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# Field Instrumentation Studies of Earth Tremors and Their Geologic Environments in Central Utah Coal Mining Areas

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 693





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*By* FRANK W. OSTERWALD, JOHN B. BENNETTI, JR., C. RICHARD  
DUNRUD, *and* JOHN O. MABERRY

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1971

**UNITED STATES DEPARTMENT OF THE INTERIOR**

**ROGERS C. B. MORTON, *Secretary***

**GEOLOGICAL SURVEY**

**W. A. Radlinski, *Acting Director***

Library of Congress catalog-card No. 72-180658

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For sale by the Superintendent of Documents, U.S. Government Printing Office  
Washington, D.C. 20402 - Price 35 cents (paper cover)  
Stock Number 2401-1209

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## FIELD INSTRUMENTATION STUDIES OF EARTH TREMORS AND THEIR GEOLOGIC ENVIRONMENTS IN CENTRAL UTAH COAL MINING AREAS

By FRANK W. OSTERWALD, JOHN B. BENNETTI, JR., C. RICHARD DUNRUD, and JOHN O. MABERRY

### ABSTRACT

Temporary field-recording networks were installed at Gentry Mountain and Little Park Wash, Utah, during the summers of 1967 and 1968 respectively, to study seismic activity related to coal mining and geologic conditions. Tremors, many of which were small manmade earthquakes, were recorded both on chart paper and on magnetic tape; instruments were designed or modified to operate for extended periods with minimum maintenance. Hypocenter positions were estimated to be accurate within 750 feet.

Results at Gentry Mountain indicated that tremors occur near mining areas and along large north-trending faults west of the mining area. At Little Park Wash they indicated that nearly all tremors originated near the south part of the Geneva mine. A well-defined belt of faults crossing Little Park Wash 5 miles south of the mine was seismically quiet.

### INTRODUCTION

The U.S. Geological Survey has studied geologic features that may be related to dangerous coal mine bumps that have occurred in the mines of east-central Utah for several years. Bumps, which are violent, spontaneous disruptions of coal faces and ribs, are a common hazard to lives and property in many of these mines. This work originally was undertaken at the request of, and in cooperation with, the U.S. Bureau of Mines. Since July 1961, the work has been carried on by the U.S. Geological Survey, but the Bureau of Mines has given continuous informal cooperation in the field. Most of the work was done in the Sunnyside district, about 25 miles east of Price, Utah (fig. 1). An important part of this study is a seismic monitoring network, operated continuously at Sunnyside since 1963, to locate sources of tremors with respect to geologic features and to mining. Preliminary studies of data from this network indicate that: (1) tremors are very common within the mining district; (2) although many tremors occur at considerable distances from the mine workings, cyclic variations in numbers of tremors per day seem to be related to variations in mining cycles; (3) many tremors originate near faults; and (4) dangerous bumps may occur in the mines during times of markedly increased daily

number of tremors (Dunrud and Osterwald, 1965; Osterwald and Dunrud, 1966). Seismic activity was much greater at Sunnyside than was anticipated; for example, about 50,000 tremors were recorded during 1967 (Barnes and others, 1969). These findings were somewhat unexpected because it was thought that the Sunnyside district was aseismic and that only a few tremors, directly related to bumps, would be recorded.

As a result of these unexpected findings, two seismic monitoring experiments were conducted outside the area of the Sunnyside monitoring network by means of a specially designed mobile recording laboratory. One experiment was conducted above another coal mining area, and one above a prospective coal mining area. These experiments were designed to answer these questions: (1) Is the unexpectedly high degree of seismic activity at Sunnyside unique, or does similar activity occur in other areas from which Cretaceous coal is mined, and (2) does the intensity of seismic activity at Sunnyside stem from the mining, or is it related to stress accumulations along fault belts near but outside the district? Sites for the two experiments were selected at Gentry Mountain near Hiawatha, Utah, and at Little Park Wash, 15 miles south of Sunnyside (fig. 1). Site selection was based on geologic structure, position with respect to mine working, accessibility, and topography suitable for installing the networks.

This report describes the instruments in the mobile laboratory and presents some results obtained from the field installations. The geology of both sites is described briefly, with emphasis on features related to coal mining and to seismic activity. Responsibilities for various aspects of the work were divided among the authors. Osterwald planned and directed experiments at both sites and also planned and set design limits for the instrumentation system. Bennetti designed electronic components or modifications of components so that all

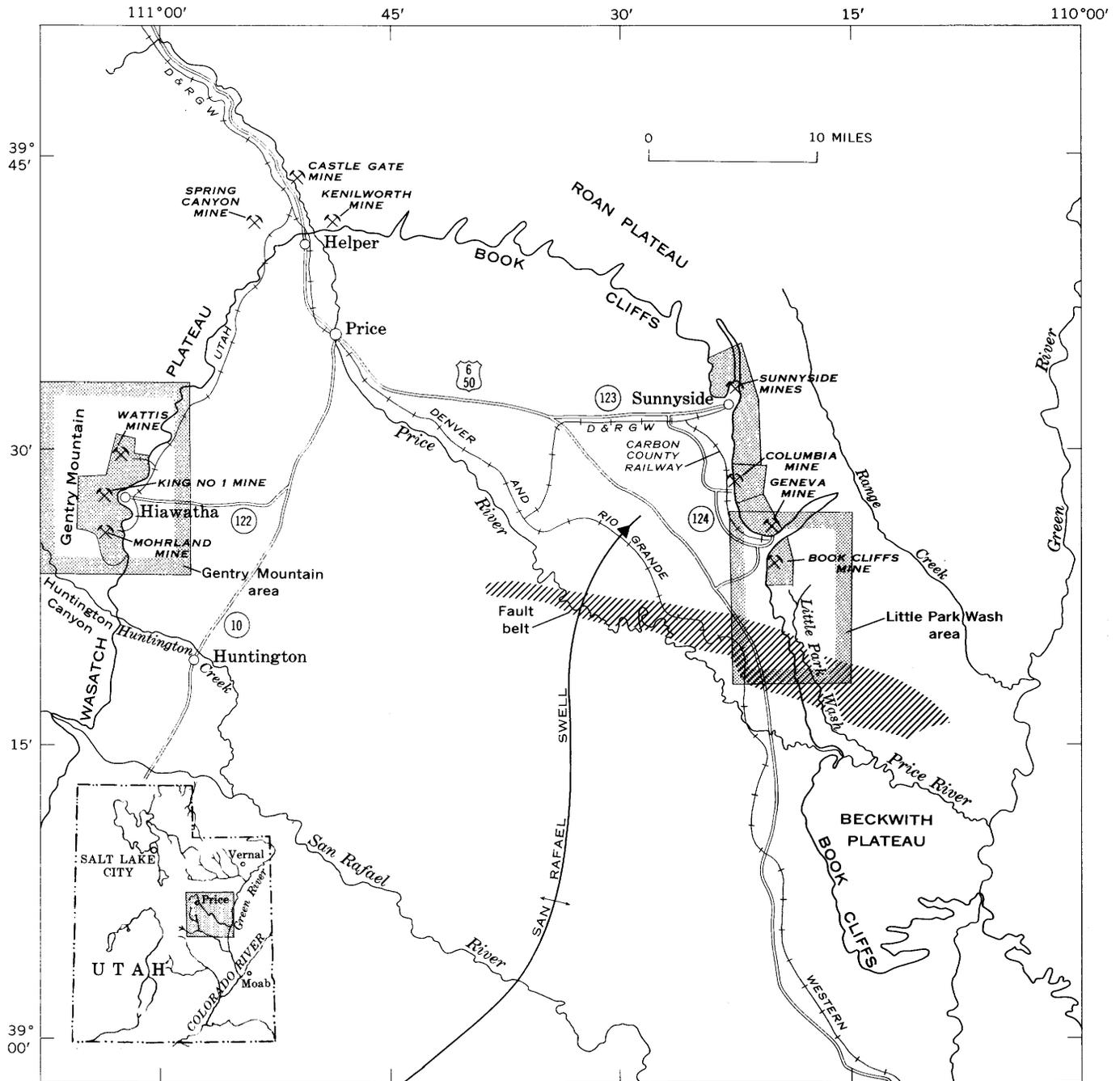


FIGURE 1.—Map of east-central Utah showing areas of this report. Mine areas stippled.

parts of the instrumentation system matched. He also assembled, tested, and calibrated the entire system and assisted with its field operation. Dunrud supplied geologic and mining data for the Gentry Mountain experiment and determined epicenters and foci of tremors at both sites. Maberry operated the instrument van, made playbacks from tape-recorded data at both sites, and supplied geologic data for the Little Park Wash experiment. All the men participated in installing, operating, maintain-

ing, and removing both networks after the seismic monitoring experiments were completed.

#### ACKNOWLEDGMENTS

Thanks are due many persons who directly or indirectly supported the investigations. Ira W. Hatch and Dean Collard, of the U.S. Forest Service, gave permission to use National Forest Land at Gentry Mountain and aided in selecting sites for the field camp, seismic network, and recording truck. Max

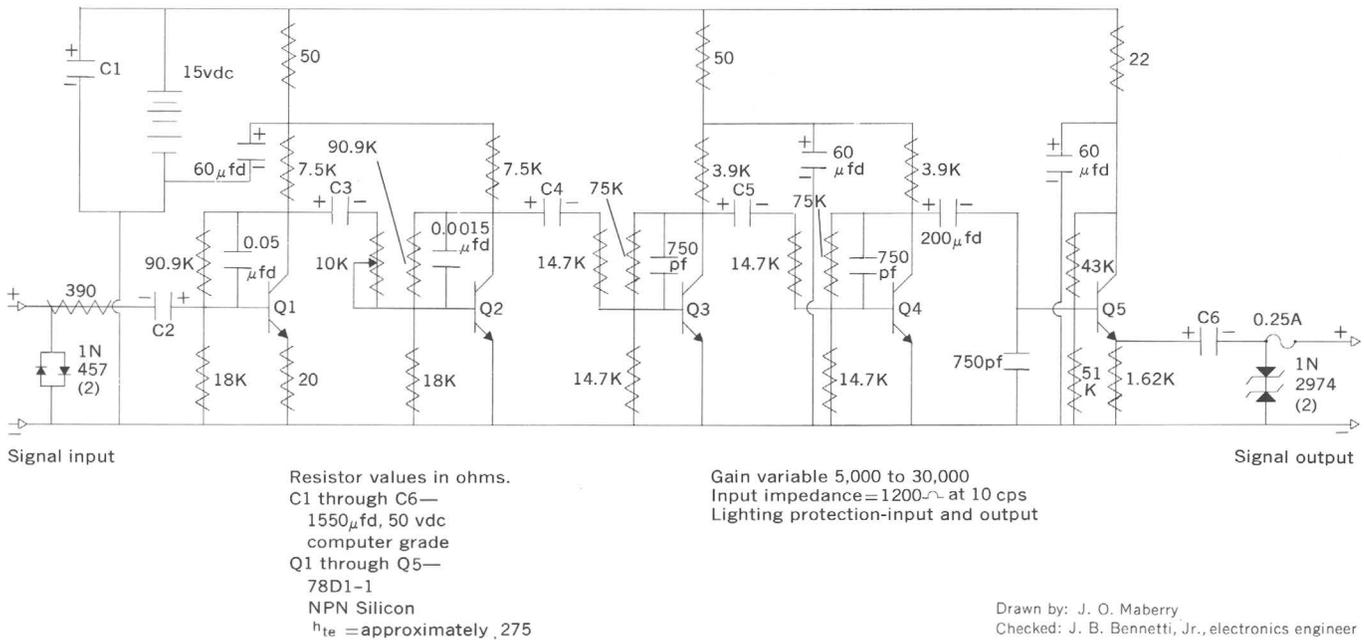


FIGURE 2.—Schematic diagram of preamplifier circuit.

A. Robb provided mining data and times of underground blasting during the Gentry Mountain monitoring. Gary Hansen, U.S. Bureau of Land Management, gave permission to use land and roads administered by the Bureau at Little Park Wash. R. M. von Storch, Joseph A. Harvey, and John Peperakis allowed access to lands and facilities administered by their companies during the monitoring at Little Park Wash. Special thanks are given to Friederich-Wilhelm Wellmer of the Mining University of Clausthal, Germany, for assistance in installing the network and for helpful geologic discussions at Gentry Mountain. Jerome Hernandez and Barton K. Barnes assisted the authors during the installation, operation, and removal of the Gentry Mountain network. Ray W. Osterwald voluntarily helped install the Little Park Wash network and maintained the signal wires throughout most of the recording period during an emergency at the beginning of the study in which additional personnel were needed to do the scheduled work. Mark Pradovich of Dragerton, Utah, provided logistic support during the work at Little Park Wash.

#### INSTRUMENTATION

Six Electro-Tech EV-17 vertical component seismometers arranged in two crudely L-shaped arrays were used in each field network. Total length of each network was about 7 miles; as a result, both direct and refracted compressional seismic waves were recorded on the seismograms. Sites for the seismometers were selected so that the instruments

could be buried in contact with bedrock; each site was surveyed to locate its position accurately within 100 feet. Each seismometer was wrapped in a plastic sack, placed on bedrock, and firmly covered with soil to insure good coupling.

Signals from the seismometers were fed into transistorized, high-gain, low-frequency preamplifiers specially designed for low drift and low power drain (figs. 2, 3). These battery-powered preamplifiers, modified from the design of preamplifiers used at Sunnyside (Maberry, 1966, p. 9; Osterwald and Dunrud, 1966, p. 101), operate without battery changes for long periods of time (fig. 4) under widely varying temperatures and were designed to transmit signals through as much as 20 miles of wire. The preamplifiers boosted electrical signals generated by the seismometer coils 7,500 times. The input impedance of these preamplifiers could be changed easily to match several types of transducers by installing suitable damping resistors inside the preamplifiers. Frequency response was flat, within 2 percent between 0.5 cycle per second to 300 cycles per second (fig. 5). Devices were incorporated in each preamplifier (fig. 2) to prevent high-voltage buildups in the signal lines which might result in lightning discharges. These devices, specially designed for the purpose, were installed on both the input and the output of preamplifiers, because earlier experience at Sunnyside indicated that high-voltage buildups between seismometer cases and coils frequently caused damage to seismometers and

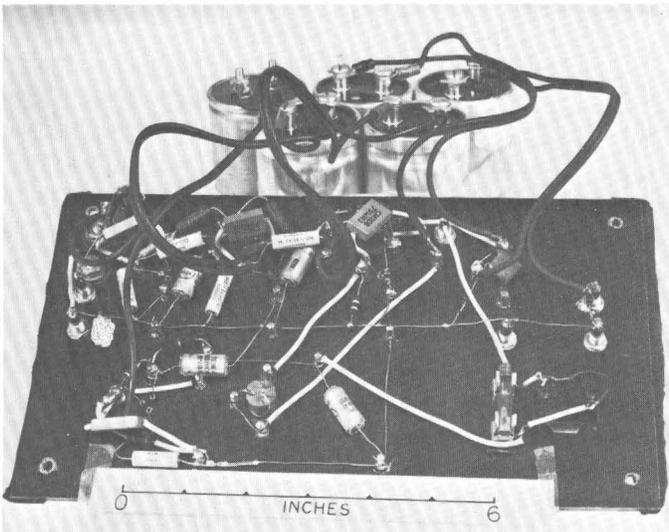
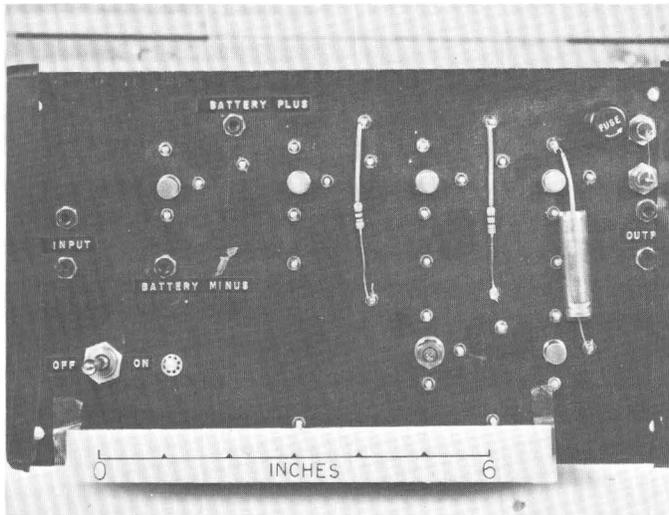
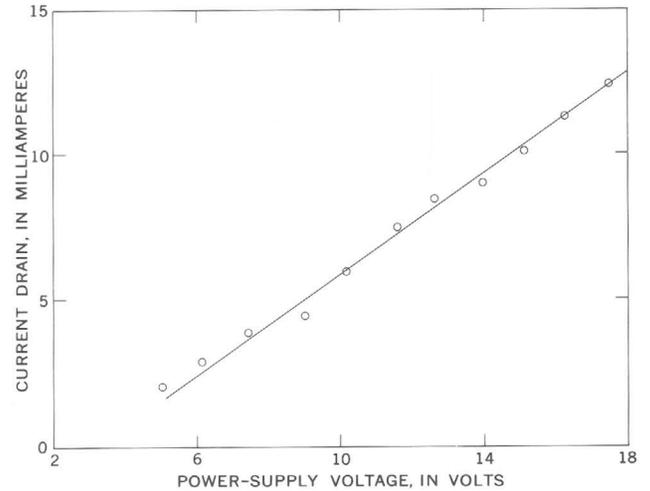


FIGURE 3.—Transistorized preamplifier. *Upper*, Exterior, showing packaging; *Lower*, Interior, showing construction.

preamplifiers. If electrical potential in the wires due to storms exceeded plus or minus 10 volts, these lightning safety devices shorted the potential in both wires to a one-point ground at the van. When used in a mobile network, each preamplifier, with its battery pack, was placed in a military surplus steel ammunition box near the seismometer.

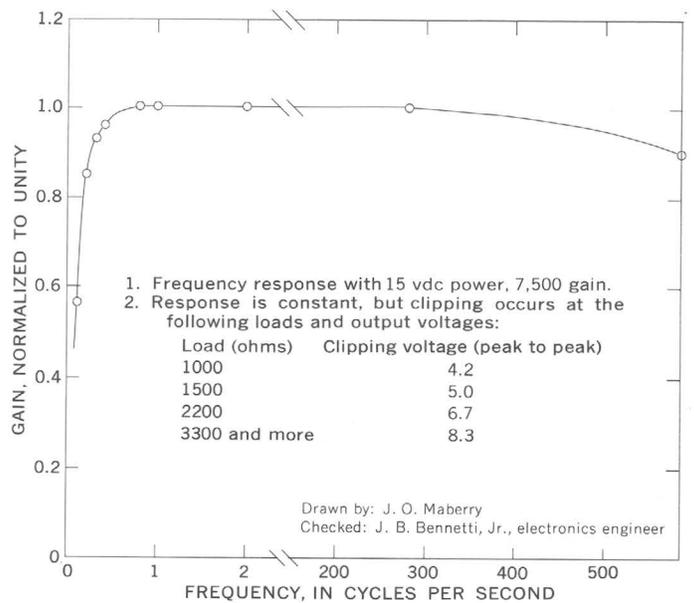
Signals from the preamplifiers were transmitted through military surplus twisted-pair telephone wires, which were laid on the ground or in brush or trees. The wires led directly to recording equipment mounted in a military surplus instrument van. Field camps were established near the van, because the operation of the instruments needed 24-hour supervision. Signals were divided inside the van (fig. 6); one part passed through variable attenuators (fig.



Drawn by: T. E. Miller, electronics technician  
Checked: J. B. Bennetti, Jr., electronics engineer

FIGURE 4.—Transistorized preamplifier current drain plotted against power-supply voltage.

7c) and then through specially designed pen-drive amplifiers (fig. 7a; fig. 8) to a 6-channel, electric-writing paper recorder (fig. 7b), and the other part passed through FM oscillators (fig. 7d) to a specially modified magnetic tape recorder (fig. 7e). The tape recorder, which had 14 channels for data, used 1-inch magnetic tape and was operated at a tape speed of 1.5 inches per second. Frequency response of the pen-drive amplifiers is shown on figure 9. Time marks were placed on paper records each minute by a chronograph (fig. 7f) consisting of a relay circuit closed by a 1-rpm (revolutions per minute) synchronous timing motor. The time marks



Drawn by: J. O. Maberry  
Checked: J. B. Bennetti, Jr., electronics engineer

FIGURE 5.—Frequency response of preamplifier.

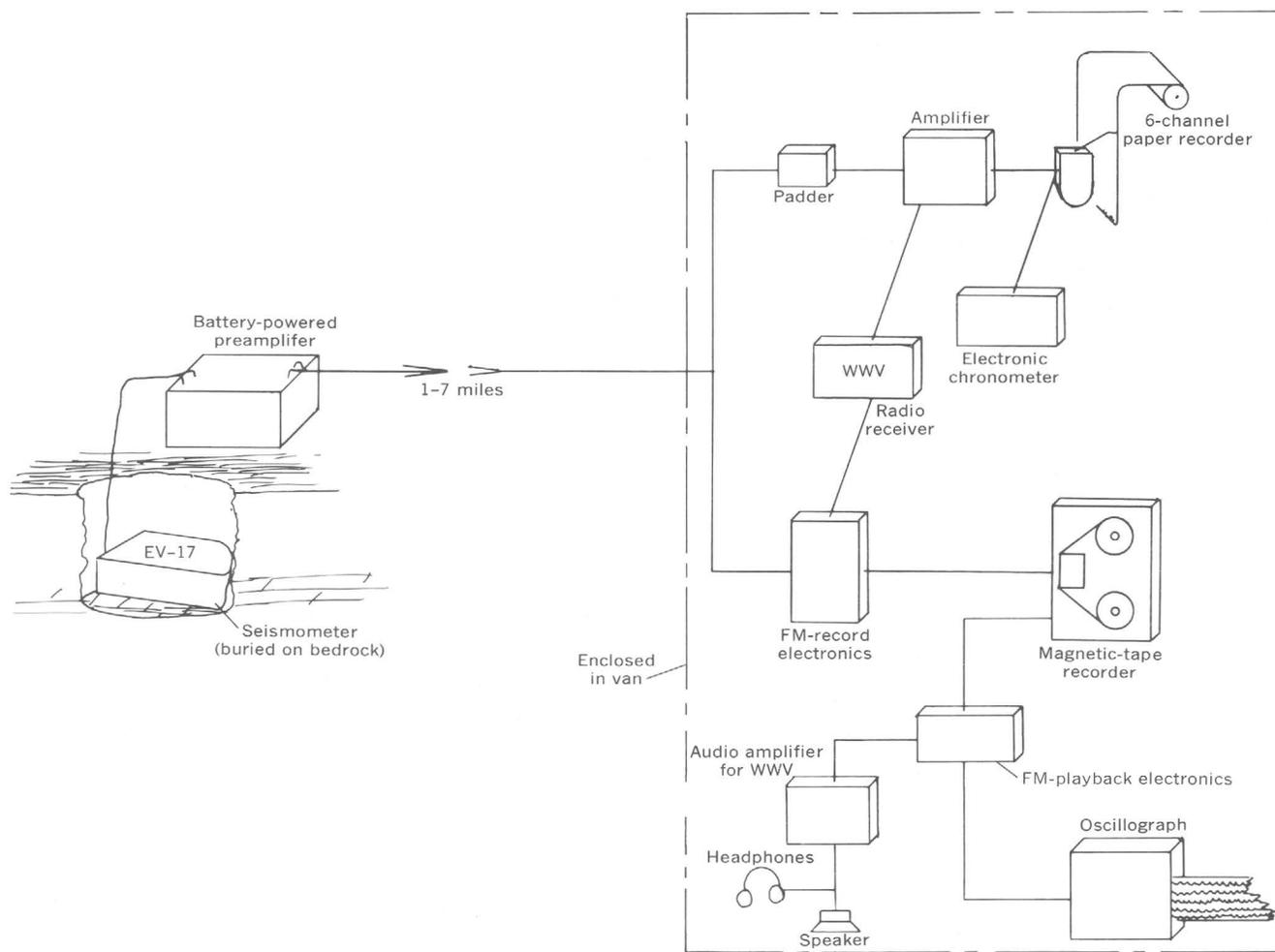


FIGURE 6.—Block diagram of field instrumentation.

provided a visual index so that tremors recorded on the magnetic tape could be located rapidly, as described briefly below. Radio time signal tones broadcast by the National Bureau of Standards radio station WWV were automatically recorded on paper records by means of a manually closed relay circuit (fig. 7*g*). The operator of the equipment referred the marks to Greenwich Mean Time by scaling the distance on the paper record from each time signal mark to the nearest minute mark recorded by the chronograph.

Recordings of tremors selected from the paper records by inspection were played back from the magnetic tape using specially designed transistorized playback and filter units (fig. 7, *h*) and a light-beam oscillograph (fig. 7, *i*). Direct-writing light-sensitive paper that required no liquid processing was used. Frequency response of the tape

system was flat from 0 to 200 cps (cycles per second); however, a filter (fig. 7, *k*) was usually inserted during data playback to prevent extraneous 60-cps noise from entering the oscillograph (fig. 10). Frequency response of the galvanometers in the oscillograph was flat from 0 to 100 cps. Voice and International Morse code time announcements from WWV were recorded continuously on one tape channel. Signals from this tape channel passed from the playback unit through an amplifier-filter unit (fig. 7, *j*) to headphones to enable an operator audibly to locate time signals on the tapes.

Electric power for the recording laboratory was provided by a 15 kilovolt-ampere gasoline-powered motor-generator unit mounted in a trailer. Voltage was maintained automatically at a constant level. Frequency, monitored by a meter on the unit, was adjusted manually by use of a throttle and was

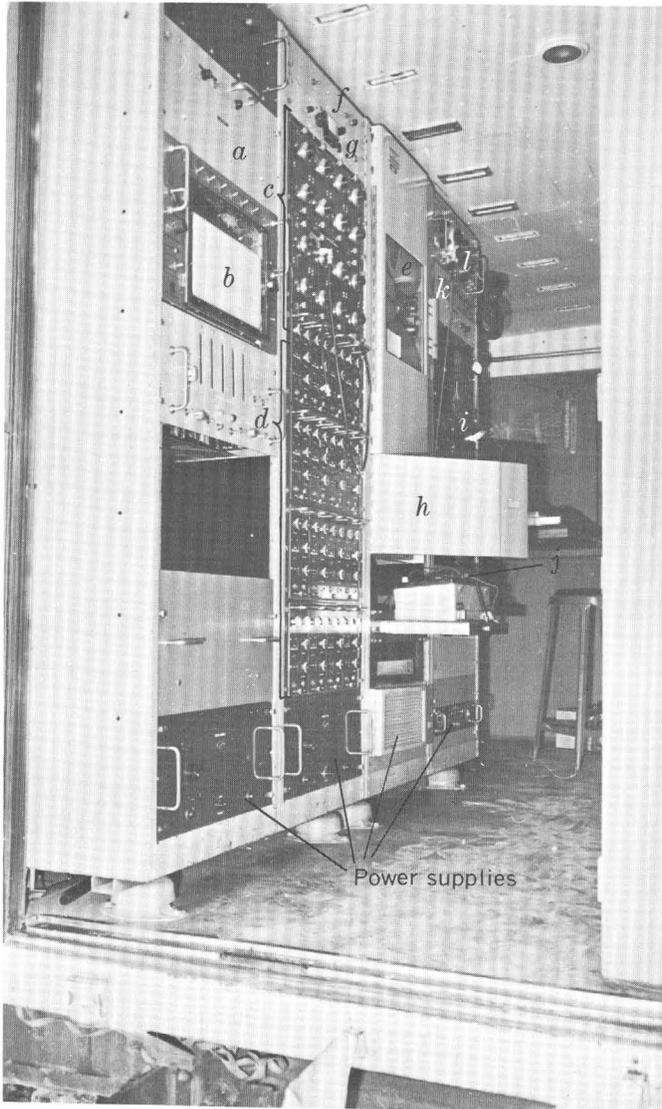


FIGURE 7.—Field seismic instrumentation installed in van. *a*, pen-drive amplifiers for paper recorders; *b*, paper recorder; *c*, attenuators; *d*, FM oscillators; *e*, magnetic tape recorder; *f*, chronograph; *g*, WWV radio receiver; *h*, tape playback and filter sections; *i*, oscillograph; *j*, audiodetector for WWV; *k*, low-pass filters; *l*, oscilloscope for visual monitoring of any channel.

maintained by a governor control. Usually the frequency was maintained at 59 to 61 cps. All components in the recording system were designed for long-term, but not necessarily continuous, operation. Nearly continuous operation could have been maintained for the 2-week periods if various mechanical cooling-system failures had not occurred in the motor-generator unit.

#### METHODS OF SEISMIC INTERPRETATION

Hypocenters (map positions and focal depths) of tremors recorded by both temporary networks were

determined using methods developed in the operation of the Sunnyside network. Seismic wave travel-time curves were plotted in color on clear mylar to make a protractor to be laid over a map of the area, using information obtained from three seismic refraction profiles in the Sunnyside district (Tibbets and others, 1966). The curves were drawn in different colors for easy reference by the operator. Because available geologic information indicated that seismic velocities in the Gentry Mountain and Little Park Wash area were about the same as at Sunnyside, this protractor was used without modification in both experiments.

To locate a tremor hypocenter, the operator measured from the seismogram the arrival time of the compressional wave and shear wave at each seismometer. A graph was then constructed to determine the origin time of a tremor, by plotting the difference in arrival times between compressional and shear waves at each seismometer against lapse of time, on the assumption that both waves were generated simultaneously at the tremor source. Travel times of the waves to each seismometer were determined by measuring the arrival time of the compressional wave at each seismometer and subtracting from it the graphically determined origin time.

Compressional wave traveltimes for a selected tremor were fitted to traveltime curves on the protractor by a method of repeated trials using successive approximations and gradually reduced errors to obtain the best solution. The hypocenter was located at one of the intersections of two families of irregularly elliptical curves when a best fit was achieved (fig. 11).

The traveltime curves on the protractor show in three dimensions the distance that direct and refracted compressional waves will travel radially from a source, in 0.1-second intervals for tremor sources ranging from 0 to 10,000 feet deep. When the oscillograph was operated at a speed of about 2 inches per second, timing lines were placed on the oscillograms every 0.1 and 0.01 second so that milliseconds could be interpolated if necessary. Interpolation between the curves on the protractor, coupled with the accuracy of oscillogram timing, yielded hypocenters accurate to within 750 feet horizontally and vertically of their true locations at both Gentry Mountain and Little Park Wash. Hypocenters of tremors for which no magnetic tape record was available, however, were accurate only to within 2,500 feet of their true locations, because arrival times of compressional waves were measured only on the paper records.

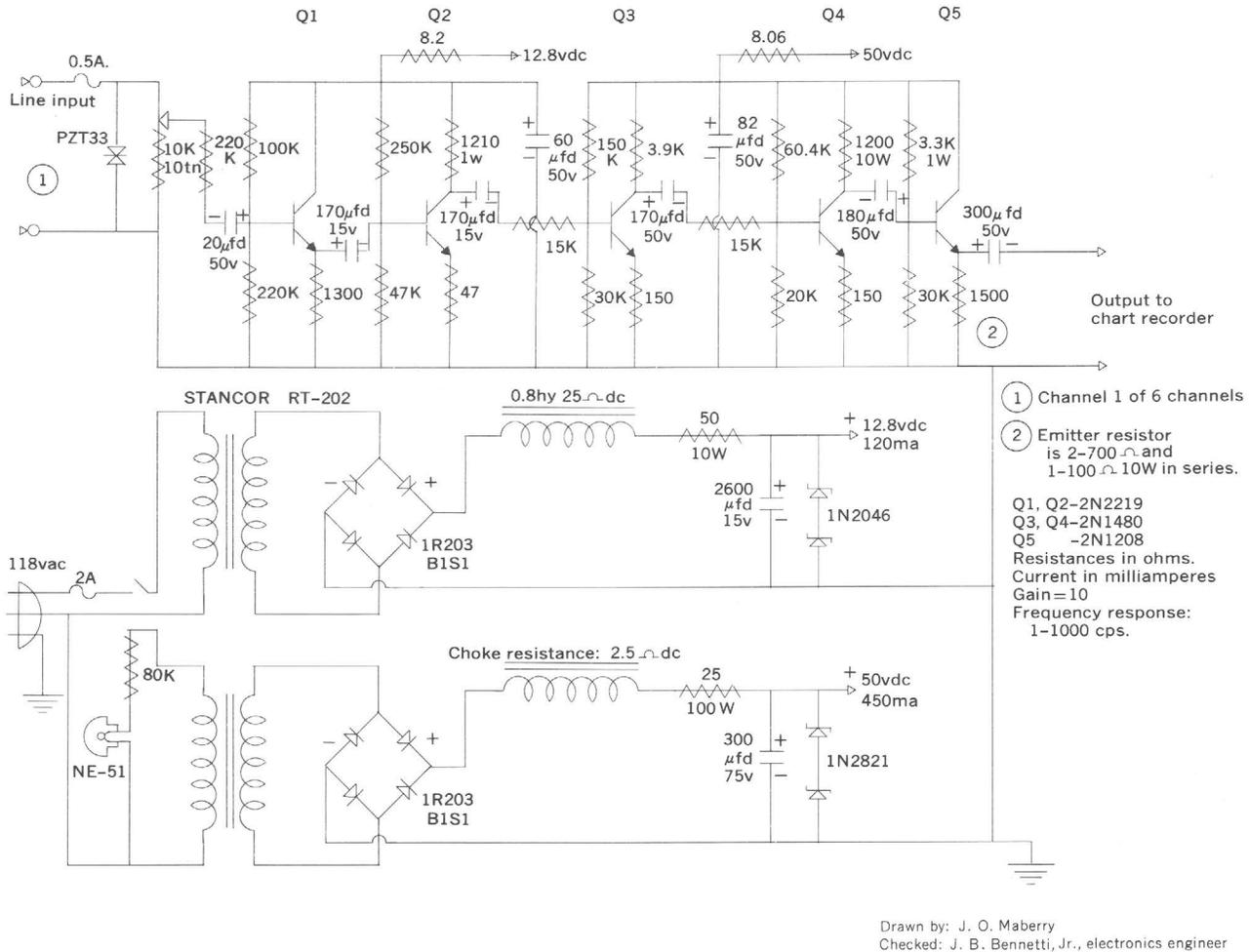


FIGURE 8.—Schematic diagram of pen-drive amplifier and power supply.

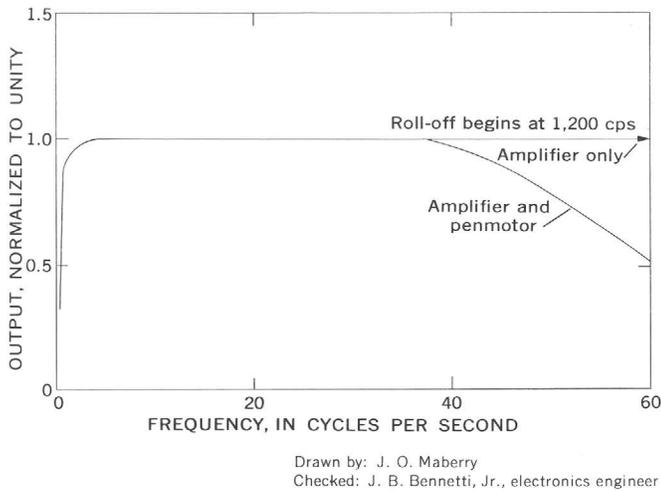


FIGURE 9.—Frequency response curves for pen-drive amplifier and for pen-drive amplifier plus penmotor.

**GENTRY MOUNTAIN MONITORING EXPERIMENT**

The vicinity of Gentry Mountain, 37 miles west of Sunnyside and 16 miles southwest of Price, Utah (fig. 1), was selected for the first seismic monitoring

experiment because of its geologic similarities to the Sunnyside district, its geographic position near the coal mining district near Hiawatha, Utah, in the Wasatch Plateau coal field, and its gently sloping upland topography.

The upland surface of Gentry Mountain is underlain by limestones and calcareous claystones of the Flagstaff Limestone (Paleocene and Eocene?). Non-coking bituminous coals in the Blackhawk Formation (Upper Cretaceous), crop out about 1,700 feet below the surface of Gentry Mountain in the cliffs to the east and along canyon walls of branches to Huntington Creek Canyon (fig. 1) to the west of the summit. These coals were deposited in a regressive sequence of marine, brackish-water, and nonmarine sediments similar to but stratigraphically below the sequence at Sunnyside, Utah (Clark, 1928, p. 15-16; Spieker, 1931, p. 26-27, 37-39; Young, 1955). Large, generally northwest-trending sandstone-filled channels in coal, known as "washouts" or "wants" by miners, occur at Hiawatha (Spieker,

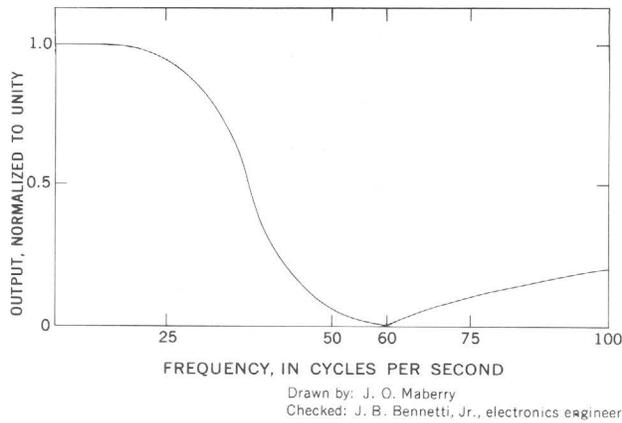


FIGURE 10.—Frequency response of optional low-pass filter for tape recorder.

1931, p. 63–64). Thick persistent beds of sandstone underlie the coals in both districts; at Gentry Mountain the sandstone beds form large, east-facing faceted cliffs which have many reentrants at the base of the Wasatch Plateau (Spieker, 1931, p. 7–8). Light-colored fine-grained igneous rocks were intruded along faults cutting rocks probably as young as Eocene (Flagstaff Limestone), both as dikes and as irregular masses west of Gentry Mountain (fig. 12). East of Hiawatha, dark-brown fine-grained micaceous igneous rocks were emplaced in Mancos Shale (Upper Cretaceous) as irregular masses along small faults.

Conspicuous north-trending faults cut the western part of the Gentry Mountain area and divide it into a series of ridges and valleys (known locally as “hollows”) (fig. 13) that corresponds to a series of horsts and grabens. These faults displace a stripped surface upon the Flagstaff Limestone by as much as several hundred feet. The stripped surface, presumably of late Tertiary or early Quaternary age, has a soil mantle as much as several feet thick. The soil locally contains residual limestone nodules, and it is found along the floors of hollows as well as on tops of ridges. Soil is thicker along the flanks of some ridges than on the tops. The soil probably is older than the major faulting.

Small stream courses are entrenched in some of the hollows, particularly near their confluence with large canyons. Large canyons tributary to Huntington Creek Canyon (such as Tie Fork Canyon shown in figs. 12 and 15) have cut across the hollows and ridges and apparently are the result of rapid erosion along modern master streams.

#### MINING IN GENTRY MOUNTAIN AREA

Room-and-pillar mines were opened at the outcrops of the coal beds near the towns of Wattis,

Hiawatha, and Mohrland (fig. 1) between 1909 and 1917 (Spieker, 1931, p. 2–3). Some sections of the mines at Hiawatha and Wattis were mined during the present study. In general, raises and slopes were driven up and down the very gentle westward and southwestward dips beneath Gentry Mountain. Entries were driven from the raises and slopes nearly parallel to the strike in both directions. Rooms were turned at intervals from the entries. Because of the very gentle dips and varying strike, mining produced a complicated pattern of workings wherein large unmined blocks of coal are surrounded by areas containing numerous pillars.

Extraction in previously mined areas is not complete. Large parts of Gentry Mountain are underlain by old mine workings that contain numerous small unextracted pillars which probably are highly stressed. Mining in the area is limited on the west by the easternmost of the north-trending high-angle faults (known locally as the Bear Canyon fault) because information from exploratory workings indicates that large inflows of water could be expected if mine workings were extended through the fault (M. A. Robb, oral commun., 1966). Large dangerous bumps have occurred in the mines (John Peperakis, oral commun., 1961), but serious mining problems have been avoided by abandoning mine sections prone to bumps.



FIGURE 11.—Traveltime-curve protractor used to locate tremor hypocenters. Each curve in a family of irregularly elliptical curves represents the traveltimes of compressional waves originating at different depths from the central area of the family of curves. When the predetermined correct traveltime curve intersects the map position of each seismometer, the hypocenter of the tremor is found at the center of the family of curves. Curves are of different colors for easy reference by the operator.



FIGURE 12.—Intrusive rocks west of Gentry Mountain, in northwest wall of Tie Fork Canyon. *Left*, Light-colored dikes in north-trending faults cutting Castlegate Sandstone (Cretaceous); *Right*, Light-colored intrusive mass in north-trending faults cutting strata from Castlegate Sandstone (Cretaceous), at bottom of picture, to North Horn Formation (Cretaceous and Paleocene) on skyline along northwest wall of Tie Fork Canyon. Fault is the east side of a graben forming Wild Cattle Hollow.

#### SEISMIC WORK AT GENTRY MOUNTAIN

Seismic activity at Gentry Mountain was monitored between August 28 and September 10, 1967. Recording was not continuous during this period because of several mechanical failures and because cattle frequently broke the signal wires. Actual recording time is estimated to be about 75 percent of the total time.

Seismometers were arranged in two elongated triangular arrays in the western part of the Hiawatha mining area (fig. 15); part of the southern array was adjacent to the active mining sections of the King mine No. 2. Geologists conducting this study lengthened the westward-trending legs of both arrays to cross some of the north-trending horsts and grabens (McCadden and Gentry Hollows) in the

hope that epicenters and focal depths of tremors originating along the faults might be accurately determined.

During the time the Gentry Mountain network was operated, 109 seismic tremors were recorded; 37 tremors were large enough to measure and to determine positions of hypocenters. Most of these were of local origin; their sources were within the area of the network. A few distant earthquakes were recorded, and the response of the mobile system was calibrated roughly by comparing the amplitudes of these earthquake records with amplitudes of the same earthquakes on records from the Sunnyside network on which magnitudes could be determined. Recorded were at least two sonic booms from aircraft that were felt and heard by project personnel.

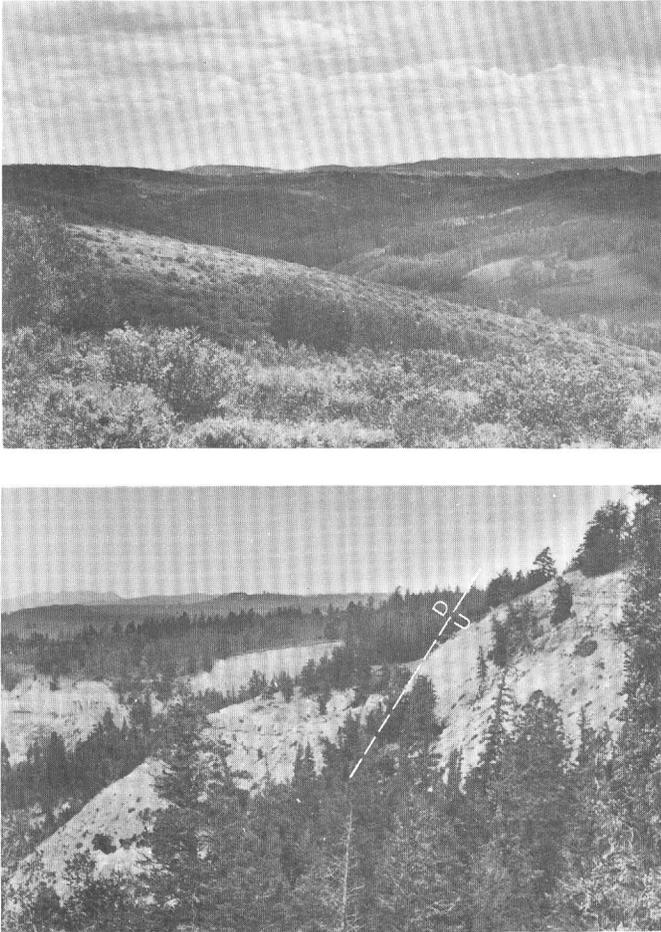


FIGURE 13.—Graben and fault near Gentry Mountain.

*Upper*, View south along crest of Gentry Mountain showing graben of McCadden (left distance) and Gentry (right foreground) Hollows; *Lower*, Bear Canyon fault cutting Flagstaff Limestone (Paleocene and Eocene?) near east margin of McCadden Hollow. Outcrop is along steep northeast wall of Huntington Creek Canyon that has resulted from late-stage rapid erosion along modern drainage systems. U, upthrown side; D, downthrown side.

Richter magnitudes of the seismic waves generated by these sonic booms were estimated to be between 1.0 and 1.8, compared with seismograms of earthquakes of similar magnitudes.

Two general types of tremors were recorded at Gentry Mountain. One type consisted of numerous small shallow-focus tremors originating within or near the mining areas and producing seismograms similar to those of most tremors recorded at Sunnyside (figs. 14, 17). Tremors of the second type produced seismograms with longer wave trains in which wave groups were separated (fig. 16) and originating at slightly greater depths than those of the first type.

Although tremors of the first type originated in or near mining areas, they were more frequent on

days when no mining was done (fig. 18A), in contrast to similar tremors at Sunnyside which are more numerous during times of active coal mining. The tremors were not caused by blasting in the mines, because nearly all occurred at times when no blasting was being done (M. A. Robb, written commun., 1967). Tremors from a few blasts were recorded, but these were of small amplitude and were detected by only one seismometer near the actively mined sections. The cyclic pattern of these tremors differs from that of similar tremors at Sunnyside (fig. 18A, B), probably because of differences in geologic structure and mining practices at the two localities. Tremors of the first type probably result from the redistribution of stresses as a result of mining. The sharp rise in daily number of tremors during mining in the northern part of the Sunnyside district as compared to the drop in daily number of tremors during mining at Gentry Mountain (fig. 18A) may be due to different mining procedures at Gentry Mountain. Most of the mining beneath Gentry Mountain is development work, in which pillars are left standing, whereas most at Sunnyside is production work in which as many pillars as possible are completely removed. Stress probably is relieved much more slowly during development work because support is removed slowly. The differences in the number of tremors in the northern and southern parts of the Sunnyside district (fig. 18B) may be the result of differences in fault patterns in the two parts of the district (Barnes and others, 1969, p. 3).

Recorded at Gentry Mountain, tremors of the second type, which originated along the major north-trending faults bounding the west side of Gentry Mountain, were much less frequent than those of the first type and showed no apparent correlation with mining. These tremors probably result from release of stress concentrated along the faults. Some of this stress concentration may be due to readjustments made in response to mining, but some may be due to release of natural stress. Existence of natural stress in the area is probable, because small earthquakes are reported commonly along similar north-trending faults a few miles to the west of Gentry Mountain (for example, see U.S. Coast and Geodetic Survey, 1968, p. 5).

#### LITTLE PARK WASH MONITORING EXPERIMENT

The area of Little Park Wash is an intermittent stream valley east of and nearly parallel to the west-facing Book Cliffs about 13 miles south of Sunnyside, Utah. It was selected for the second monitoring experiment because of access afforded by an oc-

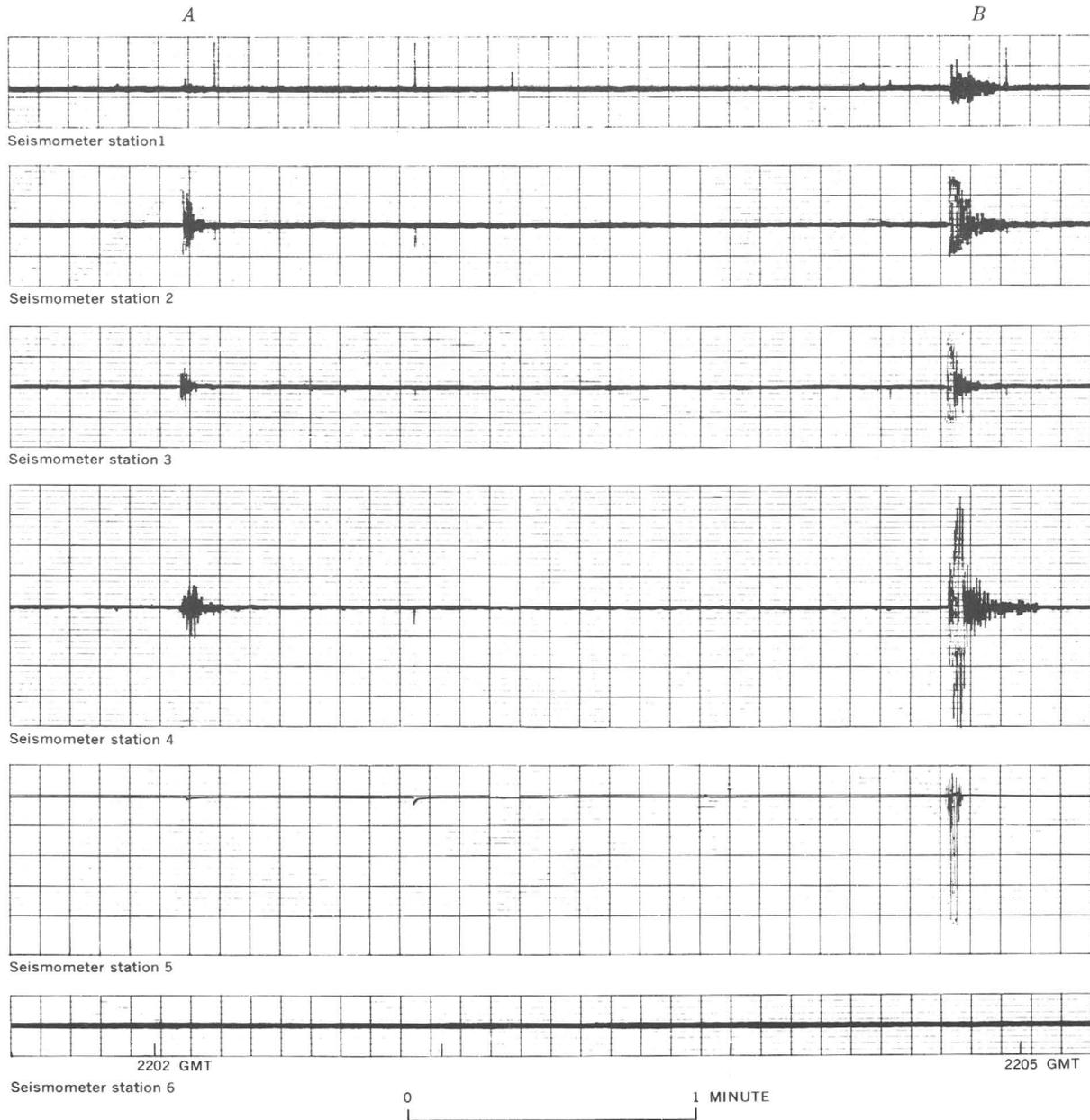


FIGURE 14.—A. Seismogram showing first type of tremor recorded at Gentry Mountain, Sept. 4, 1967; Richter magnitude, 1.4; epicenter shown on figure 15 by letter A. B. Seismogram showing first type of tremor recorded at Gentry Mountain, Sept. 4, 1967; Richter magnitude, 1.9; epicenter shown on figure 15 by letter B.

casionaly maintained road which crosses a conspicuous belt of west-northwest-trending faults—and because it overlies a large block of unmined coal about 15 miles by 5 miles in map dimensions adjacent to the Sunnyside district, where future mining is planned. Some tremors recorded by the Sunnyside monitoring network probably originated along this fault belt, even though it was impossible to determine their epicenters accurately because of their distance outside the network. Local mine officials shared the authors' opinion that movements were

occurring along faults in the belt, as indicated by the active rockfalls from the face of the Book Cliffs (J. B. McKean, oral commun., 1968). Whether or not tremors occur in an area of coal deposits before mining begins is of considerable scientific and economic interest in predicting future mining conditions and in determining whether natural stresses cause the numerous tremors that occur in the Sunnyside district.

Little Park Wash is an intermittent stream that flows generally southward an unusually short dis-



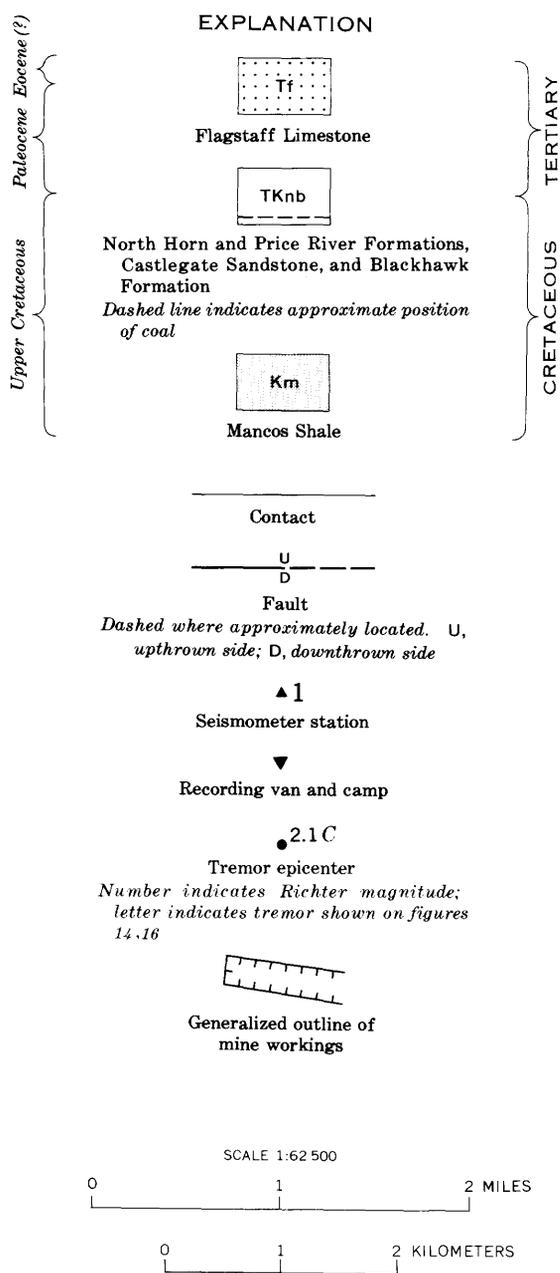


FIGURE 15.—Map of Gentry Mountain area, showing generalized geology, temporary seismometer locations, tremor epicenters, and generalized mine workings. Seismograms for hypocenters A and B shown on figure 14 ; for C, on figure 16 . Geology by C. R. Dunrud and F. W. Osterwald, 1967, modified in part from Spieker (1931). Base from U.S. Geological Survey, Hiawatha and Scofield 15-minute quadrangle maps, 1:62,500, 1923.

tance behind the main escarpment of the Book Cliffs (fig. 1). A broad alluvial flat entrenched as much as 15 feet by the present stream extends along the upper course of Little Park Wash. Meanders in the lower course are entrenched as much as 250 feet into the Bluecastle Sandstone Member of the Price

River Formation and into the Castlegate Sandstone. Near the Price River the wash is entrenched into the Blackhawk Formation. The wash is a major tributary to the Price River, which is superimposed upon the present regional structure and topography. Little Park Wash, however, soon will be captured by westward-trending watercourses down the face of the Book Cliffs. At one point near the recording van and camp (fig. 21) the bed of the wash is less than a fourth of a mile from the face of the cliffs. In sec. 26, T. 16 S., R. 14 E., one of the major tributaries to Little Park Wash already has been captured. Because they cause rapid erosion, ephemeral streams on the Mancos Shale and along the face of the cliffs are forming a new westward- and southwestward-flowing drainage pattern which is destroying the older superimposed drainage pattern.

Most of the land surface in the Little Park Wash area was formed on the Bluecastle Sandstone Member of the Price River Formation (Upper Cretaceous), the Castlegate Sandstone (Upper Cretaceous), and the calcareous mudstones, siltstones, and sandstones of the North Horn Formation (Upper Cretaceous and Paleocene). Locally, residual sandy soil has formed on the surface, and many watercourses are filled with alluvium. A steep, maturely dissected upland ridge of alternating layers of reddish cliff-forming sandstones and non-resistant calcareous mudstones of the Colton Formation (Eocene) trends northward roughly parallel to and 1 to 3 miles east of Little Park Wash. Locally, sandstones of the North Horn Formation and sandstones and limestones of the Flagstaff Limestone (Paleocene and Eocene?) form benches 25-100 feet above the alluvium-covered floor of Little Park Wash.

Structure in the Little Park Wash area is simple. Rocks near Little Park Wash dip eastward from  $5^{\circ}$  to  $10^{\circ}$ . They are cut by a few steeply dipping east- and southeast-trending normal faults and have as much as 275 feet of stratigraphic separation, although the amount of separation lessens to the east as the faults pass upward into the Colton Formation. The rocks are also cut by a swarm of west-northwest-trending faults that is part of a major fault belt, as much as 4 miles wide, which was traced northwestward about 28 miles from the confluence of Range Creek and the Green River (fig. 1). Structure sections through this fault belt suggest that it is the collapsed crest of a faulted anticline.

Bituminous coking coal in the Blackhawk Forma-

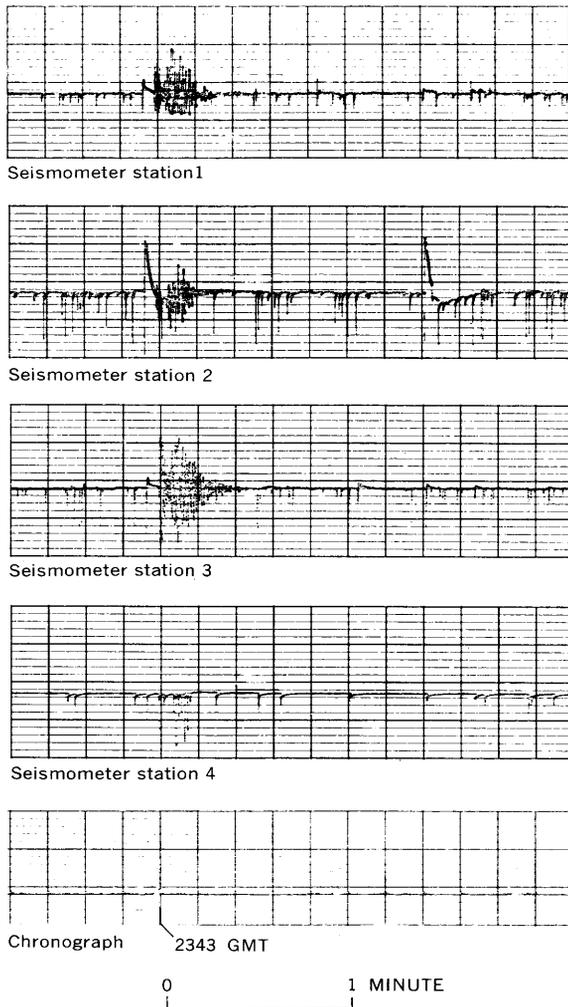


FIGURE 16.—Seismogram showing second type of tremor recorded at Gentry Mountain, Sept. 8, 1967; Richter magnitude, 1.9; epicenter shown on figure 15 by letter C.

tion (Upper Cretaceous) underlies Little Park Wash between 100 to 850 feet below the surface, in the area of figure 21. Below the coal is a persistent cliff-forming sandstone unit about 130 feet thick; above the coal is a 100- to 200-foot-thick sequence of siltstone and shale beds, containing lenses of thin-bedded sandstone, which is overlain by the Castlegate Sandstone. The coal and its associated rocks are part of a regressive sequence of marine, brackish-water, and nonmarine rocks which were formed during a generally eastward withdrawal of the Cretaceous sea (Spieker, 1949).

#### MINING AT LITTLE PARK WASH

The Geneva (Horse Canyon) coal mine, from which much of the coal mined in the Sunnyside district is produced, is a few miles north of the Little Park Wash area (fig. 21). Coal is mined in the Geneva mine by driving multiple entries nearly

parallel to the strike of coalbed outcrops in Horse Canyon; slopes are driven downdip at intervals along these entries. Other multiple entries are driven nearly parallel to the strike at intervals along the slopes. Coal beneath large westward-projecting points of the Book Cliffs that are isolated by deep canyons is mined from raises driven updip. All mining is by room-and-pillar methods, in which rooms are driven updip from various entries, and pillars are extracted during the retreat. A pair of exploratory entries were driven southeastward from the Geneva mine into a large block of unmined coal beneath the northern part of the Little Park Wash area; otherwise, no mining has been done in the area of the monitoring experiment.

Coal extraction within the Geneva mine has not been complete, partly because of difficulty in controlling the roof when some pillars are removed and partly because some large blocks of coal are lost through damage from bumps. Large bumps have occurred in the mine (Dunrud and Osterwald, 1965, p. 177, 180-181). Many earth tremors, some of them related in space or time to bumps, were recorded in and near the Geneva mine by the Sunnyside seismic monitoring network (Osterwald and Dunrud, 1966, p. 103-104).

The Book Cliffs mine also was located a few miles north of the Little Park Wash area and about 1 mile south of the Geneva mine portal (fig. 1). The mine, which was owned by the Book Cliffs Coal Co., was opened about 1945 as a source of industrial coal. Multiple entries were driven at small angles to the strike, and diagonal raises were driven at angles of about 30° to these entries. Areas between diagonal raises were opened by rooms and crosscuts driven nearly parallel to the strike and dip. Square pillars that resulted from opening the rooms and crosscuts were removed in final stages of mining. The mine was small, occupying only the area beneath two prominent westward projections of the Book Cliffs, but mining was profitable because the coal was as much as 22 feet thick. As pillars were removed, spectacular subsidence cracks appeared in the Book Cliffs, and many loose rocks fell from the cliffs. The mine was abandoned in 1967.

#### SEISMIC WORK AT LITTLE PARK WASH

Seismic activity along Little Park Wash was studied from August 17 to August 30, 1968. Two elongated triangular seismometer arrays that trended roughly north-northwest were arranged so that the northernmost seismometer was more than 7 miles from the southern (fig. 21). The northern-

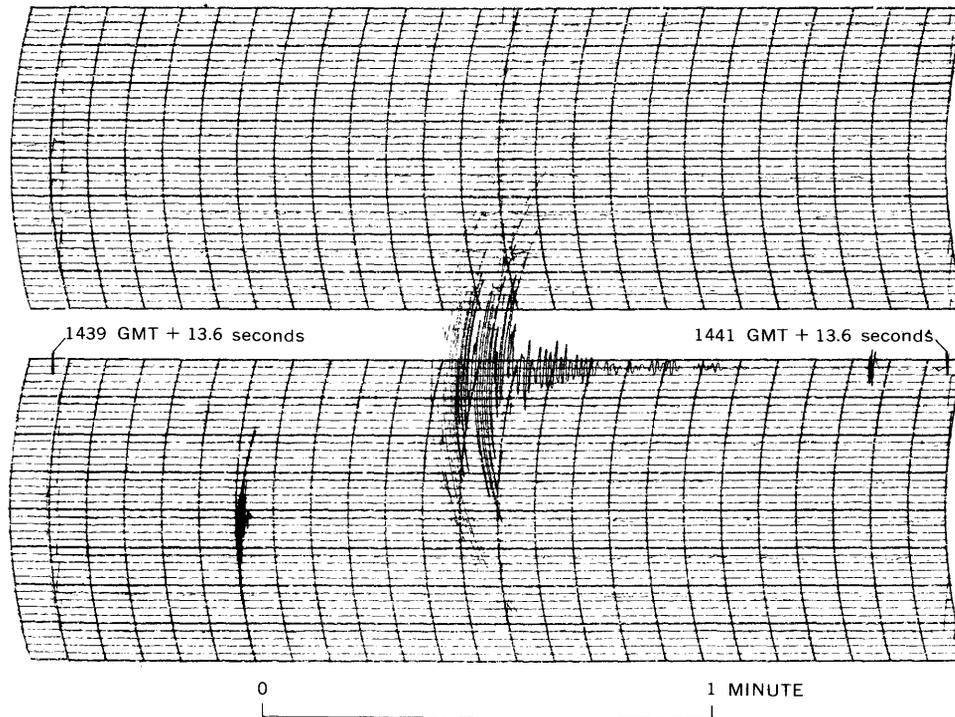


FIGURE 17.—Seismogram of large local tremor recorded in northern part of Sunnyside district, Dec. 26, 1963; Richter magnitude, 3.7.

most seismometer was about a half mile north of the southern boundary of the Geneva mine. This distance between the two seismometer arrays was considered necessary to insure a distinction between compressional seismic waves that were refracted along a layer of Paleozoic carbonate rocks (Tibbetts and others, 1966) and compressional waves that traveled directly from their sources. Consequently, focal depths of the tremors could be determined accurately.

Recording on chart paper was almost continuous during the monitoring period except for short times when the motor-generator was shut down for servicing, and it was estimated to be effective more than 90 percent of the total time. Recording on magnetic tape was lost for about 36 hours during the first part of the recording period because some personnel were unfamiliar with operation of the tape deck. High winds produced excessive "tree noise" during the first few days of recording. "Tree noise" is caused by wind moving trees, which in turn locally move the ground. After a few trees near the seismometers were removed, records became very clear.

About 70 tremors were recorded by the network along Little Park Wash. Nearly all of these tremors large enough to measure (Richter magnitudes rang-

ing from 1.5 to 2.8) originated in or near the southern part of the Geneva mine at depths of as much as 3,000 feet below the mine level and within 7,000 feet laterally of the active mining area (fig. 21). Most were restricted to a block bounded on two sides by eastward-trending faults. Nearly all the tremors too small to measure were recorded only by the seismometers closest to the Geneva mine, which indicates that these small tremors also originated in or near the southern part of the Geneva mine (fig. 19). A few tremors of small amplitude and long wave train were recorded (fig. 20); their epicenters were southwest of the network and probably were within the San Rafael Swell (fig. 1). Some of the tremors within or under the Geneva mine were sufficiently large to be recorded also by the Sunnyside network; therefore, amplitudes could be compared between the two networks.

The occurrence pattern of tremors recorded at Little Park Wash corresponds generally with the occurrence pattern of those recorded at Sunnyside. The pattern particularly corresponds to the mining work cycle in the Geneva mine (fig. 22A), although individual peaks and troughs during the latter part of the recording period do not precisely coincide. This lack of coincidence is not clearly understood, but it is probably the result of the response of the

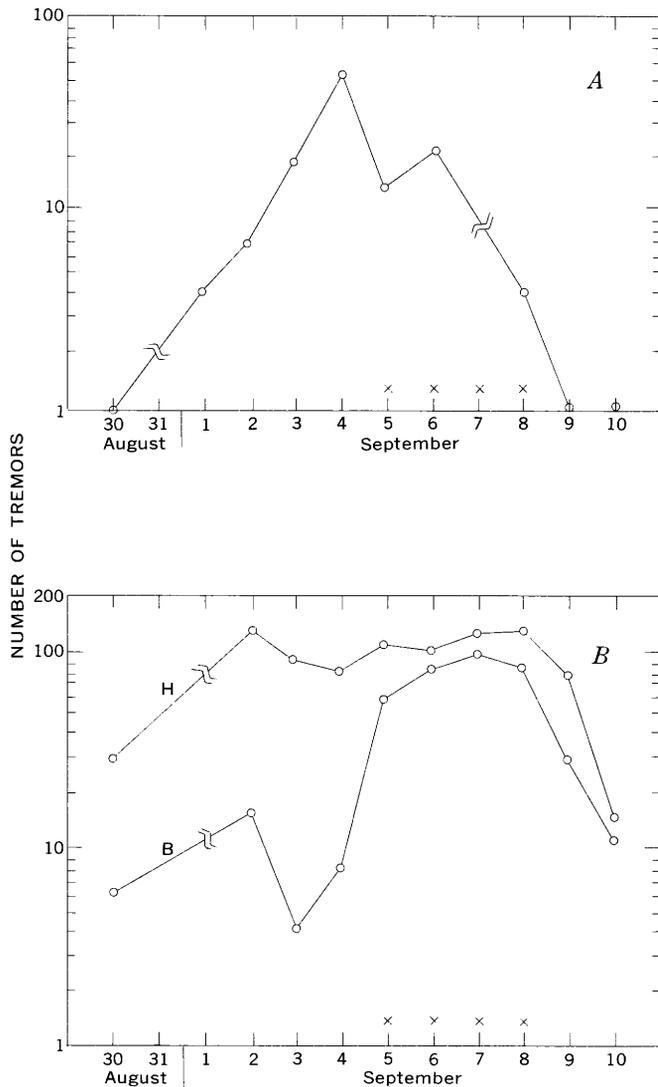


FIGURE 18.—Semilogarithmic plot of recorded tremors per day at Gentry Mountain (A) and at Sunnyside (B) for the period August 30 to September 10, 1967. H, Horse Canyon seismometer (southern part of Sunnyside district); B, Bear Canyon seismometer (northern part of Sunnyside district). X, day the mines were worked. Broken curve indicates day of poor data because of equipment failures.

Horse Canyon seismometer to stress readjustments along faults in the abandoned Columbia mine (fig. 1). Differences were expected in the occurrence pattern curves from the seismometers of the network at Little Park Wash and that at the Bear Canyon locality of the Sunnyside district. These differences, which are similar to those noted previously by Barnes and others (1969, p. 3), probably arise because geologic features and mining practices are different in the northern (Bear Canyon) and southern (Horse Canyon) parts of the Sunnyside district.

Seismograms are affected by the source mechanism at the focus of tremors, by the paths of seismic waves through the earth, and by geologic features along the paths of waves (Simon, 1968, p. 1). Similar seismograms, therefore, if recorded on similar instruments, suggest similar tremor origins and similar paths of the resulting waves. Most tremors recorded at Little Park Wash yielded seismograms similar to many of those recorded at Sunnyside, as well as to those of the first type recorded at Gentry Mountain (figs. 14, 16, 17, 19, 20). These similarities indicate that all these tremors were of similar origin and were caused by shallow stress readjustments to mining activity. They were small manmade earthquakes.

#### SUMMARY AND CONCLUSIONS

Earth tremors that originate in coal mining areas are related to geologic features and to active coal mining. Because of the cyclic pattern of occurrence of such tremors, special components and techniques are needed to permit nearly continuous seismic monitoring under difficult field conditions for a period of at least 2 weeks, or for a period long enough to include at least one cycle of repetition. Results from seismic monitoring experiments at Gentry Mountain and Little Park Wash, Utah, indicate that the seismic activity recorded by a fixed network in the Sunnyside district, Utah, is not unique because similar kinds and similar numbers of tremors occur in and around at least one other active coal mining area. Shallow-focus tremors at Gentry Mountain occur in and around active mining areas, as do similar tremors at Sunnyside. A large block of unmined coal adjacent to the Sunnyside district in the Little Park Wash area was seismically quiet during the monitoring period. These facts indicate that large stress concentrations may be caused by removal of coal. As shown by the distribution of hypocenters, stress readjustment may extend thousands of feet below, and as much as 2 miles distant from, active mining areas.

Faults are convenient loci for stress concentrations resulting from mining in nearby areas. Although some tremors originated along faults outside active mining areas at Gentry Mountain, very few tremors occurred in similar environments at Little Park Wash. Natural stress may have more influence on the generation of some tremors at Gentry Mountain because of the major faults that form the eastern margin of the Wasatch fault zone. These faults are sources of many earthquakes.

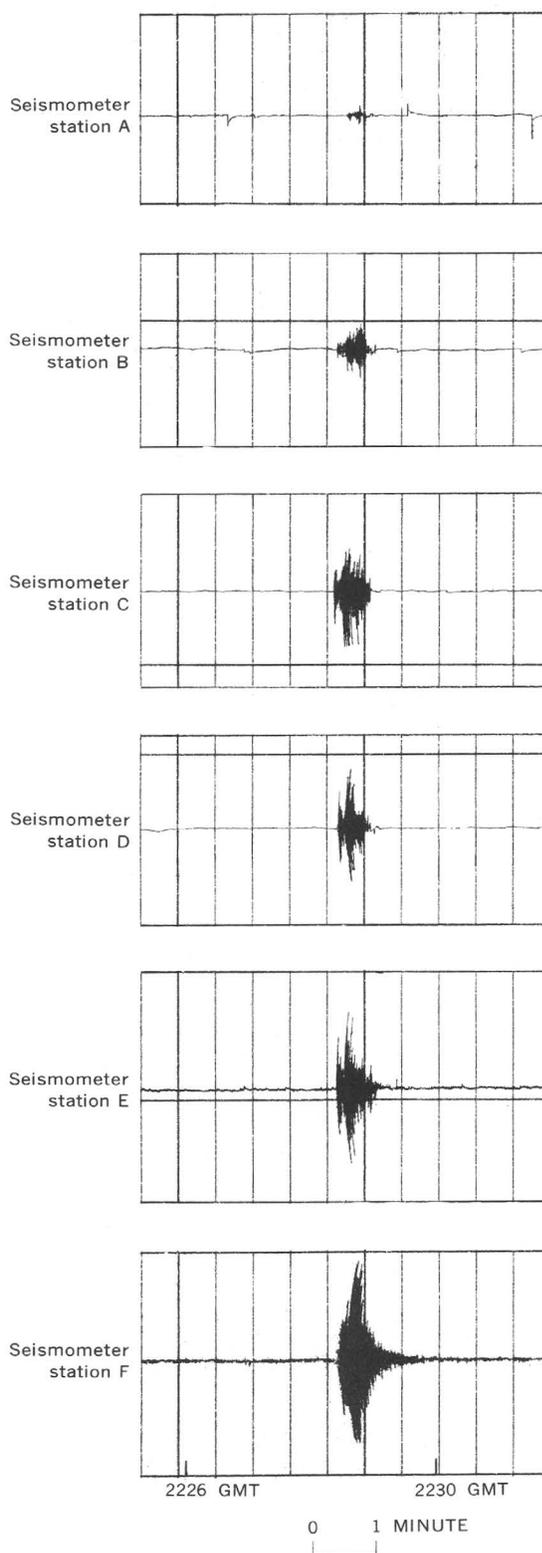
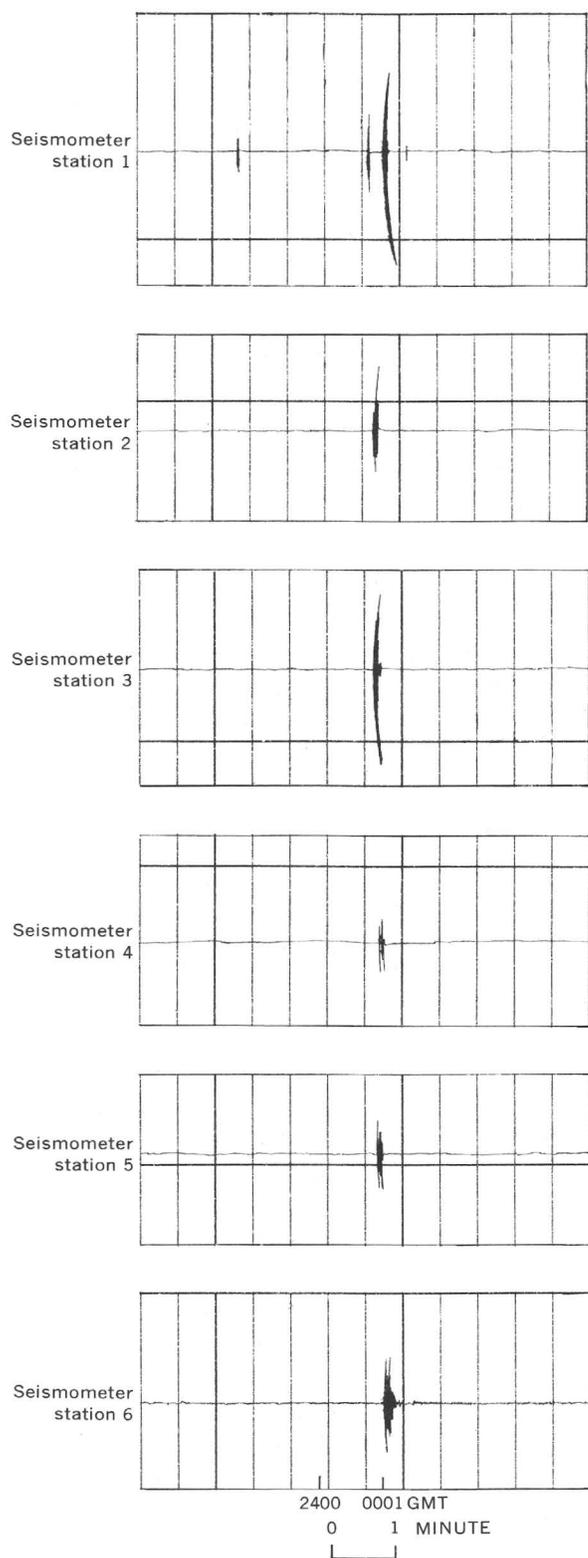


FIGURE 19.—Seismogram of tremor in southern part of Geneva mine, recorded at Little Park Wash, Aug. 26, 1968; Richter magnitude, 2.0; hypocenter is marked D on figure 21.

FIGURE 20.—Seismogram of tremor recorded at Little Park Wash, Aug. 26, 1968, from source south and west of network; Richter magnitude unknown.



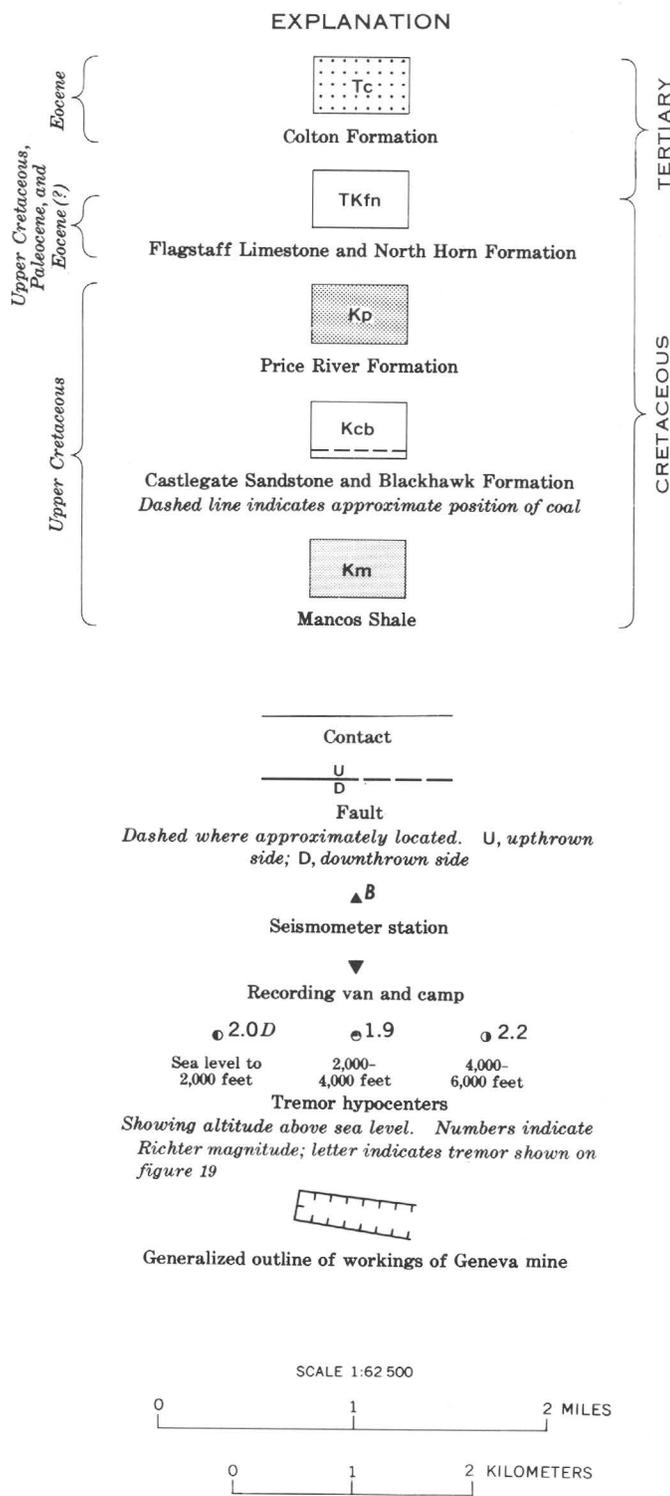


FIGURE 21.—Map of Little Park Wash area, showing generalized geology, temporary seismometer stations, tremor epicenters, and generalized mine workings. Geology by J. O. Maberry and F. W. Osterwald, 1968. Base from U.S. Geological Survey, Woodside, 15-minute quadrangle map, 1:62,500, 1948.

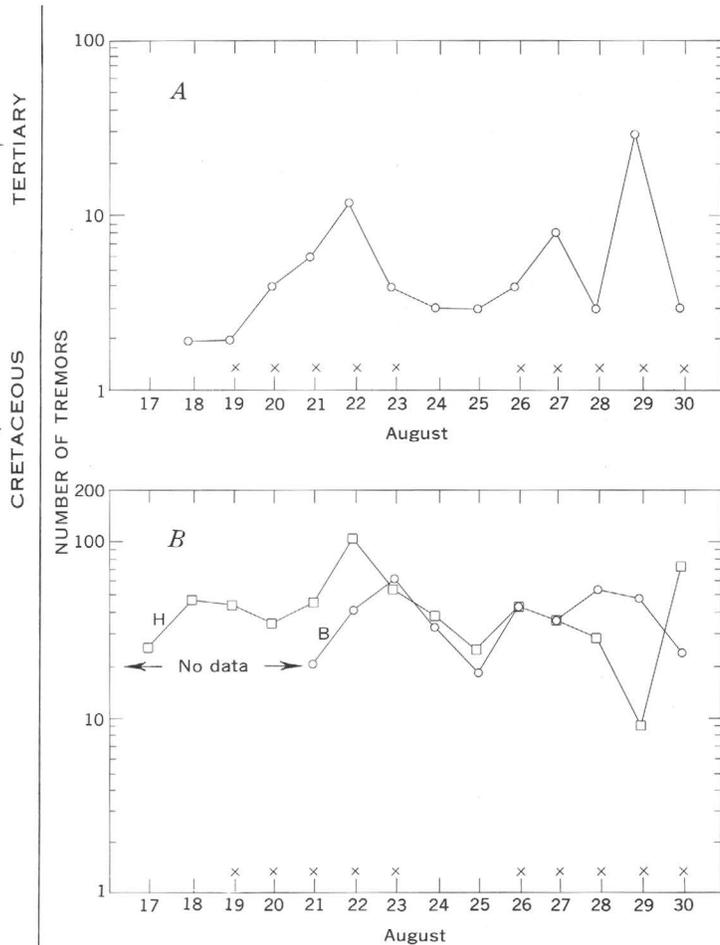


FIGURE 22.—Semilogarithmic plot of recorded tremors per day at Little Park Wash (A) and at Sunnyside (B) for the period August 17-30, 1968. H, Horse Canyon seismometer (southern part of Sunnyside district); B, Bear Canyon seismometer (northern part of Sunnyside district). X, day the mines were worked.

Cyclic repetition of shallow-focus tremors recorded at Little Park Wash shows a general relation to mining work cycles, as do similar tremors recorded in the southern part of the Sunnyside mining district. Similar cyclic repetition of tremors at Gentry Mountain does not coincide with mining workweeks, however, possibly because the mines there are engaged primarily in development work and both stress accumulation and stress release are slower at Gentry Mountain than in the Sunnyside district. Rapid release of stress as pillars are removed in the Sunnyside district accompanies actual mining work cycles, as indicated by the daily correlations between tremors and work cycles. The stress-relief effectiveness of pillar removal and the resulting collapse of mine roofs were shown vividly by final operations of the Book Cliffs Mine.

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