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Preliminary investigation of seismic tremors in the general area of the Leyden coal mine gas-storage reservoir, Colorado

by

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PRELIMINARY INVESTIGATION OF SEISMIC TREMORS IN THE GENERAL AREA OF THE LEYDEN COAL MINE GAS-STORAGE RESERVOIR, COLORADO

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Introduction

The Leyden coal mine, now used as a storage reservoir for natural gas (R. E. Kelly, written commun., undated; Jain, 1961), is about 13 miles northwest of the center of the city of Denver, Colo., at the edge of the rapidly expanding metropolitan area (fig. 1). The reservoir stores about 2.1 billion cu ft (cubic feet) of gas, at a pressure less than 250 psig (pounds per square inch gage pressure) (R. E. Kelly, written commun., undated), in mine workings underlying about 2 1/2 sq mi (square miles) of land currently used for agriculture. Gas is withdrawn from the mine during times of peak demand, and is injected at times of low demand (Jain, 1961). Overburden above the mine varies from 700 to 1,000 feet (R. E. Kelly, written commun., undated). The geology and coal mines of the Leyden area were described by Van Horn (1957, 1972), Sheridan, Maxwell, and Albee (1967), and Gardner, Simpson, and Hart (1971).

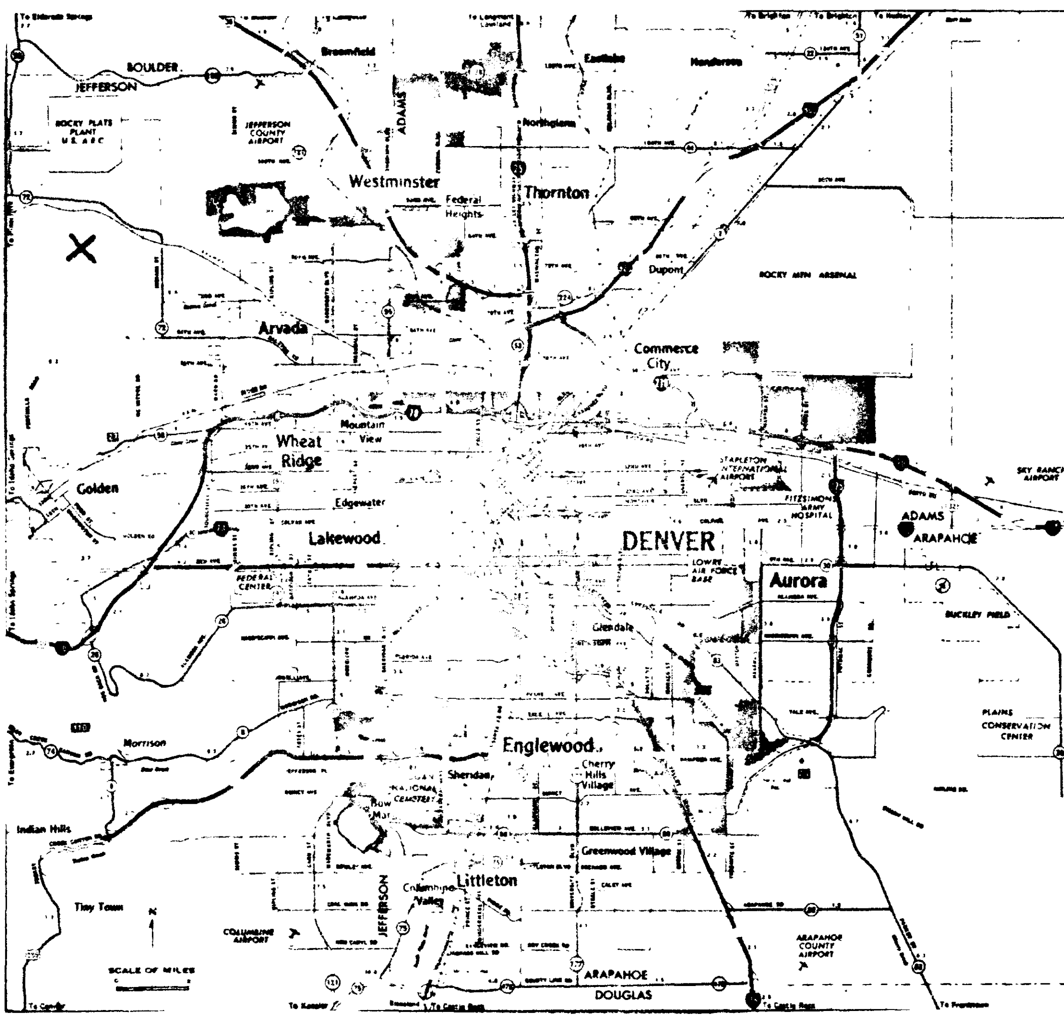

Fig. 1. Index map of Denver area, Colorado, showing location (X) of Leyden coal mine gas storage reservoir. From State map by Colorado, Division of Highways, 1972

The U.S. Geological Survey made a preliminary seismic investigation of the Leyden coal mine area (fig. 2) during the winter of 1971-72, primarily as an engineering geologic study to determine the response of coal mine pillars and overburden to changes in stress. Based on prior mine deformation studies elsewhere, it was anticipated that cyclic loading and unloading of the pillars, during alternate withdrawal and injection of gas, might cause small seismic tremors in or near the mine area, similar to those reported from active coal mining areas (Osterwald and others, 1971, 1972). The investigation was planned to span at least one period of severe cold weather, so that the response of the mine to at least one cycle of gas withdrawal and injection could be monitored. We also planned to monitor during the summer when the reservoir was idle to establish a record of seismic background, but were unable to do so. This report presents the preliminary results of the investigation in commonly used physical terminology for the information of all interested parties.

Sites for eight seismometers and for the recording van were prepared before January 11, 1972. The recording equipment was installed on January 12, just before a severe winter storm was anticipated. High winds severely damaged the signal wires and, with the cold and snow, hampered attempts to repair the wires. As shown on figure 3, three seismometers were operating on January 12, seven by the morning of January 16, and the eighth was finally connected on January 19.

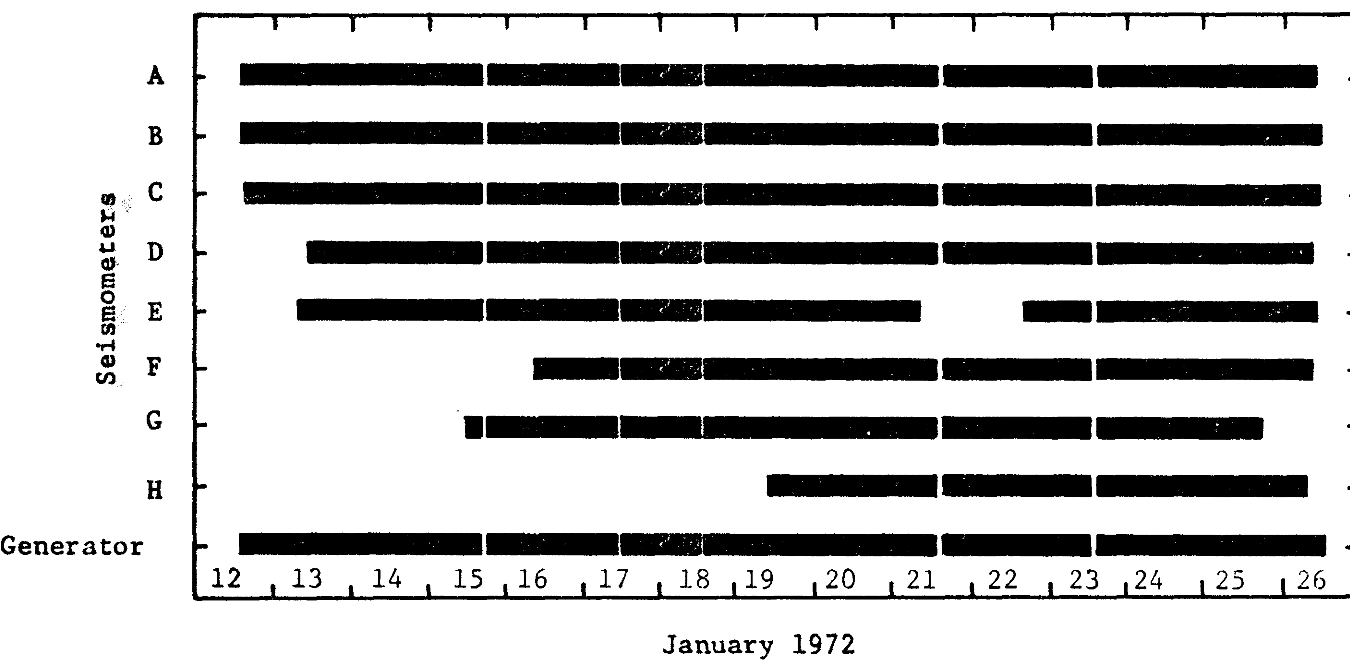

Figure 3. Operating time of each seismometer and of the electric-power generator.

All seismometers were removed and recording equipment was stopped by 1:00 p.m. January 26, after a review of the paper records in the field indicated that sufficient information had been obtained to make preliminary determinations of the sources of the tremors.

Field investigations

Field procedures and instruments used at Leyden were similar to those used in seismic studies of some coal mining areas in Utah and Colorado (Osterwald and others, 1971, 1972). Modifications of the instruments and procedures used at Leyden, as compared to the previous work, will be described where pertinent.

Eight seismometers were placed around the Leyden coal mine as shown on figure 2. Six were located near the margins of the mine in order to detect and locate any small seismic tremors that might occur in the immediate vicinity of the mine. Two other seismometers were located at greater distances from the mine, one a mile west of the mine and the other about 1 1/3 miles north and west. These two seismometers were used to give greater breadth to the network so that waves refracted and reflected from strata below the mine could be detected.

Seismometers were sealed in plastic sacks and buried 6 inches to 1 foot below ground level. Seismometers A, B, and C were the new L-4 type, rather than the older EV-17 type used at all other locations. Frequency responses of the L-4 and EV-17 seismometers are shown on figure 4.

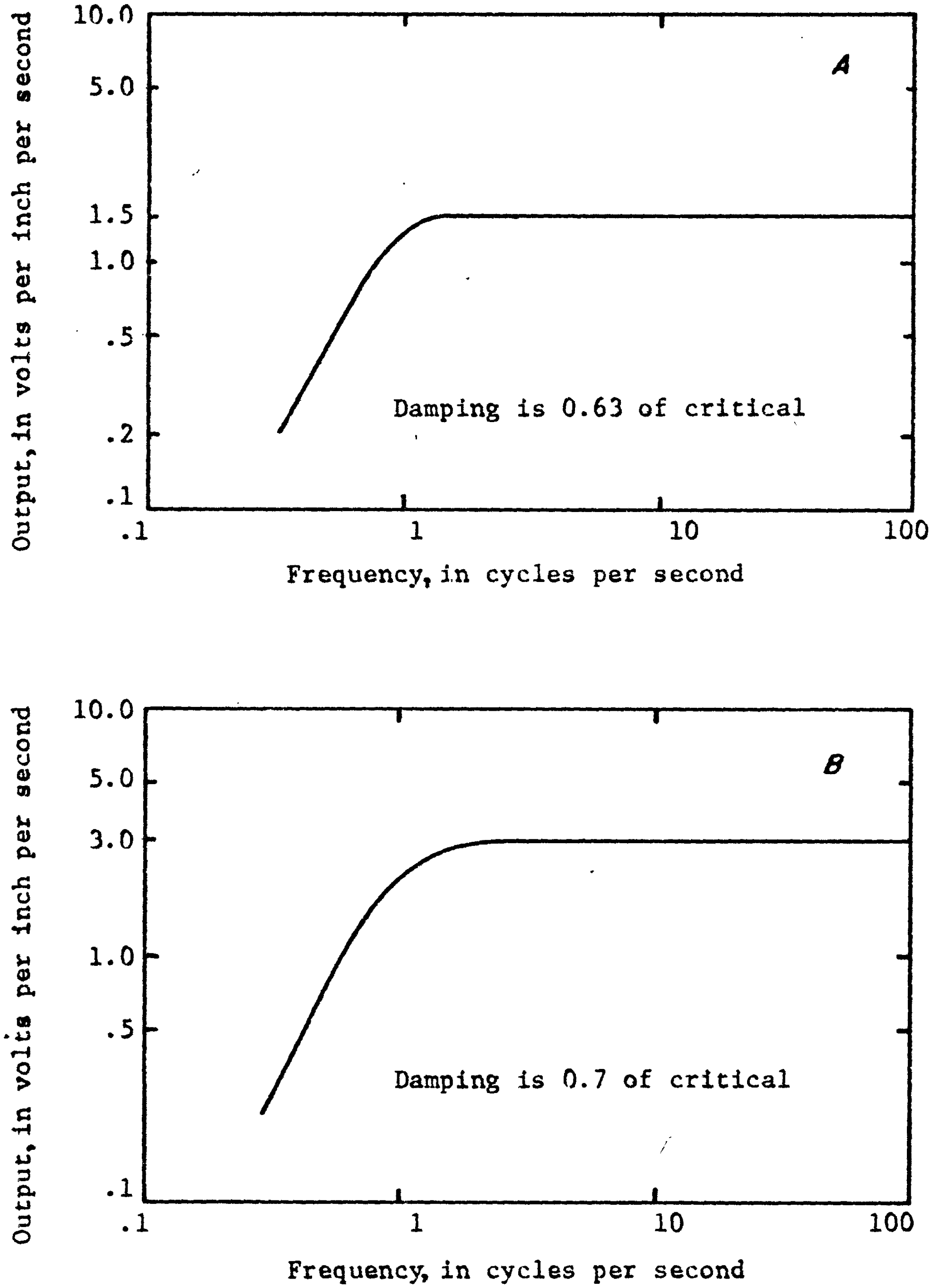

Figure 4. Frequency response curves for L-4 (4A) and EV-17 (4B) seismometers, manufacturer's specifications.

Signals from all seismometers were boosted by battery-powered transistorized preamplifiers similar to those described previously (Osterwald and others, 1971, p. 3-4; 1972, p. 10-11). The voltage gain of the preamplifiers used with the L-4 seismometers, however, was adjusted so that the voltage output equaled the voltage output from the preamplifiers used with EV-17's, thus making the output from both units compatible. The preamplifiers were powered with nickel-cadmium battery packs.

The recording equipment was mounted in a 20-foot van body on a 2-ton truck. The rear of a 2 1/2-ton 6X6 van was placed against the rear part of the side of the recording van in an L-shaped arrangement as a safety measure against strong winds. During high winds in the late stage of the recording period it was also found necessary to support the lee side of the recording van with two heavy-duty jacks to prevent severe shaking of the van.

Seismic signals were divided inside the van so that the outputs from seismometers A through F were recorded simultaneously on paper (real-time recording system) and on magnetic tape (storage recording system). Signals from seismometers G and H were recorded only on magnetic tape. Time signals from National Bureau of Standards radio station WWV were recorded continuously on the magnetic tape using a direct-record system; all other channels were recorded by an FM system on the same tapes. Time signals also were placed simultaneously on paper and tape records each minute by an electronic chronometer, which had been synchronized with minute tones from WWV. Accuracy of the electronic chronometer is about 1 part in 10^6 per day.

The real-time recording system consisted of the seismometers, preamplifiers, pen-drive amplifiers, and a 6-channel electric-write recorder; the storage-recording system consisted of the seismometers, preamplifiers, and a 14-channel tape recorder. The real-time system operated at a recording speed of 25 cm per hour; the storage system operated at a recording speed of 1 7/8 inches per second, but the tape records were played back on a light-beam oscillograph at a recording speed of 1 inch per second. Timing lines were placed photographically on the oscillograph records every 0.1 second and 0.01 second. By using the storage system, a high degree of resolution was obtained in determining arrival times of the seismic tremors, when wind noise was not excessive. The FM recording and playback electronic sections in the storage system are conventional commercially available units.

The recording equipment ran on 60-cycle 115-volt single-phase electric power, provided by a 10-kilowatt gasoline-powered generator unit mounted in a 1/4-ton jeep trailer. The generator also supplied interior light and heat for the two vans. Voltage was maintained automatically; frequency was manually adjusted to 60 cycles by the throttle and by an adjustment on the governor linkage.

Recording equipment was operated 24 hours a day during the monitoring period, except for brief intervals when the generator was shut down for servicing. The instrument van was occupied 24 hours a day, and the operation of the instruments, the output voltage, and the frequency of the generator unit were checked every 4 hours, except that the 4:00 a.m. checks were omitted to relieve physical strain on operators. Operating time for the generator and real-time recording times for each seismometer are shown on figure 3.

Each seismometer installation was calibrated daily with its corresponding recording channel by a manually actuated calibrator built into each preamplifier. These calibrators injected a 5-cps (cycles per second) signal into the input of the preamplifier at a predetermined amplitude so that the output of the preamplifier was 5 volts peak-to-peak. These calibration signals were then adjusted by variable attenuators in the recording van to 20 mm peak-to-peak on the real-time system. Frequency response of the storage system was determined by the seismometers on the low-frequency end and by the tape recorder on the high-frequency end. During all calibrations the frequency response and output of the seismometers were assumed to correspond to manufacturer's specifications.

Arrival times of seismic tremors were indexed on the paper (real-time) records; individual tremors were later located on the magnetic tapes by listening to the recorded voice time announcements from WWV while observing the recorded signals on an oscilloscope. Tape records of individual tremors were then played back on the light-beam oscillograph.

Seismic interpretation

Two types of seismic tremors originating within the general area of the Leyden coal mine were recorded. Type I, the most abundant, consisted of low-velocity, low-amplitude, low-frequency, amplitude-modulated wave trains (fig. 5) continuing as long as 20 or 30 seconds. Each of these tremors had a frequency between 2 and 15 cps. Many wave envelopes pinched and swelled every ½ to 4 seconds. It is assumed that the 2- to 15-cps waves are amplitude modulated by slower, 0.25- to 2-cps waves. Type II tremors consisted of short duration, high-amplitude waves with frequencies between 3 and 20 cps, that were both frequency and amplitude modulated (fig. 6). In addition, two distant earthquakes were recorded, as well as numerous tremors caused by aircraft and railroad trains. The records from these sources are quite distinct and cannot be confused with the records of the two types of local seismic tremors.

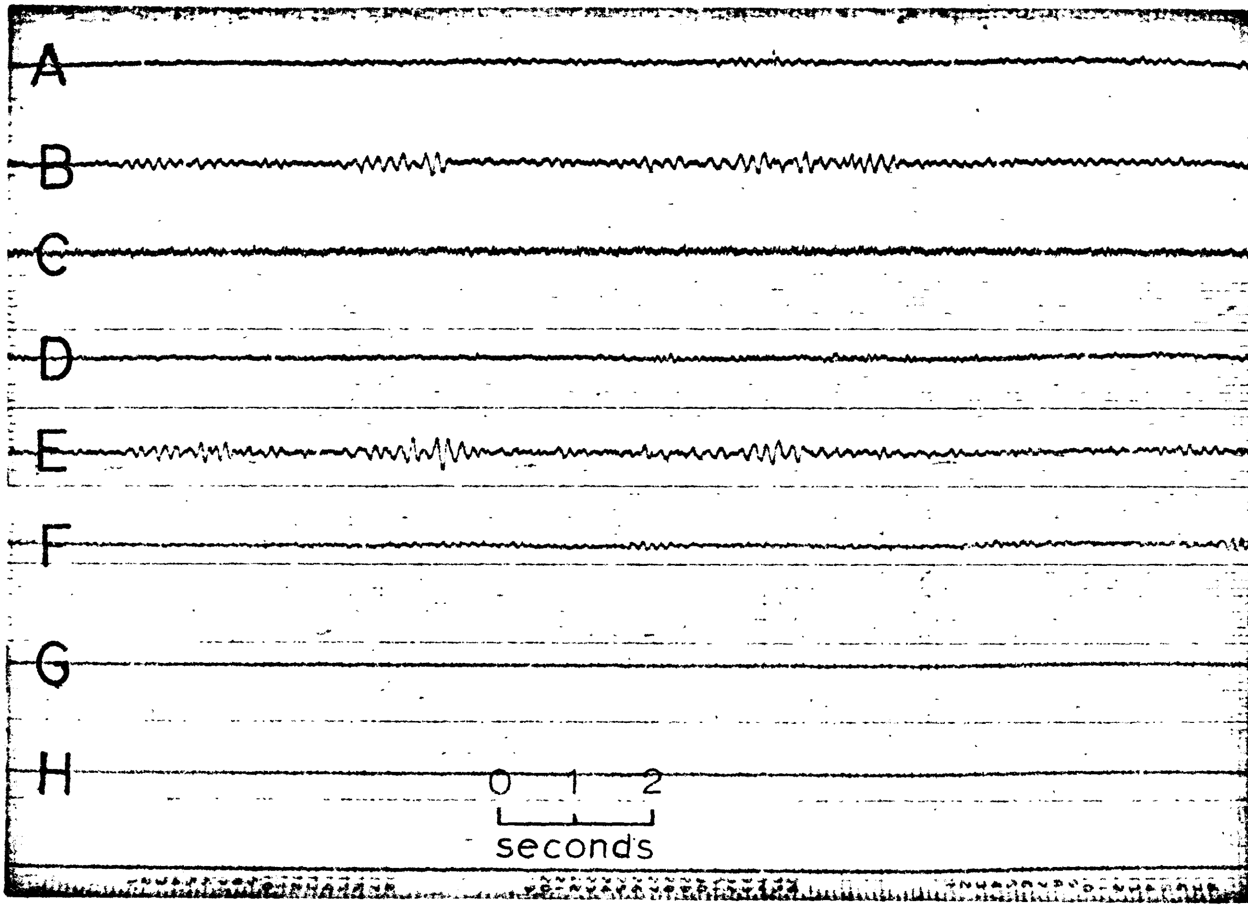

Figure 5.--Oscillogram of Type 1 seismic tremor that occurred at 6:35 p.m., m.s.t., January 16, 1972 (0135 G.m.t., Jan. 17), in the Leyden coal mine area, Colorado. Letters indicate seismometers as shown on figure 2.

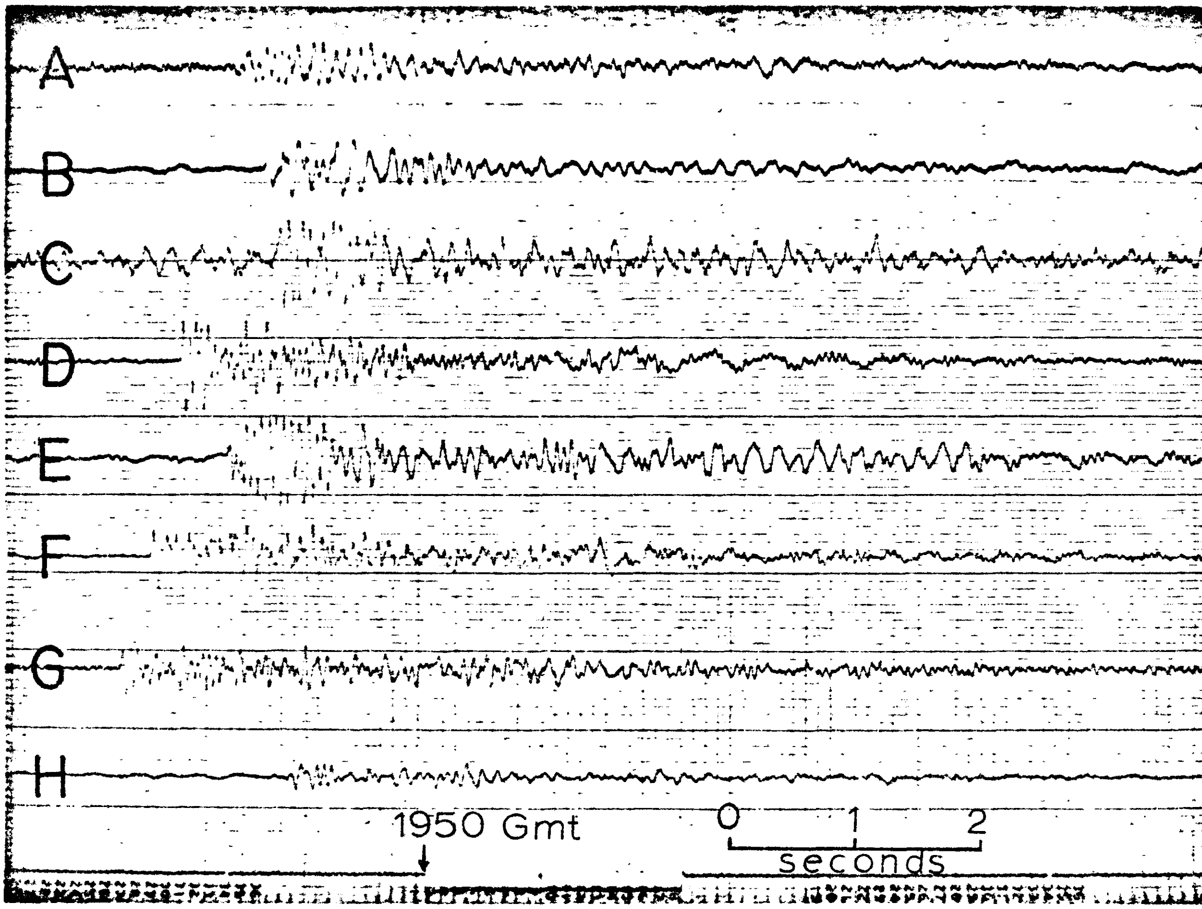

Figure 6.--Oscillogram of Type II seismic tremor that occurred at 12:50 p.m., m.s.t., January 25, 1972 (1950 G.m.t.), in the Leyden coal mine area, Colorado. Letters indicate seismometers as shown on figure 2.

Type I seismic tremors were recorded only from those seismometers that were above or very near the mined area (fig. 2). Apparent traveltimes from the sources of these tremors to the seismometers are long, indicating slow velocities. Precise arrival times of the first waves from the Type I tremors are difficult to determine because of the low amplitudes, but relative arrival times at different seismometers indicate that all Type I tremors originated in or near the mine. Because the seismometers in the interior of the network were only about 1 mile apart, each symbol on figure 2 representing the source of a Type I tremor probably is located within a quarter of a mile of its true location. Judging from their low apparent velocities, uniform and low frequencies, and modulated wave trains, the Type I tremors may be resonant vibrations caused by movement of fluids within the mine openings.

Records of seismic tremors of Type II resemble those of small, near-surface tremors that were recorded with similar equipment in Colorado and Utah coal mining areas (Osterwald and others, 1971, p. 10, 16-17; 1972, p. 14-15).

Sources of the Type II tremors were located by measuring on the oscillograms the times of arrival of the first seismic waves (compressional) detected by each seismometer and of the next clearly defined wave groups. Traveltimes of the wave from the tremor source to each seismometer were determined by subtracting the arrival times of the first waves (compressional) at each seismometer from the graphically determined origin time of the tremor. The traveltimes of the compressional waves then were converted to distances, using a time-to-distance conversion protractor (a delay-time curve overlay) that was used previously (Osterwald and others, 1971, p. 6, 8) but modified to fit compressional wave velocities in the Leyden area (average velocity = 13,000 feet per second). The tremor sources were then located by a method similar to triangulation, with the use of the time-to-distance conversion protractor.

Source locations and depths could be determined for only six of the Type II tremors that we recorded (fig. 2). The others could not be precisely located, because wind noise on some records, even after filtering, obscured the arrivals of the first waves, and because many were not recorded on enough channels to determine the sources accurately. The approximate arrival times of the Type II tremors for which sources could not be located, as well as the general characteristics of their wave envelopes, indicate that these tremors occurred in the same areas as those whose sources were located. Furthermore, the source locations probably are not so accurate as those in our previous investigations, because the sources were too far outside the network of seismometers. It is estimated that the sources shown on figure 2 are within half a mile of their true positions.

The traveltimes of Type II tremors to some of the seismometers were difficult to fit to the protractor curves for two reasons: (1) First arrivals at seismometer station G were earlier than expected (velocities of 15,000 to 17,000 feet per second), probably because the waves traveled rapidly from the sources through a water-saturated rock mass near Ralston Reservoir or through an intrusive igneous rock mass southeast of the reservoir (fig. 2); and (2) first arrivals at seismometer C were later than expected (velocities of 12,000 to 13,000 feet per second), probably because the waves traveled more slowly through the area of the mine workings than through the surrounding unmined areas. Adjustment of the plotting procedures to fit these conditions undoubtedly introduced some additional errors into the source locations shown on figure 2. All these sources probably were within 3,000 feet of the ground surface, except for one about two-thirds of a mile southeast of Lower Long Lake (fig. 2), which may be as much as 6,000 feet deep.

During the time the instruments were operated, 80 Type I tremors and 40 Type II tremors were recorded. Most of the Type I and Type II tremors occurred during January 16-22, with a large number of the Type I tremors occurring on January 16 (fig. 7).

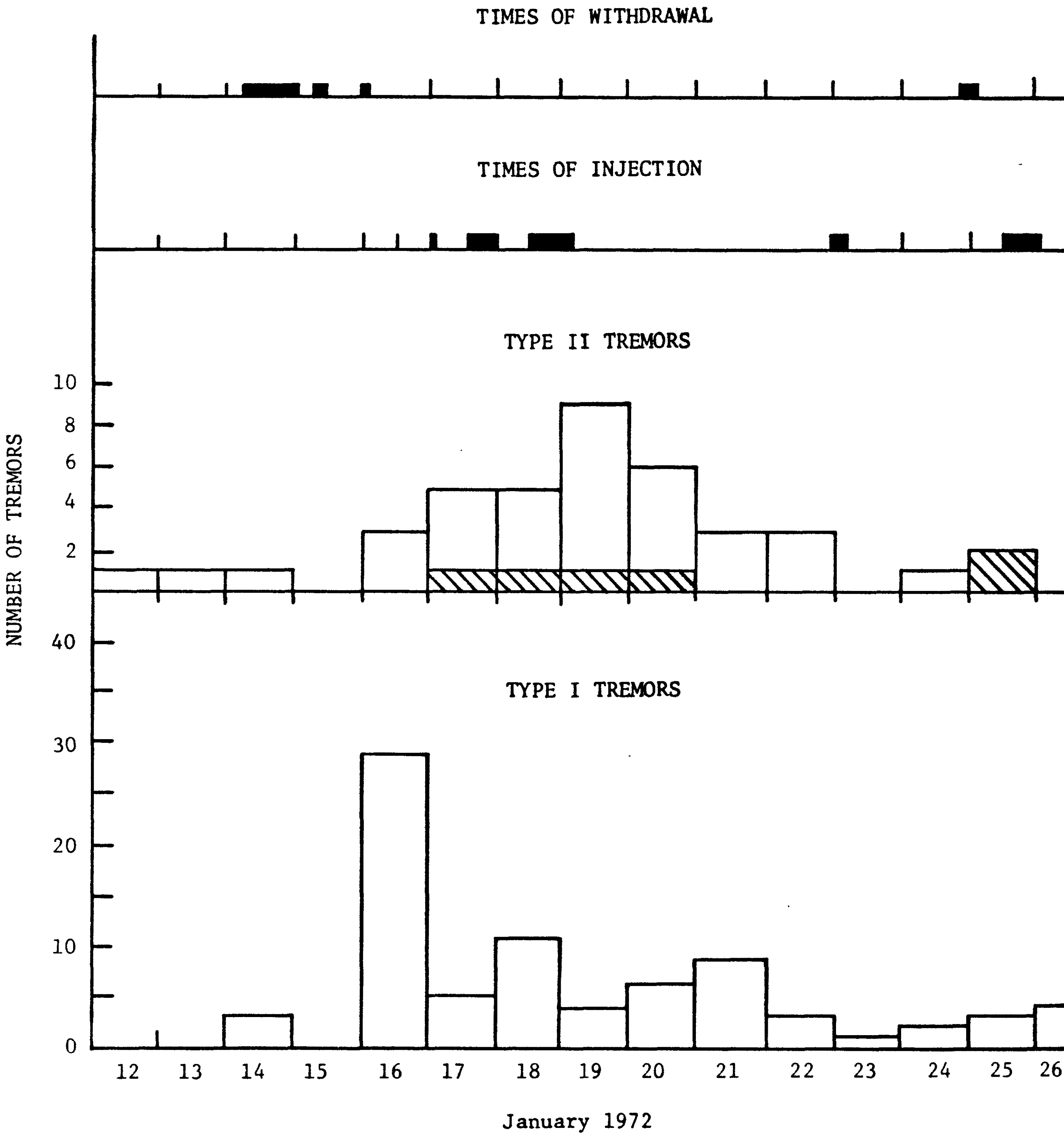

Figure 7.--Histograms showing number of the two types of seismic tremors per day, times of natural gas withdrawal from the Leyden coal-mine reservoir, and times of gas injection into the reservoir. Type II tremors shown crosshatched are those whose sources are approximately located on figure 2.

Recommendations

It must be emphasized that this investigation was preliminary, and cannot be considered definitive without additional research. Three specific phases of research should be pursued before any conclusions can be drawn. These phases are:

(1) Seismic monitoring during a period when the reservoir is idle, using the same seismometer sites, plus two additional sites southwest of the mine area;

(2) Seismic monitoring during another winter period, but covering a longer span of time and including two additional seismometer sites southwest of the mine area. The longer time span should include more than one cycle of gas withdrawal and injection;

(3) Measurements with recording tiltmeters during both of the additional seismic monitoring periods, to detect surface ground movements during withdrawal and injection.

Acknowledgments

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References cited

Gardner, M. E., Simpson, H. E., and Hart, S. S., 1971, Preliminary engineering geologic map of the Golden quadrangle, Jefferson County, Colorado: U.S. Geol. Survey Misc. Field Studies Map MF-308 [1972].

Grosvenor, Niles, 1964, Coal mines of Jefferson County, Sheet 1: Golden, Colo., Colorado School Mines Found., Inc.

Jain, Bob, 1961, The Leyden "gas mine": Denver, Colo., The Denver Post, Empire Mag. (Sunday supp.), Nov. 26, 1961, p. 37.

Osterwald, F. W., Bennetti, J. B., Jr., Dunrud, C. R., and Maberry, J. O., 1971, Field instrumentation studies of earth tremors and their geologic environments in central Utah coal mining areas: U.S. Geol. Survey Prof. Paper 693, 20 p.

Osterwald, F. W., Dunrud, C. R., Bennetti, J. B., Jr., and Maberry, J. O., 1972, Instrumentation studies of earth tremors relating to geology and mining at the Somerset coal mine, Colorado: U.S. Geol. Survey Prof. Paper 762, 27 p.

Sheridan, D. M., Maxwell, C. H., and Albee, A. L., 1967, Geology and uranium deposits of the Ralston Buttes district, Jefferson County, Colorado, *with sections on* Paleozoic and younger sedimentary rocks, by Richard Van Horn: U.S. Geol. Survey Prof. Paper 520, 121 p.

Van Horn, Richard, 1957, Bedrock geology of the Golden quadrangle, Colorado: U.S. Geol. Survey Geol. Quad. Map GQ-103.

______1972, Surficial and bedrock geologic map of the Golden quadrangle, Jefferson County, Colorado: U.S. Geol. Survey Misc. Geol. Inv. Map I-761-A.