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U. S. DEPARTMENT OF COMMERCE
ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION
COAST AND GEODETIC SURVEY
ROCKVILLE, MARYLAND

MASTER

SEISMIC ACTIVITY IN SEPTEMBER 1969 NEAR THE RULISON NUCLEAR TEST SITE

THIS DOCUMENT CONFIRMED AS UNCLASSIFIED
DIVISION OF CLASSIFICATION
BY J. H. Kahn /amh
DATE 8/25/70

By

R. Navarro and S. R. Brockman

June 15, 1970

Special Projects Party
Las Vegas, Nevada

Kenneth W. King
Chief of Party

P6372

INTRODUCTION

Project Rulison was a joint experiment sponsored by Austral Oil Company, Incorporated, Houston, Texas, the United States Atomic Energy Commission and the Department of the Interior, with the Program Management provided by CER Geonuclear Corporation of Las Vegas, Nevada under contract to Austral. Its purpose was to study the economic and technical feasibility of using underground nuclear explosions to stimulate production of natural gas from the low productivity, gas bearing Mesaverde formation in the Rulison field.

The nuclear explosive for Project Rulison was detonated successfully at 1500:00 $\pm$ 0.1 Mountain Daylight Time, September 10, 1969 at a depth of 8,422.5 feet below ground level and was completely contained. Preliminary results indicate that the Rulison device behaved about as expected, i. e., with a yield of $40 {}^{+20}_{-4}$ kt.

The wellhead of the emplacement well, Hayward 25-95A, was at an elevation of 8,154 feet above mean sea level (MSL) and was located 1,976.31 feet east of west line, and 1,813.19 feet north of south line of Section 25, Township 7 South, Range 95, West of 6th P.M., Garfield County, Colorado which corresponds to geodetic coordinates of longitude 107 degrees 56 minutes 53 seconds West and latitude 39 degrees 24 minutes 21 seconds North.

This report presents all pertinent information regarding the second major program of pre- and post-event earthquake investigations of the Special Projects Party, U. S. Coast and Geodetic Survey (C&GS).

PROCEDURES

The Special Projects Party monitored seismic activity in the vicinity of Rulison during the month of September, 1969. There were no detected earthquakes within 100 kilometers of Rulison in the pre-event period of September 3 to September 10.

At the time of detonation, all seismic stations were operated at low gains in order to record the ground motions produced by Rulison without saturation of the instrumentation. During the period of low gains, no seismic activity was recorded. To record seismic activity after the detonation, the station sensitivities were increased as soon as possible.

Three seismic stations were returned to the higher background sensitivities within 30 minutes after Rulison was detonated, and two additional stations within 2 hours. (See Figure 1 for station location.) Because of high cultural noise (vehicular traffic, personnel movements), it was not possible to achieve maximum sensitivities at the stations closest to Rulison (Observer Point, Rifle and Collbran). However, calculations indicated that shocks originating at the Rulison cavity having an approximate magnitude of 1.0 to 1.5 or greater would have been detected by the three stations; therefore, it is assumed that there were no aftershocks in this magnitude range or greater which originated at the cavity. A C&GS memorandum providing preliminary seismic information to the AEC stated that a magnitude 3.5 cavity collapse occurred after Rulison; later analysis indicated that the magnitude determination was incorrect. The U. S. Geological Survey stated in an open-file report (1) that there were 16 aftershocks in 43 minutes after Rulison, all of which had Richter magnitudes of less than 1.0 and were located within one kilometer of the explosion. The USGS did not identify any other shocks during the 18-hour post-detonation period in which they were recording.

Monitoring by the Special Projects Party was continued until September 30. A total of twenty-seven seismic events were detected between September 10 and September 30; of these, fourteen were less than 100 kilometers from Rulison. The largest local shock had an approximate Richter magnitude of 2.3 and occurred September 13, 1969. It was not possible to locate some of the local shocks, because of timing difficulties or because many were of such a small size that they were recorded by only one station. When possible, distances from the epicenters to the recording station were calculated using S minus P intervals and magnitudes then compared. Nine of the fourteen were large enough to be adequately recorded and are presented in this discussion. The reduced ground motions and computed magnitudes of the nine larger earthquakes are given in Table 1.

A communication was received by the AEC in which ten earthquakes were reported to have occurred between September 12 and September 27. Six of the earthquakes had assigned magnitudes ranging up to 4.0 on the Richter Scale. The information contained in the communication is also tabulated in Table 1.

In order to resolve the wide disparity between the reported magnitudes, the Special Projects Party felt it was necessary to recalibrate their instruments and recalculate the magnitudes. Records from the Flaming Gorge, Utah (FGU) and Uinta Basin Observatory, Utah (UBO) stations were also inspected.

CALIBRATION OF THE S-13 AND THE L-7 SYSTEMS

Two types of seismic detection systems, the Mark Products L-7 and the Geotech S-13, were utilized in the seismic studies in Colorado. The L-7 system has been in use in and around Nevada since 1967, while the S-13 system has been in field use for a relatively short period of time. The scaled amplitudes are pertinent to the magnitude studies; therefore, a re-evaluation of the magnitudes necessitated laboratory calibration of the S-13 system.

The Geotech S-13 system consists of the S-13 seismometer and companion amplifier. The system used at Rulison was recorded on a Brush recorder and was capable of displacement magnification exceeding one million, with a flat response to velocity from 1.0 to 34 Hz, and a dynamic range of 120 db in 6 db steps. After the system was operated for Rulison, it was calibrated on the shake-table of the USC&GS Seismological Laboratory in Albuquerque, New Mexico to confirm published specifications. The displacement magnification and velocity sensitivity curves obtained are shown in Figure 2. The derived curves agree within ± 5% of the manufacturer's specifications.

The L-7 system has a flat velocity response from 0.1 to 34 Hz, and a dynamic range of 120 db. The amplifier output is recorded on magnetic tape. The initial calibrations of this system were made in 1967 (2) and all field units have been periodically recalibrated since then. Figure 3 indicates the displacement magnification and velocity sensitivity curves derived from the shake-table tests. The curves agree within ± 5% of the theoretical and internal oscillator curves.

MAGNITUDE CALCULATIONS

Magnitude is defined as a measure of the energy released as seismic waves at the source of an earthquake. The greater the energy released, the greater the magnitude of the shock. There are several types of magnitudes; the most commonly quoted is the Richter magnitude. Magnitudes are calculated, generally, on the basis of ground-motion amplitudes recorded by a seismograph and the distance of the seismograph from the epicenter of the earthquake.

Intensity is an indication of how strongly an earthquake is felt at a given location and is not the same as magnitude although there are approximate relationships between the two. For California, a Richter magnitude 2 earthquake may or may not be felt by a person very near the epicenter, a magnitude 3 may be felt strongly within 15 kilometers of the epicenter, and a magnitude 4 may be felt slightly at approximately 80 kilometers and strongly at the epicenter.

Magnitudes of earthquakes originating at short distances from the recording sites may vary as much as two or more magnitudes when the computations involve different methods and wave forms. This variance is due to radiation pattern differences, propagational velocities, energy losses at interfaces, energy absorption factors, and other factors. These factors become increasingly significant as distances between earthquakes and recording stations decrease.

Two procedures were used primarily for determining magnitudes, while a third method was to verify the other results. Each is based on the use of body waves.

The three procedures were considered to be the most appropriate for the special situation of very near earthquakes. Surface wave methods were not considered for the near region studies. For ease of explanation, the calculated magnitudes will be referred to as M_1, M_2 and M_3. The procedures are:

1) M_1: Using the maximum vertical P-phase ground particle velocity,

2) M_2: Using the maximum horizontal particle displacement, and

3) M_3: Using the maximum vertical ground particle displacement.

Procedure 1: Magnitude M_1 - maximum vertical P-phase velocity.

This method is an adaption of $M = \log_{10} \frac{A}{T} + Q$, using the established C&GS magnitude of Rulison to evaluate the constant. Since velocity is being measured, the formula may be stated $M_1 = \log_{10} U + F$, where:

U = Maximum vertical zero to peak velocity in microns per second of the P-phase of the recorded earthquakes, and

F = Station distance correction factor.

The ground motion data from the Rulison explosion are substituted into the equation, as is the C&GS M_b magnitude; the equation is then solved for F. The results are plotted against epicentral distances, as shown in Figure 4. The established C&GS M_b magnitude of 4.9 is based on 100 stations at 25 degrees or greater from Rulison. The M_1 method is attractive, as both the S-13 and L-7 systems have flat responses to velocity in the frequency range of interest. However, this method may be used only in the general area of Rulison or some other detonation where the detonation magnitude is known.

Procedure 2: Magnitude M_2 - effective Wood-Anderson (WA) maximum displacement.

$M_2 = \text{Log}_{10} A - \log_{10} A_o$, where:

A = Maximum recorder trace amplitude in millimeters, zero to peak,

A_o = Amplitude of a magnitude "zero" earthquake on a standard WA torsion seismometer at 2800 magnification.

This method, with a slight modification, was obtained from C. F. Richter (3). The M_2 magnitudes were obtained using the maximum horizontal amplitudes occurring in the "P" or "S" phases. The effective WA amplitude "A" was obtained by converting the S-13 or L-7 system recorded amplitudes to an equivalent WA amplitude at a magnification of 2800, with a correction for the displacement response differences of the systems. Though the M_2 magnitudes may be calculated for distances up to 600 kilometers, Richter cautions in using this method with instruments other than a Wood-Anderson and for areas outside of California.

Procedure 3: Magnitude M_3 - maximum vertical zero to peak displacement.

$$E = \rho \pi^3 R^2 f d^2 V Q 10^{2KR} \qquad \text{Eq. 1 (4)}$$

$$M_3 = \frac{\log_{10} E - 5.8}{2.4} \qquad \text{Eq. 2}$$

where:

ρ = density in gm/cm^3
R = distance from source to station in cm
f = frequency in Hz of measured phase
d = transitory peak maximum motion in cm of displacement
V = propagational velocity of measured phase in cm/sec
Q = factor for energy loss at seismic interface
K = absorption coefficient per cm
E = total source seismic energy, ergs.

E was calculated from the C&GS magnitude for Rulison (M_b = 4.9) and substituted into the energy formula (Eq. 1). By requiring that the earthquakes occur in the same general areas as Rulison, Eq. 1 may be simplified to:

$$E = B R^2 f d^2, \text{ where}$$

$$B = \rho \pi^3 V Q 10^{2KR}$$

In general, the quantity 10^{2KR} is approximately 1.0 at near distances. By substitution of the Rulison explosion data into the simplified Eq. 1, a constant B may be derived for each station used for magnitude calculations.

This method of determining magnitudes is somewhat more prone to wide variance at near distances than the M_1 and M_2 methods, due to its dependence on more variables in the equations.

DISCUSSION AND CONCLUSIONS

In August, 1969, two and occasionally three portable S-13 systems were operated in 10 different locations for an average of 4 days per location, to sample local seismicity in the region around Rulison. During this investigation period, little natural seismic activity was detected (5).

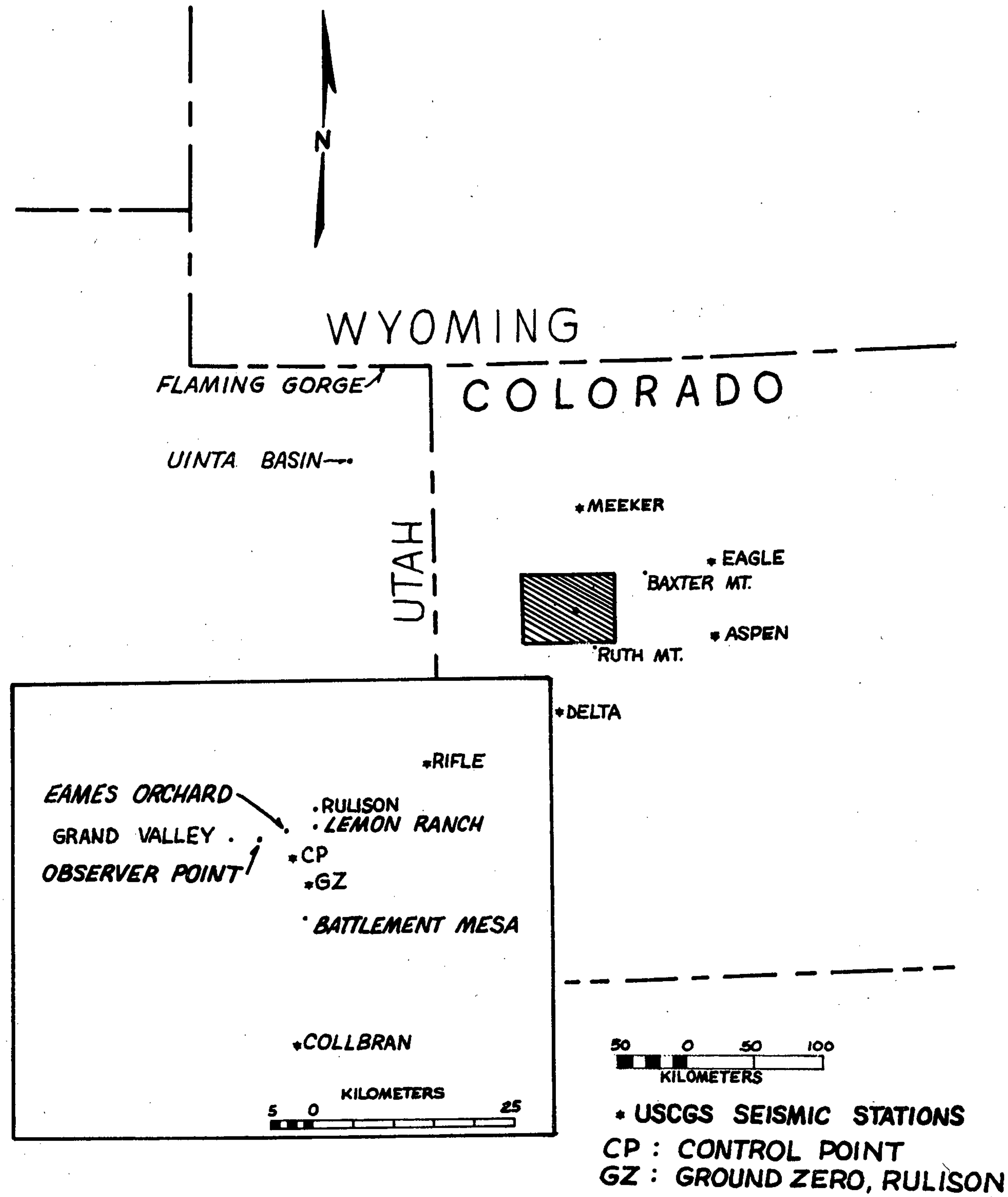
In September, 1969, the C&GS operated five continuously recording seismic stations in the vicinity of Rulison. The number of detected earthquakes occurring within 100 kilometers of Rulison in September is interpreted by the authors as reflecting the increased density of stations available to detect the earthquakes, rather than an increase in the rate of activity in September.

The C&GS L-7 seismograph located at Collbran, was located approximately 20 kilometers from the epicenter of the magnitude 4.0 earthquake reported in the communication to the AEC. The station, which was recording at approximately 56,000 displacement magnification, recorded very small particle displacements instead of completely saturating the system's amplifiers, indicating a considerably smaller magnitude.

Data from the shocks, obtained from the FGU and UBO stations, were reduced to magnitudes and are given in Table 1. The magnitudes were calculated using the M_2 method. The Flaming Gorge magnitudes are very nearly the same as those obtained from the near-distance stations. Magnitudes obtained from the Uinta Basin data are somewhat high compared with those calculated from the other stations.

It is possible that a station correction factor exists that would result in lower magnitudes.

The magnitudes resulting from this study appear to compare favorably. The magnitudes were less than 3.0 in all cases and indicate the level of magnitudes were at least seven tenths of a magnitude smaller than those reported in the communication to the AEC.



RULISON SEISMIC STATION LOCATIONS

FIGURE 1

TABLE 1 REPORTED EARTHQUAKES

DATE	TIME APPROX. ORIGIN TIME (GMT)	C&GS SEISMIC STATION	RECORDED GROUND MOTION: Maximum P-Phase Particle Velocity o-p μ/sec	Period sec	Maximum Particle Displacement of Disturbance o-p mm	Period sec	MAGNITUDE METHODS M_1	M_2	M_3	OTHER SEISMIC STA. MAGNITUDES M3 FGU	UBO	DATA REPORT IN COMMUNICATION TO AEC Location	Mag.
12/9/69	1804	Collbran	0.615	0.2	3.47×10^{-5}	0.25	1.0	1.3	1.0			Grand Valley	NC
12/9/69	1850	CP	NR	NR	1.1×10^{-6}	0.23	--	0.8				Rulison	3.5
13/9/69	0015	Collbran	1.23	0.2	6.9×10^{-5}	0.25	2.3	2.1	1.9	2.3	2.8	Baxter Mt	3.5
16/9/69	1906	Collbran	0.692	0.15	2.15×10^{-5}	0.25	2.1	1.6	1.5	2.2	2.4	Baxter Mt	3.5
18/9/69	1705	Collbran	0.538	0.2	6.94×10^{-5}	0.25	0.7	1.0	0.9			Ruth Mt.	NC
18/9/69	2123	Collbran	9.2	0.08	4.3×10^{-4}	0.25	2.0	2.1	1.7	2.4	2.8	Ruth Mt.	4.0
24/9/69	1714	CP	NR	NR	7.2×10^{-7}	0.25	--	-0.1				Baxter Mt.	3.5
25/9/69	2348	--------	NR	NR	NR	NR	--	--				Grand Valley	NC
27/9/69	0007	GZ	NR	NR	1.45×10^{-4}	0.25	--	1.7				Rulison	2.5
27/9/69	2012	Collbran	NR	NR	3.47×10^{-5}	0.4	--	2.1	2.2	2.25	2.7	Aspen	NC

NR: Not recorded; indicates station was at a low magnification, earth tremor signal was emergent, or station was in the process of changing records. NC: Not calculated; indicates communication to AEC did not give a magnitude. FGU: Flaming Gorge, Utah; UBO: Uinta Basin Observatory.

TABLE 1 REPORTED EARTHQUAKES

DATE	TIME APPROX. ORIGIN TIME (GMT)	C&GS SEISMIC STATION	RECORDED GROUND MOTION: Maximum P-Phase Particle Velocity		RECORDED GROUND MOTION: Maximum Particle Displacement of Disturbance		MAGNITUDE METHODS			OTHER SEISMIC STA. MAGNITUDES M3		DATA REPORT IN COMMUNICATION TO AEC	
			o-p μ/sec	Period sec	o-p mm	Period sec	M_1	M_2	M_3	FGU	UBO	Location	Mag.
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18/9/69	2123	Collbran	9.2	0.08	4.3×10^{-4}	0.25	2.0	2.1	1.7	2.4	2.8	Ruth Mt.	4.0
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25/9/69	2348	--------	NR	NR	NR	NR	--	--				Grand Valley	NC
27/9/69	0007	GZ	NR	NR	1.45×10^{-4}	0.25	--	1.7				Rulison	2.5
27/9/69	2012	Collbran	NR	NR	3.47×10^{-5}	0.4	--	2.1	2.2	2.25	2.7	Aspen	NC

NR: Not recorded; indicates station was at a low magnification, earth tremor signal was emergent, or station was in the process of changing records. NC: Not calculated; indicates communication to AEC did not give a magnitude. FGU: Flaming Gorge, Utah, UBO: Uinta Basin Observatory.

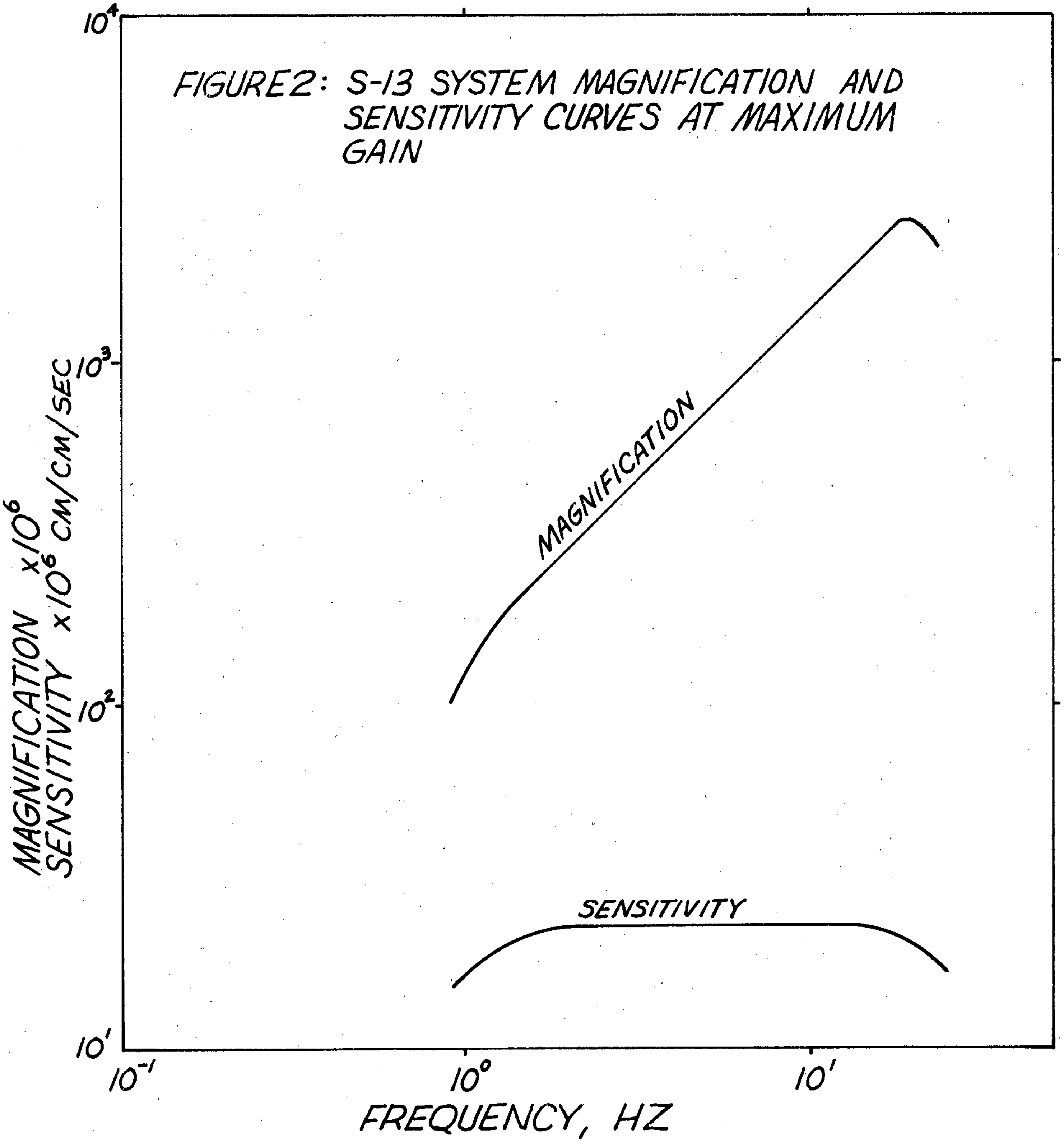

FIGURE 2: S-13 SYSTEM MAGNIFICATION AND SENSITIVITY CURVES AT MAXIMUM GAIN

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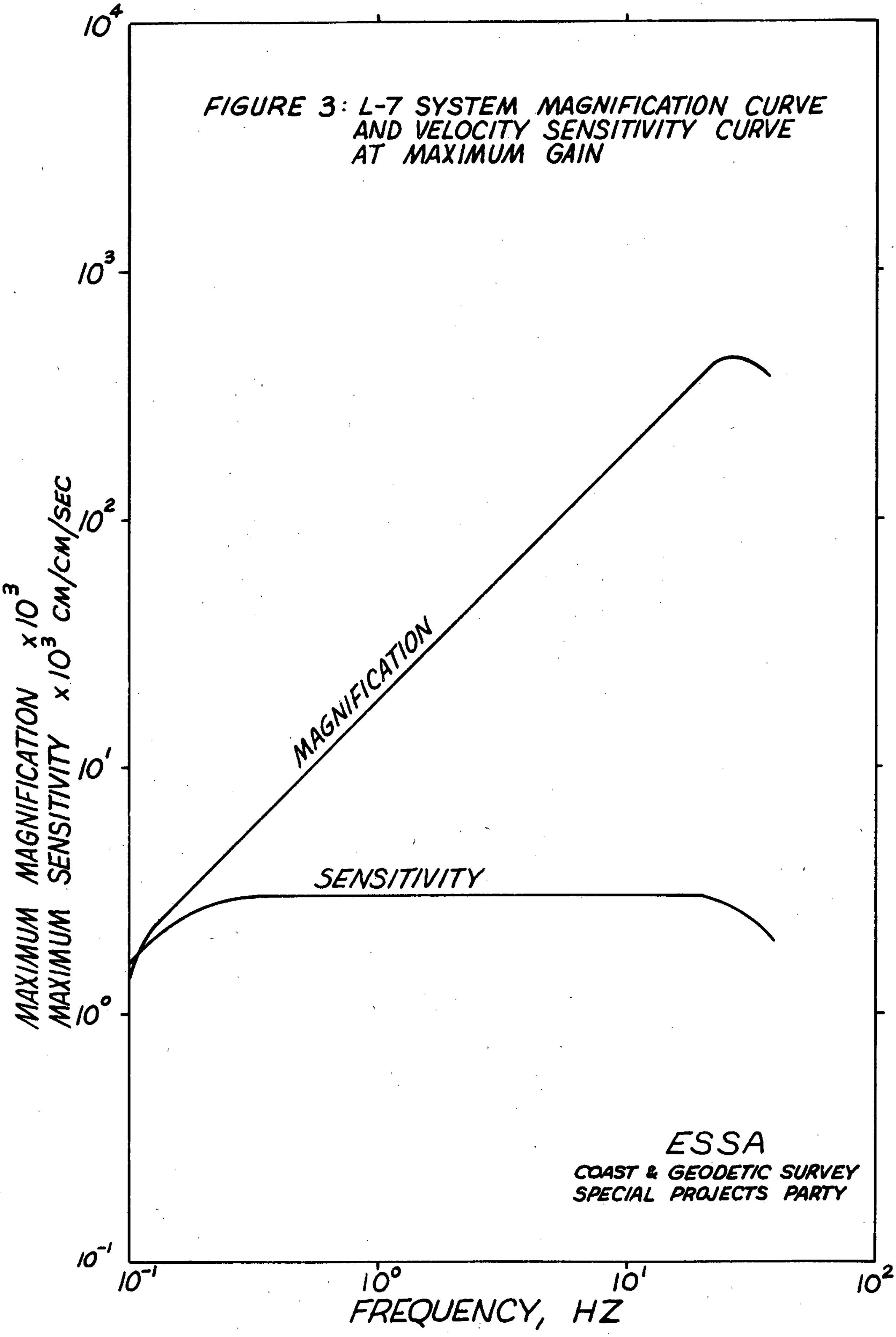
FIGURE 3: L-7 SYSTEM MAGNIFICATION CURVE
AND VELOCITY SENSITIVITY CURVE
AT MAXIMUM GAIN
MAXIMUM MAGNIFICATION x 10^3
MAXIMUM SENSITIVITY x 10^3 CM/CM/SEC
10^4
10^3
10^2
10^1
10^0
10^-1
MAGNIFICATION
SENSITIVITY
ESSA
COAST & GEODETIC SURVEY
SPECIAL PROJECTS PARTY
10^-1
10^0
10^1
10^2
FREQUENCY, HZ

RULISON STATION CORRECTION FACTORS

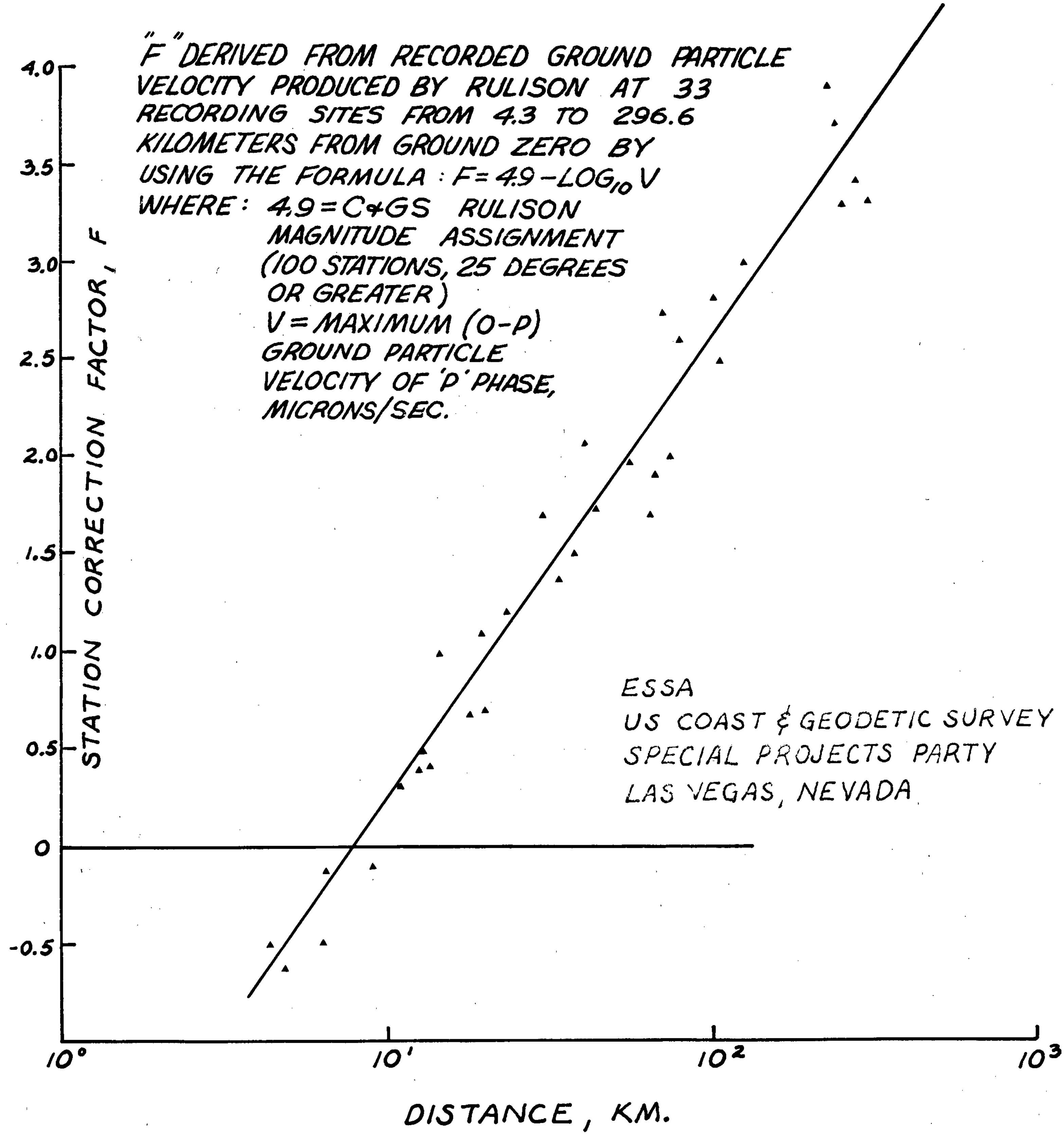

FIGURE 4

RECORDED MAX. PARTICLE VELOCITIES
VERTICAL COMPONENT VALUES

REFERENCES

1. Hamilton, R. M., Smith, B. E., and Healy, J. H.; "Seismic Monitoring of the Rulison Underground Nuclear Explosion near Rifle, Colorado on 10 September 1969"; U. S. Geological Survey Open File Report, 16 February 1970.

2. Navarro, R., "Preliminary Calibration of the SCATT-1 System", CGS-C-119, 16 February 1968.

3. Richter, C. F., "Elementary Seismology", W. H. Freeman and Company, San Francisco, 1958.

4. Carder, D. S., Murphy, L. M., Pearce, T. H., Mickey, W. V., and Cloud, W. K.; "Operation Hardtack Phase II, Surface Motions from Underground Explosions", WT-1741; March 1961.

5. Navarro, R., and Wuollet, G.; "Rulison Seismic Effects", CGS-746-2, 16 February 1970.

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