Seismicity of Colorado: Consistency of Recent Earthquakes with Those of Historical Record

Abstract. *Earthquakes instrumentally recorded from 1966 to 1968 have occurred in the same regions of western Colorado, the Arkansas and Platte river valleys, as those felt back to 1870 (from newspaper reports), despite the increasing cultural effects of mining, highway construction, reservoir building, and loading. Thus it appears unnecessary to explain the Denver earthquakes in terms of pressure induced by the introduction of waste fluid. However, the assumption of preexistent tectonic strains in the area of the Rocky Mountain Arsenal seems to be confirmed.*

Colorado is considered a region of minor seismicity. However, the advent of hundreds of earthquakes in the area of northeastern Denver since 1962, when the Rocky Mountain Arsenal began pumping fluids under pressure into a 3600-m disposal well, caused concern that a more destructive earthquake might possibly occur there in the future. This study does not consider a sufficiently long interval of time to yield seismic information on the distant past before the Rocky Mountain region became populated. The data collected do show a picture of seismicity for 1966 through 1968 consistent with that derived from reports of felt shocks in newspapers published 100 years ago. Figure 1 shows the known locations of earthquakes in Colorado from 1870 to 1967. This map, adapted from Hadsell's study (*1*), indicates that the majority of Colorado earthquakes in this period have occurred west of the Rocky Mountain Front Range and within 30 km of post-Oligocene extrusive rocks. Reports of felt shocks from 25 newspapers, published in 1882 and later, were used by Hadsell to estimate the intensities listed in Table 1.

Table 1. Summary of earthquakes in Colorado for the years 1966, 1967, and 1968 compared to historical record.

Location	1966	1967	1968	Historical records†	Nos. (Fig. 1)
Aspen	10	12	13	1880 VI, 1889 V (Glenwood Springs), 1941 IV, 1960 V	1
Baxter Mountain	4	20	6		
Cabin Creek	19	73	17	1871 IV (Georgetown), 1894 V	2
Castle Rock	1	0	0		
Climax	12	31	0		
Colorado Springs	0	0	3		
Denver (Derby)	189	314*	99	1882 VII, 1916 IV (Boulder), 1962–65 VII	3
Dulce, New Mexico	161*	31*	14	1952 V (Conejos County)	4
Elkhead Mountains	152	177	85		
Four Corners	0	3	5	1941 V (Durango)	5
Golden Fault	0	31	0		
Grand Valley	2*	6	2	1954 IV (Grand Junction)	6
Harvey Gap Reservoir	0	1	0		
Lake Hattie Reservoir	16	4	1		
Leadville	28*	13	4	1901 VI (Buena Vista), 1961 IV	7
Montrose	12	22*	11	1960 VI, 1962 IV (Cimarron)	8
Mount Evans	0	5	0		
Mount Gunnison	47	67	29	1882 IV, 1944 VI	9
Mount Wilson	8	12	5	1913 V (Ouray)	10
North of Elkhead	11	7	17		
Pueblo	5	12*	10	1870 VI, 1888 IV (San Isabel National Forest), 1955 IV (Rocky Ford), 1956 V, 1963 IV	11, 12
Rangely	6*	25	4	1891 VI (Axial Basin)	13
Ruth Mountain	16	51	13		
Sheep Mountain	1	0	0	1955 VI (Lake City), 1928 V (Creede)	14
Silverton	2	1*	2	1882 IV	15
Snowmass Mountain	1	5	8		
Steamboat Springs	5	20	59	1895 V, 1955 V	16
Tenderfoot Mountain	0	16	3		
Trinidad	5*	2	1		
Urad	15	15	71		
White River	1	6	4		
Yampa	0	7	16		
Totals	729	989	502		

* Magnitude ≥ 4.0. † Roman numerals refer to estimated intensities on the modified Mercalli scale (*10*).

A detailed study of seismograms from the Colorado School of Mines station (GOL) (*2*) with additional data from the Uinta Basin Observatory (UBO) at Vernal, Utah (*3*), produced sufficiently accurate information on the epicenter locations to make possible reports of events recorded in the years 1966, 1967, and 1968. Figure 2 shows locations of seismic events for these years. The trend of epicenters for all 3 years is north-south, parallel with the Continental Divide, with most epicenters placed west of the divide. Eastern Colorado is nearly aseismic, with a few epicenters in the Arkansas and Platte river valleys. There are conspicuous areas of the state where no earthquakes occurred, either historically or in the 3-year study. These inactive regions, in addition to the eastern plain, are in the northwestern and southwestern corners of Colorado. The Sangre de Cristo Mountains in the south-central part of the state also remain inactive. Table 1 lists the annual number of events in each epicentral region.

Nine of these epicentral regions have produced earthquakes of Richter magnitude greater than 4.0. Only one of these locations had shocks of large magnitude in both 1966 and 1967. This was at Dulce, New Mexico, on the southern border of central Colorado; these shocks were widely felt in southern Colorado. Other epicenters in 1966 having earthquakes larger than magnitude 4.0 were Grand Valley, Leadville, Rangely, and Trinidad. In 1967 northeastern Denver (Derby) earthquakes were the largest in the state, with three shocks above magnitude 5, and the greatest number, 314 events, recorded at GOL (*4*). Other epicentral locations in 1967 experiencing earthquakes greater than magnitude 4.0 were Dulce, Montrose, Silverton, and Pueblo. In 1968 there were no earthquakes with magnitude > 4.0 recorded at GOL. Seismicity of Colorado for 1968 was less than for the previous 2 years.

Earthquakes reported in this study were of magnitude ≳ 1.0; most were greater than magnitude 2.0, with the exception of the Denver events. Den-

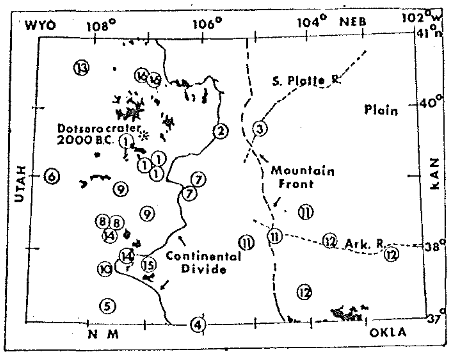

Fig. 1. Historical seismicity of Colorado adapted from studies of F. A. Hadsell (*1*). Circles represent locations of epicenters. Numbers on map refer to numbers in the last column of Table 1. Large, irregular, solid-black regions represent post-Oligocene (less than 26×10^6 years) extrusive volcanic rocks.

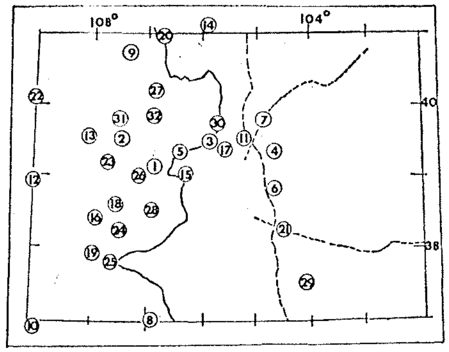

Fig. 2. Map represents locations of earthquakes during 1966, 1967, and 1968 instrumentally recorded in Colorado at GOL and in Utah at UBO. Circles represent areas approximately 15 km in diameter. Numbers within each circle refer to numbers in the first column of Table 1.

ver is 45 km from the Bergen Park Observatory; thus events of magnitude 1.0 could be easily interpreted, even in winter months when the magnification of the instruments is lowered to reduce background noise.

Possibly 20 percent of the total number of events recorded are due to mining operations. At Urad, for instance, reports were regularly received of charge sizes and approximate times of blasting. In 1968 this operation reached its peak, with the planned cave-in of a mountain. Fifty natural events at Urad occurred within a month of this collapse, half of this number within a few days. At other locations it is not always possible to distinguish between natural earthquakes and explosive sources. Several epicentral locations where blasting operations are known to occur are Elkhead Mountains, Climax, and Mount Gunnison. Usually mining is carried on only during daylight hours, so that events occurring between the hours of 2400 and 1200 G.M.T. are probably natural events. Blasting at Climax has been carried on here around the clock. No large blasts were recorded from Climax in 1968. Highway blasting has been omitted from the data when it is known to have occurred. Construction companies notified us in advance of large blasts.

Seismic activity has been observed at some reservoir sites, namely Cabin Creek, Lake Hattie, Harvey Gap, and Mount Gunnison (Blue Mesa Reservoir). Carder described earthquakes occurring along the southern edge of Lake Mead, Nevada, with water-loading of the reservoir in 1932 (*5*). On the other hand, no earthquakes have occurred at sites in Colorado where the U.S. Bureau of Reclamation has been constructing reservoirs, several of which are already filled. Nine of these sites are within a radius of 150 km of the Bergen Park Observatory, a distance where even small events would be well recorded. No events were observed from these nine sites in the 3 years studied. Earthquakes did occur in the historical record at locations wh reservoirs have since been construct especially at Mount Gunnison a Harvey Gap, in western Colorado, a Cabin Creek (Georgetown) in cent Colorado. The occurrence of ear quakes at reservoir sites would seem depend not on the size of the body water but rather on the geologic stru ture beneath it.

Recent earthquakes began at Der in April 1962. This was shortly af the U.S. Army began pumping wa fluids under pressure into the de disposal well at the Rocky Mount Arsenal in northeastern Denver. Eva a Denver-based consulting geologist, pothesized a connection between Denver earthquakes and this well (Healy *et al.* theorized that the Den earthquakes are man-made (*7*).

The arsenal well was constru through 3650 m of sedimentary la into fractured Precambrian basen rock. Studies were carried out at Colorado School of Mines with a d network of instruments to deter whether there was any relation betw the Denver earthquakes and the ars well (*4*). Pumping of wastes into well was stopped in February 1 The earthquakes continued. The n bers of earthquakes recorded at Ber Park Observatory for the years 1 through 1968, with monthly and ye totals, are listed in Table 2.

The largest earthquakes in the D ver area occurred in 1967, a year a the cessation of pumping of w fluids into the Rocky Mountain Ars well. The relation of frequency of currence to magnitude of the Den earthquakes is similar to that obse in other geographic regions w earthquake activity is not influen by man. However, in 1967, the pected great number of small sh that usually accompany a few l ones did not occur.

As debate about the causal rela between earthquakes in Denver and arsenal well continued, Army Engin began a series of pumping tests in S tember and October 1968 to deter whether removal of small amount fluid from the well would change earthquake occurrence. A report their results indicates that many sm shocks (as low as magnitude − did occur near the well during the riod studied (*8*). Accordingly, the were discontinued. The number earthquakes in the Denver area, corded at GOL in 1968, was 99.

Table 2. Number of Denver earthquakes per month, magnitude $\gtrsim 1.0$, recorded at Bergen Park Observatory (GOL) for the years 1962 through 1968.

Month	1962	1963	1964	1965	1966	1967	1968
January	0	24	5	4	25	4	10
February	0	35	2	32	11*	19	8
March	0	38	8	12	20	2	3
April	2	72	9	27	11	72	9
May	30	26	3	25	18	31	11
June	45	14	4	68	12	14	10
July	24	21	5	132	18	11	14
August	30	11	9	65	11	74	9
September	23	14	4	105	22	11	10
October	9	20	13	23	9	16	6
November	8	4	3	43	23	44	7
December	20	5	8	14	9	9	2
Totals	191	284	73	550	189	314	99

* Pumping stopped at the Rocky Mountain Arsenal disposal well.

in November. The total number of Denver earthquakes recorded since the Bergen Park Observatory began operations in 1962 is 1698 of magnitude $\geq$ 1.0.

Rangely, Colorado, a seismically active region during the years studied, is near the southeastern edge of a large oil field. An earthquake of magnitude 4.1, located by the U.S. Coast and Geodetic Survey, occurred there in 1966. Munson tried to correlate numbers of earthquakes near Rangely with millions of gallons of water pumped into the field as oil was withdrawn (*9*). He found no change in numbers of earthquakes whether pumping rate increased or decreased in the period of time considered.

Colorado seismicity has been virtually unchanged in the last 100 years. The same areas that were seismically active in the historical record were seismically active in the years 1966, 1967, and 1968; those areas that were seismically inactive 100 years ago were inactive in 1966, 1967, and 1968. The intervening years have seen a large population growth in the Rocky Mountain region, along with increased interest in seismic activity and the earthquake hazard problem for construction projects.

The possibility of a devastating earthquake which might cause loss of life and extensive damage to property, always exists. On the basis of this seismicity study, however, the possibility that Colorado will experience a larger magnitude shock than has yet occurred, and its location and time, cannot be predicted.

RUTH B. SIMON

Department of Geophysics, Colorado School of Mines, Golden 80401

References and Notes

1. F. A. Hadsell, *Colo. Sch. Mines Quart.* **63** (1), 57 (1968).
2. The Cecil H. Green Geophysical Observatory of the Colorado School of Mines (GOL), located at Bergen Park, Colorado, is one of the World Wide Standard Seismograph Stations network supported by the Environmental Science Services Administration and the U.S. Coast and Geodetic Survey.
3. The Uinta Basin Seismological Observatory (UBO), located at Vernal, Utah, is operated by Geotech Corporation for Advanced Research Projects Agency. I thank these agencies for data provided for this study.
4. M. W. Major and R. B. Simon, *Colo. Sch. Mines Quart.* **63**(1), 9 (1968).
5. D. S. Carder, paper given at the meeting of the Geological Society of America, Rocky Mountain Section, 10–14 May 1967.
6. D. M. Evans, *Mountain Geol.* **3**, No. 1 (1965).
7. J. H. Healy, W. W. Rubey, D. T. Griggs, C. B. Raleigh, *Science* **161**, 1301 (1968).
8. D. B. Hoover and J. A. Dietrich, *U.S. Geol. Surv. Circ. 613* (1969).
9. R. C. Munson, thesis, Colorado School of Mines (1968).
10. C. F. Richter, *Elementary Seismology* (Freeman, San Francisco, 1958), p. 137.
11. Supported by the State of Colorado, the Colorado School of Mines, and the U.S. Army Corps of Engineers.

22 April 1969; revised 17 June 1969

Obstructive Lung Disease and α_1-Antitrypsin Deficiency Gene Heterozygosity

Abstract. *The phenotypes of serum α_1-antitrypsin were determined by antigen-antibody crossed electrophoresis. There were five homozygotes and 25 heterozygotes for the deficiency gene found in a group of 103 patients with obstructive lung disease. The frequency of heterozygotes was 14 and 9 percent in two control groups with different mean ages of 36 and 80. There was only one heterozygote among 39 healthy males over 70 years of age. Heterozygosity may be a predisposing factor in chronic obstructive lung disease, especially in the male population.*

Inherited deficiency of serum α_1-antitrypsin in man is transmitted by an autosomal codominant gene (*1*). The serums of homozygotes for the deficiency gene have persistently low levels of α_1-antitrypsin (mean, 25 ± 6 mg per 100 ml), approximately 10 percent that of normals (212 ± 32 mg) (*2*). Such a very low level of proteinase inhibitor in the serum predisposes an individual to lung disease, as judged by the fact that more than 90 percent of such individuals who have reached the age of 50 years have chronic obstructive lung disease and often well-defined emphysema.

The serums of heterozygotes have intermediate levels of α_1-antitrypsin (125 ± 46 mg per 100 ml); previously heterozygotes were thought not to have a higher incidence of obstructive lung disease than normal individuals (*3*). However, heterozygotes may develop a similar but less severe form of chronic obstructive lung disease (*4*). Lieberman has reported a higher than expected incidence of heterozygosity in patients with emphysema (*5*).

Our data suggest that heterozygosity as well as homozygosity for the α_1-antitrypsin deficiency gene may be a predisposing factor in as many as 30 percent of patients with chronic obstructive lung disease or emphysema. Our working hypothesis is that lung tissue is destroyed in individuals whose serums are deficient in α_1-antitrypsin because of their inability to inactivate proteolytic enzymes released during inflammatory processes in the lung (*6*). Accordingly, we tested for an association between heterozygosity and obstructive lung disease.

We determined the α_1-antitrypsin phenotypes of a group of patients with chronic obstructive lung disease and two control groups. By means of antigen-antibody crossed electrophoresis (*7*), α_1-antitrypsin from homozygotes can be distinguished from that of heterozygotes (Fig. 1). The difference between the two minor α_1-antitrypsin components in serum from homozygotes for the normal gene and heterozygotes for the deficiency gene is small but consistent in all known heterozygotes, that is, offspring from matings between homozygotes for the deficiency gene and homozygotes for the normal gene. The pattern (Fig. 1B) for the heterozygotes can best be explained by the presence of two electrophoretically distinct but antigenically identical species of α_1-antitrypsin in the heterozygote. A mixture of equal parts of serum of the two homozygotes yields the same pattern as that of a heterozygote (*8*). The antigen antibody crossed electrophoresis is a more reliable method for determining the α_1-antitrypsin genotype, as it is based on a qualitative electrophoretic difference and not merely on the serum concentration of α_1-antitrypsin; the concentration can be raised in heterozygotes to the normal range by a variety of pathologic and physiologic conditions such as infection and pregnancy (*9*).

We selected two control groups. Group 1 consisted of 100 healthy individuals (62 males, 38 females); their mean age was 36 years (range 18 to 67 years). Group 2 consisted of 88 older individuals (49 females, 39 males); their mean age was 80 years (range 70 to 97 years). All of group 2 were residents of a home for old people; none had a history of obstructive lung disease.

Group 3 consisted of 76 males and 22 females who had obstructive lung