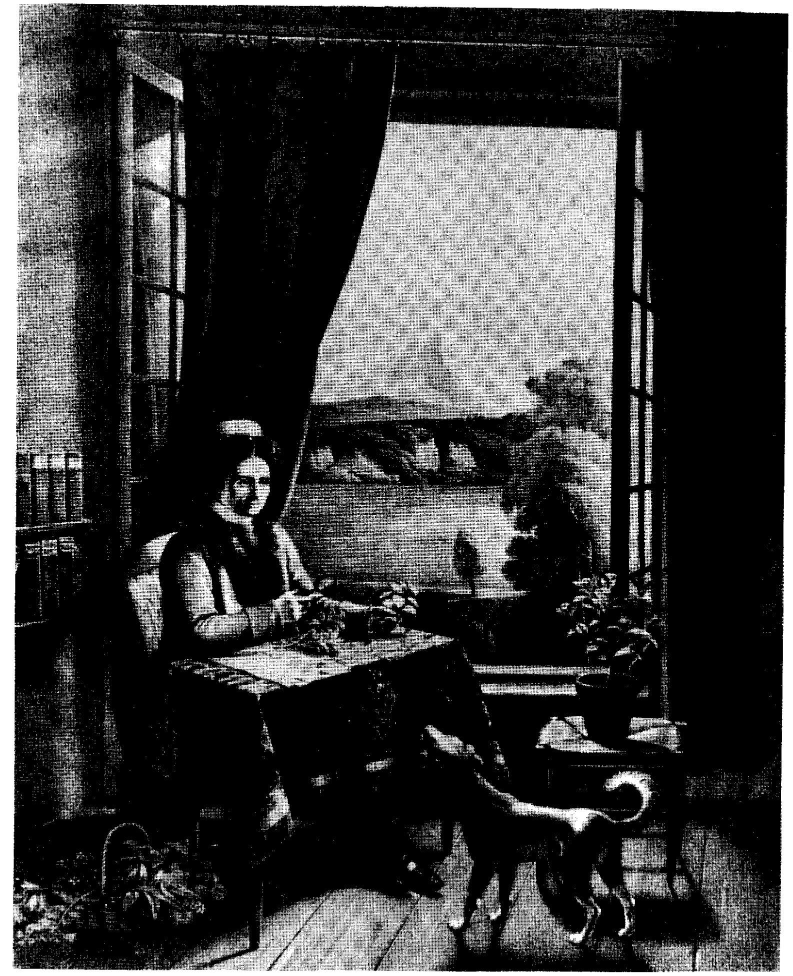


oltaire (1694–1778). British useum, London.

life in this world under the benevolent protection of a divine providence that could be counted on to reward virtuous behavior. Humans were weak, helpless, ignorant of their destiny, and exposed to fearful dangers. The optimism of the age would have to be replaced by little more than apprehensive hope.

> What may the most exalted spirit do?
> Nothing. The Book of Fate is closed to view.
> Man, self-estranged, is enemy to man,
> Knows not his origin, his place or plan,
> Is a tormented atom, which at last
> Must condescend to be the earth's repast;
> Yes, but a thinking particle, whose eyes
> Have measured the whole circuit of the skies.
> We launch ourselves, like missiles, at the unknown,
> Unknowing as we are, even of our own.

Rousseau rejected Voltaire's gloomy conclusions. The optimism Voltaire's poem attacked had, he said, helped him endure the



Jean-Jacques Rousseau (1712–1778). Bibliothèque–Publique et Universitaire Genève, Geneva.

unendurable. Voltaire argued that an omnipotent God could have prevented the Lisbon earthquake; Rousseau countered that God had not done better by mankind because He did not, He could not, exercise control of things through Nature.

To anyone even minimally influenced by the stunning rise of science since these men had their say, and by the rise of the scientific method of proposing a hypothesis about the nature of reality and then framing tests of those hypotheses, this second-guessing of God and His unfathomable capacities may seem rather quaint. The largely unpredictable violence of earthly seizures appears to such people as the outcome of only partly understood processes that take place without moral judgments about the behaviour of the planet's temporary inhabitants. For most such people, evil is a result only of human activity, while planetary processes are neutral, causing what can be thought of loosely as "evil" only to the extent that morally unmotivated events can be imagined to be malevolent. If people living in a city located in a region where earthquakes are almost certain to occur at some point wish to refer to them, when they eventually do happen, as "acts of God," this is their privilege, but such events have little to do with the real world as we now understand it. Bad things can happen to good people.

Nevertheless, the matter raised by Rousseau and Voltaire still haunts us. Is Mother Earth benign? For some one who has suffered through a natural disaster of any kind, it would be hard to float off in Wordsworthian ecstasies and Rousseauvian optimism. On the other hand, this is the only planet we've got. It's a plentiful place, the platform of life—indeed, perhaps the *only* platform for life in the universe—but it is quite capable of taking life abruptly away. Indeed, the question is now different from that framed by Rousseau and Voltaire. It has to do with the suitability of mankind, but that must wait (here at least) for more tales of the Earth.

CHAPTER THREE

There Have Been Frequent Flooding and Sea-Level Change Events on Earth

Someone once said that there is nothing like a waiting noose to focus the mind. It is possible to argue that the mind is equally focused by waters rising above one's feet of clay. Most of the people in the world still live along watercourses or near seacoasts, as water is a life-sustaining element. But water, impelled by planetary forces and following its own agenda, often rises up and destroys. Floods are so common, in fact, that we tend to lose track of them as a matter of importance in a catalog of natural disasters. Few floods cause great, concentrated losses of life, except the ones that—remote from our lives—carry off tens of thousands of citizens in places like Bangladesh. We are more apt to think of floods as photographs of people making do, sloshing around in a few feet of water in the aftermath of a hurricane or surprisingly heavy rainstorm, their houses full of muck, their tax and other records, perhaps, a soggy mass of useless pulp. The U.S. Weather Bureau tracks hurricanes these days, and local governments, warned well in advance, tyically evacuate their citizens. After a century of levee building and other engineering works designed to "tame" rivers, we don't expect our watercourses to rise up from their snug, ordained paths and threaten our lives and livelihoods. But in terms of property damage, floods are by far the greatest natural hazard humans face. In the 1970s, the total cost that society bore