UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

OPEN FILE REPORT

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SURFACE SEISMIC MEASUREMENTS OF THE PROJECT GASBUGGY EXPLOSION AT INTERMEDIATE DISTANCE RANGES*

by

David H. Warren and Wayne H. Jackson

MENLO PARK, CALIFORNIA

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National Center for Earthquake Research
345 Middlefield Road
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*Work done under ARPA Order No. 1094

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National Center for Earthquake Research

U.S. Geological Survey, Menlo Park, California

INTRODUCTION

Project GASBUGGY was an experiment performed by the Atomic Energy Commission, the El Paso Natural Gas Company, and the Bureau of Mines, U.S. Department of the Interior, to determine the effectiveness of a method for increasing the recovery of natural gas by large-scale fracturing of a gas-bearing formation with an underground nuclear explosion.

The Project GASBUGGY nuclear explosive of 26 kilotons design yield was detonated on Sunday, December 10, 1967, at 1230:00 Mountain Standard Time. Lawrence Radiation Laboratory reported that the explosive was emplaced at 4240 ft below the ground surface, 1770 ft from the west line and 1218 ft from the south line in Section 36 of Township 29 North, Range 4 West, in Rio Arriba County, New Mexico, about 55 air miles east of the city of Farmington, New Mexico. The geodetic coordinates are: Latitude 36°40'40.4" North, and Longitude 107°12'30.3" West. The elevation of surface ground zero was 7204 ft above Mean Sea Level. The detonation occurred in the Lewis shale about 40 ft below its contact with the gas-bearing Pictured Cliffs sandstone. Early indications are that the explosive performed satisfactorily.

This document is submitted as a preliminary data report. Additional analyses of the data will be prepared at a later time.

FIELD RECORDING

The U.S. Geological Survey recorded seismic waves generated by GASBUGGY along five lines radiating from the shot site (Figure 1), primarily to determine traveltime and amplitude variations with azimuth and distance. Table 1 summarizes the recording systems used. Most seismograms were written by one of two different recording systems, distinguished here as attended (type no. 1) or unattended (type no. 2). The attended system has been described by Warrick, and others (1961).

Briefly, the attended system is truck mounted and contains six vertical geophones arranged in a linear array 2.5 km long, and two horizontal geophones located at one of the vertical geophones near the center of the array. The signals are amplified and recorded on both photographic paper and magnetic tape. The unattended systems consist of usually one but occasionally three vertical geophones. Signals are recorded on magnetic tape only. All USGS systems recording the GASBUGGY event used Electro-Tech, EV-17, 1-cycle geophones. In addition to the two dominant systems, two variations (types 3 and 4) of the attended recording units were used at a few stations (Table 1).

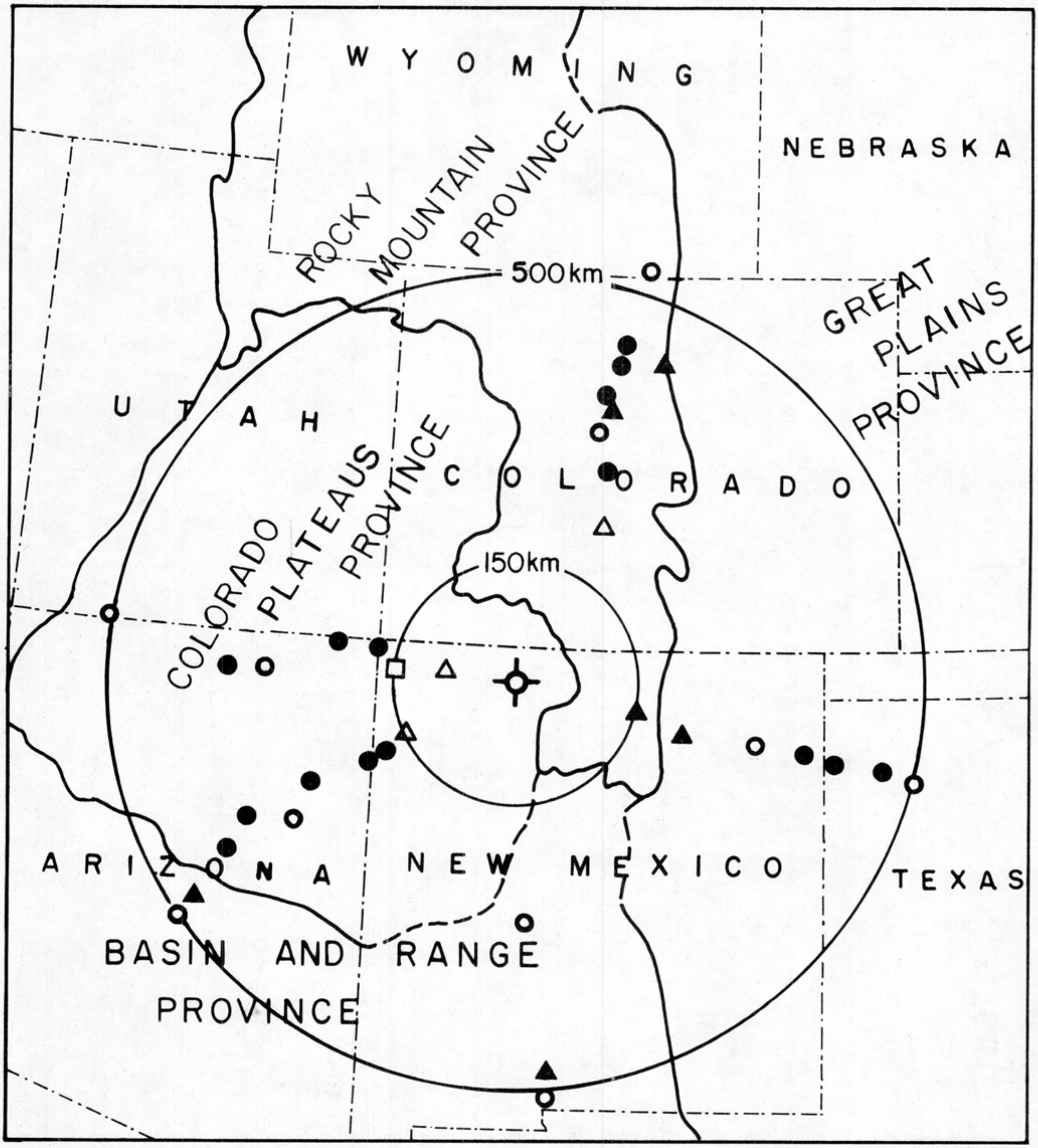

Figure 1. Location of recording sites. GASBUGGY is located at the center of the rings. Recording systems used at the sites are coded by type number as given in Table 1: ○ Type 1; ● Type 2; △ Type 3; □ Type 4; ▲ Type 5.

Table I. Recording Systems

Type	No. of Systems	No. of Geophones	Electro-Tech EV-17, coil resistance ohms	Truck Mounted	Amplifier and Filter Unit[1/]	Tape Recording Unit [1/]	System Pass Band, Hz	Monitor Record
1	10	8	500	Yes	SIE TGA-2	Ampex CP-100	1-37	Yes
2	20	1-3	5000	No	UED EA-210	PI-5100	1-17	No
3	3	4	5000	Yes	SIE TGA-2	None	1-37	Yes
4	1	1	500	No	SIE TGA-2	None	1-37	Yes
5	Other organization. See text.							

[1/] SIE: Southwestern Industrial Electronics, Houston, Texas.

UED: United Electro Dynamics, division of Teledyne, Inc., Pasadena, California.

PI: Precision Instrument Company, Palo Alto, California.

Additional data, furnished by other groups operating stations near the USGS recording lines, have been included in this report (Table I, type 5). We wish to express our appreciation to the following organizations and individuals for making this data available to us. Wayne Helterbran of the Air Force Technical Applications Center (AFTAC) furnished data at Kanab, Utah; Tonto Forest Observatory, Arizona; and Las Cruces, New Mexico, from their Long Range Seismic Measurements Program in advance of their event report for GASBUGGY (Thorpe and others, 1968). Jon Peterson of the U.S. Coast and Geodetic Survey furnished data at Taos and Mora Ranch, New Mexico, on the recording line to the east. The recording line to the south will be described in greater detail in a report by the U.S. Coast and Geodetic Survey; Geological Survey data for the southern line are included in this report for completeness. James Taggart of the Environmental Sciences Laboratory furnished data at Poorman Mine, Colorado.

Table 2 lists coordinates and distances for all recording sites included in this report.

RESULTS

Amplitudes were measured on monitor or play-back seismograms (Appendix I) using the AFTAC convention: (a) rest position to first peak of initial upward motion, (b) first peak to first trough, (c) first trough to second peak, and (d) maximum peak-to-peak amplitude of first phase. Measurements of (d) were made no later than about one-half second after the time of first upward motion, even though a much higher amplitude might occur within the next half second. Even this restriction did not always result in freedom from phase interference.

Table 2. Station Locations and Distances

Direction	Name	Unit Type*	Unit Identification	Trace Number	Location Latitude, North	Location Longitude, West	Distance km	Distance degrees
NORTH	Cochetopa, Colo.	3	Zulu	1	38° 20.53'	106° 44.62'	189.23	1.703
	" "	"	"	4	38° 20.82'	106° 43.85'	190.00	1.710
	Buena Vista, Colo.	2	134		38° 45.39'	106° 4.47'	251.43	2.263
	Climax, Colo.	1	Papa	1	39° 19.25'	106° 13.25'	305.91	2.753
	" "	"	"	6	39° 20.50'	106° 13.25'	308.12	2.773
	Breckenridge, Colo	5		1	39° 31.60'	106° 02.70'	332.26	2.990
	" "	"		12	39° 32.80'	106° 02.35'	334.52	3.011
	Dillon, Colo.	2	130		39° 43.53'	106° 7.71'	351.23	3.161
	Granby, Colo	2	174	1	40° 3.02'	105° 56.17'	390.51	3.515
	" "	"	"	3	40° 3.53'	105° 56.08'	391.45	3.523
	Poorman Mine, Colo.	5			40° 1.80'	105° 20.22'	406.48	3.655
	Timber Creek, Colo.	2	129		40° 22.83'	105° 50.96'	427.75	3.850
	Tie Siding, Wyo.	1	Lima	1	41° 1.55'	105° 33.00'	503.68	4.533
	" "	"	"	6	41° 2.87'	105° 32.80'	506.09	4.555
	Taos, N.M.	5			36° 22.99'	105° 33.05'	152.00	1.368
	Mora Ranch, N.M.	5			36° 10.91'	104° 54.25'	213.83	1.924
EAST	Roy, N.M.	1	Juliet	1	36° 3.45'	103° 55.75'	302.21	2.720
	" "	"	"	6	36° 3.45'	103° 54.20'	304.47	2.740
	Rosebud, N.M.	2	176		35° 51.60'	103° 21.45'	357.71	3.219
	Romero, Tex.	2	150		35° 43.45'	102° 55.58'	399.35	3.594
	Channing, Tex.	2	108		35° 42.46'	102° 23.30'	446.66	4.020
	Amarillo, Tex.	1	Tango	1	35° 31.47'	101° 50.45'	499.93	4.496
	" "	"	"	6	35° 31.03'	101° 48.90'	502.41	4.518
SOUTH	Socorro, N.M.	1	India	1	33° 58.86'	106° 57.72'	300.03	2.700
	" "	"	"	6	33° 57.85'	106° 56.75'	302.01	2.718
	Las Cruces, N.M.	5			32° 24.13'	106° 35.97'	478	
	Mesquite, N.M.	1	Kilo	1	32° 12.85'	106° 36.13'	498.27	4.484
	" "	"	"	6	32° 11.97'	106° 35.34'	500.02	4.500

Table 2. Station Locations and Distances (Continued)

Direction	Name	Unit Type	Unit Identification	Trace Number	Location: Latitude North	Location: Longitude West	Distance km	Distance degrees
SOUTHWEST	Gallup, N.M.	3	Alpha	1	35° 57.15'	108° 38.15'	151.36	1.362
	" "	"	"	4	35° 56.75'	108° 39.00'	152.84	1.376
	Twin Lakes, N.M.	2	136		35° 42.28'	108° 48.20'	179.56	1.616
	St. Michaels, Ariz.	2	139		35° 38.80'	109° 6.80'	206.09	1.855
	Sunrise Springs, Ariz.	2	175	1	35° 34.35'	109° 49.52'	265.59	2.390
	" "	"	"	3	35° 34.06'	109° 50.10'	266.62	2.400
	Holbrook, Ariz.	1	Hotel	1	35° 6.25'	110° 1.75'	308.79	2.779
	" "	"	"	6	35° 5.40'	110° 3.00'	311.24	2.801
	Winslow, Ariz.	2	154	1	35° 3.65'	110° 39.05'	358.94	3.231
	" "	"	"	3	35° 3.20'	110° 39.38'	359.80	3.238
	Chevelon, Ariz.	2	144		34° 36.57'	110° 52.87'	404.10	3.637
	Tonto Forest Obs., Ariz.	5			34° 17.20'	111° 16.05'	454	
	Sunflower, Ariz.	1	Sierra	1	33° 51.52'	111° 25.97'	495.52	4.460
	" "	"	"	6	33° 50.62'	111° 26.67'	497.43	4.477
WEST	Farmington, N.M.	3	Mike	1	36° 46.40'	108° 9.20'	85.08	0.766
	" "	"	"	4	36° 46.60'	108° 9.80'	86.01	0.774
	Shiprock, N.M.	4	Charlie		36° 48.75'	108° 45.75'	139.60	1.256
	Teec Nos Pas, Ariz.	2	152		36° 54.85'	109° 4.80'	169.09	1.522
	Mexican Water, Ariz.	2	101		36° 55.25'	109° 35.75'	214.77	1.933
	Shonto, Ariz.	1	Quebec	1	36° 36.25'	110° 36.10'	303.56	2.732
	" "	"	"	6	36° 36.20'	110° 37.75'	306.02	2.754
	Kaibito, Ariz.	2	153		36° 32.92'	111° 7.44'	350.57	3.155
	Kanab, Utah	1	Romeo	1	37° 1.44'	112° 48.15'	500.34	4.500
	" "	"	"	6	37° 1.15'	112° 49.67'	502.56	4.520
	" "	5			37° 1.37'	112° 49.65'	503	

*See Table 1 for explanation of code.

Measured amplitudes were then converted to microns per second (μ/sec) velocity amplitude as described in Appendix 2. Velocity amplitudes (Table 3) are plotted according to azimuth from GASBUGGY in Figures 2 through 6. A dashed reference line of $10^{12}/r^5$ μ/sec is shown on each plot.

It is possible to attain a measure of amplitude precision for array stations having 4 or more geophones, but the number of measurements is barely sufficient to conduct a statistical analysis. Amplitudes from each geophone were individually measured and averaged to obtain one value for each array. Whenever 4 or more samples were available for one station, a standard deviation was computed (Table 3). Standard deviations are also indicated on the amplitude plots (Figures 2 through 6) by vertical bars.

The simple average of the ratios of standard deviations to amplitudes is 20 percent. Amplitude errors introduced by the recording system will result in deviation ratios of 10 percent or less; therefore, the larger value of standard deviations indicates that amplitude fluctuations are real. Major differences are perhaps related to the surface geophone plants and geologic conditions immediately under the array. Examples of either extreme are provided by the Mesquite and the Farmington locations. At Mesquite, where the array extended from an alluvial valley into a mountain having granite outcrops, there are extreme variations in surface and geologic conditions, resulting in a very large standard deviation. Most of the other stations were in areas where geologic conditions were less extreme, as suggested by

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Table 3. Amplitude Measurements

Direction	Name	Distance, km	Amplitudes and standard deviations (μ/sec) a[1] No. of samples	a[1] Amplitude	a[1] Standard deviation	b[2] No. of samples	b[2] Amplitude	b[2] Standard deviation	c[3] No. of samples	c[3] Amplitude	c[3] Standard deviation	d[4] No. of samples	d[4] Amplitude	d[4] Standard deviation	Dominant period, sec
NORTH	Cochetopa	190	1	1.4		4	7.8	1.3	4	17	2	4	19	4	0.34
	Buena Vista	251	1	2.2		1	4.0		1	4.5		1	21		0.12
	Dillon	351	1	2.6		1	19		1	28		1	28		0.20
	Granby	391	2	1.24		2	6.5		2	9.5		2	9.5		0.24
	Timber Creek	428	1	0.077		1	0.65		1	1.33		1	1.33		0.21
	Tie Siding	505	1	<0.05		1	0.17		5	0.78	0.14	5	0.96	0.11	0.26
EAST	Taos	152	1	17		1	45		1	63		1	63		0.50
	Mora Ranch	214	1	1.7		1	2.9		1	14.6		1	105		0.50
	Roy	303	1	0.17		5	1.7	0.3	6	3.8	0.7	6	4.9	1.2	0.24
	Rosebud	358	1	0.30		1	1.29		1	1.67		1	3.2		0.24
	Romero	399										1	<0.38		0.25
	Channing	447	1	0.04		1	0.36		1	0.87		1	0.87		0.30
	Amarillo	501	1	<0.09		5	0.17	0.02	5	0.32	0.11	6	0.54	0.12	0.24
SOUTH	Socorro	301	1	0.23		4	0.77	0.16	4	1.4	0.3	4	1.5	0.2	0.40
	Las Cruces	478										1	0.81		0.2
	Mesquite	499	4	0.0015	0.0011	6	0.10	0.02	6	0.21	0.09	6	0.34	0.16	0.29
SOUTHWEST	Gallup	152	1	0.85		4	14.0	1.0	4	32	5	4	54	4	0.44
	Twin Lakes	180	1	1.4		1	11.0		1	22		1	22		0.40
	St. Michaels	206	1	1.1		1	12.2		1	35		1	268		0.31
	Sunrise Springs	266	2	1.4		2	6.0		2	10.0		2	14.6		0.22
	Holbrook	310	1	0.10		6	0.30	0.06	6	0.49	0.11	5	7.9	0.4	0.27
	Winslow	359	2	0.24		2	1.81		2	1.72		2	10.6		0.12
	Chevelon	404	1	0.77		1	1.44		1	0.55		1	12.3		0.23
	Tonto Forest Obs.	454										1	12.2		0.23
	Sunflower	496	5	0.14	0.02	6	0.52	0.09	1	12.3		1	29.2		0.27
WEST	Farmington	86	4	40	6	4	205	5	4	294	4	4	294	4	0.19
	Shiprock	140	1	6		1	32		1	56		1	56		0.25
	Teec Nos Pas	169	1	3.1		1	21		1	37		1	37		0.22
	Mexican Water	215	1	0.3		1	4.7		1	5.4		1	311		0.24
	Shonto	305	1	0.15		5	1.2	0.2	5	2.9	0.4	6	19	2	0.32
	Kaibito	351	1	0.47		1	0.77		1	0.39		1	9.9		0.18
	Kanab	501	1	0.02		4	0.09	0.02	4	0.277	0.013	6	6.0	1.1	0.24
	Kanab	503										1	5.4		0.4

1/ Measured from rest position to first peak

2/ Measured from first peak to first trough

3/ Measured from first trough to second peak

4/ Maximum peak-to-trough measurement within the first half second

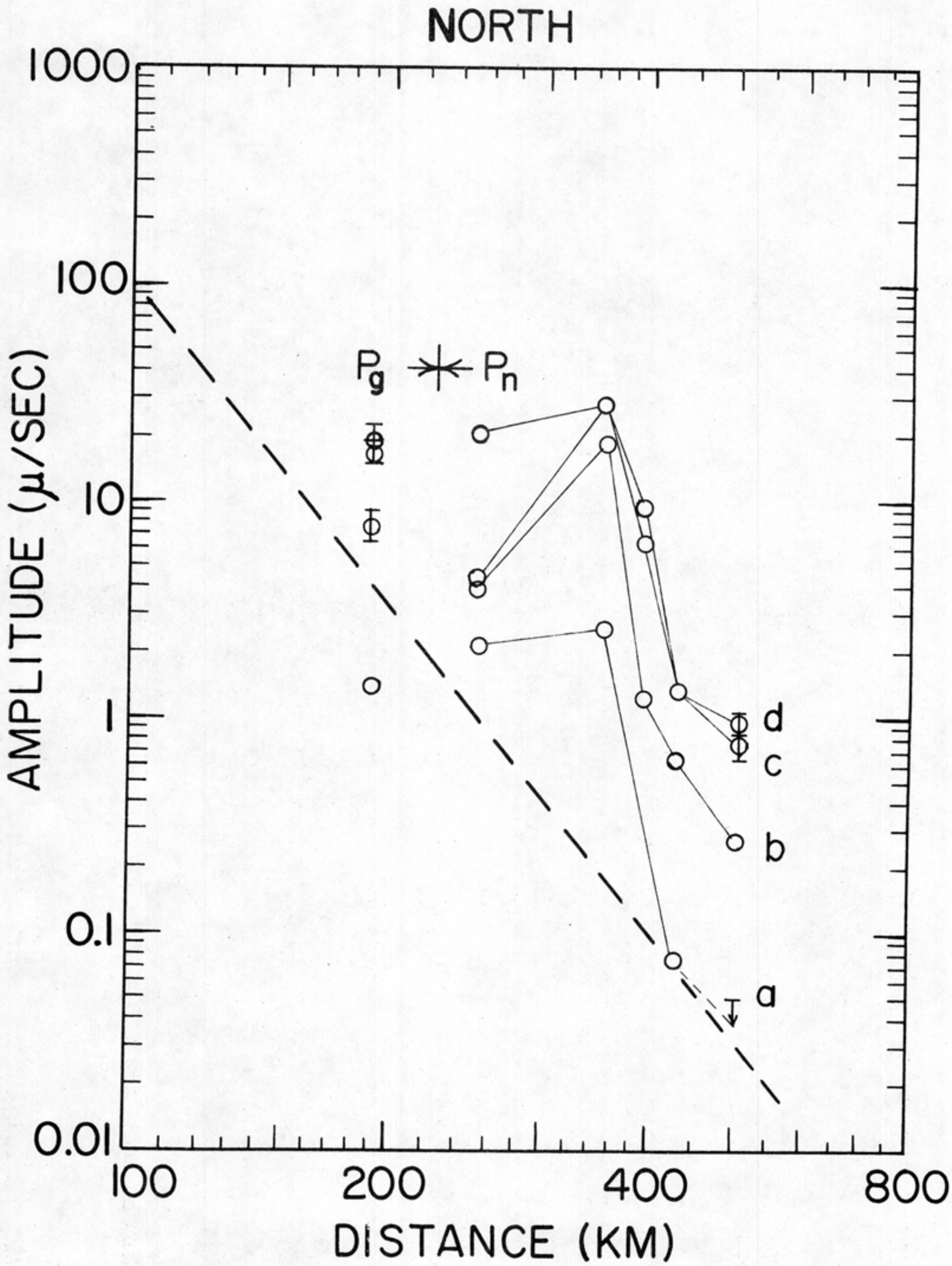


Figure 2. Amplitudes to the north. All measurements are for various features of the first arrival, as described in the text. Crossover from P_g to P_n occurs just beyond 200 km. The bar of the downward-pointing arrow indicates a maximum possible value.

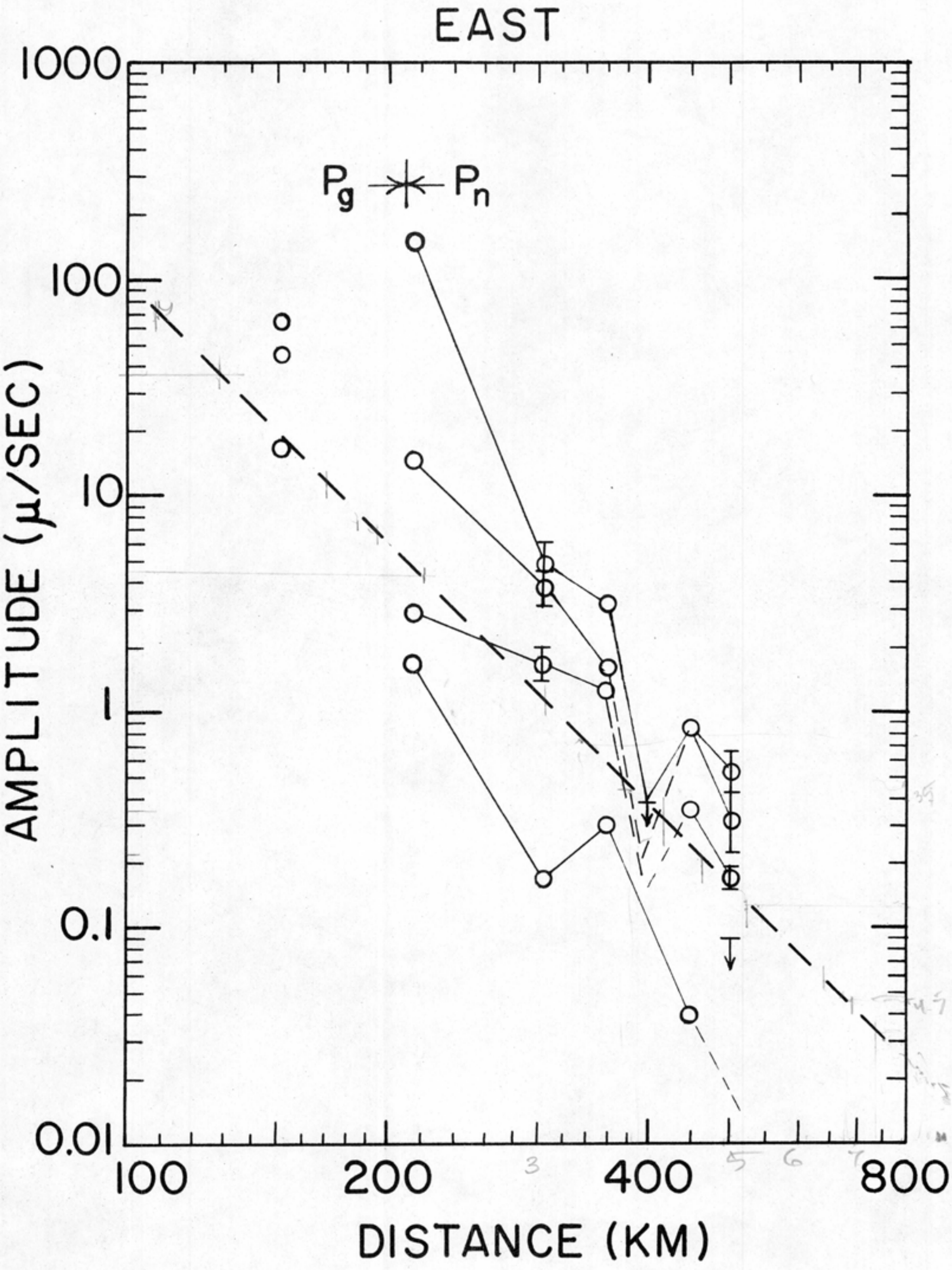


Figure 3. Amplitudes to the east. All measurements are for various features of the first arrival, as described in the text. Crossover from P_g to P_n occurs just beyond 200 km. The bar of the downward-pointing arrow indicates a maximum possible value.

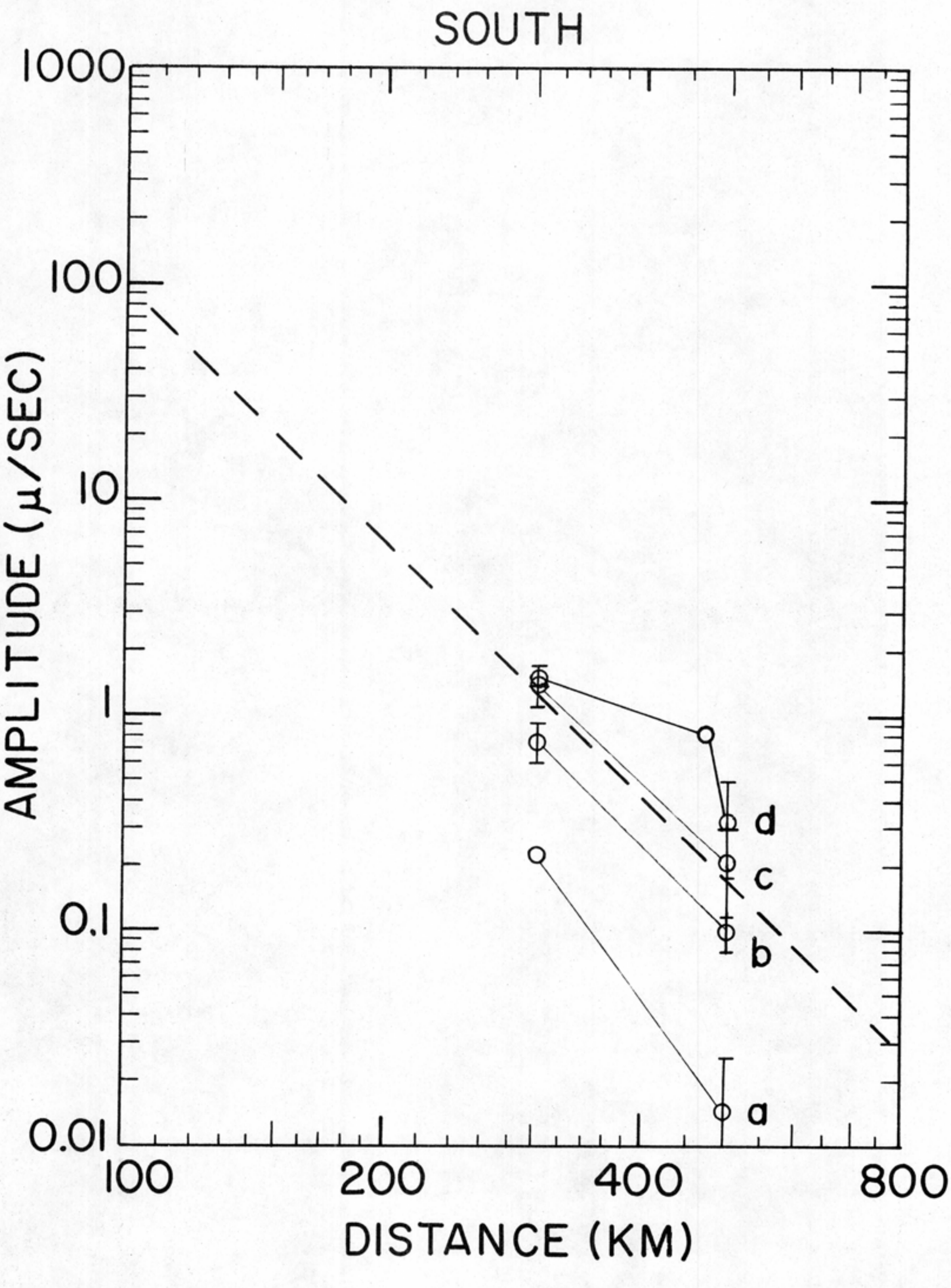


Figure 4. Amplitudes to the south. All measurements are for various features of the first arrival, as described in the text.

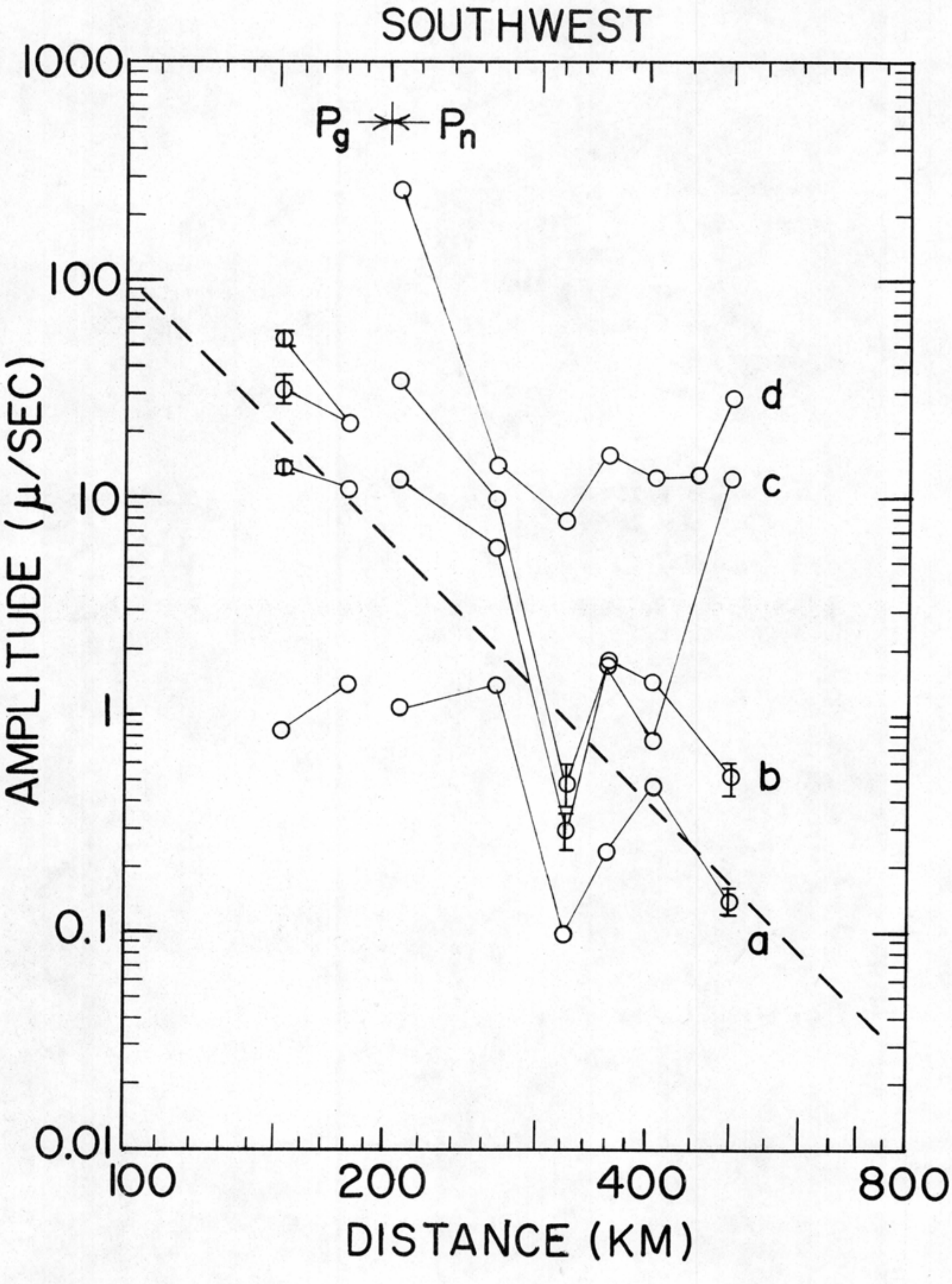


Figure 5. Amplitudes to the southwest. All measurements are for various features of the first arrival, as described in the text. Crossover from P_g to P_n occurs just beyond 200 km.

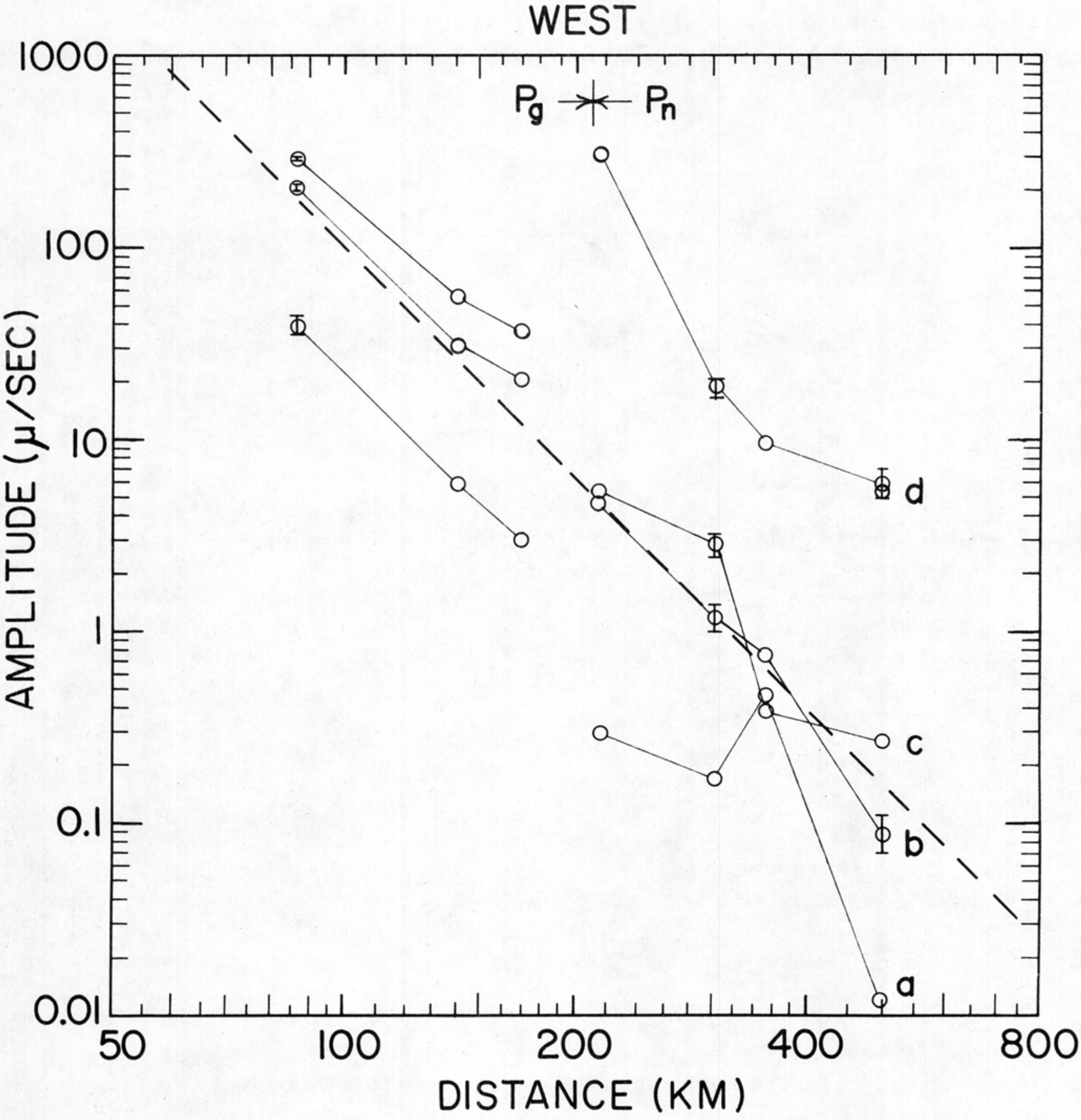


Figure 6. Amplitudes to the west. All measurements are for various features of the first arrival, as described in the text. Crossover from P_g to P_n occurs just beyond 200 km.

much smaller deviations. At Farmington, where each geophone of the array was on sandstone of the same lithologic unit, the standard deviation ratio is 5 percent, which approaches the instrumental accuracy.

Reduced traveltimes were calculated by subtracting from each observed traveltime a value equal to the distance divided by a velocity of 8.0 kilometers per second (Table 4). Elevation corrections were applied to these reduced traveltimes, using a datum elevation of 1.5 km. The correction ΔT is given by

$$\Delta T = \frac{\Delta h \cos \Theta}{V_1} \qquad \text{(seconds)}$$

where: Δh is elevation above or below 1.5 km,

V_1 is the velocity of the upper crust, assumed to be 6.0 km/sec,

Θ is arcsin $\frac{V_1}{V_2}$,

V_2 is the propagation velocity, assumed to be 6.4 km/sec for crustal arrivals and 8.0 for P_n arrivals.

INTERPRETATION

The purpose of this report is to present the data that were recorded; a detailed interpretation is not intended. However, it may be well to point out some preliminary observations, realizing that they have not been subjected to detailed analysis.

The GASBUGGY traveltime data are in reasonable agreement with previous seismic-refraction surveys in surrounding areas. These include surveys in the Southern Rocky Mountains of Colorado (Jackson and Pakiser, 1965), in the Great Plains of eastern Colorado (Jackson and others, 1963), in Eastern New Mexico (Stewart and Pakiser, 1962), in Central Arizona (Warren and others, 1965, and Roller and others, 1964),

Table 4

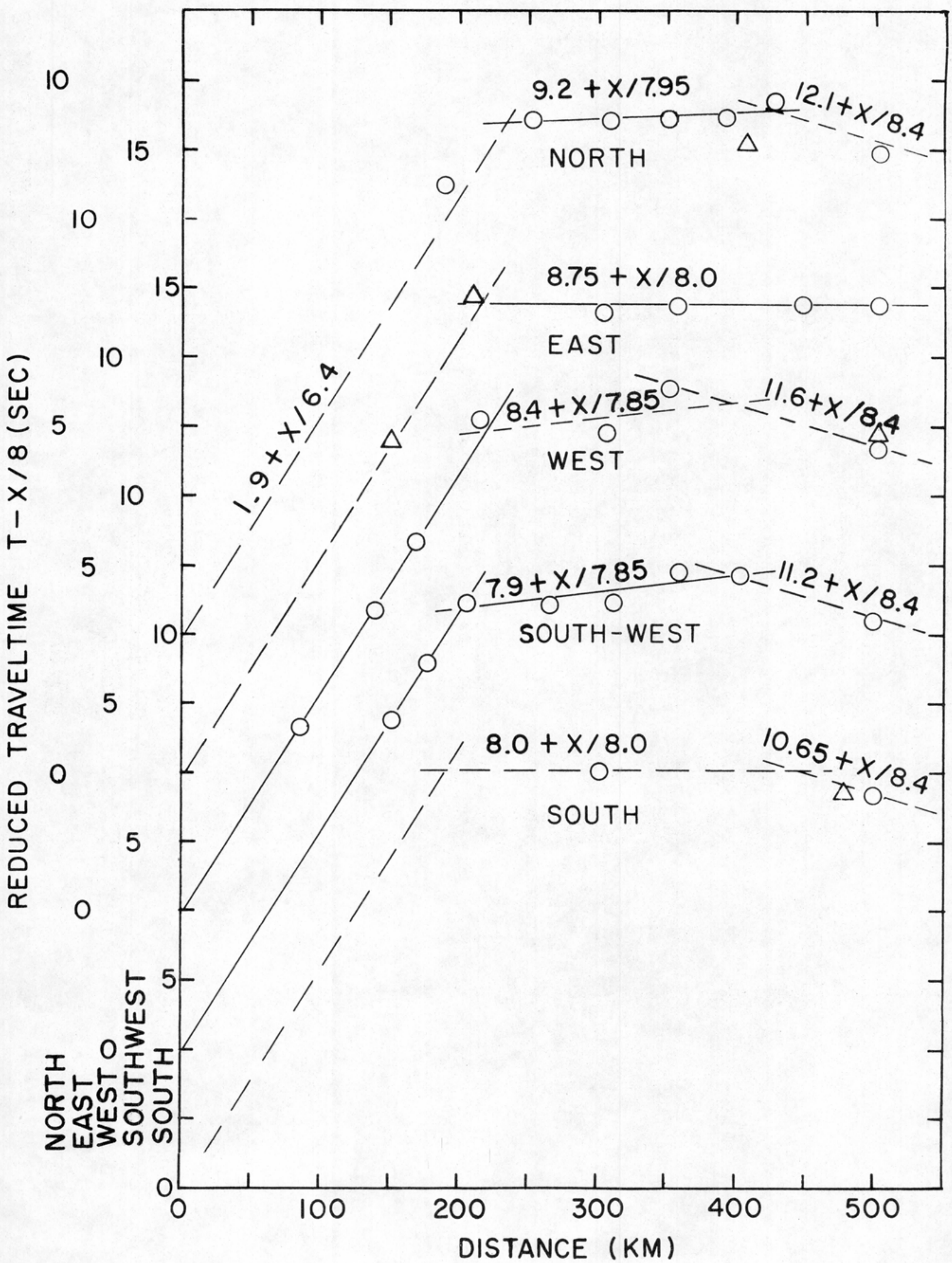
Traveltime Measurements

Direction	Location Name	Trace Number	Distance, km	Travel-time, sec	Elevation, km	Reduced Travel-time, sec
NORTH	Cochetopa	2	189.5	31.98	2.76	8.25
	Buena Vista		251.4	40.80	2.35	9.35
	Climax		307.7	47.89	3.17	9.40
	Breckenridge	1	332.3	51.09	2.84	9.49
	Dillon		351.2	53.44	2.58	9.50
	Granby	1	390.5	58.36	2.46	9.40
	Poorman Mine		406.5	59.94	1.99	9.09
	Timber Creek		427.7	63.14	2.72	9.61
	Tie Siding	3	504.6	72.1	2.41	9.0
EAST	Taos		152.0	25.80	2.19	6.79
	Mora Ranch		213.8	35.58	2.19	8.84
	Roy	5	304.0	46.64	1.69	8.67
	Rosebud		357.7	53.38	1.50	8.72
	Romero		399.4	59.7 ?	1.26	9.8 ?
	Channing		446.7	64.45	1.16	8.70
	Amarillo	5	501.9	71.4	1.03	8.8
SOUTH	Socorro	5	301.6	45.69	1.58	8.03
	Las Cruces		418	67.5	1.59	7.7
	Mesquite	5	499.6	70.09	1.40	7.70
SOUTHWEST	Gallup	2	151.9	25.73	1.82	6.76
	Twin Lakes		179.6	29.95	1.96	7.50
	St. Michaels		206.1	34.14	2.08	8.39
	Sunrise Springs	2	266.1	41.62	1.84	8.38
	Holbrook	6	311.2	47.35	1.63	8.48
	Winslow	1	358.9	53.65	1.47	8.83
	Chevelon		404.1	59.30	2.02	8.79
	Tonto Forest Obs.		464	65.6	1.50	8.8
	Sunflower	5	497.0	70.24	1.11	8.20
WEST	Farmington	2	85.5	15.29	1.71	4.63
	Shiprock		139.6	23.77	1.52	6.35
	Teec Nos Pas		169.1	28.37	1.64	7.25
	Mexican Water		214.8	35.8	1.53	9.0
	Shonto	5	305.5	47.10	2.01	8.91
	Kaibito		350.6	53.30	1.89	9.50
	Kanab	5	502.1	71.5	1.69	8.7
	Kanab		503	71.8	1.74	8.9

and in the Eastern Colorado Plateaus Province in Utah and Arizona (Roller, 1965). The apparent velocities of P_n observed here are not reliable because the recording stations are generally too far apart. When the earlier surveys are relied upon, it is possible to fit the observations into a consistent picture. Figure 7 shows a composite plot of the reduced traveltime data separated by azimuth. Apparent velocity lines of 8.0 km/sec, or slightly less, are drawn to fit the P_n data and to be consistent with surveys of surrounding regions. The narrow range of apparent velocities of P_n suggests the crust-mantle interface to be structurally uncomplicated. P_n intercepts range from a low of approximately 8 seconds toward the south to approximately 9 seconds toward the north, indicating a slight regional dip to the north.

Arrival times for the most distant stations, except for those to the east, are uniformly early (Figure 7). The amplitude plots generally show a disturbed region from 300 to 400 km (Figures 2 through 6). These facts suggest the emergence of a new phase as a first arrival at distance ranges approaching 500 km, consistent with previous observations of a deeper layer in the upper mantle having a velocity of about 8.4 km/sec. Roller and Jackson (1966) reported an 8.5-km/sec layer at a depth of about 100 km between Lake Superior and Central Arizona. Earlier, Ryall and Stuart (1963) reported first-arrival apparent velocities of 8.4 km/sec beyond 390 km east of the Nevada Test Site. None of the earlier mentioned surveys reported this high apparent velocity; however, none of those surveys recorded at distances beyond 400 km.

Figure 7. Reduced traveltime plots for all azimuths. Lines shown represent preliminary interpretive equations, as described in the text. Traveltimes have been shown as open triangles if furnished by another organization. These are generally on the recording line, but the measurement at 408 km on the north line was on the opposite side of a major mountain range (Front Range) in the Rocky Mountains.



9.2 + X/7.95
12.1+X/8.4
NORTH
8.75 + X/8.0
EAST
1.9 + X/6.4
8.4 + X/7.85
11.6+X/8.4
WEST
7.9 + X/7.85
11.2 + X/8.4
SOUTH-WEST
8.0 + X/8.0
10.65 + X/8.4
SOUTH
REDUCED TRAVELTIME T - X/8 (SEC)
NORTH
EAST
WEST
SOUTHWEST
SOUTH
DISTANCE (KM)
0
100
200
300
400
500

Other interpretations are possible. For example, in Northern Colorado, Jackson and Pakiser (1965) deduced an abrupt decrease in crustal thickness to the north. The traveltimes to the north (Figure 7) might qualitatively fit this interpretation, without the necessity for an 8.4-km/sec layer at greater depth.

First arrivals, with apparent velocities of 6.4 km/sec, appear on the west and southwest profiles and possibly on others (Figure 7). Upper crustal velocities reported by other work in this region are lower. The data are not sufficient to deduce if this is a true velocity or due to structural complications.

These brief observations indicate that the GASBUGGY data will significantly add to our knowledge of the crust and upper mantle structure in North America.

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APPENDIX I

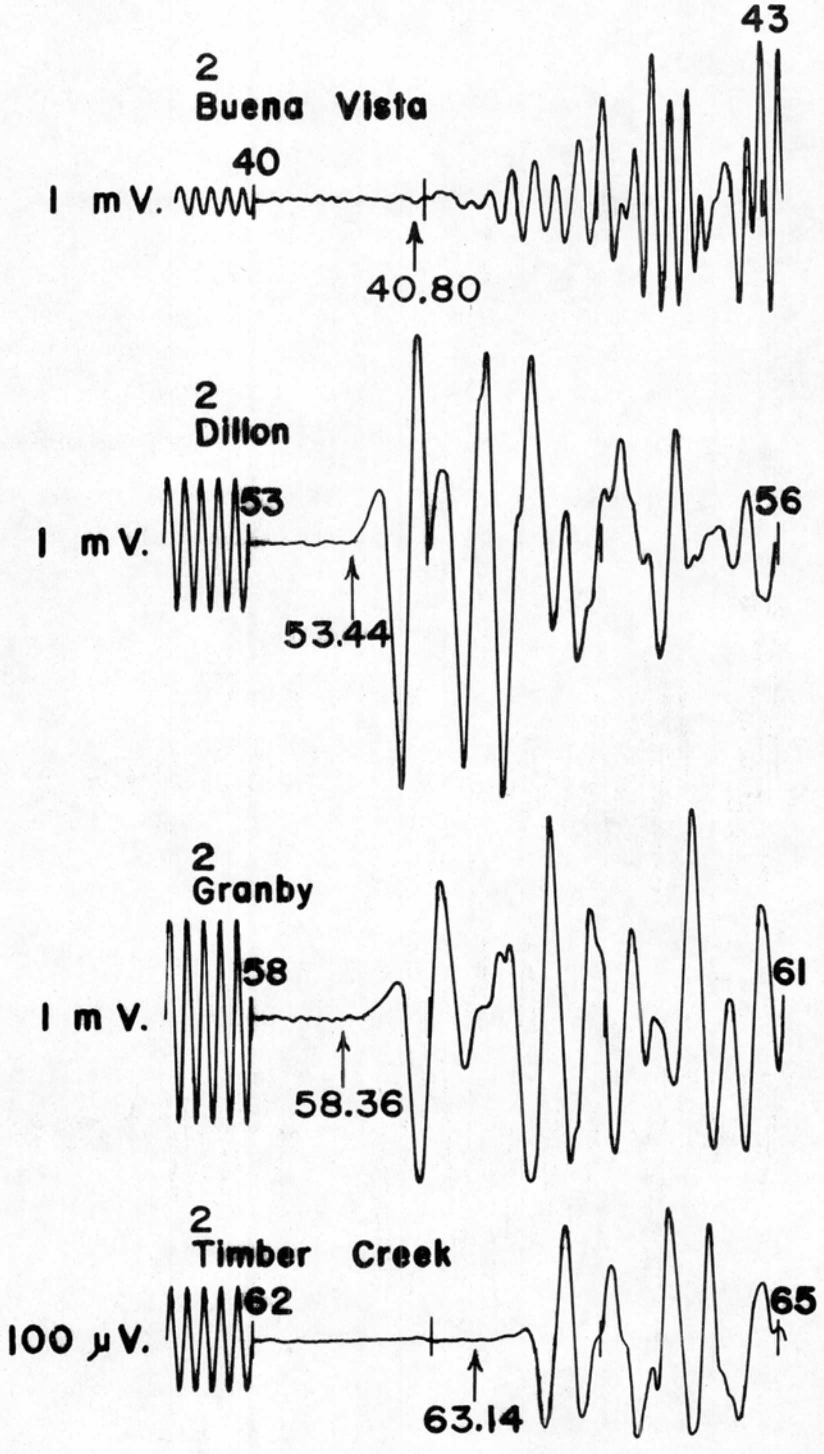
FIRST ARRIVALS AND CALIBRATIONS

The following pages contain a copy of the portion of each seismogram that includes the first arrival. The topmost number of the label refers to the system number as given in Table I. Underneath is the station name and, in the case of truck-mounted systems, the unit designation as well. The monitor records are reproduced for the truck-mounted systems (types 1 and 3). Tracings were made of playbacks for the unattended system (type 2) and of the direct-print recording for type 4. Only one trace was selected for type 2 recordings of more than one channel.

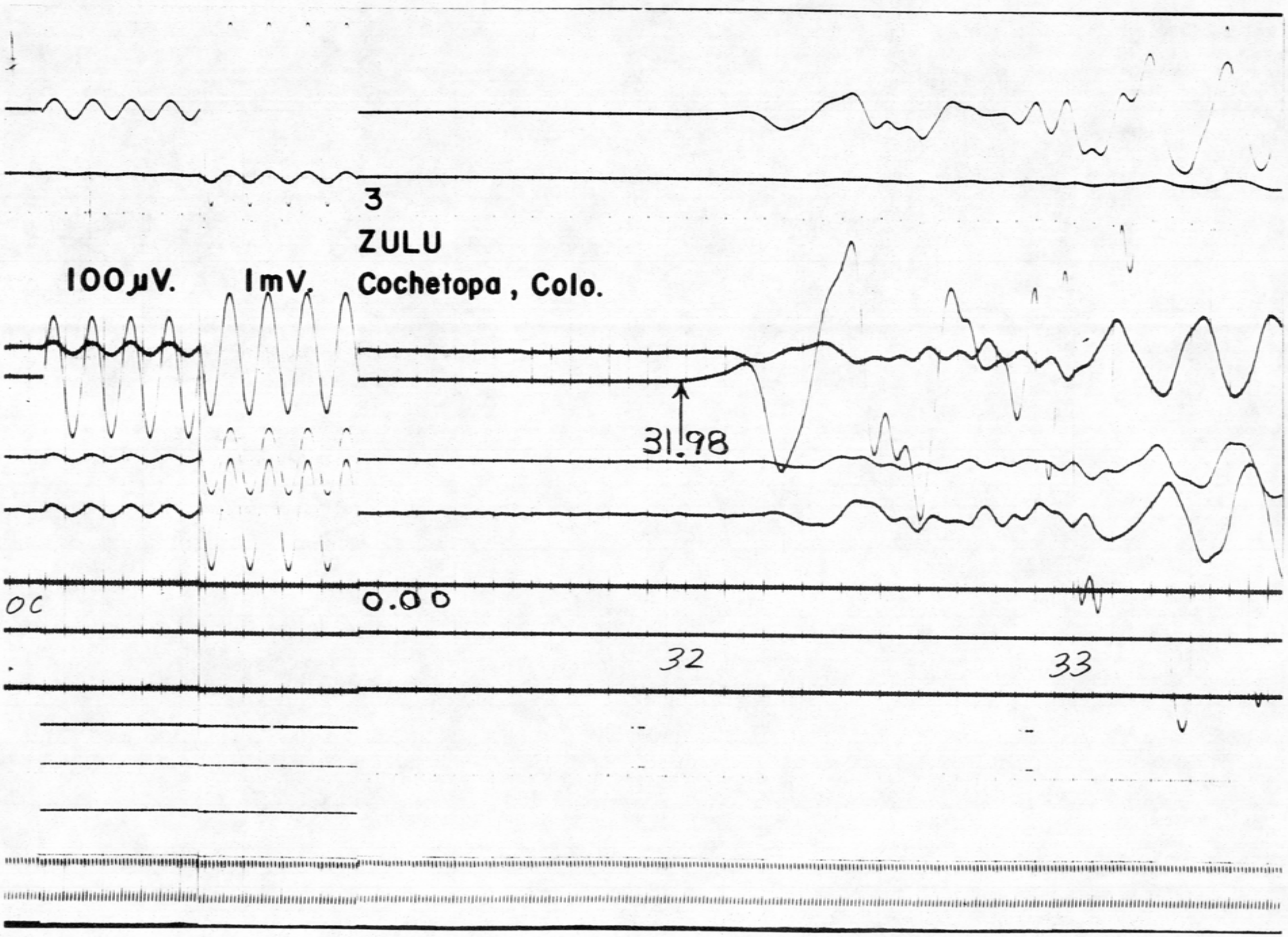
Seismograms from type 1 and 3 systems have 2 levels, separated by 15 db. Trace order is from top to bottom with increasing distance from the event. The type 1 system has two horizontal geophones, radial (channel 7) and transverse (channel 8), at the location of the vertical geophone of either channel 3 or 4. Underneath the geophone channels are a series of timing channels including both a conventional and a rectified WWV radio trace, a coded and a clean 100-Hz trace, and a chronometer trace. Timing lines have been labeled so that by adding the correction given near the left, true traveltimes may be read. The traveltime of first arrival is labeled.

Type 2 and 4 seismogram tracings are time-labeled by uncorrected marks over a 4-second interval, with zero time taken as 19:30. The type 2 system uses a WWVB receiver; the type 1 a WWV receiver. The time of first arrival indicated, however, has been corrected for shot-time delay.

The oscillator calibration applied to the amplifier input is superimposed on the left side of each seismogram. See Appendix 2 for a description of its use in measuring amplitudes. The voltage of each calibration is marked in millivolts (mv) or microvolts (µv).

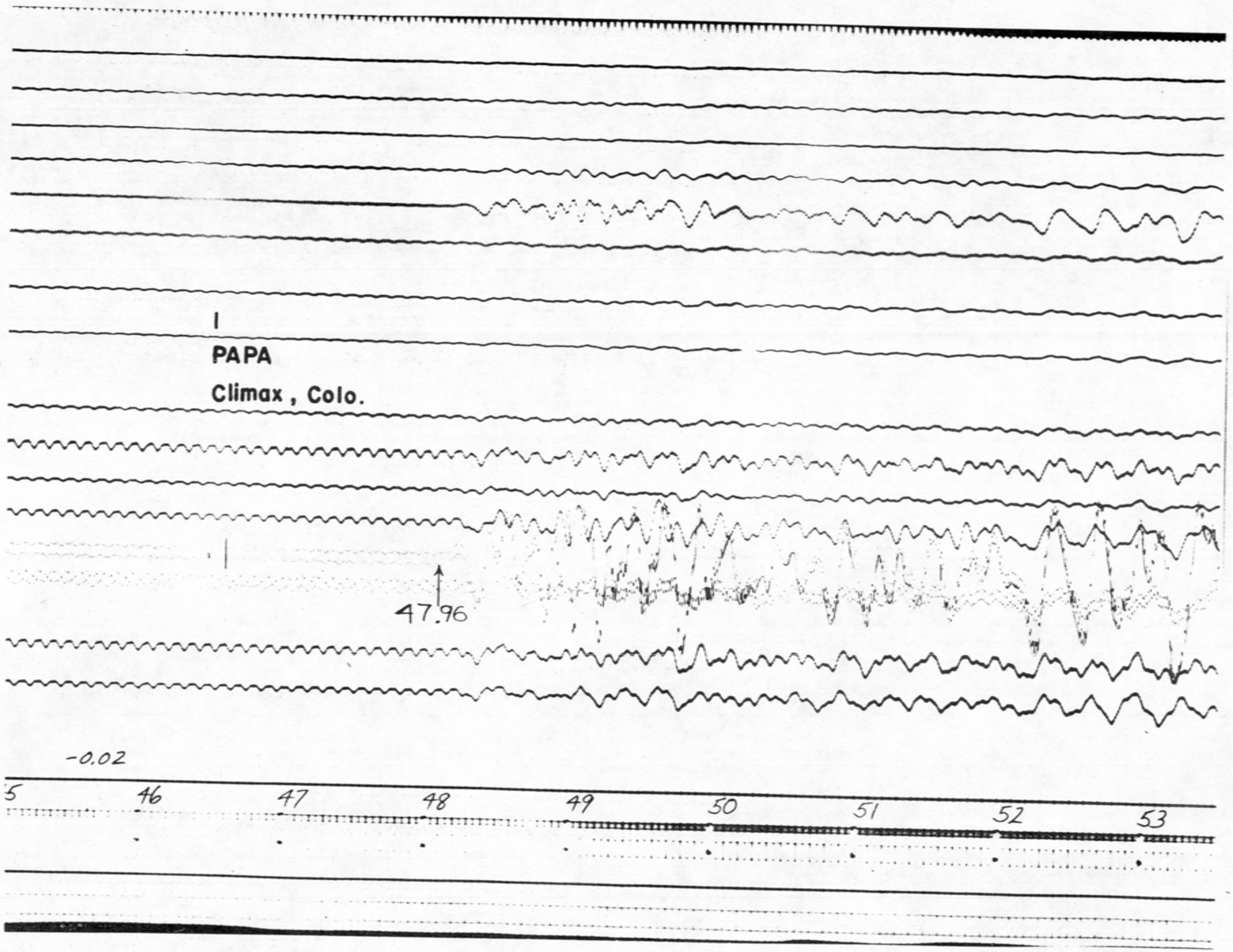

43
2
Buena Vista
40
1 mV.
40.80
2
Dillon
53
56
1 mV.
53.44
2
Granby
58
61
1 mV.
58.36
2
Timber Creek
62
65
100 μV.
63.14

North line

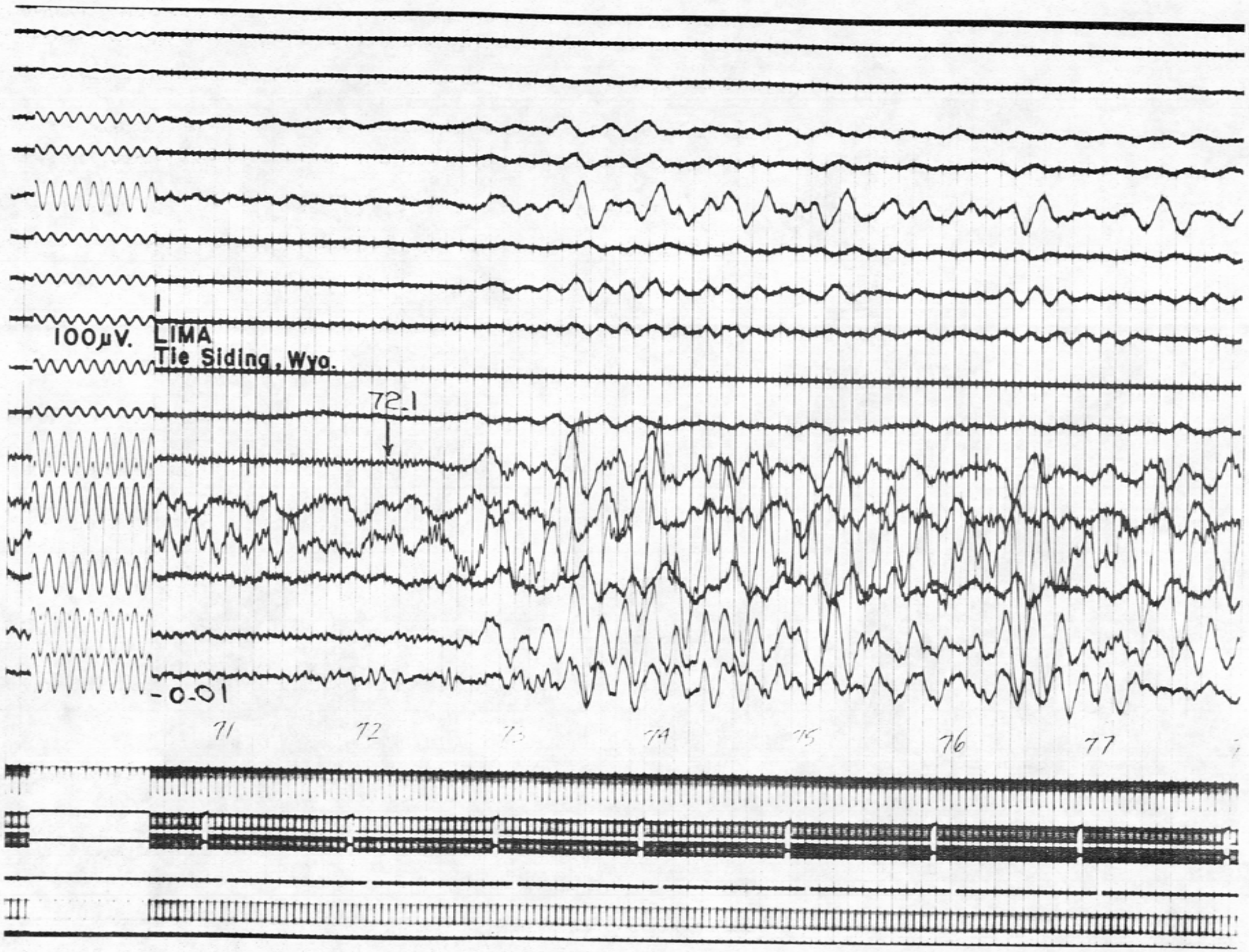


North line

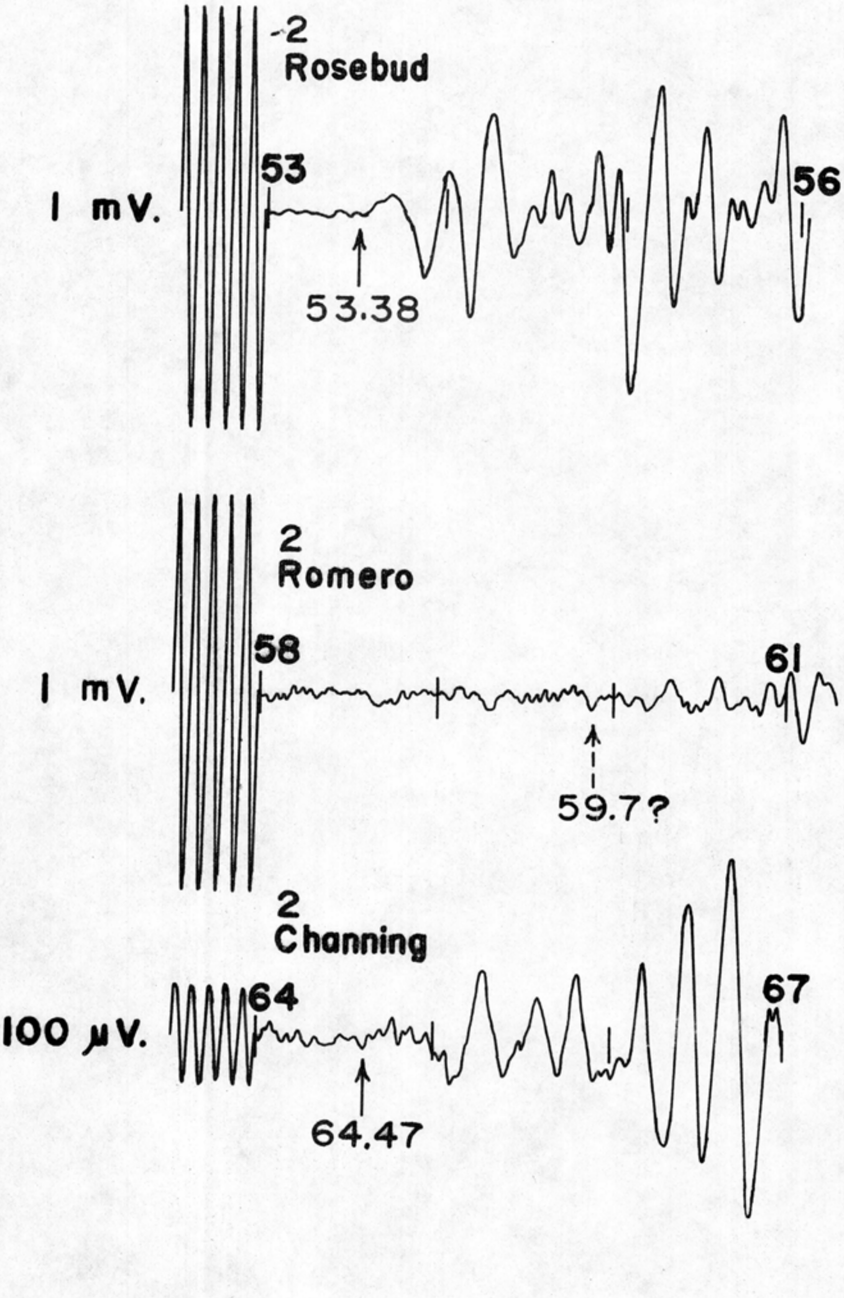
24



North line



North line

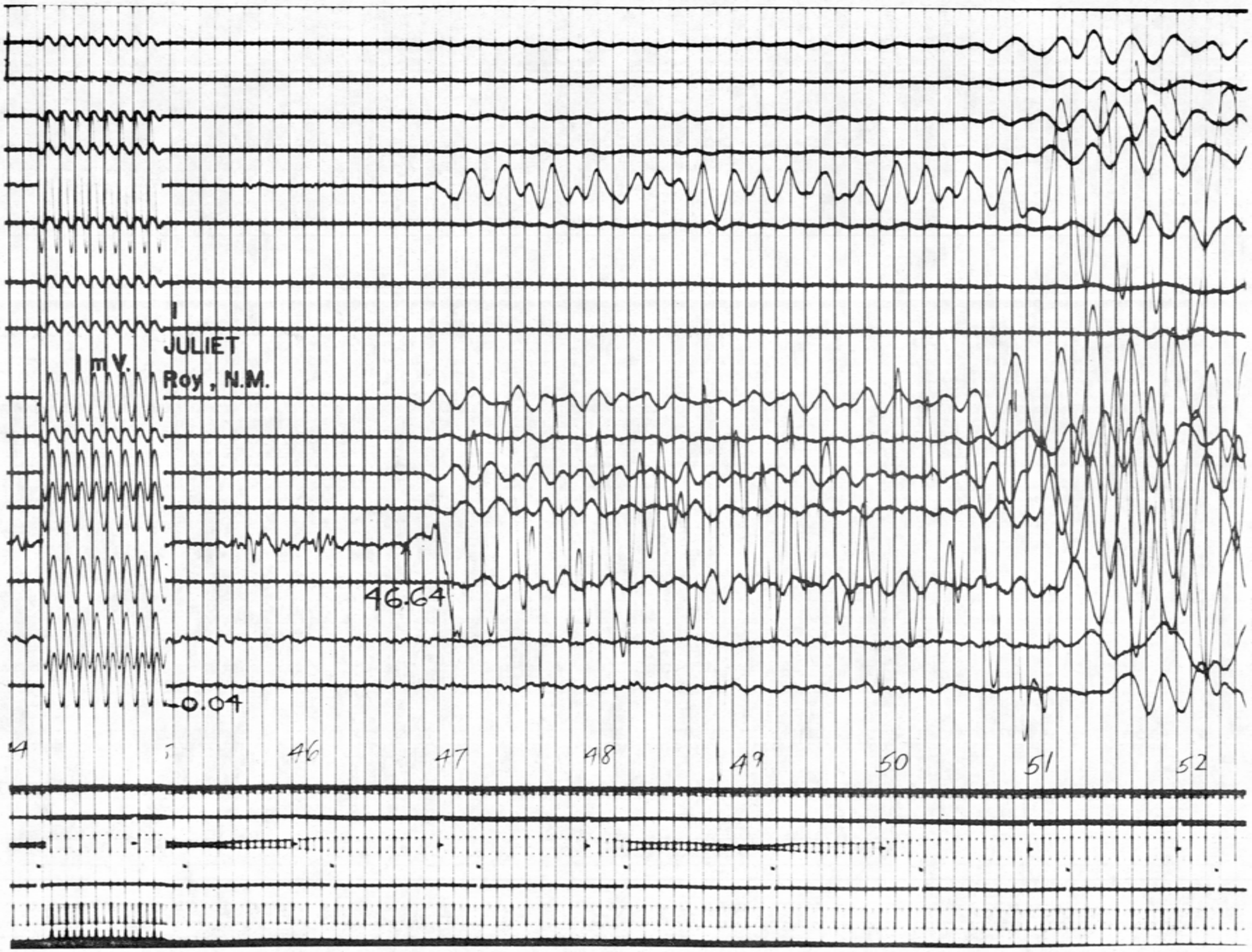


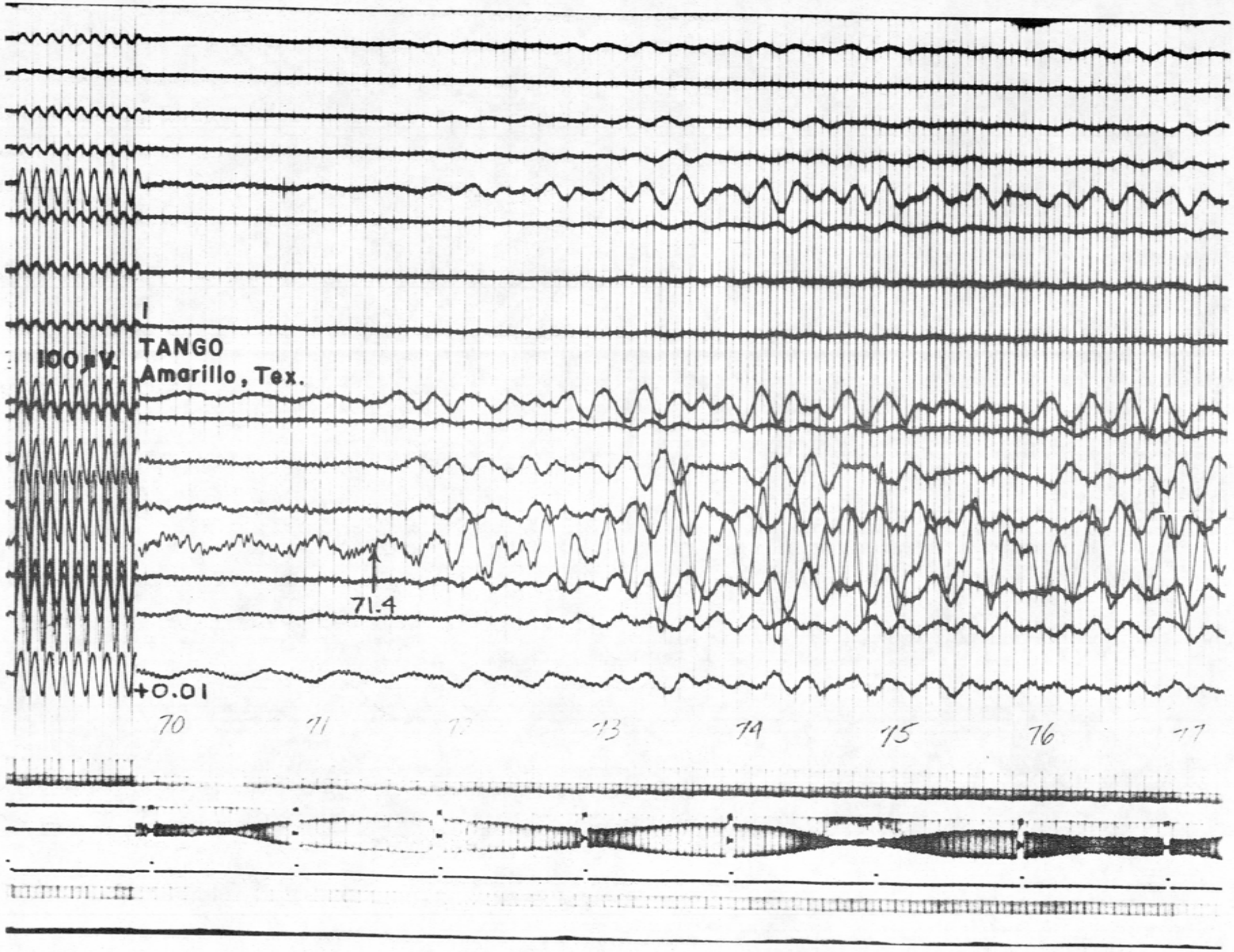
2
Rosebud
53
1 mV.
53.38
56
2
Romero
58
1 mV.
59.7?
61
2
Channing
64
100 μV.
64.47
67

East line

East line

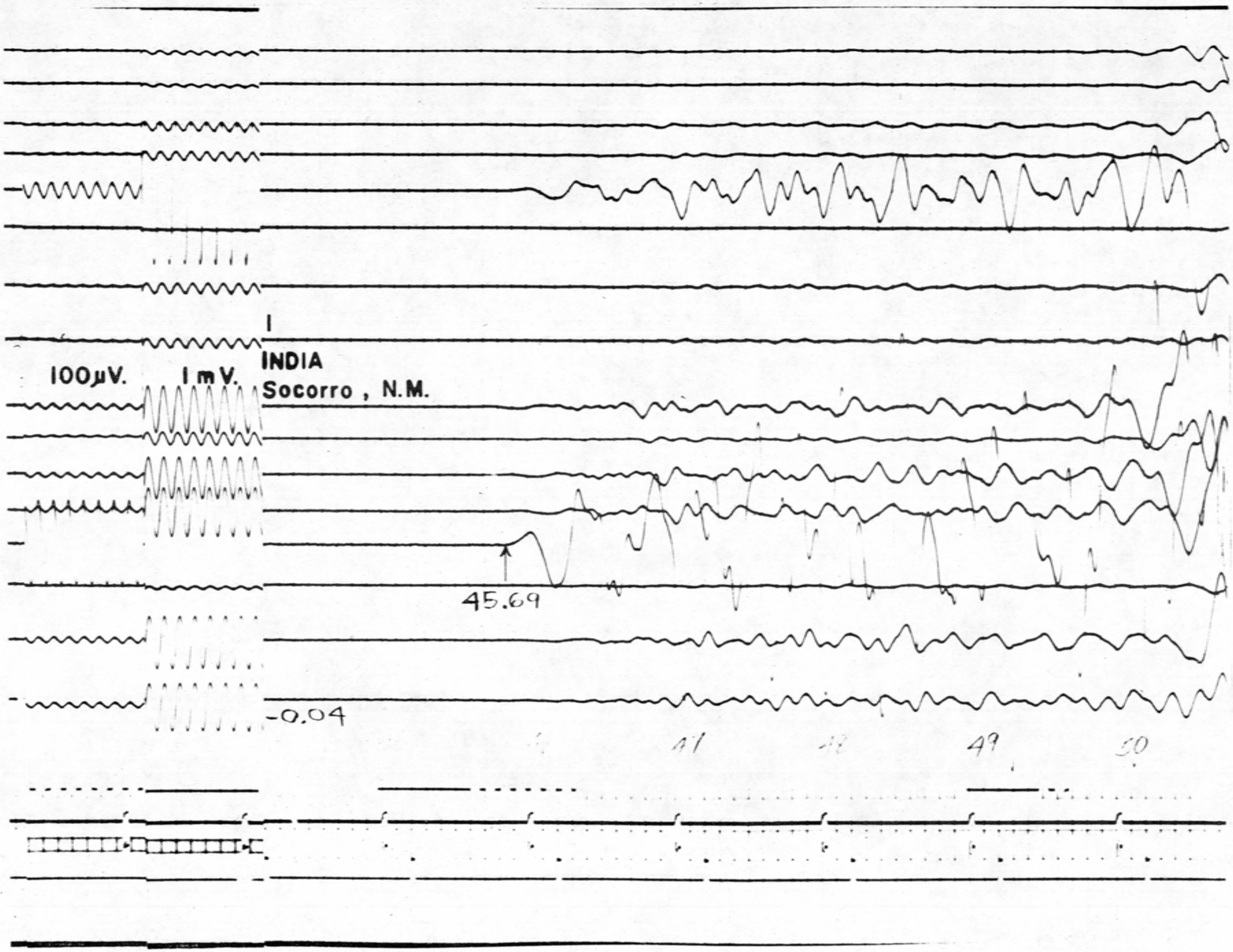
28



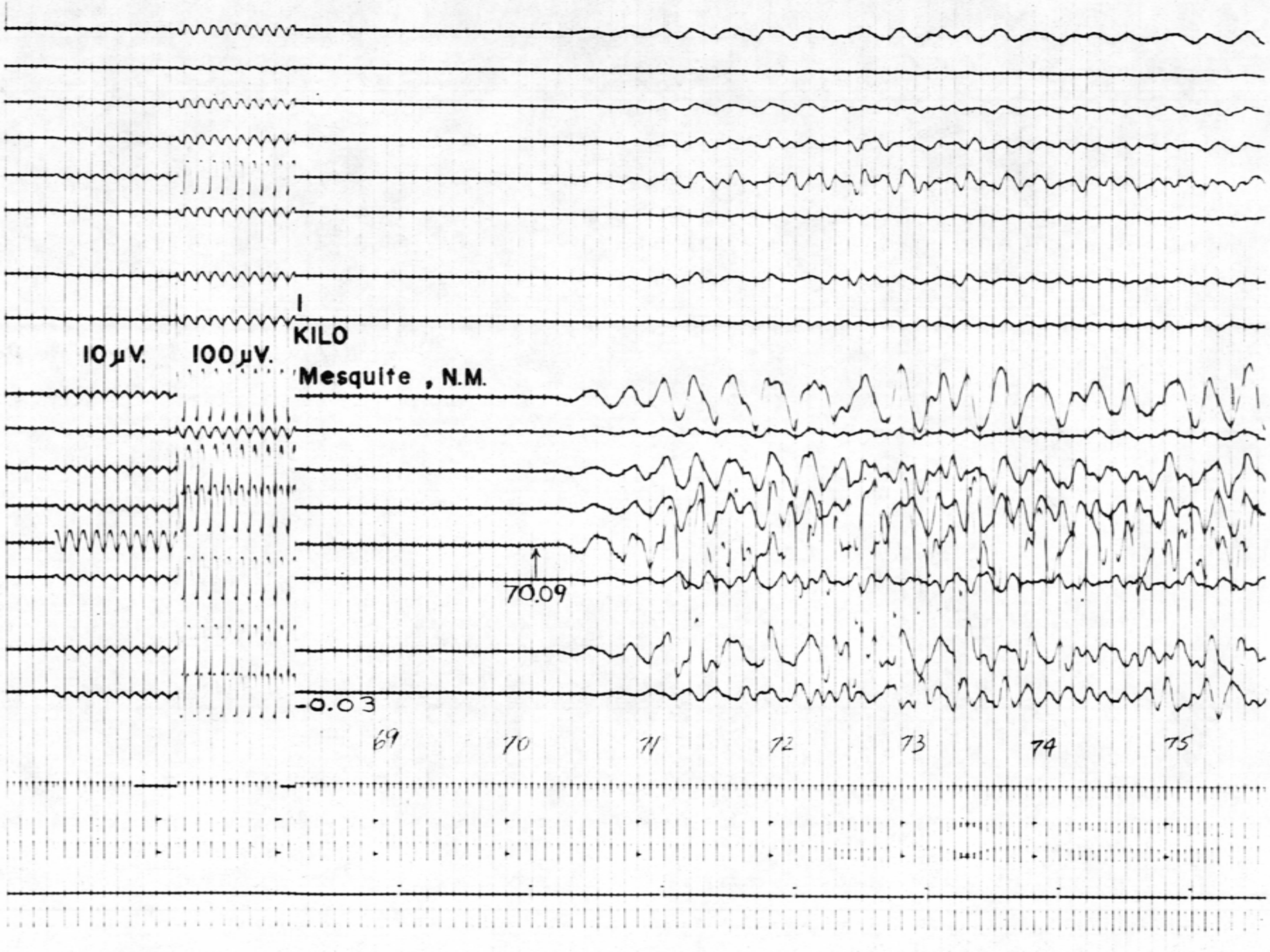


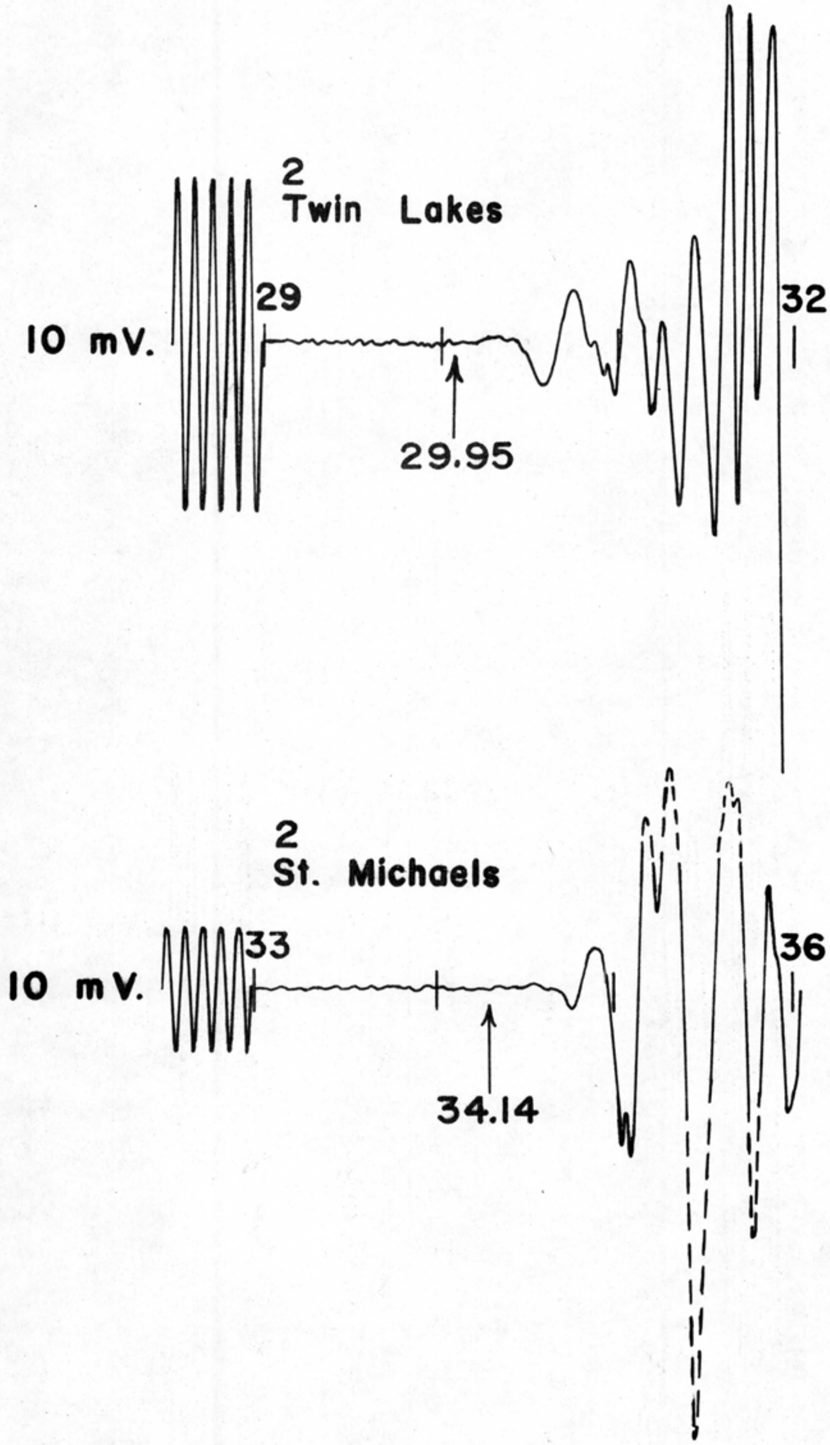
East line
29

South line
30

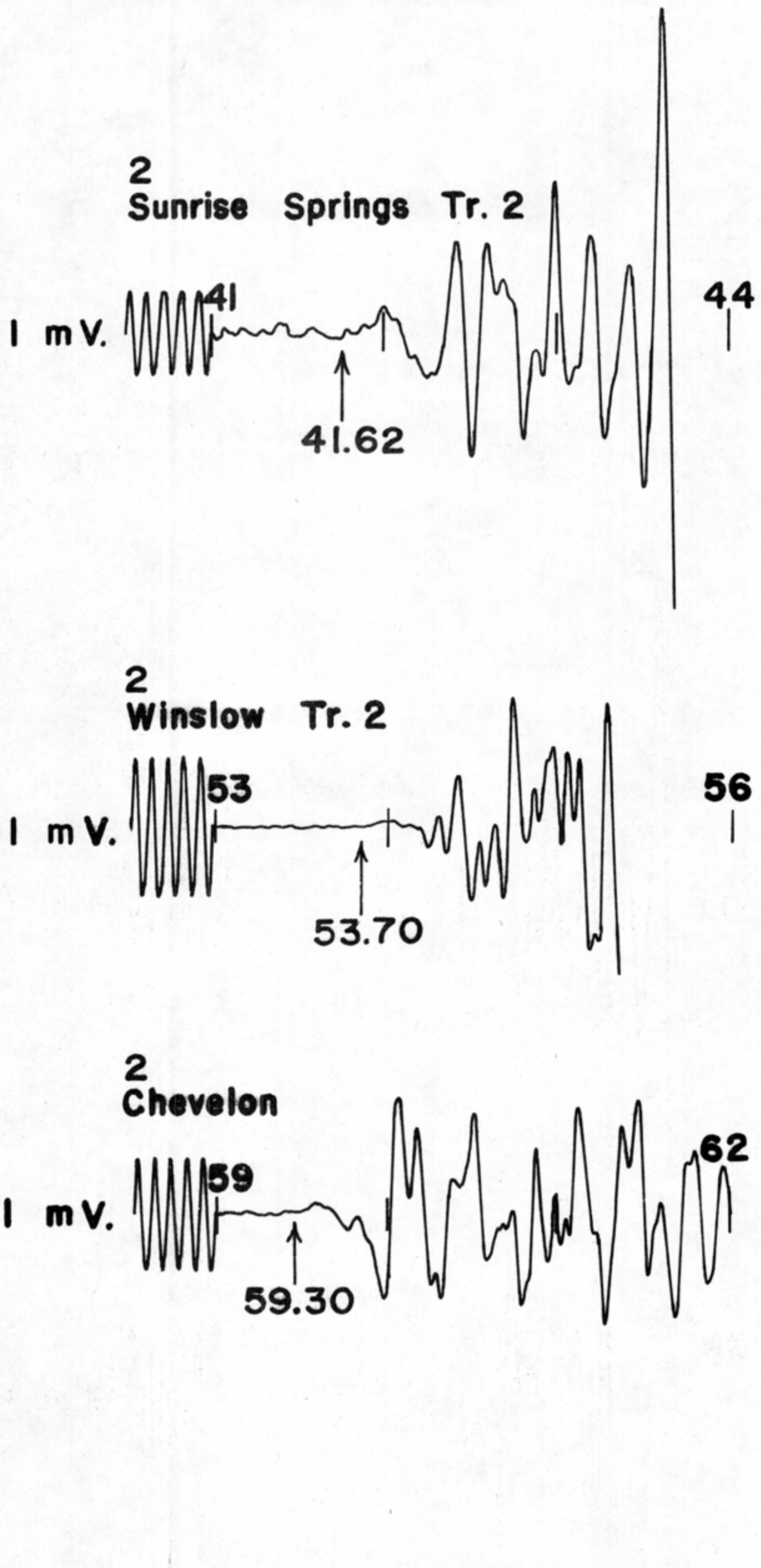


South line
31

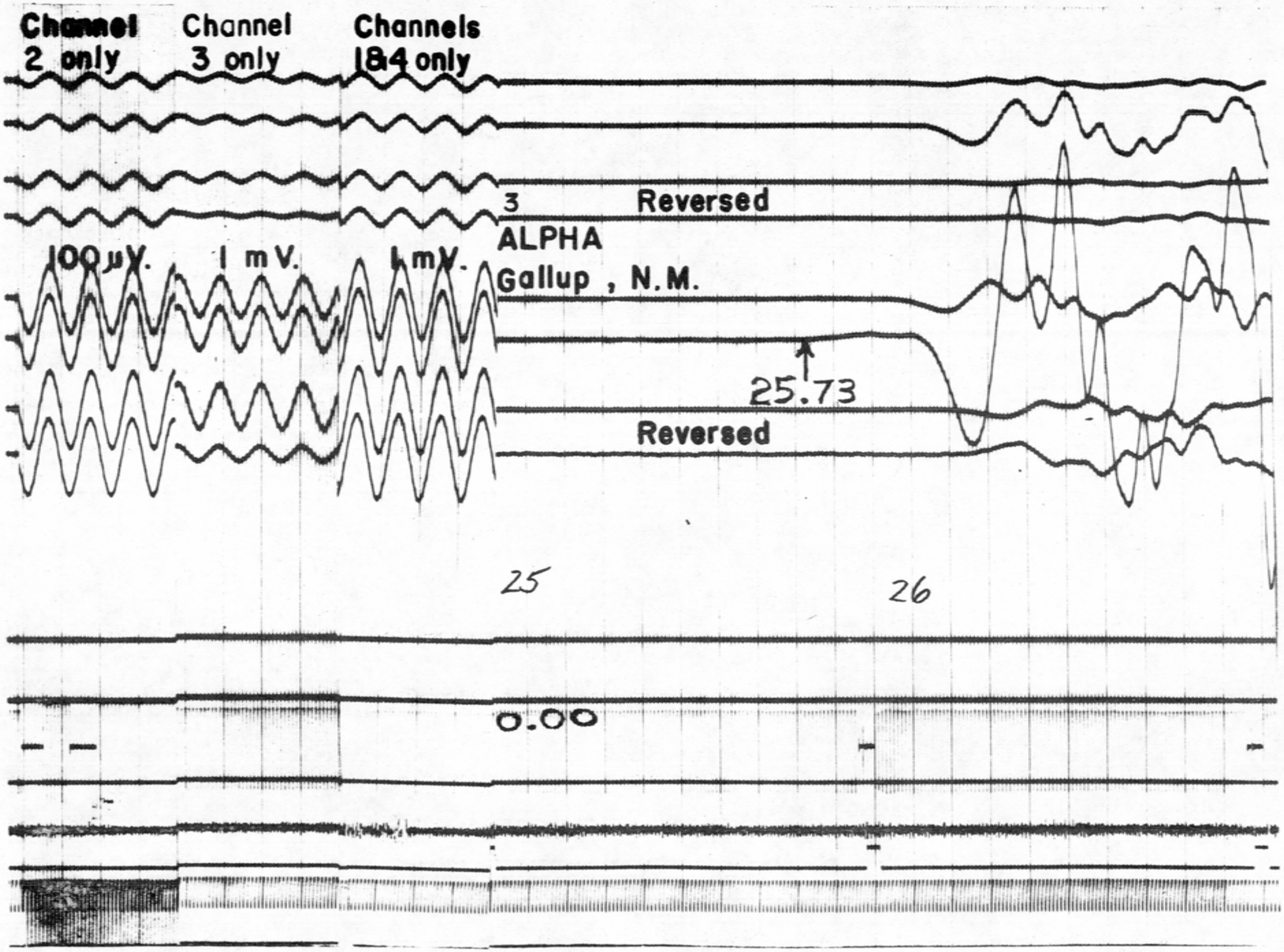




Southwest line

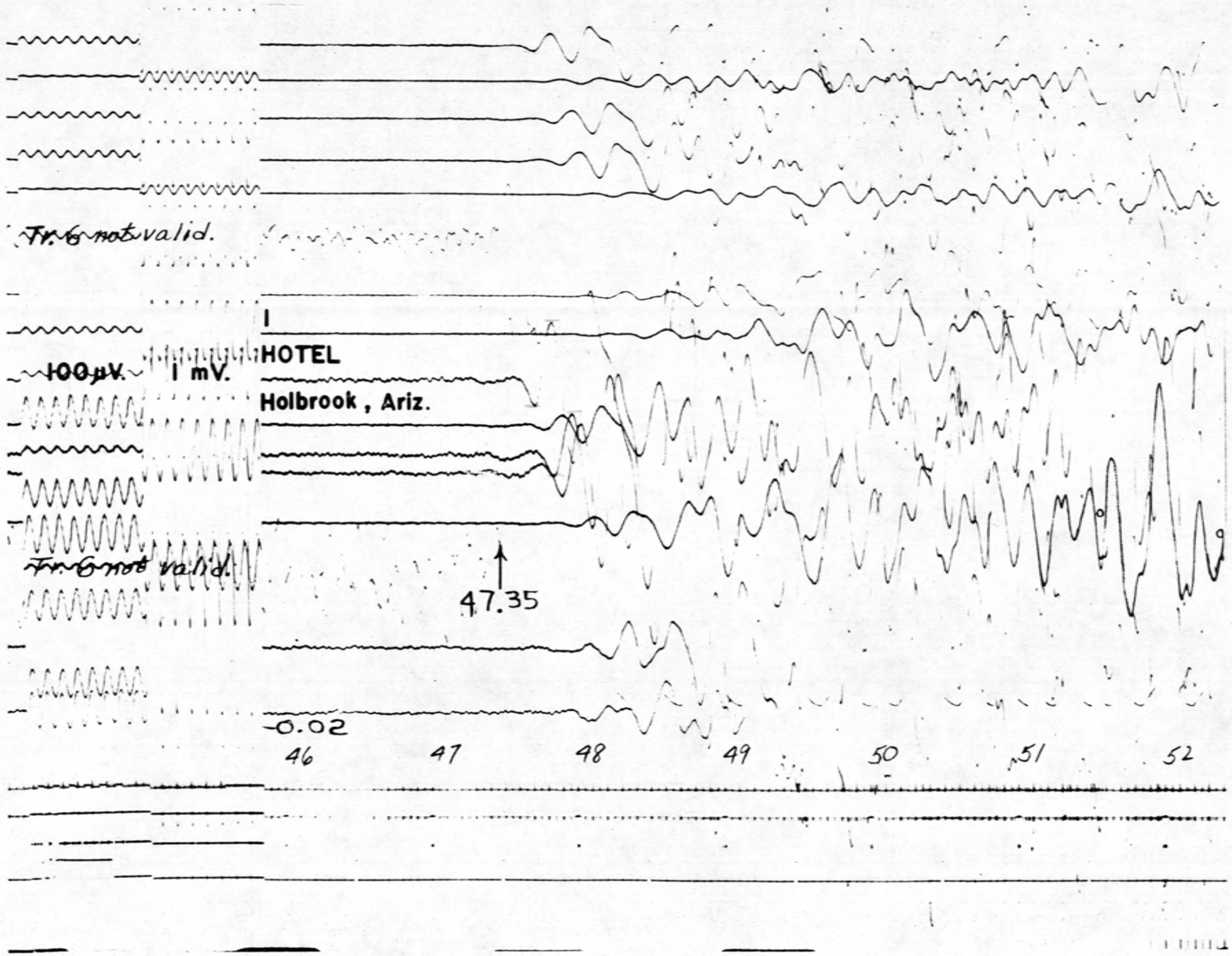


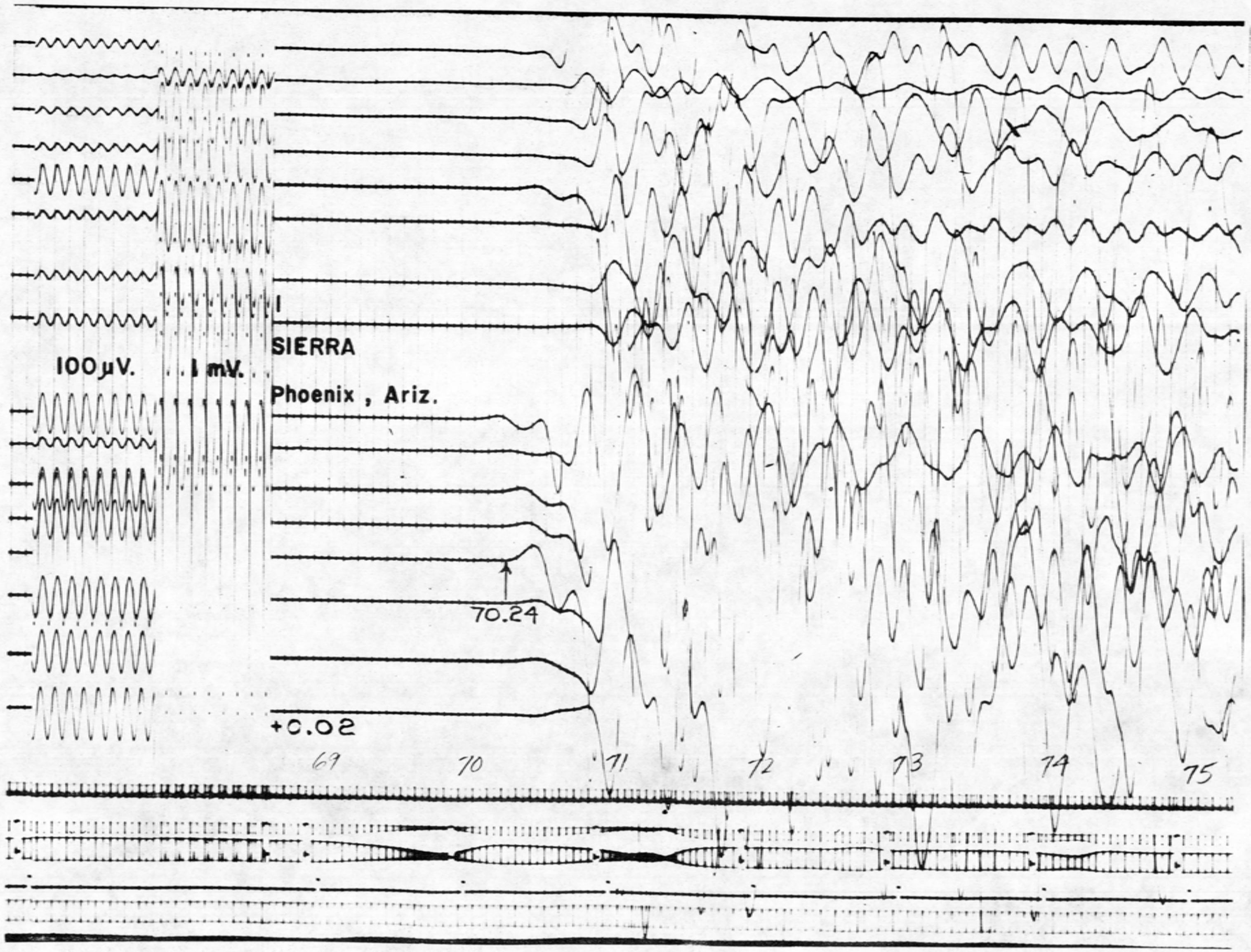
Southwest line

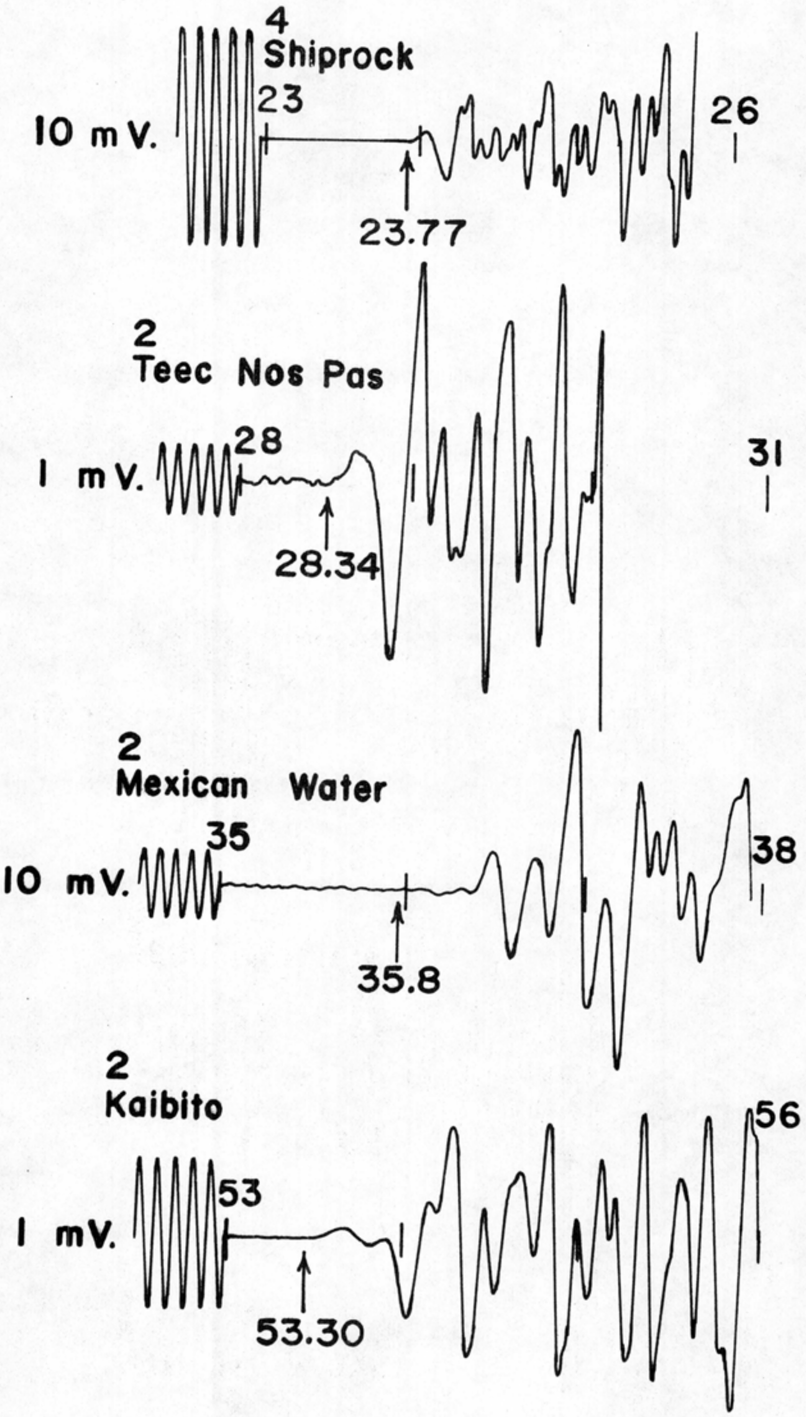


Southwest line

34


Tr. 6 not valid.
I
HOTEL
100 μV.
1 mV.
Holbrook, Ariz.
Tr. 6 not valid.
47.35
-0.02
46
47
48
49
50
51
52

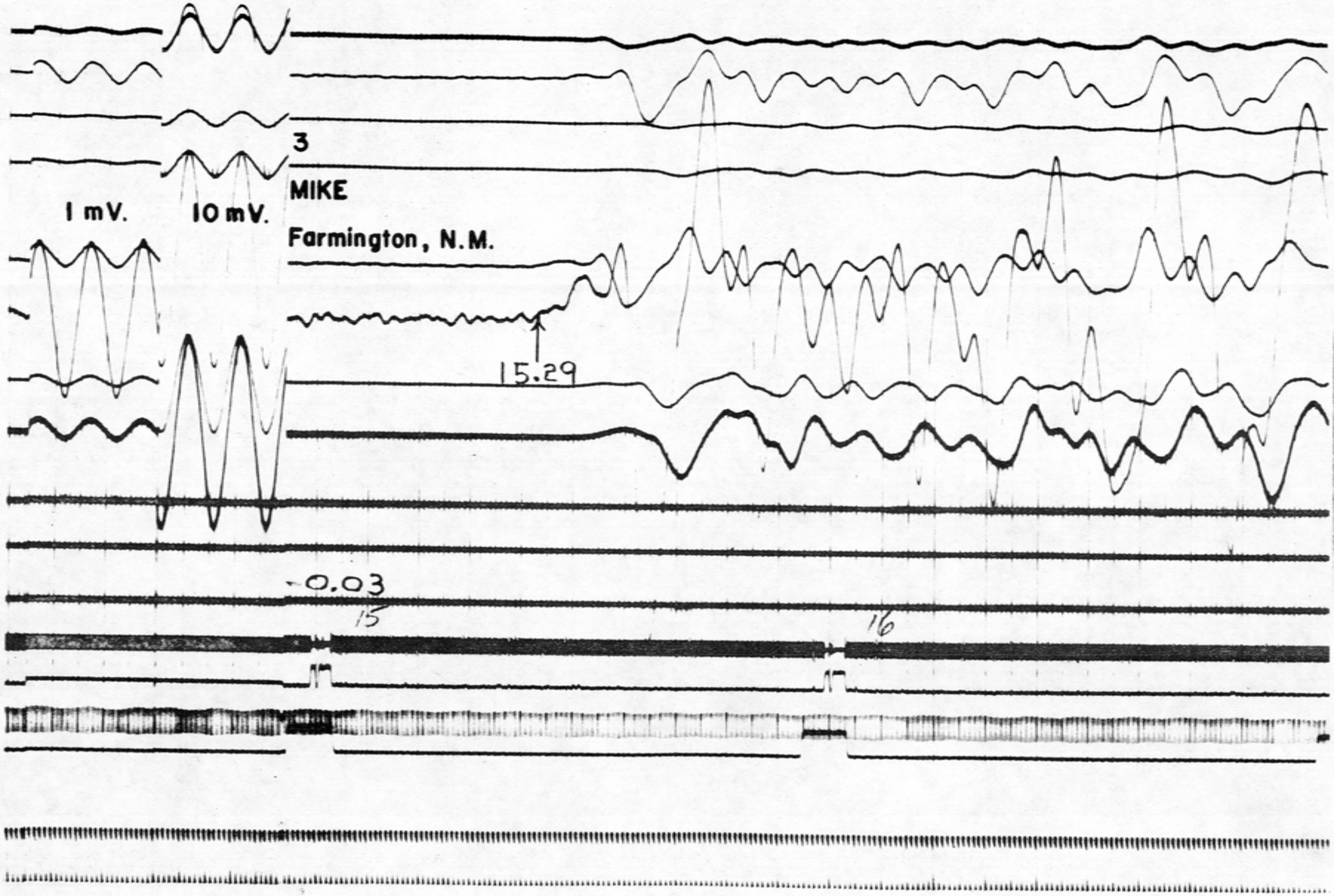

100 µV.
1 mV.
I
SIERRA
Phoenix , Ariz.
70.24
+0.02
69
70
71
72
73
74
75

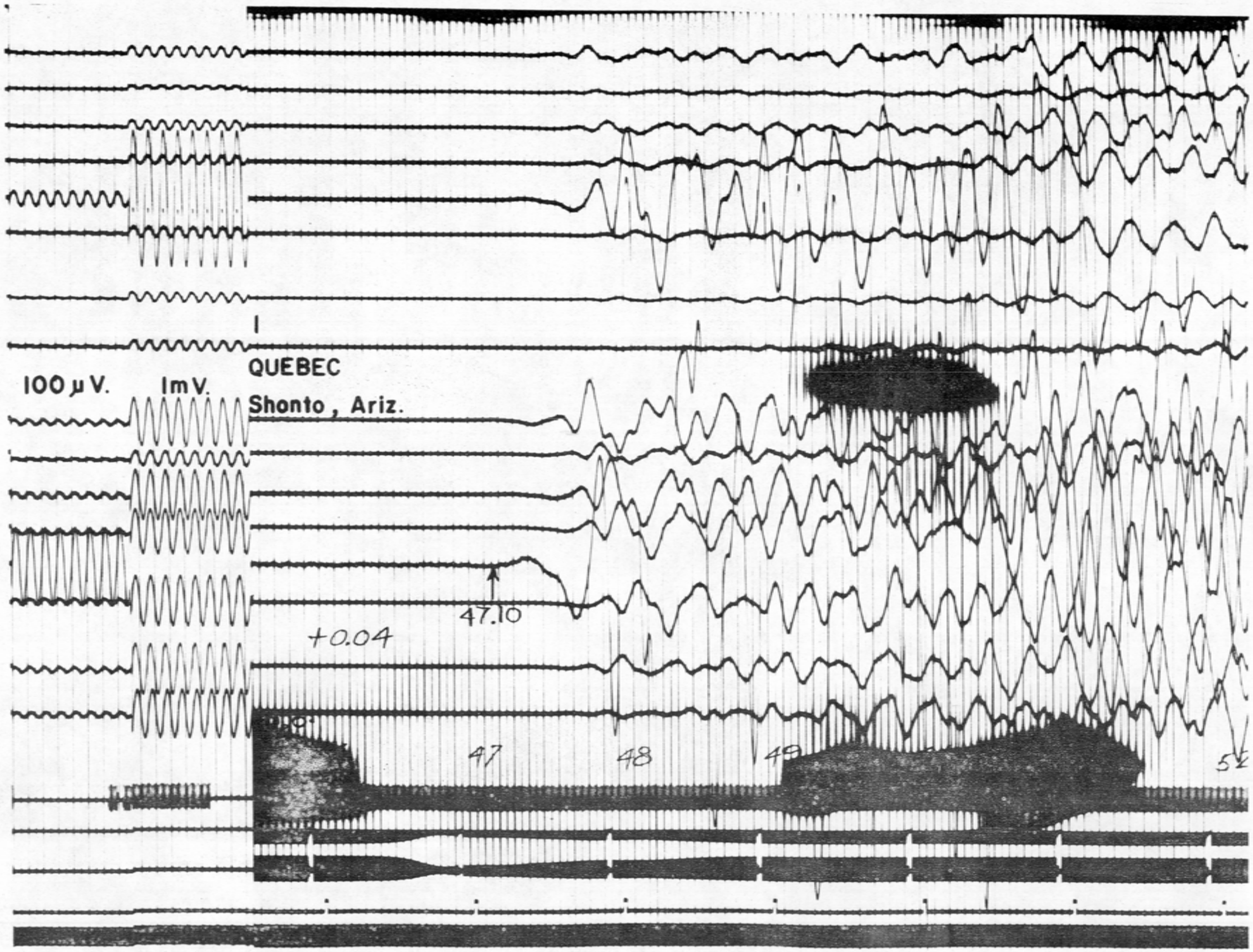

4
Shiprock
10 mV.
23
23.77
26
2
Teec Nos Pas
1 mV.
28
28.34
31
2
Mexican Water
10 mV.
35
35.8
38
2
Kaibito
1 mV.
53
53.30
56

West line

West line

38

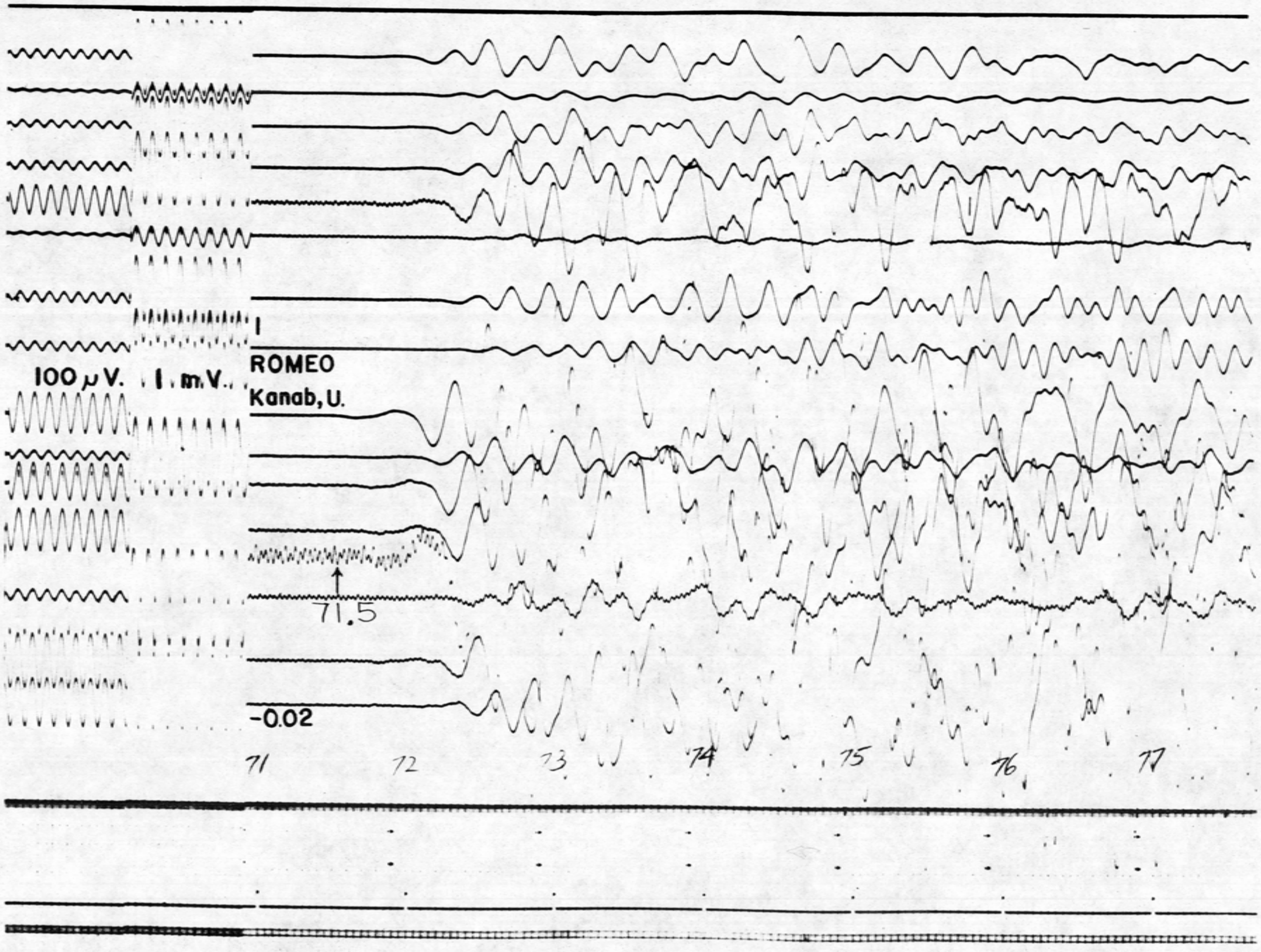




West line

West line

40



APPENDIX 2

CALIBRATION OF THE RECORDING SYSTEM

Amplitude measurements were made in a manner similar to that described by Eaton (1963). A calibration record, from known RMS voltages applied to the input of the amplifier, is used to measure the input voltage that corresponds to the recorded signal amplitude. Then it is assumed that the ground-motion amplitude is that of a simple-harmonic component required to produce the measured input voltage. The harmonic character of the recorded waveforms is approximated by measuring the period at the location of amplitude measurement on the seismogram. The effect of this approximation can be minimized by making the measurements in units of velocity, because over the frequency range of measurements the seismometer has a relatively flat velocity response.

A form of the seismometer release test is routinely made on the attended system. A known, constant voltage is applied to the seismometer coil to displace the mass. Then a switch simultaneously stops the current flow and connects the seismometer to the amplifier input. The resulting pulse is recorded. The use of this test requires spectral analyses which have not been made for this preliminary data report.

The recording system described by Eaton (1963) is essentially the same as the attended system used here for the GASBUGGY recording, except that Electro Tech, EV-17, seismometers were used instead of Hall-Sears, HS-10's. The ground displacement may be found by combining equation (2) and (3) and dropping the oscillatory cosine multiplier to arrive at a general form of equation (4) (Eaton, 1963, p. 5791-5792):

$$A_d = \frac{S}{C} V \frac{\left[\left(\frac{F_0^2}{f^2} - 1\right)^2 + 4\beta^2 \frac{F_0^2}{f^2}\right]^{1/2}}{\sqrt{2}\pi f G\left(\frac{Z}{Z+L+r}\right)}$$

where:

S = peak-to-peak amplitude of an event on the seismogram, scaled in any convenient units,

C = peak-to-peak amplitude of the sinusoidal calibration signal on the same seismogram, scaled in the same units as S,

V = rms voltage of the calibration signal,

F_0 = resonant frequency of the seismometer in cycles per second (cps) = 1.033 cps,

f = frequency of the ground motion in cps,

β = damping constant of the seismometer circuit,

G = intrinsic sensitivity of the seismometer to motion along a line vertical to the seismometer frame,

Z = input impedance of the recording system (resistive at operating frequencies),

L = line resistance,

r = coil resistance of the seismometer.

Ground velocity amplitude may be found by multiplying by $2\pi f$:

$$A_v = \frac{S}{C} V \left\{ \frac{\sqrt{2}\left[\left(\frac{F_0^2}{f^2} - 1\right)^2 + 4\beta^2 \frac{F_0^2}{f^2}\right]^{1/2}}{G\left(\frac{Z}{Z+L+r}\right)} \right\}$$

The term in brackets, {}, is the frequency factor in microns/second-millivolt (μ/sec-mv) needed to convert seismogram amplitude in mv to ground velocity in μ/sec, and this factor must be evaluated for each recording system used. The parameters that vary with recording system are β, G, Z, L, and r.

There are three possible combinations corresponding to the recording systems described in Table I. The 500-ohm coil seismometer was used with the attended, truck-mounted system (type I); the 5000-ohm coil seismometer was used with the unattended system (type 2); and the 5000-ohm coil seismometer was used with the attended, truck-mounted system without tape recording (type 3) with an attenuation pad in each seismometer line. The parameters for these varying conditions are as follows:

Parameter	Units	Type I	Type 2	Type 3
β		0.64	1.1	1.0
G	mv-sec/μ	0.156	0.50	0.50
Z	ohms	1550	4100	5060
L	ohms	460	Neglected	Neglected
r	ohms	524	5000	5000

A complication arises from the insertion of attenuation pads in the seismometer lines for type 3, in which the amplifier input impedance of the amplifier is the same as type I. The value of Z given here is that seen by the seismometer, including the effect of the pad. The calibration signal is applied at the amplifier input so the attenuation factor (14.1) of the pad must be considered in making amplitude measurements. Attenuation pads were also used on some of the unattended systems (type 2) at short-distance ranges. However, in each one of these cases the calibration signals were applied to the attenuation-pad input so the attenuation factor need not be considered. The pads were designed so that the impedance seen by the seismometer is 3960 ohms, which is not significantly different from the Z of the amplifier.

The accompanying graph (Figure 8) shows values of the period factor for the three possible conditions. (For type 3 measurements an additional multiplier of 14.1 must be used for the attenuation-pad loss.) The plots are inverse response curves. The low-frequency behavior of the input impedances of the systems has not been checked in detail; thus, the curves may not be precise above 0.5-sec period.

For the single-channel attended system (type 4) all parameters are identical to those of type 1.

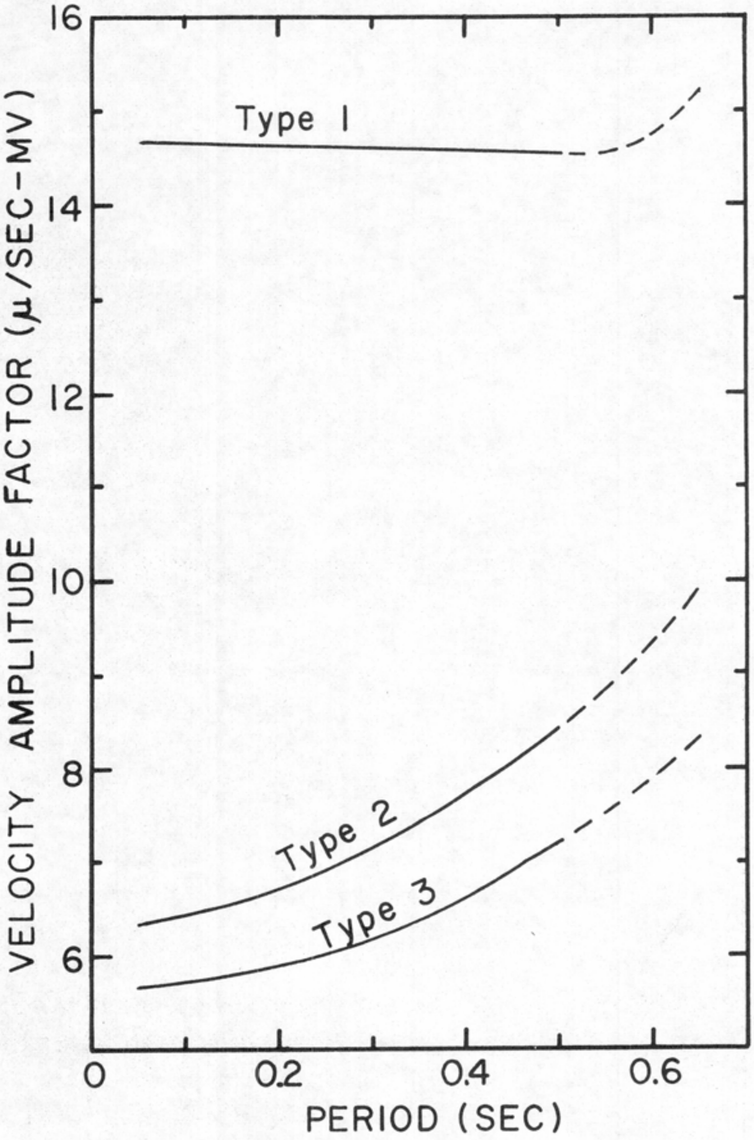


Figure 8 -- Velocity amplitude factor plots for system types 1. 2, and 3.

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