JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86, NO. B2, PAGES 903–920, FEBRUARY 10, 1981

A Reservoir Analysis of the Denver Earthquakes: A Case of Induced Seismicity

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Injection of fluid wastes into the fractured Precambrian crystalline bedrock beneath the Rocky Mountain Arsenal near Denver triggered earthquakes in the 1960's. An analysis, based on the assumption that fluid flow in the fractured reservoir can be approximated by flow in a porous medium, is presented. The configuration and hydrologic properties of the reservoir are determined from two lines of evidence: (1) locations of earthquake hypocenters determined by seismic arrays installed at the Arsenal and (2) observed long-term decline in fluid levels in the injection well. Together these two sets of data indicate that a long, narrow reservoir, aligned in the direction N 60°W, exists. The reservoir is 3.35 km in width, extends 30.5 km to the northwest and infinitely to the southeast, and spans a depth interval from 3.7 to 7.0 km below land surface. It has a transmissivity of 1.08×10^{-5} m^2/s and a storage coefficient of 1.0×10^{-5}. Computed pressure buildup along the length of the reservoir is compared with the spatial distribution of earthquake epicenters. The comparison shows that earthquakes are confined to that part of the reservoir where the pressure buildup exceeds 32 bars. This critical value is interpreted as the pressure buildup above which earthquakes occur. The migration of earthquake epicenters away from the injection well, a phenomenon noted by previous investigators, can be accounted for by the outward propagation of the critical pressure buildup. The analysis is extended to examining the effects of rapid flow in fractures opened by high injection pressure. The results show that the effect is confined to a small region within 1 km of the injection well. The existence of a critical pressure buildup above which earthquakes occur is completely consistent with the theory on the role of fluid pressure in fault movement as presented by Hubbert and Rubey.

INTRODUCTION

During 1961 a deep injection well was drilled by the U.S. Army Corps of Engineers at the Rocky Mountain Arsenal (RMA), located northeast of Denver, Colorado, for the purpose of disposing of contaminated waste water. The well completely penetrated the sedimentary rocks of the Denver Basin and was drilled to a depth of 3671 m into crystalline Precambrian bedrock. Injection took place into the bottom 21 m of open hole, which was completed in a highly fractured Precambrian gneiss.

Routine waste disposal operations began on March 8, 1962. Pressure injection was accomplished by using one or more of four constant displacement pumps (approximately 380 l/min each). During injection the pressure at wellhead varied from zero (gravity flow) to a maximum of about 72 bars.

The injection history from 1962 to 1966 can be divided into four characteristic periods. From March 1962 to September 1963, waste fluid was injected under pressure into the well. Between October 1963 and September 1964, no injection took place. From October 1964 to March 1965, injection was accomplished by gravity flow. Pressure injection resumed in April 1965 but was discontinued in February 1966. A total of 625 million liters of waste fluid was disposed of in the well during the 4-year period.

Shortly after the start of the injection program, minor earthquakes were detected in the Denver area. Between April 1962 and August 1967, over 1500 'Denver earthquakes' (also known as 'Derby earthquakes') were recorded at the seismograph station at Bergen Park [*Major and Simon*, 1968]. Some of the earthquakes exceeded Richter magnitudes of 3 and 4.

In November 1965, David Evans, a Denver geologist, publicly suggested a direct relationship between fluid injection at the RMA well and earthquakes in the Denver area [*Evans*, 1966]. He based his hypothesis on (1) an apparent correlation between the volume of fluid injected into the well and the frequency of the earthquakes (Figure 1) and (2) a study by *Wang* [1965] which showed that the majority of the earthquakes had epicenters within 8 km of the well. Because of Evans' suggested injection-earthquake relationship, the waste disposal operation at the RMA was discontinued. This was followed by a number of more detailed investigations conducted by the Colorado School of Mines, the U.S. Geological Survey, and the U.S. Army Corps of Engineers.

Although no fluid has been injected into the well since February 1966, the earthquake activity continued. In 1967, three major earthquakes, each with a magnitude greater than 5, shook the Denver area and caused minor structural damages. After 1967, however, the number of earthquakes began to decline (Figure 1). The present indication is that the swarm of activity that occurred between 1962 and 1967 has virtually disappeared (M. W. Major, personal communication, 1978).

Although various investigators have pointed out that the three major earthquakes of 1967 reduced the quality of Evans' original correlation between injected volume and the number of earthquakes [*Major and Simon*, 1968], *Healy et al.* [1968] were able to provide a theory that accounts for the earthquake activity that took place after injection was discontinued. Their theory was based on a conceptual model which assumes that the Precambrian bedrock contains a large number of fractures. Earthquakes were theorized to be triggered by the increase in fluid pressure in the fractures. As noted by *Healy et al.* [1968], '. . . 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 advance of the pressure front was taken as the explanation of the earthquake activities after 1966.

In the present study we examine in a quantitative manner the conceptual model presented by Healy et al. This quantitative examination is carried out by the use of a mathemati-

Paper number 80B1095.

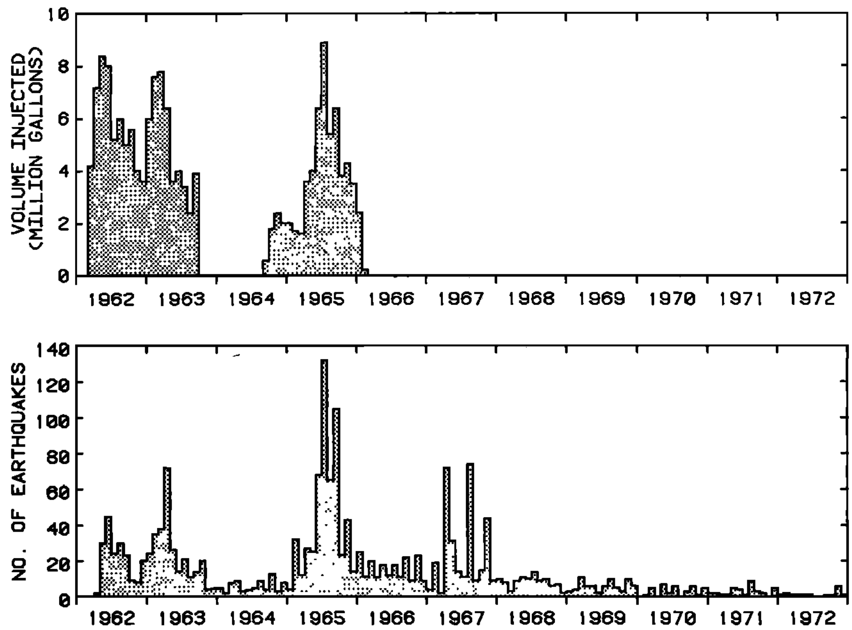


Fig. 1. Comparison of fluid injected and the frequency of earthquakes at the Rocky Mountain Arsenal. Upper graph shows monthly volume of fluid waste injected in the disposal well. Lower graph shows number of earthquakes per month. The apparent correlation for the period 1962–1966 was first noted by *Evans* [1966].

cal model that simulates pressure buildup in the Precambrian reservoir. The first portion of the study is directed to determining an appropriate mathematical model that describes fluid flow in the reservoir. The pressure buildup due to fluid injection is next calculated. Finally, a comparison is made between the spatial distribution of fluid pressure in the reservoir and the spatial distribution of earthquake epicenters. Through this comparison the relationship between fluid injection and earthquakes can be examined.

THE PRECAMBRIAN RESERVOIR

It has been established that the waste fluid from the RMA was injected into a fractured reservoir in the Precambrian rocks beneath the Denver Basin. Examination of cores from

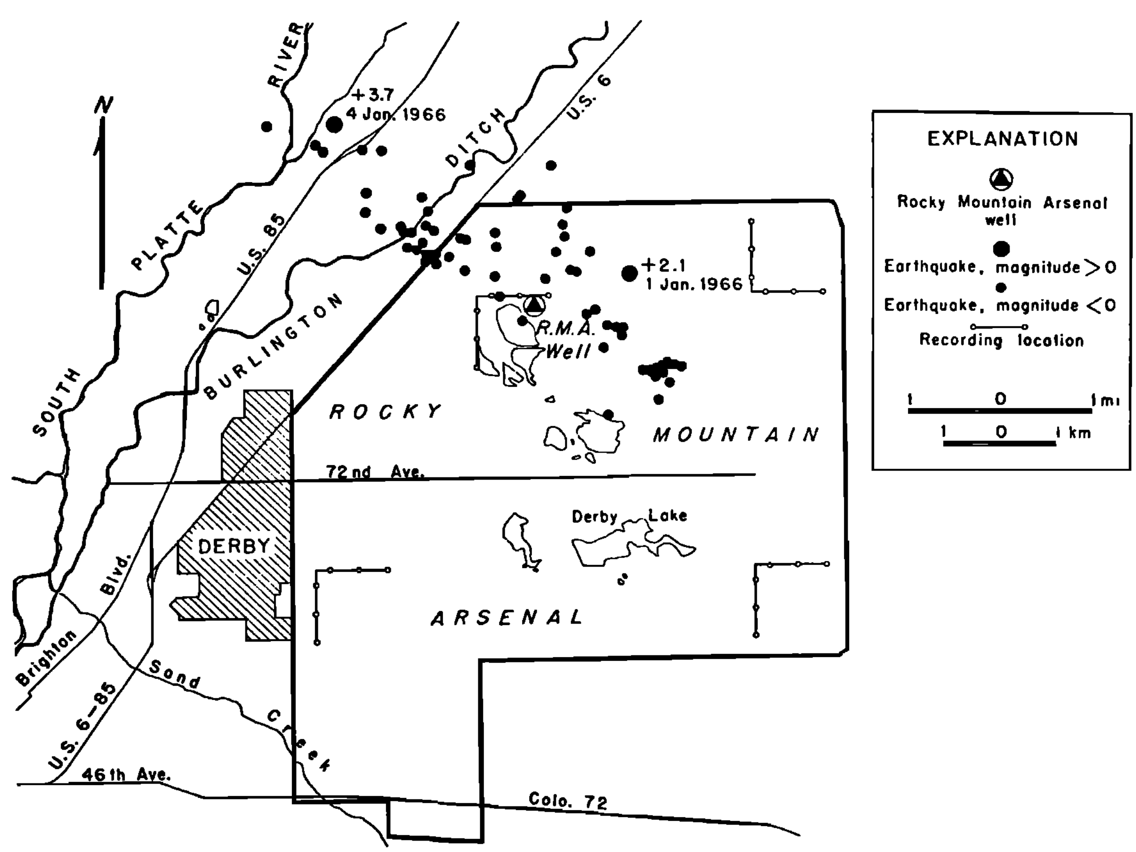


Fig. 2. Locations of earthquakes recorded from mobile microseismic stations during January and February 1966 [from *Healy et al.*, 1966].

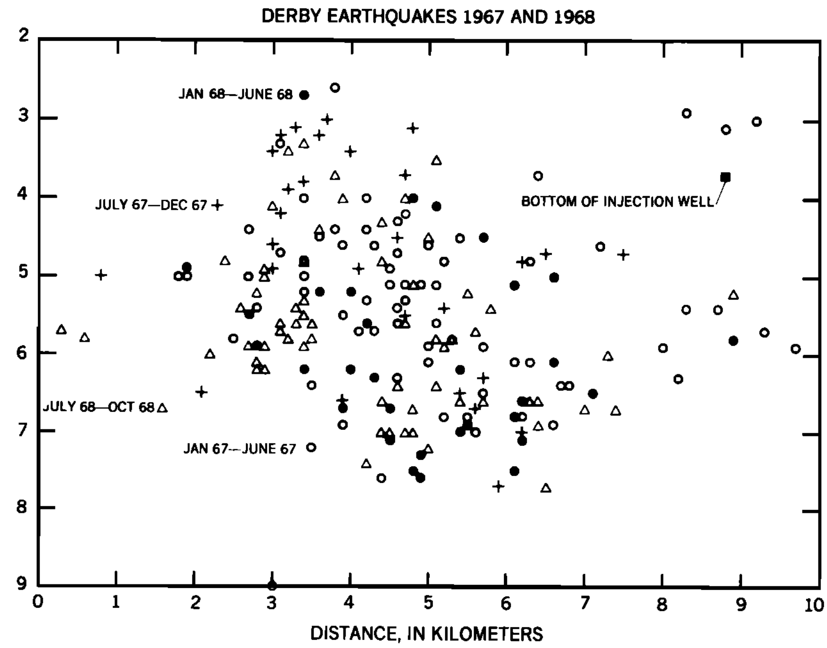


Fig. 3. Northwest-southeast cross section on which are plotted the earthquakes reported by *Hoover and Dietrich* [1969] for 1967 and 1968.

the RMA well confirmed the presence of fractures in the Precambrian interval [*Scopel,* 1964]. It is believed that the reservoir permeability is confined primarily to these fractures; the reservoir rock itself is much less permeable. *Evans* [1966] found that the Precambrian core was split apart along a vertical fracture plane. He theorized that this might have been an open fracture. *Sheridan et al.* [1966] studied the petrography of the core and further found that the fractures and microbreccias in the cores were very similar to fracture zones in the Front Range granites. They suggested that a fracture zone may occur in the general vicinity of the RMA well. In a later study, *Snow* [1968] also suggested that the fractured Precambrian rocks beneath the Denver Basin are of common origin with the fractured Precambrian rocks of the Front Range.

Another line of evidence that suggests the existence of fractures in the Precambrian bedrock is the locations of the earthquake epicenters that were recorded in the vicinity of the RMA. Between 1966 and 1968, various seismic arrays were installed by the U.S. Geological Survey at the RMA. Although these devices were in operation intermittently, sufficient data were collected so that a zone of earthquake epicenters could be clearly outlined. The result of this survey indicated that the earthquake epicenters were consistently located in an area that is elliptical in shape, approximately 10 km long and 3 km wide, and contains the RMA well (Figure 2). The trend of the major axis of this seismic zone was approximately N 60°W. The analysis of these earthquakes suggested that they occurred as results of shear motions along near-vertical planes having the same trend as the seismic zone [*Healy et al.,* 1966, 1968; *Hoover and Dietrich,* 1969].

The vertical extent of the reservoir can be inferred from the depth range of the Denver earthquakes. Depths of earthquake hypocenters have been investigated by *Wang* [1965], *Healy et al.* [1966], and *Hoover and Dietrich* [1968]. Wang reported that a number of earthquakes were located at depths greater than 30 km. Healy et al. inspected Wang's data and noted that most of the earthquakes reported in Wang's study were located with less than four stations. These four stations were not optimally located to detect earthquakes in the RMA vicinity. Healy et al. concluded that Wang's locations were subject to errors of 10 km or more.

Using early data collected by the U.S. Geological Survey seismic array installed on the RMA, Healy et al. found that the earthquake hypocenters clustered much more closely around the RMA well than was indicated in Wang's study. All the earthquakes studied by Healy et al. were located at depths between 4.5 km and 5.5 km below land surface.

A comprehensive list of earthquake hypocenters recorded during 1967 and 1968 by the U.S. Geological Survey seismic array was given by *Hoover and Dietrich* [1969]. In Figure 3 the hypocenters of these earthquakes are plotted on a northwest-southeast cross section taken through the trend of the epicenters. This plot suggests that the earthquake zone extends approximately 3.3 km in depth from 3.7 km to 7.0 km below land surface. The vertical extent of the reservoir in the Precambrian rocks in expected to be confined to this range.

Numerous pressure measurements have been made in the

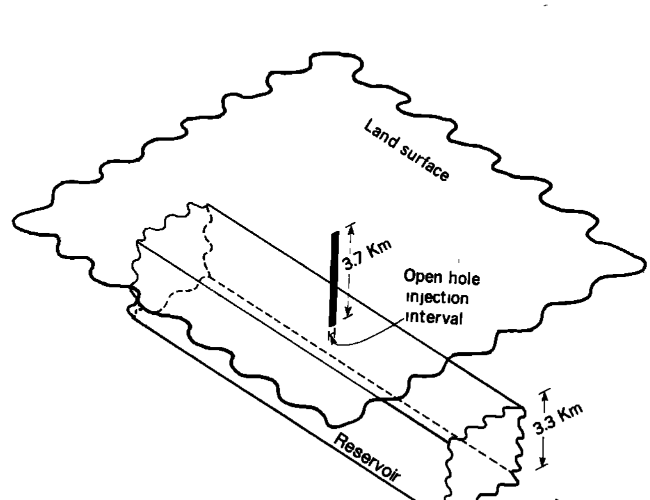


Fig. 4. Oblique view of the idealized reservoir modeled as a long, narrow prism of isotropic, porous medium.

TABLE 1. Range of Calculated Transmissivity Values

Dates	Type of Test	Number of Tests	Range of Calculated Transmissivity, m^2/s Low	High	Average	References
Sept. 19–20, 1961	injection	5	1.11×10^{-6}	4.05×10^{-5}	2.36×10^{-5}	*van Poollen* [1966]
Jan. 1–3, 1962	injection	4	2.50×10^{-5}	9.13×10^{-5}	7.05×10^{-5}	*van Poollen* [1966]
March 8, 1962, to Feb. 20, 1966	change of injection rate	15	8.78×10^{-6}	3.13×10^{-5}	1.63×10^{-5}	*van Poollen* [1966]
Sept. 2 to Oct. 26, 1968	pumping	3	3.61×10^{-6}	1.05×10^{-5}	6.76×10^{-6}	*van Poollen* [1969]

RMA well for the purpose of estimating the transmissivity of the Precambrian reservoir. These data can be divided into three categories: (1) injection tests conducted prior to the start of the waste disposal operations, (2) continuous pressure recordings during the 4-year disposal operation period, and (3) pumping tests conducted in the fall of 1968.

Prior to the waste injection operation, a total of nine injection tests were performed for the open interval between 3650 m and 3671 m. Five of these injection tests were conducted during September 1961 and the remaining four during January 1962. For all the injection tests, pressure measurements were made only during the shut-in period following injection. Pressure data are given by *Rowland* [1962] and *Ball et al.* [1966].

The September 1961 tests were conducted through the drill pipe, using the drilling rig equipment. Except for the last two runs, during which Amerada subsurface gauges were used, pressure readings were taken with a surface recorder. In general, the pressure data were of poor quality. Using the Horner method of analysis, *van Poollen* [1966] calculated transmissivity values ranging from 1.11×10^{-6} m^2/s to 4.05×10^{-5} m^2/s, with a probable average of 2.36×10^{-5} m^2/s.

In January 1962, after the well was completed, four additional injection tests were performed. Pressure recordings from a subsurface Amerada gauge were available for the latter three tests, and the data obtained were generally of better quality than those from earlier tests. The calculated transmissivities, however, ranged from 2.5×10^{-5} m^2/s to 9.13×10^{-5} m^2/s [*van Poollen,* 1966]. These values are somewhat higher than those computed from the September 1961 tests. Van Poollen suggested that the high values could be explained by a cleaning of the fractures during the long period of fluid withdrawal prior to the January injection tests.

In addition to data from the injection tests, transient wellhead pressure, which was continuously recorded during the actual waste disposal operation, may also be used to estimate reservoir transmissivity. Continuous daily wellhead pressure charts are available for the periods from May 1962 to September 1963 and from April 1965 to February 1966. Although the injection rate changed frequently, there were several occasions where a long period of constant injection was followed by another long period of either constant injection at a different injection rate or by shut-down. Pressure data for these periods are particularly suitable for estimating reservoir transmissivity. Using 15 such periods, *van Poollen* [1966] calculated transmissivity values which ranged from a low of 8.78×10^{-6} m^2/s to a high of 3.13×10^{-5} m^2/s. In general, however, most of the calculated transmissivities were close to the average value of 1.63×10^{-5} m^2/s.

In the fall of 1968 a series of pumping tests were conducted at the RMA well. Drawdown data from these tests can be used as additional estimates of the reservoir transmissivity. From the results of these pumping tests, *van Poollen* [1969] noted that transmissivity in the Precambrian reservoir appeared to be a function of pumping rate. The calculated transmissivities were 1.05×10^{-5}, 6.17×10^{-6}, and 3.61×10^{-6} m^2/s for pumping rates of 7.89×10^{-4}, 1.28×10^{-3}, and 1.58×10^{-3} m^3/s, respectively.

A summary of the calculated reservoir transmissivities is shown in Table 1. The wide range of values, spanning 2 orders of magnitude, is not unexpected considering the quality of the data, mechanical difficulties, and the many factors (such as variable pumping rates, wellbore damage, fluid composition, and temperature) that were not taken into account. It was decided that the average value of 1.63×10^{-5} m^2/s, computed from the 15 periods of rate change during the waste injection operation, was probably a good estimate of reservoir transmissivity determined from short-term data. While the pressure data from the September 1961 tests were poor, and the calculated transmissivity values from January 1962 tests were much higher than the rest, the 15 periods analyzed span the entire 4-year operation of the RMA well; calculated transmissivities were constantly close to the average value.

The initial downhole pressure in the Precambrian reservoir is not known. During the final stages of well construction, considerable lost circulation was encountered while drilling the Precambrian interval. Loss of circulation generally alters the natural fluid pressure in the vicinity of the well, and the initial downhole pressure in the reservoir could not be determined.

In 1966, after injection was discontinued at the RMA well, *Ball and Downs* [1966] estimated the initial downhole pressure

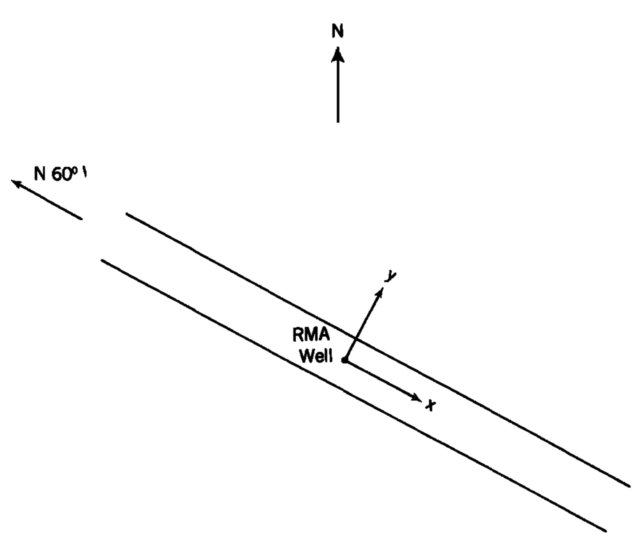


Fig. 5. Plan view of infinite strip reservoir used for analysis.

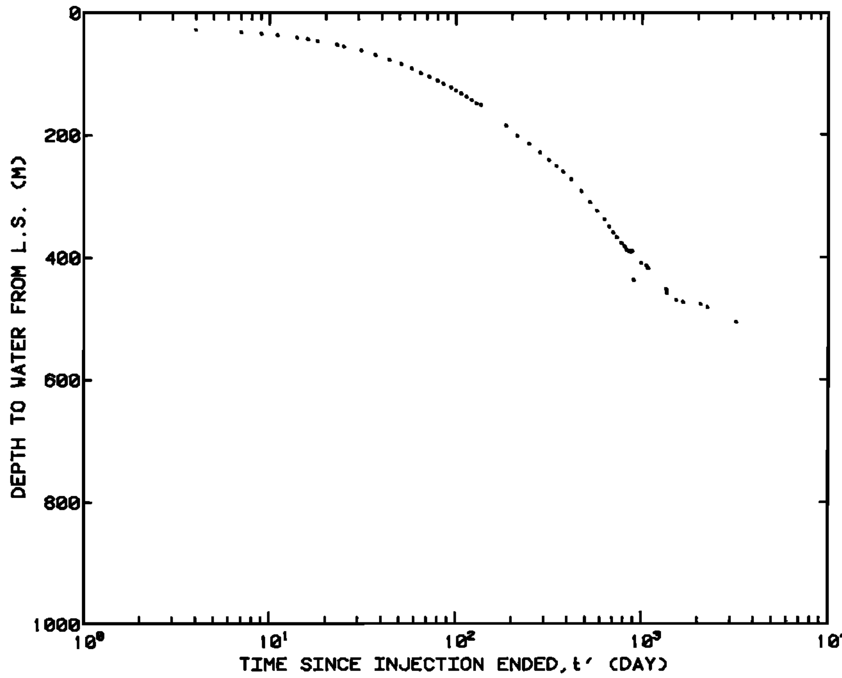


Fig. 6. Observed water levels in the RMA disposal well since injection ended.

to be 328 bars. At about the same time, *van Poollen* [1966] computed a value of 339 bars. Assuming fresh water at 20°C in the well tubing, Ball and Downs' value would put the initial fluid level at 325 m below land surface, while van Poollen's estimate would give an initial fluid level of 208 m below land surface.

By the end of 1967, however, it became apparent that the earlier estimates of initial reservoir pressure were incorrect. On December 22, 1967, fluid level in the RMA well had already dropped to 350 m below land surface [*van Poollen,* 1968] and was continuing to fall off at a rate of 0.3 m per day. In a later calculation, *van Poollen* [1968] revised the pressure estimate to 269 bars (fluid level at 923 m below land surface). Water level measurements since the beginning of 1968 indicate that this value is a more reasonable estimate of the initial downhole pressure in the Precambrian reservoir [*Healy et al.,* 1968].

IDEALIZED MODELS OF THE RESERVOIR

To compute pressure buildup and the subsequent falloff caused by fluid injection, an idealized model of the reservoir is proposed. Fluid flow in the idealized reservoir can be described in terms of a partial differential equation. Given the

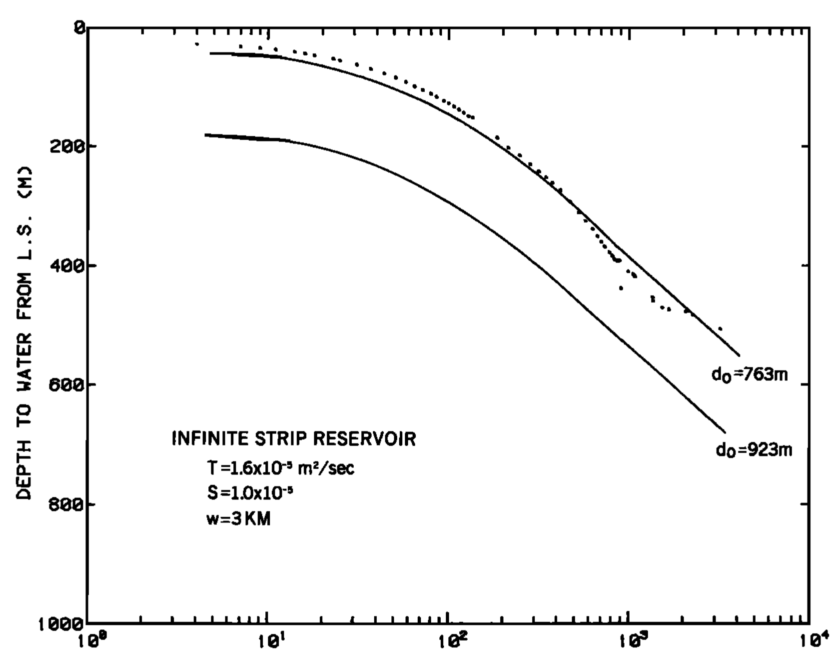


Fig. 7. Comparison of computed and observed water levels following injection in the RMA well—first trial for infinite strip model.

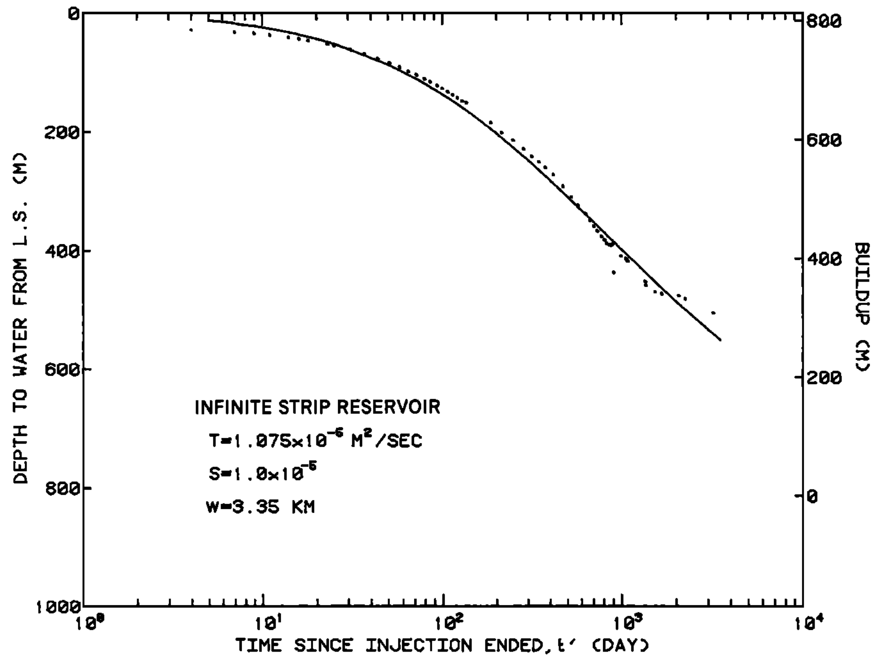


Fig. 8. Comparison of computed and observed water levels following injection in the RMA well—best fit for the infinite strip reservoir model.

appropriate initial and boundary conditions, the equation can be solved to determine the pressure history.

In the present study we assume the reservoir to be composed of a series of connected vertical fractures, which are more or less parallel to one another and are generally aligned in the direction of the zone of earthquakes, N 60°W. The reservoir is taken to extend in depth over the depth range of the earthquake hypocenters, from 3.7 km to 7.0 km below land surface, and confined above and below by impermeable boundaries. We further assume that fluid flow in the fractured reservoir can be approximated by flow in a homogeneous, porous medium so that a continuum model may be used.

Based on the present knowledge of the reservoir, two different reservoir configurations seem reasonable. If the northwesterly trending fractures are present throughout the Precambrian bedrock, then it is reasonable to model the reservoir as an anisotropic porous medium of infinite lateral extent, the principal major direction of anisotropy being colinear with the trend of the fractures, i.e., N 60°W. On the other hand, if the fractures are confined to a narrow, linear zone, then the reservoir can be considered as a long, narrow prism whose longitudinal axis is aligned in the N 60°W direction. An oblique view of this reservoir model is shown in Figure 4. An isotropic, porous medium is sufficient for this model, because

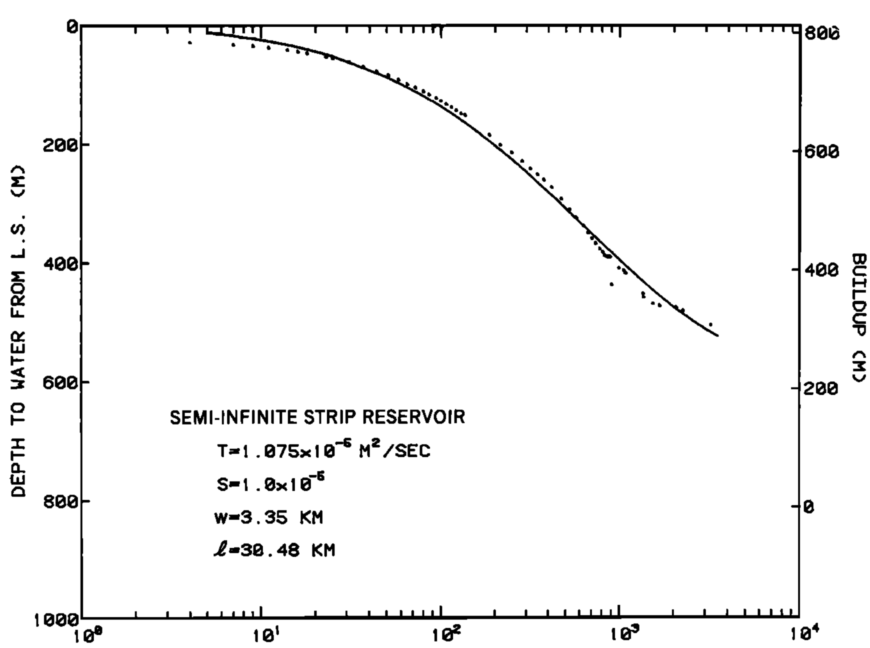


Fig. 9. Comparison of computed and observed water levels following injection in the RMA well—best fit for the semi-infinite strip reservoir model.

the dominant flow direction is along the longitudinal axis of the reservoir. Introduction of anisotropy into the model will not change the flow pattern appreciably.

As a further simplification, horizontal two-dimensional flow is assumed. Although two-dimensional flow is a somewhat restrictive assumption, we feel that it is acceptable for four reasons:

1. Pressure buildup computed from a two-dimensional model may be interpreted as the average pressure buildup over the depth of the reservoir [*Bear*, 1979]. We feel that a comparison of the horizontal distribution of earthquake epicenters with the vertically averaged pressure buildup is a reasonable approach to examining the earthquake–pore pressure relationship.

2. The long-term seismic data (1962–1972) give only the horizontal spread of earthquake epicenters. Good depth data are only available for 1967 and 1968. Thus even if the three-dimensional pressure field can be calculated, for most of the 11-year period, the earthquake-pressure comparison can only be made on a two-dimensional basis.

3. Present available information is insufficient to warrant a three-dimensional analysis. For example, *Snow* [1968] studied the hydraulic character of fractured metamorphic rocks of the Front Range and found that fracture permeability decreased with depth due to the increase in fracture spacing and the decrease in fracture aperture. Unfortunately, we do not know the manner in which permeability varies with depth in the reservoir below the RMA.

4. Data used for model calibration consist of water level measurements made at the RMA well after injection was discontinued. During the falloff period, vertical head gradients in the reservoir quickly vanish, and the fluid flow becomes essentially horizontal. Thus the hydraulic heads observed during falloff should be reasonably close to the vertically averaged heads computed by the two-dimensional model.

Development of the partial differential equation governing vertically averaged hydraulic head buildup in the reservoir can be found in the work of *Bear* [1979]. For the infinite, anisotropic reservoir model, the governing equation is

$$T_x \frac{\partial^2 h}{\partial x^2} + T_y \frac{\partial^2 h}{\partial y^2} = S \frac{\partial h}{\partial t} - Q(t)\delta(x)\delta(y) \qquad (1)$$

where h is the vertically averaged buildup of hydraulic head above the initial head, T_x and T_y are the principal value of the transmissivity tensor, S is the storage coefficient, and $Q(t)$ is the variable injection rate. In writing (1), it is assumed that the x axis is aligned in the principal major direction of anisotropy, i.e., N 60°W, and the injection well is located at the origin of the axis system.

A similar partial differential equation can be written for vertically averaged buildup of hydraulic head in the narrow, fracture zone model. The equation is

$$T\left[\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right] = S \frac{\partial h}{\partial t} - Q(t)\delta(x)\delta(y) \qquad (2)$$

Equation (2) is similar to (1) except that transmissivity is not a tensor but a scalar, T.

Analytical solutions for both models are well known in groundwater hydrology. Assuming that the hydraulic head is the same everywhere in the reservoir before injection, the analytical solution of (1) for the case of constant injection rate can be found in the work of *Papadopolus* [1965]. Varying injection rates can be approximated as a series of steps and analyzed using the convolution theorem; the vertically averaged hydraulic head buildup after n step changes in injection rate is

$$h(x, y, t) = \frac{1}{4\pi(T_x T_y)^{1/2}} \sum_{i=1}^{n} (Q_i - Q_{i-1}) W\left\{\frac{(x^2 T_y + y^2 T_x)S}{4T_x T_y(t - t_{i-1})}\right\} \qquad (3)$$

where t is the time from start of injection, W is the well function, t_i is the starting time of period i, and Q_i is the injection rate for that period. (Note that $t_0 = 0$ and $Q_0 = 0$.) The hydraulic head after shut-in can be computed by setting the last injection rate to zero.

In a two-dimensional formulation the narrow fracture zone model is analyzed as an 'infinite strip' (Figure 5). The solution of (2) for an infinite strip reservoir can be obtained by using the solution for a well in an infinite, isotropic reservoir [*Theis*, 1935] and applying image well theory [*Ferris et al.*, 1962]. For a step-varying injection rate the solution for a well located at the center of the infinite strip is

$$h(x, y, t) = \frac{1}{4\pi T} \sum_{i=1}^{n} (Q_i - Q_{i-1}) \sum_{m=-\infty}^{m=\infty} W\left\{\frac{[x^2 + (y + mw)^2]S}{4T(t - t_{i-1})}\right\} \qquad (4)$$

where w is the width of the strip.

In both models the vertically averaged pressure increase, Δp, can be computed from h by

$$\Delta p = h\gamma \qquad (5)$$

where γ is the specific weight of the fluid.

MODEL IDENTIFICATION AND CALIBRATION

The two reservoir models were calibrated using the history of observed water levels in the RMA well after waste injection was discontinued (Figure 6). These measurements were made by the U.S. Geological Survey as part of a continuous well monitoring program. The falloff data (T. Hurr, 1977, written communications) were taken over a period of 9 years (February 1966 to March 1975) following final shut-in. Only the earlier data were available to previous investigators. The later measurements added significant information to the present analysis.

The purpose of the model calibration was to find appropriate values of model parameters such that, given the injection history, the analytical solutions would produce a falloff curve which would closely match the falloff data observed in the RMA well. For the infinite, anisotropic reservoir model the parameters to be estimated were T_x, T_y, S, and d_0, the initial depth of the water level from land surface. For the infinite strip reservoir model the parameters to be estimated were T, S, w, and d_0. It was expected from the outset that there would probably be no unique solution to this calibration problem. Our purpose, rather, was to determine parameters that are consistent with values calculated in previous studies.

The calibration method was basically one of trial and error. The vertically averaged hydraulic head buildup in the well was computed from the analytical solutions using a distance of 0.086 m (radius of the open hole) from the injection point. (The exact distance is unimportant because the hydraulic head distribution near the well is relatively uniform during falloff.) A set of parameters was chosen, and the computed falloff curve was compared to the observed data. If the agreement was poor, then one or more of the parameters were

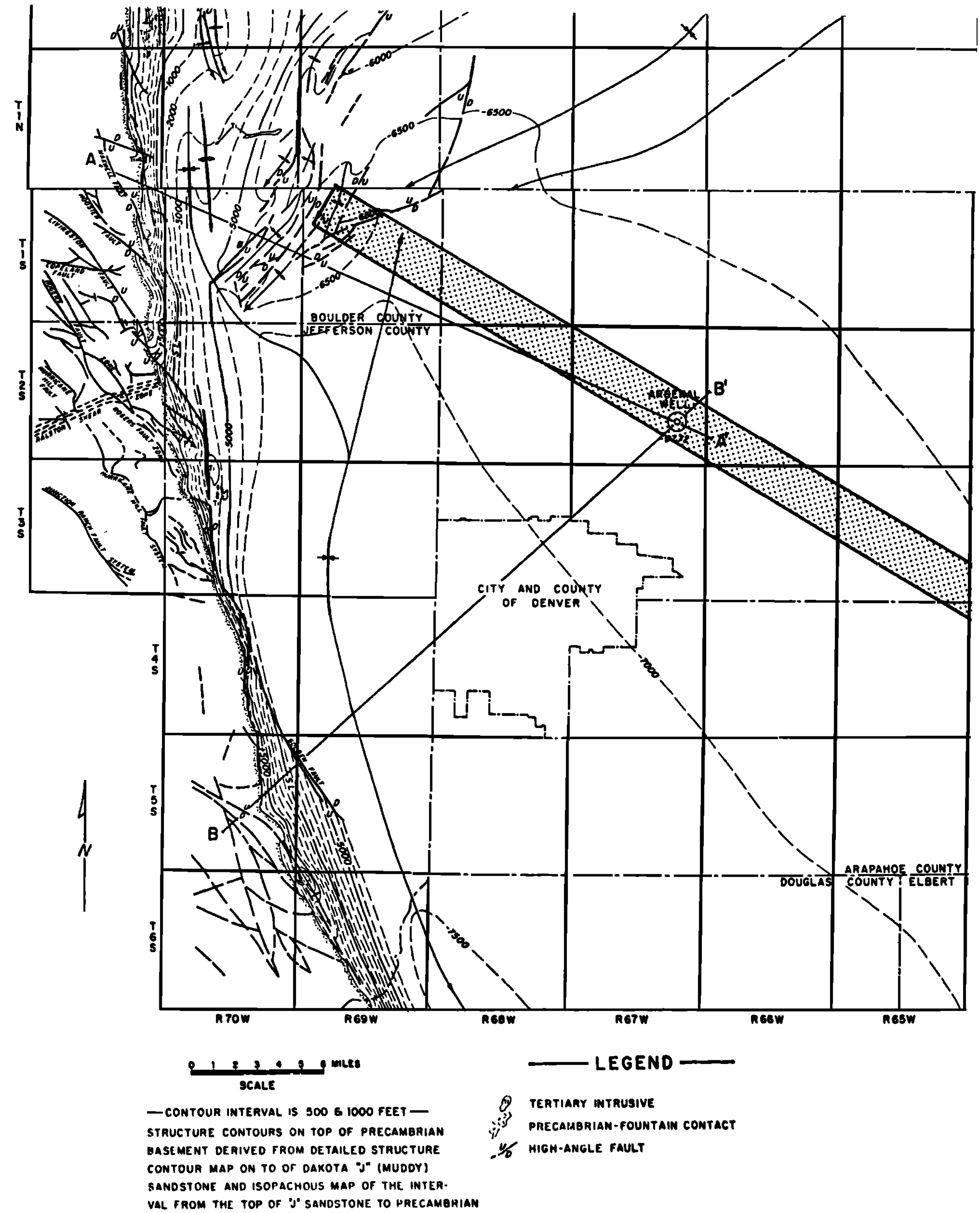


Fig. 10. Precambrian structural contour map of the Denver Basin with the semi-infinite strip reservoir indicated (modified from *Haun* [1968]).

changed and a new falloff curve was computed. This procedure was repeated systematically until a set of parameters that generated a falloff curve that fitted the observed data to a satisfactory degree was found.

In our attempt to calibrate the infinite, anisotropic reservoir model, it became apparent that this model could not produce a falloff curve that would match the observed data. The reason behind the lack of fit is clear when one realizes that flow

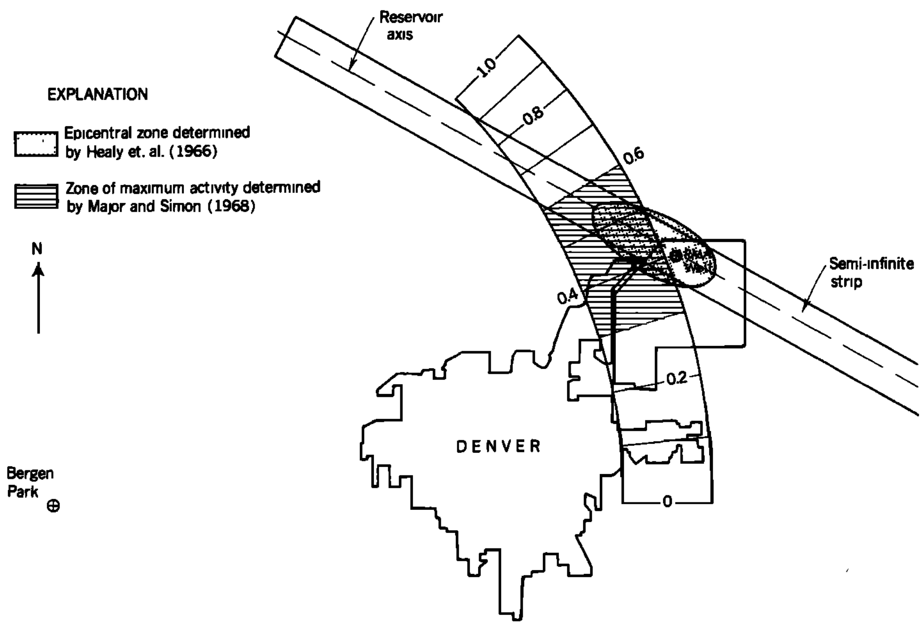


Fig. 11. Map showing the semi-infinite strip reservoir and its relationship to epicentral zone of earthquakes mapped by *Healy et al.* [1966] and epicentral zone determined by *Major and Simon* [1968]. Numbers are N/E ratios.

in an infinite, anisotropic reservoir is inherently radial. Although the cone of hydraulic head buildup about the injection well is elliptical and suggests that dominant flow is along the major principal direction of anisotropy, it should be noted that flow in an infinite, anisotropic reservoir can be analyzed as flow in an equivalent infinite, isotropic reservoir through a spatial transformation. Thus the behavior of hydraulic head with time at a point in an infinite, anisotropic reservoir is identical to the behavior at a transformed point in an equivalent infinite, isotropic reservoir.

Van Poollen and Hoover [1970], however, suggested that the flow system in the Precambrian bedrock is essentially linear or one dimensional. Their suggestion was based on the observation that during the first $3\frac{1}{2}$ years after shut-in, the water level in the RMA well decreased linearly with the square root of time since shut-in. This type of transient behavior is a strong indication that fluids were injected into a narrow, linear fracture zone in the Precambrian bedrock. Our analysis supports *van Poollen and Hoover*'s [1970] conclusion; the falloff data cannot be fitted using an infinite, anisotropic reservoir model.

The infinite, anisotropic reservoir model was abandoned, and the calibration effort was concentrated on the infinite strip (narrow fracture zone) model. As a first guess, we used parameter values suggested by previous studies, i.e., $T = 1.63 \times 10^{-5}$ m^2/s and $d_0 = 923$ m. The width of the strip was set to 3 km (width of the earthquake zone), and the storage coefficient was arbitrarily set at 1.0×10^{-5}. The computed falloff curve is shown in Figure 7. Comparing the computed curve with the observed data, we can immediately see that our original estimate of d_0 is too large. Notice, however, that if the initial depth were decreased by 160 m to 763 m below land surface, the computed curve would match the observed data remarkably well (Figure 7).

At the end of the calibration process the parameters that gave the best fit were found to be $T = 1.08 \times 10^{-5}$ m^2/s, $S = 1.0 \times 10^5$, $w = 3.35$ km, and $d_0 = 813$ m. A comparison of the falloff curve computed using the best fit parameters with the observed data is shown in Figure 8. Although the fit is not perfect, and the residuals appear to be correlated, such imperfections are not unexpected considering the fact that a greatly simplified model was used to simulate the flow in what must be a highly complex system of fractures beneath the Denver Basin.

It should be noted, however, that a significant difference in the shape of the computed and observed falloff curves can be seen for the later times. After approximately 1000 days from shut-in, the observed data exhibited a sharp decrease in the rate of falloff. Such a feature was not found in any of the falloff curves generated during the calibration process. In fact, we were unable to incorporate this feature into the computed curves by modifying the four model parameters.

To account for this late time feature, we decided to modify the reservoir model itself. One method of producing a sudden change in falloff rate at late times is to replace the infinite strip model by a semi-infinite strip model with an impermeable boundary at one end. If the impermeable end were located sufficiently far from the well, then the falloff curves for early times computed by both models would be the same. For later times, however, the effect of the impermeable end would no longer be negligible and the falloff rate in the semi-infinite strip would be slower than in the infinite strip.

The analytical solution of (2) for a semi-infinite strip reservoir is

$$h(x, y, t) = \frac{1}{4\pi T} \sum_{i=1}^{n} (Q_i - Q_{i-1}) \sum_{m=-\infty}^{m=\infty} \left[W\left\{ \frac{[x^2 + (y + mw)^2]S}{4T(t - t_{i-1})} \right\} + W\left\{ \frac{[(x + 2l)^2 + (y + mw)^2]S}{4T(t - t_{i-1})} \right\} \right] \quad (6)$$

Note that an additional model parameter, the distance (l) from the injection point to the impermeable end, has now been introduced.

The calibration procedure for the new model was essentially the same trial and error method as before. We have, however, kept the same values for T, S, w, and d_0, since we

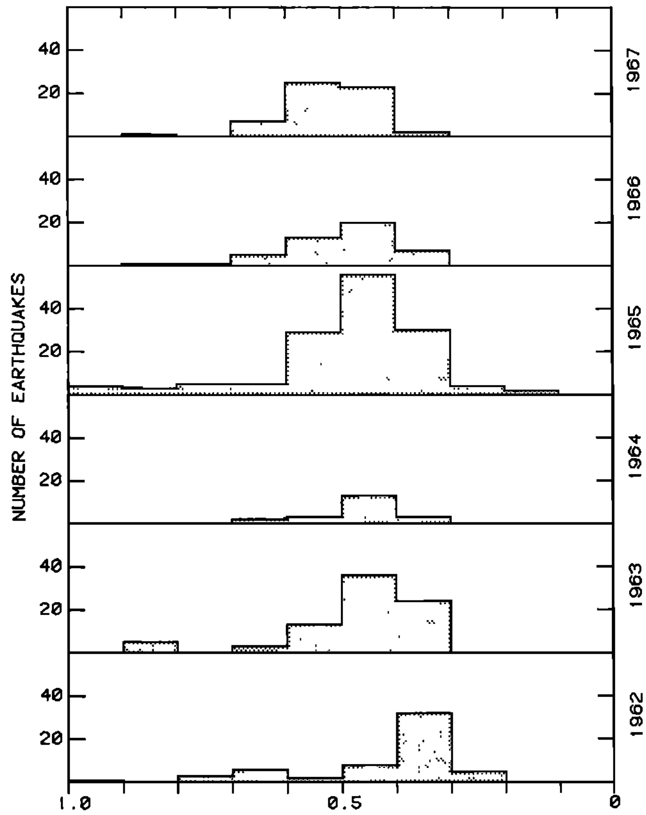


Fig. 12. Azimuthal distribution of Denver earthquakes observed at Bergen Park from April 1962 to August 1967 [*Major and Simon*, 1967].

wanted to obtain the same falloff curve as the infinite strip case for early times. Only the value of *l* was varied. The best fit value for *l* was found to be 30.5 km. A comparison of the computed and observed falloff curve is shown in Figure 9.

At first we anticipated that the existence of the impermeable end could be explained by the discontinuity in the Precambrian rocks at the mountain front. On reviewing a Precambrian structural map of the Denver Basin [*Haun*, 1968], however, we found that the mountain front was considerably further than 30 km from the RMA well. Instead, the best fit value of *l* placed the impermeable end in an area in which the reservoir is intersected by a set of vertical faults trending in a northeasterly direction (Figure 10). Displacements along these faults were found to be vertical [*Haun*, 1968]. The linear fracture zone in the Precambrian rocks may thus have been rendered discontinuous by vertical displacements along these northeasterly trending faults.

We feel that the falloff data observed in the RMA well can best be explained by the semi-infinite strip reservoir model because this model is supported by hydrologic, geophysical, and geologic evidence. In particular, we note the following:

1. The transmissivity of the semi-infinite strip model was calibrated using data recorded over a period of 9 years. In contrast, transmissivity values estimated in previous studies were calculated with the Horner method (which assumes an infinite reservoir) using pressure data recorded over periods of days or hours. Both the long-term and short-term data lead to similar estimates of reservoir transmissivity.

2. The width of the semi-infinite strip reservoir as determined by the reservoir analysis closely approximates the width of the observed seismic zone. This correlation further supports the hypothesis that a fracture zone exists in the Precambrian rocks beneath the RMA.

3. The position of the impermeable end of the semi-infinite strip as determined by reservoir modeling is supported by geologic evidence of vertical faulting.

4. The calibrated initial fluid pressure falls within the range estimated in previous studies.

SEISMIC DATA

Two seismic recording stations were in operation when the first Denver earthquake occurred in April 1962. One station, operated by the Colorado School of Mines, was located 34 km west of Denver at Bergen Park. The other station was located at Regis College in Denver. Between 1966 and 1968, additional seismic recording networks were installed by the U.S. Geological Survey and the Colorado School of Mines in the Denver area and at the RMA.

Because of high background noise from the Denver area, the seismograph at Regis College was operated at low magnification; earthquakes of small magnitude were undetected at Regis College. The U.S. Geological Survey network, which was installed after 1966, was in operation for only a few years. Consequently, seismograms from the Bergen Park observatory provided the only continuous, reliable record of earthquake activity in the Denver area.

Major and Simon [1968] presented a seismic study of the Denver earthquakes using seismograms from the Bergen Park observatory for the period from April 1962 to August 1967. By measuring the time interval between *P* and *S* wave arrivals and calculating the ratio of amplitude of the first motion on the N/S seismogram to the amplitude of the first motion on the E/W seismogram (defined as the *N/E* ratio), they were able to determine the approximate distance between an earth-

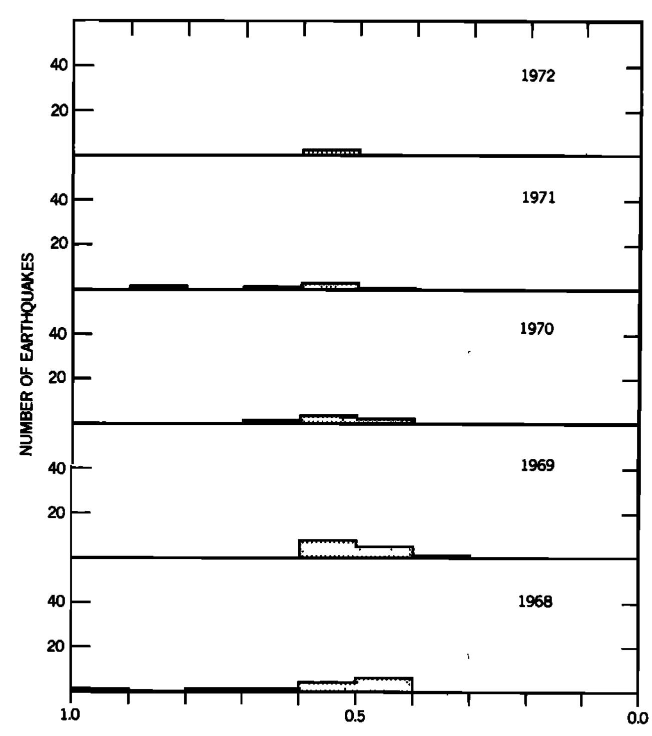


Fig. 13. Azimuthal distribution of Denver earthquakes observed at Bergen Park from 1968 through 1972.

quake epicenter and the observatory and the apparent direction of the epicenter from the observatory. The study was limited to those earthquakes that produced first motions large enough to be measured accurately but small enough not to be off scale.

Results from the seismic study showed that the time interval between *P* and *S* wave arrivals from the Denver earthquakes was nearly the same, but there were significant variations in the direction from the observatory to the epicenters as determined by the *N/E* ratios. From these observations, Major and Simon concluded that most of the earthquakes occurred about 44 km from the observatory and that the width of the active zone was probably less than 6.4 km. The areal extent of this zone is shown in Figure 11.

Figure 12, taken from the same study, shows the azimuthal distribution of the Denver earthquake observed at Bergen Park from 1962 to 1967. The distributions indicate that most of the Denver earthquakes occurred between *N/E* ratios of 0.3 and 0.6. A comparison of this zone of concentrated earthquake activity with the epicentral zone determined by *Healy et al.* [1966] shows that the Bergen Park data are consistent with the data recorded by seismic arrays at the RMA (Figure 11).

Major and Simon noted an interesting phenomenon in the azimuthal distribution of the Denver earthquakes. They suggested that there seemed to be a slow migration of the center of maximum activity to the northwest (in the direction of higher *N/E* ratios). This phenomenon was also observed in a later seismic investigation by *Hoover and Dietrich* [1969].

To extend the azimuthal study for the period after August 1967, seismograms from the Bergen Park observatory for the period from September 1967 to December 1972 were obtained. A catalog of the Denver earthquakes during this period was provided by *Presgrave* [1978]. Following the same method used by Major and Simon, a similar azimuthal study of the Denver earthquakes was conducted. The azimuthal distribution from 1968 through 1972 is shown in Figure 13. Because of the significant decrease in the number of earthquakes, the northwestward migration noted by Major and Simon is no longer observable. In general, however, the maximum activities are still centered in the zones of higher *N/E* ratios.

Comparison of Earthquake and Reservoir Pressure

Having determined a likely model for the Precambrian reservoir, the pressure buildup caused by fluid injection can be computed. If the Denver earthquakes are related to the waste injection program at the RMA, then a correlation will most likely be found between pressure buildup in the reservoir and earthquake epicenters. In this section we will compare the areal distribution of the computed pressure buildup with that of the earthquake epicenters for the period 1962 to 1972.

There is one problem which makes the direct comparison of reservoir pressure buildup with epicenter locations more difficult. While the pressure buildup is computed on a semi-infinite strip, the earthquake distributions (from the azimuthal study described earlier) are given in the active zone defined by two concentric arcs and two lines emanating from Bergen Park. To facilitate a meaningful comparison between pressure and earthquake distribution, we must choose a common base on which the distribution can be compared.

In this study we will make this comparison along the axis of the reservoir. Since flow in the reservoir is essentially linear, pressure variations across the width will be small. Thus the pressure profile along the reservoir axis will be a good indication of the overall pressure distribution in the reservoir.

To construct the distribution of earthquake epicenters along the reservoir axis, we divided the axis line into 10 segments using the 11 points of intersection between the reservoir axis and the 11 lines (with *N/E* ratios of 0 through 1.0) emanating from Bergen Park. The number of earthquakes in each section of the active zone is then lumped into the corresponding segment of the reservoir axis. Constructed in this manner, the bar graphs for earthquake distribution will have a horizontal scale in terms of distance along the reservoir axis, and the divisions between *N/E* ratios will be progressively smaller as the ratio varies from 0 to 1.0.

Figures 14*a*–14*i* permit comparisons of reservoir pressure buildup and earthquake distribution for nine characteristic periods from 1962 to 1972 (given in Table 2). For each period, two graphs are shown. The upper graph shows the distribution of earthquakes for a given period. The lower graph shows the computed reservoir pressure buildup along the reservoir axis for the first, middle, and last months of that period.

If the Denver earthquakes were caused by pressure buildup in the Precambrian reservoir, there should be a critical or threshold pressure buildup above which earthquakes will occur. (The earthquake mechanism will be discussed below.) This critical pressure buildup can be estimated in the following way. Since the earthquake activity essentially ceased by the end of 1972, the pressure buildup everywhere in the reservoir must have dropped below the critical value by this time. The maximum pressure buildup during January 1973 was computed to be 32 bars. We will therefore take this value to be the critical pressure buildup in the reservoir.

Examination of Figures 14*a*–14*i* reveals that the spatial distribution of the earthquakes is indeed governed by the critical pressure buildup hypothesis. Horizontal lines were drawn corresponding to 32 bars on each graph of pressure buildup. The figures show that earthquakes are largely confined to that part of the reservoir where the pressure buildup is above the critical value. In addition, the northwestward migration of the earthquake activity, a phenomenon noted by *Major and Simon* [1968], can now be explained by the outward propagation of the critical pressure buildup from the injection well. This feature is best illustrated in Figures 14*e*, 14*f*, and 14*g*. As the critical pressure buildup propagates from *N/E* ratios of 0.6 to 0.7, the number of earthquakes in this section also increased significantly.

It should be noted that there is a consistent lack of seismic activity in the section southeast of the well (between *N/E* ratios of 0.2 and 0.3) even when the pressure buildup in this section exceeds the critical value. Our present model cannot explain this observation. Such a lack of activity may be attributed to several possible factors among which are changes in the regional stress field or changes in the reservoir transmissivity.

Earthquake Mechanism

Most seismologists now agree that the Denver earthquakes were of tectonic origin, i.e., they resulted from sudden releases of tectonic strain energy stored in the Precambrian rocks beneath the Denver Basin. Seismic studies by *Major and Simon* [1968] and *Healy et al.* [1968] showed that the Denver earthquakes exhibit a frequency versus magnitude relationship that

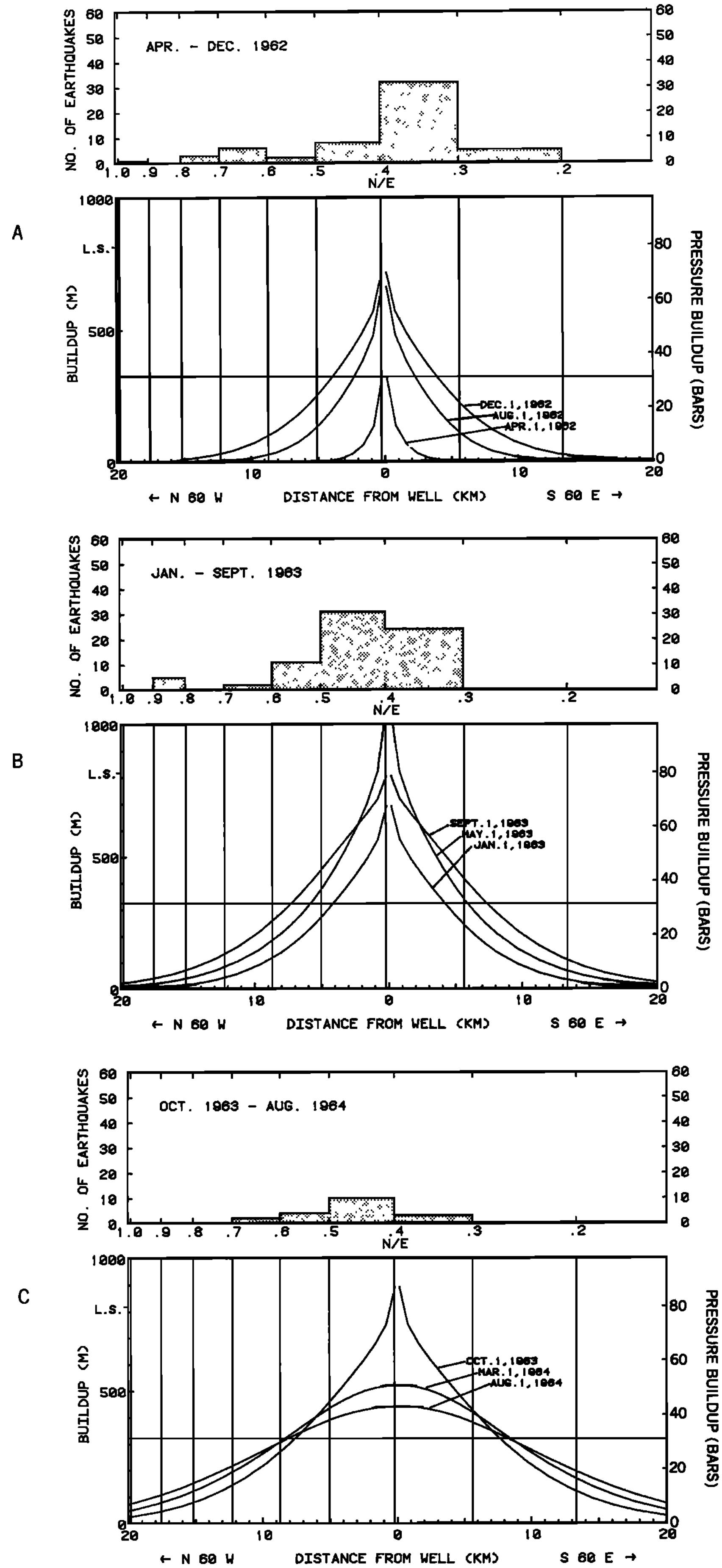


Fig. 14. Comparisons of earthquake distribution with computed pressure buildup in the Precambrian reservoir for nine characteristic periods.

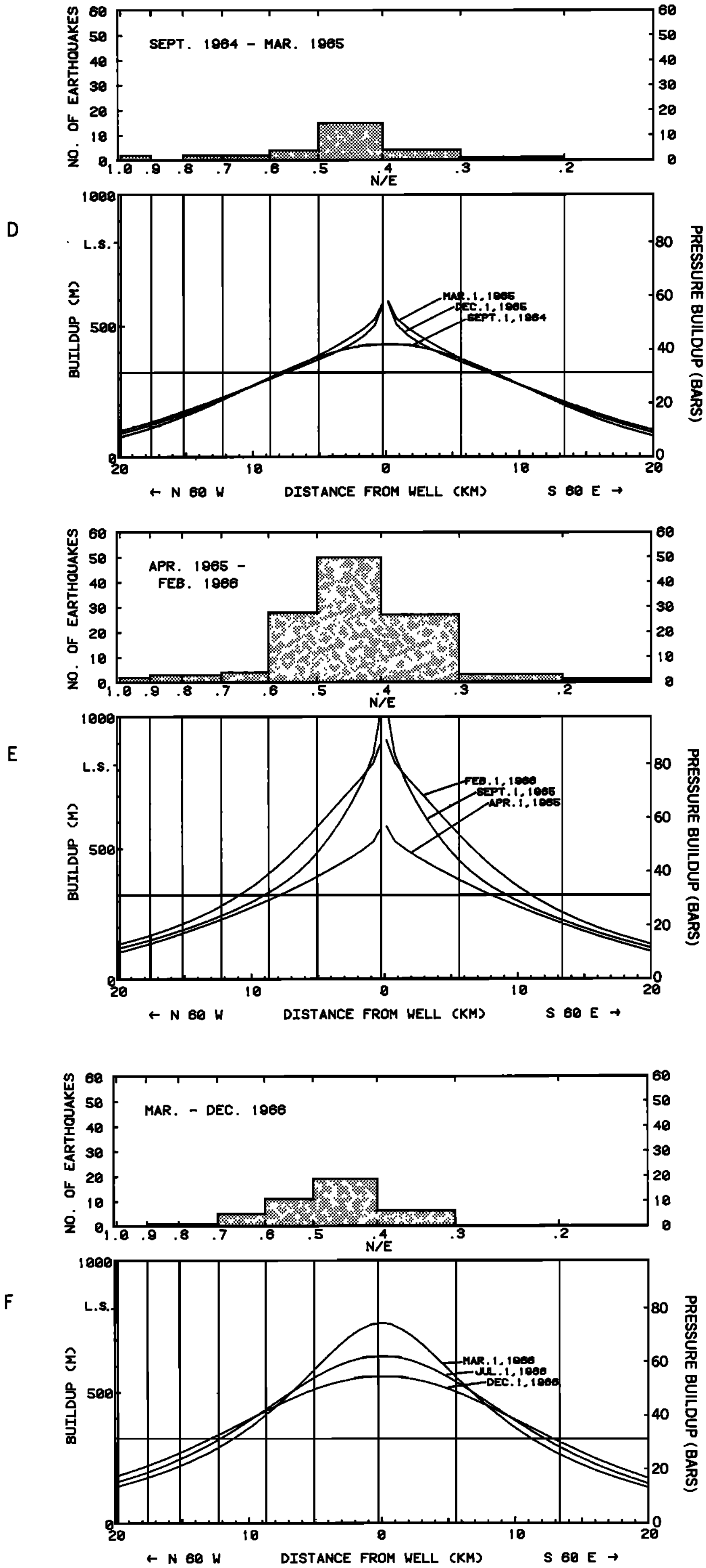
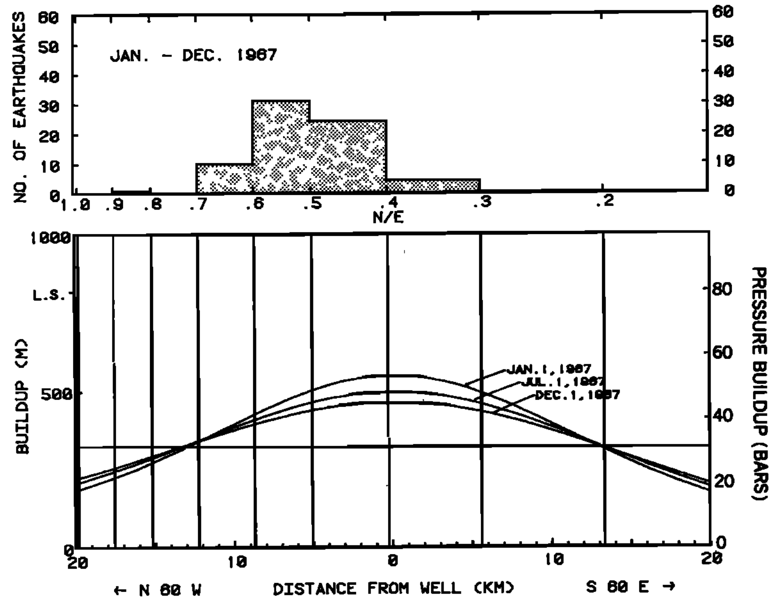


Fig. 14. (continued)

G



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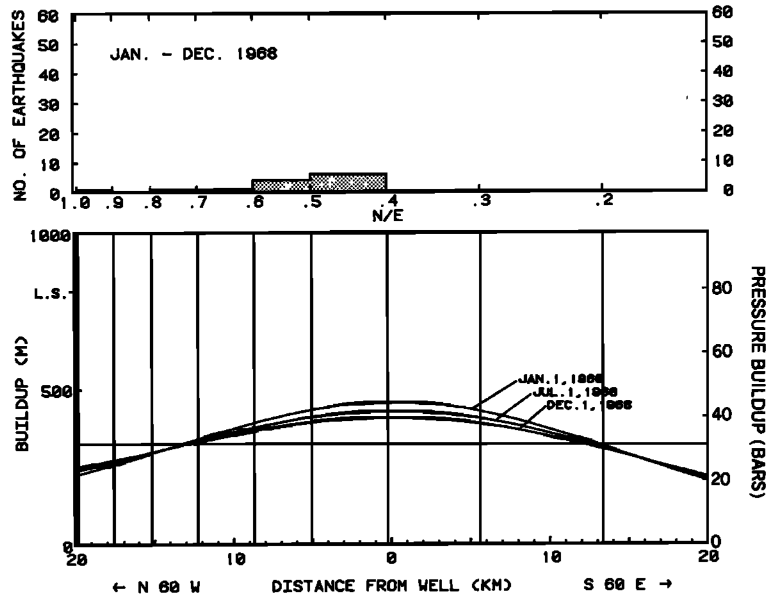

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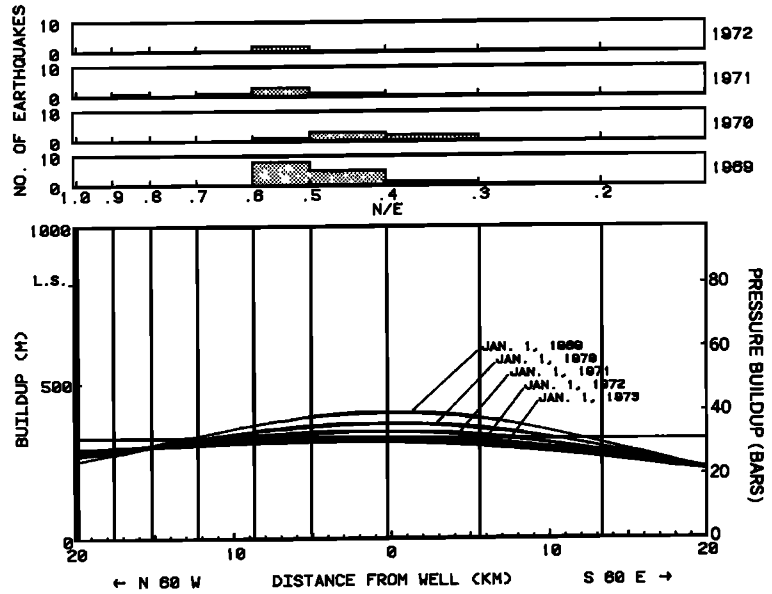

Fig. 14. (continued)

TABLE 2. Nine Time Periods for Which Earthquake Distribution and Computed Pressure Buildup Are Compared

Period	Operation
April–December 1962	pressure injection
January–August 1963	pressure injection
October 1963–August 1964	shut-in
September 1964–March 1965	gravity injection
April 1965–February 1966	pressure injection
March–December 1966	shut-in
January–December 1967	shut-in
January–December 1968	shut-in
January 1969–January 1973	shut-in

is similar to other tectonically active areas such as Southern California. Energy calculations by *Carder* [1966] and *Rubey* [1966] also showed that the total energy released by the earthquakes cannot be accounted for by the work done in injection of the waste fluid into the reservoir. *Ball and Downs* [1966] also argued that the geological setting of the Denver area was conducive to stress buildup within the rock. Consequently, most investigators who believe in the injection-earthquake relationship are of the opinion that fluid injection 'triggered' the release of strain energy that was stored in the basement rock by natural process of deformation.

Many triggering mechanisms have been proposed in previous studies. For example, thermal stress caused by the injection of cold fluids (20°C) into an initially hot reservoir (150°C) was suspected to be a major triggering force. Chemical reactions between the waste fluid and the reservoir rock may also have weakened the strength of the rock, thus allowing slippage to occur along fracture planes.

The most widely accepted mechanism, however, attributes the occurrence of the earthquakes directly to the increase of fluid pressure in the reservoir. This hypothesis states that the increase in fluid pressure serves to reduce the frictional resistance against the shear stress along a fracture plane. If the fluid pressure is increased to a point where the frictional resistance becomes less than the shear stress on the fracture plane, slippage will occur, and the result is an earthquake. This mechanism has been generally referred to as the Hubbert-Rubey mechanism.

The original work of *Hubbert and Rubey* [1959] actually concerns the role of pore pressure in the mechanics of overthrust faulting. They introduced the concept of rock movements caused by a Mohr-Coulomb type failure in a fluid-filled rock environment. This concept was first cited by *Evans* [1966] in his paper on injection-earthquake relationship and subsequently gained wide acceptance as the mechanism through which injection has caused the earthquakes.

The Hubbert-Rubey mechanism has been applied to the Denver earthquakes by *Healy et al.* [1968]. Although they did not perform any reservoir simulation, they showed that the occurrence of the Denver earthquakes were consistent with the Hubbert-Rubey theory. The present study further shows a correlation between spatial distribution of earthquake epicenters and fluid pressure buildup above a critical value. The existence of this critical pressure build-up is an additional feature that suggests that the Hubbert-Rubey mechanism is the dominant mechanism through which fluid injection has triggered earthquakes.

An important result of the present study is that the Denver earthquakes were triggered by a relatively small increase in reservoir pressure (32 bars). Such a small value of critical pressure buildup suggests that the basement rock at the RMA was already very close to failure prior to injection. This observation opens up the possibility that the Denver earthquakes may also occur spontaneously.

Prior to 1962, the only useful seismic data were from the seismograph station at the University of Colorado in Boulder. This station was in operation between 1954 and 1959. A study of the seismograms for this period by *Krivoy and Lane* [1966] revealed 13 events which might have been earthquakes in the Denver area. Since all the events occurred during normal working hours, Krivoy and Lane attributed them to the results of artificial explosions. Reexaminations of the seismograms by *Leet* [1966] and *Carder* [1966], however, cast doubts as to whether all the 13 events were from artificial sources. Both Leet and Carder are of the opinion that some of the events were natural earthquakes. *Hadsell* [1968] made a search of newspaper accounts of earthquakes in Colorado and found reports of a major earthquake on November 7, 1882. Using reports from 25 newspapers, he determined that the earthquake came from the Denver area and that the Richter magnitude was over 5. This earthquake is not unlike the three major earthquakes of 1967, which suggests that the Denver area may not have been totally immune to earthquake activities prior to 1962. If this hypothesis is true, the role of the waste disposal operation was to greatly increase the number of earthquakes during the injection period and during the subsequent few years after shut-in.

EFFECT OF HIGH PRESSURE ON RESERVOIR TRANSMISSIVITY

Van Poollen [1966, 1969] and *Ball et al.* [1966] have noted that the transmissivity of the Precambrian reservoir appeared to be much greater during injection than during shut-in or fluid withdrawal. In addition, the transmissivity seemed to increase as injection pressure was increased. They interpreted this observation to mean that the fractures in the reservoir were forced open as fluid was injected under pressure. These fractures may then close again when fluid is withdrawn and the pressure in the reservoir lowered.

Such changes in transmissivity with fluid pressure are common in fractured reservoirs and may indicate that hydraulic fracturing occurred during injection under high pressure. From the theory of hydraulic fracturing [*Hubbert and Willis*, 1957], it is known that if the well bore is connected to a preexisting fracture in a reservoir and if the reservoir pressure beyond the influence of stress disturbance caused by the borehole exceeds the original regional stress normal to the plane of the fracture, the fracture will be held open to allow more rapid flow. For the RMA well, *Healy et al.* [1968] noticed a large discontinuity in injection rate with fluid pressure. They took this to be evidence of hydraulic fracturing.

To further investigate the occurrence of hydraulic fracturing at the RMA well, daily pressures recorded at the wellhead during the injection operations were examined. It was found that at the start of most shut-in periods, the wellhead fluid pressure dropped abruptly to approximately 17.2 bars, after which the falloff would proceed at a much slower rate. Such a sudden drop in fluid pressure to a particular level followed by slow decay is another indication that hydraulic fracturing took place during injection. The 'instantaneous shut-in pressure' of 17.2 bars at wellhead (377 bars downhole) must be the pressure that is just sufficient to hold the fractures open and

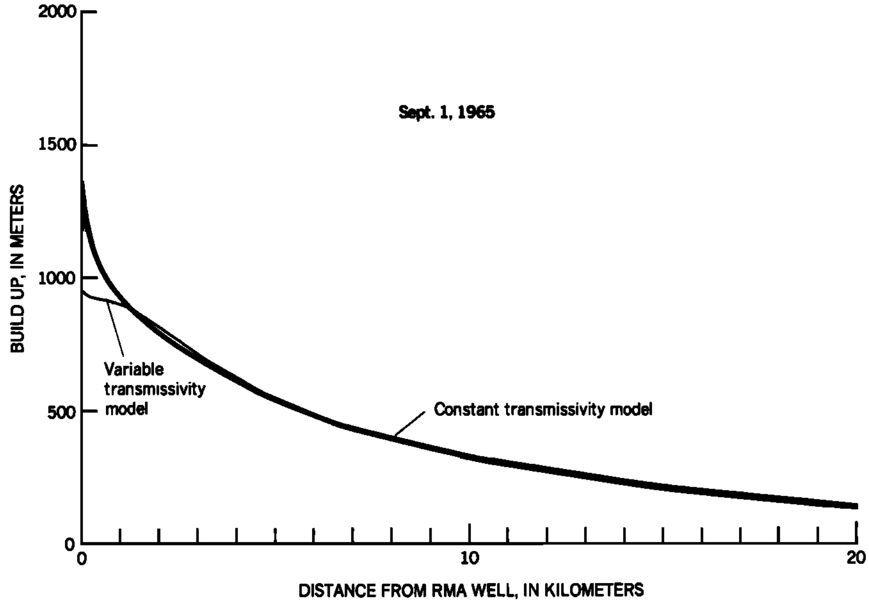

Fig. 15. Comparison of hydraulic head buildup computed by constant transmissivity model and variable transmissivity model. The variable transmissivity model simulates the effect of rapid fluid flow in fractures opened by high pressure.

should be equal to the regional stress component that acts in the direction normal to the fracture plane [*Kehle,* 1964].

During the periods of fluid injection at the RMA well, downhole fluid pressure was sometimes increased to 430 bars. Since this value exceeds the pressure needed to hold the fractures open, rapid fluid flow in open fractures must play an important role in determining the reservoir pressure near the well.

To determine the areal extent of the open fracture flow, the reservoir model was modified so that transmissivity was made a function of hydraulic head. The transmissivity at any point in the reservoir was set at 1.08×10^{-5} m^2/s when the hydraulic head buildup at that point was below 989 m (377 bars downhole pressure). At any point in the reservoir where the hydraulic head buildup was above 989 m, the transmissivity was abruptly increased to a much higher value. Such a transmissivity–hydraulic head relationship was formulated to simulate rapid flow in fractures opened by high fluid pressure.

This formulation makes the model nonlinear; the solution must be obtained by numerical techniques. In this study the Galerkin finite element method was employed. The nonlinear solution technique used a simple iteration procedure whereby the transmissivity was lagged as new estimates of hydraulic head buildup were computed. The transmissivity was then updated and the entire procedure was repeated until convergence was achieved.

A trial run was made assuming the open fracture transmissivity to be 100 times the normal transmissivity value. As expected, the computed hydraulic head buildup near the well during periods of high pressure injection was found to be much lower than the hydraulic head buildup computed using a constant transmissivity model. A comparison of the hydraulic head profiles of September 1965 computed by the two models is shown in Figure 15. These two profiles are shown because they exhibit the greatest difference in computed heads. As shown in Figure 15, the effects of rapid flow in open fractures are restricted to near the well; the two profiles differ by less than 10% at distances greater than 1 km from the well. In fact, for most of the injection period, the pressure profiles computed by the two models were almost identical.

It should be noted that the downhole pressure computed from the variable transmissivity model never reached 430 bars at any time during the trial simulation. This suggests that the transmissivity–hydraulic head relationship used in our trial run represents an extreme case of fracture opening near the well. Even for such an extreme case, we have shown that except for a small region near the well, the pressure profile computed by the variable transmissivity model is essentially the same as that computed by the constant transmissivity model. Thus the quality of the correlation between earthquake and pressure distribution discussed above remains unchanged.

CONCLUSIONS

Waste fluids were injected into a fractured reservoir in the Precambrian bedrock below the Rocky Mountain Arsenal between 1962 and 1966. Soon after injection began, earthquakes were detected in the vicinity of the RMA. These earthquakes were found to occur along a long, narrow seismic zone aligned in the direction N 60°W. Many investigators have suggested that a reservoir composed of connected vertical fractures aligned in the direction N 60°W exists in the Precambrian bedrock. Earthquakes were believed to be results of movements along the fracture planes and triggered by the increase in fluid pressure due to injection. This fluid pressure–earthquake hypothesis is examined in this paper by analyzing the pressure history in the Precambrian reservoir.

The fractured Precambrian reservoir can be visualized as either (1) a crystalline basement that contains a system of dominantly northwesterly trending fractures present throughout the area or (2) a narrow, linear fracture zone. In the former case the reservoir can be considered as a strongly anisotropic porous medium of infinite lateral extent; the major principal axis of anisotropy is taken parallel to the northwest trend of the fractures. In the latter case the reservoir is best considered as a long, narrow, rectangular prism of porous medium whose longitudinal axis is parallel to the northwest trend. In either case the reservoir is modeled as a porous medium that extends over the observed depth range of earthquake hypocenters, from 3.7 to 7.0 km below land surface.

The two reservoir models were calibrated using observed water levels in the RMA well after injection was discontinued. During the calibration process, it was found that the infinite, anisotropic reservoir model was unsatisfactory; the observed data could not be fitted by the model. On the other hand, calibration of the infinite strip reservoir model yielded parameter values that are consistent with those estimated in previous studies. The infinite strip model that provided the best fit has a transmissivity of 1.08×10^{-5} m^2/s, a storage coefficient of 1.0×10^{-5}, and a width of 3.35 km. It was also found that an improvement in the match between computed and observed water levels can be attained by placing an impermeable boundary at one end of the strip, i.e., replacing the infinite strip model by a semi-infinite strip model. A distance of 30.5 km from the injection well to the impermeable boundary was found to provide the best fit. The existence of the impermeable boundary is supported by geological studies which indicate vertical faulting in the vicinity of the best fit location of the boundary. Movements along these faults may have rendered the fracture zone discontinuous. The semi-infinite strip reservoir model is the best hydrologic representation of the fractured reservoir in the Precambrian basement rocks beneath the RMA.

Comparison of horizontal distribution of pressure buildup and earthquake epicenters for the period from 1962 to 1972 indicates that earthquakes are confined to that part of the reservoir where pressure buildup exceeds 32 bars. This critical value is interpreted as the pressure buildup above which earthquakes occur. This result is consistent with the results found at Rangely, where earthquakes were controlled by controlling fluid pressures [*Raleigh et al.*, 1976]. The earthquakes at the RMA, along with the experiment at Rangely, indicate that the Hubbert-Rubey hypothesis on the role of fluid pressure in faulting is the dominant process at work.

The reservoir analysis is extended to examining the effects of rapid flow in fractures opened by high injection pressures. The result of this investigation shows that the pressure distribution computed with the effects of fracture widening differs from the distribution computed without the effect in only a small region within 1 km of the injection well. The quality of the correlation between earthquake and pressure distribution remains unchanged.

At this point, the evidence seems rather conclusive that the increase of fluid pressure triggered the swarm of earthquakes at the RMA. This is not an original thought with us; as pointed out above, a number of investigators, starting with David M. Evans, have made this point. We believe that our analysis of fluid flow in the Precambrian reservoir ties up many of the loose ends left by earlier investigators.

Acknowledgments. The authors wish to acknowledge data provided by several of their colleagues. Ted Hurr, U.S. Geological Survey, Denver, has continued to make observations in the RMA disposal well. Without his observations, this paper would not have been possible. Maurice Major, Colorado School of Mines, Golden, provided us with the seismic records from the Bergen Park observatory. These records allowed us to extend the seismic data beyond that previously analyzed. Bruce Presgrave, U.S. Geological Survey National Center of Earthquake Information, Golden, provided us with a catalog of the Denver earthquakes for the period from 1967 to 1972. The catalog made possible an analysis of the Bergen Park data. The authors are indebted to a number of their colleagues for their reviews and comments, in particular, R. Hamilton, J. Handin, M. K. Hubbert, L. Wood, and M. Zoback. John Handin gave the authors a particularly perceptive review along with some additional ideas for the analysis.

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(Received August 15, 1979;
accepted January 18, 1980.)