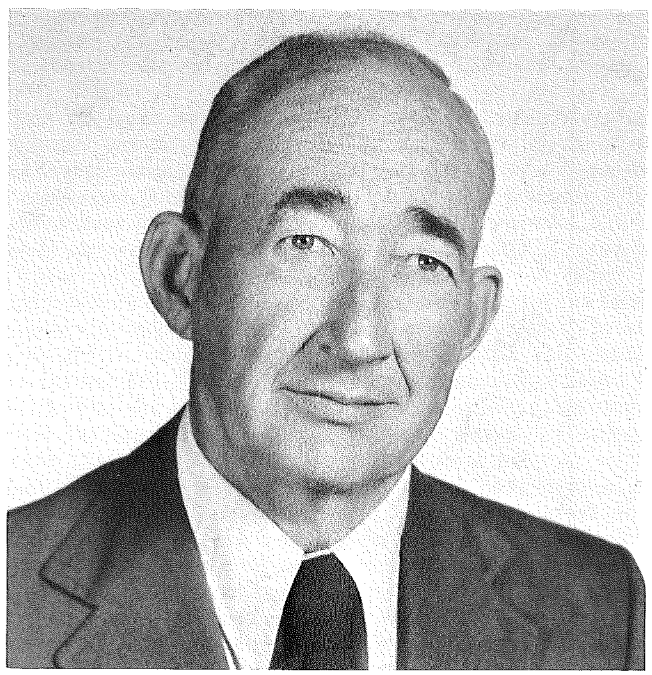
FIELD NOTES FROM THE ARIZONA BUREAU OF MINES

Vol. 6, No. 1 Earth Science and Mineral Resources in Arizona March, 1976

Earthquakes in Arizona

by John S. Sumner



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Fortunately, our state has been relatively free from the awesome devastation by earthquakes that has become so well-known elsewhere. But we cannot be lulled into believing that it will never happen here, because there have been earthquakes in Arizona's past and there will be more in the future. Earthquakes are an important part of the earth's natural dynamic processes, and we can learn to live with them. Seismology is the study of these earth vibrations, and it has taught us much of what we know about the earth's interior. This article is intended to be a brief review of earthquakes, particularly as they might affect people living in Arizona.

Arizona's Historic Earthquakes

The southwestern part of this state is not far from the San Andreas fault system, and indeed some related fault structures must now underlie this region. Yuma has felt tremors on several occasions from disturbances whose epicenters were located in nearby California and Mexico. Noteworthy seismic vibrations were felt in the Yuma area in 1968, 1948, 1947, 1942, 1940, and 1934 and continuing back in time at irregular intervals as long as can be remembered. The vibrational intensities felt in Yuma have caused damage to irrigation systems, and there was a considerable property loss sustained from the Imperial Valley earthquake of May 18, 1940.

The most devastating Arizona earthquake was the May 3, 1887 event, felt extensively in the southeastern part of the state. It destroyed the village of Charleston (Ready, 1962) on the San Pedro River near Tombstone and killed 42 people in Bavispe, Sonora, the largest town (1,500 people) in the region. Tucson was strongly affected, and the San Xavier Mission was damaged as were many structures in the Old Pueblo. The *Arizona Citizen* carried many stories on the event, as did all major newspapers of the time in North America.

From eyewitness accounts, the 1887 event must have been one of the most severe in historic times on this continent. The following version was presented in *Arizona Highways* of April 1940 by James G. Wolf:

> I was over in the Huachuca mountains on May 2nd, 1887, when suddenly all the ground around me commenced to ripple and wave. It rose in billows to a height of two or three feet and would then drop almost in its old place, but leaving pronounced cracks.
>
> The suddenness of it dazed me for one wild minute and I wondered if what I was seeing was actually occurring. I was panicked, but finally managed to calm down enough to figure out exactly what I had to eat and drink the previous few days. In that way I calculated for sure I had been all out of snakebite preventive for many days, and thus I knew an earthquake was quaking.
>
> The rocky ledges along the sides of the Huachucas rose up and fell outward, breaking into all sizes of boulders that rolled down the mountain sides, snapping off all trees and brush that were in their path . . . .
>
> I could see deer, coyotes and rabbits running from the hills. The wild cattle from along the San Pedro, who had never known what fear was before and only one generation back had scattered the Mormon Battalion, just stuck their tails straight into the air and, with eyes popping out, beat it for elsewhere, no two of them in the same direction.
>
> The ground was heaving all around and there was nothing to indicate where a really safe refuge was to be found, but you could see their main idea was to be somewhere else immediately. I felt exactly the same way myself . . . .
>
> On my way to Charleston from the Huachucas, I saw sheets of water spurting into the air at many places as I neared the river. Later I learned from others, this had occurred in hundreds of places on both sides of the river and for its entire length. The quake had shattered rock strata and this underground water escaped through the fissures thus made. Some of these new springs flowed a short time. A few flowed for a month and a very few longer than that . . . .

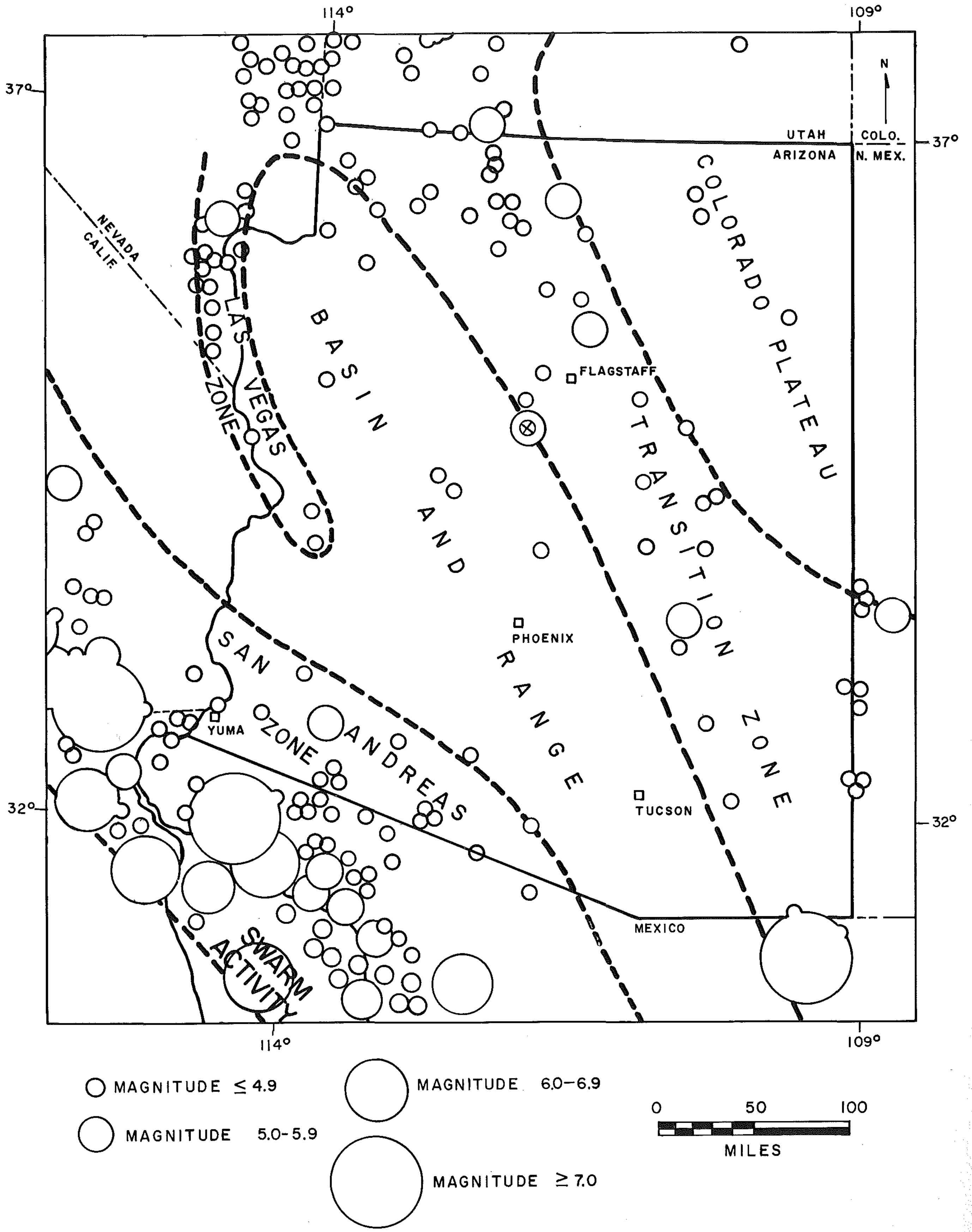

Figure 1. Seismicity map of Arizona. Note that the interpreted seismic zone boundaries are different than the related physiographic province boundaries, but that they have been given the same names.

One still-visible 7-meter-high scarp from the 1887 temblor extends for almost 100 km south from the border near San Bernardino, Arizona, to near Bavispe, Sonora. Good scientific accounts of this earthquake are to be found in reports by Aguilera (1920), Richter (1958) and Goodfellow (1888).

The most recent Arizona earthquake occurred on February 3, 1976 in Chino Valley northeast of Prescott with a Richter magnitude of 5.2. The location is shown with an X on Figure 1. Two aftershocks were felt, and numerous smaller tremors were recorded. This earthquake could have been damaging if the area was more habitated. Effects of this temblor were observed and reported from Clarkdale by Paul Handverger, a former member of the Department of Geosciences, the University of Arizona.

The Seismicity of Arizona

With sufficient seismic information about an area, it is possible to make a map of earthquake activity. Figure 1 is a compilation from several sources, including U.S. Geological Survey records, Sturgul and Irwin (1971), and Fugro, Inc. (1975). Reliable location and magnitude data from 1850 to the present are plotted as epicentral circles. It is obvious that most of the reliable data are the most recently obtained values, so that the map is only a biased sample of the true seismicity over the past 126 years. Nevertheless, patterns in activity are starting to emerge, and it is now possible to see trends.

The San Andreas zone is related to the strike-slip fault boundary between the Americas and the Pacific lithospheric plates. Although several faults and mechanisms are evident, the predominant type of displacement is as shown on Figure 2a. The area between the heavier lines on Figure 2a is a "spreading center" where the earth's crust is being extended. On or near continents, such an area is typically a depression, such as the Salton Sea area, and volcanism can occur here.

The "transition zone" of Figure 1 probably has the type of fault displacement shown on Figure 2b. This supposition is based on studies by Smith and Sbar (1974) in Utah and northern Arizona and field observations of Quaternary and Holocene fault scarps.

The central part of the Colorado Plateau physiographic province is relatively quiescent, which correlates with surface

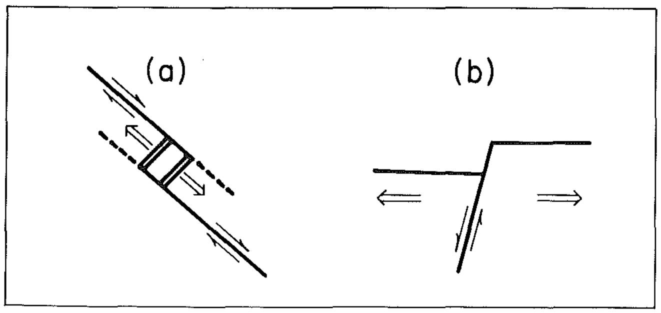

Figure 2. Fault motions. (a) Plan view of strike-slip movement such as on the San Andreas fault. (b) Section view of a normal or gravity fault.

geological observations. The higher heat flow in the Basin and Range province may indicate a more plastic behavior of depths in the crust, allowing a slow yielding to stress rather than a brittle failure.

Besides geological observation of structure and faulting, heat flow studies, seismic observations of crustal structure, and gravity data support the interpretation of the seismic zones of Figure 1. However, future seismic data probably will modify the zone interpretation and will certainly add to our understanding of the seismicity of the state.

Causes of Earthquakes

According to the recently developed plate tectonic theory of Isacks, Oliver, and Sykes, (1968), the earth's surface is divided into several rigid plates consisting of a 70-km thickness of strong, lithospheric rock, and these plates are in motion. Most of the observed earthquakes occur at the contacts between lithospheric plates. The plate boundaries may be in tension, as at ocean ridges, in compression as at oceanic trenches, or the plate edges may be sliding past one another in a type of contact known as a transform fault (Fig. 2a). Plate edges are usually found in oceanic areas where the lithosphere is thinner and weaker, but they are sometimes found on the geologically more complex continents. Earthquake mechanisms at plate edges are fairly well observed and understood, but the energy release mechanism within plates is more complex. Strain builds up to the point where the strength of the rock is exceeded, then the material ruptures.

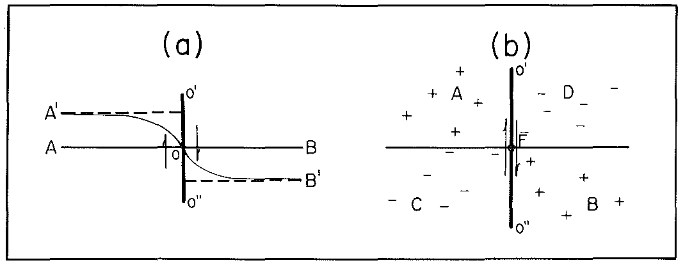

Figure 3. Earthquake mechanisms. (a) Strain buildup. (b) Elastic rebound showing relative direction of ground movement.

After the great 1906 San Francisco earthquake, an acceptable mechanism was proposed (Fig. 3a) to explain the cause of this type of earthquake. In plan view, the rock A and B on either side of a fault zone O'O" is gradually displaced to a position A'OB'. When stresses exceed the strength of the fault, it breaks, and the line A'O springs to A'O' and the line OB' becomes O"B', relieving the strain within the region. This concept has been called the elastic rebound theory, and it can be used to explain the failure mechanism for many earthquakes. The point O at which the fault first breaks is called the focus of the earthquake. It is usually below the surface. The place on the surface vertically above the focus at which the effects are most severe is called the epicenter.

There are two broad categories of seismic waves depending on whether the waves travel in the interior of a body or on the surface. These wave categories are called body waves and surface waves. The type of body wave propagated in a longitudinal direction, like a sound wave in air, is the fastest and because it is the first to arrive at a seismograph station is called a primary wave. A secondary wave is slower and is due to a shearing or transverse motion. Surface waves are the slowest of the seismic waves, but they cause the most damage. One type of surface wave has a shearing motion with little or no vertical displacement and the other kind has motion which rotates in a vertical plane with a surface direction opposite to that of the propagation.

In the vicinity of the earthquake focus, a simplified model of elastic rebound would show primary wave motion as indicated on Figure 3b. If a person were at point A or B facing the focus F, ground movement would be toward him and could be called compressional. If our observer were at points C or D, the ground movement would be away, in a direction that could be called dilatational. Thus, the vicinity of the epicenter would be divided into four quadrants alternately compressional or dilatational, and if there were seismographs in these quadrants, it would be possible to interpret the orientation of the fault plane and the direction of relative movement. Ambiguities are possible, but aftershock data will usually be used to make the final interpretation. Of course, on a spherical earth, the fault plane solution becomes complicated by curved ray paths and spherical trigonometric relationships.

Seismic Observations

The major discontinuities within the earth have been identified by their body wave velocity characteristics. The boundaries of the earth's crust, mantle, and core can reflect or refract energy and the resulting patterns are detected at seismic stations on the earth's surface. From a number of repeated observations, it is possible to see that velocity generally increases with depth and that the outer core of the earth behaves like a fluid.

Before seismic instruments were in wide use, the strength of an earthquake could best be judged by the amount of damage imposed on the works of man. Earthquake intensity scales were devised, but they have been found to be rather subjective for the purposes of scientific study. The earthquake damage scale in present use is called the modified Mercalli (MM) intensity scale; it ranges in value from I (barely felt by some) to XII (super panic). Unfortunately, many people still do not understand that the more modern Richter magnitude scale, based on standardized instrument response and energy release, is not necessarily an earthquake damage scale.

The Richter magnitude scale is calibrated by the logarithmic displacement of a standard seismograph at a given distance from the focus. The reason for this type of calibration is that the total range in values of earthquake energy is very large and the logarithmic relationship compresses the scale. The magnitude M of a given earthquake is then defined as

$$M = \log A - \log A_o$$

where A is the initial primary (P) wave amplitude of the given earthquake and A_o is the P wave amplitude of a "zero" magnitude earthquake. Thus, it is possible to have a minus magnitude earthquake and because of the logarithmic scale a magnitude 8 earthquake is ten times greater than a magnitude 7 earthquake. It has been observed that small magnitude earthquakes are much more common than ones with larger magnitudes, and that no recorded earthquake has a magnitude of greater than 8.9 (Japan, 1933), although even larger events are possible.

The amount of energy released by an earthquake has been generally expressed by the empirical relationship

$$\log E = 11.4 + 1.5M$$

where E is the energy in ergs. A magnitude 5 earthquake has about the energy of a medium-sized atomic bomb.

Safety and Damage Prevention

Earthquake safety starts with pre-planning. Building on active faults is to be avoided and construction in earthquake-prone areas should be earthquake resistant. Our city planners and structural engineers are hopefully taking heed of these matters, but there is much that an individual can do for protection.

A single-story dwelling can suffer much damage by oscillatory ground motion as is illustrated in Figure 4. Masonry walls are heavy, frequently loosely bound, and may support a heavy roof. Cross braces, tie rods, or at least adequate roof supports can readily prevent a structure from collapsing under earthquake-imposed lateral loads. Frame buildings are relatively light in weight, and they often have shear wall construction and cross braces, which have usually allowed these buildings to survive with only minor damage. Yanev (1974) has several good suggestions for minimizing damage to structures.

If an earthquake occurs, an individual should remember how his environment will react and should act accordingly. Many parts of a building may be quite safe, such as in a doorway or under a heavy table, but ceilings may fall and light walls may collapse. If outside, avoid remaining near tall buildings that may shed window glass or cornices.

Much of the tragedy of earthquakes has come from the aftermath, due to panic, landslides, fire, and disease. The causes of these problems are rather obviously related to the civilized nature of our environment, and in time we may have to modify our ideas about construction practices and economic outcome.

Earthquake Prediction

Prediction is appealing because of the personal security offered by foretelling the time, place, and intensity of an earthquake. Eventually, prediction may indeed become well developed, but it is unlikely to be exact because of the large number of uncertainties concerning the earth's detailed structure at depth. There have been some successful earthquake predictions by Russian, Japanese, Chinese, and American scientists, which importantly indicate that we are improving our knowledge of earthquake phenomena.

Volcanic earthquakes and eruptions are often related to foreshocks, earth tilts, magnetic anomalies, and earth conductivity variations. Creepmeters can show the buildup of stress with time along faults (Fig. 3a). A considerable amount of scientific effort is being devoted to prediction, and many different concepts are being tested. Earthquake risk maps are useful, such as Figure 1, and in situ stress measurements are helpful, but they do not specify the occurrence time.

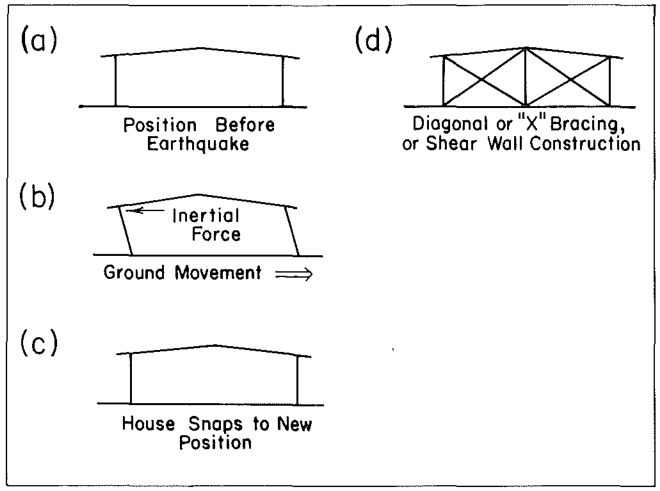

Figure 4. Dwelling damage in successive stages. (a) The original structure. (b) Ground motion with resulting inertial force in the opposite direction. (c) Second position of house. (d) Cross bracing of walls.

In 1969, Russian geophysicists (Fig. 5a) noted that there was a change in the ratio of compressional wave velocity (Vp) to shear wave velocity (Vs) just before an earthquake in the Garm region of the U.S.S.R. Each point on the graphs of Figure 5 shows a velocity ratio for a very small earthquake, less than 2.0 Richter magnitude. But there were two larger ones with Richter magnitudes of 4.2 and 5.4, and before each, the ratio at first decreased and then increased. The ratio had just regained its normal value when the large earthquakes occurred.

L.R. Sykes of Lamont-Doherty and A. Nur of Stanford have also tried the velocity-ratio prediction method shown on Figures 5b and 5c. As can be seen, the method certainly applies to the areas being tested. In fact, the Adirondack earthquake of 1971 was accurately predicted the day before it happened. However, the velocity-ratio method may not apply universally.

The reason for the drop and then buildup of velocity ratio seems to be due to the opening of microcracks throughout the region. The pore fluid already present in the rock flows into the new cracks. This increases the resistance of rock to fracture and also reduces the value of the compressional wave velocity. The effects delay the earthquake and cause a decrease in the velocity ratio. Additional pore fluids flow in more slowly from neighboring rocks to fill the empty spaces created. This causes the velocity ratio to increase again, while reducing the strength of the rock. By the time the original pore fluid pressure is recovered, or soon after, the earthquake is triggered.

Earthquake Control

It has been discovered (Fig. 6) that relative movement may take place without accompanying earthquakes along some faults of the San Andreas system. Parts of a fault may creep at a rate of up to 10 cm per year, while other parts may become locked and therefore accumulate strain energy. This energy will later be released, producing an earthquake.

It might be possible to inject a fluid into the locked, or sticking, portions of a fault, allowing the crustal blocks to slip past one

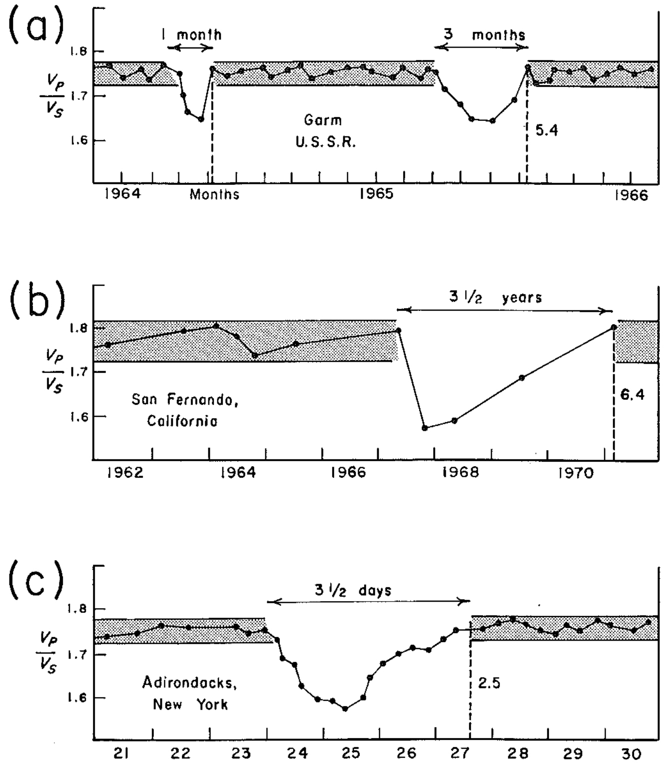

Figure 5. Ratios of compressional wave velocity (Vp) to shear wave velocity (Vs) plotted against time for earthquakes in three areas. (a) Garm, U.S.S.R. (b) San Fernando, California. (c) Adirondacks, New York.

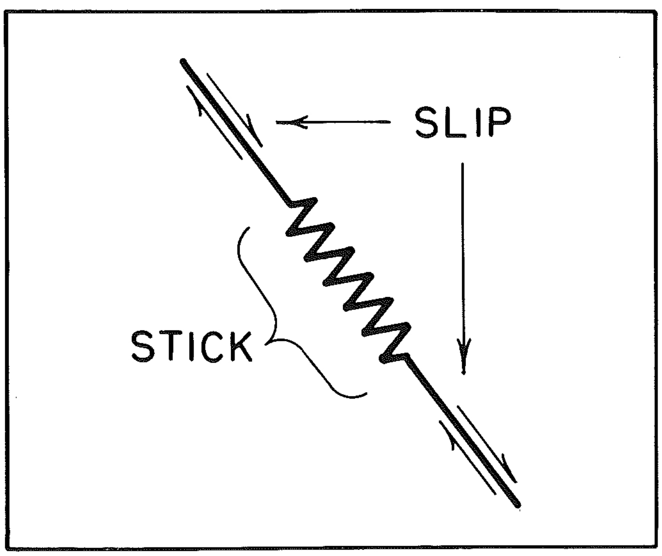

Figure 6. The stick-slip type of motion on some of the faults of the San Andreas system. Along some parts of the fault the motion becomes locked.

another with only small energy-dissipating tremors or, perhaps, none at all. The next best thing to preventing an earthquake is to produce a smaller earthquake at a more convenient time. A scheme for releasing the accumulating strain energy is shown on Figure 7.

Between 1962 and 1966, waste fluids were injected into a deep well in Denver's Rocky Mountain Arsenal. Small earthquakes followed. When the pumping stopped the earthquakes stopped. The case is strong for a cause-and-effect relationship between the injection of fluids and the triggering of earthquakes in the Denver region. However, there is a nagging legal question of responsibility for any damage resulting from these kinds of operations.

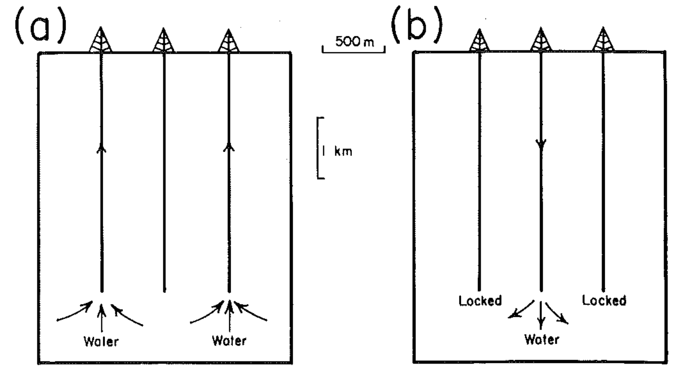

Figure 7. Control of earthquakes by fluid injection in deep drill holes. Pumping and injection are alternated, (a) to (b), to release small amounts of seismic energy at different points.

Water injection in the Rangely oil field of northwest Colorado has also demonstrated that earthquakes can be artificially produced.

Summary

Among the western states, Arizona has been relatively earthquake free, but there is no reason for complacency. Earthquakes and evidence of the past presage the earth's activity of the future. Earthquakes are the result of rupture-failure of rocks where displacement has exceeded the elastic limit. Most earthquakes occur at the boundaries of lithospheric plates, but on occasion severe quakes occur within plates.

Earthquake damage probably cannot be completely prevented but can be minimized in the interests of safety and economy of construction. There are cautionary measures to be taken in planning and building as well as during the aftermath of an earthquake.

It is possible to scientifically foretell seismic events, and limited success has been demonstrated in achieving this goal. The gradual release of seismic energy by fluid injection into fault zones may hold promise for future earthquake control.

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