THE DENVER AREA EARTHQUAKES AND THE ROCKY MOUNTAIN ARSENAL DISPOSAL WELL

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ABSTRACT: During 1961, a deep well was drilled at the Rocky Mountain Arsenal northeast of Denver, Colorado, to dispose of contaminated waste water. The well is bottomed in 75 feet of highly fractured Precambrian gneiss. Pressure injection of waste water into the fractured Precambrian rock was begun in March 1962. Since the start of fluid injection, 710 Denver-area earthquakes have been recorded. The majority of these earthquakes had epicenters within a five-mile radius of the Arsenal well. The volume of fluid and pressure of fluid injection appear to be directly related to the frequency of earthquakes. Evidence also suggests that rock movement is due to the increase of fluid pressure within the fractured reservoir and that open fractures may exist at depths greater than previously considered possible.

INTRODUCTION

Products for chemical warfare have been manufactured on a large scale under the direction of the Chemical Corps of the U. S. Army at the Rocky Mountain Arsenal since 1942. A by-product of this operation is contaminated waste water and, until 1961, this waste water was disposed of by evaporation from dirt reservoirs (Scopel, 1964).

When it was determined that Arsenal waste water was contaminating the local groundwater supply and endangering crops (Gahr, 1961; Walker, 1961), the Chemical Corps tried evaporation of the contaminated waste from water-tight reservoirs. This proved unsuccessful. The Chemical Corps and the Corps of Engineers then decided to drill an injection disposal well for the purpose of disposing of the contaminated waste water (Scopel, 1964).

The U. S. Army Corps of Engineers, Omaha District, commissioned the firm of E. A. Polumbus, Jr., and Associates, Inc., to design the well, supervise the drilling and completion, provide the necessary engineering geological services, and manage the project. Louis J. Scopel, as an associate, was the Project Geologist and was responsible for all geological aspects of the operation. Another geological associate was George R. Downs,

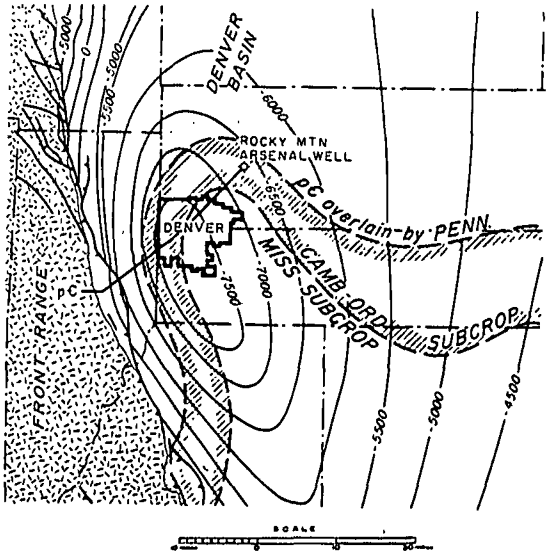

Figure 1. Structural map of a portion of the Denver-Julesburg Basin (after Anderman and Ackman, 1963), showing the location of the Rocky Mountain Arsenal well.

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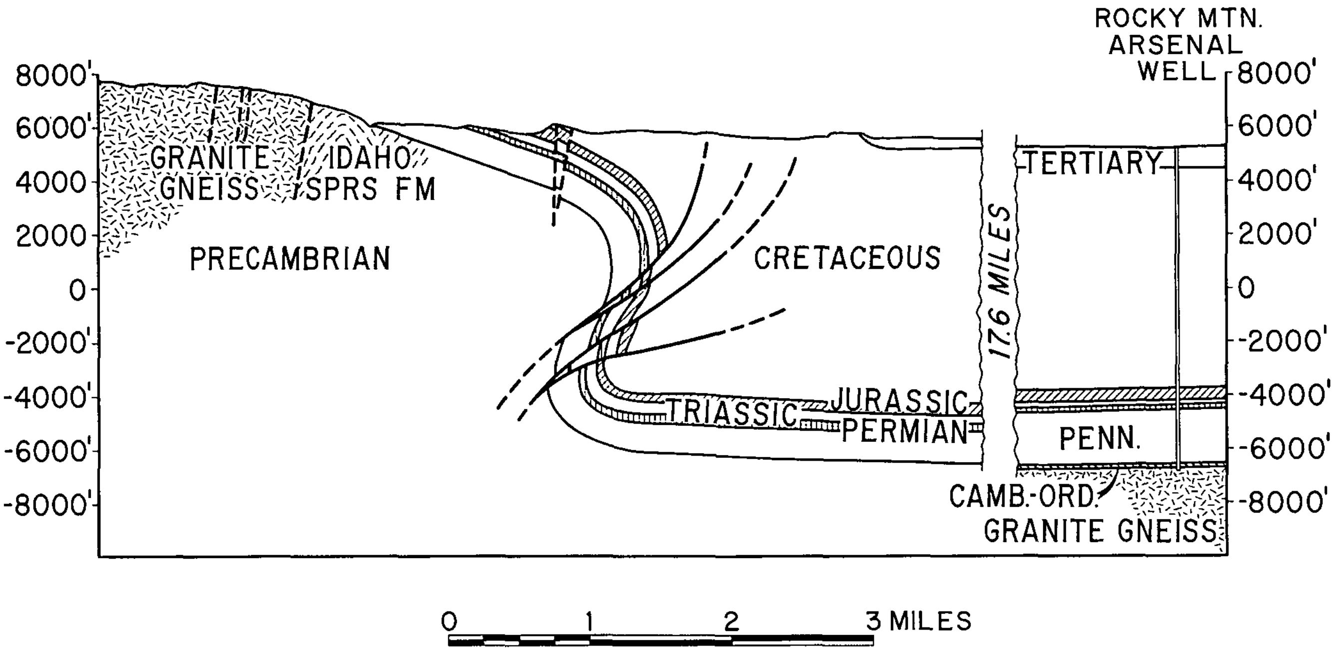

Figure 2. Cross-section showing the subsurface geology from the Arsenal well to the outcrop of Precambrian granite gneiss west of Denver (after M. F. and C. M. Boos, and H. H. Odiorne). The line of cross-section is shown in figure 1.

who contributed materially to the intial design of the project and acted in an advisory capacity throughout the the operation.

The well was located and drilled in the NW/4 NE/4 sec. 26, T. 2 S., R. 67 W. (39°-51.5' N., 104°-51' W.), Adams County, Colorado. It was spudded 10 March 1961 and completed at a total depth of 12,045 feet 11 September 1961.

REGIONAL GEOLOGY

The Rocky Mountain Arsenal Disposal well is located on the gently dipping east flank of the Denver-Julesburg Basin, just a few miles west of the axis of the basin. As indicated in figure 1, the Arsenal well is located in a region of the subcrop of Cambro-Ordovician rocks, near the area where these rocks are truncated by Pennsylvanian sediments.

Figure 1 is a structural map of a portion of the Denver-Julesburg Basin in the vicinity of the Rocky Mountain Arsenal well after Anderman and Ackman (1963). Figure 2 is a cross section after M. F. and C. M. Boos and H. H. Odiorne which shows the subsurface geology from the Arsenal well to the outcrop of Precambrian granite gneiss west of Denver.

The granite gneiss is identified as the Mount Morrison Formation by C. M. and M. F. Boos (1957), who describe typical Mount Morrison granite as medium to fine grained, pink to tan, and delicately gneissic. Parts of the granitic gneiss are permeated with ill-defined pegmatite.

Approximately 13,000 feet of structural relief exists between the top of the Precambrian in the Arsenal well and the Precambrian outcrop west of Denver.

STRATIGRAPHIC SECTION IN INJECTION DISPOSAL WELL

A diagram and log of the well are shown in figure 3 (Scopel, 1964). Figure 4 is a log of the pre-Pennsylvanian portion of the well by Scopel (1964). Scopel (1964) described the Precambrian section cut by the well as follows:

Precambrian

The above-described sediments [Ordovician or Cambrian] overlie 20 feet of bright green weathered schist which con-

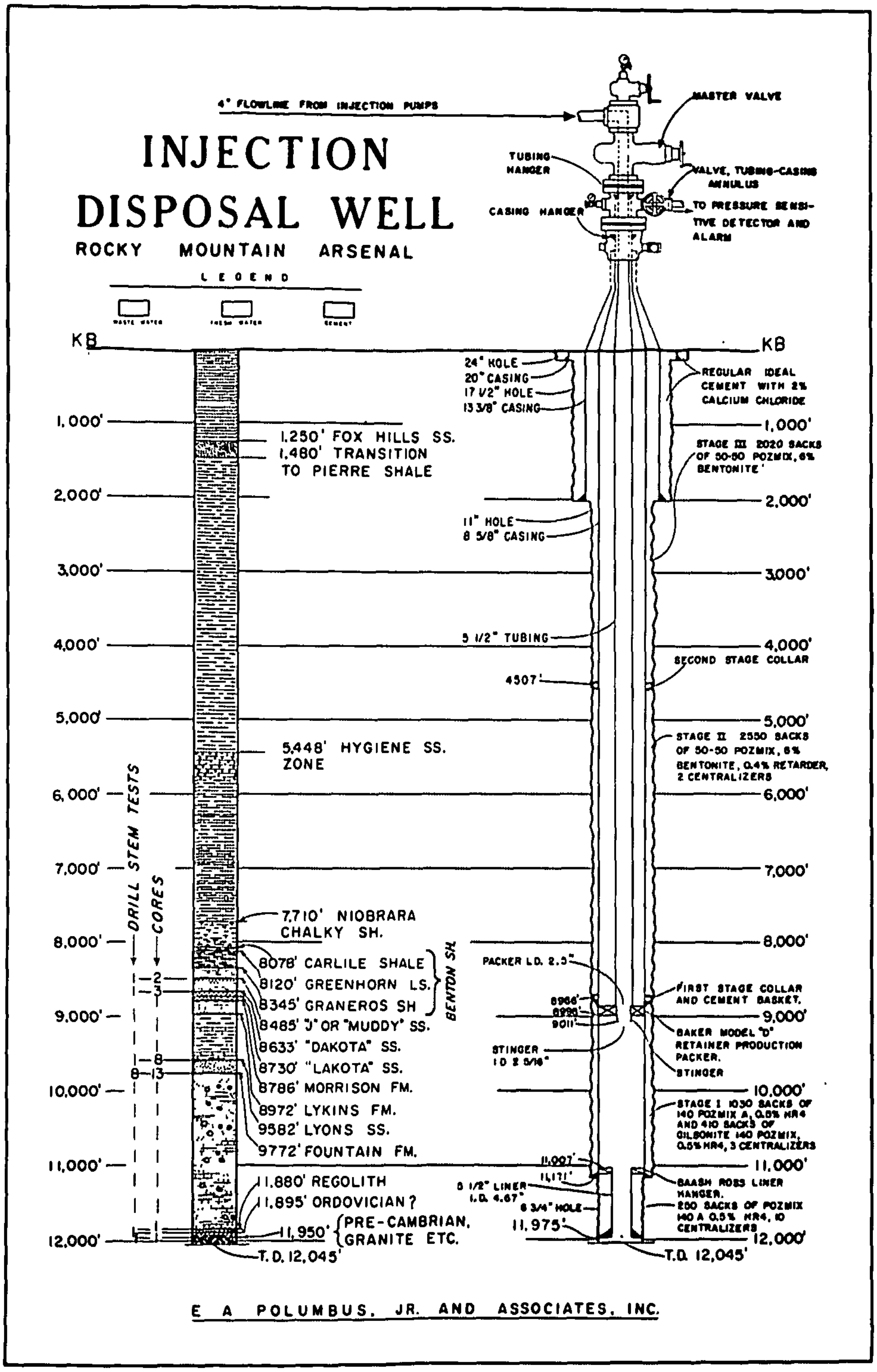

Figure 3. Diagram and log of the Rocky Mountain Arsenal Injection Disposal Well (Scopel, 1964).

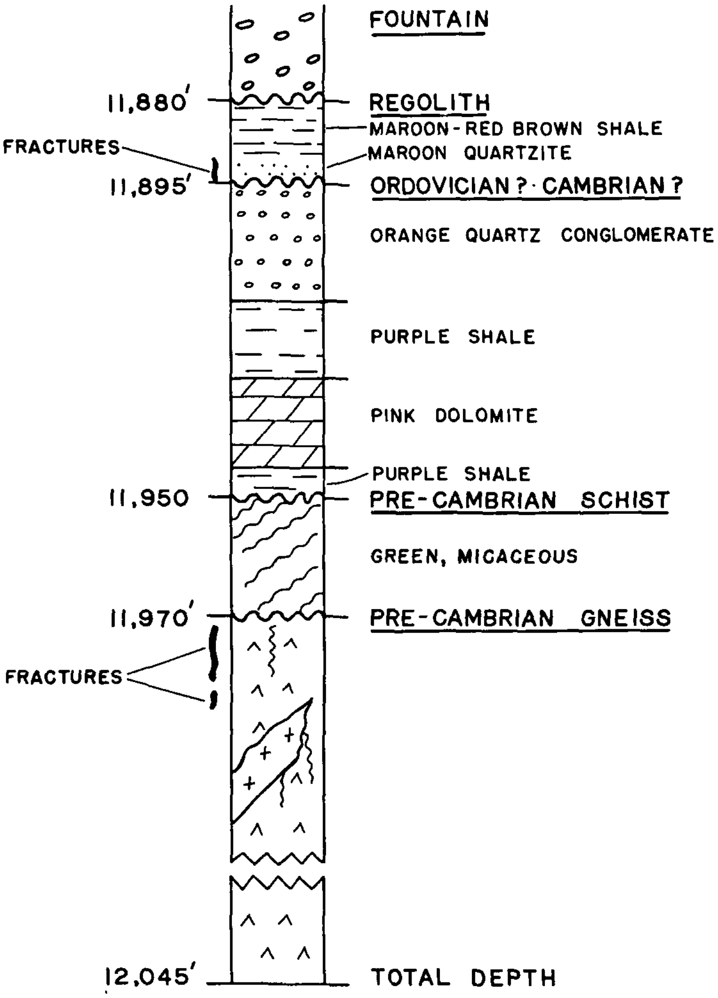

Figure 4. Log of pre-Pennsylvanian portion of disposal well (Scopel, 1964).

tains brown to copper-colored mica and kaolinite. The pre-Pennsylvanian sediments and the Precambrian were not cored.

The Precambrian schist is immediately above highly fractured hornblende granite gneiss which contains pegmatite intrusions. The top eight-foot section of the gneiss was cored. Hedge and Walthall (1963) have dated the gneiss to be 1,350 x 10^6 years old.

A portion of the core mentioned above was examined by the present author. The fractures observed were almost vertical and from one-half-inch to two inches apart. When taken from the core barrel, the core was found to be split apart along one fracture plane, and the lack of cementing material suggested that this might have been an open fracture. The other fractures observed were partially to completely cemented with quartz.

TESTING OF THE WELL

A drill stem test was taken of the basal Fountain Formation, the pre-Pennsylvanian rocks and Precambrian rocks from the bottom of the 8-5/8-inch casing at 11,171 feet to the total depth of 11,985 feet Recovery was 5,400 feet of salt water, in addition to 2,000 feet of water cushion, in 156 minutes. Ninety-three-minute final shut-in pressure was 4,128 pounds, measured at 11,002 feet. Density of the water was 1.05 gm./cc.

The well was drilled ahead to 12,045 feet where it was completed in Precambrian gneiss Considerable lost circulation was experienced while coring, testing, and drilling the Precambrian gneiss from 11,970 to 12,045 feet.

A 5-1/2-inch liner was cemented five feet into the Precambrian gneiss from the bottom 64 feet of the 8-5/8-inch casing. Five-and-one-half-inch tubing was run to 9,011 feet to complete the well.

During November and December 1961 a conventional oil field pump was run in the well, and pumping tests were conducted. After pumping 1,100 barrels of water, a quantity in excess of the amount of fluid that had been lost into the formation during drilling operations, the well pumped down and fluid recovery became negligible. It was concluded, at the time of testing, that fluid recovery was from fractures. It was further believed that as fluid was withdrawn from these fractures, they were squeezed shut by compressive forces which restricted fluid entry into the well bore.

Pressure injection tests were conducted on the well during January 1962 to determine the rates and injection pressures at which the Precambrian would take the fluid. As a result of these tests, it was noticed that calculations of the drainage radius and formation capacity increased as fluid was injected (see Calhoun, 1953, for more on reservoir calculations).

As a result of the testing program, it was concluded that the formation would take fresh water at 400 gallons per minute under 650 pounds pressure, and that the reservoir consisted of fractures which expanded as additional volumes of fluid were injected.

THE PRESSURE INJECTION PROGRAM

Contaminated waste from the Arsenal

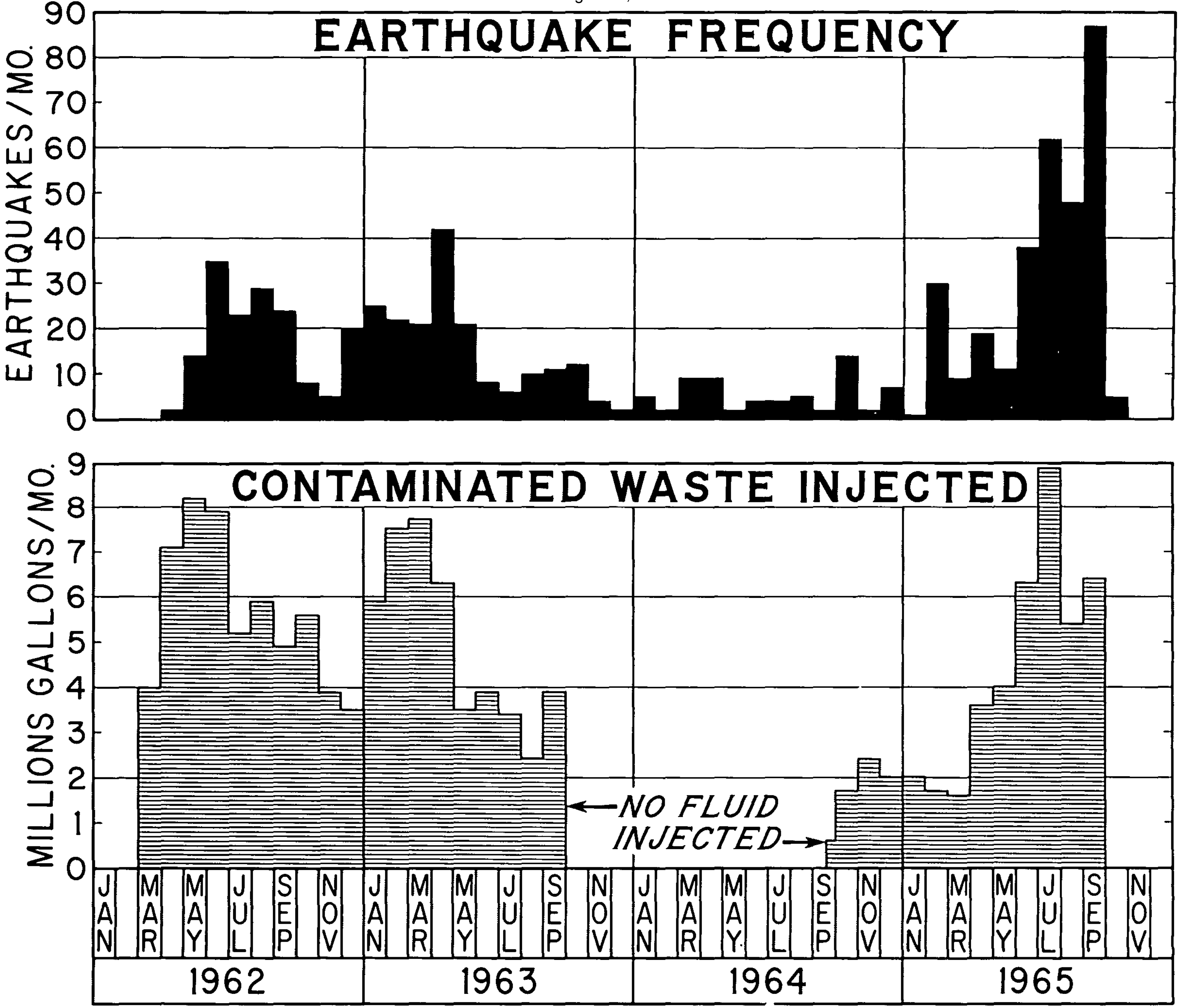

Figure 5. Upper half: number of earthquakes per month recorded in the Denver area.
Lower half: monthly volume of contaminated waste water injected into the Arsenal well.

plants is first collected and allowed to settle in a two-hundred-million-gallon waste-settling basin that is sealed with an asphaltic membrane to prevent seepage. It is then flocculated and clarified. Next it is filtered to less than 20 parts per million of suspended solids less than 5 microns in diameter. It is sterilized and monitered for bacteria, then pumped into the well. Four 130-horsepower positive-displacement electric pumps are available. Normally, two or three pumps are used.

The first contaminated waste was injected into the well during March 1962, when 4.2 million gallons of waste were injected into the well. The monthly volume of waste injected into the well is shown in the lower half of figure 5. During the first year of operation, considerable trouble was experienced with the filter plant with the result that the injection well was often shut down for a few days or weeks at a time. From March 1962 until September 1963 the maximum injection pressure is reported to have been about 550 pounds, with a fluid injection rate of 200 gallons per minute.

At the end of September 1963 the injection well was shut down, and no fluid was injected until operations were resumed 17 September 1964. During the shut-down period, surface evaporation, from the settling basin, was sufficient to handle the plant output.

From 17 September 1964 until the end of March 1965, injection operations were resumed by gravity discharge into the well. No well-head pressure was necessary to inject the maximum of 2.4 million gallons of waste per month into the well.

Beginning in April 1965 larger quantities of fluid were injected. The filter plant operated efficiently, and fluid was usually injected 16 to 24 hours daily. During April and May a maximum pump pressure of 800 pounds was required. From June to the end of September 1965 a maximum pressure of 1,050 pounds was required to inject 300 gallons per minute into the well

THE DENVER EARTHQUAKES

The U. S. Coast and Geodetic Survey reports that on 7 November 1882 an earthquake was felt in the Denver, Louisville, Georgetown, and S.E. Wyoming area (Wang, 1965). From that date until April 1962 no earthquake epicenters were recorded in the Denver area by either the U. S. Coast and Geodetic Survey or by the Regis College Seismological Observatory, located ten miles southeast of the Rocky Mountain Arsenal well (Joseph V. Downey, personal communication, 1965).

During the period from April 1962 to the end of September 1965, 710 earthquakes were recorded with epicenters in the vicinity of the Arsenal at the Cecil H. Green Observatory, Bergen Park, Colorado, operated by the Colorado School of Mines (Pan, 1964, Wang, 1965, Jones, 1965, Mines Magazine, 1965).

The total number of earthquakes reported in the Denver area is plotted in the upper half of figure 5. The magnitude of the earthquakes reported range from 0.7 to 4.3 on the Richter scale. Table 1 lists the earthquakes in Colorado of magnitude 3 and larger, according to the U. S. Coast and Geodetic Survey reports (Wang, 1965). Wang (1965) calculated the epicenters and hypocenters of the 1963-65 Denver earthquakes, and the results of his calculations are shown in figure 6.

The majority of the earthquake epicenters are within a five-mile radius of the well. All epicenters calculated from four or more recording stations are within seven miles of the well.

Wang (1965) calculated the best-fitting plane passing through the zone of hypocenters calculated from four or more recording stations. He concluded that this plane might be a fault along which movement was taking place. The plane dips to the east, and passes beneath the arsenal well at a depth of about six and one-half miles (fig. 6).

ROCK MOVEMENT AND EARTHQUAKES

An attempt has been made to develop a method of estimating, directly from seismograms, wave energy radiated during an earthquake. Using the formula favored by Tocher (1964) and Richter (1958), the elastic wave energy of a magnitude 3 earthquake could be provided by dropping a 100 foot cube of rock a distance of a few feet.

Admittedly, the formula applies to distant earthquakes and is not routinely applicable to large number of earthquakes, but it does suggest that the Denver earthquakes may be caused by relatively minor rock movements.

Table 1. COLORADO EARTHQUAKES, MAGNITUDE 3 AND LARGER
(From U. S. Coast and Geodetic Survey Reports)

No.				Greenwich Mean Time			**Longitude	Latitude	Depth	Mag-	
	Year	Mon.	Day	Hour	Min.	Sec.	(N)	(W)	(km)	nitude	Felt Area
1.	1882	Nov.	7				?	?	?	?	Denver, Louisville, Georgetown and S. E. Wyoming
2.	1960	Oct.	11	01	05	30.5	38.3°	107.6°		5.5	Cimarron, Lake City, Montrose, Ophir, Ouray, Placerville, Powderhorn, Ridgeway, Telluride
3.	1961	Nov.	27	00	55	45.7	39.0°	106.1°	(33)	?	Fairplay, Hartsel, Leadville, Jefferson, Buena Vista, Alma
4.	1962	June	18	00	46	05.0	?	?	?	3.1	Denver, Derby, Henderson
5.	1962	Aug.	7	00	51	00.0	?	?	?	3.0	Denver, Derby, Henderson
6.	1962	Dec.	4	17	49	59.4	39.8°	104.7°	(33)	3.6	Denver, Jefferson, Adams
7.	1962	Dec.	5	13	48	00.4	39.9°	104.6°	(33)	3.8	Denver, Pueblo
8.	1963	Jan.	30	23	05	09.6	39.8°	104.6°	(33)	3.2	Denver, Boulder
9.	1963	April	8	00	03	59.1	39.6°	104.9°	(33)	3.2	Denver, Derby, Henderson
10.	1963	April	24	22	29	35.7	39.7°	104.8°	(33)	3.2	Denver, Derby, Henderson
11.	1963	May	25	10	44	38.1	39.8°	104.7°	(33)	3.5	Denver, Derby, Henderson
*12.	1963	June	5	00	13	56.6	39°52.5'	104°55.5'	2.6	3.0	Denver, Derby, Henderson
13.	1963	July	2	08	02	54.1	39.8°	104.7°	(15)	3.0	Denver, Boulder
14.	1963	July	28	13	18	47.0	?	?	?	3.1	Denver, Derby, Henderson
*15.	1965	Jan.	5	01	05	31.2	39°54.7'	105°15.8'	15.6	?	Western Denver, Louisville
16.	1965	Feb.	16	20	17	54.0	39.9°	105.1°	5	4.6	Western Denver, Louisville
*17.	1965	Feb.	16	22	21	46.9	39°52.4'	104°55.2'	8.3	3.7	Western Denver, Louisville
18.	1965	July	31	13***	41	43.0	39.7°	104.9°	5	4.6	Western Denver, Louisville
19.	1965	Sept.	14	22***	46	24.0	39.9°	104.6°	5	4.7	Western Denver, Louisville
20.	1965	Sept.	29	18***	59	56.0	39.8°	105.1°	5	4.7	Western Denver, Louisville
21.	1965	Sept.	29	19***	20	41.0	39.7°	104.9°	5	4.6	Western Denver, Louisville

* Determined from local seismogram data.
** For Mountain Standard Time, subtract 7 hours.
*** For Mountain Daylight Savings Time, subtract 6 hours.

(Wang, 1965, with additions)

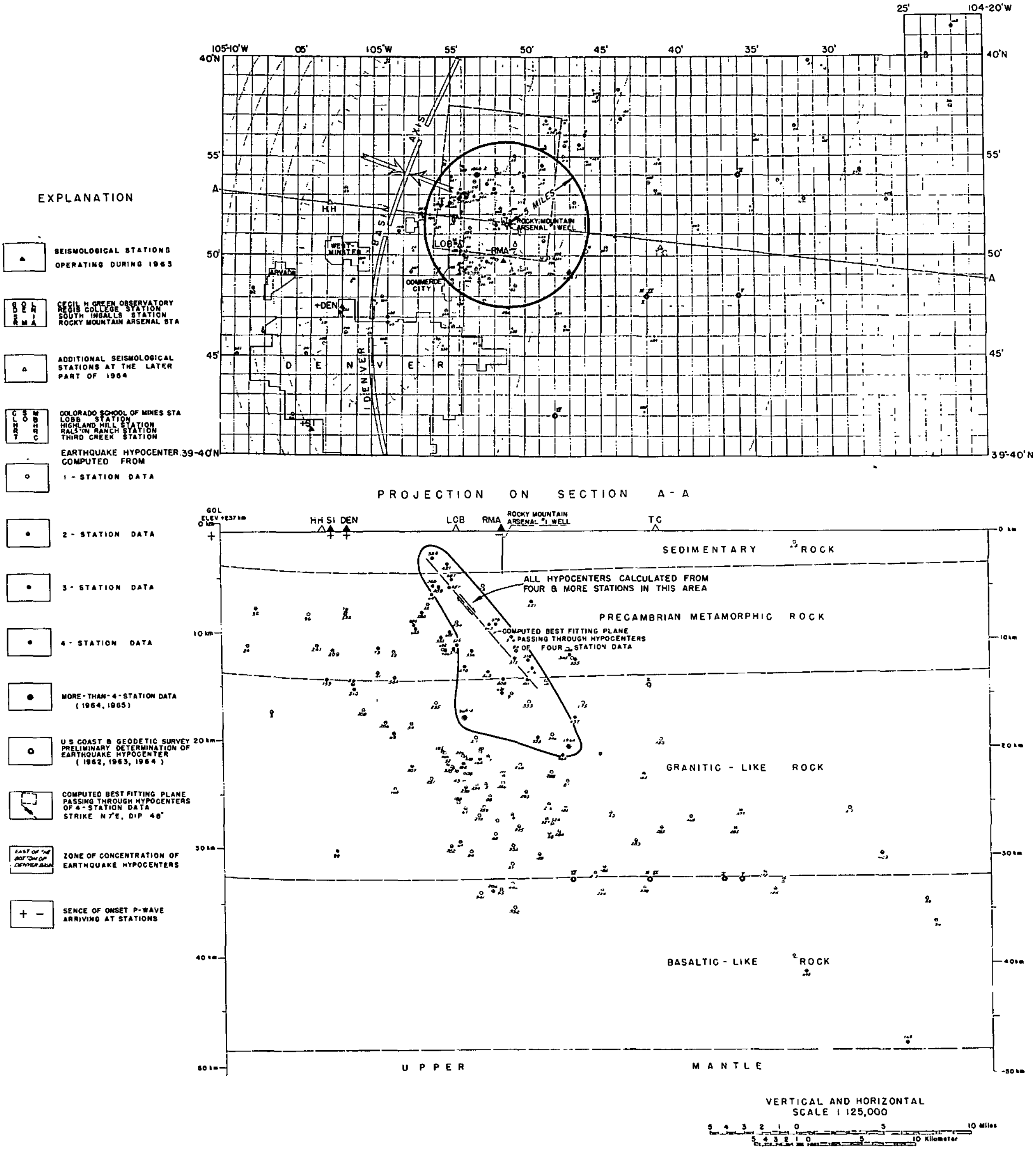

Figure 6. Earthquake hypocenters during 1963-64 from local seismological stations in the Denver area (after Wang, 1965). All epicenters calculated from four or more recording stations are within seven miles of the Arsenal well. All hypocenters calculated from four or more recording stations are within area indicated on section A - A.

PRESSURE INJECTION AND EARTHQUAKE FREQUENCY

Pressure injection began in March 1962. The first two earthquakes with epicenters in the Arsenal area were recorded during April 1962.

The lower half of figure 5 is a graph of the monthly volume of waste injected into the Arsenal well. The total number of earthquakes recorded in the Arsenal area is plotted each month in the upper half of the graph.

During the initial injection period from March 1962 to the end of September 1963, the injection program was often shut down for repairs to the filter plant. During this period there does not appear to be a direct month by month correlation. However, the high injection months of April, May and June 1962 seem to correlate with the high earthquake frequency months of June, July and August. The high injection months of February and March 1963 may correlate with the high earthquake month of April.

The period of no injection from September 1963 to September 1964 coincides with a period of minimum earthquake frequency. The period of low volume injection by gravity flow, from September 1964 to April 1965, is characterized by two months (October and February) of greater earthquake frequency than experienced during the preceeding year.

The most direct correlation of fluid injection with earthquake frequency is during the months of June through September 1965. This period was characterized by the pumping of 300 gallons per minute, 16 to 24 hours a day, at pressures of from 800 to 1,050 pounds.

A review of the injection program reveals that there have been five characteristic periods of injection into the well (fig. 7):

1. April 1962-April 1963: High injection at medium pressure.
2. May 1963-September 1963: Medium injection at medium pressure.
3. October 1963-September 1964: No injection.
4. September 1964-March 1965· Low injection at zero pressure (gravity).
5. April 1965-September 1965. High injection at high pressure.

The average numbers of earthquakes per month are plotted in figure 7 above the average volumes of fluid injected per month for each of these five periods. The injection for March 1962 is not used in the average because the exact day when injection was started is not known.

Figure 7 indicates that there is a direct correlation between average monthly injection and earthquake frequency when an injection program is carried out for a period of five months.

Bardwell (1966) has prepared a statistical analysis, presented elsewhere in this issue of The Mountain Geologist, that suggests that a mathematical relationship exists between the Denver earthquakes and the volume of contaminated waste injected into the Arsenal well.

EFFECT OF EARTHQUAKES ON INJECTION PRESSURE

The wellhead-pressure injection charts were not available for the years 1962 and 1963. Only the earthquakes of magnitude 3 or larger were checked against the pressure injection charts for 1965. These earthquakes are listed in table 1.

No charts were being recorded at the time of the February and July 1965 earthquakes. Three pumps were maintaining a pressure of 725 pounds when the September 14 earthquake occurred. There was no change in injection at the time of the event.

Allowing for a few minutes time discrepancy between the chart time and recorded time of the earthquakes, the two earthquakes of 29 September may have affected the injection pressure. During the first earthquake, at 12:59 P.M. MDST, the pressure recording needle on the pressure chart jumped from 970 pounds to 940 pounds and also repeated a ten minute time interval on the chart. During the second earthquake, at 1:20 P.M. MDST, the pressure dropped from 960 pounds to 780 pounds. Whether this 180-pound pressure drop was due to the earthquake or to the slowing up of one of the pumps is not known.

FLUID PRESSURE AND THE ARSENAL EARTHQUAKES

The evidence gained from drilling and testing the Arsenal disposal well indicates that the Precambrian reservoir is composed of a highly fractured granite gneiss which is substantially impermeable. The fractures are almost vertical, and porosity of the reservoir is formed by these fractures. The evidence

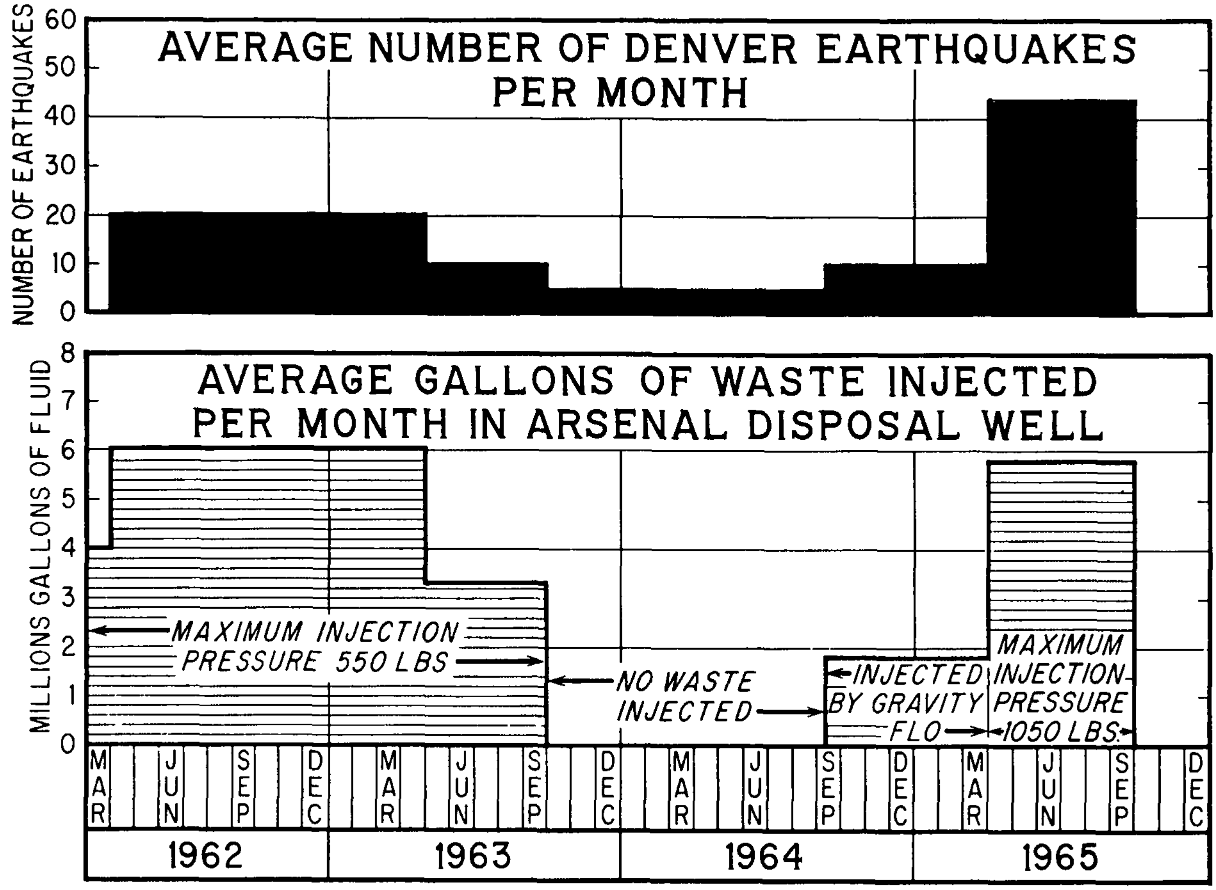

Figure 7. Earthquake frequency - waste injection relationships during five characteristic periods.

indicates that as fluid was pumped out of the reservoir the fractures closed, and as fluid was injected into the reservoir the fractures opened. In other words, the pumping and injection tests indicated that rock movement occurred as fluid was withdrawn or injected at relatively low pressures.

The pressure-depth relations of the Precambrian reservoir, showing hydrostatic and lithostatic pressure variations with depth, are shown in figure 8. These data were determined from the drill stem test. As shown on the chart, the observed pressure of the Precambrian reservoir is almost 900 pounds less than hydrostatic pressure.

Hubbert and Rubey (1959) devised a simple and adequate means of reducing by the required amount the frictional resistance to the sliding of large overthrust blocks down very gentle slopes. This arises from the circumstance that the weight of such a block is jointly supported by solid stress and the pressure of interstitial fluids. As the fluid pressure approaches the lithostatic pressure, corresponding to a flotation of the overburden, the sheer stress required to move the block approaches zero.

If high fluid pressures reduce frictional resistance and permit rocks to slide down very gentle slopes, it follows that, as fluid pressure is decreased, frictional resistance between blocks of rock is increased, thus permitting them to come to rest on increasingly steep slopes. The steeper the slope upon which a block of rock is at rest, the lower the required raise in fluid pressure necessary to produce movement.

In the case of the Precambrian reservoir beneath the Arsenal well, these rocks were at

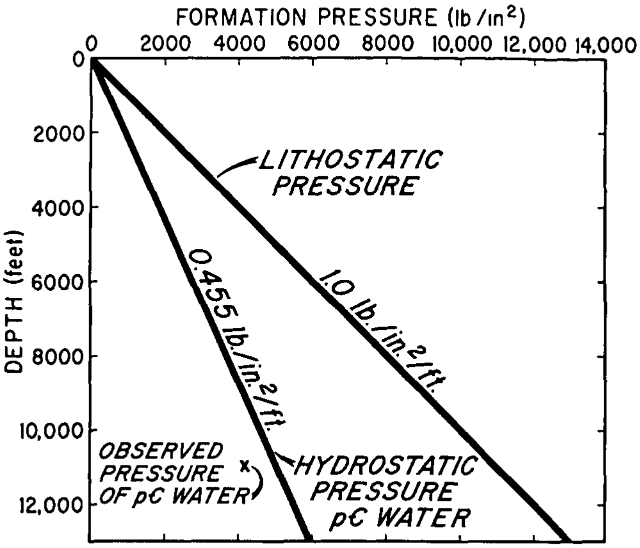

Figure 8. Pressure-depth relations, Precambrian reservoir, Rocky Mountain Arsenal Disposal well.

equilibrium on high-angle fracture planes with a fluid pressure of 900 pounds less than hydrostatic pressure before injection began.

As fluid was injected into the Precambrian reservoir, the fluid pressure adjacent to the well bore rose, and the frictional resistance along the fracture planes was thereby reduced. When, finally, enough fluid pressure was exerted over a large enough area movement took place. The elastic wave energy released was recorded as an earthquake.

Since the formation fluid pressure is 900 pounds sub-hydrostatic, merely filling the hole with contaminated waste (mostly salt water) raises the formation pressure 900 pounds, or to the equivalent of hydrostatic pressure. Any applied injection pressure above that of gravity flow brings about an increase in pressure resulting in a total in excess of hydrostatic pressure. For example, an injection pressure of 1,000 pounds would raise the reservoir pressure adjacent to the well bore 1,900 pounds, or by the amount necessary to bring the pressure to hydrostatic (by filling the hole) plus 1,000 pounds.

Apparently a rise in fluid pressure within the Precambrian reservoir of from 900 to 1,900 pounds is sufficient to allow movement to take place.

OPEN FRACTURES

The hypocenters in the Arsenal area plotted from data derived from four or more recording stations indicate that movement is taking place beneath the Arsenal well at depths of from 1-1/2 to 12 miles. If the Precambrian fracture system extends to a depth of 12 miles, then fluid pressure could be transmitted to this depth by moderate surface injection pressure as long as the fracture system was open for the transmission of this pressure.

Secor (1965) concluded that open fractures can occur to great depths even with only moderately high fluid pressure-overburden weight ratios. It appears possible that high-angle, open fractures may be present beneath the Arsenal well at great depths with much lower fluid pressure-overburden weight ratios than has formerly been considered possible.

Almost 150 million gallons of contaminated waste had been injected into the Arsenal well by the end of September 1965. Since this amount of water would be enough to fill four continuous 1/16-inch fractures each seven miles long (the maximum distance of epicenters from the well located by four or more recording stations) and five miles deep, it can be seem that a relatively small area is being affected by the injection program.

TIME LAG BETWEEN FLUID INJECTION AND EARTHQUAKES

The correlation of fluid injected with earthquake frequency (fig. 5) suggests that a time lag exists between the two. Bardwell (1966) notes that the frequency of Denver earthquakes appears to lag injected waste by approximately one to four months. This phenomenon is probably the same as that described by Serafim and del Campo (1965). They describe the observed time lag between water levels in reservoirs and the pressures measured in the foundations of dams, and ascribe this to an unsteady state of percolation through open joints in the rock mass due to the opening and closing of these passages resulting from internal and externally applied pressures.

The time lag between waste injected in the Arsenal well and earthquake frequency is probably due to an unsteady state of percolation through fractures in the Precambrian reservoir due to the opening and closing of these fractures resulting from the applied fluid pressure of the injected waste. The delayed application of this pressure at a distance from the well bore is believed to trigger the movement recorded as an earthquake.

EARTHQUAKES DURING SHUT-DOWN PERIOD

In considering the earthquake frequency during the year the injection well was shut down, it is unfortunate that neither periodic bottom-hole pressure tests nor checks of the fluid level in the hole were run. Had these measurements been made, then speculation as to how long it took for the bottom-hole pressure to decline would have been unnecessary.

By the end of September 1963, 102.3 million gallons of fluid had been injected into the well. It is believed that this injection had raised the fluid pressure in the reservoir for some distance surrounding the well bore. During the shut-down period this elevated pressure was equalizing throughout the reservoir and at increasing distances from the well bore. As this fluid pressure reduced the frictional resistance in fractures farther away from the well, movement occurred, and small earthquakes were the result.

SUMMARY AND CONCLUSION

The Rocky Mountain Arsenal Pressure Injection Disposal well was drilled for the purpose of disposing of contaminated waste water, which is a by-product of chemical warfare products manufactured at the Arsenal.

During the month following the initiation of injection of waste water into the almost vertically fractured Precambrian rocks there were two earthquakes with epicenters in the Arsenal area.

A summary of the evidence relating the Arsenal injection program with the earthquakes is:

1. The first earthquakes observed during the present century with epicenters in the Denver area were recorded during the month following the initiation of the Arsenal injection program.
2. Since the initiation of the injection program in March 1962, 150 million gallons of waste have been injected into the Arsenal well, and there have been 710 earthquakes (to 1 October 1965).
3. The majority of the earthquake epicenters are located within five miles of the Arsenal well. All epicenters determined from four-or-more station data are within seven miles of the well.
4. There is evidence that the earthquake activity is taking place along a plane that dips eastward and passes beneath the Arsenal well at a depth of 6.5 miles (Wang, 1965).
5. When the Arsenal injection program is considered on the basis of high, medium, low, or no injection, there is a correlation between the fluid injected and earthquake frequency.
6. The best correlation of earthquake frequency with fluid injected occurred during July, August and September 1965, when relatively large amounts of fluid were injected at higher pressures and for longer periods of time than previously.
7. A statistical analysis (Bardwell, 1966) is cited that suggests a mathematical relationship between Arsenal earthquakes and volumes of waste injected into the Arsenal well.

The volume of fluid injected appears to be affecting the Precambrian reservoir only for a limited distance from the well bore, and rough estimates of the energy released by a single earthquake suggest that relatively minor rock movement is involved.

The Precambrian reservoir receiving the Arsenal waste is highly fractured granite gneiss of very low permeability. The fractures are nearly vertical. The fracture porosity of the reservoir is filled with salt water. Reservoir pressure is 900 pounds sub-hydrostatic.

It appears that movement is taking place in this fractured reservoir as a result of the injection of water at pressures from 900 to 1,950 pounds greater than reservoir pressure.

Hubbert and Rubey (1959) point out that rock masses in fluid-filled reservoirs are supported by solid stress and the pressure of interstitial fluids. As fluid pressure approaches lithostatic pressure, the shear stress required to move rock masses down very gently slopes approaches zero.

It appears that these principles offer an explanation of the rock movement in the Arsenal reservoir. The highly fractured rocks of the reservoir are at rest on steep slopes under a condition of sub-hydrostatic fluid pressure. As the fluid pressure is raised within the reservoir, frictional resistance along fracture planes is reduced and, eventually, movement takes place. The elastic wave energy released is recorded as an earthquake.

If earthquake hypocenters indicate the point at which movement is taking place and injected fluid is triggering this movement, then there is evidence that open fractures exist at depths of 12 miles under conditions of lower fluid pressure-overburden weight ratios than has formerly been considered possible (Secor, 1965). It is believed that the high angle of this fracture system is an important factor. Because the fractures are almost vertical, only a small part of the lithostatic pressure is acting to force the fractures closed, and they can remain open under conditions of lower fluid pressure, and at greater depth than if they were horizontal or inclined at a lower angle.

The time lag between fluid injection and earthquake frequency is believed to be due to the unsteady state of percolation of fluid through the fractures in the reservoir due to the opening and closing of these passages resulting from the applied pressure of the injected waste.

It is believed that as fluid continues to be injected into this reservoir fluid pressure will be increased at greater distances from the well bore, and rock movement will be occurring at ever increasing distances.

In the present case it is believed that a stable situation in this Precambrian reservoir is being made unstable by the application of fluid pressure. However, it is interesting to speculate that the principle of increasing fluid pressure to release elastic wave energy might have an application in the subject of earthquake modification. That is, it might someday be possible to relieve the stresses along some fault zones in urban areas by increasing the fluid pressures along the zone using a series of injection wells. The accumulated stress might thus be released at will in a series of non-damaging earthquakes instead of eventually resulting in one large event that might cause a major disaster.

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