GEOPHYSICAL AND GEOLOGICAL INVESTIGATIONS

RELATING TO EARTHQUAKES IN THE DENVER AREA, COLORADO

by J. H. Healy and others

U. S. Geological Survey

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Geophysical and geological investigations relating to earthquakes in the Denver area, Colorado

Introduction

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A series of minor earthquakes in the Commerce City (Derby) area, just north of Denver, Colorado, started in the Spring of 1962. The earthquakes have ranged from felt shocks of magnitude 4.3 to instrument shocks of magnitudes less than zero.

In November, 1965, David Evans, Denver area consulting geologist, proposed that the earthquakes were being triggered by the injection of waste fluids into a 12,000-foot disposal well at the Rocky Mountain Arsenal near Commerce City. His suggestion was documented by charts showing apparent time correlations between frequency of earthquakes and rate of injection of fluids into the well..

The U. S. Geological Survey, in cooperation with the Colorado School of Mines, Regis College, and the University of Colorado, has undertaken a series of studies of the distribution of the earthquakes in time and space, and their relations to local and regional geology. Preliminary results of the geophysical and geological investigations relating to the earthquakes are reported here by scientists of the U. S. Geological Survey and the Colorado School of Mines.

The report is in five parts. Part one is a discussion of the general geologic setting of the Commerce City area, and it contains the conclusion that faulting is not evident from the surface geology. In the second part, records are presented which indicate the probable absence of seismic activity in the Commerce City area prior to the injection of fluids into the Rocky Mountain Arsenal well. The operation of a seismic station in Bergen Park by the Colorado School of Mines is described in part three, which contains a list of earthquakes reported in the Commerce City area between 1962 and the present time. In part four, the possibility that a Precambrian fracture zone was penetrated in the bottom 110 feet of the Arsenal well is supported by petrographic description of the well core. The results of new seismological studies reported in part five show an even closer clustering of earthquake epicenters around the well than was evident from the original data used by Evans. Analysis of 62 additional earthquakes show their epicenters to be located in a roughly ellipsoidal area 6 miles by 3 miles surrounding the well, and their depth to range from 4.5 to 5.5 kilometers.

We would like to express our thanks for the cooperation and assistance of the following institutions and individuals:

Officials of the Rocky Mountain Arsenal who allowed access to the Arsenal grounds for installation of seismic equipment and for information on injection rates and pressures at the disposal well

Rev. Joseph V. Downey, S. J., Director of the Regis College Seismological Observatory

Dr. Warren Longley, University of Colorado

Dr. J. C. Harrison, University of Colorado

Dr. Maurice Major, Colorado School of Mines

Dr. John Hollister, Colorado School of Mines

PART 1

GENERAL GEOLOGY OF THE ROCKY MOUNTAIN ARSENAL AREA, ADAMS AND DENVER COUNTIES, COLORADO

By Robert M. Lindvall

INTRODUCTION

This report summarizes the geology of a 323-square-mile area centering on the Rocky Mountain Arsenal, which is about 10 miles northeast of Denver. The report includes a generalized geologic map of the area, a map showing the configuration of part of the bedrock surface in the area, a structure contour map of the Denver basin, and a generalized east-trending geologic cross section. This material has been assembled from published reports by Hunt (1954), Finley, Dobbin, and Richardson (1955), Van Horn (1957), Scott (1963a, b), J. H. Smith (1964), R. O. Smith, Schneider, and Petri (1964), and Scopel (1964); from unpublished data by J. A. McConaghy and G. H. Chase; and from data acquired through fieldwork by the author.

GENERAL GEOLOGIC SETTING

The Rocky Mountain Arsenal is located on the High Plains of Colorado about 20 miles east of the Front Range of the Central Rocky Mountains. Geologically the area lies in the Colorado Piedmont section of the Great Plains physiographic province and is underlain by about 12,000 feet of sedimentary rocks ranging in age from Paleozoic to Cenozoic. The sedimentary rocks are underlain by an unknown thickness of Precambrian metamorphic rocks. Denver and the Rocky Mountain Arsenal are located over the deepest part of the north-trending asymmetrical Denver basin (fig. 1). Sedimentary rocks which are exposed on the west flank of the basin dip steeply eastward; those on the east flank dip gently to the west.

A system of steeply dipping faults trends southeasterly from the metamorphic rocks of the Front Range into the sedimentary rocks of the Denver basin. The generalized geologic section (fig. 2) shows the general subsurface relationship between the sedimentary and metamorphic rocks across the Denver basin. In the area shown on the generalized geologic map of the Rocky Mountain Arsenal area (fig. 3), only the youngest of the sedimentary bedrock units crops out at the surface. The bedrock is covered in many places by unconsolidated surficial deposits of silt, sand, and gravel of Pleistocene and Recent age.

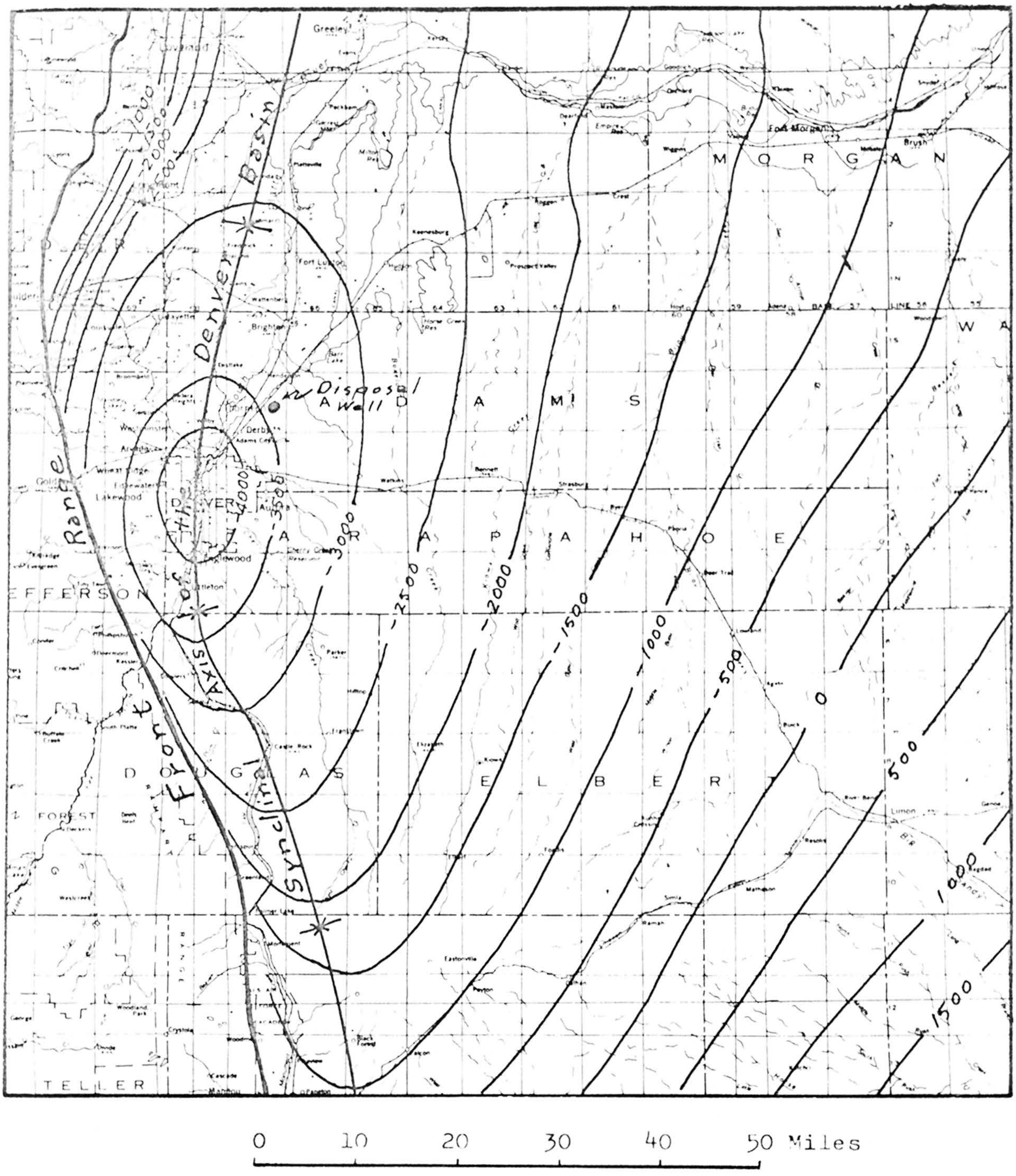


Figure 1.--Structure contour map of the Denver area, Colorado. Structure contours drawn on top of the Dakota Sandstone; contour interval 500 feet; datum is mean sea level. Adapted from U.S. Geological Survey Oil and Gas Investigations Map OM 176 (Finley and others, 1955).

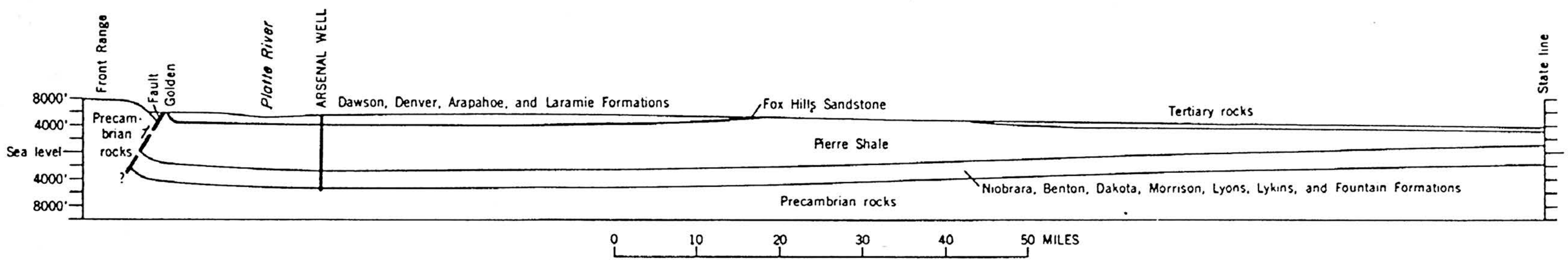
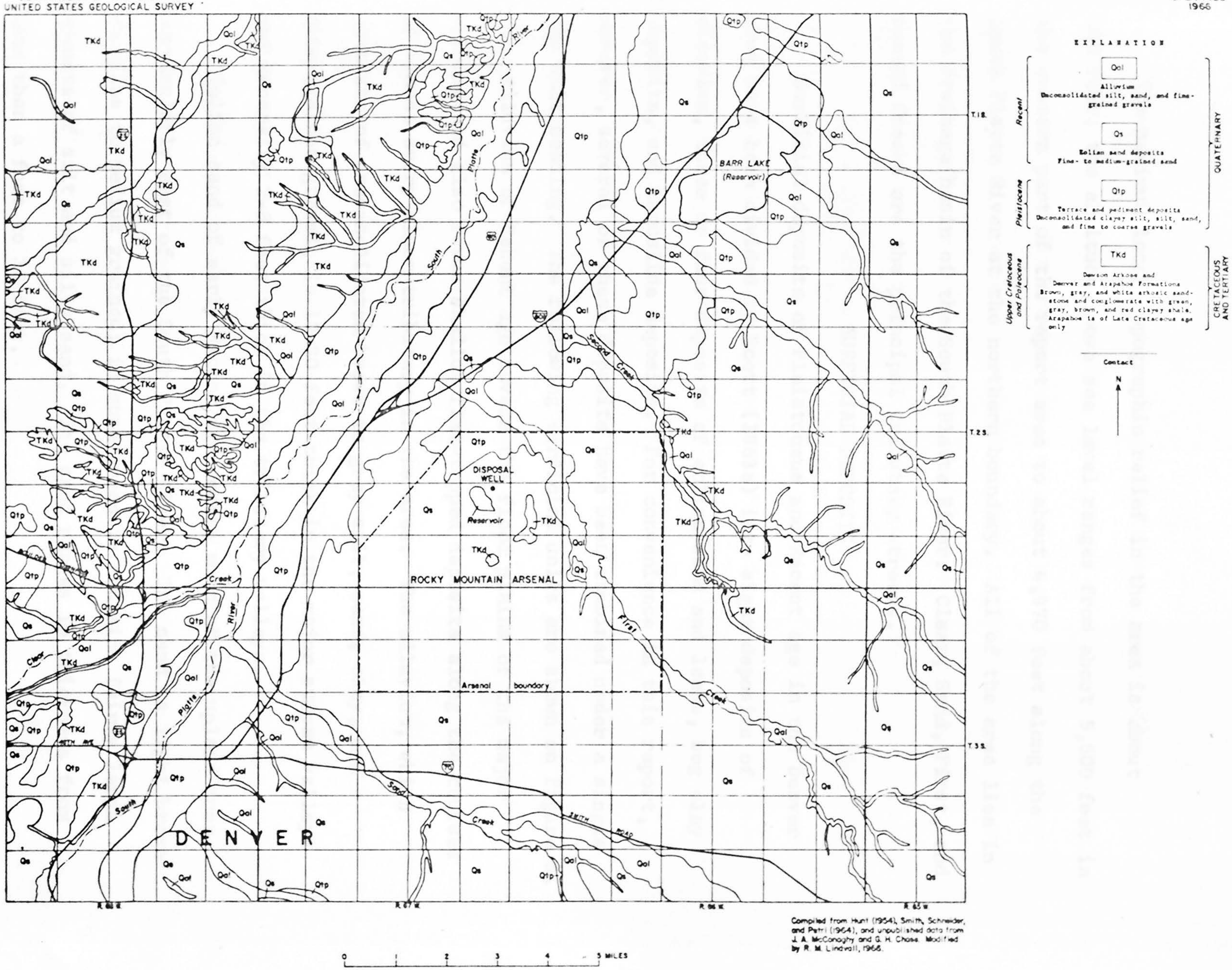


Figure 2.--Generalized geologic section of the Denver basin from the Front Range near Golden to the Colorado-Kansas State line near Wray. Vertical exaggeration 5X.



Compiled from Hunt (1954), Smith, Schneider, and Petri (1964), and unpublished data from J. A. McConaghy and G. H. Chase. Modified by R. M. Lindvall, 1966.

Figure 3. GENERALIZED GEOLOGIC MAP OF THE ROCKY MOUNTAIN ARSENAL AREA, COLORADO

The maximum local topographic relief in the area is about 500 feet; the altitude above sea level ranges from about 5,500 feet in the western part of the report area to about 4,970 feet along the South Platte River at the northern boundary. All of the area lies in the drainage basin of the South Platte River. Clear, Sand, First, and Second Creeks are the principal tributary streams.

SURFICIAL DEPOSITS

Surficial deposits of Pleistocene and Recent age in the Denver area have been divided by Scott (1963a) into eight deposits of alluvium, three or four deposits of eolian sand and loess, bog clay deposits, and landslide deposits. For convenience in this report, however, several of these deposits have been combined under a single map unit heading. The following surficial units are shown on figure 3.

Alluvium of Recent age covers the flood plains of the major streams and also forms shallow flat-topped deposits along the courses of almost every minor tributary in the area. The alluvium, which consists of unconsolidated brown to gray silt, sand, clay, and fine-grained gravel, is 10-20 feet thick in the major stream valleys and generally 2-8 feet thick in the tributary valleys.

Eolian sand of early Recent age covers much of the upland area, particularly east of the South Platte River. The sand is light brown and fine to medium grained; in some areas it contains fairly large amounts of silt and silty sand. The sand ranges in thickness from less than a foot to 30 feet.

Terrace and pediment deposits of Pleistocene age consist of unconsolidated clayey silt, silt, sand, and fine- to coarse-grained gravel. The deposits are generally exposed in well-developed terraces along the major streams and on isolated flat-topped erosional remnants on the uplands. In some areas the flat terrace surfaces also are covered by relatively thin eolian sand deposits. The terrace deposits in the mapped area are as much as 40 feet thick in places, particularly along the South Platte River valley.

Figure 4 shows the configuration of the top of the bedrock under the surficial deposits, as determined from borehole data, for a part of the area near the Rocky Mountain Arsenal.

SEDIMENTARY ROCKS

Sedimentary rocks in the mapped area are at least 11,920 feet thick, as revealed in the log of the Rocky Mountain Arsenal disposal well (table 1). The sedimentary rocks range in age from Paleocene to Pennsylvanian, or possibly to Ordovician or Cambrian. Along the Front Range in the Morrison quadrangle about 15 miles southwest of the Rocky Mountain Arsenal area, J. H. Smith (1964) measured more than 12,500 feet of sedimentary strata (table 2).

The name, thickness, and a brief description of the lithology of each sedimentary formation penetrated in the Arsenal disposal well are presented in table 1 and will not be repeated here.

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Adapted from Smith, Schneider, and Petri (1964)

Figure 4. MAP OF THE ROCKY MOUNTAIN ARSENAL AREA, COLORADO, SHOWING THE CONFIGURATION OF A PORTION OF THE BEDROCK SURFACE

Table 1.--Log of the stratigraphic units in the Rocky Mountain Arsenal disposal well, Adams County, Colorado. Modified from L. J. Scopel (1964)

[A more detailed log of this well from the surface through the Pierre Shale is published in Colorado Water Conservation Board Basic-Data Report 15 (McConaghy and others, 1964, p. 97 - 98)]

Group or formation	Depth (feet)	Lithology
Surficial deposits (Quarternary age)	0- 30	Unconsolidated dune sand, sand, silt, and gravel.
Arapahoe Formation (Late Cretaceous age)	30- 460	Light- to dark-gray shale, siltstone, sandstone, and conglomerate.
Laramie Formation (Late Cretaceous age)	460- 1,250	Alternating fine-grained gray glauconitic sandstone and dark-gray shale and coal beds.
Fox Hills Sandstone (Late Cretaceous age)	1,250- 1,480	Gray fine-grained sandstone interbedded with gray to dark-gray shale.
Pierre Shale (Late Cretaceous age)	1,480- 7,710	Predominantly light-gray and dark-gray shale, interbedded with siltstone and sandstone. Hygiene Sandstone Member at 5,448 ft to about 5,490 ft.
Niobrara Formation (Late Cretaceous age)	7,710- 8,078	Calcareous to chalky, light-gray to gray shale and limestone.
Benton Group (Early and Late Cretaceous age)		
Carlile Shale	8,078- 8,120	Dark-gray shale.
Greenhorn Limestone	8,120- 8,345	Dense shaly gray to brown limestone.
Graneros Shale	8,345- 8,485	Black micaceous shale. Thin beds of bentonite near base.

Table 1.--Log of the stratigraphic units in the Rocky Mountain Arsenal disposal well, Adams County, Colorado. Modified from L. J. Scopel (1964)--Continued

Group or formation	Depth (feet)	Lithology
Dakota Group (Early Cretaceous age)		
"J" Sandstone	8,485- 8,633	Fine-grained quartzitic sandstone.
"Dakota" Sandstone	8,633- 8,730	Sandstone and dark-gray shale.
"Lakota" Sandstone	8,730- 8,786	White hard quartzitic sandstone.
Morrison Formation (Jurassic age)	8,786- 8,972	Varicolored shales, thin beds of fresh-water limestone, white hard sandstone, and anhydrite.
Lykins Formation (Triassic age)	8,972- 9,582	Red silty shale. Top 15 ft is a fine, hard quartzitic sandstone. Bottom 80 ft is anhydrite and red shale.
Lyons Sandstone (Permian age)	9,582- 9,772	Fine-grained, highly fractured, orange crossbedded quartzitic sandstone.
Fountain Formation (Pennsylvanian age & Early Permian age)	9,772-11,880	Coarse-grained arkosic conglomerate, siltstone, maroon shale, and a few thin beds of limestone. Upper third of formation is highly fractured.
Regolith (Fossil Soil)	11,880-11,895	Weathered maroon to dark-brown shale. Bottom 1 foot is a dark-reddish-brown highly fractured quartzite.
Rocks of Ordovician(?) or Cambrian(?) age		Quartz conglomerate.
		Purple fissile shale.
	11,895-11,950	Coarsely crystalline, pink to white dolomite containing green chert fragments, purple shale.
Schist (Precambrian age)	11,950-11,970	Bright-green weathered mica schist.
Gneiss (Precambrian age)	11,970-12,045	Highly fractured hornblende granite gneiss containing pegmatite intrusions.
Total depth of hole	12,045	

Table 2.--Description of the stratigraphic units in the Morrison quadrangle, Colorado. Modified from J. H. Smith (1964)

Group or formation	Thickness (feet)	Lithology
Denver Formation (Late Cretaceous and Paleocene age)	950	Yellowish-gray to moderate-brown poorly sorted tuffaceous fossiliferous claystone, siltstone, mudstone, arkosic sandstone, conglomerate beds, and interlayered latite.
Arapahoe Formation (Late Cretaceous age)	400	Coarse- to fine-grained sandstone and mudstone in upper part, poorly sorted pebble conglomerate in lower third of formation.
Laramie Formation (Late Cretaceous age)	700 - 1,000	Sandstone, claystone and coal. Sandstone is light gray to yellowish-brown, silty to clayey, fine to medium grained. Claystone is light gray to light olive, and massive to blocky in structure. Coal in many thin seams in lower 200 feet of the formation; subbituminous to impure lignite.
Fox Hills Sandstone (Late Cretaceous age)	180	Upper 105 ft is olive-gray to dark-yellowish-brown shale and interbedded sandstone. Lower 75 ft is yellowish-brown, massive to thin bedded, friable fine-grained, locally crossbedded sandstone and interbedded shale and claystone.
Pierre Shale (Late Cretaceous age)	6,200	Upper part is interbedded yellowish-brown to olive-gray silty sandstone, sandy shale, and shale. Middle part is grayish-brown clayey fine-grained sandstone of the Hygiene Sandstone Member. Lower part is olive-gray to yellowish-brown shale.

Table 2.--Description of the stratigraphic units in the Morrison quadrangle, Colorado. Modified from J. H. Smith (1964)--Continued

Group or formation	Thickness (feet)	Lithology
Niobrara Formation (Late Cretaceous age) Smoky Hill Shale Member	410	Pale-brown to reddish-brown, soft thin-bedded, calcareous shale and interbedded thin layers of limestone.
Fort Hays Limestone Member	35	Light-yellowish-gray, dense, hard, fine-grained limestone in beds 1 to 7 ft thick.
Benton Shale (Early and Late Cretaceous age)	530	Dark-gray to black shale, silty claystone, sandstone, calcarenite, thin beds of bentonite, siltstone, and massive limestone. Upper part is chalky and silty shale and sandstone that constitute Carlile equivalent. Middle part is fossiliferous calcareous shale, calcarenite, and limestone that constitute Greenhorn equivalent. Lower part is noncalcareous black shale that constitutes Graneros equivalent, and bottom 15 ft is light- to dark-gray platy siltstone equivalent to Mowry Shale.
Dakota Group (Early Cretaceous age) South Platte Formation Lytle Formation	300	Tan to light-yellowish-gray medium-grained crossbedded sandstone and interbedded siltstone and claystone.
Morrison Formation (Late Jurassic age)	300	Gray and red shale and gray claystone that contain sandstone and thin limestone beds.
Ralston Creek Formation (Late Jurassic age)	90	Grayish-yellow siltstone and dull-red and greenish-yellow variegated mudstone. Contains thin gypsum beds.

Table 2.--Description of the stratigraphic units in the Morrison quadrangle, Colorado. Modified from J. H. Smith (1964)--Continued

Group or formation	Thickness (feet)	Lithology
Lykins Formation (Permian(?) and Triassic(?) age)	450	Moderate reddish-brown, thin-bedded silty shale with several thin beds of limestone.
Lyons Sandstone (Permian age)	115-200	Grayish-orange to yellowish-gray or white massive medium- to fine-grained friable crossbedded quartz sandstone. Lenses of arkosic conglomerate and reddish-brown siltstone in lower part.
Fountain Formation (Pennsylvanian and Early Permian age)	1,650	Moderate reddish-brown to yellowish-gray conglomerate, arkosic sandstone, and thin layers of micaceous siltstone. Crossbedded; cut-and-fill channels.
Crystalline metamorphic rocks (Precambrian age)		Metamorphosed sedimentary rocks including gneiss, schist, quartzite, slate, and marble; and intrusive igneous rocks such as granite and pegmatite.

PRECAMBRIAN ROCKS

Precambrian rocks were penetrated in the Arsenal well at a depth of from 11,950 feet to 12,045 feet, which is the bottom of the hole (table 1). According to Scopel (1964), the rocks consist of weathered mica schist and highly fractured hornblende granite gneiss. Sheridan, Wrucke, and Wilcox (this report) have recently examined the core and cuttings samples from the lower part of the well and have concluded that the rocks from a 11,935- to 11,950-foot depth are also of Precambrian age. They report that the rocks from the bottom 75 feet of the well are gray, fine- to medium-grained hornblendic biotite-quartz-feldspar gneiss, which is locally fractured and veined.

STRUCTURE

The Rocky Mountain Arsenal is located near the deepest part of the asymmetrical Denver basin (fig. 1). The synclinal axis of the basin, as shown by Finley, Dobbin, and Richardson (1955), lies about 6 miles west of the Arsenal well. The steeply dipping sedimentary rocks on the west flank of the basin are faulted in many places along the mountain front. Typical examples of such faulting are shown on the geologic maps of the Golden (Van Horn, 1957) and Morrison (Smith, 1964) quadrangles. Both quadrangles are located about 15 miles west and southwest of the Rocky Mountain Arsenal area. The sedimentary rocks on the east flank of the Denver basin, where no faulting has yet been reported, dip very gently westward (fig. 2).

No faults which cut the bedrock surface or the surficial deposits are known in the mapped area (fig. 3). The nearest faults cutting the Cretaceous and Paleocene rocks are those in the Golden and Morrison quadrangles. Several faults were mapped by Spencer (1961) near Superior, Colo., in the Louisville quadrangle, about 15 miles northwest of the Rocky Mountain Arsenal. These faults occur in the Laramie, Fox Hills, and Pierre Formations. Spencer reported vertical displacements of as much as 500 feet along the fault planes.

G. R. Scott (oral communication, 1966) has reported that a fault in the Fox Hills Sandstone near Boulder, Colo., about 25 miles northwest of the Rocky Mountain Arsenal, displaces gravel of middle Pleistocene age.

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Part 2

Recorded seismic activity prior to 1962

By

Harold L. Krivoy and M. P. Lane

As part of the investigations of seismic activity in the vicinity of Commerce City (Derby), Colorado, seismograph data previously studied primarily for distant earthquakes were reviewed for the occurrence of local earthquakes.

The primary source of information was the University of Colorado's seismogram library covering the years 1954-1959. This material was made available to us through the cooperation of Dr. Warren Longley, at the Department of Geology. The seismograms were recorded on 35-mm film by two horizontal and one vertical Benioff seismometers, located in the basement of the Geology Building on the Boulder campus.

Regis College, in North Denver, has had a longer history of seismic observations, starting in 1909. However, the Regis seismometers were low-gain mechanical instruments, and so the Regis' record files were consulted primarily for verification of other data. Access to the Regis' files was provided through the cooperation of Rev. Joseph Downey, S.J., Director of the Seismographic Observatory at Regis.

United States Earthquakes, published annually by the U. S. Coast and Geodetic Survey, lists earthquake activity according to region of origin, and includes both instrumental and non-instrumental, or felt, reports of earthquakes.

The seismic networks of the Coast and Geodetic Survey and the Jesuit Seismological Association have provided valuable information on origin times and epicenters for larger earthquakes all over the world, but for small earthquakes possibly originating in the Derby area prior to 1962, it is likely that the Coast and Geodetic Survey instrumental or non-instrumental screening missed events of magnitude 2 or smaller.

Method of Study

Seismograms from Boulder, covering an interval of about 3 years, were reexamined and studied in close reference to Dr. Longley's original notes. It was found that his notes omitted very few local quakes or blasts, even though these data were not transmitted to the U. S. Coast and Geodetic Survey. Therefore, Dr. Longley's notes were used as a guide for the screening of the seismograms covering the remaining two years.

Results of examination of the Boulder Seismograms

Evidence was found indicating that seismic activity in Derby may have begun before 1962. Thirteen events that might possibly fit into the "Derby" category were identified and studied, but many or all of these may have been of artificial origin rather than natural origin. They seemed similar in magnitude--less than M-2.

Earthquakes originating in Derby since 1962 commonly have prominent post-P arrivals, as recorded at the South Ingalls, Golden and Bergen Park stations. Events on the Boulder seismograms during the 1954-1959 interval that displayed similar prominent post-P arrivals are designated "Derby" type events in table 1. Such arrivals are best explained as compressional waves generated at the free surface by incident transverse waves and then refracted and reflected in the area between the focus and recording site.

Table 1.--Chronological summary of some seismic events recorded at Boulder, Colo., station, 1954-59.

[Recording began on January 1, 1954, and was discontinued on June 9, 1959. MST, Mountain Standard Time; C&GS, Coast and Geodetic Survey; M., magnitude; S-P, time interval between arrival of P-waves and S-waves]

Date	Description and comments
1954	
Jan. 20	13:50 MST: widely felt in southeastern Wyoming; ca 1900 MST: second (smaller) felt quake, FOXPARK type.
Jan. 25	S-P 16.7 sec.; FOXPARK type.
Feb. 1	S-P ca 2.4 sec.; possible DERBY.(Monday)
Feb. 21	13:20 MST: northwestern Colorado; felt GRAND JUNCTION, REDLANDS, DINOSAUR
Feb. 26	S(?)-P ca 1.8 sec.; possible DERBY.(Friday)
March 7	S-P probably 5.0 sec.; possible DERBY
March 18	Large California quake.
March 28	Good deep event off Spain; M=7
June 17	05:47 MST; S-P 23 sec. (not noted by C&GS)
July 24	3 events: 02:49, 03:15, 04:14 MST; S-P 25.3 sec., (not noted by C&GS)
Aug. 23	Fallon, Nev.; M=6.8
Oct. 3	01:52 and 01:59 MST; first local event that was felt at DOUGLAS-WHEATLAND, WYO.
Oct. 9	11:38 MST; possible local event S-P, 15 to 30 sec. (not noted by C&GS)
Oct. 31	Ca 20:00 MST; S-P ca 1.5 sec.
Nov. 1	Ca 05:00 MST; S-P 2.4 or 4.3 sec. Both quakes (?) small and both from the northwest quadrant; they do not otherwise seem to be related.
Dec. 15	Fallon, Nev.; M = 7.0, 6.8 etc.

Date	Description and comments
1955	
Feb. 10	10:26 MST; felt strongly at STEAMBOAT SPRINGS (?).
May 1	10:26 MST; S-P ca 12.5 sec. (not reported by C&GS)
May 22	05:46 MST; S-P ca 16.2 sec., felt in MEDICINE BOW, WYO.
July 30	19:05 MST; local, S-P (not reported by C&GS) (May be CREEDE foreshock)
Aug. 1	21:18 MST; S-P ca 37 sec. (not reported felt) CREEDE foreshock.
Aug. 2	23:31 MST; felt, CREEDE foreshock. 23:40 MST; CREEDE main shock, felt strongly CREEDE, OURAY, TELLURIDE, LAKE CITY, etc.
Sept. 2	14:51 MST; possible DERBY. (Friday)
Oct. 2	09:51 MST; S-P 13 sec., 81,000-pound blast at CLIMAX, COLO. (Sunday)
Oct. 27	07:32 MST; very clear event close to station; probably a blast.
Nov. 27	22:25 MST; S-P 20 to 25 sec.; from SE quadrant, felt strongly in SUGAR CITY and ROCKY FORD.
Dec. 13	08:17 MST; S-P ca 50 sec.; felt in LANDER, WYO.
1956	
Jan. 6	04:59 MST; S-P ca 20 sec.; epicenter near COLDWATER, KAN.; felt in OKLAHOMA and KANSAS.
Jan. 14	11:43 and 11:49 MST; both felt in LAMAR, COLO.
Jan. 16	07:21 MST; S-P 27.7 sec. (good record; not noted by C&GS)
Feb. 11	18:08, 19:45, 21:02, 21:07 (strongest), 22:04 MST; 5 shallow, interesting similar (S-P 44 sec.) events. At about 20:00 and 21:15 MST; felt reports from VERNAL, UTAH. (These two events have a shallow and artificial character)
May 6	One small possible event; questionable due to noisy background. S-P ca 4 sec.
June 5	One local---small and questionable; S-P ca 10 sec.

Date	Description and comments
1956 continued	
June 28	01:36 MST; S-P ca 17 sec.; typical FOXPARK event.
July 5	07:08 MST; S-P 2.7 or 5.0 sec.; good recording of DERBY type. (Thursday)
July 7	19:51 MST; S-P ca 17 sec.; typical FOXPARK event.
July 9	23:34 MST; S-P ca 17 sec.; small FOXPARK event.
July 19	08:44 MST; S-P 2.7 or 5.0 sec.; good example of DERBY type. (Thursday)
Aug. 15	06:12 and 06:29 MST; S-P 16.7 sec.; two good FOXPARK events.
Aug. 27	06:16 MST; S-P 2.7 or 5.0 sec.; good example of DERBY type. (Monday)
Oct. 3	13:22 MST; reported felt in southwestern Wyoming.
Nov. 1	One small event at S-P 8.6 sec.; not characteristic of any recognized type locality.
Nov. 24	Small event; S-P 4.5 sec.; possible DERBY. (Saturday)
1957	
Jan. 5	19:32 MST; S-P ca 35 sec.; reported felt in ESTERBROOK, WYO.
Jan. 25	14:26 MST; S-P 17 sec.; FOXPARK type (recorded and studied by Univ. Wyoming).
Feb. 13	One possible blast; S-P ca 2 sec.
Feb. 25	A questionable event; S-P ca 10 sec.
April 21	22:25 MST; S-P ca 27.5 sec. (not noted by C&GS).
May 3	01:30 MST; reported felt in CREEDE, COLO. (not seen on Boulder records)
July 15	12:44 MST; S-P ca 16.5 sec.; FOXPARK type (not noted by C&GS)
1958	
Jan. 28	04:17 MST; S-P ca 18 sec.; one event of FOXPARK type.

Date	Description and comments
1958 continued	
Feb. 13	15:53 MST; PROVO, UTAH; damage at Provo and Wallsburg, Utah. Berkeley and Univ. Utah stations estimated magnitude at between 4.0 and 4.5.
Mar. 12	13:47 MST; S-P either 3 or 5 sec.; DERBY type event. (Wednesday)
May 1	13:32 MST; S-P either 3 or 5 sec. DERBY type event. (Thursday)
May 5	17:55 MST; similar to May 1st DERBY type event. (Monday)
Aug. 6	17:47 MST; S-P ca 16 sec. felt in FOXPARK and LARAMIE. FOXPARK type.
Aug. 7	03:22 MST; S-P 16.5 sec. FOXPARK type (not reported by C&GS)
Aug. 15	13:35 MST; S-P ca 17 sec.; FOXPARK type (not reported by C&GS)
Oct. 7	13:47 MST; S-P ca 3 sec. DERBY type. (Tuesday)
Dec. 28	05:25 MST; S-P ca 16 sec.; good event of FOXPARK type (not noted by C&GS)
1959	
Jan. 15	One very poor local event; S-P 2.7 or 7.2 sec.; may be DERBY type. (Thursday)
May 6	One poor event at S-P ca 14 sec.
	(No further local events registered.)

For earthquakes or artificial seismic events originating near Derby, the S-P time interval, as recorded at Boulder, should be about 5 seconds, depending on the focal depth. The strongest arrivals at Boulder for the events designated "Derby" occur at about 2.8 seconds after P. These would ordinarily be identified as S, but if the events did come from Derby, the arrivals are too early to represent S-waves.

Some recordings are reproduced in figures 1 and 2 for comparison of events of the "Derby" type recorded at Boulder with a known Derby earthquake of magnitude 2.1 recorded Jan. 1, 1966 by a newly established seismograph at Boulder.

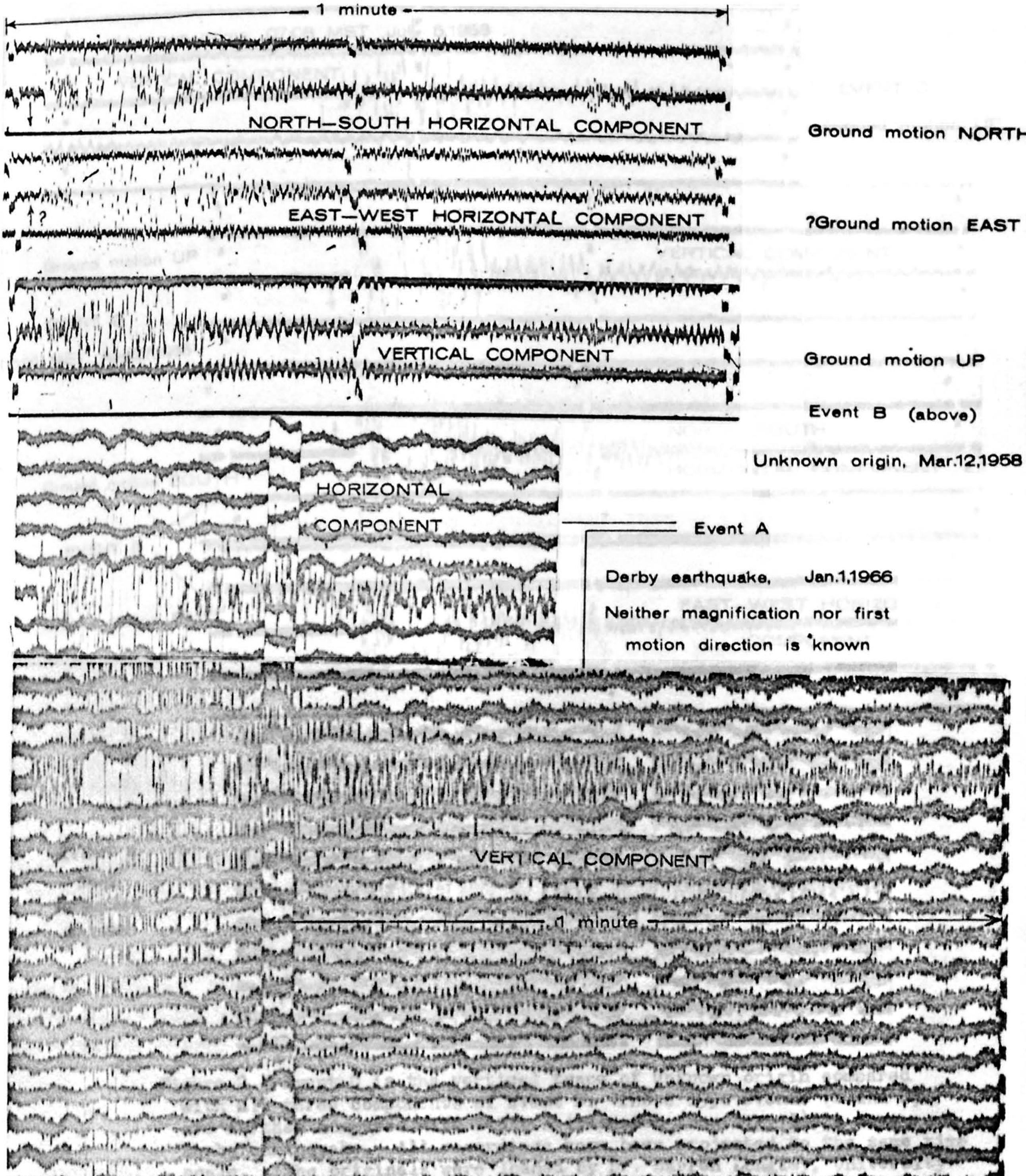


Figure 1.--Comparison between a recent Derby earthquake of Jan. 1, 1966 (M = 2.1) and an event copied from the records of March 12, 1958. Both records were written by high-gain, short-period instruments operated at the University of Colorado, Boulder, Colo. All recordings have been projected to the same time scale. (The originals were loaned by Dr. Warren Longley, University of Colorado, Boulder.)

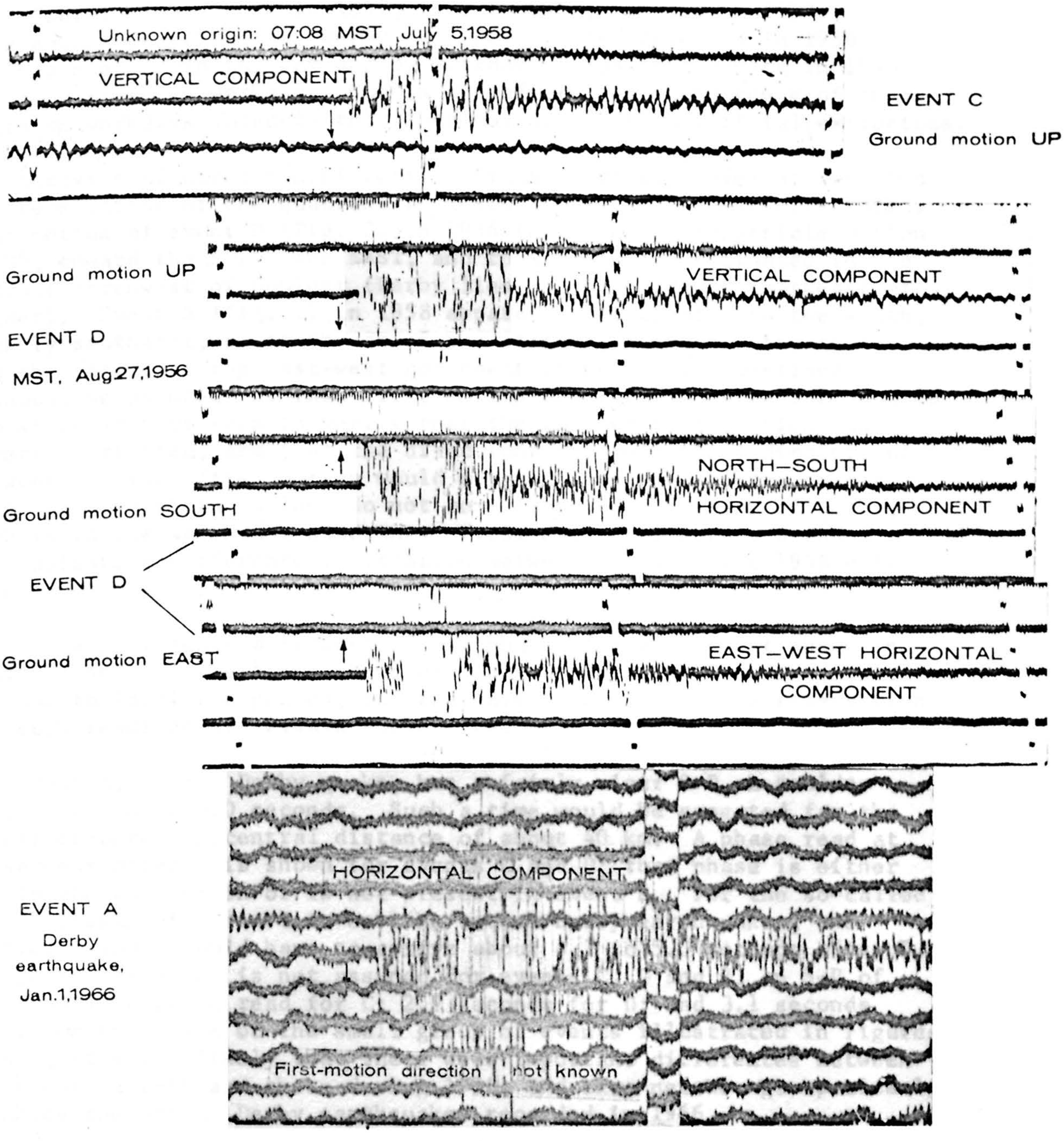


Figure 2.--Event C is the vertical trace of unknown origin compared with all three components of Event D. These 1956 events (C and D) are further compared with Event A (repeated from fig. 1), a true Derby earthquake. All recordings have been projected to the same time scale. (The originals were loaned by Dr. Warren Longley, University of Colorado, Boulder.)

Three events described as "Derby" were recorded in 1954, one in 1955, four in 1956, none in 1957, four in 1958, and one in 1959. Three events described as "Derby" or "Derby type" recorded in 1956 took place early in the day and on workdays. The four events in 1958 also took place on workdays, but in the afternoon. Occurrence of these events on workdays suggests that they may have been artificial explosions.

Analysis of direction of first motions of ground movement assisted in determination of the quadrant in which the seismic event originated. First motion of event D (Fig. 2) in 1956 indicates that particle motion was UP, toward the SOUTH and EAST, and thus probably originated in the quadrant northwest of Boulder (Derby lies in the quadrant southeast of Boulder). Event B (Fig. 1) in 1958 apparently originated to the south, slightly southeast, or southwest of the station; the ambiguity arises from the fact that the east-west component of motion is questionable. It should be pointed out that first motion observed in other earthquakes from known sources seem to verify that the Boulder installation was correctly oriented, and that the directions are reliable indicators of the source. Thus first motion would suggest that some of the events listed as "Derby" in table 1 do not come from the direction of Derby, which is in the southeast quadrant. First motion of events B and D also indicate a difference in location between the 1956 and 1958 epicenters.

Table 2 presents a readout of all phases for each event shown in figures 1 and 2. The times shown are in seconds after P. No attempt was made to label the phases, and they are offered with the reservation that such readings are always subjective.

Event A, a true Derby quake, has a fairly clear S-P on Boulder records of around 5.0 seconds. Such a time would be expected for the Boulder-to-Derby epicentral distance of about 40 km. A phase read at 4.6 seconds after P is shown for events C and D; that phase is either lost in the wave train or is not present in event B. For the so-called "Derby" events of table 1 to be like recent Derby earthquakes, the transverse waves would have to arrive about 4.7 to 5.0 seconds after P. If a derby epicenter is not assumed for events C, D and B, an S-P of 2.7 seconds would be read for C; 2.7 seconds for D; and 3.1 seconds for B. On the basis of the small group of events illustrated in figures 1 and 2, it seems likely that there were important differences between events during 1956 and those during 1958, and that neither group clearly resembles the actual Derby earthquakes recorded in 1966.

Table 2--Schedule of readings from events illustrated in figures 1 and 2 to show outstanding phases in terms of the time by which they lag P-arrivals. Three chronological groupings are also used: two events in 1956, a single (true Derby) event in 1966 and a single case recorded in 1958.

Seconds after P

Event

1956

C
(Fig. 2)----- 0.9 ---- 2.0 ---- 2.7 ---- 4.7 ---- 6.6 ---- 8.3? ?

D, (Z, First motion up)
(Fig. 2)----- 0.9 ---- 1.8? --- 2.6 ---- 4.6 ---- 6.7 ---- 8.1 ---- 13.2

D, (S, First motion toward south)
(Fig. 2)----- 0.9? --- 1.7? --- 2.7 ---- ? ---- 6.4? --- 8.2 ---- 13.2

D, (E, First motion toward east)
(Fig. 2)----- ? ---- 1.8 ---- 2.7 ---- ? ---- ? ---- 8.2 ---- 13.3

1966

A, (Horizontal component seismometer)
(Figs. 1&2) ------1.2--------------------5.2-------------------------

A, (Z)
(Fig. 1) --------------------------------4.8--------------------------
(spot is too active on this 1966 quake; only the above three phases, exclusive of P, were prominent)

1958

B, (Z, First motion up)
(Fig. 1) -----0.8--1.3 ------- 3.4? -----many phases--- 11.8

B, (E, First motion toward east)
(Fig. 1) ---- ? -- ? ---------2.9? ------many phases--- 11.6

B, (N, First motion toward north)
(Fig. 1) ---- 0.8--1.3? -------3.1--------many phases--- 11.6

Conclusions

Two conclusions are possible from this investigation:

1. It is possible that the events listed as "Derby" in table 1 are real earthquakes resulting from the same or a similar mechanism as that now existing near the Rocky Mountain Arsenal.

2. It is more probable that the events picked on Boulder records between 1954 and 1959, were either natural earthquakes or demolition shocks from some other epicenter or epicenters. Their occurrence only during the daytime working hours and only on workdays suggests an artificial disturbance. On the basis of a 3-second S-P interval and a P-velocity of 5 Km/sec, a source should be sought within 20 Km of Boulder.

Part 3

THE DENVER EARTHQUAKES AS RECORDED AT THE CECIL H. GREEN GEOPHYSICAL OBSERVATORY

By Maurice Major, Colorado School of Mines

The Cecil H. Green Geophysical Observatory was established by the Colorado School of Mines in December 1961 as an integral part of the Geophysics Department. The observatory is located 15 miles southwest of Golden at Bergen Park, Colo. (39°42'01" N., 105°22'16" W.), at an elevation of 7,770 feet. A three-component short-period Benioff seismograph installation has operated continuously at this site since that date.

These instruments, running at magnifications of 400,000 during the summer and 200,000 during the winter, are about 28 miles from the center of the seismic activity in the Derby[1/] area. They are capable of detecting Derby events as small as magnitude 0.8 on a quiet day, but the average threshold of detection during the past 5 years has probably been closer to 1.1. The lower limit of felt reports from the Derby area, by comparison, is slightly above 2.0.

No Derby earthquakes were detected by these instruments between the initiation of recording at this station, late in December 1961, and April 24, 1962. A complete list of the dates, P-wave arrival times at Bergen Park, and the magnitudes of all Derby events detected between April 24, 1962, and February 28, 1966, is presented in table 1. This

1/ The seismic events located near Commerce City (formerly known as Derby) are referred to as "Derby" events in this report.

list represents the results of interpretive work by several investigators: 1962, Mr. Poh-His Pan; 1963, Dr. Yung-liang Wang; 1964, Mr. Peter Jones; 1965, Mr. Charles Wideman; and 1966, Dr. Maurice Major. It is probable that the threshold of recognition was not the same for all investigators and that therefore a number of Derby events in the magnitude range 0.8-1.2 have escaped detection.

The Richter magnitude, M, of a local earthquake is defined in terms of the response of a Wood-Anderson torsion seismometer with a magnification of 2800:

$$M = \log_{10}A - \log_{10}Ao$$

wherein A is the amplitude in millimeters of the maximum trace amplitude and Ao is the corresponding trace amplitude expected from an M = 0 shock at the same distance. Values of $-\log_{10}Ao = f(\Delta)$ have been tabulated by Richter after study of the records of a dense network of stations in Southern California. Because of the paucity of data no corresponding study can yet be made in Colorado. Possibly Richter's tabulation does not well represent the decrease in amplitude of ground motion with increasing distance which actually occurs in Colorado near Derby but the discrepancy, if present, is considered not to be large.

The initial magnitude determinations by Pan in 1962 were based on Richter's tabulated values for $-\log Ao = f(\Delta)$ and a simple conversion of the Benioff response to that of the standard Wood-Anderson. This is equivalent to assuming that the wave of maximum recorded amplitude has the same period on both types of instruments. In the spring of 1965 two Wood-Anderson seismometers were installed at Bergen Park. Records from these instruments were compared directly with Benioff-seismometer records of Derby earthquakes in the magnitude range 3-3.5. The comparison indicated that the magnitude-determination technique used prior to 1965 was correct.

It is noteworthy that the magnitudes so determined are systematically smaller, by about 0.5, than the corresponding magnitudes assigned in the U.S. Coast and Geodetic Survey's preliminary epicenter cards. This anomaly may be due to the known high efficiency of the propagation path from Denver eastward and an accidental bias of the U.S. Coast and Geodetic Survey data in favor of stations in the eastern United States.

Future studies of the Derby activity will involve a quantitative comparison of the work done by the pumps and the elastic energy radiated from the hypocenters. Such a study would naturally be a part of the effort to establish a reasonable source mechanism. From strictly preliminary studies of this sort, based upon Gutenberg and Richter's relationship $\log_{10}E=11.4+1.5M$ (1958), we were not able to conclude that the energy contribution of the pumps has been negligible.

Reference cited:

Richter, Charles, 1958, Elementary seismology: San Francisco, W. H. Freeman and Co.

Table 1.--Denver area earthquakes recorded at the Colorado School of Mines Cecil H. Green Geophysical Observatory, April 24, 1962, to February 28, 1966.

GCT, Greenwich Civil Time; C&GS, Coast and Geodetic Survey; Mag., magnitude. Compass directions in Remarks column refer to direction from the observatory

Date		Time (GCT) h	m	s	Magnitude	Remarks
				1962		
Apr.	24	11	10	32.3	1.5	
	28	11	48	58.8	1.8	
May	1	7	47	52.7	1.5	
	1	23	07	32.6	1.7	
	10	9	56	26.7	1.0	
	19	9	42	51.0	1.7	
	20	6	18	58.9	1.7	
	22	2	18	50.8	1.6	
	22	4	19	53.5	1.1	
	22	13	22	20.3	1.1	
	24	4	43	32.1	1.5	
	24	10	02	27.5	1.2	
	24	10	18	15.8	1.4	
	24	10	49	51.2	1.4	
June	3	9	29	03.0	1.5	
	5	14	34	10.0	1.6	
	5	15	28	03.4	2.3	
	5	16	21	04.7	0.8	
	6	1	28	44.5	1.3	
	6	7	49	24.8	1.8	
	6	15	33	13.0	1.2	
	6	16	25	35.5	1.3	
	7	3	27	21.1	1.6	
	8	00	43	02.2	2.0	
	8	15	27	46.0	1.3	
	10	2	47	50.8	2.2	
	13	20	24	52.7	1.1	
	14	6	09	47.8	1.3	
	14	9	55	53.7	1.2	
	18	00	45	10.6	1.3	
	18	00	46	11.5	3.1	
	18	1	36	06.4	2.1	
	18	1	28	00.4	1.6	
	18	4	52	42.0	1.1	
	18	8	26	22.7	1.4	
	18	21	38	59.1	1.3	
	19	4	48	54.4	2.3	
	19	10	03	53.5	1.1	
	20	21	02	04.8	1.3	
	22	22	05	24.5	2.5	

Table 1--Continued

Date		Time (GCT) h	m	s	Magnitude	Remarks
				1962		
June	22	22	31	57.5	1.4	
	23	15	14	28.4	1.0	
	23	15	19	14.1	1.1	
	23	15	58	51.6	1.0	
	25	9	53	47.7	1.1	
	26	9	33	22.0	1.1	
	29	6	29	05.5	1.3	
	29	7	35	37.0	1.4	
	29	11	27	13.3	1.4	
July	2	1	04	42.0	1.1	
	2	4	24	19.5	0.8	
	2	7	40	38.8	1.8	
	2	21	28	52.6	2.1	
	9	6	35	39.0	1.9	
	9	6	44	31.0	1.2	
	11	15	29	04.4	1.3	
	14	3	46	28.8	1.5	
	14	3	49	57.5	2.0	
	14	4	39	44.9	1.2	
	14	14	45	12.7	0.8	
	14	15	13	50.0	2.1	
	15	20	14	00.2	1.6	
	15	23	53	33.1	0.8	
	16	00	17	22.0	? ?	
	16	11	06	33.1	1.6	
	16	11	51	57.0	1.1	
	28	6	15	09.1	1.2	
	28	6	23	43.0	1.6	
	28	7	59	43.5	1.6	
	28	9	16	34.7	1.4	
	28	14	45	34.8	1.1	
	29	16	56	20.2	1.1	
Aug.	7	00	51	00.2	3.0	
	7	1	22	09.6	1.8	
	7	1	30	10.7	1.5	
	7	1	40	30.6	2.5	
	7	2	07	21.1	1.0	
	7	2	52	24.2	0.8	
	7	15	09	41.1	0.8	
	8	12	47	25.5	1.9	
	8	23	53	38.6	2.0	
	10	23	29	50.0	1.6	
	11	00	28	05.4	1.2	
	15	22	06	26.5	1.5	
	15	23	55	52.9	1.8	
	16	00	00	01.2	1.3	
	16	2	03	17.7	2.6	
	16	2	09	28.4	1.1	
	16	2	10	15.9	1.1	
	16	4	06	48.4	1.6	

Table 1.--Continued

Date		Time (GCT) h	m	s	Magnitude	Remarks
				1962		
Aug.	16	10	17	55.0	1.3	
	16	23	15	48.7	1.2	
	18	22	40	37.5	1.2	
	20	4	07	30.5	1.1	
	20	8	28	49.3	1.5	
	20	9	48	42.9	0.8	
	20	10	01	02.0	1.1	
	23	3	41	13.2	1.4	
	24	9	35	10.7	2.0	
	27	10	34	11.8	1.7	
	31	2	08	09.2	1.2	
Sept.	2	11	40	07.7	0.8	
	2	21	43	39.8	1.2	
	2	23	53	23.4	2.3	
	3	00	09	16.6	1.4	
	6	01	07	15.3	1.8	
	8	17	26	39.2	1.5	
	9	03	25	56.4	1.7	
	9	03	37	51.1	1.0	
	9	16	38	04.0	1.2	
	9	16	52	31.5	1.6	
	10	1	40	38.0	1.3	
	10	7	51	09.2	1.6	
	10	17	27	05.2	0.8	
	11	22	01	49.9	1.3	
	12	11	22	55.0	1.0	
	12	23	37	05.0	1.7	
	13	21	43	11.5	1.2	
	13	22	19	52.5	1.0	
	14	1	15	29.1	1.8	
	14	2	03	24.6	1.4	
	14	2	12	39.1	1.7	
	16	00	38	24.7	1.8	
	16	14	37	56.3	2.4	
	26	9	58	02.2	1.4	
Oct.	7	8	47	15.3	1.4	
	8	16	41	12.2	2.4	
	8	16	53	37.2	0.7	
	8	19	08	28.9	0.8	
	8	19	15	53.2	0.8	
	8	20	43	57.3	1.4	
	8	20	45	12.9	2.5	
	9	23	39	10.0	1.7	
Nov.	1	19	31	18.3	1.6	
	3	4	21	11.1	2.1	
	8	2	41	11.1	1.1	
	11	3	29	18.6	1.4	
	28	12	11	52.2	1.4	
	30	2	32	24.7	1.7	

Table 1.--Continued

Date		Time (GCT) h	m	s	Magnitude	Remarks
				1962		
Dec.	4	17	50	06.4	3.6	
	4	18	33	02.9	1.6	
	4	21	18	31.5	1.6	
	4	22	58	02.4	2.3	
	4	23	22	32.8	1.3	
	5	4	22	13.1	1.2	
	5	6	26	49.9	2.1	
	5	13	48	07.1	3.8	
	6	2	13	13.8	1.6	
	14	8	18	37.1	1.1	
	16	20	16	56.4	2.4	
	17	23	30	52.4	1.1	
	19	22	22	20.3	1.2	
	24	00	08	07.8	2.1	
	24	07	47	33.0	1.1	
	24	9	00	53.9	1.2	
	24	9	02	14.6	1.4	
	24	9	10	10.1	1.2	
	26	5	59	05.6	0.8	
	29	22	44	11.8	2.3	

Table 1.--Continued

Date		Time (GCT) h	m	s	Magnitude	Remarks
				1963		
Jan.	1	16	41	51.2	1.3	
	3	21	26	38	1.1	
	3	22	02	41.2	2.3	
	6	00	02	09.7	1.5	
	7	22	02	??	0.9	
	7	22	53	56.2	1.3	
	8	21	12	??	1	
	8	22	16	??	0.5	
	10	12	35	51.5	1.5	
	25	14	26	21.7	1.1	
	26	00	22	36.9	2.5	Felt.
	26	00	36	12.6	1.0	
	26	06	35	46.1	0.7	
	26	12	27	14.9	0.7	
	26	19	09	06.7	0.7	
	27	06	15	40.2	1.2	
	27	09	52	23.0	0.5	
	27	13	56	08.5	1.1	
	28	03	33	05.2	1.3	
	28	07	29	45.9	1.9	Felt.
	28	07	57	40.6	0.6	
	28	12	54	21.8	1.5	
	28	14	00	25.8	1.1	
Feb.	3	05	24	12.6	1.5	
	3	22	05	01.3	1.2	
	4	00	29	46.3	1.4	
	11	00	36	08.3	1.5	
	11	19	05	35.5	0.9	
	12	07	48	57.2	1.6	
	12	08	01	40.3	0.6	
	15	05	43	45.8	1.2	
	15	07	38	22.1	1.6	
	16	05	11	01.0	1.2	
	17	21	13	10.1	0.6	
	22	06	51	52.3	1.6	
	22	10	47	45.7	1.0	
	25	13	36	26.3	1.4	
	25	13	57	05.2	0.9	
	25	14	24	17.8	1.2	
	26	02	53	47.6	1.5	
	26	05	28	38.0	1.2	

Table 1.--Continued

Date		Time (GCT) h	m	s	Magnitude	Remarks
				1963		
Mar.	5	15	22	58.6	1.1	
	6	17	51	46.4	1.1	
	6	21	31	05.3	0.9	
	6	21	48	32.2	1.6	
	12	12	25	35.0	0.9	
	22	07	00	26.7	0.9	
	24	10	42	35.1	1.1	
	26	00	23	29.6	1.1	
	26	13	04	56.7	1.5	
	27	02	37	26.5	1.4	
	28	17	26	13.1	2.0	
	29	08	41	40.2	1.6	
	30	06	19	09.4	1.0	
	30	06	48	47.1	1.5	
	30	19	43	54.0	1.7	
Apr.	2	00	59	17.6	1.1	
	2	01	05	16.5	1.4	
	2	01	09	50.8	1.6	
	2	01	15	55.5	1.6	
	2	01	45	37.8	1.0	
	4	02	19	01.1	1.3	
	4	02	19	49.0	2.5	
	4	02	41	27.2	1.9	
	4	03	07	04.8	0.9	
	4	03	48	59.8	0.9	
	4	08	37	20.3	1.0	
	4	08	40	01.3	2.0	
	4	10	03	31.2	1.3	
	4	10	57	32.7	1.2	
	4	11	04	36.5	1.7	
	6	01	41	44.8	1.3	
	8	09	01	43.3	1.3	
	8	04	10	12.7	1.8	
	10	12	23	57.1	0.9	
	10	20	32	25.3	1.4	
	17	01	07	31.6	1.5	
	17	12	21	06.5	0.9	
	17	14	31	28.5	1.6	
	20	20	44	25.7	1.3	
	23	04	54	47.4	0.9	
	23	14	14	17.3	0.8	
	23	14	28	53.1	1.0	
	24	00	16	35.5	2.3	
	28	23	07	01.9	0.9	

Table 1.--Continued

Date		Time (GCT) h	m	s	Magnitude	Remarks
				1963		
May	3	13	59	36.6	0.9	
	7	23	20	19.8	1.7	
	7	23	22	32.7	1.0	
	9	23	01	31.3	0.9	
	22	09	55	00.6	1.6	
	22	14	41	33.0	1.6	
	22	14	49	29.7	1.5	
	25	10	44	37.0	2.5	
	25	11	13	41.5	1.0	
	25	12	31	36.6	0.4	
	27	20	01	08.4	0.9	
	29	02	41	15.0	0.9	
June	2	11	16	19.5	0.9	
	3	19	23	27.2	1.8	
	5	00	13	56.6	3	Felt.
	18	06	45	47.4	1.6	
	24	09	42	13.5	1.4	
	26	06	27	12.7	1.8	
	28	09	36	27.5	1.0	
July	4	16	31	19.8	1.3	
	7	19	05	51.0	1.2	
	12	13	37	04.8	0.5	
	14	08	43	20.5	1.7	
Aug.	8	15	08	19.9	1.2	
	11	05	26	47.3	0.5	
	12	10	07	20.1	0.5	
	16	04	50	57.1	0.9	
	17	06	23	13.8	1.5	
	28	05	04	07.3	2.2	
	31	21	17	46.9	1.3	
Sept.	5	07	05	28.1	0.8	
	10	17	53	31.9	2.5	
	10	19	07	46.6	0.9	
	15	12	00	44.4	1.5	
	17	01	56	29.0	1.4	
	24	08	18	37.8	1.7	
	29	03	23	54.2	1.2	
	29	09	53	52.3	2.1	
	29	10	16	35.1	1.1	
	29	10	29	45.9	0.7	

Table 1.--Continued

Date		Time (GCT) h	m	s	Magnitude	Remarks
				1963		
Oct.	5	17	06	27.1	1.3	
	9	07	48	59.9	1.2	
	12	10	55	17.2	1.6	
	12	12	01	54.2	1.2	
	12	12	15	18.3	1.8	
	12	19	10	48.0	1.7	
	13	19	01	43.9	0.7	
	18	09	00	02.5	1.2	
	25	08	41	08.0	1.2	
	31	04	43	53.2	1.2	
	31	10	47	01.8	2.1	
	31	15	57	06.8	1.2	
Nov.	21	22	39	41.3	1.1	
Dec.	12	13	12	56.1	1.3	
	14	08	40	53.9	0.9	

Table 1 continued

Date	Time(GCT) h	m	s	Magnitude	Remarks
			1964		
Jan. 5	00	34	55.6	1.1	
6	02	57	50.0	1.7	
10				1.7	not enough data available. Derby?
11	07	05	0.6	1.8	
11	07	07	15.3	1.4	
Feb. 9	09	19	50.5	2.6	
15	18	59	15.5	1.9	
Mar. 9	03	25	56.9	1.0	
13	00	27	13.6		Probably a Derby shock(if so, Mag. 1.4)
19	23	50	39.2	1.0	
20	20	40	38.4		Probably a Derby shock
21	17	36	32.2		Probably a Derby shock(Mag.1.1)
22	00	05	59.2	1.4	
27	07	07	59.6	2.6	
29	08	36	56.4	1.8	
30	20	17	18.9		Probably a Derby shock(Mag. 0.7)
Apr. 9	02	36	44.5	1.4	
10	09	37	31.9	1.1	
10	17	39	28.1	2.7	
14	07	28	41.8	2.0	
14	08	32	08.9	1.8	
23	19	28	16.5	1.7	
23	20	55	04.5	1.7	
24	10	24	19.4	1.4	
26	07	51	2.8	1.7	
May 3	08	31	59.5	1.4	
17	10	02	11.3	1.8	
June 3	19	04	42.8	1.5	
9	18	18	57.3	0.7	
21	13	39	59.4	1.6	
23	22	58	07.2	1.6	
July 12	22	35	48.8	1.1	
12	22	40	9.5	1.1	
13	21	11	37.2		Probably a Derby shock (Mag. 1.6)
31	12	09	36.0	1.8	

Table 1 continued

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1964		
Aug. 6	01	28	54.6	1.8	
8	10	39	53.3	1.8	
27	09	23	01.0	1.2	
27	09	25	15.8	1.2	
27	09	32	02.8	1.4	
27	09	57	15.0	1.4	
27	12	52	40.6	1.4	
27	14	20	16.0	2.7	
Sept. 8	07	45	8.2	1.2	
13	17	49	32.8	1.2	
Oct. 17	03	13	57.6	1.4	
17	13	12	06.8	2.2	
17	13	17	24.5	2.5	
17	14	35	30.6	2.8	
17	14	39	34.1	1.2	
17	14	46	38.9	1.7	
17	16	22	12.5	1.2	
17	18	21	50.1	1.7	
17	18	32	57.3	1.4	
17	20	24	51.8	1.0	
17	21	46	30.7	1.8	
17	22	02	40.0	2.5	
18	01	12	54.4	2.4	
Nov. 2	21	25	12.1	1.6	
4	20	02	40.8		Not Derby
23	23	28	3.2	1.3	
Dec. 4	21	37	54.0	2.0	
4	21	26	57.7	2.8	
8	10	08	46.9	2.4	
8	11	43	31.8	1.4	
8	11	47	45.4	1.5	
9	11	14	57.2	1.7	
9	11	25	23.2	1.0	
24	18	26	59.2		Within Front Range.

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1965		
Jan. 5	23	25	36.7	2.1	Louisville, Colo.
9	20	03	14.7	1.8	Felt at Westminster, Colo.
9	20	52	47.5	1.1	Louisville
13	19	55	27.2	1.5	Louisville
14	19	05	55.3	1.6	Louisville
15	23	07	25.2	1.4	Derby
21	18	21	41.8	1.2	East-West component, no good
25	03	20	29.7	1.7	Derby
28	06	40	44.2		No amplitude shown
31	07	04	31.2	1.6	Derby
Feb. 4	02	09	26.1	1.5	Derby
4	05	05	50.0	1.8	Possibly Derby
5	07	01	02.9	1.5	Derby
13	23	33	44.9	1.1	Local
15	21	23	28.7	(small)	Derby
16	00	43	00.1	1.9	
16	06	43	14.9	1.5	
16	09	03	26.6	1.2	
16	19	45	47.6	1.5	
16	19	45	52.7	1.5	
16	19	45	53.7	2.1	
16	19	52	21.0	1.9	
16	20	18	02.6	2.9	
16	20	44	42.2	1.4	
16	21	36	43.2	1.4	
16	21	46	13.7	1.6	
16	22	21	53.8	3.2	
16	23	24	25.9	1.6	
16	23	42	16.6	1.5	
17	06	21	07.8	1.4	
17	09	10	45.8	1.8	
17	13	45	29.5	1.6	
17	13	56	24.2	2.0	
17	14	12	47.4	2.1	
17	14	30	02.0		No first motion (probably Derby)
17	18	01	01.2	1.7	Derby
17	19	21	16.6	1.5	
18	01	09	47.3	1.7	
18	09	57	51.6	1.5	
18	11	38	52.0	2.4	
22	03	51	35.2	1.5	
23	10	00	02.5	1.7	
23	14	05	56.7	1.5	

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1965		
Feb. 24	06	28	02.3	2.1	
Mar. 6	08	27	25.6	1.2	
8	18	01	41.6	1.1	N. 21°E.
20	00	25	43.9	1.6	
25	20	23	55.7	3.1	Derby. North-south component 48.2 east-west component 97.1
25	20	26	59.5	2.5	
25	20	33	09.5	1.85	
25	20	33	57.6	1.4	Derby(?) N.37° E.
25	20	55	11.2	1.5	
25	21	00	08.6	1.6	
25	21	00	47.0	1.2	
Apr. 8	00	29	50.0	2.0	
9	05	31	21.7	1.8	
12	23	32	35.3	2.4	
13	00	12	41.8	1.8	
13	01	03	29.0	1.7	Derby(?)
13	01	08	0.03	1.7	
13	10	22	41.4	1.9	
13	12	23	40.3	1.9	
13	15	32	44.7	2.4	
16	04	01	40.2	1.0	
16	17	24	48.1	3.4	
16	18	49	32.3	1.0	
17	07	30	33.0	1.8	
17	22	55	39.5	1.7	
20	08	45	05.9	1.3	N. 45° E.
21	19	21	35.0	2.0	
23	08	42	24.0	2.4	
23	13	24	42.2	1.7	
23	22	28	14.8	2.4	
26	23	18	17.5	1.5	
27	01	25	26.3	1.8	
29	06	17	36.7	1.7	
May 4	02	41	39.8	1.6	
5	19	27	19.8	1.8	Derby(?)
5	20	38	03.8	1.1	Derby(?)
6	12	01	05.7	1.1	N. 95° E.
7	09	01	27.1	1.4	Derby(?);no east-west component
11	06	27	01.4	1.5	
11	07	11	52.4	1.6	
11	13	00	24.2	1.4	

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1965		
May 12	18	49	02.1	1.7	
13	01	40	09.8	1.8	
18	23	47	56.0	2.8	
19	15	13	25.7	2.0	
20	00	10	13.8	1.5	
20	09	19	46.2	2.3	
20	09	27	26.3	2.4	N. 47° E.
20	10	42	53.3	2.2	
22	00	27	01.0	1.7	N. 53° E.
25	01	56	49.8	2.0	
June 3	22	01	23.8	1.5	N. 51° E.
5	21	39	24.7	1.5	N. 61° E.
12	04	22	19.5	1.6	
14	00	47	07.7	1.7	N. 23° E.
14	06	40	46.2	2.0	
14	08	36	48.8	1.5	
14	08	42	40.7	2.1	
14	09	24	43.9	3.1	
14	09	33	08.5	2.1	
14	10	14	43.6	2.0	
14	10	50	43.6	2.0	
14	12	01	14.3	2.2	
14	12	29	36.3	1.8	
14	12	44	22.3	1.7	
14	13	01	31.4	1.9	
14	13	06	08.6	1.7	
14	14	03	44.9	1.7	
14	14	52	10.0		
14	15	01	56.9	1.6	
14	15	02	47.9	1.9	
14	15	43	14.5	1.7	
14	17	15	49.3	2.1	
14	17	25	33.3	1.5	
14	21	29	04.1	1.8	
14	23	32	09.7	1.9	
14	23	40	48.0	1.8	
15	00	27	16.5	1.8	
15	00	43	20.9	1.6	
15	06	11	31.9	2.7	
15	09	52	20.8	2.1	
15	10	07	29.5	1.4	
15	12	01	37.2	1.4	N. 33° E.

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1965		
June 16	01	50	31.3	1.5	
19	23	35	20.4	1.6	N. 58° E.
24	06	48	47.3	1.8	N. 36° E.?
25	00	10	49.6	1.4	N. 45° E.
25	17	50	45.5	1.5	N. 45° E.
25	23	30	50.9	1.5	N. 61° E.
27	00	01	48.3	1.8	N. 67° E.-Derby
29	09	50	32.4	2.2	
29	10	01	47.5	1.6	
29	10	06	42.7	1.6	
29	12	51	12.9	2.2	
29	13	14	49.5	2.8	
29	13	27	40.6	1.7	
29	14	59	47.2	2.2	
29	15	30	03.9	1.8	
29	16	21	34.0	1.5	
29	18	05	37.8	1.6	N. 45° E.
30	15	42	58.8	2.3	
30	15	47	16.6	1.8	
30	16	23	45.1	1.8	
30	20	20	19.4	2.0	
July 4	01	59	48.7	1.6	N. 40° E.
5	07	42	29.2	1.6	N. 63° E.
5	07	55	05.6	1.7	
6	13	34	46.7	1.7	
6	13	27	59.6	1.9	
6	14	05	42.5	1.7	
6	15	55	07.7	1.5	
7	00	46	42.5	1.5	N. 51° E.
7	02	01	32.1	1.3	N. 45° E.
7	17	36	48.1	1.9	N. 50° E.
7	23	38	51.7	1.7	N. 61° E.
9	18	21	4.7	1.5	N. 62° E.
10	05	45	04.5	1.4	N. 57° E.
12	08	03	58.2	1.6	
12	08	23	12.5	1.7	N. 65° E.
15	04	47	28.4	1.4	N. 59° E.
17	00	07	28.7	1.7	
17	02	41	28.8	2.0	N. 59° E.
17	03	38	52.2	1.3	
17	05	47	06.0	1.5	
17	05	56	13.1	2.4	
17	06	54	33.7	1.3	
17	08	29	20.6	1.6	

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1965		
July 17	14	01	37.4	1.7	
17	20	22	59.1	1.4	
17	21	06	07.4	1.8	
17	21	46	23.2	1.6	
17	22	36	27.0	1.9	
17	23	06	36.6	1.7	
17	23	14	21.2	2.1	
17	23	56	40.7	2.2	
18	01	52	40.0	1.4	
18	03	09	39.4	1.9	
18	05	15	25.0	1.5	
18	10	21	09.3	1.0	
18	10	23	20.1	1.3	
18	21	07	28.0	2.9	
18	21	13	27.4	3.0	
18	21	20	40.0	2.3	
18	21	39	42.4	1.5	
18	21	40	53.4	3.1	
18	21	48	05.4	2.9	
18	21	53	16.7	1.8	
18	23	52	32.4	1.7	
18	23	45	14.5	1.5	
19	02	09	17.5	1.7	
19	03	48	00.3	1.6	
19	06	41	20.2	1.2	
19	10	19	23.0	2.2	
19	10	41	20.8	1.4	
19	13	21	31.1	1.2	
19	14	59	13.2	1.4	
19	21	49	22.5	1.4	
20	03	27	59.5	1.7	
20	07	04	46.5	1.4	
20	08	04	43.6	1.4	
20	15	51	31.4	2.4	
20	17	46	19.0	1.7	
20	17	56	38.1	2.9	
20	18	18	29.9	2.6	
20	19	22	27.6	1.8	
20	21	14	10.3	2.3	
20	21	23	45.5	1.8	
20	21	38	06.5	1.3	
20	22	07	24.7	1.3	
21	06	48	48.5	1.7	

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1965		
July 21	06	53	53.6	2.0	
21	06	55	50.6	1.5	
23	03	35	41.8	1.8	
26	07	25	21.5	1.8	N. 69° E.
26	16	39	16.7	1.5	
30	01	16	26.5	1.9	
30	01	21	46.0	1.3	
30	01	25	50.3	1.5	
30	01	26	24.4	2.0	
30	01	35	45.9	1.8	
Aug. 4	08	51	10.0	2.1	
4	09	07	03.6	1.8	
5	18	28	39.0	1.6	
7	11	55	33.0	2.2	
7	20	33	16.0	1.4	N. 58° E.
8	11	53	47.4	1.6	
12	18	24	36.3	2.4	N. 35° E.
12	23	56	03.5	2.1	
12	23	58	00.4	2.0	
12	23	59	11.5	1.9	
12	23	59	54.4	2.0	
13	03	43	08.6	1.4	
13	07	45	03.2	2.1	
13	07	50	33.4	1.4	
13	08	08	22.7	1.8	
13	08	24	01.0	1.7	
13	12	10	17.2	1.3	
10	23	19	41.0	2.3	
10	23	25	11.6	1.7	
11	07	56	11.6	1.6	
11	13	04	39.2	1.6	
11	18	22	04.9	1.8	
9	15	38	39.5	3.0	
9	21	58	36.8	1.5	
9	22	00	21.4	2.8	
9	22	02	25.9	1.8	
9	22	57	28.1	1.8	
9	23	17	39.4	2.0	
9	23	18	20.2	3.0	
9	23	21	35.1	2.4	
10	03	44	23.7	2.6	
10	04	02	22.8	2.8	
10	05	12	06.0	2.5	
10	22	33	50.0	1.8	
10	21	09	56.9	1.6	

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1965		
Aug. 14	22	52	18.4	2.9	
14	23	15	42.4	1.5	
17	05	45	15.3	1.7	
17	06	57	15.0	1.4	
20	13	40	38.2	1.4	
22	12	17	45.7	1.7	
22	12	18	45.2	1.5	
22	18	16	17.2	2.8	
23	02	25	34.0	1.6	
23	04	09	34.0	1.6	
23	07	14	29.1	1.5	
24	02	51	36.1	1.5	
26	02	41	43.7	1.8	
27	15	08	19.1	1.4	
27	20	15	40.0	1.8	
27	20	32	10.5	2.6	
27	20	43	53.2	1.7	
27	21	02	39.6	1.7	No north-south component.
30	23	46	59.2	1.5	
Sept. 2	19	11	15.5	2.6	
1	05	00	42.3	1.5	
1	17	10	56.6	2.0	
1	18	01	01.2	1.9	
5	07	15	31.4	1.0	
9	23	50	24.5	1.5	
10	08	17	07.7	1.4	
10	14	39	57.5	1.4	
10	15	51	25.9	1.4	
11	15	42	38.7	1.7	
11	20	02	30.5	1.6	N. 22° E.
12	11	49	32.2	1.8	
13	09	58	26.3	3.8	
13	10	14	57.3	1.8	
13	10	43	42.0	2.0	
13	11	03	24.5		
13	11	28	01.5	1.5	
13	11	29	21.6	1.4	
13	11	52	24.1	2.0	
13	11	54	38.0	1.8	
13	18	21	43.4	2.3	
13	21	25	20.0	1.4	
13	21	39	20.5	1.4	
13	22	47	08.0	2.4	
14	00	24	57.2	1.5	
14	04	32	22.2	1.6	

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1965		
Sept. 14	04	45	02.0		
14	05	08	10.3	1.5	
14	06	05	26.0	1.5	
14	09	08	07.6	1.4	
14	11	42	53.7	2.1	
14	16	36	55.1	2.8	
14	16	47	18.7	1.5	
14	18	47	16.4	1.0	
14	20	52	21.7	1.9	
14	21	00	05.5		
14	22	10	29.5	1.7	
14	22	12	12.3	1.7	
14	22	46	33.2	4.1	
14	23	31	17.0		
15	00	01	29.7	1.7	
15	00	14	13.4	1.4	
15	00	27	12.1	2.2	
15	00	28	53.2	1.8	
15	00	34	26.3	1.6	
15	01	02	55.7	2.0	
15	01	33	28.2	1.6	
15	01	39	17.4	1.5	
15	01	43	45.8	1.7	
15	03	22	30.4	1.2	
15	03	35	42.3	1.2	
15	03	39	14.9	1.4	
15	03	42	22.5	1.6	
15	09	59	38.0	1.2	
15	18	05	01.2	1.8	
15	18	29	01.4	1.8	
15	19	05	50.0	1.5	
15	19	07	21.7	2.3	
15	19	02	47	1.5	
15	22	09	10.6	1.4	
16	07	08	56.5	1.4	
16	08	39	17.0	1.2	
16	22	50	14.3	1.5	
21	15	13	05.6	1.4	
21	15	14	29.0	1.4	
22	00	01	33.6	1.4	N. 41° E.
22	07	36	05.3	1.7	N. 63° E.
23	20	01	05.7	1.2	
24	13	14	30.5	1.7	
27	02	01	16.3	1.6	
27	10	34	16.0	3.1	
27	15	05	06.0	1.7	

Date	Time (GCT) h	m	s	Magnitude	Remarks
		1965			
Sept. 27	15	49	11.5	1.4	
27	21	03	49.0	1.6	
27	23	40	19.9	1.2	
28	11	51	16.9	1.4	
28	22	49	17.6	1.4	N. 52° E.
29	18	28	53.0	1.8	
29	18	31	56.1	1.9	
29	18	58	17.8	1.5	
29	18	59	51.2	1.4	
29	19	00	01.7	4.1	
29	19	17	09.4	1.7	
29	19	20	50.4	2.0	
29	19	32	55.7	2.4	
29	19	41	44.4	1.4	
29	19	47	08.4	1.4	
29	19	55	34.9	1.5	
29	20	07	36.0	2.4	
29	23	23	06.6	2.8	
30	17	30	33.0	1.5	
Oct. 1	02	26	14.1	1.7	
1	05	30	58.6	1.8	
1	16	21	57.6	1.6	
4	11	51	8.7	1.8	N. 61° E.
10	13	45	49.5	1.8	N. 43° E.
10	17	20	46.3	1.7	N. 54° E.
11	05	16	40.0	1.6	
11	06	49	44.7	1.4	
11	07	02	07.0	1.7	N. 64° E.
11	20	23	16.3	1.9	N. 68° E.
12	07	44	42.3	1.8	N. 62° E.
12	21	22	38.6	1.4	N. 58° E.
12	22	08	58.1	1.4	N. 38° E.
17	02	47	41.4	1.8	
24	08	04	45.0	1.9	N. 56° E.
25	06	23	28.2	1.4	N. 44° E.
29	02	18	35.4	1.7	N. 57° E.
31	06	47	57.4	1.7	N. 58° E.
31	16	00	57.8	1.6	N. 62° E.

Table 1 --Continued

Date	Time (GCT) h	m	s	Magnitude	Remarks
			1965		
Nov. 3	07	38	32.5	1.6	N.58°E.
3	07	56	54.5	2.0	N.64°E.
3	16	12	49.6	1.2	N.51°E.
6	09	25	14.2	2.5	N.65°E.
10	19	24	14.5	1.5	N.58°E.
12	20	32	47.3	1.8	N.50°E.
14	16	45	20.8	1.8	N.51°E.
14	16	46	37.8	1.7	N.51°E.
14	16	58	10.3	1.9	N.56°E.
14	17	16	40.0	2.3	
14	17	53	08.5	2.3	
14	18	45	23.6	2.9	
15	18	09	53.0	1.7	N.45°E.
19	03	54	38.8	1.7	N.48°E.
19	08	47	04.0	1.9	N.59°E.
21	03	59	18.8	1.7	N.48°E.
21	03	59	34.3	1.3	
21	04	00	08.0	3.5	
21	04	02	13.1	2.2	
21	04	02	38.7	4.3	
21	04	24	55.2	2.6	
21	04	28	57.1	1.7	
21	04	29	32.3	1.3	
21	04	36	31.8	1.7	
21	04	36	59.6	1.9	
21	04	39	12.8	1.4	
21	04	55	56.7	1.9	
21	05	00	36.3	3.8	
21	08	52	16.8	1.9	
21	11	46	51.3	1.9	
21	13	07	39.8	1.9	
21	14	48	35.9	3.0	
22	06	34	14.4	2.2	
22	19	06	16.8	2.0	
23	04	26	22.6	1.9	
24	13	37	21.0	2.0	
24	13	31	46.6	2.6	
26	07	03	11.1	1.9	
27	23	26	10.5	1.7	N.45°E.
28	20	59	11.3	1.9	
30	21	30	47.7	2.2	

Table 1.--Continued

Date		Time (GCT) h	m	s	Magnitude	Remarks
					1965	
Dec.	1	20	00	53.2	1.5	
	11	19	21	24.6	1.7	
	14	21	47	46.4	1.7	
	14	22	57	15.0	1.5	
	15	06	18	43.0	1.5	
	15	08	42	21.0	1.6	
	15	10	56	40.4	1.4	
	18	07	38	38.8	1.6	
					1966	
Jan.	1	00	13	49.8	2.3	
	5	00	37	26.4	3.5	5.0 (C&GS)
	5	22	33	17.0	1.0?	
	7	20	45	21.4	1.1	
	8	21	20	42.5	1.8	
	10	19	42	52.2	1.4	
	13	10	01	06.6	1.0	Lower limit
	14	07	41	40.4	1.1	
	18	06	03	00.4	1.0?	
	21	23	30	34.4	1.4	
	25	21	45	33.8	1.8	
	25	22	17	33.7	1.7	
	25	23	22	03.4	1.8	
	25	23	44	43.8	2.1	Western Derby?
	27	18	18	06.0	1.2	
	28	00	03	39.0	1.2?	
	28	03	09	48.3	1.2?	
	28	15	58	28.5	1.6	
	31	11	31	37.2	1.7	
Total	19 events					
Feb.	2	20	04	28.3	1.5	
	2	23	47	19.8	1.4	
	2	23	48	15.0	2.3	Deep?
	9	12	49	03.5	1.2	
	9	12	50	01.6	1.1	
	12	21	43	31.8	1.0	
	13	02	59	46.8	1.1	
	21	20	09	42.7	0.9	
	22	04	30	27.3	1.8	
	22	22	17	43.8	1.3	
Total	10 events					

Part 4

PETROGRAPHY OF THE PRECAMBRIAN ROCKS FROM THE DEEP DISPOSAL WELL, ROCKY MOUNTAIN ARSENAL, ADAMS COUNTY, COLORADO

By Douglas M. Sheridan, Chester T. Wrucke, and Ray E. Wilcox

INTRODUCTION

This report summarizes the results of a study of the core and cuttings of rocks of Precambrian age recovered from the deep disposal well at the Rocky Mountain Arsenal, Adams County, Colorado. Material available for this study included core of part of the Precambrian gneiss, drill cuttings of the Cambrian or Ordovician rocks, and drill cuttings of the Precambrian rocks not included in the core. The intervals from which these materials were obtained are indicated on figure 1. A total of 6.7 feet of core was recovered from the 9-foot interval cored. Of the amount originally recovered, only about 2 feet of core was available for this study.

This study shows that the Precambrian rock consists of migmatitic gneiss on which a regolith probably developed before deposition of the overlying Paleozoic rocks, and that crossing the gneiss are open fractures as well as veinlets and microbreccias. The veinlets and microbreccias resemble features in and near breccia-reef faults that are known to transect Precambrian rocks in the Front Range. Rocks of Precambrian age in the well occur from about 11,935 feet below the surface to the bottom of the well at 12,045 feet, an interval of 110 feet. Scopel (1964, p. 40) reported the boundary between Paleozoic and Precambrian rocks to be at a depth of 11,950 feet, but interpretation of material studied for this report indicates a slightly higher position for the contact at 11,935 feet. A revised section of the Precambrian rocks in the well is summarized in figure 1.

A brief petrographic study of the Precambrian core was made by R. B. Taylor (written communications, Oct. 10, 1961, and March 11, 1963) of the Geological Survey shortly after the completion of the drilling. Four thin sections of the core made at that time augmented the six thin sections cut for the present study. Part of the core was used at that time also for radiometric determination of the age of the rock, reported by Hedge and Walthall (1963, Spec. No. 38) as 1,350 million Rb/Sr years.

X-ray diffractometer patterns of several specimens were made for the present study by A. J. Gude.

MEGASCOPIC FEATURES

Core

The drill core (fig. 2), about 3 1/2 inches in diameter, has the banded appearance typical of many exposures of migmatitic metamorphic rocks in the Front Range. It consists of fine- to medium-grained gneiss, banded in shades of medium to dark gray and crossed by numerous irregular veins and lenses of reddish-stained pegmatite. Most of the pegmatite masses parallel the gneissic bands and therefore accentuate the layered nature of the rock. The gneissic layers, commonly 2 mm to 10 cm thick, result from variations in the amounts of mafic minerals. These layers are oriented at angles of 60°-70° to the core axis, suggesting a dip of 20°-30°. Pegmatite layers commonly are less than 2 cm thick, but a mass 12 cm thick occurs in one piece of core not illustrated.

Fractures cut the core samples, most of them parallel to the core axis (fig. 2) indicating a vertical or nearly vertical attitude. One dips as low as 20°. Some of the fractures are open (fig. 3, 4) and others are filled with vein minerals.

Sample	Depth (feet)	Description
		Sedimentary rocks of Cambrian or Ordovician age.
	11,935	Unconformity.
Cuttings - 11,935 to 11,976		Regolith: weathered gneiss consisting principally of bright green illite, hematite-encrusted biotite, quartz, and feldspar.
	11,970	Migmatitic gneiss: gray hornblendic biotite-quartz-feldspar rock, containing steeply dipping open fractures and thin calcite- and ankerite-filled veinlets and microbreccias.
Core - 11,976 to 11,985 (6.7 ft recovered)		
Cuttings - 11,985 to 12,045		
	12,045	Bottom of well.

Figure 1.--Log of the Precambrian portion of the well.

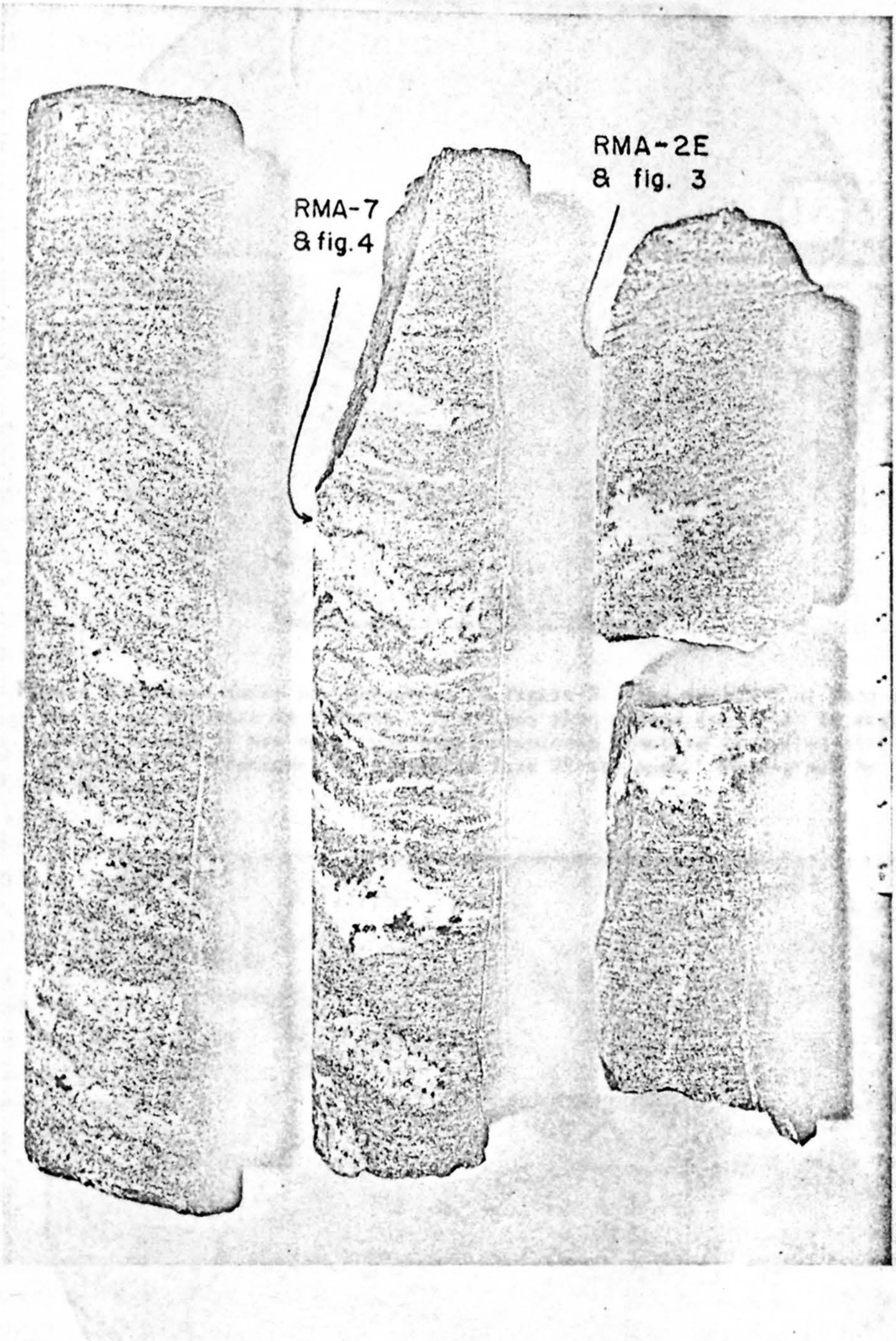


Figure 2.--Core of migmatitic gneiss showing location of two of the samples studied petrographically (RMA-2E and RMA-7) and positions of sawed faces illustrated in other figures. Note fractures parallel to core axis. Scale is marked in inches. Photograph by R. B. Taylor.

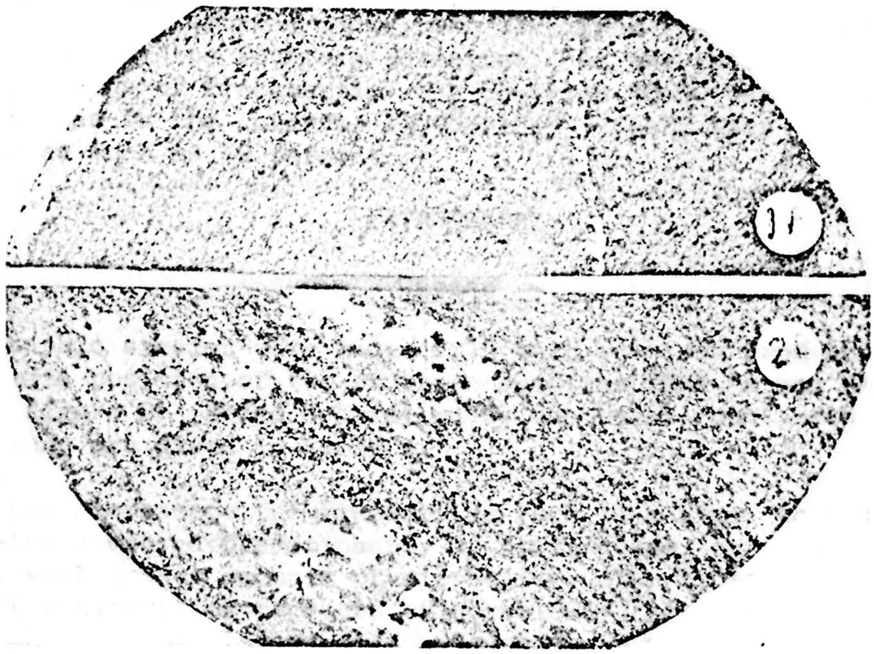


Figure 3.--Sawed faces of core shown in figure 2. The location of face 1F, above, in the core is unknown. Fractures that extend from left to right partly across 1F are open; the other prominent fracture is filled with prehnite(?). Prominent fractures on face 2E are open. Photograph by W. N. Sharp.

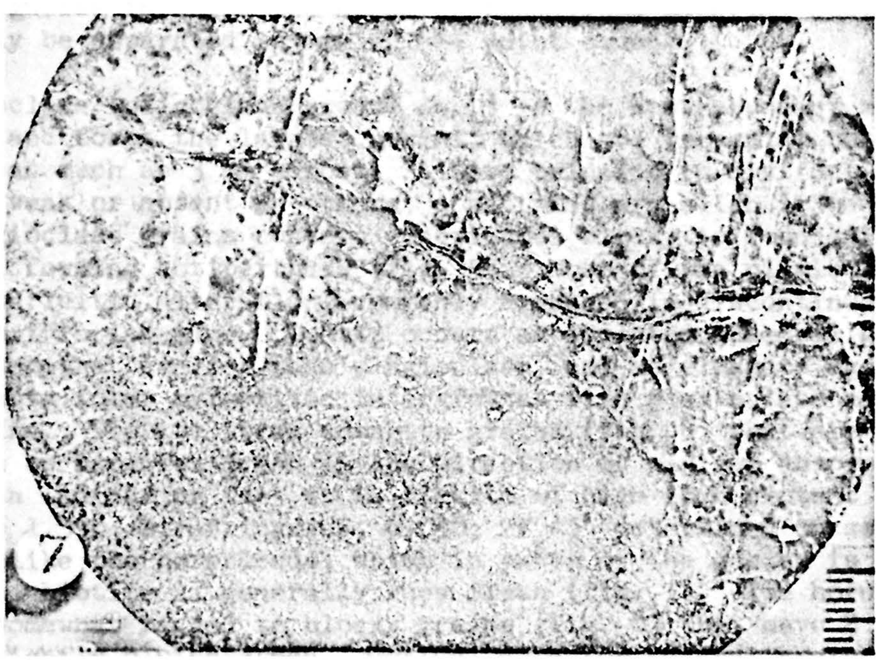


Figure 4.--Sawed face across core shown in figure 2. Thin vein that extends from left to right contains calcite, ankerite, prehnite(?), and illite(?). (See fig. 10). Some of the fractures approximately normal to the vein are open, others contain carbonate minerals. Photograph by W. N. Sharp.

Cuttings

Cuttings were available from the intervals above and below the cored interval. They consist of angular fragments, generally 0.5-5 mm across, not only from the Precambrian rocks, but also from the overlying sedimentary strata, particularly the Fountain Formation. In the interval 11,935-11,976 feet, grains of Precambrian rock comprise 30-50 percent of the cuttings, whereas in the interval 11,985-12,045 feet, they increase in abundance to as much as 70 percent.

PETROGRAPHY

Gneiss

Petrographic studies were made of 10 thin sections from the core. The approximate position of two of these sections (RMA-2E and RMA-7) is shown in figure 2. Modes determined by the point-count method on some of the sections are given in table 1.

Under the microscope the Precambrian rock is a fine- to medium-grained gneiss composed predominantly of plagioclase, quartz, biotite, and hornblende, with lesser amounts of microcline. The biotite and hornblende (or alteration products of hornblende) together form 12-25 percent of the gneiss. Layering is well shown in one thin section by dark biotite-rich layers, 2 mm thick, separated by a lighter-colored layer, 12 mm thick. The grain size ranges from less than 0.02 mm to 3.5 mm, but the major minerals most commonly are 0.3-1 mm across. Modes 1 through 6 in table 1 are typical of gneiss that contains fresh or only slightly altered hornblende; modes 7 and 8 represent gneiss in which the hornblende is largely altered. As indicated in the table, some of the modes are of migmatitic gneiss in which the areas of pegmatitic material could not conveniently be separated in making the point counts.

Plagioclase (oligoclase around An_{25}) is the most abundant mineral in the gneiss and forms the largest grains, which are irregular to somewhat blocky and as much as 3 mm across. Albite twinning is distinct in some grains but weak or absent in others; some twins are slightly bent. Many of the plagioclase grains contain conspicuous blocky to rounded patches of microcline, forming antiperthite (fig. 5). Most of the plagioclase shows only weak sericitic alteration, commonly arranged in discontinuous bands parallel to twin lamellae. Quartz occurs as isolated anhedral grains, generally somewhat smaller than plagioclase, and as elongate aggregates. Locally quartz forms myrmekitic intergrowths with plagioclase adjacent to microcline. Biotite forms elongate grains (fig. 6) that are dark-olive-brown or brownish-green in the direction of maximum absorption. Optical data indicating that it is biotite of high iron content are: n_x=1.596 to 1.598; birefringence, 0.058; $2V_x$<5° determined on several grains. Unlike the hornblende, which in parts of the gneiss is considerably altered, the biotite is generally very fresh (fig. 7). The hornblende occurs as somewhat ragged to blocky grains (fig. 8) that have Z = deep green or slightly bluish-green. Optical data for several grains of the hornblende are: n_x=1.687 to 1.690; $2V_x$ about 25° or less, strong dispersion. The high refractive index and low optic angle suggest a hornblende rich in ferrous iron.

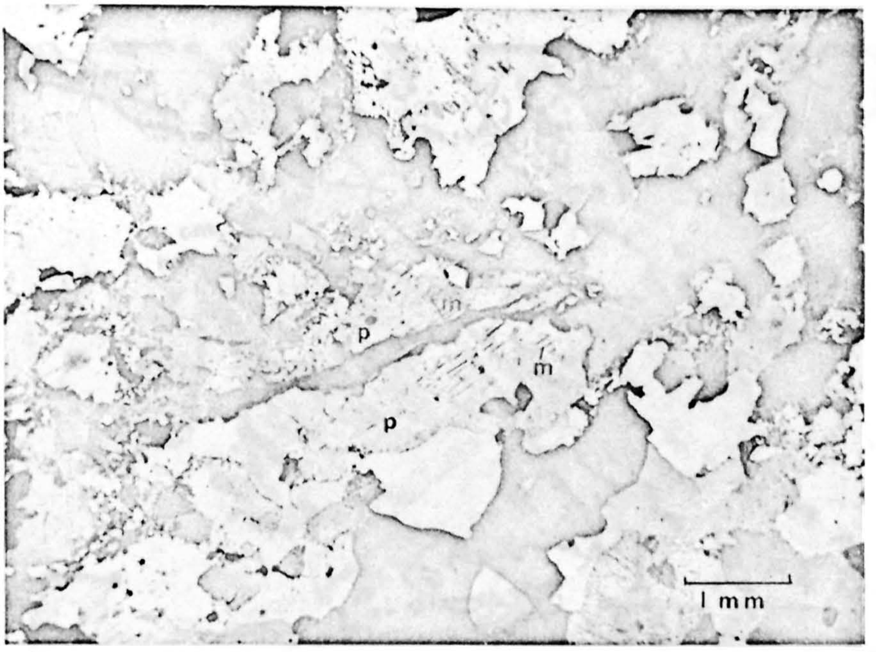


Figure 5.--Gneiss showing open fracture extending from left to right. Rounded to blocky patches of microcline (m) occur in large grains of plagioclase (p), forming antiperthite. Nicols partly crossed. Specimen RMA-4; photomicrograph by W. N. Sharp.

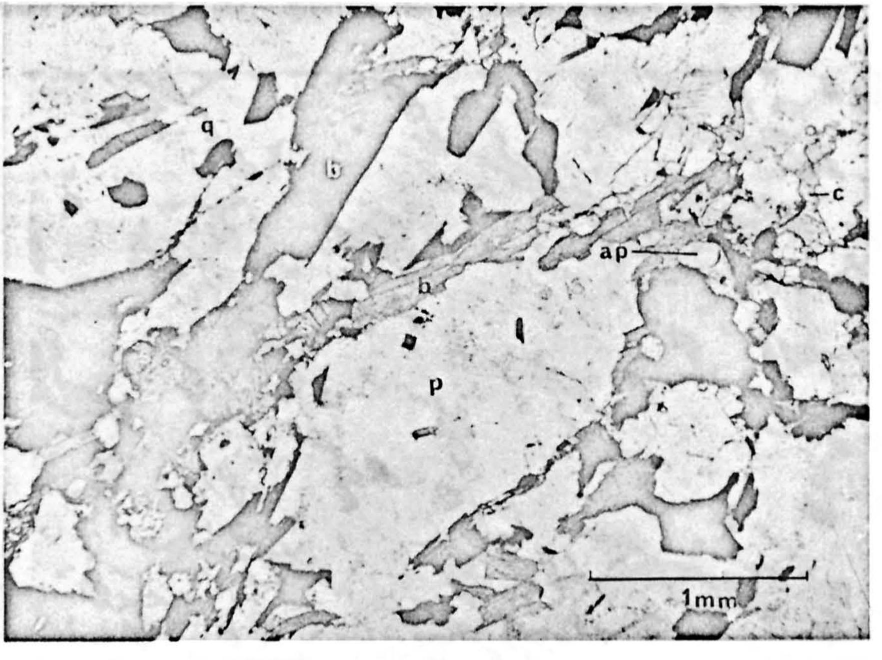


Figure 6.--Gneiss showing subparallel elongate grains of biotite (b). Other minerals are plagioclase (p), quartz (q), sphene (s), apatite (ap), and calcite (c). Plane polarized light. Specimen RMA-2E; photomicrograph by W. N. Sharp.

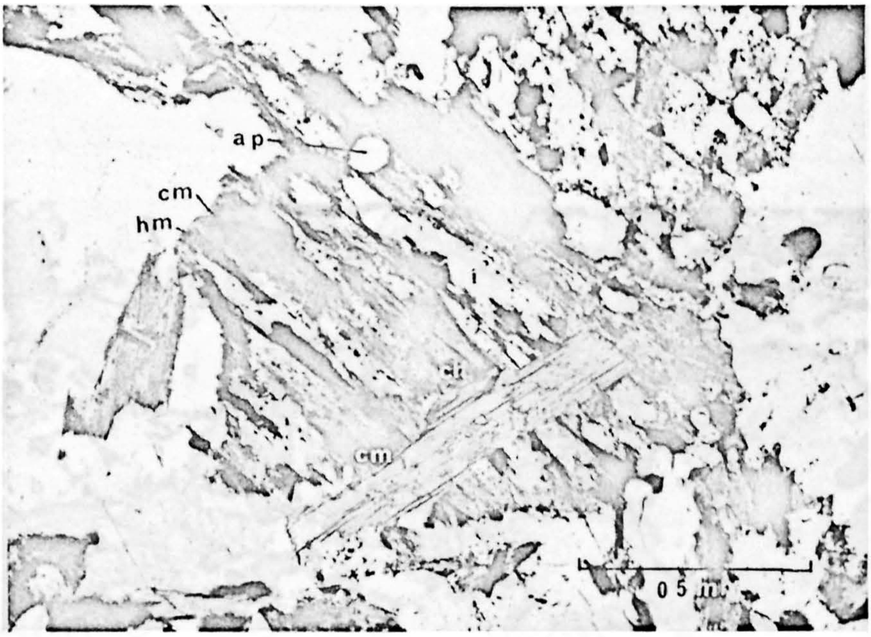


Figure 7.--Gneiss showing large blocky grain of hornblende completely altered to a complex intergrowth of illite(?) (i) and fine-grained carbonate minerals (cm) together with less abundant chlorite (ch) and hematite (hm), arranged approximately along former cleavage traces. Biotite (b) and apatite (ap) remain fresh. Plane polarized light. Specimen RMA-5; photomicrograph by W. N. Sharp.

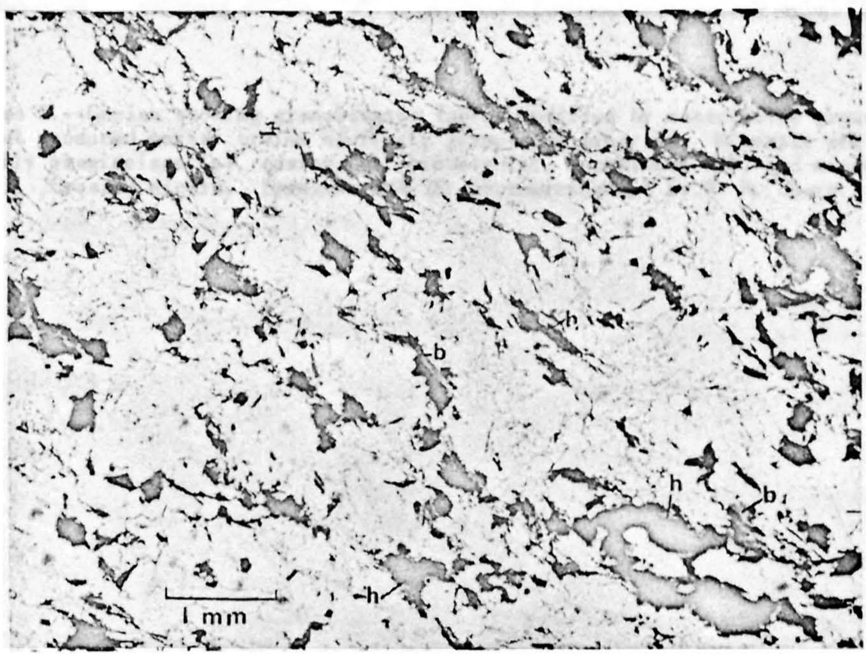


Figure 8.--Gneiss showing preferred planar orientation of biotite (b) and hornblende (h) that defines a moderately well developed foliation extending diagonally from upper left to lower right. Plane polarized light. Specimen RMA-1F; photomicrograph by W. N. Sharp.

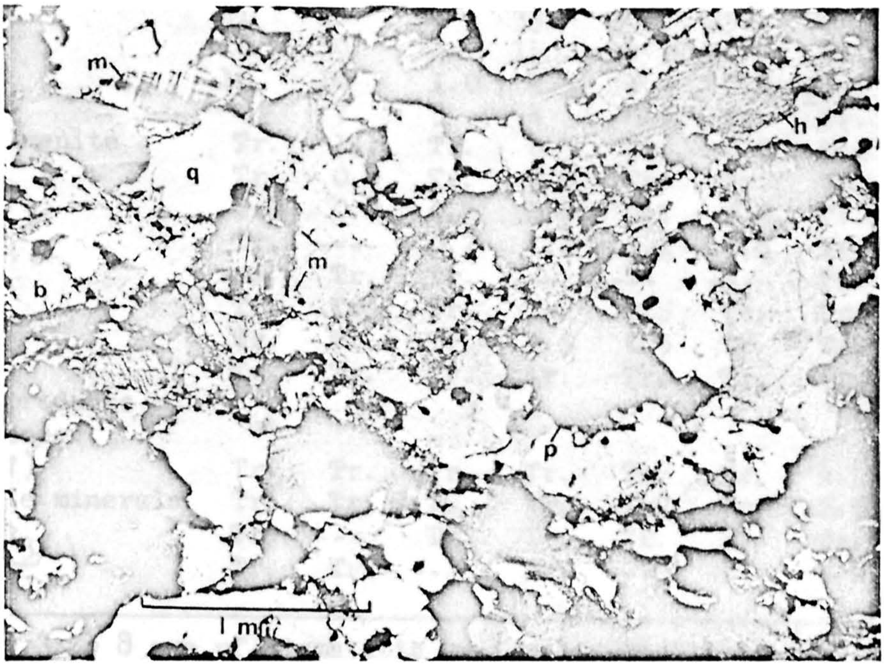


Figure 9.--Gneiss showing granoblastic fabric modified by cataclastic granulation that produced mortar trains of finely granulated minerals. Minerals are principally plagioclase (p), quartz (q), biotite (b), hornblende (h), and microcline (m). Crossed nicols. Specimen RMA-1F; photomicrograph by W. N. Sharp.

Table 1.--Modes (volume percent) of hornblendic biotite-quartz-feldspar gneiss[1/]

(Tr., trace)

Mineral	Mode 1	2	3	4	5	6	7	8
Plagioclase	42	38	40	42	51	50	52	48
Quartz	31	26	40	33	30	25	29	23
Biotite	8	9	11	15	14	20	8	15
Hornblende	10	16	1.0	2.3	1.3	0.8	2/	2/
Microcline	7	7	5	4	0.5	Tr.	Tr.	1.3
Magnetite-ilmenite	Tr.	1.1	Tr.	0.5	Tr.	0.5	0.5	Tr.
Apatite	Tr.	0.6	Tr.	0.6	Tr.	Tr.	Tr.	Tr.
Sphene	0.9	0.8	0.6	0.4	0.7	0.9	Tr.	Tr.
Calcite	Tr.	---	0.7	1.2	1.1	1.8	Tr.	0.5
Zircon	---	Tr.	Tr.	---	---	---	Tr.	Tr.
Hematite	Tr.	Tr.	Tr.	Tr.	0.5	Tr.	Tr.	Tr.
Leucoxene	Tr.	Tr.	Tr.	0.5	0.5	Tr.	Tr.	0.5
Sericite	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Alteration products of hornblende:								
Illite(?)	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	4	2.1
Carbonate minerals	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.	2.9	5
Chlorite	Tr.	---	Tr.	Tr.	Tr.	Tr.	Tr.	1.7
Hematite[3/]	Tr.	Tr.	---	Tr.	---	---	2.8	1.3

1/ Modes 3 to 8 are of migmatitic gneiss in which the areas of pegmatitic material could not conveniently be separated in making the point counts.

2/ Hornblende altered completely to alteration products indicated near bottom of table.

3/ May include some magnetite.

Mode	Specimen	Description
1.	11,988-95B	Hornblendic biotite-quartz-feldspar gneiss.
2.	RMA-1F	Ditto
3.	11,988-95A	Slightly migmatitic layered hornblendic biotite-quartz-feldspar gneiss.
4.	RMA-2E	Migmatitic hornblendic biotite-quartz-feldspar gneiss.
5.	RMA-4	Slightly migmatitic hornblendic biotite-quartz-feldspar gneiss.
6.	RMA-3A	Ditto
7.	RMA-5	Originally hornblendic biotite-quartz-feldspar gneiss in which the hornblende is completely altered.
8.	11,988-95D	Migmatitic originally hornblendic biotite-quartz-feldspar gneiss in which the hornblende is completely altered.

Of the minor minerals in the gneiss, microcline is perhaps most noteworthy. It occurs both as antiperthitic intergrowths in plagioclase (fig. 5) and as generally small grains interspersed among the more abundant minerals of the rock (fig. 9). The microcline is unaltered and generally shows well-defined grid-twinning. Sphene, apatite, and magnetite-ilmenite are common as accessory minerals whereas zircon is sparse. Irregular grains of calcite (fig. 6) form an integral part of the granoblastic fabric in several thin sections and are therefore assumed to be part of the metamorphic suite of the rock, as distinct from the carbonate in late veins.

Some thin sections show that the hornblende has been altered partly or completely to a complex intergrowth composed principally of illite(?) and fine-grained carbonate minerals together with less abundant pale-green chlorite and hematite (fig. 7). Illite(?) occurs as very fine-grained aggregates of colorless to pale-brown micaceous grains that locally are sufficiently well oriented to indicate that they are optically biaxial negative with low 2V and have a birefringence of about 0.033. An X-ray diffraction pattern of impure fine material obtained from a sample containing altered hornblende is interpreted as indicating illite or possibly sericite. Under the microscope this very fine micaceous mineral resembles the megascopically green grains from the cuttings identified by X-ray patterns with greater certainty as illite. Grains of hematite in the altered hornblende are arranged approximately along former cleavage traces. Biotite remains fresh even where hornblende is completely altered (fig. 7). Commonly the biotite contains thin platelets of hematite along the cleavage, and rarely chlorite occurs along the cleavage traces. Leucoxene forms partial to complete pseudomorphs after sphene, and together with hematite coats grains of magnetite-ilmenite.

The texture of the gneiss is predominantly granoblastic. Preferred planar orientation of biotite and hornblende is weakly to moderately well developed (fig. 8) and defines the metamorphic foliation. As shown in figure 9 the granoblastic fabric has been modified by cataclastic granulation that produced mortar trains of finely granulated minerals. The complexly interlocking borders between quartz and feldspar grains in these mortar trains and between these grains and the larger adjacent grains of relatively undeformed minerals suggest that considerable recrystallization occurred during cataclasis.

Pegmatite

Quartzofeldspathic pegmatite forms both irregular lenses and more regular layers most of them less than 3 cm thick, in the relatively dark colored gneiss. The average grain size is about 1.5 mm but plagioclase grains are as much as 7 mm across. Large grains of plagioclase and somewhat smaller grains of quartz are the principal constituents. In one thin section both refractive indices of the plagioclase are lower than the 1.54 index of the mounting medium, suggesting a composition in the albite range. In other thin sections, however, the higher index is greater than the index of the mounting medium, suggesting a composition in the oligoclase range, as in the gneiss. Minor minerals in the pegmatite are microcline (most commonly as antiperthitic intergrowths in plagioclase), biotite, hornblende, apatite, and zircon. The pegmatite owes its pale reddish color to fine hematite that occurs along minute fractures and as disseminated dust. The pegmatite generally contains no mortar trains.

Cuttings

The Precambrian constituents in the cuttings from the interval between the core and the bottom of the well include many biotite-bearing quartzofeldspathic grains thought to be fragments of gneiss similar to that of the core. Grains of clear to milky plagioclase about 1 mm across, probably from the gneiss are abundant in cuttings from the lowest 5-foot interval. They are oligoclase, An_{15-20}, as determined from two grains by the immersion method. Present also in the cuttings from below the core are numerous fragments of clear quartz and reddish feldspar, each as much as 5 mm across, and a few grains of fresh biotite and muscovite of similar size. These fragments may have come from pegmatite bodies. Grains of bright-green material in the cuttings from below the core are considered to be a contaminant from the Precambrian interval above the core.

Numerous conspicuous pale-green to bright-green grains of illite occur in all of the cuttings from the Precambrian portion of the well. The illite was identified from X-ray diffractometer patterns of two multi-grain samples. Individual grains of the illite are soft and somewhat waxy in appearance. Other grains contain variable amounts of the greenish illite, light-colored quartz and feldspar, and small specks of hematite. Many of the illite-bearing grains contain black to reddish-brown or coppery (hematitic) biotite. Feldspar in the illite-rich grains of the cuttings appears to be more highly altered in the uppermost part of the Precambrian interval. The illite-rich grains increase in abundance upward until they comprise perhaps 50 percent of the Precambrian fragments in the interval between 11,935 and 11,970 feet.

Interpretation and correlation of petrographic data

The Precambrian rock recovered as drill core may be classified as a migmatitic hornblendic biotite-quartz-feldspar gneiss. This gneiss appears to be a variety gradational in composition between microcline gneiss and hornblende gneiss, two types of metasedimentary rock that are very common as major layers in the high-grade metamorphic terrane of the east-central Front Range. Although similar in general composition to microcline gneiss, the gneiss of the drill core is somewhat more mafic and generally contains more hornblende and less microcline than most of the specimens of microcline gneiss described by Sims and Gable (1964, p. C11) and Moench (1964, p. A22-A23). The presence of noteworthy amounts of hornblende, sphene, apatite, and metamorphic calcite suggests a gradation in composition toward that of hornblende gneiss in which such minerals are more typical.

The granoblastic texture and the foliation defined by planar orientation of biotite and hornblende are identical to textural features of metasedimentary gneisses in the east-central Front Range. In that area this fabric is interpreted to be the result of relatively early Precambrian plastic deformation involving metamorphism of interlayered aluminous pelitic sedimentary rocks to a grade generally equivalent to the sillimanite zone of regional metamorphism. The superimposed mortar trains in the rocks of the drill core produce a fabric that is similar to the fabric of rocks in those parts of the Idaho Springs-Ralston shear zone that were only moderately cataclasized (Wells and others, 1964, p. 015-016). The cataclasis characteristic of that shear zone, located about 20 miles west of Denver, is correlated with a Precambrian deformation that was more localized than the earlier regional deformation.

Cuttings from the well below the cored interval may be interpreted as gneiss similar to that in the drill core. Pegmatite bodies probably occur in the gneiss, as suggested by the mineralogic nature of some of the large grains.

The presence of illite in the gneiss and as greenish grains in the cuttings only below 11,935 feet strongly suggests that this mineral is associated only with the Precambrian rocks and not with the lower part of the overlying Cambrian or Ordovician section. For this reason, the interval 11,935-11,950 feet is thought to consist of Precambrian rock rather than Cambrian or Ordovician rock as indicated previously (Scopel, 1964, p. 40-41). Moreover, we believe that the illite formed by weathering of the Precambrian gneiss prior to deposition of the Cambrian or Ordovician strata. Hence we consider the interval 11,935 to about 11,970 feet to be a regolith of altered Precambrian gneiss. This regolith is distinct from the higher regolith described by Scopel (1964, p. 40) below the Fountain Formation.

The illite(?) in the pseudomorphs after the hornblende in the core could have formed by hydrothermal alteration, as suggested by the presence of intensely altered hornblende only in specimens crossed by microbreccia. However, plagioclase in hydrothermally altered Precambrian rocks in the Front Range is as completely altered as hornblende (Tooker, 1963, p. 9,13), whereas plagioclase in the core shows only incipient alteration unrelated to fractures. No conclusive evidence was found that would clearly indicate whether the illite(?) in the core formed by weathering or hydrothermal processes.

FRACTURES, VEINS, AND MICROBRECCIA

Description

Petrographic studies show that the gneiss is cut by open fractures and by thin veins and zones of microbreccia. The open fractures commonly are oriented parallel to the core axis. They have fairly smooth walls and show little or no displacement (fig. 5). Some of the veins formed along simple fractures; others were deposited in sinuous fractures (figs. 4, 10) that contain a few angular fragments of the host rock. The microbreccia occurs in single fractures and in zones of branching and intersecting subparallel fractures (figs. 11, 12), each choked with abundant angular wallrock fragments, mostly quartz and feldspar, cemented by vein minerals.

The principal vein minerals are calcite and ankerite. Other vein minerals are prehnite(?), illite(?), and hematite. Identification of the carbonate minerals is based on X-ray examination of material from the sinuous vein illustrated in figures 4 and 10. Although the X-ray analysis showed that ankerite and calcite occur in approximately equal amounts, the

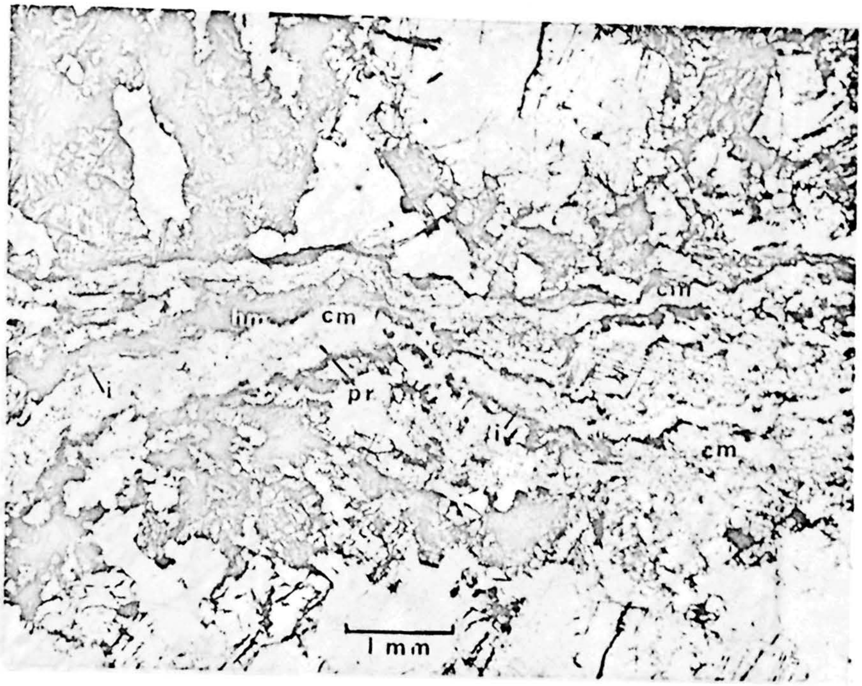


Figure 10.--Thin sinuous vein cutting gneiss. Bands of carbonate minerals (cm), illite(?) (i), hematite (hm), and prehnite(?) (pr) are parallel to vein walls. Plane polarized light. Specimen RMA-7; photomicrograph by W. N. Sharp.

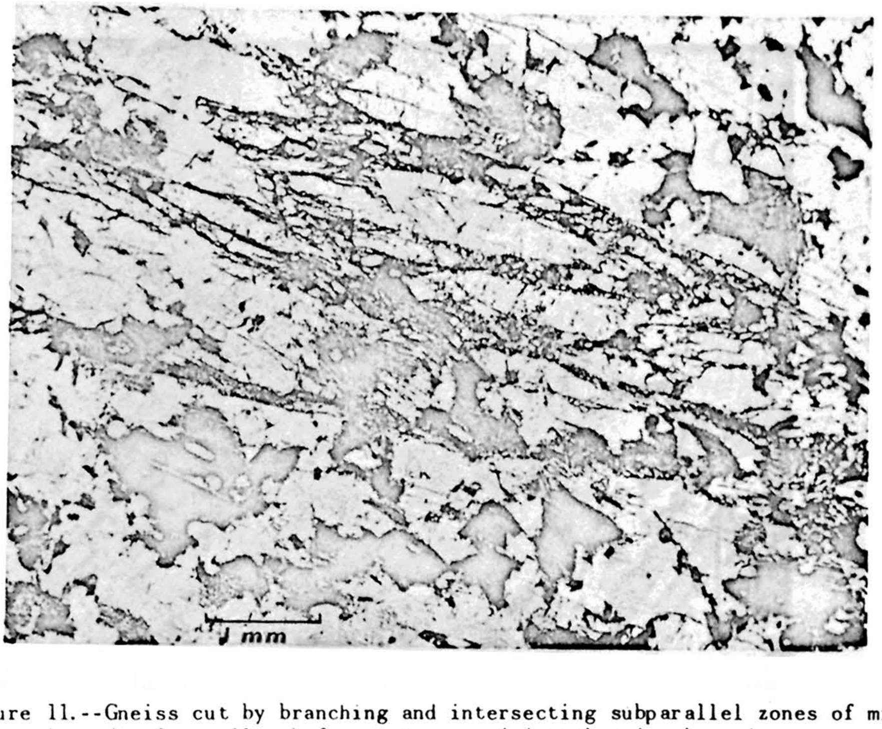
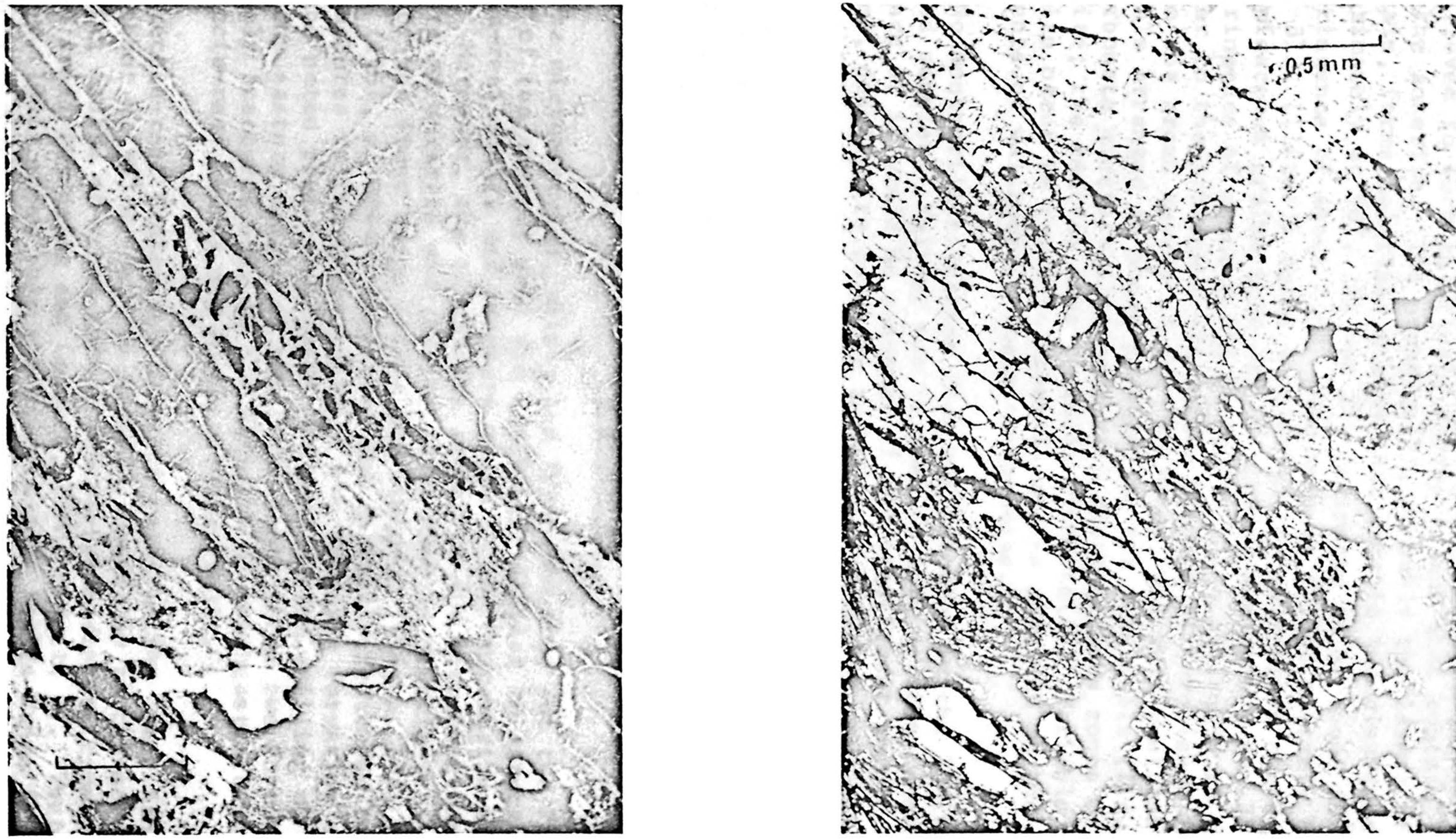


Figure 11.--Gneiss cut by branching and intersecting subparallel zones of microbreccia. Angular wallrock fragments comprising the microbreccia are cemented by carbonate minerals, illite(?), and hematite. Plane polarized light. Specimen RMA-5; photomicrograph by W. N. Sharp.



A B

Figure 12.--Microbreccia in fractures cutting gneiss. Angular wallrock fragments comprising the microbreccia are cemented by carbonate minerals, illite(?), and hematite. A, reflected light; B, nicols partly crossed. Specimen 11,988-95D; photomicrographs by R. B. Taylor.

distinction between the two is difficult in thin section. The calcite is believed to form relatively coarse grains that contain less hematite than the ankerite. The prehnite(?), probably the latest of the vein minerals, forms colorless grains that contain two cleavages intersecting approximately at 90°. It has $2V_Z$ estimated to be about 40° and a birefringence of about 0.03. One vein is filled entirely by prehnite(?) (fig. 3). Illite(?) forms a colorless to pale-brown aggregate of very fine micaceous grains that are biaxial(-) and have a low 2V and a birefringence of about 0.030 to 0.035. This illite(?) is thus optically similar to the prominent alteration product of hornblende in the gneiss and to the green masses of the cuttings. One vein contains all these minerals arranged in bands parallel to the vein walls (fig. 10). Bands of carbonate minerals alternate with discontinuous zones of illite(?) and hematite; the central zone contains prehnite(?). Variable amounts of hematite occur in the vein minerals and as coatings on the angular fragments of wallrock in the microbreccias.

No montmorillonite-type clay was detected in the limited number of X-rayed samples. Neither was it seen in thin section, where some evidence of it would be expected if any significant amount had been present, despite its tendency to be removed during grinding of the thin section in water.

In most thin sections that contain veins and abundant microbreccia, the hornblende of the host gneiss is partly to completely altered. In contrast, those thin sections that show only open fractures or no fractures contain fresh or only slightly altered hornblende.

Discussion

The microbreccias, veins, and fractures that cut the Precambrian gneiss of the Arsenal well are strikingly similar to structures in the breccia-reef faults and fracture zones in the Precambrian of the Front Range. Moreover, the calcareous cement in the microbreccias and veins consists of ankerite and calcite as it does in breccia-reef faults in parts of the Front Range (Adams and Stugard, 1956, p. 194, 199). Scopel (1964, p. 39-40) described the intensely fractured Lyons Formation and fractures in the upper third of the Fountain Formation cored in the well and noted that circulation was lost during drilling of these formations. Along the eastern margin of the Front Range these two formations are intensely fractured only in the vicinity of southeastward continuations of breccia-reef faults and along related faults.

Breccia-reef faults and fracture zones in the Front Range commonly trend about N. 30° W. and dip steeply, generally to the northeast, but branching faults of other trends and variable dip are common in complexly faulted areas (Lovering and Goddard, 1950, pls. 1, 2). Tweto and Sims (1963, p. 1001) noted that the breccia-reef faults range from single fractures through complex fault zones to broad granulated zones; they also gave evidence indicating that these faults were first active in Precambrian time but that complex movements occurred again during the Laramide orogeny. Open spaces are today abundant in veins that occur along breccia-reef faults (Sims and Sheridan, 1964, p. 24).

The similarity between many features of the microbreccias in the gneiss at the Arsenal well and the breccia reefs seems clear. This similarity and the presence of fractures in the Lyons Formation and in part of the Fountain Formation suggest that a fracture zone may occur in the general vicinity of the well at the Rocky Mountain Arsenal.

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Part 5

MICROSEISMICITY STUDIES AT THE SITE OF THE DENVER EARTHQUAKES

by

J. H. Healy, W. H. Jackson, and J. R. Van Schaack

A series of minor earthquakes occurred in the Denver area in the vicinity of Commerce City (Derby) beginning in 1962 and continues to the present time. These earthquakes were recorded by a seismograph station at Regis College and by a newly established station at Bergen Park, Colorado, operated by the Colorado School of Mines. These two earlier seismograph stations were augmented by additional temporary stations established by the U. S. Geological Survey during the middle of 1962. These additional stations provided the information necessary to obtain fairly accurate locations of the earthquakes. A list of the times and the magnitudes of the earthquakes as recorded at the Colorado School of Mines station are presented by Major elsewhere in this report (table 1).

In 1962 a 12,045-ft. disposal well was completed at the Rocky Mountain Arsenal. This well was drilled to dispose of contaminated waste developed in manufacturing processes at the arsenal. Water was pumped into this well beginning in March 1962, and continued intermittently until the present time. In November 1965, David Evans, a local consulting geologist, proposed that there was a relationship between injection of water in this disposal well and the occurrence of the Denver earthquakes. Evans' hypothesis was based on a correlation in time between the rate of earthquake occurrence and the rate of injection of water in the well. Figure 1, taken from a paper by Evans (1966), shows a plot of the number of earthquakes occurring per month between 1962 and 1965 and the number of gallons of water injected in the disposal well during this same period. A second correlation referred to by Evans was the correlation in space between the location of the earthquakes and the Rocky Mountain Arsenal well. The earthquake locations are based on the results of a thesis by Wang (1965) at the Colorado School of Mines which gave the location of the quakes as shown in figures 2 and 3.

In December 1965, the U. S. Geological Survey initiated studies that would help to determine the relationship, if any, between the disposal of contaminated water in the arsenal well and the location and frequency of earthquakes.

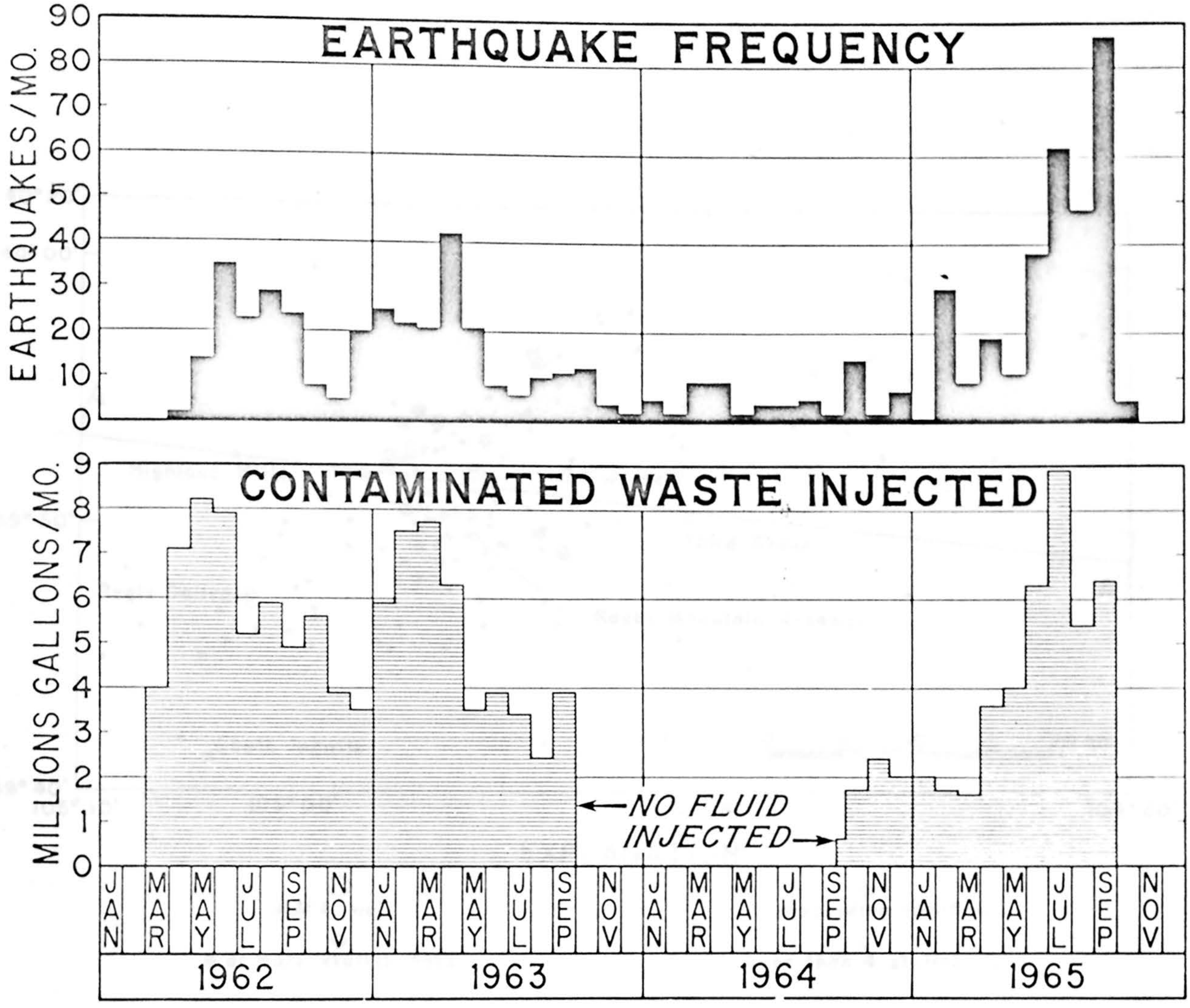


Figure 1 -- Histograms showing relation between earthquake frequency and volume of waste injected into the Arsenal disposal well. Upper half: number of earthquakes per month recorded in the Denver area. Lower half: monthly volume of contaminated waste water injected into the Arsenal well. Reprinted from Evans (1966).

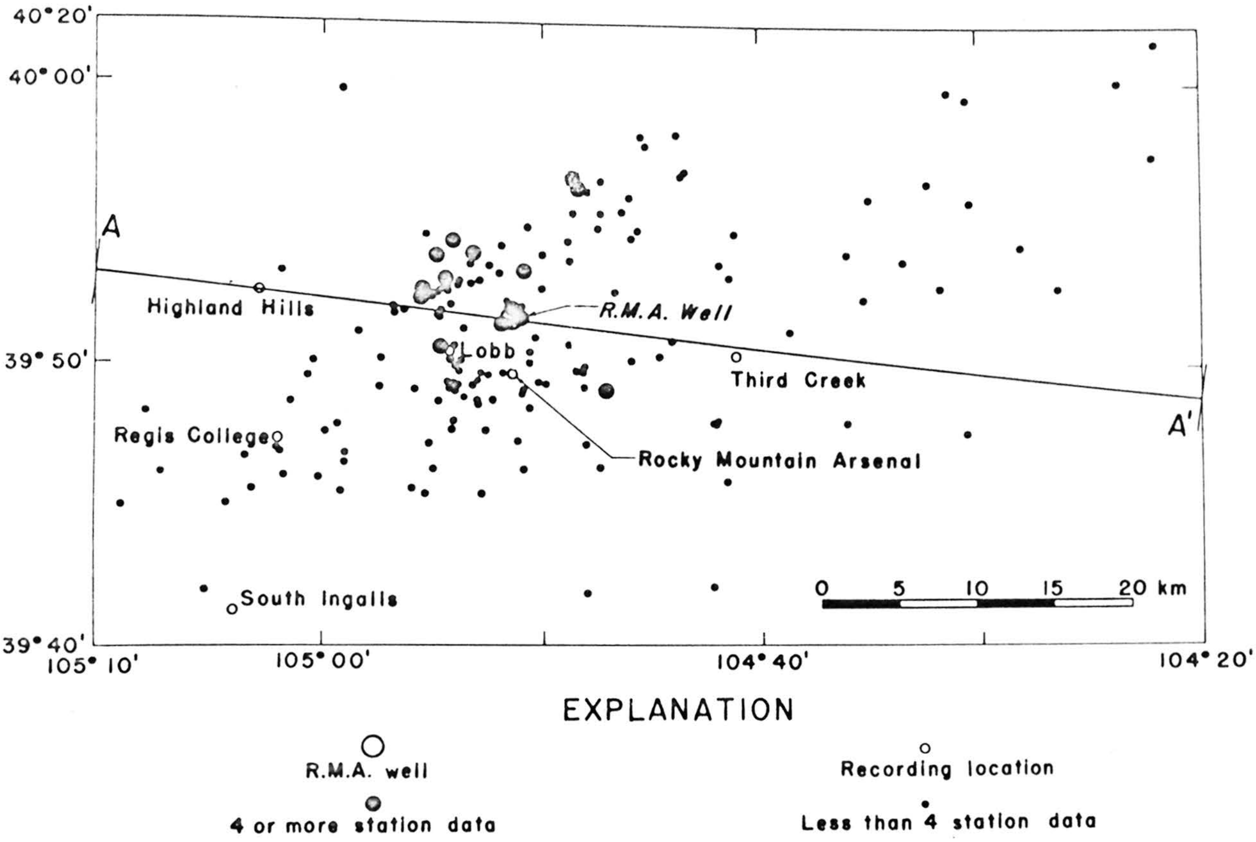
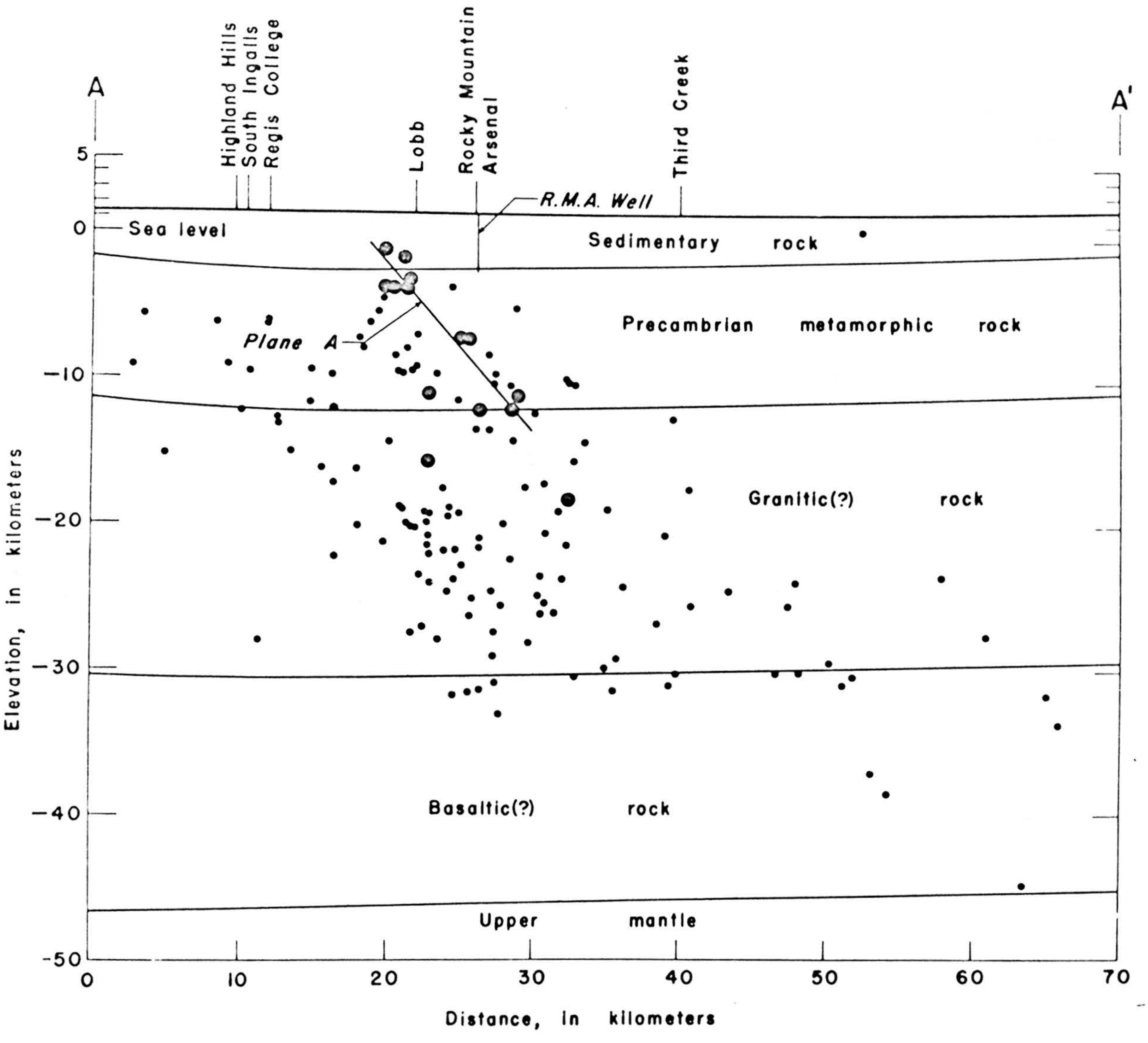


Figure 2 -- Map showing hypocenters of 1963 Denver area earthquakes, determined from local seismological stations. Modified from Wang (1965).



Plane A: computed best fitting plane passing through hypocenters of four-station data.

Figure 3 -- Cross section showing hypocenters of Denver area earthquakes and computed best fitting plane passing through hypocenters. Modified after Wang (1965).

The most impressive part of the data presented by Evans was the correlation of earthquakes with the amount of water pumped. As a first step, the source data on which these plots were based was checked and the plots were found to be a correct representation of the source information. Another aspect of the correlation which was more difficult to check was that no earthquakes were reported in this area prior to the beginning of injection of water at the Rocky Mountain Arsenal well. Unfortunately, the most sensitive station in the area, that at Bergen Park, Colorado, began operation only 3 months prior to the start of injection of water at the Rocky Mountain Arsenal well, so the data are not available from this station to extend the earthquake history back in time.

A seismograph station was operated at the University of Colorado in Boulder by Dr. Warren Longley between the years 1954 and 1959. Seismic records were obtained from Dr. Longley and analyzed and described by Knvoy elsewhere in this report. These records showed a few small events that might possibly be earthquakes in the Derby area, but we are inclined to discount this possibility because all of these events occurred during weekday working hours, suggesting that they are more likely to be construction blasting or explosives disposal at the Arsenal.

From all the evidence which we have been able to collect, it appears that the correlation shown in figure 1 is an accurate statement of the available information. One minor objection to the data presented might be raised because the records at the School of Mines were examined by different individuals during the period in question, and it is possible that some of the interpreters were more diligent than others and picked up more events from the seismograms. The re-reading of the seismograms would be a formidable task, and in our judgment would not significantly alter the data presented.

The second major piece of evidence presented by Evans in support of his hypothesis was the data on earthquake location from Wang's thesis. Evans pointed out that most of the earthquakes occurred within a 5-mile radius (8.3 km) of the arsenal well; however a significant number of earthquakes were located as far as ten miles from the well and at depths greater than 18 miles (30 kilometers). Assuming that the hypocenters of the earthquakes were correctly located, they were distributed over a large volume, on the order of 10 to 20 cubic km. The quantity of water pumped into the arsenal well is sufficient to fill only a very minute fraction of the available pore space in the volume represented by the distribution of earthquakes. If the porosity is 1 percent, the 150 million gallons of water pumped into the ground would fill only 0.0057 percent of the volume of the pores spaced in a 10-kilometer cube. If we consider a cube of 20 km to approximate the earthquake volume, then the 150 million gallons of water would fill only 0.00071 percent of the available pore space in this larger volume. It is evident that the larger the volume of rock in which the earthquakes occur, the less likely it becomes that the earthquakes are related to the injection of water in the disposal well.

Close inspection of Wang's data shows that most of the earthquakes plotted were located with less than 4 stations and only a relatively few earthquakes were located with 4 stations. Two earthquakes were located with 5 stations. If one discards all of the locations made with less than 4 seismic stations, the remaining earthquakes cluster considerably closer to the well. However, the 4 stations available to Wang in this study were not optimally positioned to locate earthquakes in the vicinity of Commerce City. It therefore appeared that a major contribution to an understanding of this problem would be to establish a seismic network that would greatly improve the accuracy of earthquake location.

If accurately located earthquakes tended to cluster in a tighter area in the proximity of the well, the hypothesis of a relationship between water injection and the earthquakes would be greatly strengthened, but if the earthquakes were actually located over the wide area as indicated by Wang's data or if they were clustered but moved some distance from the well, the hypothesis would be weakened. Studies of many seismically active regions have indicated that there is a linear relationship between the log of the number of earthquakes occurring over a period of time and the Richter magnitude of the earthquakes. Wang (1965, fig. 27) prepared a plot of this type for the Commerce City earthquakes.

If we take Wang's relationship for the number of earthquakes versus magnitude, $\log N = 3.1 - 0.78 M$, where N is the number of earthquakes per year and M is the Richter magnitude, we would expect 1259 earthquakes of magnitude 0 and 7586 earthquakes of magnitude -1 per year. These numbers indicate that a network designed to detect earthquakes with magnitudes less than zero will produce a large body of data within a few months.

The U. S. Geological Survey had a number of seismic recording units which were adaptable to the study of very small earthquakes, and a program for this study was initiated. In addition, efforts were made to improve the standard station recording network in the Denver area. Cooperative efforts between the Colorado School of Mines, University of Colorado, Regis College, and the U. S. Geological Survey were established to improve the seismic network. Figure 5 shows the augmented network of seismic stations which resulted from this effort. Seismic-refraction units, each with a capability of recording eight channels of seismic information, were used for the microseismic study. L-shaped arrays consisting of 6 vertical and 2 horizontal seismometers were established at a number of places surrounding the Rocky Mountain Arsenal well. These units required continuous attendance and were only operated for about 6 hours per day. Up to 8 units were in operation at a given time. A number of positions were occupied to look for earthquakes over a wide area (fig. 6). One to twenty microearthquakes were recorded every day during this study.

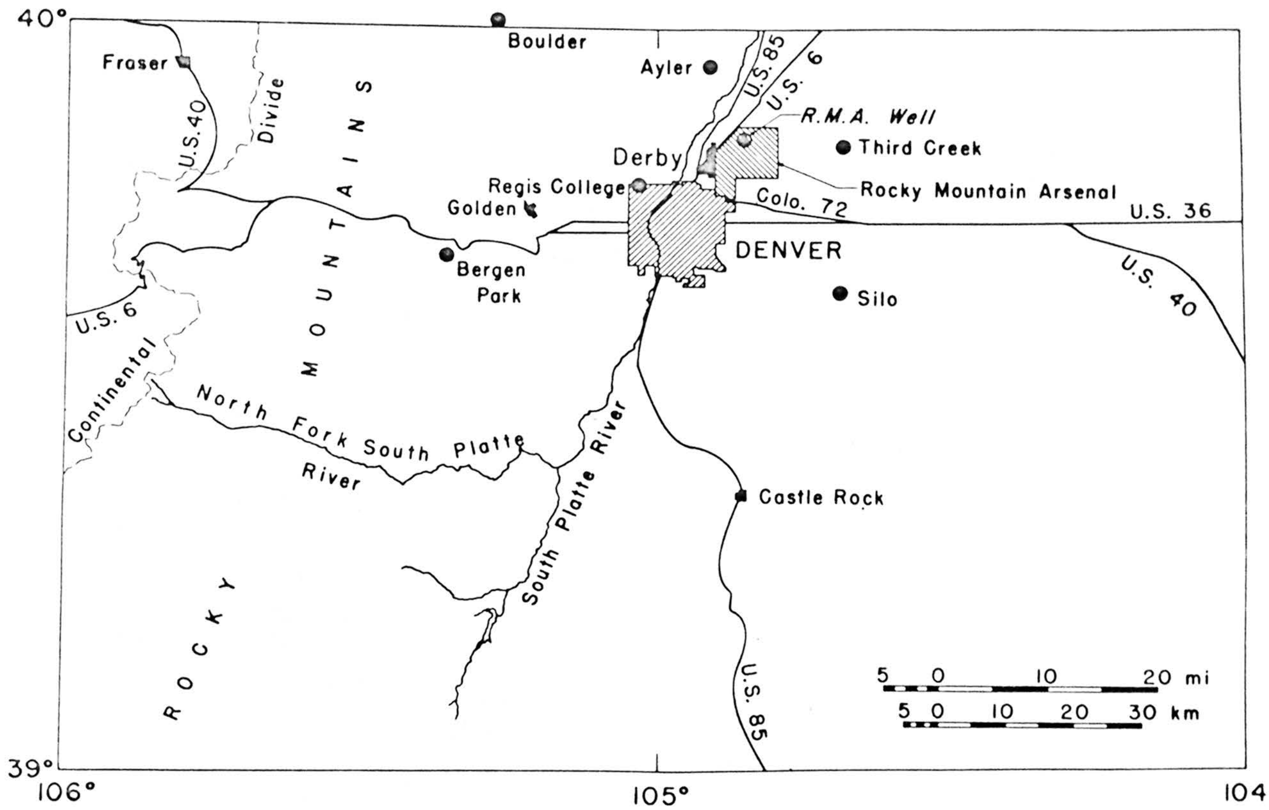


Figure 5 -- Map showing location of seismograph stations in Denver area in February, 1966.

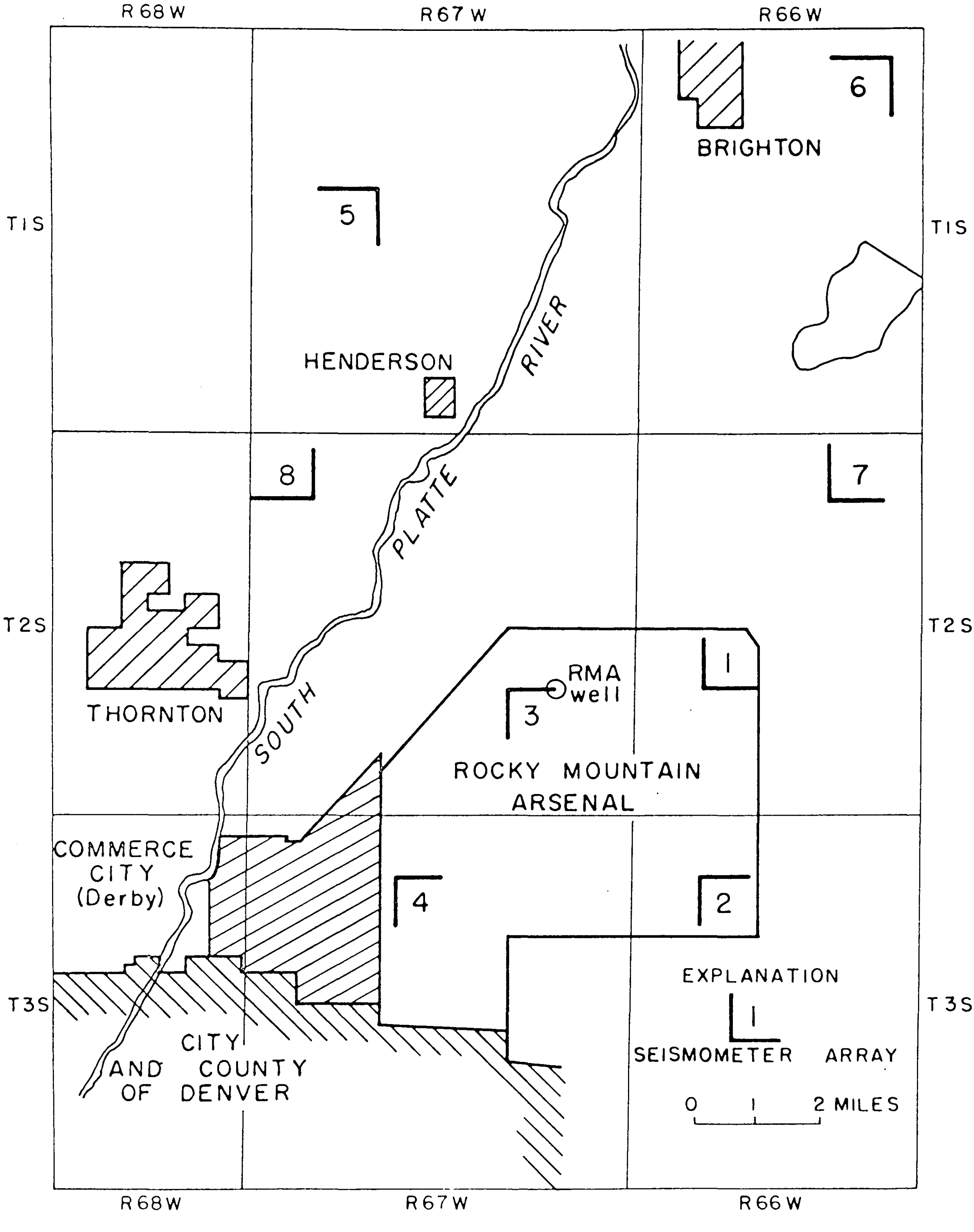


Figure 6 -- Map showing location of microseism recording arrays.

To obtain accurate locations of seismic events, it is necessary to have accurate information about the traveltimes of seismic waves in the region under study. Seismic measurements made by the U. S. Geological Survey during 1965 provided additional data on the seismic traveltimes which had not been available to earlier workers (fig. 7). The profiles show that the crystalline rock below the section of sedimentary rock has a velocity between 5.9 and 6.0 km/sec in this region, and that there is no indication of a large increase of velocity with depth in the crystalline rocks that would affect the traveltimes of waves recorded from shallow earthquakes within the network of stations used in this study. The seismic velocities from sedimentary rocks were taken from measurements made in the Rocky Mountain Arsenal well (fig. 8). Sedimentary-rock velocities were approximated by a series of 4 layers and the crystalline-rock velocities by 3 layers to get the velocity structure used for this study (fig. 9).

A number of techniques for locating seismic events were tried in this study. The first technique attempted to ascertain the direction of seismic-wave propagation across the L-shaped arrays at each recording unit which provided a series of vectors that should, in theory, point at the epicentral location (surface projection of location). A second means employed the use of the S-P traveltime information to obtain the origin time and location of the earthquake. The third, and most effective technique consisted of using an isochron chart which consists of a series of circles representing equal traveltimes from the seismic source. A separate chart must be used for each depth because the traveltime as a function of distance differs with the depth of the earthquake. These charts were laid on a map showing the location of the stations and the times of arrival at each station. The chart was shifted to minimize the differences between the time predicted by the charts and the actual arrival times at the stations.

Using this technique, we estimate that the accuracy of the locations is approximately 1000 feet (0.3 km). A slight modification of this technique was used to obtain the depth of the earthquake. When the epicenter of the earthquake is determined, the distance from the epicenter to each of the seismic stations is measured. A plot of traveltime versus these distances is superimposed upon a graph which predicts the traveltime for a series of depths based on the assumed velocity structure (fig. 10). This technique provides a sensitive check on the location because poorly located events will show a scatter of points about the theoretical curves. One example is plotted on figure 10. Using this technique, the depths of the earthquakes are probably reliable within about 1500 feet (0.5 km).

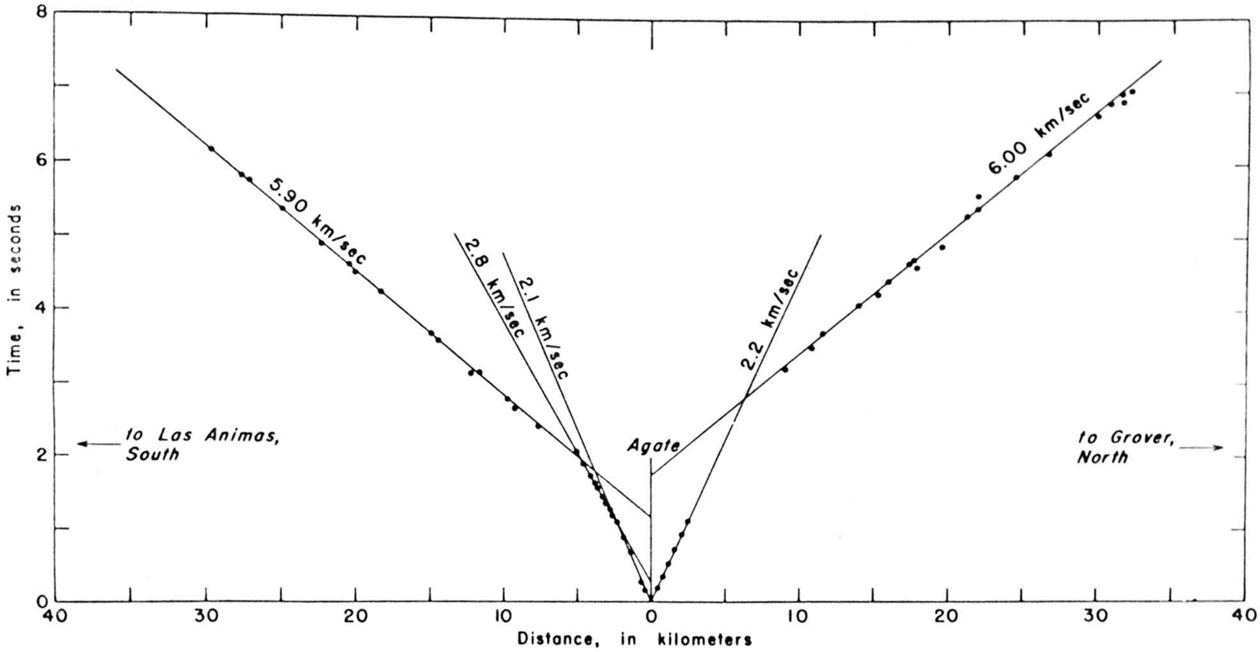


Figure 7 -- Map showing location of seismic refraction profiles near Agate, Colorado.

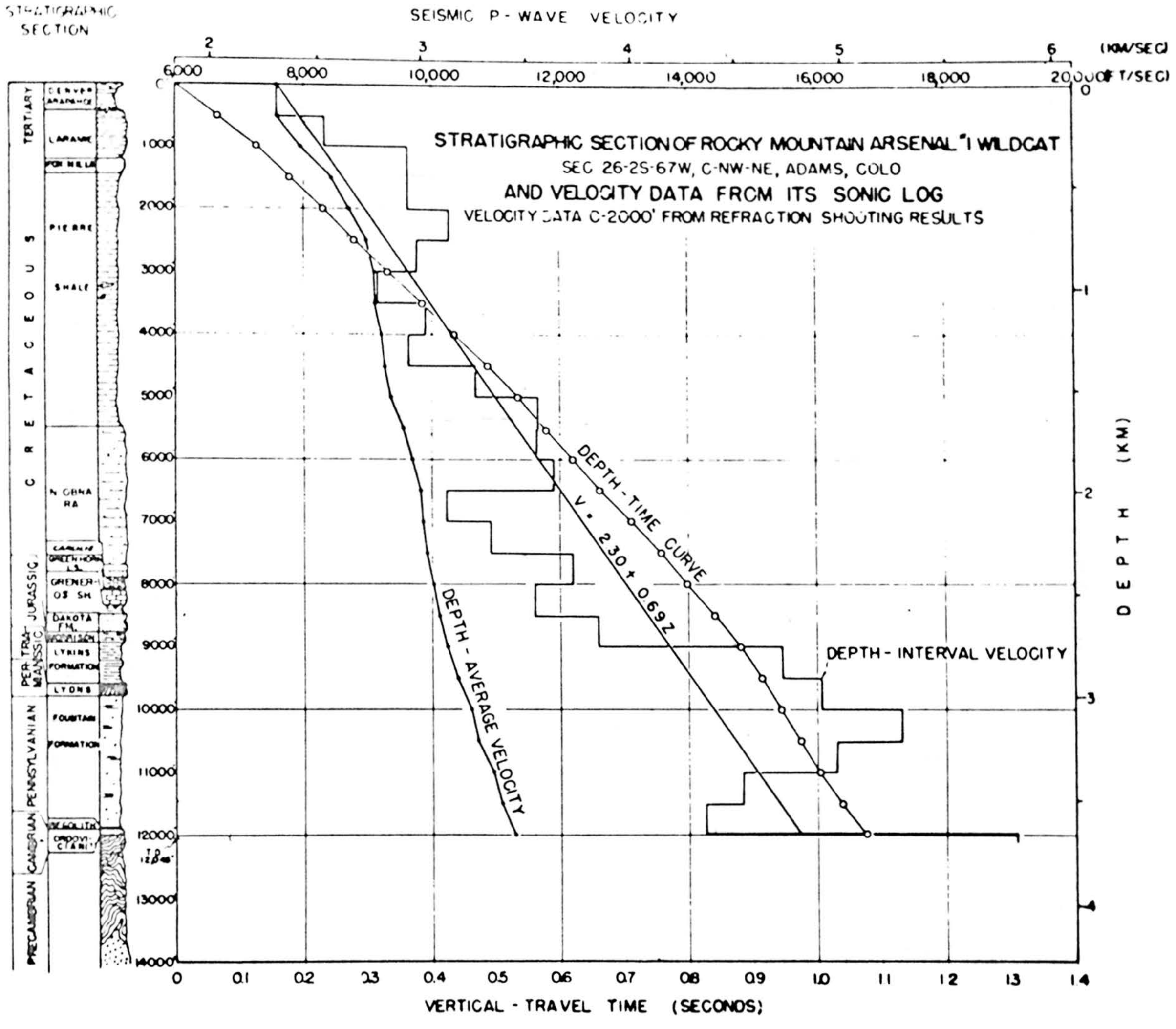


Figure 8. -- Stratigraphic section and velocity data in the Rocky Mountain Arsenal disposal well. Modified from Wang (1965).

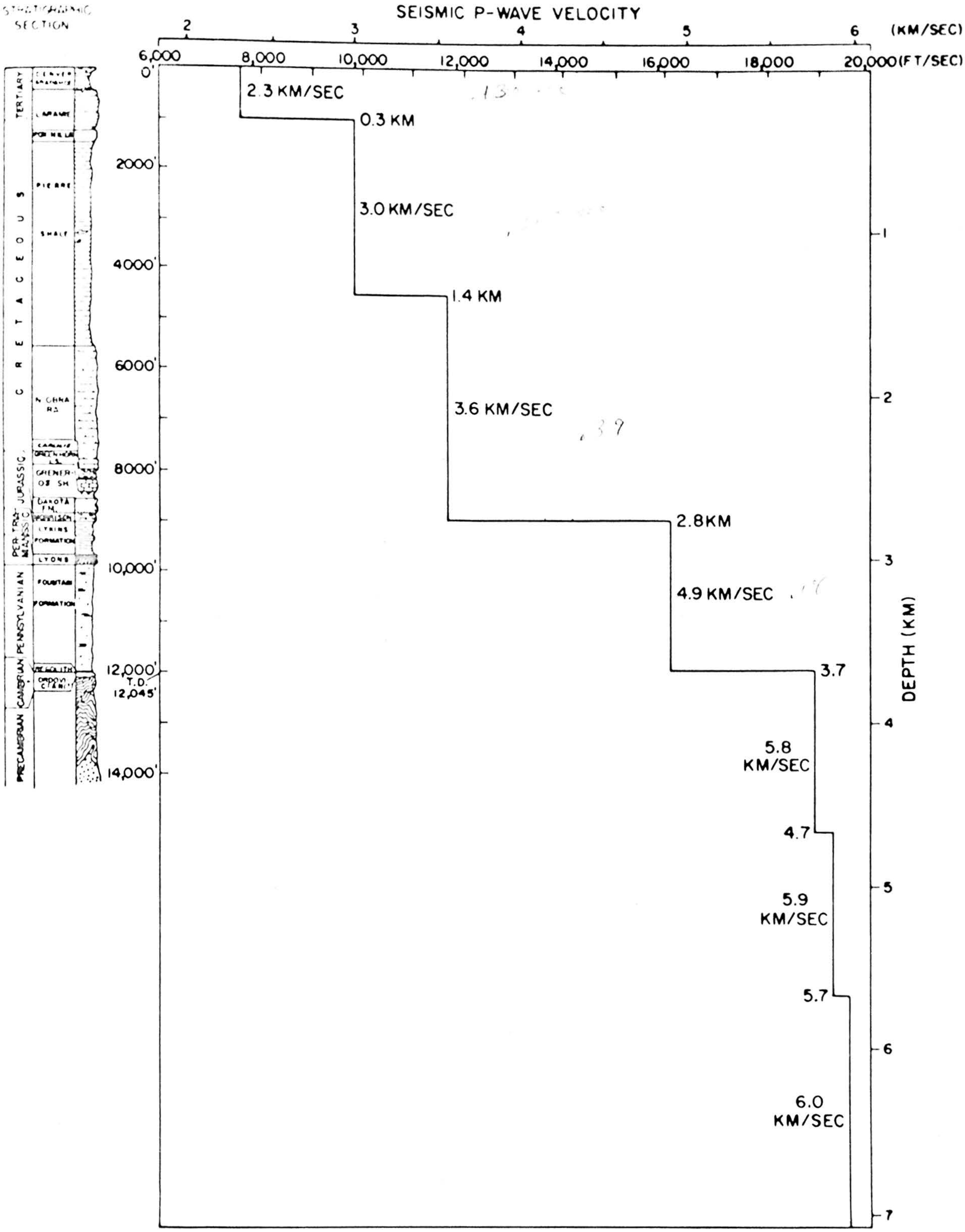


Figure 9. -- Diagram showing depth-velocity approximation in microearthquake study.

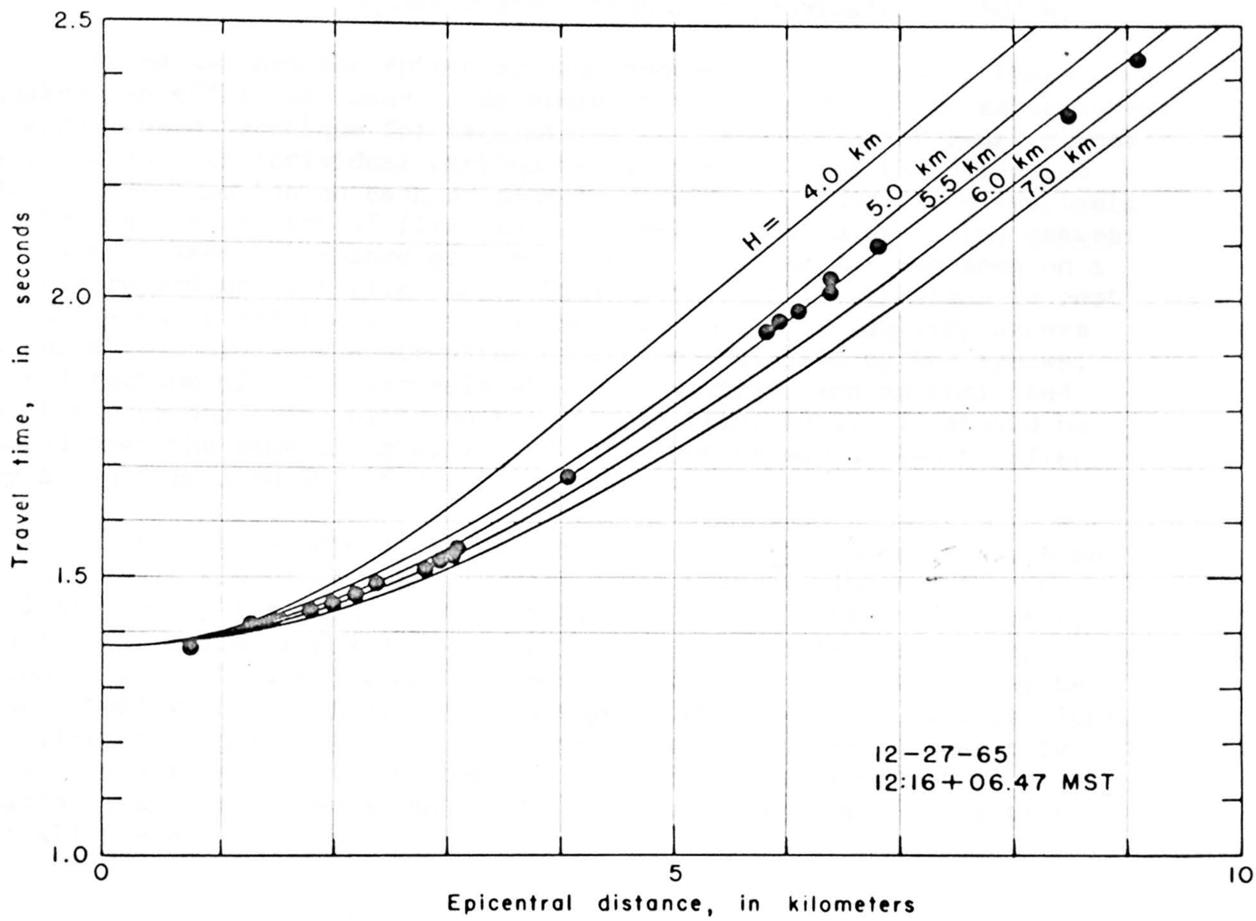


Figure 10. -- Comparison of observed traveltimes for a single event with theoretical curves for various focal depths.

About 12 earthquakes were studied in detail. All the earthquakes studied in detail were located at depths between 4.5 and 5.5 km. The hypocenters of those earthquakes that were not studied in detail are probably consistent with depths in this range. Epicenter locations of the earthquakes recorded during this period outline a roughly ellipsoidal area about 6 miles long and 3 miles wide that includes the well (fig. 11). The trend of this earthquake distribution is approximately N 60° W.

Having defined the epicenter and hypocenter locations of these quakes, an effort was made to determine the mechanism of the earthquakes. A widely used technique for determining the orientation of fault planes associated with individual earthquakes is the study of the direction of the first motion on each seismogram. Sufficient data were available to define the pattern of first motion direction for many of the quakes. For some quakes the change of direction in first motion was seen on a single recording unit (fig. 12). This pattern of first motion is best illustrated by reference to a diagram (fig. 13). If faulting occurs along a fracture in the direction of motion indicated by the arrows, the direction of first arrivals will have distribution as indicated by the plus and minus plots on the diagram (fig. 13a). It should be noted that the same distribution of first motion would also be given by a fault rotated 90° (fig. 13b).

Using this technique, it was possible to obtain some information on the fault planes from the available recordings. These data are illustrated by the plots in figure 14. Many of the faults appear to have an approximately vertical orientation with horizontal motion along the fault plane although other orientations of faulting may be consistent with the data. It is not yet clear how these distributions of first motion relate to the earthquake mechanism, but we can note that there is a correlation between the individual first motion patterns and the orientation of the ellipse defined by the location of all the earthquakes.

CONCLUSIONS

Results of this study indicate that the location data presented by Wang was subject to errors at least as large as 10 kilometers, and that when an effort is made to obtain precise locations, the earthquake epicenters cluster much more closely around the Rocky Mountain Arsenal well. These data tend to support the hypothesis that there is a relationship between the injection of water in the Rocky Mountain Arsenal well and the occurrence of earthquakes in the Denver area.

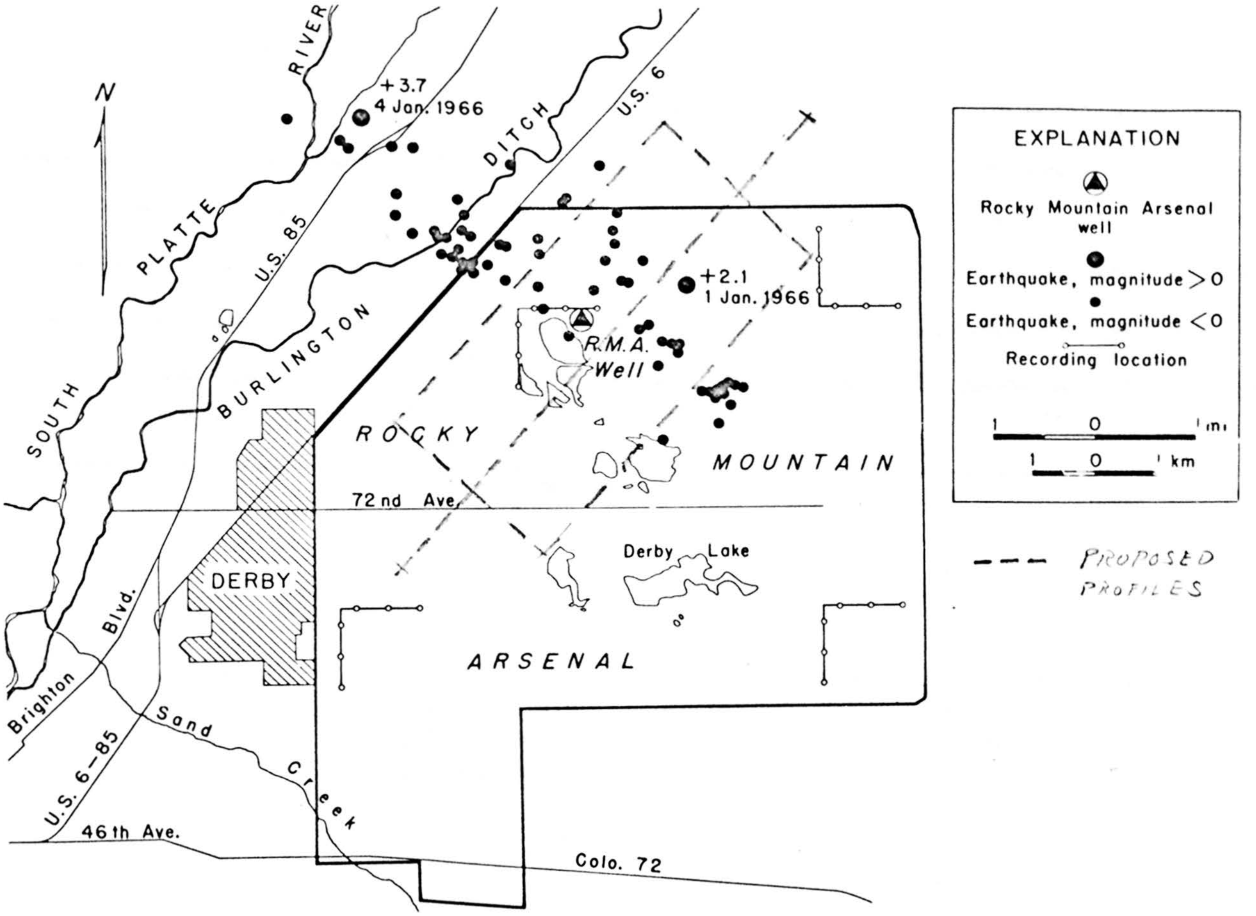


Figure 11. -- Map showing location of seismic shots recorded from mobile microseismic stations.

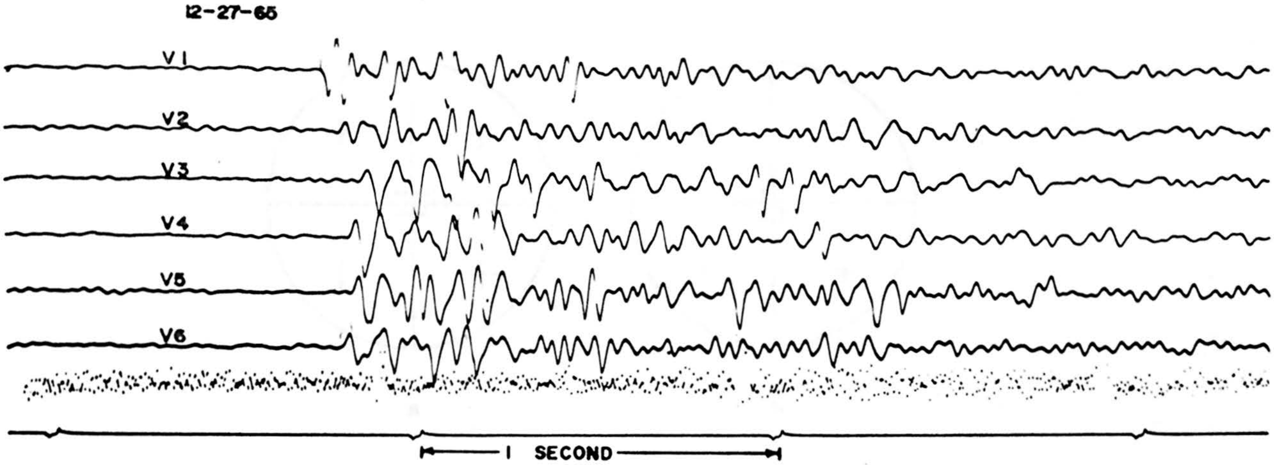


Figure 12. -- Seismogram showing compressional (upward motion) and dilatational (downward motion) arrivals. Nodal plane apparently intersects the array near seismometer 2.

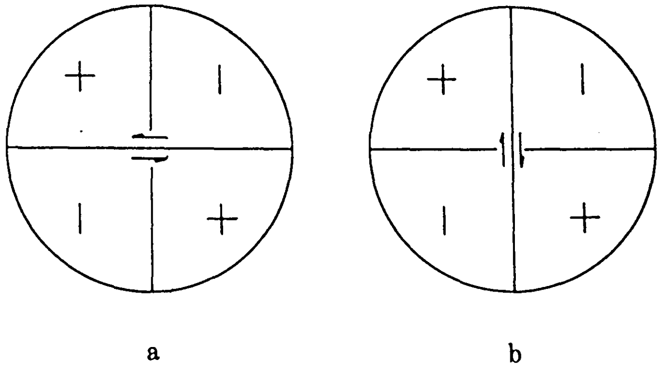


Figure 13. -- Diagram showing relation between direction of fault motion and direction of first motion of seismic waves.

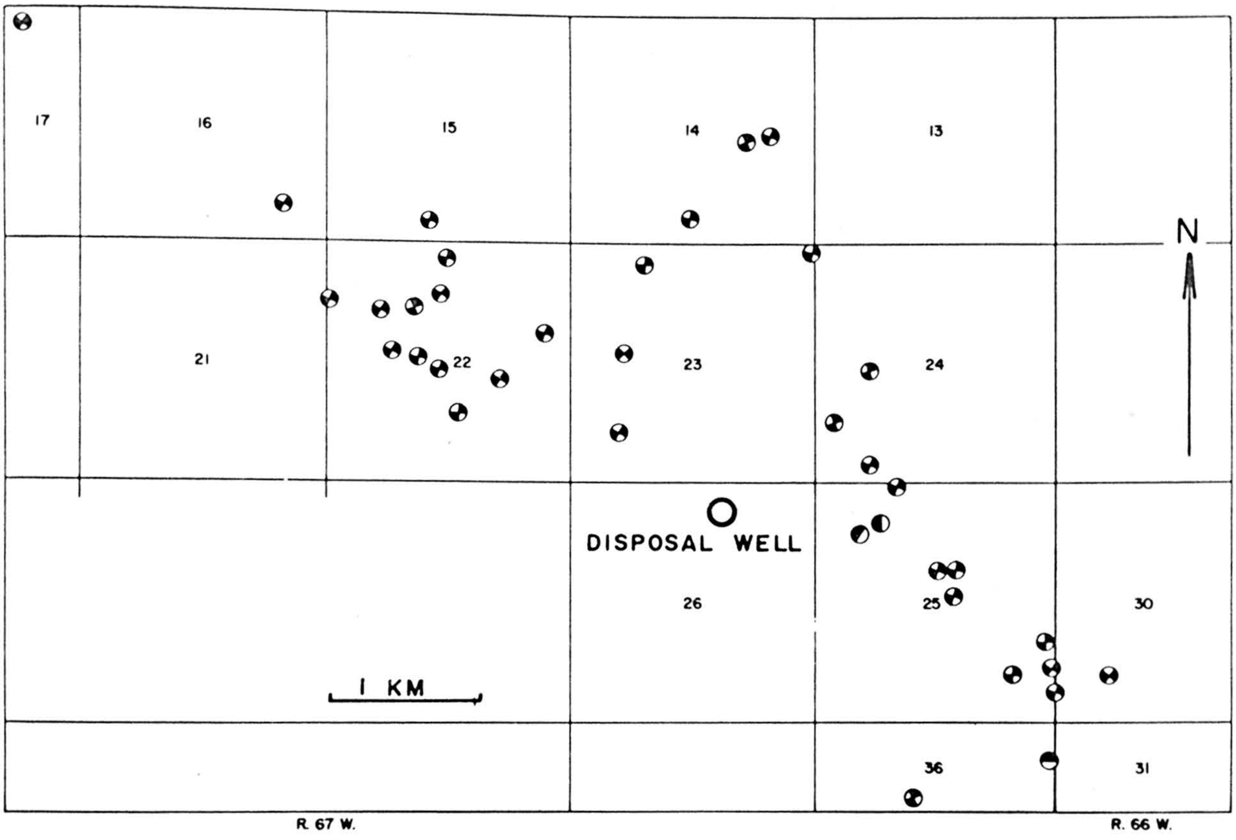


Figure 14. -- Map showing first motion of the ground at earthquake epicenters.

GPO 856-592

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