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PROSPECTS FOR EARTHQUAKE PREDICTION AND CONTROL★

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ABSTRACT

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The San Andreas fault is viewed, according to the concepts of seafloor spreading and plate tectonics, as a transform fault that separates the Pacific and North American plates and along which relative movements of 2 to 6 cm/year have been taking place. The resulting strain can be released by creep, by earthquakes of moderate size, or (as near San Francisco and Los Angeles) by great earthquakes. Microearthquakes, as mapped by a dense seismograph network in central California, generally coincide with zones of the San Andreas fault system that are creeping. Microearthquakes are few and scattered in zones where elastic energy is being stored. Changes in the rate of strain, as recorded by tiltmeter arrays, have been observed before several earthquakes of about magnitude 4. Changes in fluid pressure may control timing of seismic activity and make it possible to control natural earthquakes by controlling variations in fluid pressure in fault zones. An experiment in earthquake control is underway at the Rangely oil field in Colorado, where the rates of fluid injection and withdrawal in experimental wells are being controlled.

INTRODUCTION

The concepts of sea-floor spreading and plate tectonics have had a revolutionary impact on all the earth sciences. They have had a particularly strong influence on research for earthquake prediction. It is clear from geologic and geodetic data that parts of western California have been moving northward with respect to points on the east. Much of this motion has been observed to take place along the San Andreas fault, which most geologists recognize as a major strike-slip fault; but there has been considerable uncertainty about the present rate of movement and the total movement in past geologic time. More critically, there has been uncertainty about the way in which a great strike-slip fault is terminated at its ends.

The suggestion by Wilson (1965) that the San Andreas fault was a transform fault that separates the Pacific and North American plates and terminates on the north and south at mid-oceanic ridges brought new insight to the solution of these problems (Fig.1). Atwater's

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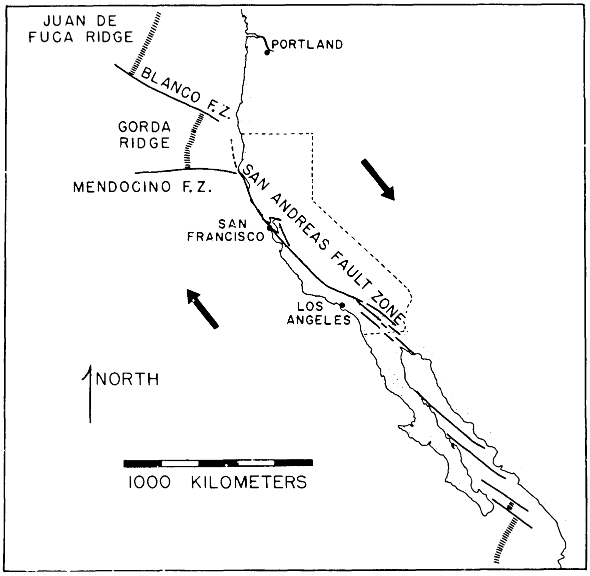

Fig.1. Schematic diagram of major plate boundaries of the San Andreas fault system in California and northern Mexico. Heavy arrows indicate relative movement between the Pacific and North American plates that is accomplished by right-lateral strike-slip displacement.

(1970) analysis of the patterns of magnetic anomalies of the oceanic plate has demonstrated that the Pacific plate has been moving northward at a rate of about 6 cm/year with respect to the North American plate. Future work can be expected to add new details to this model, but it now seems clear that relative movement of 2–6 cm/year must be accounted for along the length of the San Andreas fault. In places, such as the segment of the San Andreas fault between Hollister and Parkfield, the strain is being released by creep. In other places, for example, in the area south of Los Angeles, strain is released in earthquakes of moderate size ($M = 7.0$ or less). In two large sections of the fault, the segments nearest San Francisco and Los Angeles, strain is apparently being stored as elastic energy for future release in a great earthquake.

MICROEARTHQUAKE STUDIES

A major part of the earthquake prediction effort in the United States has been directed toward study of the distribution of microearthquakes in the transition zones between locked and creeping portions of the San Andreas fault. A very dense network of seismograph stations has been established in central California. This network has been gradually expanded from 33 stations in January 1969 to 81 stations in June 1971 (Fig.2), with accompanying improvement in the quality of the data. The data recorded in 1969 (Fig.3) clearly revealed patterns of faulting that strongly suggest microearthquake activity coincident with zones where the fault is creeping. The data show the termination of micro-

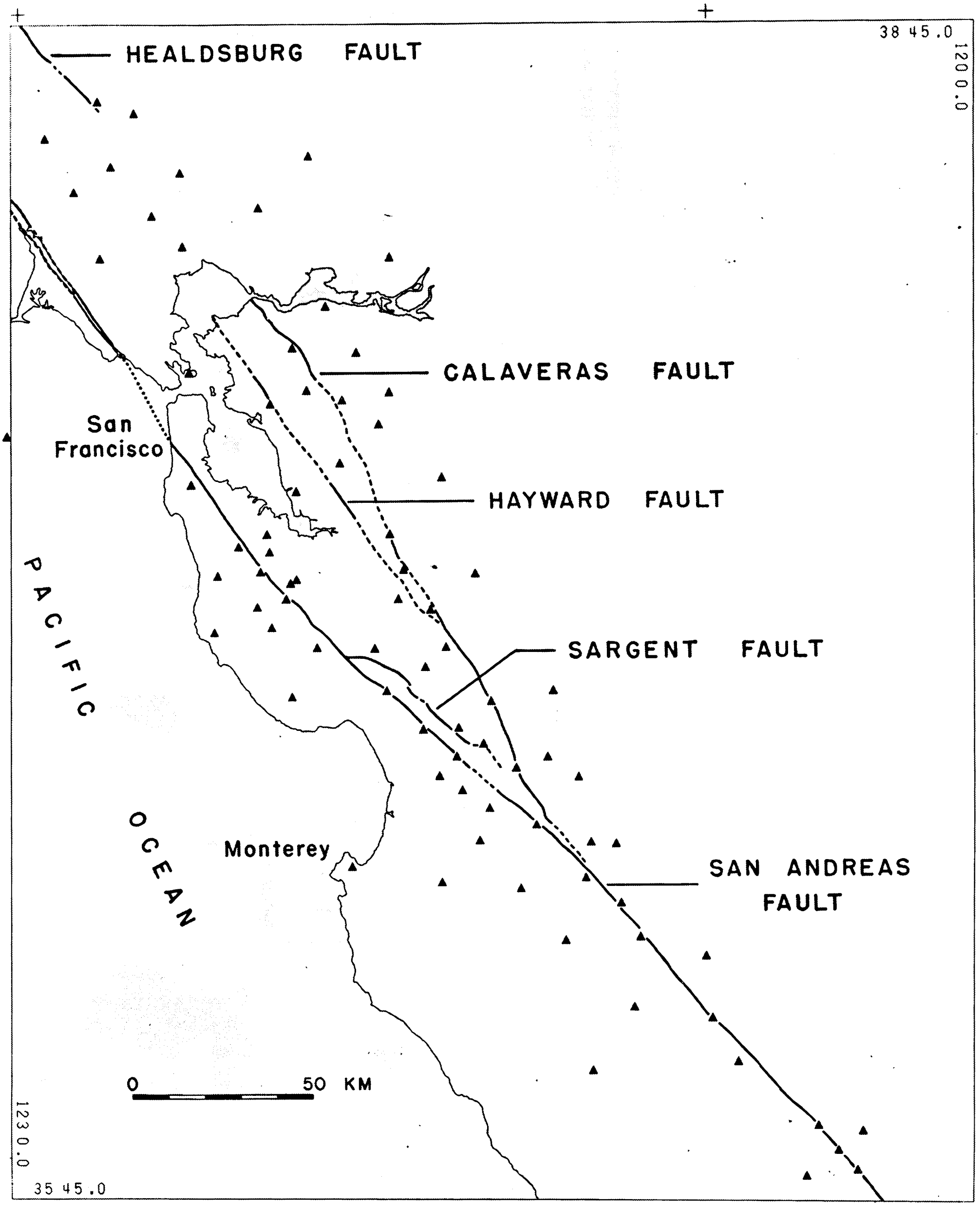

Fig.2. Location map of U.S. Geological Survey seismograph stations and major faults in central California.

earthquake activity at a point on the San Andreas fault where it is intersected by the Sargent fault. At least a part of the slip is transferred from the San Andreas to the Hayward and Calaveras faults east of San Francisco Bay. The pattern of earthquakes along these faults can be traced for a considerable distance. The data from 1970 and the first half of

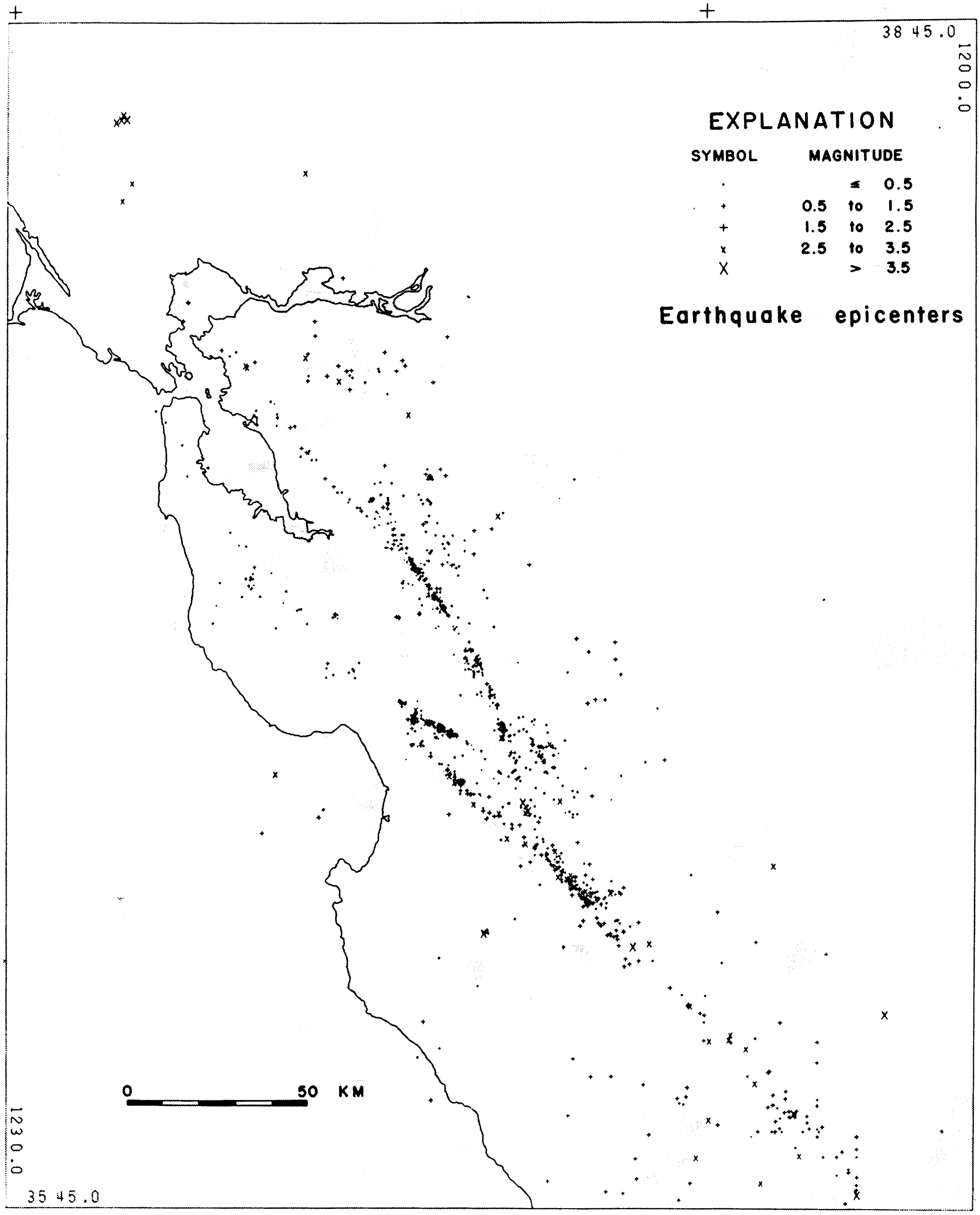

Fig.3. Central California earthquakes in 1969.

1971 (Fig.4 and 5), based on recordings from a greater number of seismograph stations, suggest the northward continuation of this movement in the vicinity of Santa Rosa.

The earthquakes on the San Francisco peninsula, where the San Andreas fault is now apparently locked, are few and scattered. We suspect that these earthquakes may be fore-

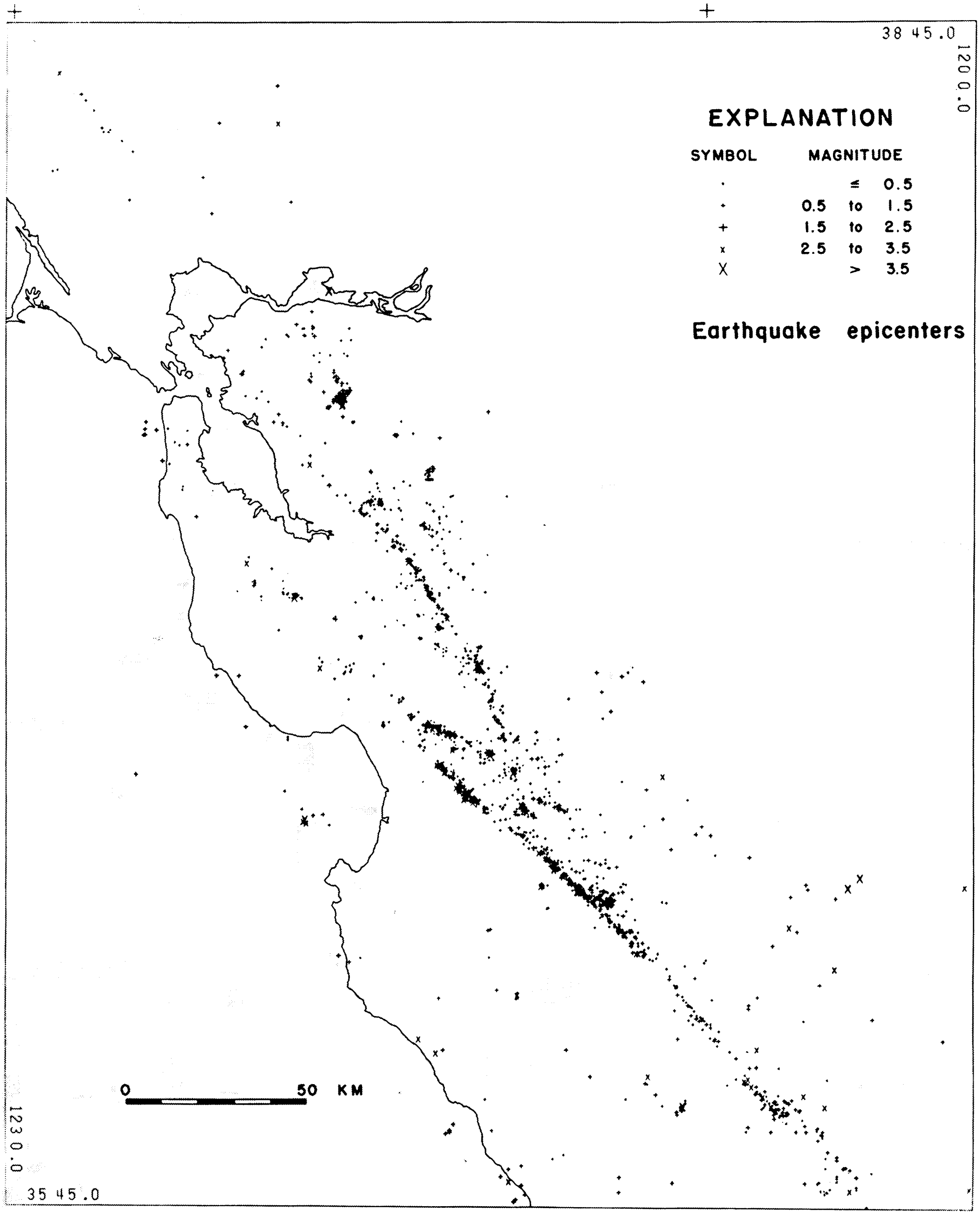

Fig.4. Central California earthquakes in 1970.

shocks that reflect regional strain build-up. Other interesting features of the data include the linear trends of earthquakes that branch from the main trends. In addition to the prominent branch at Hollister, other branches are suggested along the Hayward fault, particularly in the 1970 and 1971 data, that may reflect the distribution of the strain concentrations between locked and creeping portions of the fault.

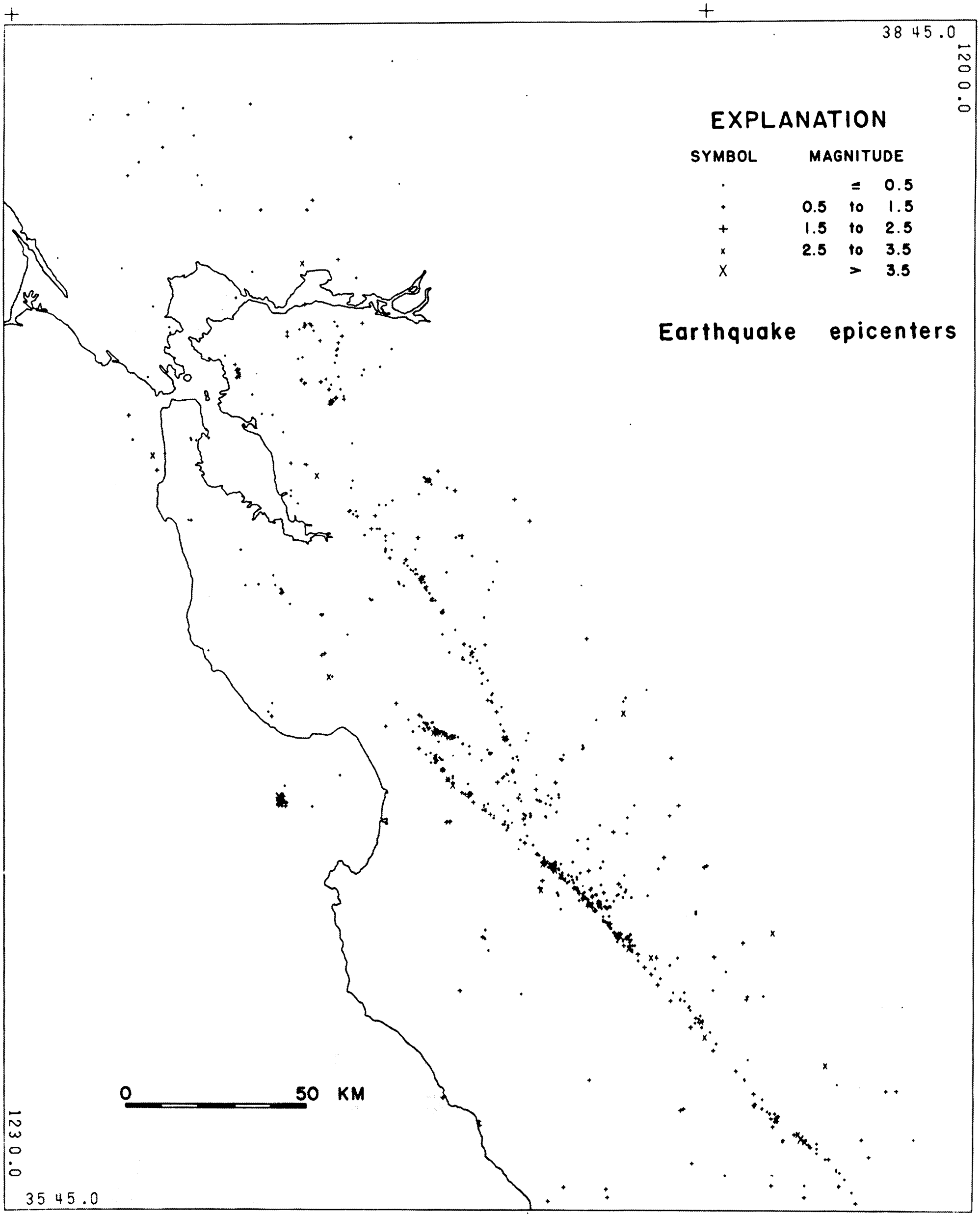

Fig.5. Central California earthquakes in the first six months of 1971.

In places, the trends of microearthquakes do not coincide directly with the fault traces identified from surface geology. This is partly the result of an inadequate model of crustal seismic velocity. At some locations, however, particularly on the east side of the Bay, earthquake patterns are defining fault trends that have not been identified by geologic mapping.

STRAIN MEASUREMENTS

The use of microearthquakes to define the boundaries of the major tectonic elements is regarded as a first step toward earthquake prediction. Further steps involve quantitative measurements of strain by various survey techniques. Such measurements are now being made, but the rate of strain relative to the precision of the measurements is such that several years are required for definitive results. A further step can be taken with the use of devices to record strain changes continuously in search of strain precursors to earthquakes. The tiltmeter seems to be the most economical instrument for continuous strain measurements, and arrays of tiltmeters have been installed for this purpose. Measurements have been recorded within tiltmeter arrays that contain several examples suggestive of premonitory strain changes before small earthquakes. There is frequently a change in the rate of tilt shortly before earthquakes of about magnitude 4 occur. The changes are small and are best seen in records that have been processed to remove the tidal tilts (Fig.6).

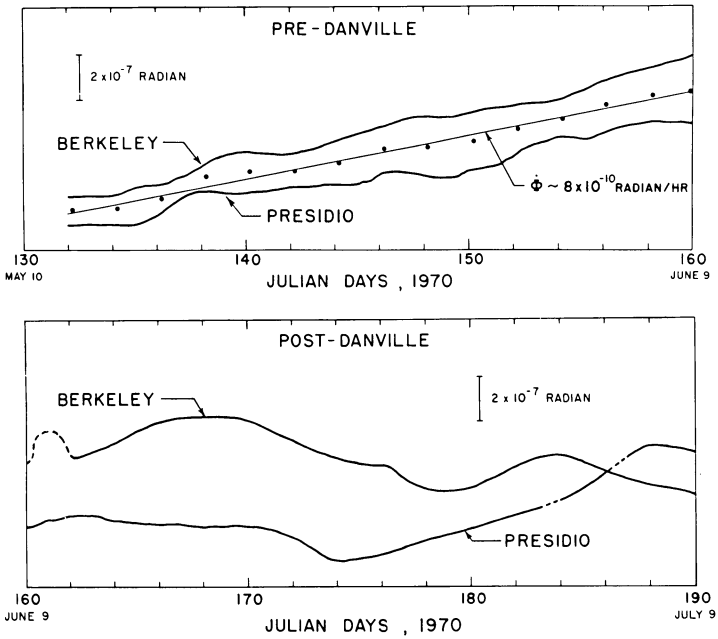

Fig.6. Possible anomalous tilt preceding a small earthquake at Danville, California; earth tides have been removed by computer processing. An earthquake occurred on June 10, 1970, accompanied by a change in the long-term trend and preceded by a short-term signal which put the instrument off scale. (From Wood, 1971.)

The research for precursors of this type presents a practical difficulty. It is probable that before all great earthquakes, there are changes in strain, magnetic and electric fields, and the pattern of microearthquakes; but if we must wait for a great earthquake to observe these changes, it may take a very long time to develop a practical system of prediction. Working with small earthquakes may be an alternative; but the premonitory signals are very small and may be obscured by background noise. To observe these small signals requires a very large number of instruments so that at least a few instruments are assured to be very near the source.

A DIRECT APPROACH TO EARTHQUAKE PREDICTION

An alternative strategy for earthquake prediction is based on intensive studies of the earthquake process followed by direct measurement within fault zones and possibly by intervention to control the time and magnitude of earthquakes.

Brace (1972, this volume) has presented an excellent review of laboratory work on the frictional properties of rocks currently in progress in the United States. Much of this work is directed toward a study of the factors that determine whether rocks will slide stably in slow creep or fail suddenly in violent stick-slip movement. The work suggests that changes in temperature, fluid pressure, and composition may all contribute to the differing characteristics of movements on a natural fault. A complete evaluation of these measurements as applied to real faults will require exploratory drilling in order to determine the properties of the fault zones.

An aspect of the laboratory work that is especially applicable to furthering our understanding of fault zones is the body of experimental results showing the effect of fluid pressure on rock strength (Fig.7). This effect was first proposed by Hubbert and Rubey (1959) to explain giant thrust faults; faults that would be physically impossible if there were not some mechanism to reduce the coefficient of friction to permit thin and weak thrust plates to slide on nearly horizontal planes. The physics of these observations is simple. The frictional forces that resist sliding along fault plane are proportional to a coefficient of friction and the normal stress acting across the fault plane. Fluid pressure

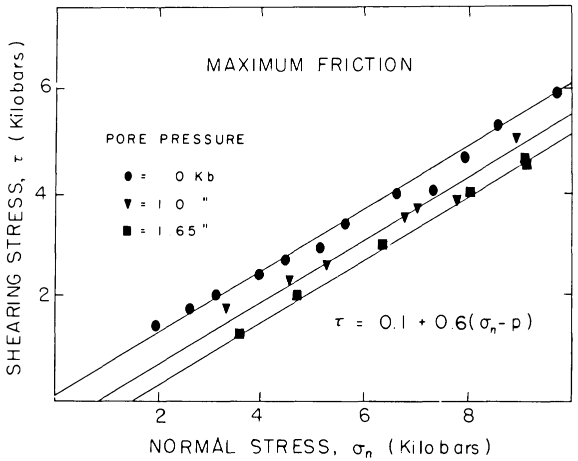

Fig.7. Shear versus normal stress for maximum friction on ground surfaces of water-saturated samples. (From Byerlee, 1967.)

reduces this normal force and weakens the rock. These observations lead directly to the conclusion that changes in fluid pressure may control the timing of seismic activity and to the possibility that control of variations in fluid pressure could lead to active control of natural earthquakes.

This phenomenon was first observed accidentally near Denver, Colorado, in the vicinity of a deep well used by the U.S. Army Corps of Engineers for disposal of waste fluids. Shortly after the beginning of fluid injection into this well of 12,000-ft. depth, a series of earthquakes commenced that has lasted for nearly 10 years. The time-space correlation of seismic activity compared with the location and rates of injection into the disposal well clearly demonstrates a causative relation between the earthquakes and fluid injection at this site (Healy et al., 1968).

To study this phenomenon, an experiment is being conducted by U.S. Geological Survey, in cooperation with the Chevron Oil Company, in an oil field at Rangely, Colorado. In this field, the oil is trapped in an anticlinal structure at a depth of approximately 2 km (Fig.8). About 1957, a program of fluid injection was begun to raise the pressure in the

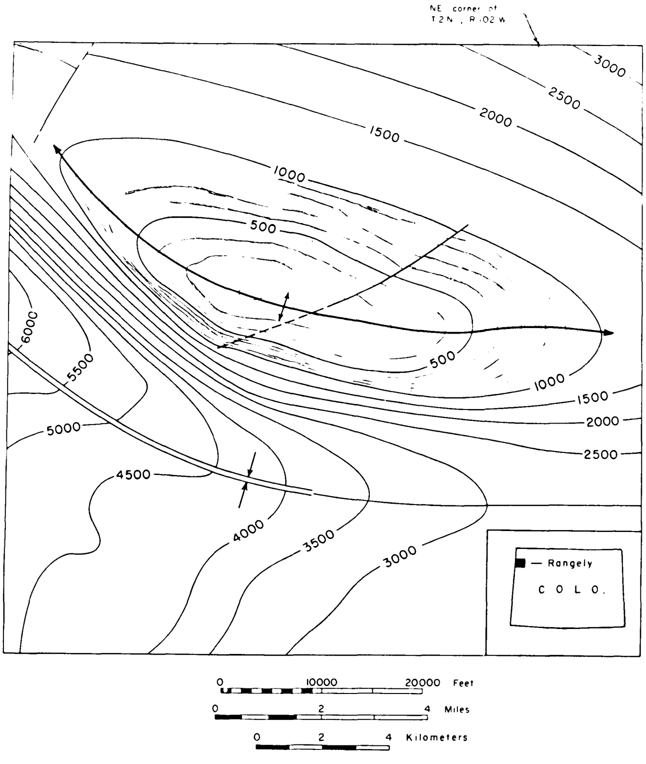

Fig.8. Structure contours (in ft. below sea-level) on the Weber Sandstone near Rangely, Colorado. The Rangely field is the closed anticline; faults shown are mapped from displacements in the elevation of the upper contact of the Weber Sandstone. Anticlinal and synclinal axes are denoted by arrows (Courtesy, Chevron Oil Company).

field in order to increase recovery of oil. Injection wells were at first drilled in a ring around the outside of the field. By 1969 pore pressure in the reservoir in the periphery of the field was raised to levels well above the original normal hydrostatic pressure in the field (Fig.9). A high-gain seismic array installed about 50 km northwest of Rangely in

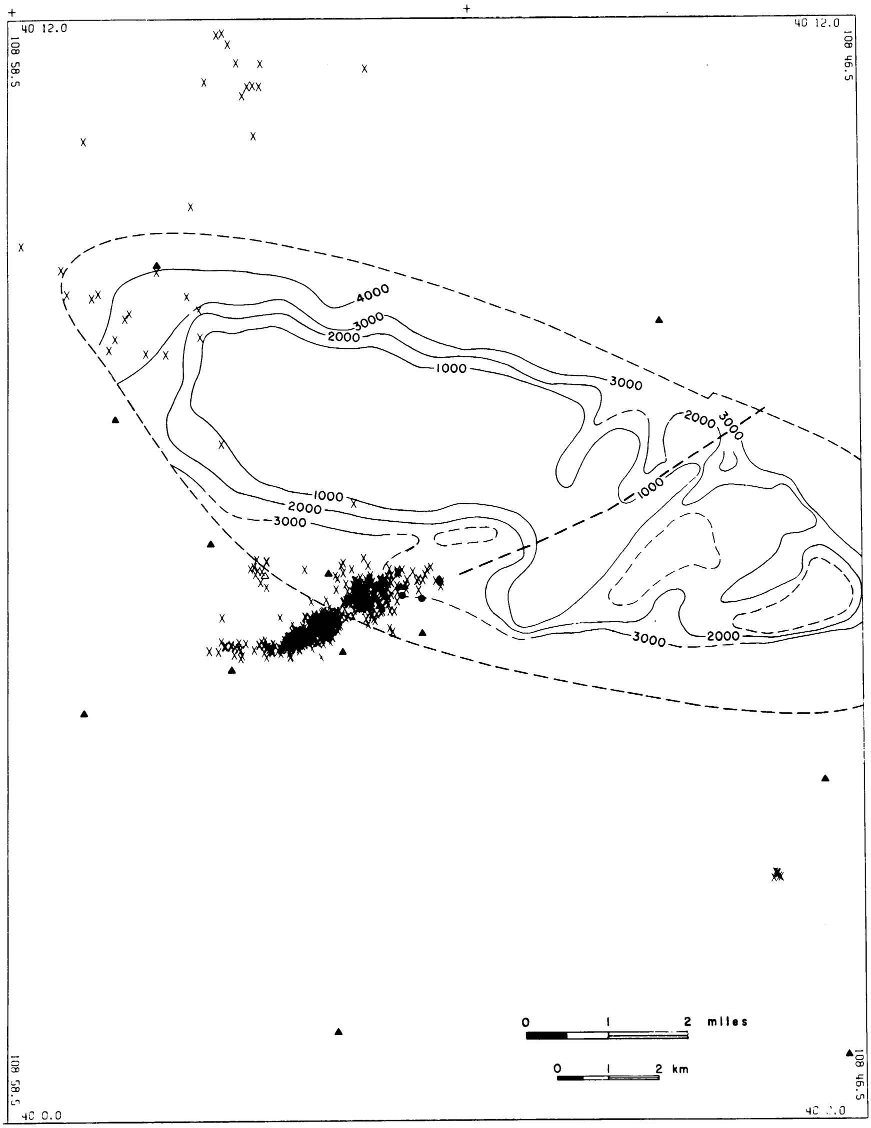

Fig.9. Distribution of bottom-hole fluid pressures in the Weber Sandstone reservoir in the Rangely oil field as of September 1969. Light dashed line is the boundary of the field; heavy dashed line is a fault mapped from the structure contours on top of the Weber Sandstone; ● = experimental well; ▲ = seismograph station; x = epicenters of earthquakes of $M_L > -0.5$ from October 1969 to October 1970. Pressure contours in pounds per square inch.

1962 made it possible to obtain approximate locations and count the number of earthquakes occurring in the field. Unfortunately, it was not possible to get an accurate distribution of earthquake activity in this region prior to the installation of the array; and even with the array, it was not possible to be certain that the earthquakes recorded were located within the field, but the data reveal continuous seismic activity in or near the oil field.

In October 1969, arrangements were made with the Chevron Oil Company to use four of the injection wells on the southwest flank of the field for a seismic experiment. A dense array of seismograph stations was installed in the vicinity of the oil field, and earthquakes were located accurately and counted carefully for one year. During this time, the rate of fluid injection in the four wells was normal. A vertical, planar zone of seismic activity was defined that passed through the base of the wells (Fig.10). In November 1970, fluid injection was terminated, and a program of removing the fluid from the wells was undertaken to reduce the fluid pressure in the earthquake zone.

At first the wells were allowed to flow under their own pressure. As the flow decreased, pumps were used to further reduce the fluid pressure in the seismic zone. During this period of fluid removal, the earthquake activity in the field was greatly reduced. Earthquake activity stopped completely within 1 km of the bottom of the injection wells (Fig. 10 and 11).

In May 1971, the wells were returned to their normal injection rate, and we are now awaiting the resumption of seismic activity. Due to difficulties in the pumping system, as of April 1972, the bottom-hole pressures have not returned to the original level.

We believe that the results of this experiment at Rangely, Colorado, will demonstrate the feasibility of earthquake control under some circumstances. The question that we now face is: How do we apply this knowledge to an active fault such as the San Andreas?

A typical cross section of seismic activity along a branch of the San Andreas fault (Fig. 12) shows that most of the earthquake activity occurs at depths shallower than 10 km, and virtually no earthquakes are recorded at depths greater than 15 km. This shallow seismic activity, which may be a property of earthquakes unique to the western United States, offers the possibility of drilling into the active seismic zones and attempting to control earthquake activity by controlling fluid pressure.

There are several strategies for modifying seismic behavior along a fault without creating a large earthquake. All involve the concept of first locking off portions of the fault and then allowing controlled slip to take place by increasing the fluid pressure between the locked points. The magnitude of any earthquake that results from fluid injection is limited by the distance between the locked points. In the area represented by Fig.12, for example, we would wish to first lock the portion of the fault shown on the right side of the figure and the portion to the left of the figure and then attempt to cause movement on the section of the fault where no earthquakes are occurring at present. No one at this time can reliably predict whether earthquake control will be feasible. Before any reasoned judgment on this matter can be reached, it will be necessary to have much more information about the physical properties and state of stress of the rocks within

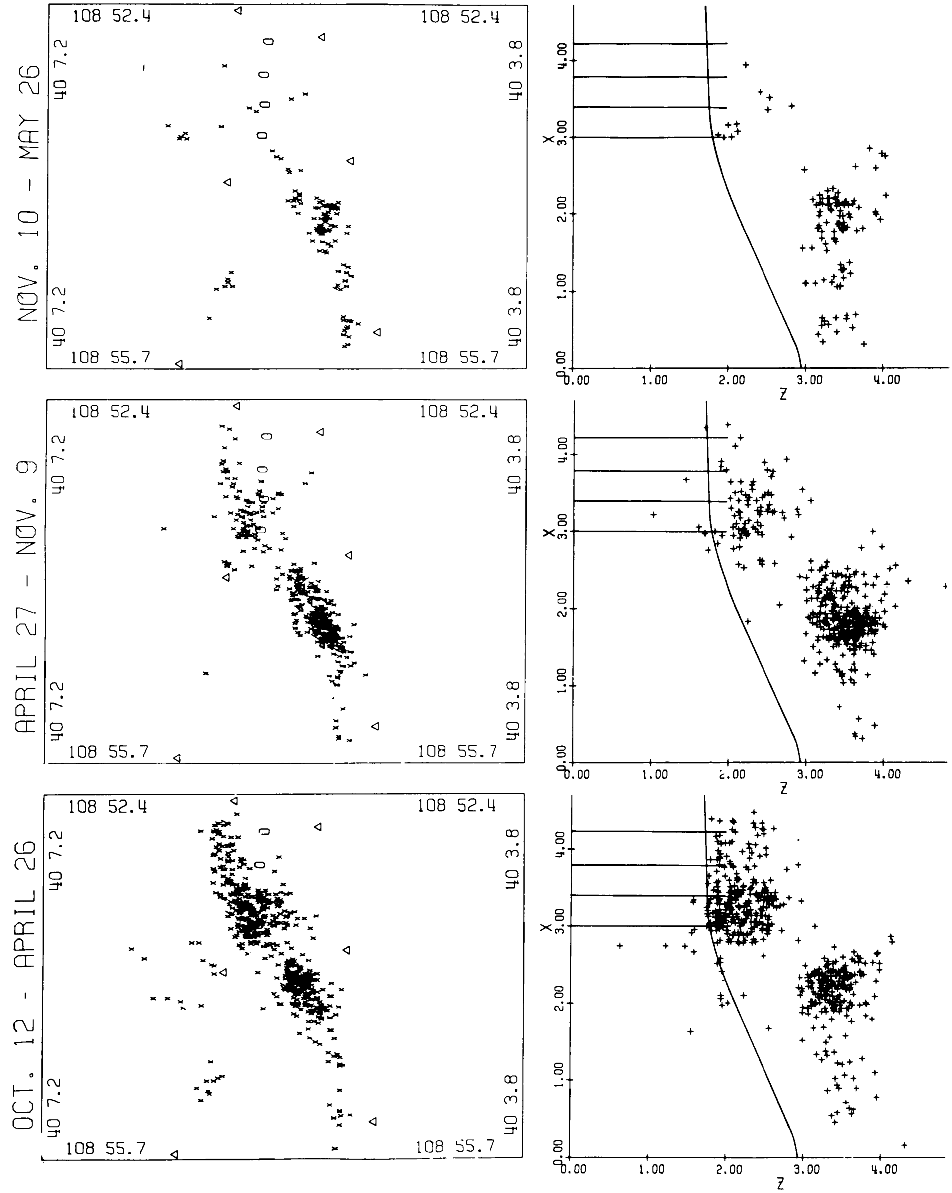

Fig.10. Epicenter map and cross sections showing earthquakes in the Rangely oil field. Open circles are experimental wells; triangles are seismograph stations. Vertical lines in cross sections represent experimental wells that penetrate the Weber Sandstone; top of Weber is denoted by a heavy line at 2–3 km depth. A and B are 6-month periods during fluid injection; C is the 6-month period of fluid withdrawal.

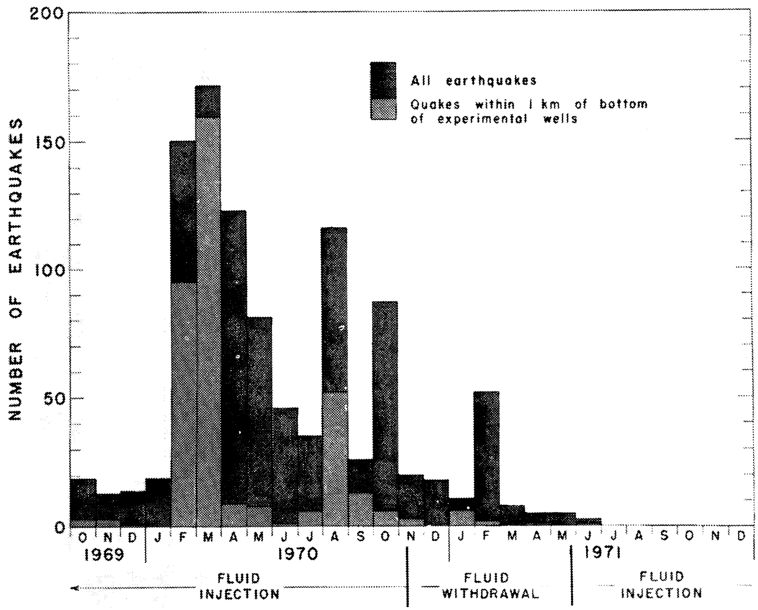

Fig.11. Monthly frequency of hypocenters of earthquakes in the Rangely oil field.

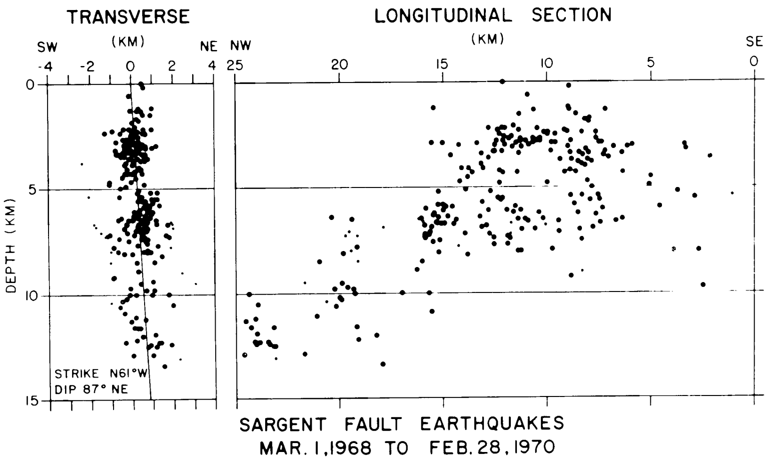

Fig.12. Earthquakes in the hypocentral zone along the San Andreas fault west of Hollister projected onto vertical planes perpendicular (left) and parallel (right) to the surface trace of the plane fitted by least squares to the hypocenters. Events that lay more than 2 standard deviations from the fitted plane are plotted as small dots.

fault zones. Such information can be obtained only by drilling many holes along the fault one proposes to control. We believe that the time for this exploratory drilling has arrived.

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