The Denver Earthquakes

Disposal of waste fluids by injection into a deep well
has triggered earthquakes near Denver, Colorado.

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Scientists and public officials are seriously considering the question of whether removal of fluid from a deeply buried reservoir will reduce the likelihood of a destructive earthquake near Denver, Colorado. The question at issue in the discussions is not so absurd as it might seem. It is widely, though not unanimously, held that injection of chemical-waste fluid into the reservoir in the Denver basin triggered the earthquakes. We attempt here to present the statistical evidence for correlating the two events—fluid injection and earthquakes—and to develop a hypothesis relating the two as cause and effect.

In 1961 a deep disposal well was completed for the U.S. Army at the Rocky Mountain Arsenal, northeast of Denver, Colorado. The well was drilled through 3638 meters of nearly flat-lying sedimentary rocks in the Denver basin into Precambrian crystalline rocks; its depth at completion was 3671 meters. The disposal of waste fluids from chemical-manufacturing operations at the arsenal had been a difficult problem, for which the deep well appeared to be an ideal solution. Injection of fluids on a routine basis was begun on 8 March 1962 and continued through 30 September 1963 at an average rate of about 21 million liters per month. No fluid was

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injected from October 1963 to August 1964. Then for a time fluid was put into the well under gravity flow at an average rate of about 7.5 million liters per month. Gravity flow was continued until 6 April 1965, when injection under pressure was resumed, at an average rate of 17 million liters per month. On 20 February 1966 injection of fluid was stopped because of a suggested connection between the well and earthquakes in the Denver area.

Two seismograph stations were operating in the Denver area in 1962, one by the Colorado School of Mines, at Bergen Park, about 34 kilometers west of Denver, the other at Regis College in Denver. Both stations began to record earthquakes from the region northeast of Denver, starting on 24 April 1962. As the sequence continued, the U.S. Geological Survey established several additional stations, and Yung-Liang Wang, a graduate student at the Colorado School of Mines, undertook a study of all the available seismic recordings. He located many of the earthquakes (1) within a region about 75 kilometers long, 40 kilometers wide, and 45 kilometers deep (Fig. 1, left). It was pointed out later that most of the earthquakes located by Wang were within 8 kilometers of the disposal well.

Father Joseph V. Downey, director of the Regis College Seismological Observatory, was among the first to suggest the possibility of a relationship between the disposal well and the earthquakes.

In November 1965 David Evans (2), a consulting geologist in Denver, showed a correlation between the volumes of fluid injected into the well and the number of earthquakes detected at Bergen Park, and publicly suggested that a direct relation did exist (Fig. 1, right).

The proximity of the earthquakes to the Denver metropolitan area created considerable public interest and concern. A number of the larger earthquakes, of Richter magnitude between 3 and 4, were felt over a wide area, and minor damage was reported near the epicenters. The sudden appearance of seismic activity close to a major city posed serious questions, and the possibility that the earthquakes were caused by operations at the Rocky Mountain Arsenal had to be evaluated as quickly as possible.

The Preliminary Program

The U.S. Army Corps of Engineers was called upon for technical support and advice, and the U.S. Geological Survey, in cooperation with the Corps of Engineers, began a program of investigation to evaluate the Evans theory. The Colorado School of Mines played a major role in those investigations, with support from the State of Colorado, the Corps of Engineers, and the Environmental Science Services Administration.

A search of the available instrumental and historical records was one of the first investigations undertaken. Any earthquakes that had occurred before the start of fluid injection would lessen the correlation between water injection and earthquake occurrence. The seismograph station at Bergen Park began operation only a few months before the start of water injection, and no earthquakes were recorded from the Denver area during that period. The station at Regis College had been in operation since 1909, but it is located in an area of high background noise and, for most of its history, was operated at low magnification. Thus, earthquakes of small magnitude could have

Table 1. Magnitude and frequency of occurrence of Denver earthquakes.

Year	Magnitude *								Total†
	1.5–1.9	2.0–2.4	2.5–2.9	3.0–3.4	3.5–3.9	4.0–4.4	4.5–4.9	5.0–5.4	
1962	72	29	4	2	1	1			189
1963	89	34	9	3	1	1			284
1964	26	8	6						72
1965	168	64	25	6	4				550
1966	61	18	3	2	1				186
1967	62	29	15	4	4	2		3	306
Total	478	182	62	17	11	4		3	1584
Average‡	83.2	30.5	9.4	2.6	1.4	0.4			

* To the nearest 0.1-magnitude unit.   † Total includes all earthquakes reported.   ‡ Average yearly activity 1962–66.

escaped detection by the local stations and the regional networks.

Between 1954 and 1959 a short-period seismograph station was operated by Warren Longley at the University of Colorado, Boulder. A search of the records from that station (3) revealed 13 events that might have been earthquakes in the Denver area, but all had occurred during normal working hours and were probably the result of construction blasting or disposal of explosives at the arsenal.

Hadsell (4), in a search of newspaper accounts and other historic records, uncovered reports of a number of earthquakes in Colorado in historic times. None had epicenters near the zone of current activity, with the possible exception of an earthquake in 1882 that was felt in the Denver-Boulder area as well as at other, widely separated points in Colorado. It appears that there is no evidence of seismic activity before 1962 similar to the earthquakes that have occurred since 1962.

A very dense network of seismic stations was established by the U.S. Geological Survey in the vicinity of the arsenal well, to obtain accurate locations of earthquake hypocenters. Slightly modified explosion seismology equipment was used, in eight small arrays. Each array consisted of six vertical seismometers at half-kilometer intervals, arranged in an L-shaped pattern, and two horizontal seismometers located at one of the vertical-seismometer positions. This special network was operated during January and February of 1966 for about 6 hours each day. During this 2-month period, between one and five earthquakes large enough to be located occurred each day during the hours of recording. A survey of the seismic velocities of the rocks penetrated by the well and a nearby seismic refraction profile were used to determine a velocity-depth function (5). The dense net of seismic stations and the unusually good control on seismic velocities made it possible to locate small earthquakes with a high degree of accuracy. Well-recorded earthquakes were located with a precision of 0.3 kilometer in the horizontal plane and 0.5 kilometer in the vertical plane. Not all the earthquakes were so well record-

ed, but all of the calculated locations are thought to be within 1 kilometer of the true locations.

Sixty-two earthquakes for which accurate locations could be obtained occurred in a roughly ellipsoidal zone about 10 kilometers long and 3 kilometers wide, which includes the disposal well (Fig. 2, top). The long axis of the zone trends N 60°W. The depths of the earthquakes ranged from 4.5 to 5.5 kilometers.

The first motion of compressional-wave arrivals reveals a pattern that is consistent with right-lateral strike-slip motion along fault surfaces that are parallel to the trend of the zone of epicenters. In many cases a nodal plane crossed a single array, showing a change in the direction of first motion within the half-kilometer interval between seismometers (Fig. 3).

First motions on the surface over the hypocenter of a vertical strike-slip fault have a quadrantal pattern. Most of the surface first-motion patterns in the study discussed here were quadrantal in nature (Fig. 4).

Following completion of the preliminary program, the Colorado School of Mines installed additional short-period seismograph stations and the U.S. Geological Survey installed a 17-element array over the zone of hypocenters. These networks are continuing to record earthquakes.

Change in the Pattern of Activity

Injection of fluids in the disposal well was terminated in February 1966, but earthquakes have continued at a rate varying from 4 to 71 per month, as
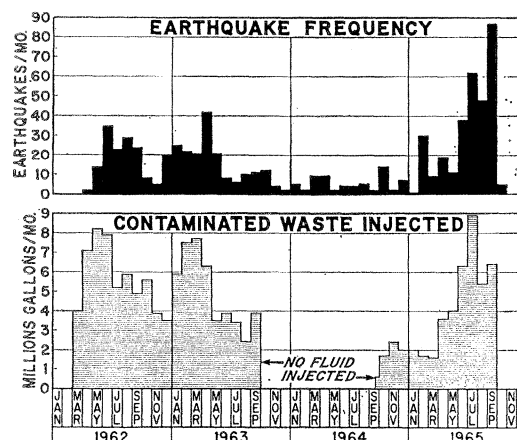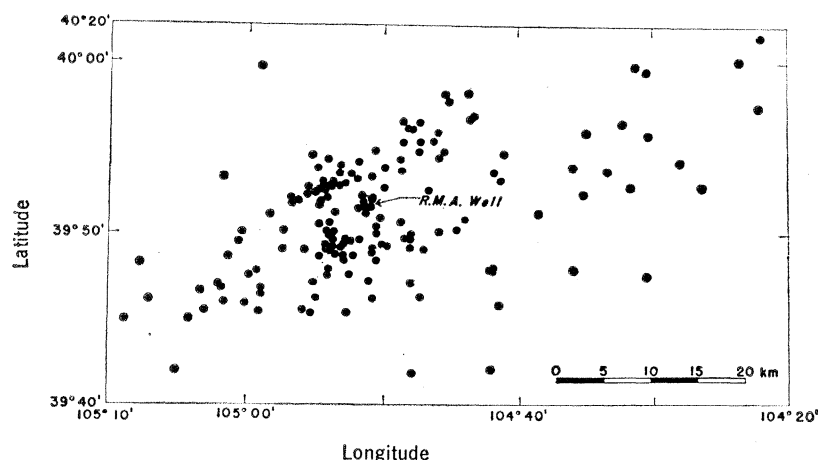

Fig. 1. Observations on which David Evans in 1965 based his theory of the relation between fluid injection and earthquakes at the Rocky Mountain Arsenal, Denver, Colorado. (Left) Epicenters (solid circles) of earthquakes as calculated by Wang using data from the Bergen Park and Regis College stations and from temporary U.S. Geological Survey stations. (Right) Correlations, by Evans, between the number of earthquakes and the volume of fluid injected.

indicated at the Bergen Park Observatory. During that period, hundreds of very small earthquakes were detected on the U.S. Geological Survey network centered on the hypocentral zone. On 10 April 1967, the largest earthquake of the series to that date shook the Denver area. Its magnitude was estimated at 5.0 by Maurice Major (6), on the basis of the Bergen Park Observatory records. The U.S. Geological Survey network located the hypocenter within the zone of previous activity. In fact, all the earthquakes located fell within or close to the bounds defined by the 2-month preliminary study (Fig. 2, top). A number of aftershocks of the 10 April earthquake define a linear pattern which trends about N 60°W (7) (Fig. 2, bottom), as the earlier earthquake locations did. From the statistics for the frequency and magnitude of the entire sequence, the large earthquake of 10 April might reasonably have been expected. But there was more to come. On 9 August there was a second large earthquake of magnitude between 5¼ and 5½, and on 26 November there was a third, of magnitude 5.1 (Fig. 2, bottom). The three large earthquakes, with their foreshocks and aftershocks, introduce a dramatic change in the pattern of activity.

Some seismologists have argued that the magnitude-frequency plot, a histogram of the common logarithm of the number of earthquakes relative to their magnitude, can be used to establish the level of seismicity in an area and to predict the rates of recurrence of large earthquakes over a period of years. A considerable number of data support this view, but there are some startling exceptions (8).

With the exception of the Los Angeles Basin, the magnitude-frequency histograms for all the southern California regions studied can be fitted with a straight line having a slope between −0.8 and −1.02. The average for southern California is −0.86.

The magnitude-frequency relationship for earthquakes in Denver was determined first by Yung-Liang Wang (1), who obtained a value of −0.78 for the slope. A recent determination of −0.82 was made by Major and Wideman (9), on the basis of data obtained through April 1967.

Only the data from the Bergen Park Observatory were used in determining magnitudes for the Denver earthquakes, because it is the only station that has been in operation at high magnification throughout the period of activity.

Recently, Ruth Simon at the Colorado School of Mines has reexamined all the Denver earthquake seismograms and has prepared a new list of earthquakes for the entire period of earthquake activity (6). These data were used in preparing the magnitude-frequency plots given here. The data on magnitude and frequency, by year, are given in Table 1.

The yearly plots (Fig. 5A) reveal a remarkably consistent pattern from 1962 through 1966, with the possible exception of 1964, for which the slope is somewhat lower. The number of earthquakes recorded in 1964 is too small to provide an adequate measure of the seismic activity.

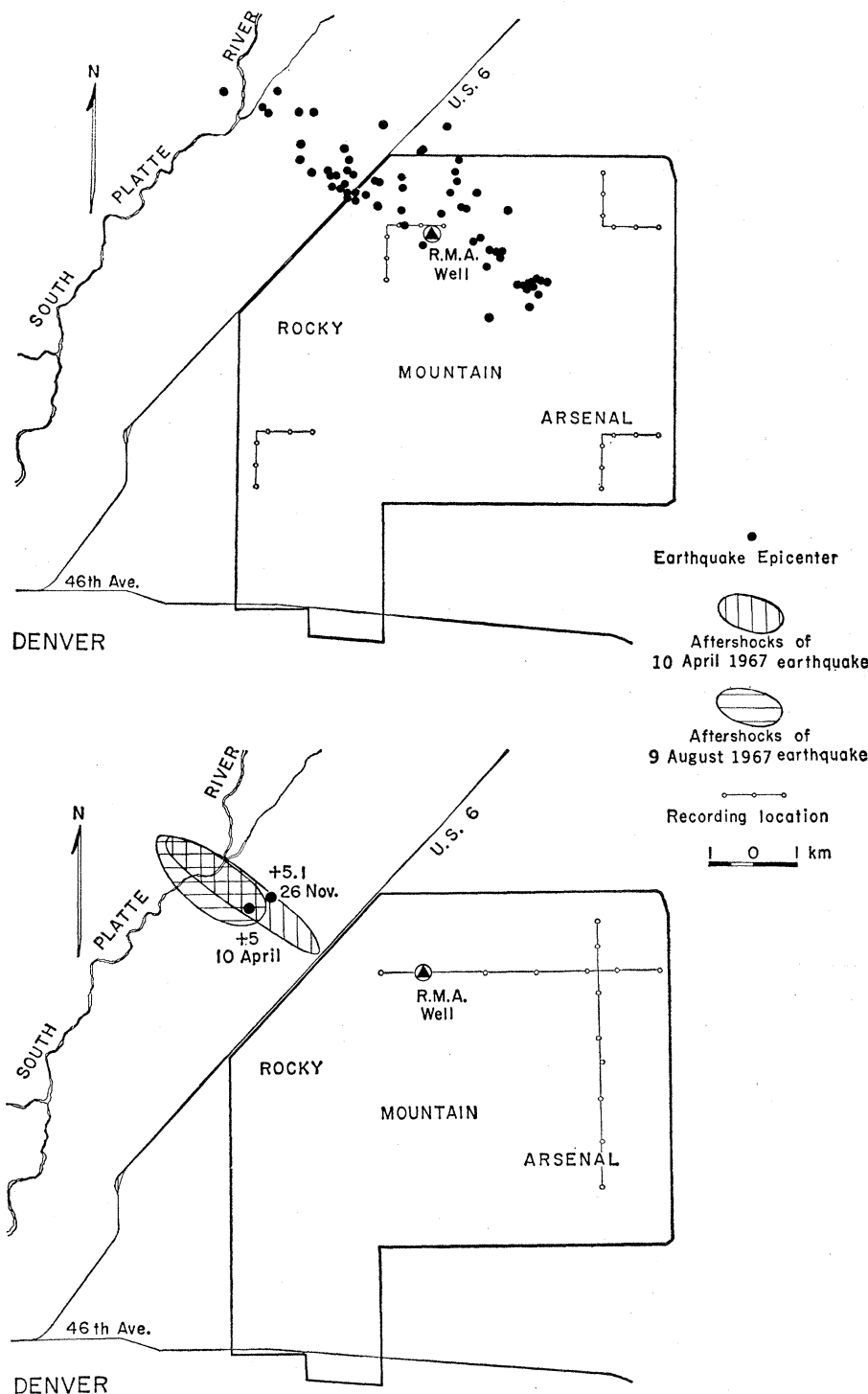With the exception of the data for 1967, the available data can be repre-

Fig. 2. (Top) Epicenters of earthquakes located in January and February of 1966 by means of a dense network of temporary seismic stations. The locations are accurate to within 1 kilometer. (Bottom) Location of (i) the earthquake of 10 April 1967 and its aftershocks; (ii) aftershocks of the event of 9 August 1967; and (iii) the epicenter of the 26 November 1967 earthquake.
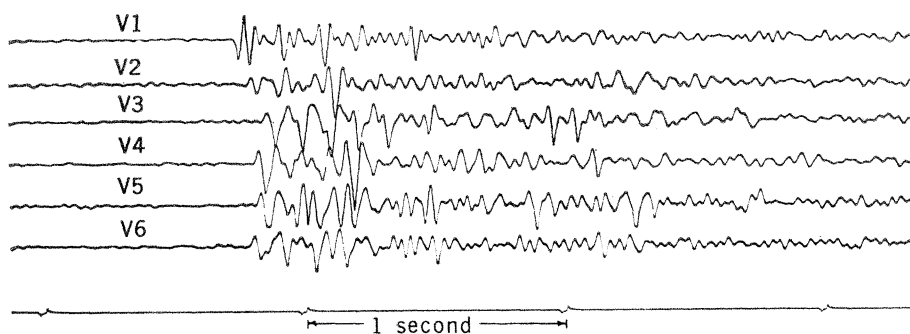
Fig. 3. Seismogram (27 December 1965) showing compressional (upward motion) and dilatational (downward motion) arrivals. The nodal plane apparently intersects the array near seismometer V2.

sented by the relationship $\log N = a + bM$, where M is the Richter magnitude, N is the number of earthquakes per year with magnitude between $M - 0.25$ and $M + 0.25$, a is a constant which indicates the level of seismic activity during the period studied, and b is a constant which determines the slope (Table 2).

The average for the data for the years 1962 through 1966 suggests that one earthquake with a magnitude of about 4.5 could be expected within a 5-year period, the total period of earthquake activity. The rate of recurrence for earthquakes of magnitude between 6.0 and 6.4 is more than 100 years. The occurrence of a single earthquake in April 1967 having a magnitude of 5.0 was not in serious conflict with expectation. However, the two succeeding

earthquakes of magnitude greater than 5 in 1967 clearly showed that the earthquakes were not following this statistical pattern, established from 1962 to 1966, which predicts about three such earthquakes in 60 years (Fig. 5B).

When the frequency-magnitude relationship for 1967 is examined more closely, it becomes clear that a significant change has occurred. The data for earthquakes smaller than magnitude 4.5 are best fitted by a straight line having a slope of -0.61, which is substantially smaller than the magnitude-frequency slope for other years (Fig. 5B). However, because of the occurrence of three earthquakes with magnitude between 5.0 and 5.5, with no earthquakes in the magnitude range 4.5 to 4.9, it is not possible to fit all the points for 1967 with a straight line.

The significance of this change in the earthquake pattern is more clearly revealed if we consider the seismic energy radiated as a function of magnitude. Richter (10, p. 366) gives the following relationship between energy, E, and magnitude, M: $\log E = 11.4 + 1.5 M$. From this relationship, a graph of cumulative energy release for each 6-month period was prepared (Fig. 6).

Because the energy of earthquakes increases by a factor of about 31 for each 1-unit increase in magnitude, the three earthquakes with magnitude greater than 5 that occurred in 1967 account for almost all of the energy released in the earthquake series. It seems clear that something new is happening, with unknown portent for the future.

Correlation of Earthquakes with Fluid Injection

We have, to this point, presented the information more or less in the order in which it became available, so that the reader can reconstruct the historical sequence of events. In the rest of the article we depart from this chronological presentation and turn to the formulation of a physical model that, we suggest, explains the observations. But first, an approximate statistical comparison can be made. What is the probability that an earthquake sequence such as that at Denver could occur by pure chance close to the time and place of the injection of fluids into the basement rock? The occurrence of swarms of small earthquakes in Colorado is probably a more common event than most people recognize. During the course of our work, several groups of earthquakes were noted that might have been similar to the Denver earthquakes. An earthquake sequence is occurring near Rangely, Colorado; another is occurring some distance to the north of Denver, perhaps in Wyoming; and others may be occurring in the San Juan Mountains of southern Colorado. Most of this activity was detected by only a few stations and has not been studied in detail. It is probable that most of these areas are somewhat less active than the area near Denver. Hadsell's (4) list of Colorado earthquakes shows 70 earthquakes between December 1870 and January 1967. The list for the years prior to 1962 is based on reports of felt earthquakes. The list for 1962 and subsequent years includes all
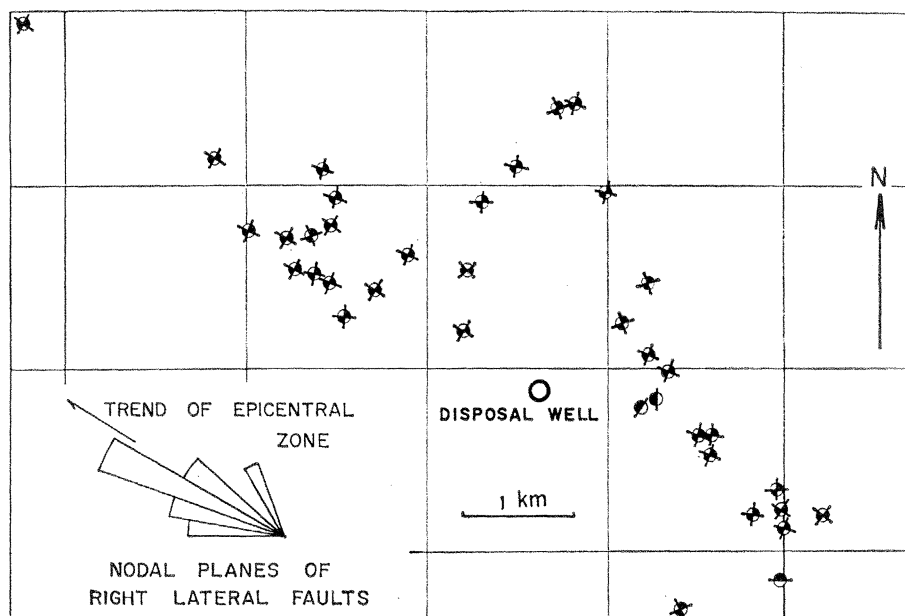

Fig. 4. Seismic radiation patterns of first arrivals from epicentral locations. (Black quadrants) Compressional first motions; (crosses) azimuthal orientations of the near-vertical nodal planes, one of which is the fault plane for the event. The compass rose diagram at lower left gives azimuthal orientations of right-lateral strike-slip faults.

earthquakes in Colorado, exclusive of the Denver area, of magnitude greater than 3.0 and all earthquakes in the Denver sequence of magnitude greater than 3.1. Of the 70 earthquakes, 28 were in the Denver sequence. We can say conservatively that not more than ten earthquake swarms similar to the Denver swarm are occurring in Colorado at any one time. Colorado has an area of 270,000 square kilometers. The accurately located earthquakes in the Denver sequence are all contained in an area of less than 65 square kilometers. The probability of finding a swarm in a randomly selected 65-square-kilometer area is therefore 1 in 4150.

What is the probability that an earthquake swarm would start within 7 weeks of the beginning of a fluid-injection program? The only known possibly similar seismic activity near the disposal well is an earthquake that occurred in 1882. The location of this earthquake is given in Hadsell's list as Vail Pass, but it was felt in the Denver area, so it may possibly have occurred near the

Table 2. Values of constants a and b (see text) computed by least squares.

Year	a	b
1962	3.06	−0.80
1963	3.33	− .85
1964	2.43	− .64
1965	3.65	− .85
1966	3.19	− .90
1967	2.77	− .60

present location of the disposal well.

If one assumes that the earthquake of 1882 occurred near Denver rather than at Vail Pass and that the recurrence rate for this activity was 80 years, the probability that an earthquake swarm would start within 7 weeks of the beginning of fluid injection in the disposal well is 1 in 600. The joint probability that the earthquakes would be so closely associated in both time and space, with the disposal well is $1/600 \times 1/4150 = 1/2,500,000$. The occurrence of a natural earthquake swarm so closely related to the disposal well would thus be an extremely unlikely coincidence.

Since shallow earthquakes are caused by movements along faults, seismic activity at the level of the Denver earthquake sequence will, if repeated at frequent intervals through geologic history, probably result in large tectonic displacements. These displacements should produce recognizable deformation of the sedimentary rocks overlying the earthquake zone. A seismic-reflection survey of the epicentral region of the Denver earthquakes revealed no extensive folding or faulting in the sedimentary rocks overlying the earthquakes (11). Several small faults, of displacement less than 30 meters, were discovered, and topographic relief over the area of the survey was less than 60 meters. This evidence suggests that there has been very little seismic activity at this site since Precambrian time.

In a search for clues to the earthquake mechanism, the original pressure charts were reexamined and, wherever possible, the average daily wellhead pressure and the volume of fluids injected were redetermined. The daily
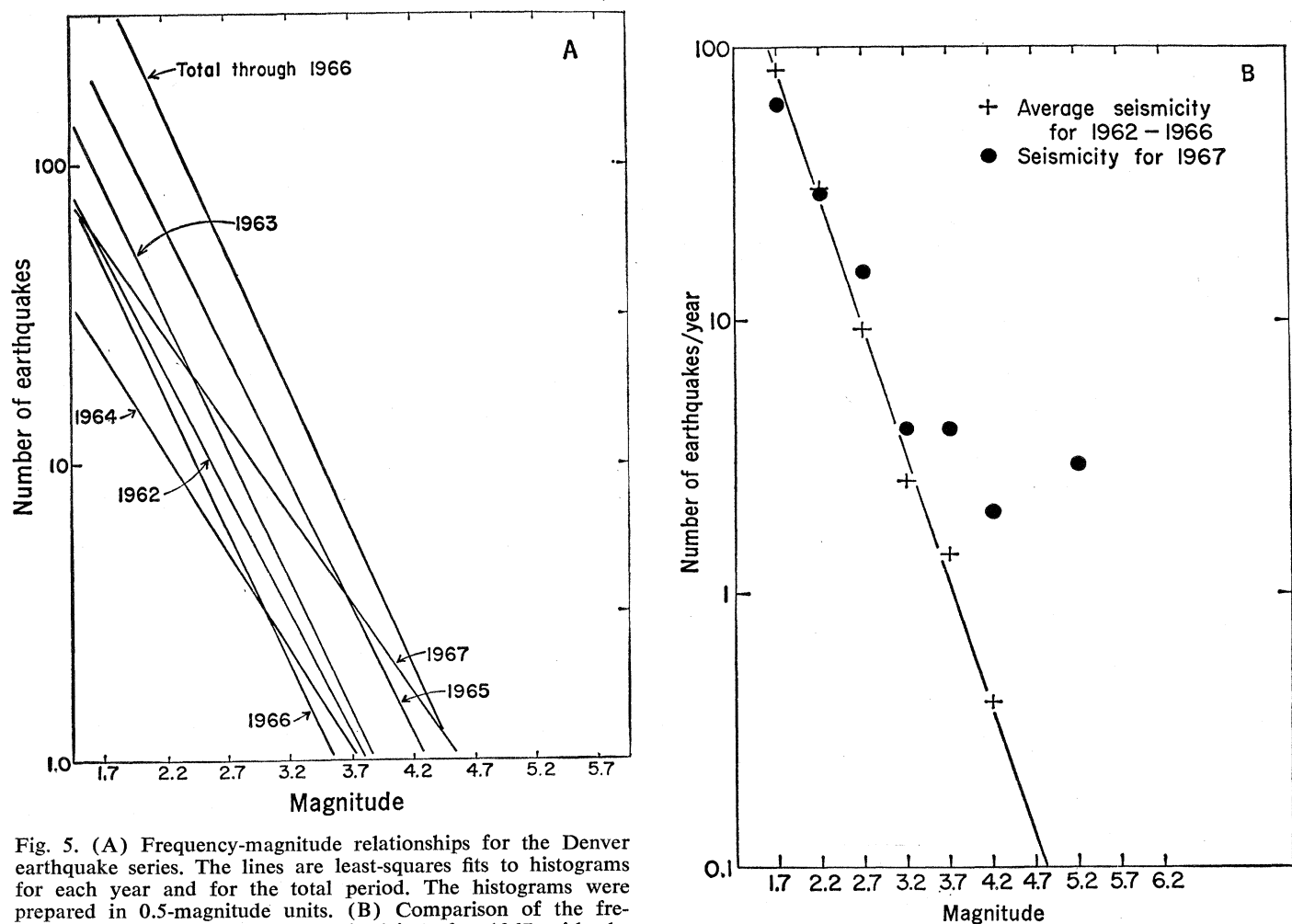

Fig. 5. (A) Frequency-magnitude relationships for the Denver earthquake series. The lines are least-squares fits to histograms for each year and for the total period. The histograms were prepared in 0.5-magnitude units. (B) Comparison of the frequency-magnitude relationship (seismicity) for 1967 with the average for the preceding 5 years.

data (Fig. 7A) were used to determine an average pressure for each month, and these averages were plotted against the number of earthquakes per month (Fig. 7B). Figure 7 shows that there is a strong correlation between fluid pressure and the level of seismic activity for the years 1962–66, but the increase in seismic activity in 1967 appears to rule out any simple direct relationship between these parameters. It could be argued that the increase in seismic activity during a period of decreasing fluid pressure is not consistent with the theory that fluid pressure triggered the earthquakes, but we will show that this activity pattern when a zone of increased pressure is spreading outward from the well is not surprising.

The cross correlation between the earthquake series and the fluid-pressure series was calculated (Fig. 8A), to determine whether there was a lag between peak fluid pressure and peak seismic activity. The cross correlation was calculated as:

$$R_{xy}(p) = \frac{1}{n-p} \sum_{q=1}^{n-p}$$

$$X_q Y_{q+p} \quad p = 0, 1, 2, \ldots, m$$

where X = data from the earthquake series, Y = data from the pressure series, $R_{xy}(p)$ = cross covariance or cross correlation, n = number of discrete data points, and p = lag; for $-p$, x and y are reversed in the above equations. In actual computation, the procedure of Lee and Cox (12) was adopted to treat data gaps in the pressure series.

The cross correlation is not symmetrical and indicates that the peak of seismic activity follows the peak pressures by approximately 10 days. The lack of symmetry in the cross correlation is a consequence of continued seismic activity for a number of months after the injection of fluid.

For comparison, a correlation coefficient was computed by means of the Rank difference method (13), with the earthquake and pressure data specified in 10-day intervals (Fig. 8B).

Mechanism of the Earthquakes

An understanding of the mechanism of these earthquakes is of great importance, not only for controlling the current sequence at Denver but also for predicting where other such sequences might occur. It now seems
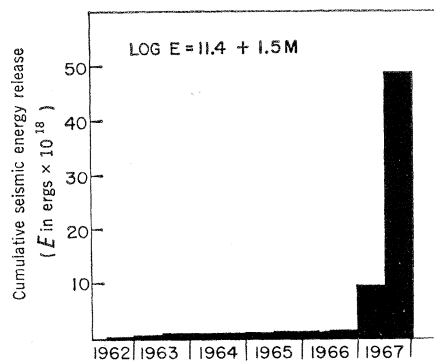
Fig. 6. Cumulative seismic-energy release in Denver earthquakes, by 6-month periods.

clear that, contrary to some early conjecture, the energy released by the earthquakes was stored in the basement rock as nonhydrostatic elastic strain. The evidence pointing to a tectonic origin for the elastic strain energy released is twofold.

1) The frequency-magnitude relationship for the early earthquakes is similar to that for tectonically active areas such as southern California.

2) The seismic-radiation patterns are consistent with right-lateral strike-slip motion on vertical fault planes aligned with the trend of the seismic zone. The prolongation of the epicentral zone in a west-northwestern direction parallel to one of the two possible fault-plane sets (Fig. 4) strongly suggests that a zone of vertical fractures existed along the trend prior to the injection of fluid. Examination of core from the basement rock has shown the presence of vertical fractures prior to such injection (14). These observations suggest that the earthquakes are produced by a regional stress field of tectonic origin.

From this evidence we consider it highly probable that the release of the stored tectonic strain was triggered by the injection of fluid into the basement rock. This hypothesis has a rational basis established theoretically by Hubbert and Rubey (15) and tested experimentally by several workers. In a rock containing fluid in its pore spaces at a pressure p, the total stress S is resolved into two components (16), a neutral stress p and an effective stress σ,

$$S = \sigma + p$$

The neutral stress p is the pressure of the ambient fluid and has no shear components. Consequently, faulting or other nonhydrostatic deformation of the rock must be in response only to the effective stress σ. In the fracture of

rocks at high pressure, the shear stress τ on the fault plane at failure is given by the empirical relation

$$\tau = \tau_o + S_n \tan \phi \qquad (1)$$

where S_n is the normal stress across the fault plane, $\tan \phi$ is the coefficient of friction, and τ_o is the cohesive strength. If a pore fluid is present at pressure p, Eq. 1 becomes

$$\tau = \tau_o + (S_n - p) \tan \phi$$
$$\sigma_n = S_n - p$$
$$\tau = \tau_o + \sigma_n \tan \phi \qquad (2)$$

The effect of increasing pore pressure is to reduce the frictional resistance to fracture by decreasing the effective normal stress, σ_n, across the fracture plane.

The parameters in Eq. 2 can be evaluated for the Denver earthquakes on the basis of the following assumptions and relations between τ, σ_n, and the principal stresses.

$$\tau = \frac{\sigma_1 - \sigma_3}{2} \sin 2\alpha \qquad (3)$$

$$\sigma_n = \frac{\sigma_1 - \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\alpha \qquad (4)$$

$$\sigma_1 = S_1 - p$$
$$\sigma_3 = S_3 - p$$

where α is the angle between σ_1 and the normal to the fracture plane.

According to conventional models of the dynamics of faulting (17), strike-slip faulting occurs where the least and greatest principal stresses are horizontal. The magnitude of the least principal stress, S_3, can be estimated from data on pressure relative to the volume injected.

The rate of injection of fluid, during periods of rapid injection, was found to vary approximately linearly with fluid pressure down to a bottom-hole pressure of about 362 bars. Below this pressure the injection rate was negligible, suggesting a sharp discontinuity in the reservoir characteristics with pressure. Over the 5 days preceding shutdown of the injection program, on 20 February 1966, the average bottom-hole pressure was 368 bars (18); the average injection rate was 114 liters per minute. Within 1 day after shutdown, the fluid level in the well dropped at a rate indicating that injection was continuing at 0.076 liter per minute, at an average bottom-hole pressure of 362 bars. A decrease of 6 bars in fluid pressure resulted in reduction of the injection rate by a factor of 1500. In an early injection test on 22 January 1962, raising the injection rate incrementally from 379 to 1414 liters per

minute required a linear increase of pressure of about 7 bars per 379-liter-per-minute increment. A linear extrapolation of the bottom-hole pressure from these data gives a pressure of 362 bars (19) at an injection rate of zero.

Such a large discontinuity in injection rate with pressure has a close parallel in numerous cases where oil-bearing reservoirs have been hydraulically fractured to increase their permeability. From the theory of hydraulic fracturing (20), the fluid pressure, p_c, required to hold fractures in the formation open to rapid injection is found to be equal to the magnitude of the least principal stress, S_3. In the reservoir rock at the Denver well, p_c would be approximately 362 bars, some 93 bars greater than the initial fluid pressure in the reservoir.

If the greatest and least principal stresses are assumed to be horizontal, the intermediate stress, S_2, is vertical and equal to the lithostatic pressure. The conventional pressure gradient for saturated sedimentary rocks is 0.226 bar per meter; on this basis, S_2 at 3671 meters below the surface is 830 bars. The maximum principal stress, S_1, must therefore be at least 830 bars.

Estimates of the pore pressure before the injection of fluid (p_o) vary widely, from as much as 328 bars (21) to as little as 269 bars (22). The first figure is too high; the fluid level in the well as of 8 April 1968 corresponds to 311 bars at depth of 3671 meters, and the rate of falloff is still 0.027 bar per day. It appears that, if the rate of falloff continues to vary with the depth of fluid in the well, as it did from 23 September 1966 through 8 April 1968, the static head may be about 900 meters below the well mouth, in which case the original reservoir pressure was 269 bars. This value is taken as the reservoir pressure in the following calculations.

The pore pressure at the time of the first recorded earthquakes can be estimated from the pumping records of the arsenal (23). The volume injected daily at the time of the events recorded in April 1962 was about 1.1 million liters, but no pressure records were kept. In the next month excess pressure of about 30 bars at the wellhead was required to achieve the same volume. The pore pressure in the reservoir at the time faulting was initiated (p_f) is therefore taken to be 389 bars.

Given $S_1 = 830$ bars, $S_3 = 362$ bars,

and $p_o = 269$ bars, the effective shear and normal stresses on a potential fault plane, from Eqs. 3 and 4, are $\tau = 203$ bars, $\sigma_n = 210$ bars. The angle α is taken to be 60 degrees, the value found typically for experimental shear fractures. In the Mohr-Coulomb criterion for failure (Eq. 1) the resistance to fracture is provided by the frictional term $\sigma_n \tan \phi$ (ϕ is about 30 degrees for many rocks) plus the cohesive strength, τ_o. In the reservoir rocks prior to injection, τ_o would have to be at least as great as 82 bars to prevent fracture.

During fluid injection, when the pore pressure was raised to 389 bars, τ would be 203 bars and σ_n would be 90 bars. The occurrence of faulting upon reduction of the frictional term $\sigma_n \tan \phi$ by 69 bars indicates a value for τ_o of 151 bars or less.

The cohesive strength for sound, crystalline rocks deformed in the laboratory is about 500 bars. For the fractured rocks present in the reservoir, a cohesive strength of 150 bars seems a reasonable assumption. Additional fracturing during the earthquake se-
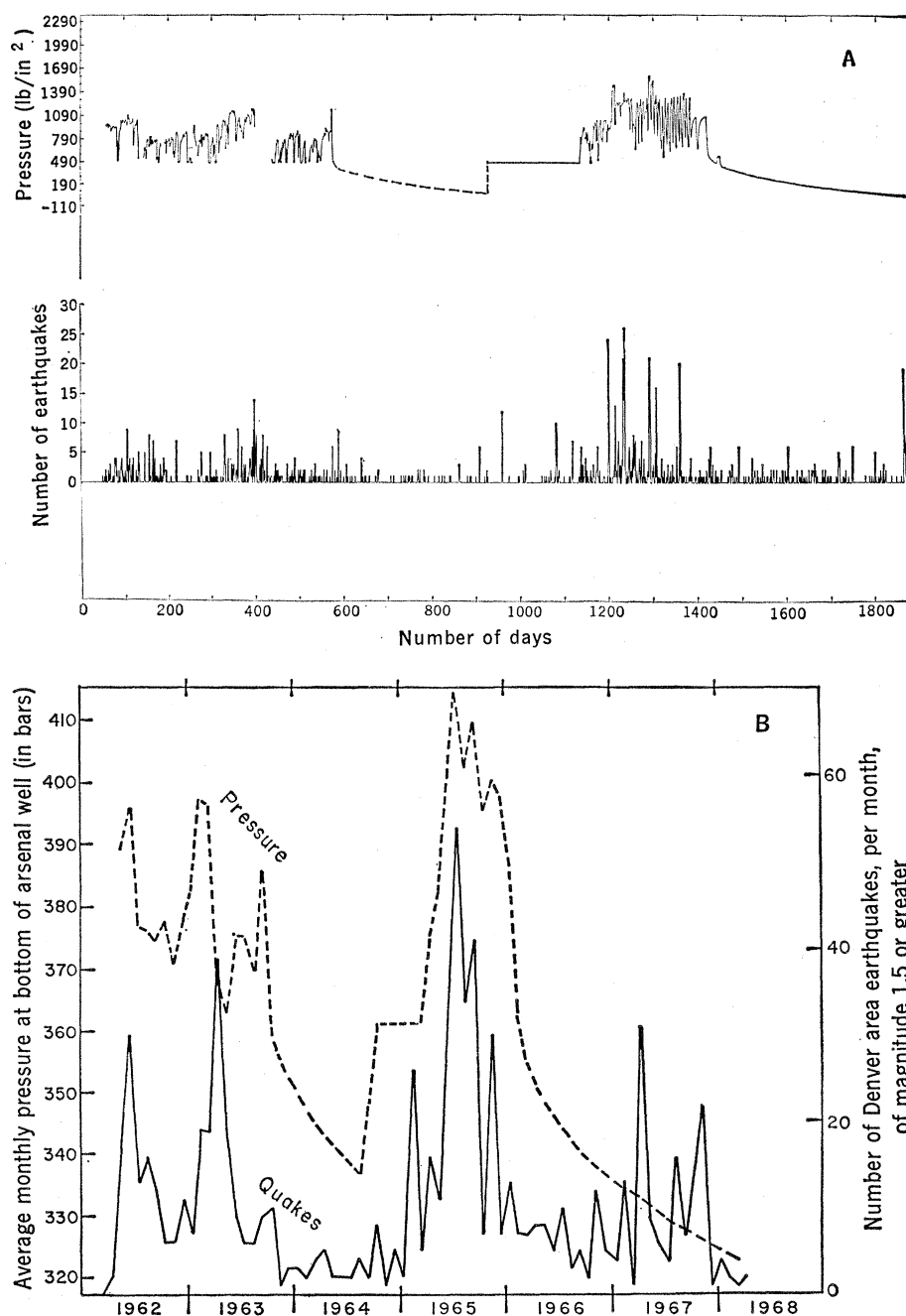

Fig. 7. (A) Daily pressure plotted relative to number of earthquakes. The dashed portions in the pressure curve are interpolated where only data on the volume of fluid injected were available. (B) Comparison of number of earthquakes and pressure, on a monthly basis.
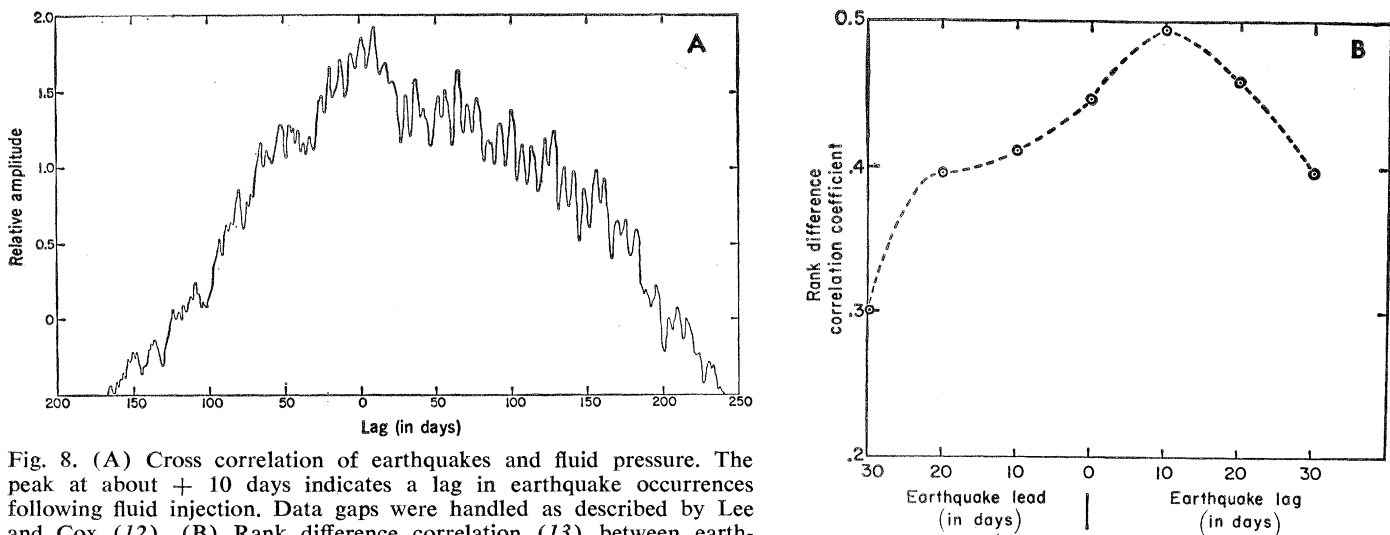
Fig. 8. (A) Cross correlation of earthquakes and fluid pressure. The peak at about $+$ 10 days indicates a lag in earthquake occurrences following fluid injection. Data gaps were handled as described by Lee and Cox (12). (B) Rank difference correlation (13) between earthquakes in 10-day intervals and pressure averaged over 10-day intervals.

quence would be expected to further decrease the cohesive strength and the resistance of the reservoir rock to fracture and frictional sliding. Upon lowering of the pore pressure, the earthquakes would be expected to continue until the frictional resistance plus the reduced cohesive-strength term exceeded the shear stress. A reduction of the pore pressure to less than the initial pressure p_o might be required before seismic faulting was finally inhibited. If $\tau_o = 50$ bars, p_o would have to be less than 214 bars.

We have assumed in the foregoing discussion, which is consistent with Hubbert and Willis's theory and experiments, that the hydraulic fractures in the well open normal to S_3. The alternative—that the fault planes already present in the basement become open to rapid flow at pressure of 362 bars—is worth considering. Migration of the epicenters along the west-northwest-trending zone parallel to the instrumentally determined fault planes suggests such a possibility. In this case, the total normal stress, S_n, across the fault surface must be exceeded at 362 bars. The horizontal least principal stress, S_3, is then given by

$$S_3 = \frac{2S_n - S_1 \ (\cos \ 2\alpha + 1)}{1 - \cos \ 2\alpha} \quad (5)$$

Taking $S_1 = 830$ bars and $\alpha = 60$ degrees, as before, we have $S_3 = 206$ bars. In this case the effective stress difference, $\sigma_1 - \sigma_3$, would be 624 bars, rather than 468 bars where S_3 was taken to be equal to the critical pressure p_c. At the pressure ($p_c = 362$ bars) for hydraulic fracturing, the least principal effective stress, σ_3, would be tensile and equal to $- 156$ bars. Rocks

generally have a tensile strength of about 50 bars and therefore could not support such a large tensile stress. We favor, therefore, the model discussed above, in which hydraulic fractures are opened perpendicular to S_3 at pore pressure of 362 bars. The pore fluid then permeates away from these fractures along preexisting faults parallel to the trend of the epicentral zone.

This analysis shows that, given reasonable values for the frictional and cohesive strength of fractured rock, the basement rock at the Denver well was stressed to near its breaking strength before injection of fluid was initiated. This conclusion is in accord with the seismological evidence of consistency of trend and sense of slip on the fault planes, features indicating a response to stresses of tectonic origin. If the unknown principal stress, S_1, is greater than S_2, rather than equal to S_2 as assumed, this conclusion is strengthened. Increasing the pore pressure in the reservoir rocks to 389 bars by means of fluid injection reduced the frictional resistance to fracture by about 69 bars and initiated the earthquake sequence.

The distribution of the Denver earthquakes in space and time has two features which at first glance seem anomalous but in fact are consistent with the Hubbert-Rubey theory.

1) Although there is a net migration of epicenters away from the well consistent with the advance of a pressure front during the period of fluid injection (24), earthquakes appear to have been occurring over the whole of the existing epicentral zone at the end of the pumping period (Fig. 2, top).

2) Since the cessation of fluid injec-

tion in February 1966, earthquake activity has continued despite reduction of pore pressure in the reservoir at the well to 311 bars in April 1968. Seismic activity near the well has ceased, but earthquakes of larger magnitude than those that occurred during the injection period have occurred near the northwesterly terminus of the epicentral zone (Fig. 2, bottom).

We assume that the rocks in the fault zone contain a large number of cracks that vary in length and have a normal distribution of orientation about the trend of the fault zone. Furthermore, the cracks parallel to the fault zone are assumed to have orientations such that τ/σ_n has a maximum value—that is, assumed to have the most favorable orientation for propagation. In the cracks where τ/σ_n exceeds the coefficient of sliding friction, irregularities along the fracture surface and the crack terminations may be considered lock points restricting movement. In effect the strength of these lock points constitutes the cohesive-strength term, τ_o, in the Mohr-Coulomb criterion for failure (Eq. 1). At the time of an earthquake, when one of these lock points fails, the break may propagate until it is inhibited by a stronger lock point along the fracture surface. The crack would also tend to arrest as it passed from a region of higher into a region of lower pore pressure.

This conceptual model of the fracture process is illustrated in Fig. 9. Fractures already present in the basement which have orientations that are favorable for propagation (cracks A and B) and orientations that are less favorable (crack C) are shown. The lengths shown correspond to the dis-

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tance along each crack between lock points. The greater the distance between lock points the greater the concentration of stress at these points and the more likely a given fracture is to propagate.

In the sequence shown (Fig. 9), certain features may be noted.

1) Propagation of crack A takes place with seismic velocity upon injection of fluid at the well and continues until the mean pore pressure over the increased length of fault is below the value required for continued propagation, or until the crack encounters a stronger lock point.

2) Crack B is shorter and, though nearer to the well, requires an additional increase in fluid pressure to propagate.

3) With continued injection of fluid, cracks A and B propagate to greater lengths, and faulting also takes place on crack C, which is shorter and less favorably oriented with respect to σ_1.

4) As shown in the idealized profiles of reservoir pressure, cessation of fluid injection results in a rapid reduction of pressure near the well but in a continued advance of the pressure front at greater distance from the well. The cracks, such as A, which have propagated out beyond the pressure front during fluid injection become reactivated as the front advances, even though the injection has ceased. The shorter and unfavorably oriented cracks within the zone near the well, in which fluid pressure is decreasing, become inactive.

A relation between the length of a fault rupture and the magnitude of the associated earthquake has been established from data on faults which break the surface (25). If this relation holds for the Denver earthquakes, our conceptual model, as outlined above, would predict a predominance of earthquakes of greater magnitude following cessation of fluid injection, when only the longer cracks are capable of propagation. Moreover, faulting near the well would diminish, in comparison with that during the injection period, when seismic activity would be more evenly distributed over the entire epicentral zone and greater numbers of earthquakes of smaller magnitude would occur.

Conclusions

Most investigators working on the Denver earthquakes have concluded that the injection of fluid triggered the

seismic activity. However, some investigators believe that the earthquakes might have occurred even if the well had not been drilled, and there is a wide range of opinion on the advisability of attempting to terminate the earthquake sequence by removing fluid from the well (26).

We consider the possibility of a coincidental occurrence of earthquakes with the onset of fluid injection at Denver to be remote. Furthermore, there is now evidence that fluid injection and swarms of earthquakes occur together at other locations (27). The mechanism by which fluid injection triggered the earthquakes is the reduction of frictional resistance to faulting, a reduction which occurs with increase in pore pressure. Other mechanisms, including reduction in the strength of the rocks, due to chemical alteration, have been investigated, but so far none of these appear to explain the seismicity adequately. The implication of the pore-pressure mechanism—that the

rocks were stressed to near their breaking strength before the injection of fluid—is in accord with the available data. Faulting is predominantly right-lateral strike-slip on faults which are parallel to the epicentral zone, an observation which also suggests release of tectonic stress rather than disturbances produced by fluid injection alone.

Prior to 1967, the frequency of occurrence of earthquakes of different magnitudes in the Denver area was such that the likelihood of a really destructive earthquake could reasonably be considered remote. In view of the 1967 earthquakes, however, there is no longer any assurance that a destructive earthquake will not occur. Hence, the question of what might be done to lessen the earthquake hazard now confronts those earth scientists who have been studying the problem.

In our view, it might be possible to reduce the size and number of the earthquakes by removing substantial quantities of fluid from the reservoir. If the
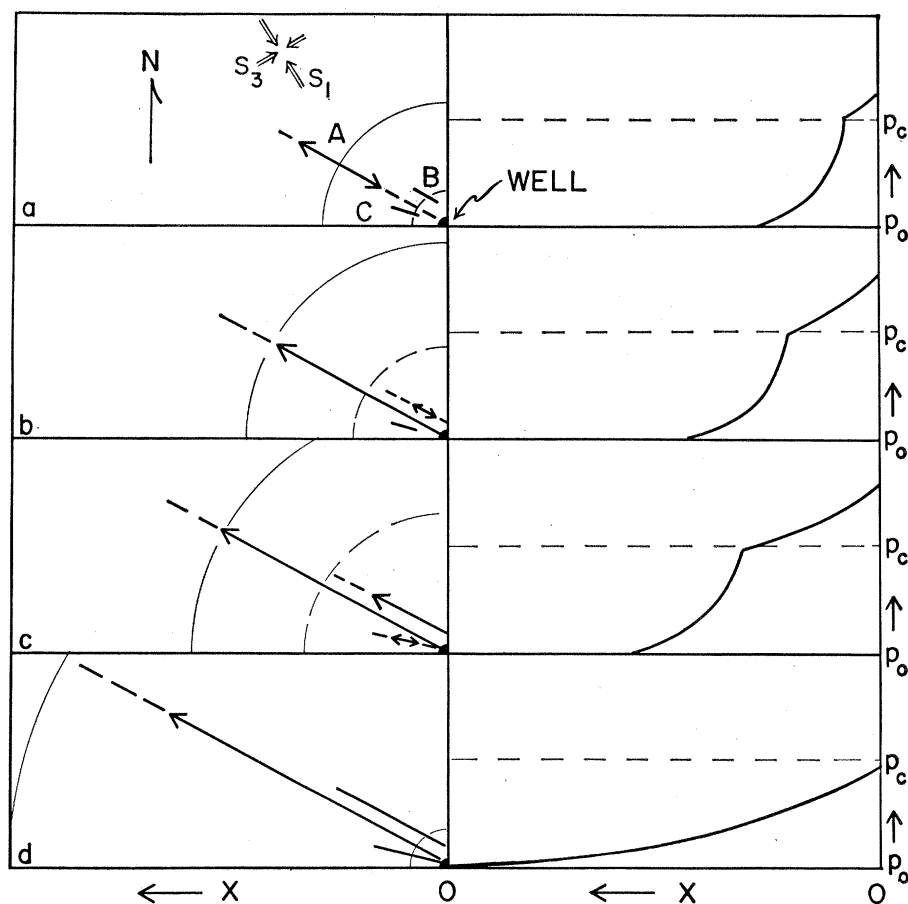

Fig. 9. (Right) Idealized profile of pore pressure in the reservoir during successive stages (a–d) of fluid injection. (X) Distance from well; (p_o) initial reservoir pressure; (p_c) hydraulic fracturing pressure. Between stages c and d, injection ceases. (Left) Idealized view of fault zone during successive stages (a–d) of fluid injection. Arrows on fractures present before injection indicate propagation and release of seismic energy during advance of the pressure front. The assumed orientations of horizontal principal stresses, S_1, S_3, are shown.

Hubbert-Rubey pore-pressure effect is the cause of the earthquakes (and, to our knowledge, it is the only mechanism yet demonstrated to explain them adequately), reducing the pore pressure should effectively strengthen the reservoir rocks and thus reduce the size and number of the earthquakes.

Despite the theoretical attractiveness of this approach, the engineering difficulties and costs involved in removing sufficient quantities of fluid from the reservoir to reduce significantly the occurrence of earthquakes may prove prohibitively expensive. Early withdrawal tests conducted before fluid injection was begun indicated a reservoir with very low transmissibility. If this low transmissibility is characteristic of the reservoir today, the removal of fluid would probably be impractical. One technique used successfully to increase the production of oil from reservoirs having low transmissibility is the propping open of fractures with coarse sand. Steps are now being taken to evaluate the properties of the reservoir and to design preliminary tests to determine the feasibility of removing the fluids (28).

Given sufficient time, the pore pressure in the focal zone will dissipate naturally, and it is hoped that, as the zone of high pressure spreads outward from the well, the maximum pressures in the reservoir will fall below the level required to trigger seismic activity. Unfortunately we do not have precise measurements of the original static pressure in the reservoir and, therefore, we cannot tell how much excess pressure remains in the reservoir rock. Because the level at which the fluid stands in the disposal well is still falling, we know that a substantial overpressure must still exist and that there-

fore the zone of high pressure is still moving out from the well. There is no reason to believe that the excess pressure will dissipate naturally before the epicentral zone is extended by further faulting and attendant large earthquakes. It appears that, unless the removal of fluid can be shown, either theoretically or by pumping tests, to constitute a real hazard, every reasonable effort should be made to remove fluids from the reservoir in order to reduce the reservoir pressures and minimize the earthquake hazards. To best achieve this goal and to test the hypothesis presented here, we favor removal of fluid by means of a second well drilled into the currently active focal zone.

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27. One example that has been studied is at Rangely oil field in western Colorado; see J. H. Healy, C. B. Raleigh, J. M. Coakley, paper presented before the 64th annual meeting of the Seismological Society of America, 1968.
28. Pumping tests were initiated at the arsenal well on 1 September 1968.
29. Publication of this article (publication No. 679 of the Institute of Geophysics and Planetary Physics) has been approved by the director of the U.S. Geological Survey. The work described has been supported in part by NSF grant G.A. 277. We thank M. Major and R. Simon of the Colorado School of Mines for providing us with a list of the times of occurrence and the magnitudes of Denver earthquakes recorded at the Cecil H. Green Observatory, Bergen Park, Colorado; W. H. K. Lee for making his spectral analysis program available to us; and M. K. Hubbert for discussions on hydraulic fracturing.