Report No. 1506-11

UNIVERSITY OF CALIFORNIA
SEISMOGRAPHIC STATION
BERKELEY, CALIFORNIA 94720

Director of Physical Sciences
Air Force Office of Scientific Research
Attn: SRPG
Washington, D.C. 20333

SEMI-ANNUAL TECHNICAL SUMMARY REPORT

June 1966 - December 1966

Project Code No. 5810
Contractor: The Regents of the University of California
Date of Contract: January 1, 1965
Amount of Contract: $199,094
Contract No. AF 49(638)-1506
Contract Termination Date: December 31, 1966
Project Scientist: Cinna Lomnitz
Telephone: 415-845-6000, Ext. 3977

Short Title of Work: RESEARCH ON THE CENTRAL CALIFORNIAN LARGE-SCALE SEISMIC ARRAY

Sponsored by

Advanced Research Projects Agency
ARPA Order No. 292 Amnd. #20

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RESEARCH ON THE CENTRAL CALIFORNIAN LARGE-SCALE SEISMIC ARRAY

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SEMI-ANNUAL TECHNICAL SUMMARY REPORT

June 1966 - December 1966

1. INTRODUCTION

A. Extension of Contract.

Under a Supplemental Agreement, effective 1 January 1967, Contract AF 49 (638)-1506 has been extended until 31 December 1968.

Hence, this report is not a Final Report of research but the Semi-Annual Technical Summary Report. Nevertheless, we thought it appropriate to bring together here in summary form the investigations undertaken during the first two years (1965-1966) of the contract.

B. Research Scope.

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The contract is entitled "Research on the Central California Large-Scale Seismic Array". The objectives of the study are as follows:

1. Maintain and operate the telemetered network of stations in the seismically active Coast Range.

2. Conduct research on the seismic data recorded from this network. This research should include the following:

    a. Focal mechanism and aftershock characteristics of small earthquakes.

    b. Propagation of S waves across the network

    c. P-wave coherence from teleseisms

    d. Improved travel-time curves.

2. SUMMARY OF RESEARCH ACCOMPLISHED

A telemetry network of ten telemeter stations has been kept in operation in 1965-1966. The array is 240 km long (Priest Valley to Berkeley) and 160 km wide (Granite Creek to Jamestown). This is the heart of 16 seismographic stations operated by the University of California, Berkeley.

The network has allowed high-quality simultaneous recording of seismic signals on film and magnetic tape. An extensive library of recorded wave trains from earthquakes (local and distant) and explosions has been built up.

A careful study of the morphology of earthquakes in central and northern California has been carried out; the telemetry facility allows locations to be determined with more precision than previously. Attention has been given to the variation of low-energy (magnitudes between 2.5 and 5) earthquakes with time and in relation to mapped fault traces.

Three earthquake sequences associated with main shocks of magnitude 5 and greater have been analyzed. These and earlier sequences begin to suggest a division into two types of behavioral patterns.

Considerable work has been done on the propagation of P, pP and PKP waves from teleseisms across the array. We were among the first to report the existence of large-scale azimuth anomaly functions for the travel-times of P waves between source and station. Anomaly functions for most of the Berkeley stations have been measured; the geological consequences are being worked out.

Again, we were among the first to estimate (and publish) mean azimuth (and slowness) anomaly functions for a seismic array. The functions have been incorporated into the routine rapid location of teleseisms carried out at Berkeley. We have found that, for example, surprisingly close locations for Longshot, the French nuclear tests near Tahiti and the U.S.S.R. nuclear tests, can be computed with the Berkeley network first-arrivals if the anomaly functions are taken into account.

A comparison between the signatures of the Chase V explosion and an earthquake near Chico, California has drawn attention to a number of different elastic wave properties. These events were of similar magnitude and were recorded on the augmented network of seismographs specially planned by us for the Chase V blast.

Our research is all directly or indirectly germane to the problem of the nature of the crust and upper mantle in this part of the globe. We have used travel-times of P and S from quarry blasts, local earthquakes, Nevada atomic explosions and Chase V to determine the local crustal structure. We have extended the traditional analysis to include the use of S particle motion, crustal transfer function for P waves of high frequency, and the station azimuth anomaly functions.

3. READ OR PUBLISHED PAPERS ACKNOWLEDGING CONTRACT SUPPORT
(1965-1966)

Bolt, B.A. and Nuttli, O. (1966). "P Wave Residuals as a Function of Azimuth, I, Observations", J. Geophys. Res., 71, 5977.

Filson, J.R. (1966). "The S Phase from Local Earthquakes", Meeting of Seism. Soc. Am., Reno.

Freedman, H.W. (1966). "A Statistical Discussion of P_n Residuals from Explosions", Bull. Seism. Soc. Am., 56, 677.

Lomnitz, C. (1966). "On Estimating Earthquake Risks". Third Upper Mantle Symposium on Theory and Computers, Cambridge, July 5, 1966.

Lomnitz, C. (1966). "Magnitude Stability in Earthquake Sequences", Bull. Seism. Soc. Am., 56, 247.

McEvilly, T.V. (1966). "The Earthquake Sequence of November 1964 near Corralitos, California", Bull. Seism. Soc. Am., 56, 755.

McEvilly, T.V. (with Takeuchi, H.) (1966). "Some Observations on the Effects of Crustal Parameters on the Inversion of Surface Wave Dispersion Data", Meeting of Seism. Soc. Am., Reno.

McEvilly, T.V. (1966). "Crustal Structure Estimation within a Large-Scale Array", Geophys. J., Roy. Astr. Soc., 11, 13.

McEvilly, T.V. (1966). "Parkfield Earthquakes of June 27-29, 1966, Monterey and San Luis Obispo Counties, California - Preliminary Report. Preliminary Seismic Data, June-July, 1966", Bull. Seism. Soc. Am., 56, 967.

McEvilly, T.V. and Casaday, K.B. (1967). "The Earthquake Sequence of September, 1965 near Antioch, California", Bull. Seism. Soc. Am., 57, (in the press).

Mikumo, T. (1965). "Crustal Structure in Central California in Relation to the Sierra Nevada", Bull. Seism. Soc. Am., 55, 65.

Mikumo, T. (1965). "Determination of Phase Velocity and Direction of Wave Approach from Station Arrays", Bull. Dis. Prev. Res. Inst. (Kyoto), 15, 31.

Otsuka, M. (1966). "Azimuth and Slowness Anomalies of Seismic Waves Measured on the Central California Seismographic Array. Part I. Observations", Bull. Seism. Soc. Am., 56, 223.

Otsuka, M. (1966). "Azimuth and Slowness Anomalies of Seismic Waves Measured on the Central California Seismographic Array. Part II. Interpretation", Bull. Seism. Soc. Am., 56, 655.

Rodgers, P.W. (1965). "Sub-resonant Response of a Mechanical System Parametrically Excited at Its Resonant Frequency", Nature, 207, No. 4999, 853.

Rodgers, P.W. (1966). "A Phase Sensitive Parametric Seismometer", Bull. Seism. Soc. Am., 56, 947.

Udias, A. (1965). "A Study of the Aftershocks and Focal Mechanism of the Salinas-Watsonville Earthquakes of August 31 and September 14, 1963", Meeting of AGU, Washington. Bull. Seism. Soc. Am., 55, 85.

4. NETWORK OPERATION

W.C. Marion and R.W. Sell

The Berkeley network of stations (telemetered and photographic) has continued to operate, with preventive and corrective maintenance, in a satisfactory manner. Down time for the last two years has been, on the average, less than one per cent per station; all records are in archive storage. Table 1 lists the Berkeley net as of December 31, 1966.

Magnetic Tape Recording. The magnetic tape data acquisition and analysis system was brought up to full capacity in June of 1965 by the addition of nine recording and playback channels of electronics, a time code generator, generating B.C.D. code in I.R.I.G.C. format, a time code translator and tape search unit, and filters for data processing with visual playout. The translator will decode Vela Uniform as well as I.R.I.G.C. codes. Table 2 shows station tape channels by channel number and date, listing all changes during the two-year period.

Seismic events recorded on tapes are dubbed onto the array library tapes, which now contain a large collection of local earthquakes and teleseisms.

A device was constructed (design assistance was given by Dr. P.W. Rodgers) to resolve the outputs of the horizontal components of the analog magnetic seismograms into longitudinal and transverse components (Figure 1). The system utilizes three operational amplifiers as analog multipliers and integrators to present true ground particle displacement for direct conversion to motion diagrams. J.R. Filson has used this device successfully for detailed studies of the particle motion of the S phase from local earthquakes.

Changes in Central California Seismic Array. As of January 1, 1965 the following telemeter array stations were in operation:

VIN - Vineyard
PRI - Priest
CNC - Concord
MHC - Mount Hamilton
SCC - Santa Cruz
PRS - Paraiso
LLA - Llanada

On February 4, 1965 a visible recording seismograph was installed at the U.S. Coast and Geodetic Survey station at Ukiah:

UKI: 39° 08.2' N, 123° 12.6' W, Elevation 199 m.

A 14 kg Benioff vertical seismometer amplified by a photo-tube amplifier with 0.2 sec galvanometer and filtered by a special low-pass RC filter designed by P.W. Rodgers was recorded on a helicorder (Figure 2).

A new telemetered station known as Granite Creek was installed February 26, 1965:

GCC: 37° 01.8' N, 121° 59.8' W, Elevation 122 m.

This location is about 2 km north of the Santa Cruz (SCC) station. After this location had greatly improved signal/noise characteristics, the Santa Cruz station was discontinued March 3, 1965.

A three-component set of matched Sprengnether seismographs (0.46 kg, T_o = 2 sec) were installed after careful calibration at the Vineyard telemeter station March 24, 1965. Signals were recorded on magnetic tape to provide data for the study of S waves in the crust (Figure 3).

A new telemetered station was installed on the San Francisco Peninsula, about 20 miles south of that city, on April 29, 1965. The new station, known as Pilarcitos Creek, will provide the necessary control for epicenter determination in the Bay Area:

PCC: 37° 30.0' N, 122° 22.9' W, Elevation 91 m.

On July 1, 1965 the two horizontal Sprengnether seismometers at Vineyard were replaced with Willmore seismometers (4.75 kg, T_o = 3.0 sec) (Figures 4 and 5).

A new telemetered station was installed at the Jamestown seismographic station September 16, 1965:

JAS: 37° 56.8' N, 120° 26.3' W, Elevation 457 m.

The three-component set of seismometers at Vineyard was removed on October 25, 1965 and the station was put on standard operation with a vertical 14 kg Benioff seismometer. Due to construction at the winery the Vineyard station was moved to a temporary site on the Harris Ranch on March 17, 1965:

HRC: 36° 46.2' N, 121° 24.8' W, Elevation 228 m.

Upon completion of the underground vault at the San Andreas Geophysical Observatory the station was moved again on July 11, 1966:

SAO: 36° 45.9' N, 121° 26.7' W, Elevation 230 m.

A microearthquake channel with a 6-20 cps bandpass and a helicorder magnification of 8 million at 20 cps started telemetering from SAO on September 16, 1966. Near events below the detection threshold of the standard system are being clearly recorded on the microearthquake channel at a rate of several per day (Figure 6).

The visible recording seismograph was removed from Ukiah November 6, 1966. The Concord (CNC) signal telemetered to Berkeley was discontinued effective December 7, 1966. Recording is now being done locally on a helicorder.

Mobile Operations. An earthquake of magnitude 3.7 occurred on June 28, 1965 in the vicinity of Calaveras Reservoir, latitude 37° 31' N, longitude 121° 45' W. Mobile equipment was sent out and established on location a few hours after the event.

An earthquake of Richter magnitude close to 5 occurred on September 10, 1965 in the vicinity of Mt. Diablo, about 25 km east of Berkeley. One foreshock and a sequence of about 80 aftershocks were observed. A mobile station was operated for 10 days in the epicentral area.

An earthquake of Richter magnitude 3.6 occurred on July 18, 1965 in the area southwest of Vineyard. The mobile unit was sent out but no significant aftershock sequence was recorded.

An earthquake of Richter magnitude 4.1 occurred on January 17, 1966 near San Felipe Lake. A recording truck was sent out January 14 and recorded the main shock and several dozen aftershocks.

The mobile unit was operated at the former U.C. seismographic site at Shasta for the Chase V explosion on May 24, 1966.

The mobile station operated in the epicentral area of the Parkfield earthquake of June 28, 1966 through July 9, 1966. It was also used to record recent calibration blasts by the U.S.G.S. near Parkfield.

The mobile station was sent to the area of Tres Pinos, 7 miles southeast of Hollister to record the NTS blast of December 20, 1966 at the request of the U.S.G.S. of Menlo Park.

<u>Special Projects</u>. An additional telemetry channel with 0-20 cps response was operated from Pilarcitos (MCC) from December 30, 1965 to January 29, 1966. The output from a Willmore 1 cps seismometer was amplified by an operational amplifier and transmitted on this channel. Late in January a swarm of microearthquakes (1.5 sec S-P time) were recorded. On February 4 a 1 km triangular array of similar instruments was installed. By March 12, when the array was removed, no more such earthquakes had been observed.

An attempt to record the very low velocity (1 km/sec) surface waves across the Great Valley to Jamestown (JAS) from quarry blasts on the west side was made. A 4-sec Willmore seismometer was installed with a DC transistorized amplifier at JAS from February 22, 1966 to March 15, 1966. Since the surface waves were in the 5-8 sec microseism range, it was found that the largest quarry blasts generated insufficient amplitude in the surface wave train for good detection in the Sierra foothills. In fact, the study showed at least a magnitude 3 earthquake is required as a source of perceptible waves at JAS.

An additional telemetry channel was operated from JAS on December 20, 1966. The output from a Press-Ewing vertical seismometer set at 10 sec free period was amplified by an operational amplifier and transmitted on this channel. The system was operated at very low magnification for the underground explosion on that date, at the Nevada Testing Site.

Table 1

SEISMOGRAPHIC STATIONS OPERATED BY OR AFFILIATED WITH THE UNIVERSITY OF CALIFORNIA

December 31, 1966

Key:

Instrument Types

B = Benioff 100 KG
b = Benioff 14 KG
P = UED Long-Period
S = Sprengnether Long-Period
G = Geotech Long-Period
W = Wood-Anderson
L = Loucks-Omori
s = Sprengnether Short-Period
Z,N,E = Components operating. Vertical, North-South, East-West
nw, ne = Components operating, N45°W, N45°E
H = 6-20 cps Microearthquake system

Recording Method

S = Smoked paper
P = Photographic
H = Helicorder
Hm = Helicorder telemetry monitor, sequenced daily
V = Other visible 'Mary'
F = 16 mm film (Develocorder)
T = Magnetic tape

Magnification

(V) = 16 mm film viewed at 20X

	Location				Instruments			Magnification		
Station	Area (Calif.)	Elev. (m)	Latitude (N)	Longitude (W)	Type	T_s	T_g	Max.	1 cps	Recording Method
ARC	Arcata	59	40° 52′.6	124° 04′.5	bZ	1.0	0.2		5900	P
			(.877)	(.075)	WNE	0.8	-	2800		P
BRK	Berkeley	81	37° 52′.4	122° 15′.6	WNE	0.8	-	100		P
	(E.S.B.)		(.873)	(.260)	WNE	0.8	-	4		P
					BZ	1.0	0.2		24000(V) 2400(V)	F, Hm
	(Hav. H.)				BZ	1.0	8.0	3000±		V
					PZ^{nw}_{ne}	30	-	200 & 20 v/cm/ sec .04-10 cps	-	T, H(Z)
					PZ	15	30	1000	-	H
					Pne	45	300	650 (40 sec)	-	P
BKS	Berkeley	276	37° 52′.6	122° 14′.1	WNE	0.8	-	2800	-	P
	(Strawberry		(.877)	(.235)	BZNE	1.0	0.75	35000	25000	P
	Canyon)				SZNE	15	100	3000 (15 sec)	-	P
CNC	Concord	36	37° 58′.1	122° 04′.3	BZ	1.0	0.2		40000	H
			(.968)	(.072)						

Table 1 (continued)

	Location				Instruments			Magnification		
Sta-tion	Area (Calif.)	Elev. (m)	Latitude (N)	Longitude (W)	Type	T_s	T_g	Max.	1 cps	Recording Method
FRE	Fresno	88	36° 46.'0 (.767)	119° 47.'8 (.797)	sZNE	2.0	2.0		6500(NE) 10900(Z)	P
GCC	Granite Creek	122	37° 01.'8 (.030)	121° 59.'8 (.996)	bZ	1.0	0.2		40000(V)	F, Hm
JAS	Jamestown	450	37° 56.'8 (.947)	120° 26.'3 (.438)	BZNE bZ	1.0 1.0	0.75 0.2		260000 600000(V)	P T,F.H
LLA	Llanada	475	36° 37.'0 (.617)	120° 65.'6 (.943)	bZ	1.0	0.2		50000(V)	F, Hm
MHC	Mt. Hamilton	1282	37° 20.'5 (.341)	121° 38.'5 (.642)	bZ WNE	1.0 0.8	0.2	 2800	60000(V)	T,F,H P
MIN	Mineral	1495	40° 20.'7 (.345)	121° 36.'3 (.605)	BZ WNE	1.0 0.8	0.4	 2800	75000	P P
MLC	Manzanita Lake	1800	40° 32.'2 (.537)	121° 33.'7 (.563)	LNE	6.0	-	250		S
ORV	Oroville	1180	39° 33.'3 (.555)	121° 30.'0 (.500)	BZNE GZNE	1.0 15	0.75 100	 3000	100000	P P
PCC	Pilarcitos	91	37° 30.'0 (.500)	122° 22.'9 (.382)	bZ	1.0	0.2		50000(V)	T,F,Hm
PRI	Priest Valley	1187	36° 08.'5 (.142)	120° 39.'9 (.665)	bZ	1.0	0.2		70000(V) & 7000(V)	T,F,H
PRS	Paraiso Springs	363	36° 19.'9 (.332)	121° 22.'2 (.370)	bZ	1.0	0.2		70000(V)	T,F,Hm
SAO	S.A.G.O. 10 km SW of Hollister	230	36° 45.'9 (.765)	121° 26.'7 (.445)	bZ HZ	1.0 0.15	0.2 -	 $2x10^7$(V)	100000(V)	T,F,Hm H,F

Table 2

MAGNETIC TAPE CHANNEL ASSIGNMENT - FROM JUNE 19, 1964 TO JANUARY 13, 1966

	6-19-64	10-13-64	3-26-65	4-2-65	4-5-65	4-29-65	5-3-65	5-4-65
1	Time	Time	Time	Time	Time	Time	Time	Time
3	BRK Z	BRK Z	VIN Z	BRK Z	VIN Z	BRK Z	VIN Z	BRK Z
5	MHC	BRK NS	VIN NS	BRK NS	VIN NS	BRK NS	VIN NS	BRK NS
7	Comp	Comp	Comp	Comp	Comp	Comp	Comp	Comp
9	BRK EW	BRK EW	VIN EW	BRK EW	VIN EW	BRK EW	VIN EW	BRK EW

	5-5-65	6-18-65	7-1-65	8-3-65	10-26-65	1-1-66
1	Station Time	Station Time	Station Time	Station Time	Station Time	Time Code
2	-	VIN Z (S)	VIN Z (S)	VIN Z (S)	VIN Z (B)	VIN Z (B)
3	VIN Z (S)	BRK Z	BRK Z	BRK Z	BRK Z	BRK Z
4	-	VIN NS (S)	VIN NS (W)	VIN NS (W)	JAS	JAS
5	VIN NS (S)	BRK NS	BRK NS	BRK N45°W	BRK N45°W	BRK N45°W
6	-	PCC	PCC	PCC	PCC	PCC
7	Comp	Comp	Comp	Comp	Comp	Comp
8	-	VIN EW (S)	VIN EW (W)	VIN EW (W)	-	-
9	VIN EW (S)	BRK EW	BRK EW	BRK N45°E	BRK N45°E	BRK N45°E
10	-	PRI	PRI	PRI	PRI	PRI
11	-	MHC	MHC	MHC	MHC	MHC
12	-	GCC	GCC	GCC	GCC	GCC
13	-	PRS	PRS	PRS	PRS	PRS
14	-	-	-	-	Time Code	-

Table 2 (continued)

MAGNETIC TAPE CHANNEL ASSIGNMENT - FROM JANUARY 14, 1966 TO JANUARY 23, 1967.

	1-14-66	2-8-66	3-13-66	8-12-66
1	Time Code	Time Code	Time Code	Time Code
2	BRK Z (SM)	BRK Z (SM)	BRK Z (SM)	BRK Z (SM)
3	BRK Z	BRK Z	BRK Z	BRK Z
4	BRK N45°W (SM)	PCC North	BRK N45°W (SM)	BRK N45°W (SM)
5	BRK N45°W	BRK N45°W	BRK N45°W	BRK N45°W
6	PCC	PCC East	PCC	PCC
7	Comp	Comp	Comp	Comp
8	BRK N45°E (SM)	PCC West	BRK N45°E (SM)	BRK N45°E (SM)
9	BRK N45°E	BRK N45°E	BRK N45°E	BRK N45°E
10	PRI	PRI	PRI	PRI
11	MHC	MHC	MHC	MHC
12	GCC	GCC	GCC	SAO
13	PRS	PRS	PRS	PRS
14	JAS	JAS	JAS	JAS

	12-15-66	12-20-66	1-5-67	1-11-67
1	Time Code	Time Code	Time Code	Time Code
2	BRK Z (SM)	BRK Z (SM)	BRK Z (SM)	BRK Z (SM)
3	BRK Z	BRK Z	BRK Z	BRK Z
4	BRK N45°W (SM)	BRK N45°W (SM)	BRK N45°W (SM)	BRK N45°W (SM)
5	BRK N45°W	BRK N45°W	BRK N45°W	BRK N45°W
6	JAS B-B	PCC	PCC	GCC
7	Comp	Comp	Comp	Comp
8	BRK N45°E (SM)	BRK N45°E (SM)	BRK N45°E (SM)	BRK N45°E (SM)
9	BRK N45°E	BRK N45°E	BRK N45°E	BRK N45°E
10	PRI	PRI	PRI	PRI
11	MHC	MHC	MHC	MHC
12	SAO	SAO	SAO	SAO
13	SAO H-F	SAO H-F	PRS	PRS
14	JAS	JAS	JAS	JAS

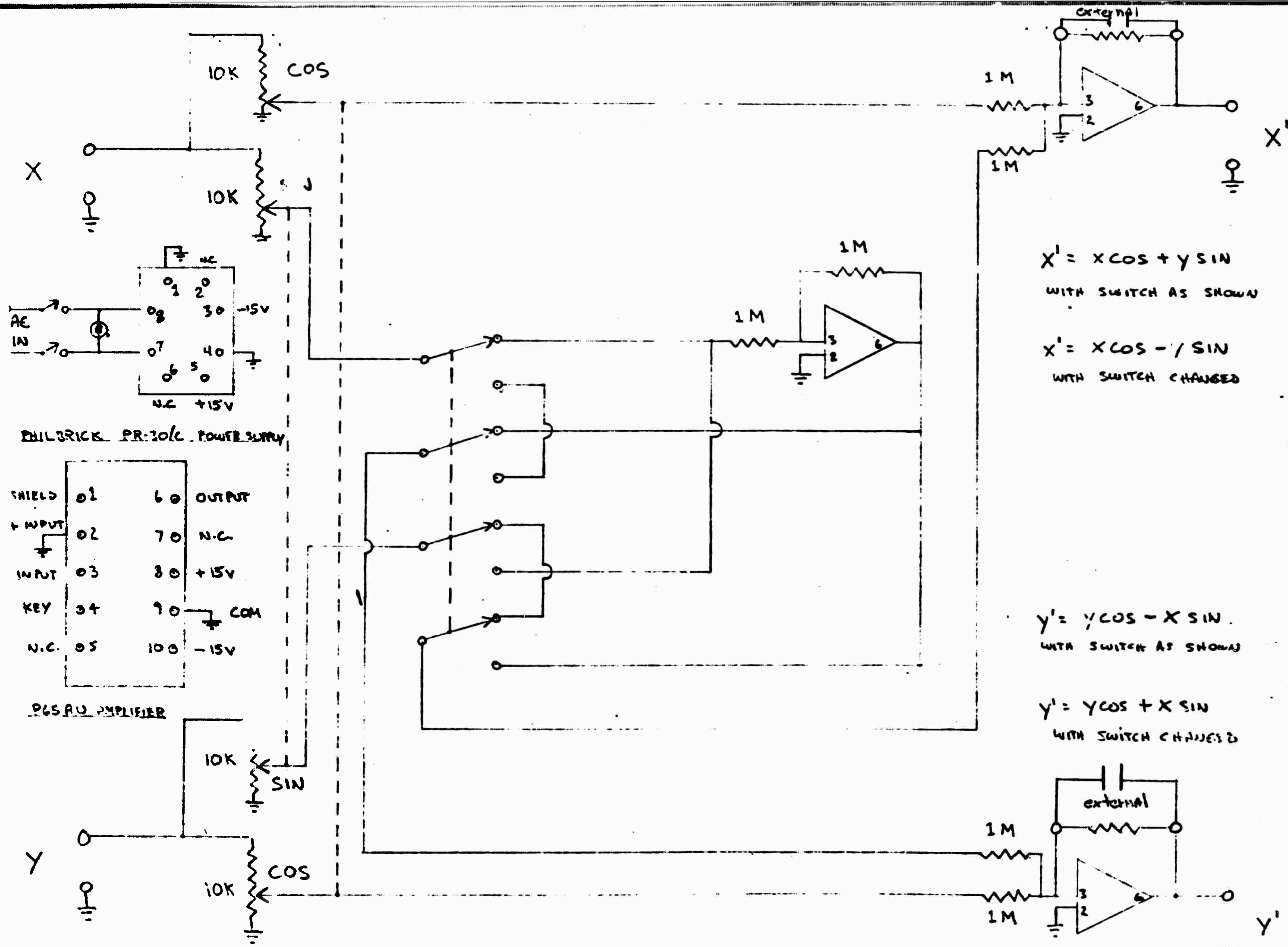
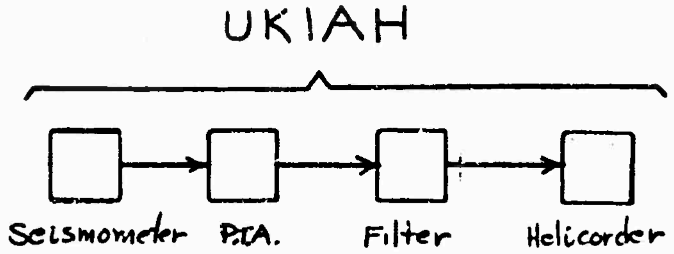
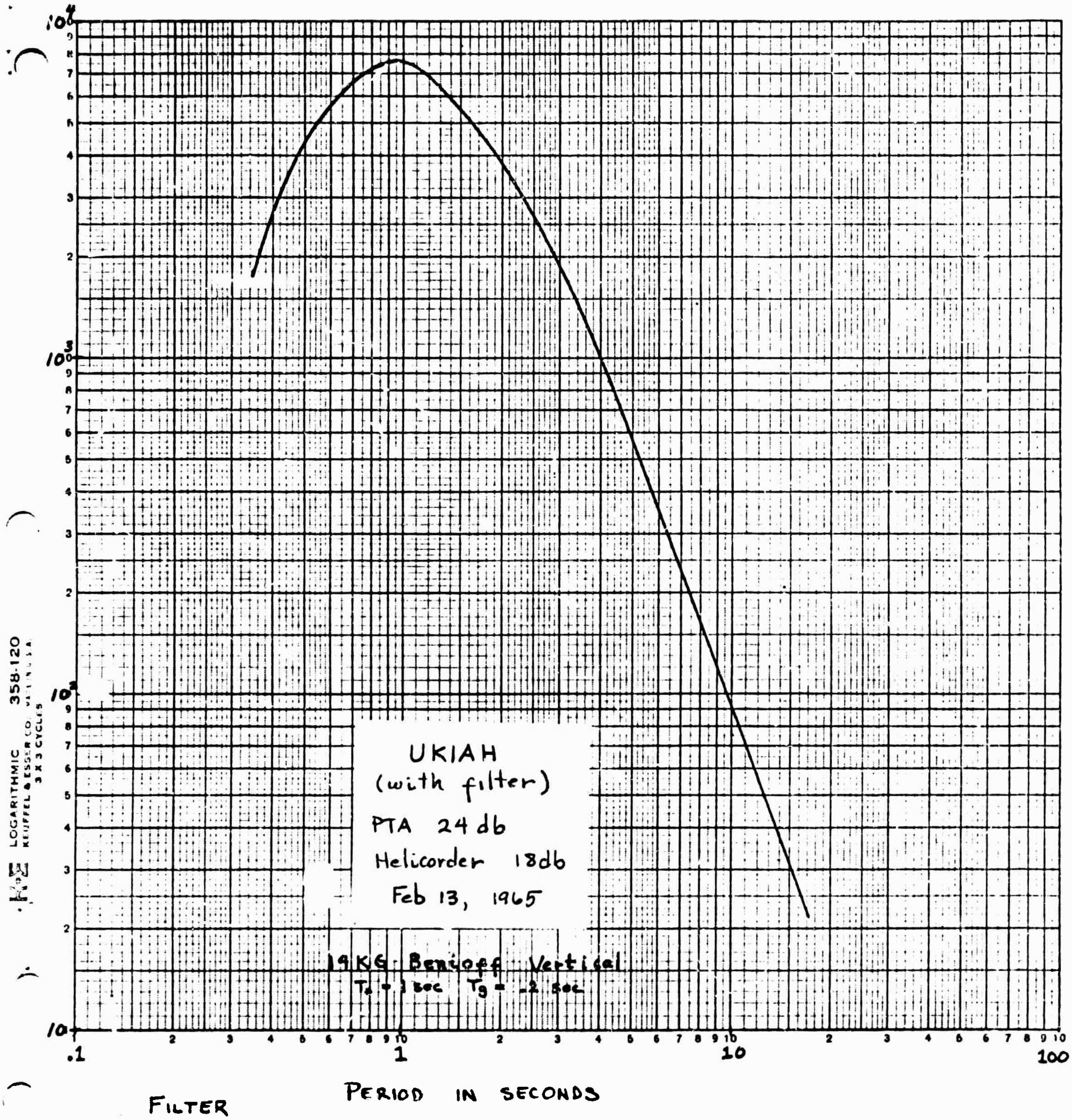
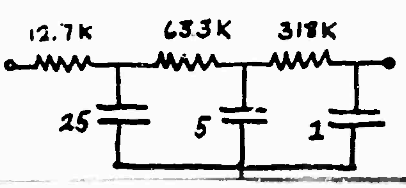

10K
COS
X
10K
J
AC IN
0 1
2 0
NC
3 0 -15V
0 8
0 7
4 0
0 6
5 0
N.C
+15V
PHILBRICK PR-30/C POWER SUPPLY
SHIELD 0 1
+ INPUT 0 2
INPUT 0 3
KEY 3 4
N.C. 0 5
6 0 OUTPUT
7 0 N.C.
8 0 +15V
9 0 COM
10 0 -15V
P65AU AMPLIFIER
10K
SIN
Y
10K
COS
1M
1M
3
2
6
external
X'
1M
1M
3
2
6
X' = X COS + Y SIN
WITH SWITCH AS SHOWN
X' = X COS - Y SIN
WITH SWITCH CHANGED
Y' = Y COS - X SIN
WITH SWITCH AS SHOWN
Y' = Y COS + X SIN
WITH SWITCH CHANGED
external
1M
1M
3
2
6
Y'

Fig. 1







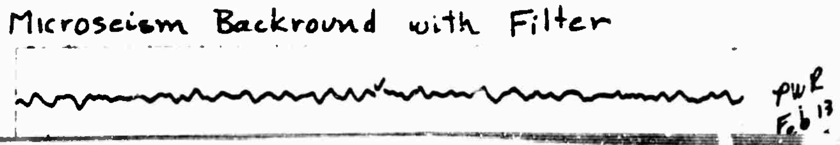
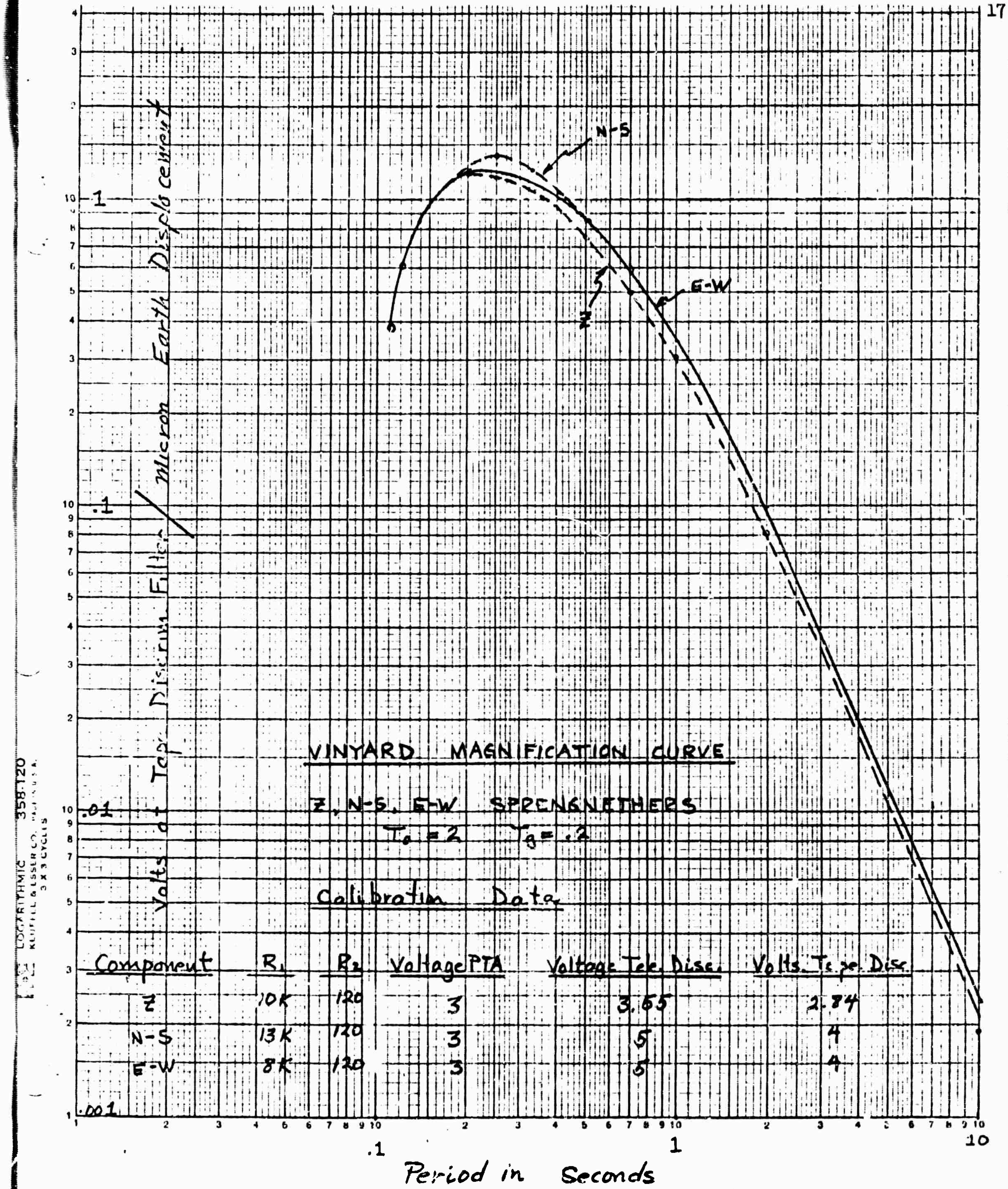


Fig. 2

PWR
Feb 13



VINYARD MAGNIFICATION CURVE

Z, N-S, E-W SPRENGNETHERS

$T_o = 2$ $T_g = .2$

Calibration Data

Component	R_1	R_2	Voltage PTA	Voltage Tele. Disc.	Volts Tape Disc.
Z	10K	120	3	3.65	2.84
N-S	13K	120	3	5	4
E-W	8K	120	3	5	4

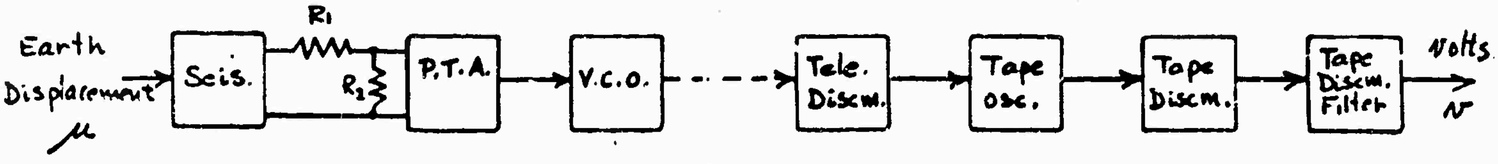


Fig. 3

April 14 '64

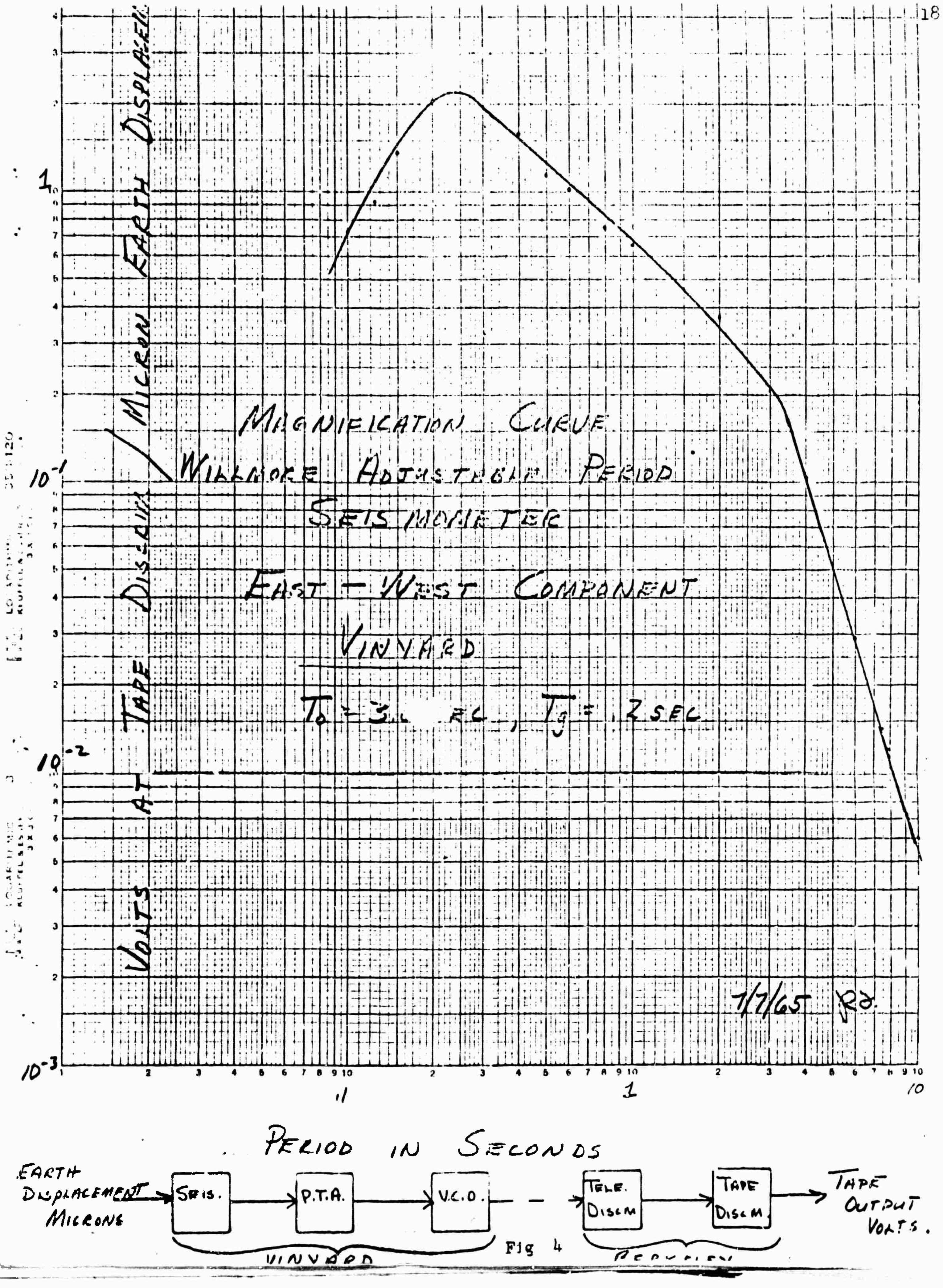

MAGNIFICATION CURVE
WILLMORE ADJUSTABLE PERIOD
SEISMOMETER
EAST - WEST COMPONENT
VINYARD
T_0 = 3 [illegible] EC , T_g = .2 SEC
VOLTS AT TAPE DISCRIM / MICRON EARTH DISPLACEM
1
10^{-1}
10^{-2}
10^{-3}
.1
1
10
PERIOD IN SECONDS
7/7/65 RJ.
EARTH DISPLACEMENT MICRONS
SEIS.
P.T.A.
V.C.O.
TELE. DISCM
TAPE DISCM.
TAPE OUTPUT VOLTS.
VINYARD
BERKELEY

Fig 4

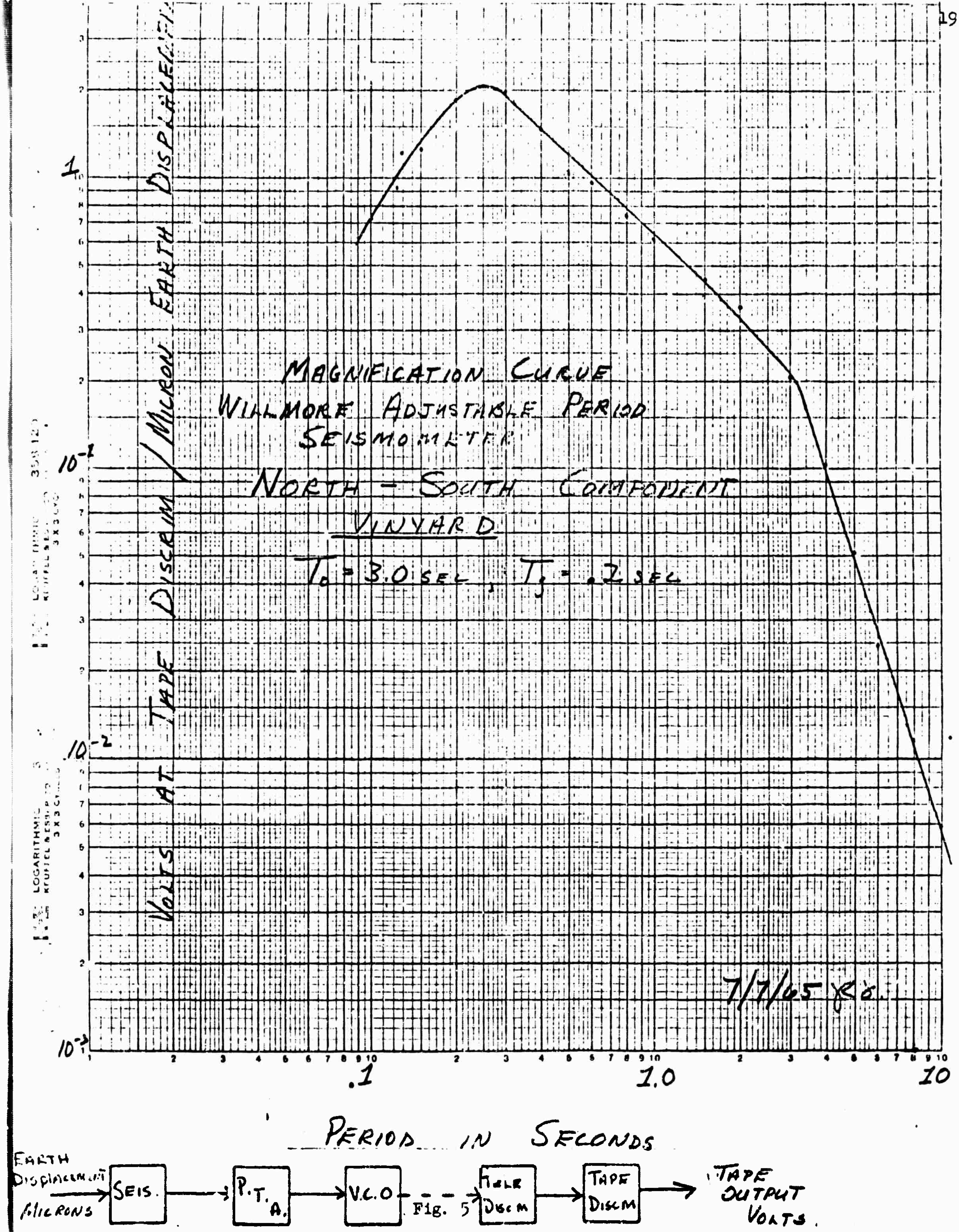

MAGNIFICATION CURVE
WILLMORE ADJUSTABLE PERIOD
SEISMOMETER
NORTH - SOUTH COMPONENT
VINYARD
$T_0 = 3.0$ SEC, $T_g = .2$ SEC
VOLTS AT TAPE DISCRIM / MICRON EARTH DISPLACEMENT
1
10^{-1}
10^{-2}
10^{-3}
.1
1.0
10
PERIOD IN SECONDS
7/7/65 RO.
EARTH DISPLACEMENT MICRONS
SEIS.
P.T.A.
V.C.O
TELE DISCM
TAPE DISCM
TAPE OUTPUT VOLTS

Fig. 5

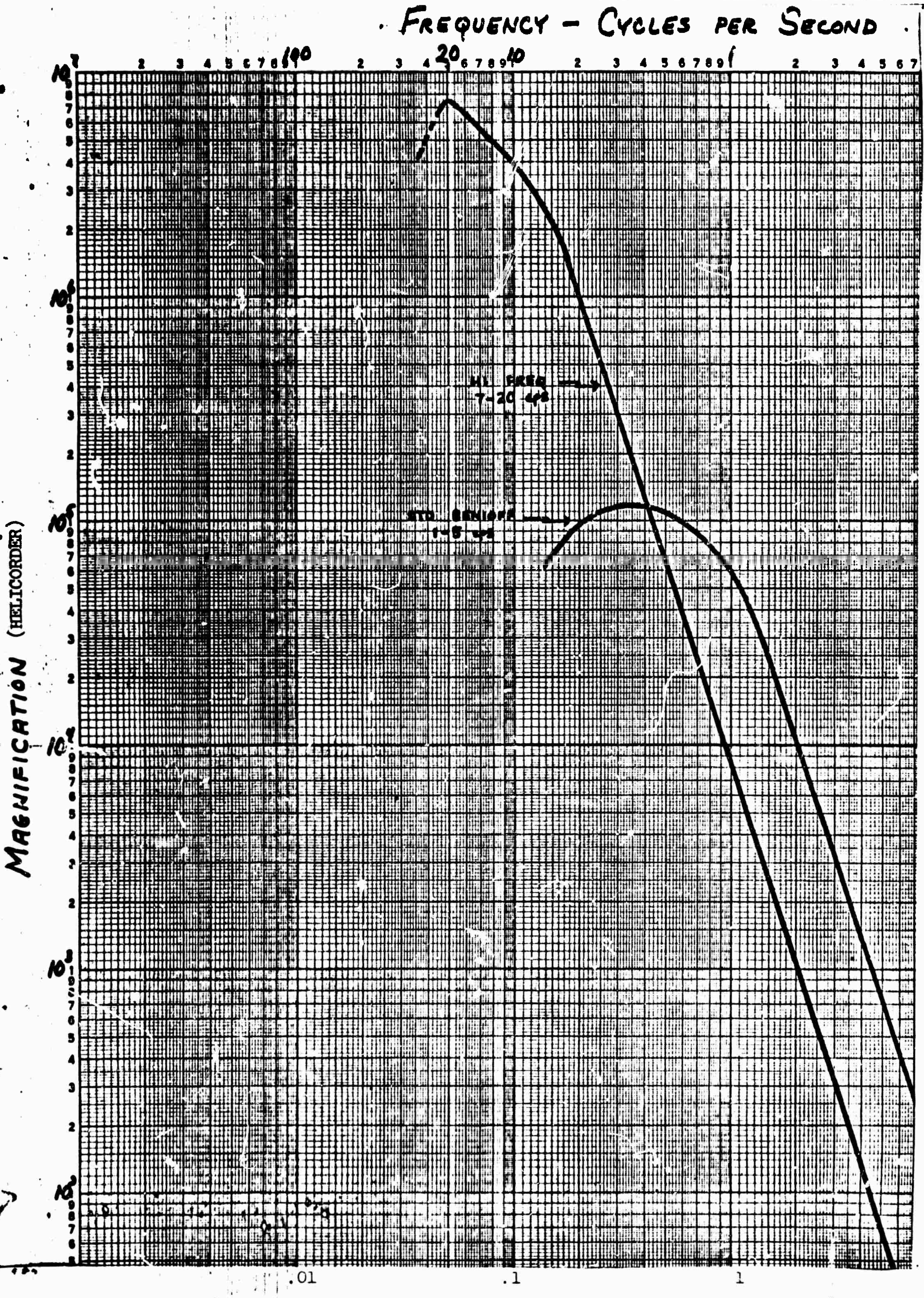

FREQUENCY - CYCLES PER SECOND
100
20
10
1
MAGNIFICATION (HELICORDER)
10^7
10^6
10^5
10^4
10^3
10^2
HI FREQ
7-20 cps
STD BENIOFF
1-5 cps
.01
.1
1
PERIODS-SECONDS

Fig. 6

5. TELESEISM ANALYSIS

B.A. Bolt and W.H. Bakun

Many seismograms from teleseisms are studied in the course of the work of the Seismographic Station. The seismograms are used for many purposes, some of a routine nature (e.g., hypocenter location and tsunami warning) and some for specialized research. As an illustration of the latter, recently Berkeley recordings of PKP waves were used in the design of an experiment involving the construction of a special array in Antarctica to study core phases. Two examples of research at the Seismographic Station with a general interest are now presented.

First, with the important assistance of Dr. O.W. Nuttli, empirical P wave delay times, relative to the Berkeley station, have been calculated for 12 stations in central and northern California. Eight stations of the telemetry network were involved. A number of important results emerged:

(a) The telemetry stations must be divided into two groups; the northern group (CLS, PRC, MHC, SCC, VIT, BRK) evidently lie on a reasonably uniform crust and upper mantle while the southern telemetry groups (LLA, PRS, PRI) are situated on a basement which significantly differs from the northern one. The stations in the Central Valley of California show relative delays which are quite unlike those of the telemetry stations. (Jamestown has not yet been studied.)

(b) The particular division of northern California into regions based on the contouring of station residuals published by J. Cleary and A.L. Hales is probably not correct.

(c) The azimuth anomaly functions provide a new way of determining regional variations in the Earth's upper mantle. The causal velocity inhomogeneities must occur at depths of order 100 km.

As a separate study a frequency analysis of crustal reverberations of dilatational waves from teleseisms is in progress; the goal is to obtain information on the fine structure of the crust of central California.

A search was made of the magnetic tape library for earthquakes suitable to such a study. From June 1964 to October 1966, over 110 earthquakes were recorded by the Berkeley array with magnitude $\geq$ 5 and focal depth $\geq$ 60 km. Almost all were in the Circum-Pacific Belt and 90 per cent had epicentral distances of 55 to 80°. Of these earthquakes, 40 had magnitude $\geq$ 5.8, which was judged to be the cutoff for earthquakes having a signal to noise ratio of 2 to 1. Eighteen were from the South Pacific area, 12 were from South America, and 12 were from the Japan Islands-Kurile Islands area. These earthquakes were examined in detail and 7 were selected using the following criteria:

(1) Signal to noise ratio of 4 to 1.

(2) P-phase duration of 10-20 seconds, uncomplicated by other phase arrivals (PcP or pP). This would yield 10-20 cycles of pure P-phase crustal reverberations.

Five of the earthquakes selected were from South America and 2 from Japan. (PcP follows P too closely at the Berkeley array for all South Pacific earthquakes of interest in this study.) In making these selections, there was some indication that P-phase amplitudes from earthquakes having azimuths relative to Berkeley in the range N75°W to S75°W (Marianas Islands-Solomon Islands region) were less than expected from comparisons of South American, Japanese, and other South Pacific shocks.

A comparison of the traces recorded by stations across the array (Figure 1) indicates that the response to a dilatational wave incident at the base of the crust below central California is generally uniform with moderate variations from station to station. This suggests a generally uniform crustal structure under the central California array. Of special interest are the phases a1, a2, a3, and a4 marked on the Mount Hamilton trace (MHC). These phases can be seen to some degree on all the traces. The deep-focus character of the source indicates that these phases do not originate in crustal reverberations at the source. The near normal incidence (20-25°) of the waves at the base of the crust suggests that these prominent phases in the vertical component are not P to S conversions at the base of the crust. One explanation of the large amplitude of the a1 phase, especially on the GCC, PRS, and PRI traces, is that the source consists of at least two pulses, separated by an interval of several seconds. The phases a2 and a4 could then be interpreted as crustal reverberations of P and a1.

Another possibility is that a1, a2, a3, and a4 are reflections from a crustal interface of the first P impulse. Interference with the PcP phase could account for a3 not being prominent. The 3 to 4 second period would then indicate a reflecting surface 5 to 10 kilometers deep. Further analysis of this and other earthquakes should limit the range of proposed crustal models for central California.

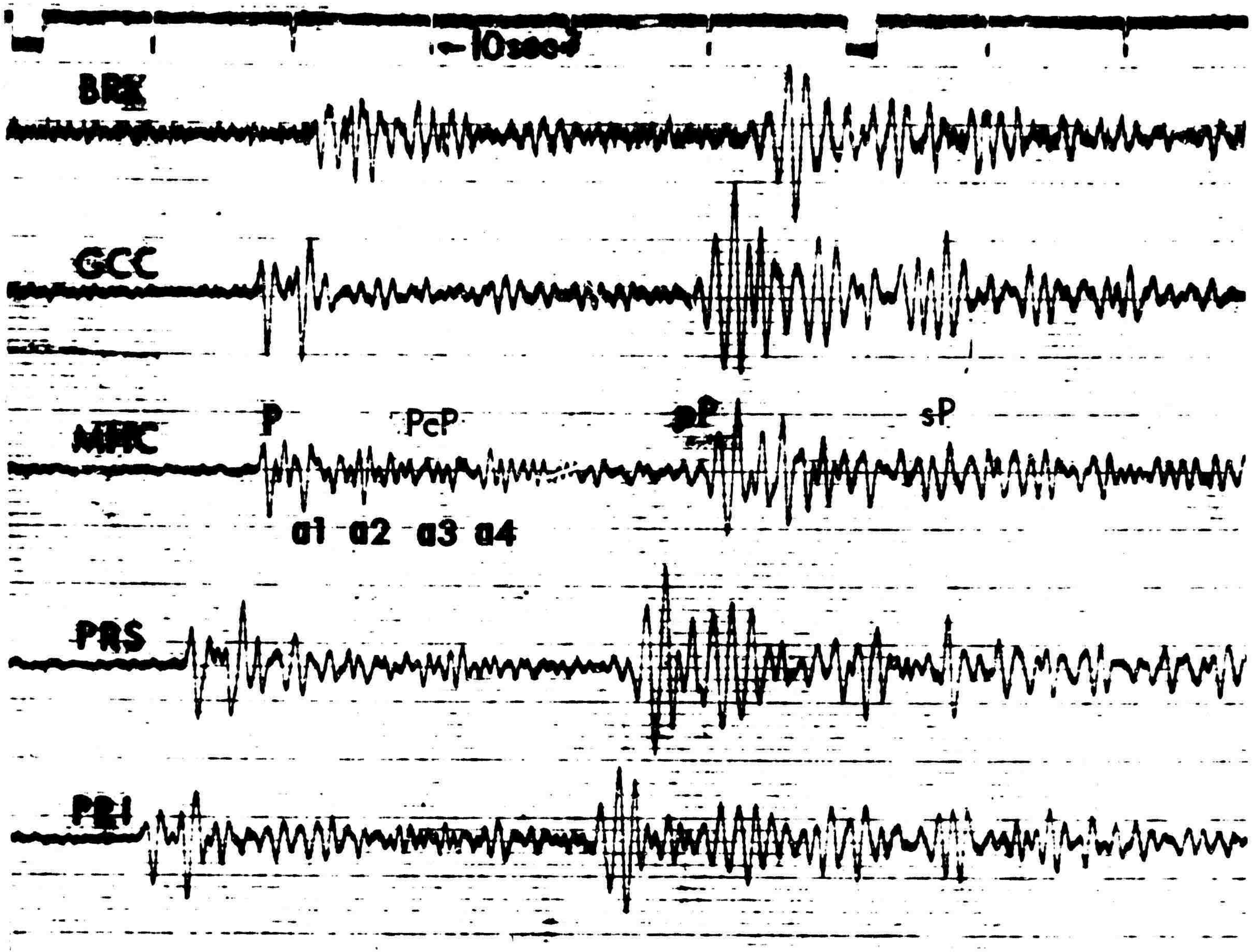


Fig. 1. Northern Chile Earthquake of August 20, 1965; Magnitude 6.0; Focal Depth 129 km.

6. AFTERSHOCK SEQUENCES

T.V. McEvilly and K.B. Casaday

A primary research objective of the large-scale telemetered array installation and operation is the study of properties of aftershock sequences in the area. In the original contract period, only one significant sequence (magnitude 5 or greater) occurred and was analyzed by Udias (1965).

During the period covered by this report, three aftershock sequences have been studied in detail. These are the Corralitos sequence of November, 1964 (McEvilly, 1966a), the Antioch (Mt. Diablo) sequence of September, 1965 (McEvilly and Casaday, 1967), and the Parkfield sequence of June-July, 1966 (McEvilly, 1966b and Bakun *et al.*, 1966).

Studies of aftershock sequences are considered important because they reflect the nature of continued stress release in the focal region of larger earthquakes and contain valuable information on the focal mechanisms of related earthquakes. In general, the data acquired through these studies constitute basic material on sequence characteristics which must be taken into account in any theory of earthquake generation.

When an aftershock sequence begins within the Berkeley array, it is detected and located quickly by means of the telemetered data. The procedure at Berkeley is then to dispatch mobile vans to the inferred epicentral region so that hypocenter determinations will be more accurate and very small magnitude events can be monitored. Coordination is also established with the various other organizations in the area concerned with seismic studies.

The first sequence to be studied in detail at the Berkeley Seismographic Station was the Salinas-Watsonville sequence of 1963. The methods applied and the parameters established to describe that sequence are similar to those measured in the three more recent sequences and therefore a comparison of four sequences can be made below.

Corralitos sequence - November, 1964. A sequence of more than 100 aftershocks with magnitudes as low as -0.1 was recorded following a magnitude 5.0 earthquake on November 16, 1964 on the San Andreas fault zone of central California. The sequence was monitored in detail by three temporary seismographic stations at distances less than 15 km and by the surrounding telemetry array. Nearly all of the 35 earthquakes which could be located clustered in a focal region about 4 km in diameter at a depth near 12 km and exhibited uniform first motion radiation patterns. The slope of the cumulative frequency vs. magnitude curve (a measure of large aftershocks) was -0.66. First motion fault plane solutions are consistent with the right lateral transcurrent motion characteristic of the San Andreas fault. Exceptions to this uniform radiation pattern in the concentrated focal region occurred near the times of two large aftershocks apparently on another fault about 5 km away.

Antioch sequence - September 1965. A foreshock-aftershock sequence associated with an earthquake of magnitude 4.9 on September 10, 1965 in the San Francisco Bay region was recorded. The sequence was monitored by nearby Berkeley network stations and by one temporary station in the epicentral region. Precise hypocenters were determined for 29 of the shocks and these clustered in a small focal region with dimensions on the order of a few kilometers and at an average depth of 12 km. Within the focal region a north-south trend was observed with shocks apparently migrating down and then back up the trend. First motion radiation patterns were uniform throughout the sequence, and a P-wave fault plane solution for the main shock gave, as a possible source, a north-south trending fault with right-lateral motion. The log cumulative frequency of shocks vs. magnitude plot exhibits a slope of -0.78.

Parkfield sequence - June-July, 1966. Two earthquakes of magnitude 5.1 and 5.5 shook the Parkfield area in southern Monterey County, California on June 28, 1966. Moderate damage was incurred and ground rupture was evident. These large shocks were preceded by two foreshocks of magnitude 3.1 and 1.3. Following the second large shock, a major aftershock sequence began, with half of the shocks occurring in the first 24 hours. On June 29, about 39 hours later, a third large shock of magnitude 5.0 occurred. The sequence has continued for several months with some 200 shocks of magnitude 1.5 or greater recorded.

At the time of the initial shocks, there were three stations monitoring the area at distances less than 100 km., Priest and Paraiso of the Berkeley network and Gold Hill of the U.S. Geological Survey. As the sequence began, the Berkeley Seismographic Station dispatched a mobile van to the area and assisted ESSA personnel in installing some of their mobile units. Within a few days approximately 20-25 temporary stations were installed by various groups within the region.

Although the data acquired from this sequence are undergoing continuing study, the bulk of it has been subjected to the standard analysis and is reported here.

Locations for the foreshocks, main shocks, and for 108 aftershocks, all of magnitude ≥ 1.5 have been reasonably well determined, and lie in a region some 5 km in width and 35-40 km in length along the San Andreas fault zone and coinciding with the zone of surface cracking and maximum intensity. The average depth appears to be 8 km or less, although this is subject to further revision. Cumulative frequency vs. magnitude gives a -0.49 slope, indicating a large proportion of higher magnitude aftershocks.

A study of aftershocks during a short time interval within the sequence was carried out and shows a similar spatial distribution of shocks as the entire sequence. Uniform migration in time or space of the shocks was not observed.

The surface cracking exhibited right lateral displacement where measurable, continuing throughout the sequence. The extent of cracking is greater than expected for a magnitude 5.5 earthquake (Tocher, 1958) if we assume that the entire zone of surface rupture evident the following morning (10 hours later) was involved in the main shock. Tocher's data would associate a magnitude 7.0 earthquake with a 35 to 40 km fault rupture. Intensity data, though basically imprecise, indicate an elongated source (Bakun et al., 1966). Acceleration along the surface rupture zone some 30 km from the main shock epicenter reached 0.5 g (Cloud, 1966) along the rupture and maximum values decrease away from the rupture zone. The relationship of the large zone of surface breakage to the total energy release in the main shock is not clear.

A P-wave first motion focal mechanism analysis was applied to the two large earthquakes of June 28 using some 25 stations at distances up to several hundred km. Both events had the same radiation pattern. The solution, with no inconsistent points and observations in all four quadrants, gives a vertical strike-slip right lateral fault strike of N33°W, coincident with the surface rupture and fault trace in the area. Strike and dip are well determined, to within 5° allowable variation, by the data. The motion appears to have an upward component on the west side, at 20° from the horizontal, with the data allowing no more than 10° variation in this value.

Comparison of Aftershock Studies. In the process of studying central California aftershock sequences, attempts have been made to develop parameters with which to characterize a particular sequence. The various sequences studied can then be compared. In the studies considered, the following parameters have been employed: (1) main shock magnitude; (2) relative magnitude of the largest aftershock as compared to the main shock; (3) slope of the cumulative frequency vs. magnitude curve (also a measure of proportion of large aftershocks); (4) average focal depth of the aftershocks; (5) long dimension of the focal region (defined as the region of aftershock activity). Tabulated results for the Salinas-Watsonville, Corralitos, Antioch, and Parkfield sequences are shown below.

Sequence	Main Shock Magnitude	Relative Magnitude of Largest Aftershock	Slope	Ave. Depth	Long Dimension of Focal Region
Watsonville 1963	5.4	.9	-.41	7	30
Corralitos 1964	5.0	.7	-.66	12	4
Antioch 1964	4.9	.6	-.78	12	6
Parkfield 1966	5.5	.9	-.49	8	35-40

From these measures of the aftershock sequences it appears that in all characteristics used, Corralitos and Antioch are similar and Salinas-Watsonville and Parkfield are similar. The geographic location of the sequence appears immaterial. Salinas-Watsonville and Corralitos are in nearly the same area. Antioch is in a much less seismically active area than the remaining three.

It seems from these parameters that a larger focal region and greater number of large aftershocks occur together, not surprisingly in conjunction with the larger main shocks. The magnitude difference of one-half unit between similar pairs, however, seems somewhat small relative to the order of associated variations in the other sequence characteristics. Sequences associated with larger main shock magnitudes are also characterized by shallower average depths.

Whether or not these results reveal two distinct types of earthquake sequences in central California, two points on a continuous variation in parameters with magnitude or chance observations from a wide variety of sequence behaviour, will have to be determined on the basis of subsequent aftershock studies. Complementing such further studies with observations of ultramicroearthquake activity, strain variations, S-wave characteristics, and spectral information will add valuable data in the search for understanding the mechanisms of an earthquake.

References

Bakun, W.H., K.B. Casaday and T.V. McEvilly (1966). The Parkfield Aftershock Sequence. AGU Meeting-Western Section, September 1966, UCLA Campus.

Cloud, W.K. (1966). The Parkfield, California, Earthquake of June 27, 1966 - Preliminary Engineering Seismological Report, Publ. U.S. Department of Commerce, ESSA.

McEvilly, T.V. (1966a). The Earthquake Sequence of November 1964 near Corralitos, California. Bull. Seism. Soc. Am. 56, 755-773.

McEvilly, T.V. (1966b). Parkfield Earthquakes of June [illegible]-29, 1966, Monterey and San Luis Obispo Counties, California - Preliminary Report. Preliminary Seismic Data, June-July, 1966. ibid., 967-971.

McEvilly, T.V. and K.B. Casaday (1967). The Earthquake Sequence of November 1965, near Antioch, California. Bull. Seism. Soc. Am. (in press).

Tocher, Don (1958). Earthquake Energy and Ground Breakage. Bull. Seism. Soc. Am. 48, 147-154.

Udias, Agustin, S.J. (1965). A Study of the Aftershocks and Focal Mechanism of the Salinas-Watsonville Earthquakes of August 31 and September 14, 1963. Bull. Seism. Soc. Am. 55, 85-106.

7. CHASE V AND THE CHICO EARTHQUAKE

C. Lomnitz

The original purpose of the Chase V experiment was as follows:

(1) Calibration of travel-time curves used to locate earthquakes in the offshore Cape Mendocino area. The seismicity of this region is of interest in relation to the structure at the intersection of the San Andreas fault with the Mendocino Escarpment.

(2) Determination of crustal structure and seismic velocities in northern California.

In 1965, a seismological experiment involving the detonation of at least 500 tons of explosives in the Pacific Ocean was proposed by B.A. Bolt and C. Lomnitz to the Office of Naval Research. The coordinates suggested and subsequently approved by ONR were 40° 36' N, 125° 45' W, in the center of an active seismic region about 75 miles west of Cape Mendocino.

Operation Chase V. An explosion of surplus ammunition of approximately 1000 tons of TNT equivalent occurred on May 24, 1966 off the coast of California. The explosives had been loaded into an expendable Liberty ship and towed to a location off Cape Mendocino. Because of operational problems, the detonation occurred earlier and at a different location than originally planned.

We undertook the task of planning and coordinating the seismic experiment on shore, with the participation of recording units from the California Department of Water Resources, ESSA, Stanford Research Institute, U.S. Geological Survey, University of British Columbia, University of Nevada, and University of Oregon. Observations obtained by ARPA, the California Institute of Technology, and Columbia University have also been utilized.

The sites of the temporary stations were selected to provide long profiles oriented on the main axis of the U.C. Berkeley seismic array, plus two shorter profiles terminating in the Oroville and Jamestown stations. Since the detonation occurred about 130 km to the south of the intended shotpoint, the geometry of the experiment was substantially altered (Figure 1).

Two hours before the CHASE V explosion a natural earthquake of magnitude 4.5 occurred in the vicinity of Chico, California. This earthquake was well enough located (Figure 1) to provide comparisons of travel-times and amplitudes with Chase V; accurate epicentral location was facilitated by the temporary stations which had recorded both events.

Table 1 gives a list of selected readings for Chase V and for the Chico earthquake. The focal coordinates and Berkeley magnitudes are also given. This list was combined with reported arrival times from other stations to produce the travel-time graph for P shown in Figure 2 over the range of distances from 0° to 10°.

The following preliminary conclusions are suggested by these results:

(1) There are systematic differences between the seismic velocities computed from the separate sets of data. In general, these differences can be attributed to the circumstance that seismic paths from Chase V were largely off shore or grazing the coast line, while the paths for the Chico earthquake were all continental.

(2) The average apparent surface velocity of P_n for Chase V was 7.97 km/sec (Figure 2) which is close to the value proposed many years ago by Byerly for central California.

(3) The average apparent surface velocity of P_n for the Chico earthquake was significantly lower, 7.58 km/sec (Figure 2).

(4) Seismic paths which cross the roots of the Sierra Nevada are significantly delayed in both events; thus the times to Tinemaha, Mina (Nevada), China Lake, Isabella, and Eureka are late by an average 2.6 seconds with reference to either average P_n travel time curve, of 7.97 km/sec for Chase V, and 7.58 km/sec for the Chico earthquake (Figure 2).

(5) Paths which are purely or mostly offshore tend to produce earlier arrivals, which appear to be consistent with a P_n velocity of the order of 8.2 km/sec.

It is also of interest to compare the character of the signals for the two events. Figure 3 shows a playback from the magnetic tape system using two array stations which were located at comparable distances from the source (about 400 km). In each case, the upper trace (a) is the unfiltered signal;

the other traces were obtained by narrow band-pass filtering at frequencies of (b) 4 cps, (c) 1.8 cps, and (d) 1 cps.

For Chase V, a large proportion of the energy is contained in the 1.8 cps band, which corresponds to the frequency of the bubble pulse. No significant S phase is apparent. It is also of interest that later phases in the P-group, such as P* and $\overline{P}$, are much more prominent in the Chico earthquake than in Chase V.

The large-amplitude wave train observed in the late portion of the Chase V record presumably corresponds to a surface wave which propagates in the ocean bottom sediments, since its velocity (about 1.75 km/sec) is higher than expected for a T phase (1.45 km/sec).

The structure of the initial portion of the seismograms for both events may be compared in Figure 4, a high-speed playback with the same settings as for Figure 3.

A more complete discussion of these results will be given at the forthcoming meeting of the Seismological Society of America in Santa Barbara in a paper now under preparation by C. Lomnitz and B.A. Bolt.

Table 1

	Chase V (Supplied location)	Chico Earthquake (Preliminary location)
Latitude	39° 28' N	39° 43' N
Longitude	125° 48' W	121° 44' W
Depth	3,750 ft	25 km
Water depth	12,500 ft	-
Bubble pulse period	0.576 sec	-
Magnitude	4.7	4.5
Origin time	05-49-06.8	03-49-54.3
	P Arrival Times	
OBS Ocean Bottom	05-49-31.2	-
PAR Pt. Arena	34.2	03-50-23.4
ARC Arcata	37.4	29.5
UKI Ukiah	38.1	17.0
PLA Plantation	39.7	22.1
PSK Paskenta	75.1	06.8
CLS Calistoga	45.8	14.8
PRC Point Reyes	47.8	24.2
RUM Rumsey	48.8	11.9
SHS Shasta	51.5	11.3
QUE Quebec	-	19.8
TAN Tango	-	21.0
KIL Kilo	-	21.5
BRK Berkeley	54.8	24.2
BKS Berkeley (Byerly)	55.0	24.4
CNC Concord	56.4	22.5
ROM Romeo	-	22.5
JUL Juliet	-	25.2
ORV Oroville	57.0	02.0
PCC Pilarcitos Creek	56.6	30.0
MIN Mineral	57.7	05.8
GCC Granite Creek	50-04.0	36.1
MHC Mt. Hamilton	04.8	32.2

(continued)

Table 1 - continued

P Arrival Times

	Chase V	Chico Earthquake
KFO Klamath Falls	10.7	35.5
HRC Harris Ranch	11.7	40.9
SPR Spreckels	11.4	42.8
JAS Jamestown	12.9	28.5
LLA Llanada	16.8	43.9
PRI Priest	23.9	51.2
FRE Fresno	28.7	47.5
COR Corvallis	28.8	51-11.0
EUR Eureka, Nevada	58.5	02.0
BMO Blue Mountains Obs.	51-08.6	-
TIN Tinemaha	50-43.5	50-59.7
WDY Woody	43.4	51-04.7
ISA Isabella	49.0	09.7
SBC Santa Barbara	45.2	17.8
FTC Ft. Tejon	51.4	16
CLC China Lake	54.8	15.2
PAS Pasadena	51-04	28
GLC Goldstone	05.7	24
MWC Mt. Wilson	04.6	29
RIV Riverside	-	35
PLC Palomar	20.7	47
BRT Barrett	30.0	56
VIC Victoria, B.C.	23.3	-

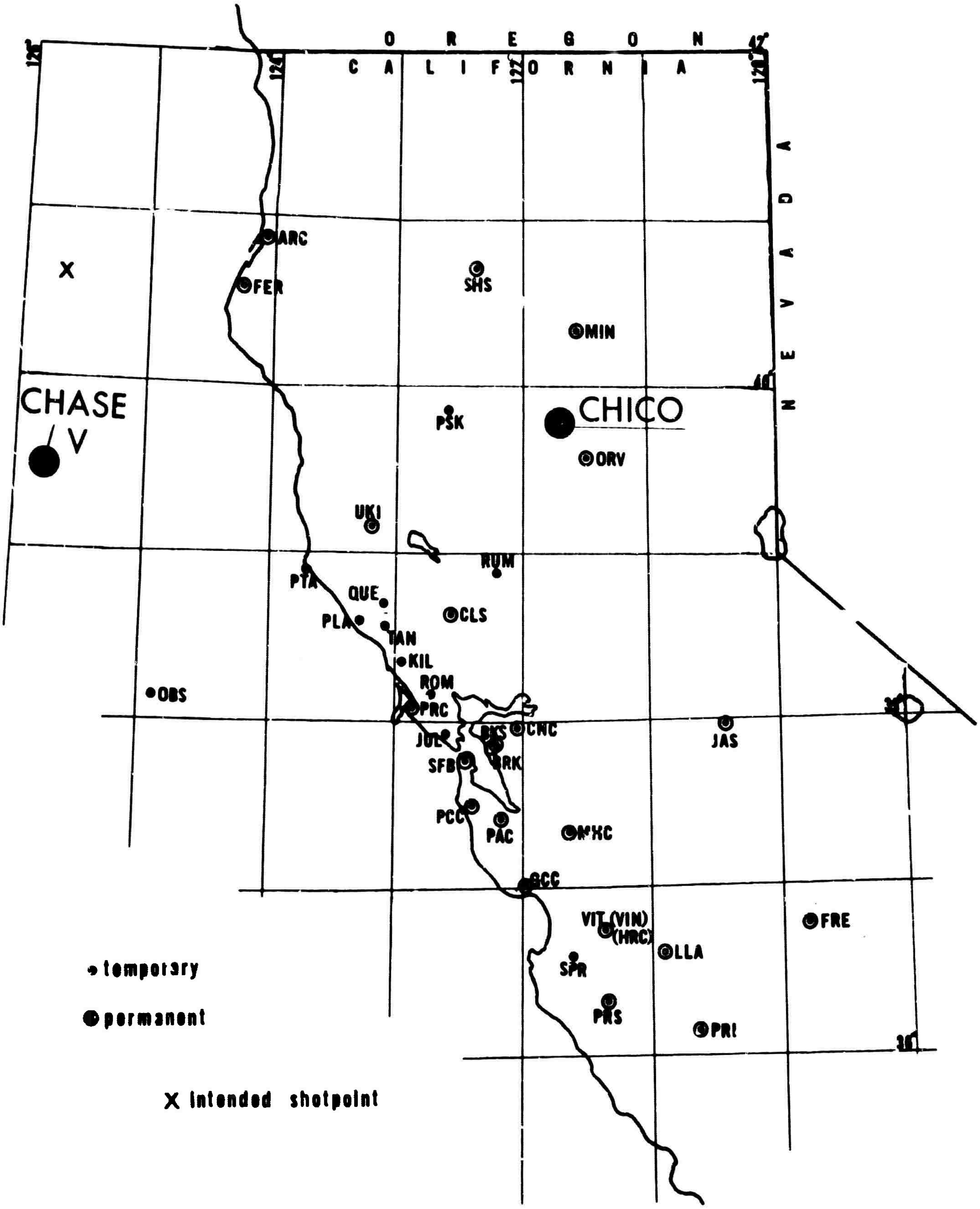

OREGON
CALIFORNIA
NEVADA
126°
124°
122°
120°
42°
40°
38°
36°
X
CHASE V
CHICO
ARC
FER
SHS
MIN
PSK
ORV
UKI
RUM
PTA
QUE
PLA
TAN
CLS
KIL
ROM
OBS
PRC
CNC
JAS
JUL
BKS
SFB
BRK
PCC
PAC
MHC
GCC
VIT (VIN)
(HRC)
FRE
LLA
SPR
PRS
PRI
• temporary
◉ permanent
X intended shotpoint

FIG. 1

FIG. 2

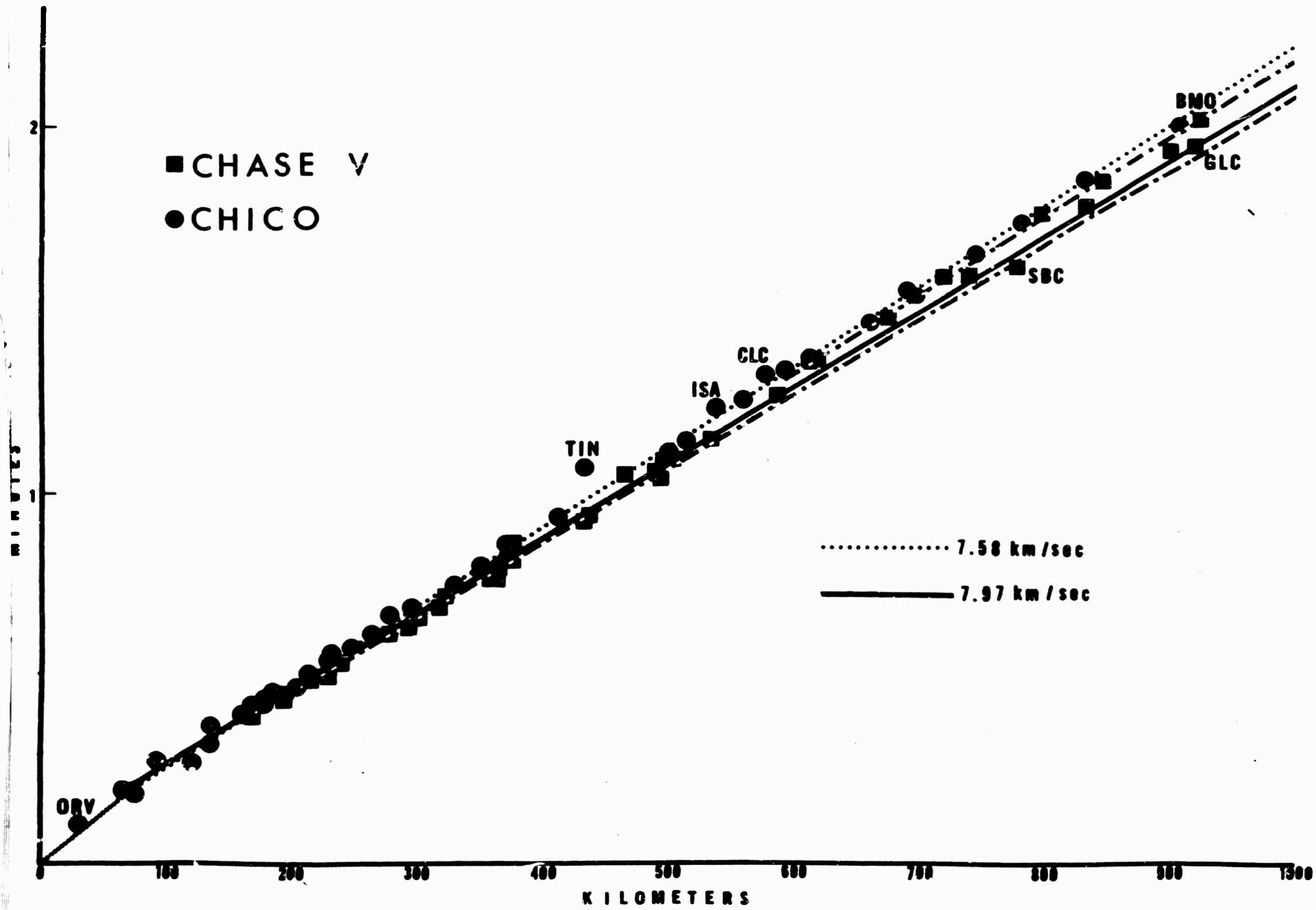

■CHASE V
●CHICO
ORV
TIN
ISA
CLC
SBC
BMO
GLC
7.58 km/sec
7.97 km/sec
MINUTES
1
2
0
100
200
300
400
500
600
700
800
900
1000
KILOMETERS

FIG. 3

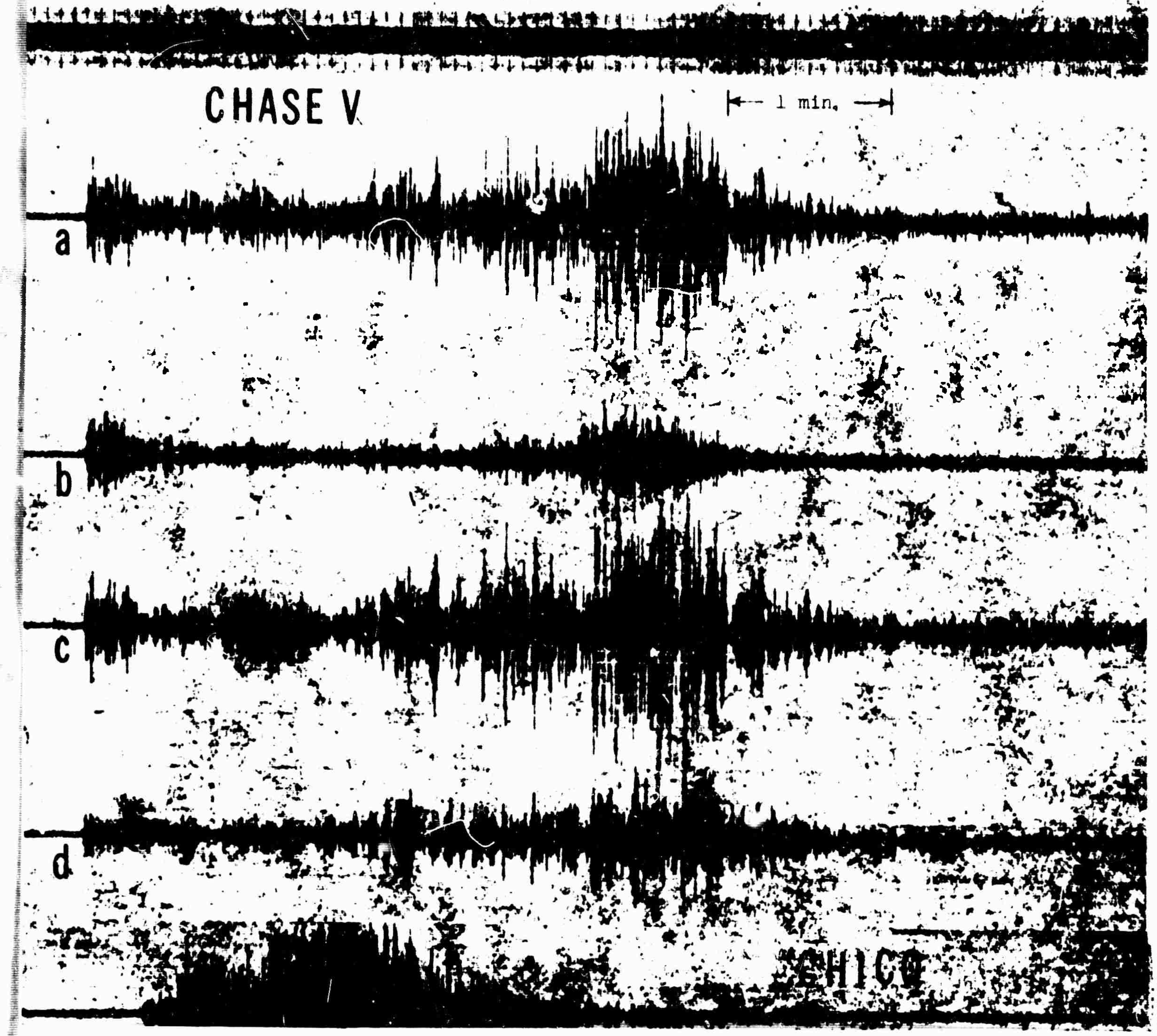
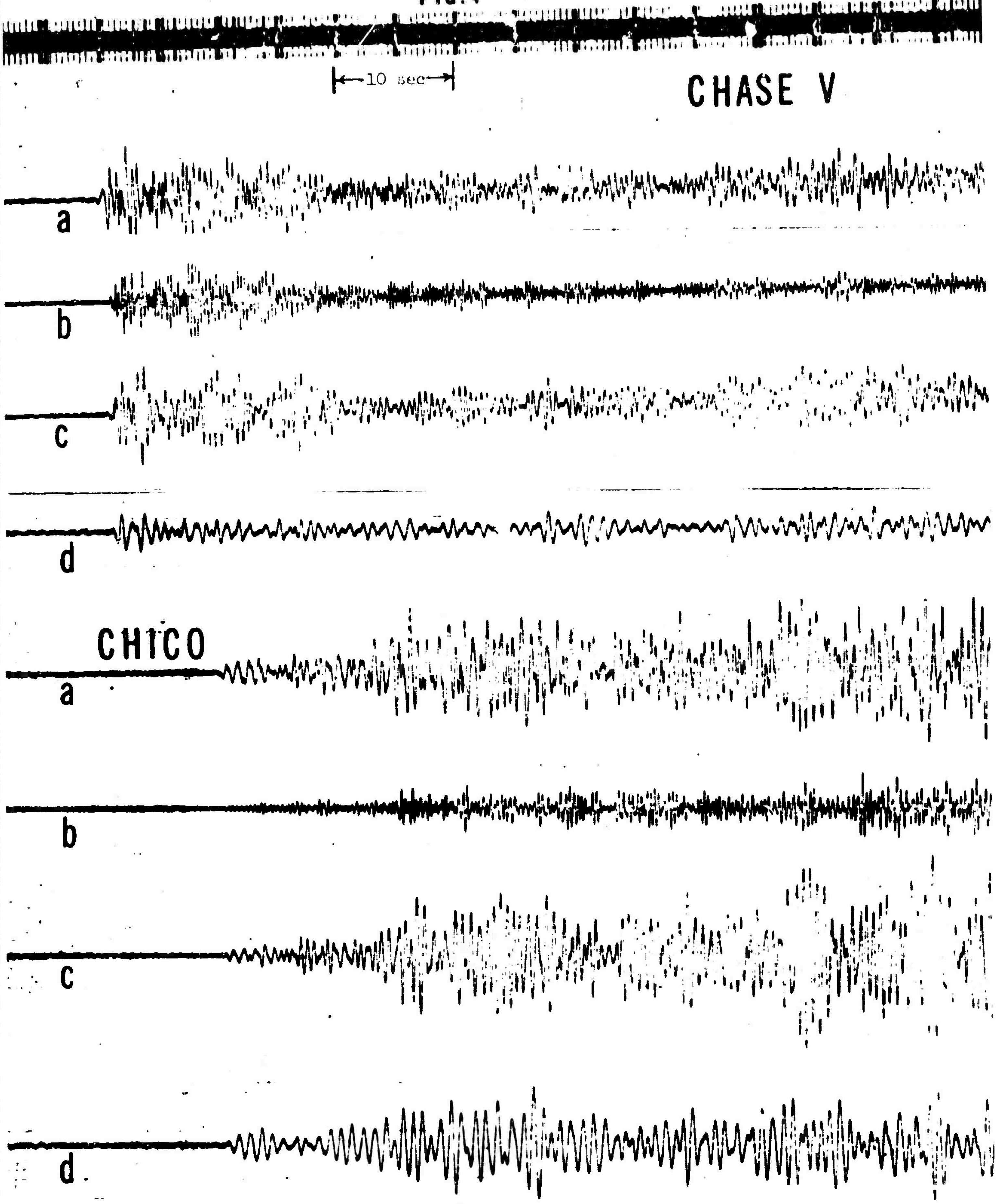


FIG. 4



8. SEISMICITY OF THE REGION

B.A. Bolt, C. Lomnitz and T.V. McEvilly

We have taken the point of view that one of the major research objectives for which the Central California Seismic Array could be used is the study of seismicity patterns in the Coast Ranges of California. The recent locations of array stations have been selected in large part to give optimum control in hypocenter determinations in the seismically active regions.

Figure 1 shows a composite map of earthquake epicenters of magnitude 2.5 and greater in the central California region (aftershocks not included), as determined by stations of the Berkeley network during the years 1962, 1963, and 1964 (first three quarters). Results for 1965 are now being processed. The following points of special interest deserve to be mentioned.

(1) In the Coast Ranges most of the seismic activity during 1962, 1963, 1964 has occurred in two main regions both within the Gabilan Range: (a) the Salinas-San Juan Bautista-Watsonville region west of Hollister; (b) the Pinnacles-Bear Valley region south of Hollister.

Both regions are situated to the west of the San Andreas fault trace. We believe that this is probably a genuine offset but the effect of systematic errors in epicenter determinations, due to different velocities east and west of the fault, is being investigated.

(2) North of Corralitos, no seismicity is apparent (magnitude ≥ 2.5) on the San Andreas fault until the fault goes out to sea off the San Francisco Peninsula. A possible exception is an earthquake of magnitude 4.6 in the Butano Ridge area, about 15 km west of the fault trace. The recorded seismicity off the San Francisco Peninsula is interpreted as a remanent effect of the aftershock sequence following the 1957 Daly City earthquake (magnitude 5.7).

(3) No earthquakes of magnitude greater than 2.5 were recorded on the San Andreas fault between Marin County and Pt. Arena with the possible

exception of the single event southeast of Pt. Arena, some 13 km east of the fault trace.

(4) In the Diablo Range near the junction of the Hayward and Calaveras faults there are active seismic loci which, in this case, are very closely correlated with the surface strike of the major faults. The seismic activity continues northwest into the area of Calaveras Reservoir, north of San Jose.

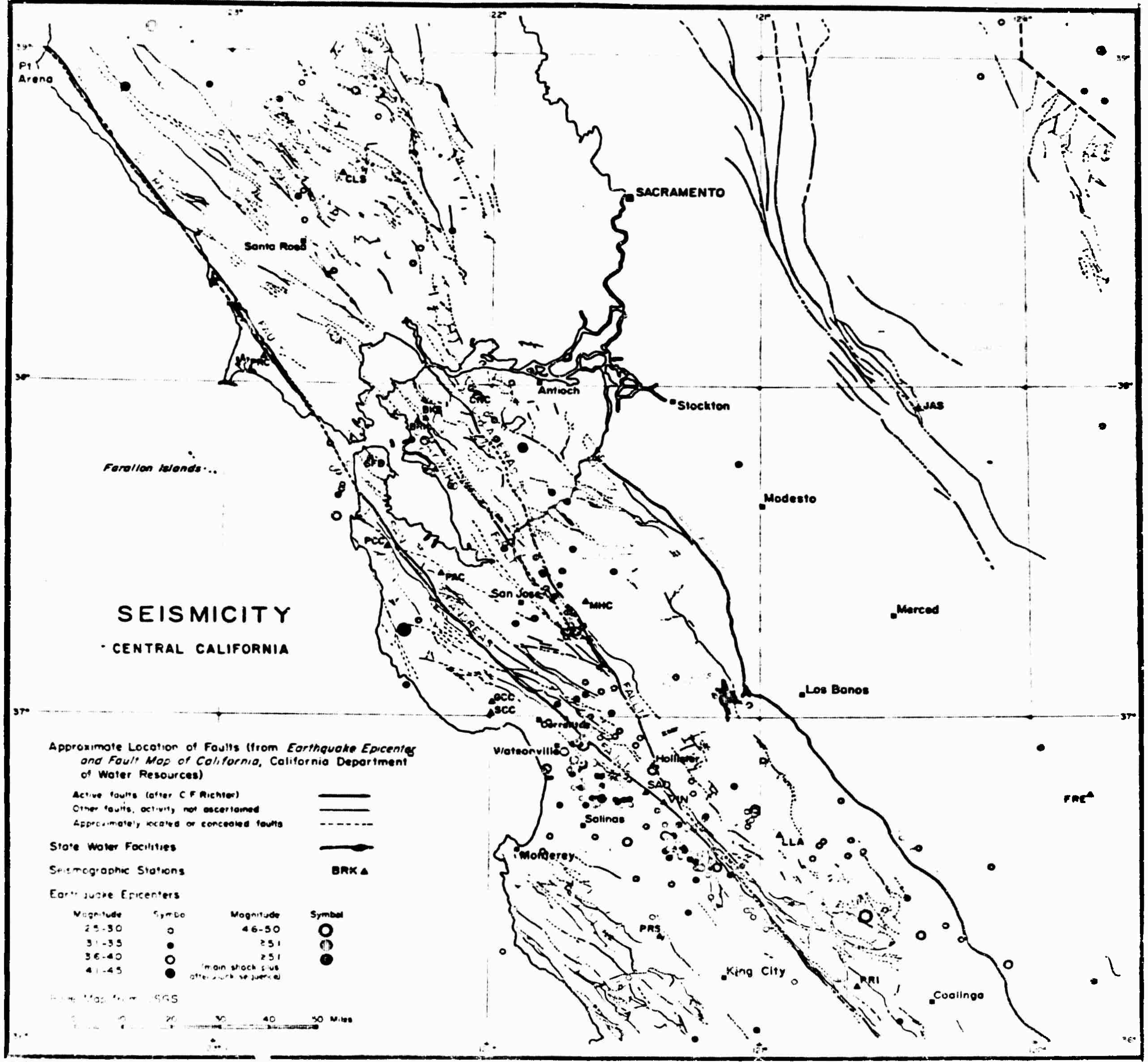
(5) Earthquakes along the Hayward fault tend to cluster slightly to the west of the fault trace. Most of the activity has been in Alameda County.

(6) Activity along the Calaveras fault was concentrated principally between Mt. Diablo and Livermore, slightly east of the fault trace. This corresponds to the epicentral area of the Antioch earthquake of September 10, 1965.

(7) There is an indication of sporadic seismicity on the eastern flank of the Coast Ranges. These epice[illegible] mostly around Panoche Valley and into the western San Joaquin Valley; this seismicity deserves close attention because of the potential hazard to the California Aqueduct.

(8) There are scattered epicenters in the northern Coast Ranges, north of Carquinez Straits, particularly in Sonoma, Lake, and Napa Counties. Geologic mapping of faults is difficult in this area due to lack of surface contacts.

(9) Determination of focal depths of earthquakes plotted in the Coast Ranges indicates in this interval of study (1962-1964) at least 80 per cent of the better-determined shocks are no more than about 5 km deep. Focal depths in excess of 10 km are exceptional.



SEISMICITY

CENTRAL CALIFORNIA

9. PROPERTIES OF S-WAVES AT NEAR DISTANCES

J. Filson

An effort has been made to study the elastic shear wave from sources at near distances. The research has been directed toward determining the ground particle motion due to the arrival of the shear wave at these distances; and toward determining the mechanism of propagation which will produce the observed motion. The latter, of course, involves properties of the medium and the source.

To solve the observational problem, the responses of two horizontal and one vertical Press-Ewing seismometers, located at Berkeley, are recorded on magnetic tape. These seismometers have a free period of 30 seconds and like damping; they have been calibrated and their response characteristics are considered identical. Upon playback, the horizontal components are referred to a resolving device which electronically rotates the seismometer response to the longitudinal and transverse directions with respect to the station to epicenter line. Thereupon, the vertical, longitudinal, and transverse signal components are passed through operational amplifiers whose response characteristics are such that the response of the seismometer-amplifier system is rendered constant with respect to displacement between 30 and .1 seconds. Particle motion diagrams in the vertical-transverse, vertical-longitudinal, and transverse-longitudinal (horizontal) planes are then constructed from recorder traces. In some cases additional filtering is required to suppress the microseisms. Examples of ground particle motion due to the arrival of the shear wave from sources within 40 km are shown in Figure (1).

In consideration of a theory which might predict the observed particle motions, an isotropic homogeneous half space propagating plane harmonic waves serves as a simple model. For further simplification, the theoretical S motion is resolved into vertical SV and horizontal SH components. At the point of observation on the surface, the SH motion is reflected without change in amplitude while at certain angles of incidence a portion of the SV motion may be converted into pure longitudinal motion, a P wave being generated. Upon this conversion at the surface, the angle between the P wave front normal and the surface normal is greater than for the reflected SV wave. Thus there is a critical angle of incident SV above which there is no generated P wave. The surface particle motion for angles of incidence less than this critical angle is linear; however, for incidence angles greater than this critical angle, the SV component changes phase with respect to the SH component and the resulting particle motion describes a three dimensional figure in space.

A program was written for the plane wave, half-space model, to compute and draw the theoretical particle motion for any angle of incidence and for any ratio of original SH and SV components. Figure (2), drawn by the program, shows the three planes of motion as the angle of incidence passes through the critical angle (here about 37°) in 5° steps. Notice that the motion is linear up to 35°, then elliptical at 40°, linear again at 45° with no longitudinal component, and finally elliptical again at 50°. For all angles of incidence greater than 50° the motion is non-linear. The P and S wave velocities used in drawing Figure (2) are 8.1 and 4.6 km/sec, respectively.

Now note the particle motion of the S wave of earthquake #4 in Figure 1. It is nearly linear with a definite longitudinal component. For this linearity to be explained by the model, the focal depth would have to be greater than the epicentral distance of 37 km. This earthquake, which is one of the Antioch sequence discussed in Section 6, is probably not deeper than 12 km. Thus this direct S wave should give rise to non-linear motion at the surface. In this case, a shallow surface layer of greatly reduced shear velocity, say 1.2 km/sec, is required to yield the observed linear motion. If this zone exists its thickness would have to be such that it would have little effect on the longer period S phases from earthquakes at intermediate distances. These waves give rise to elliptical SV motion as reported by Nuttli and Whitmore (1962). Although the remaining two examples in Figure 1 appear complicated, they and most of the S arrivals from epicenters within 80 km are more linear than not, and certainly not elliptical as predicted by the plane wave, half space model. Thus this model is considered to fail, except for the possible variation employing the surficial low velocity zone.

The model presently being studied is one of a buried impulsive source in a single layer, over a half space. Again, the half space and the layer are isotropic and homogeneous; the layer modeling the crust, the half space, the mantle. Here one must consider the direct, reflected, and conical waves and the P wave when generated at the upper and lower boundaries of the layer. Although theories of handling this problem have been developed in general by Brekhovskikh (1960), Cagniard (1962), and Heelan (1953), the specific case the surface motion due to the arrival of the conical S wave remains to be worked. It is toward the solution of this problem that this research is now directed.

References

Brekhovskikh, L., 1960. Waves in Layered Media, Academic Press, New York.

Cagniard, L., 1962. Reflection and Refraction of Progressive Seismic Waves, McGraw-Hill, New York.

Heelan, P., 1953. On the Theory of Head Waves. Geophysics 18, 871-894.

Nuttli, O. and J. Whitmore, 1962. On the Determination of the Polarization Angle of the S Wave. Bull. Seism. Soc. Am. 52, 95-107.

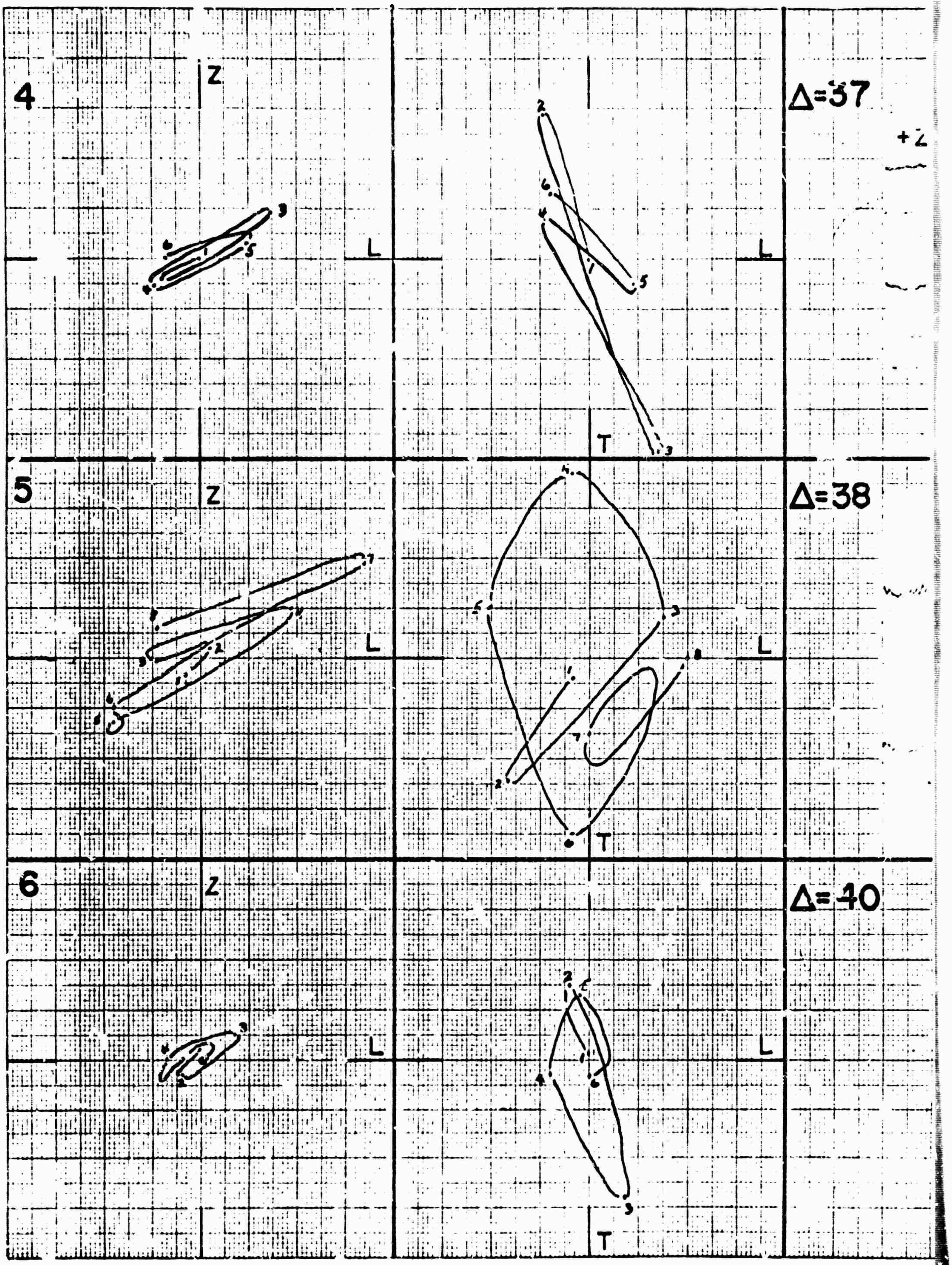


Fig. 1

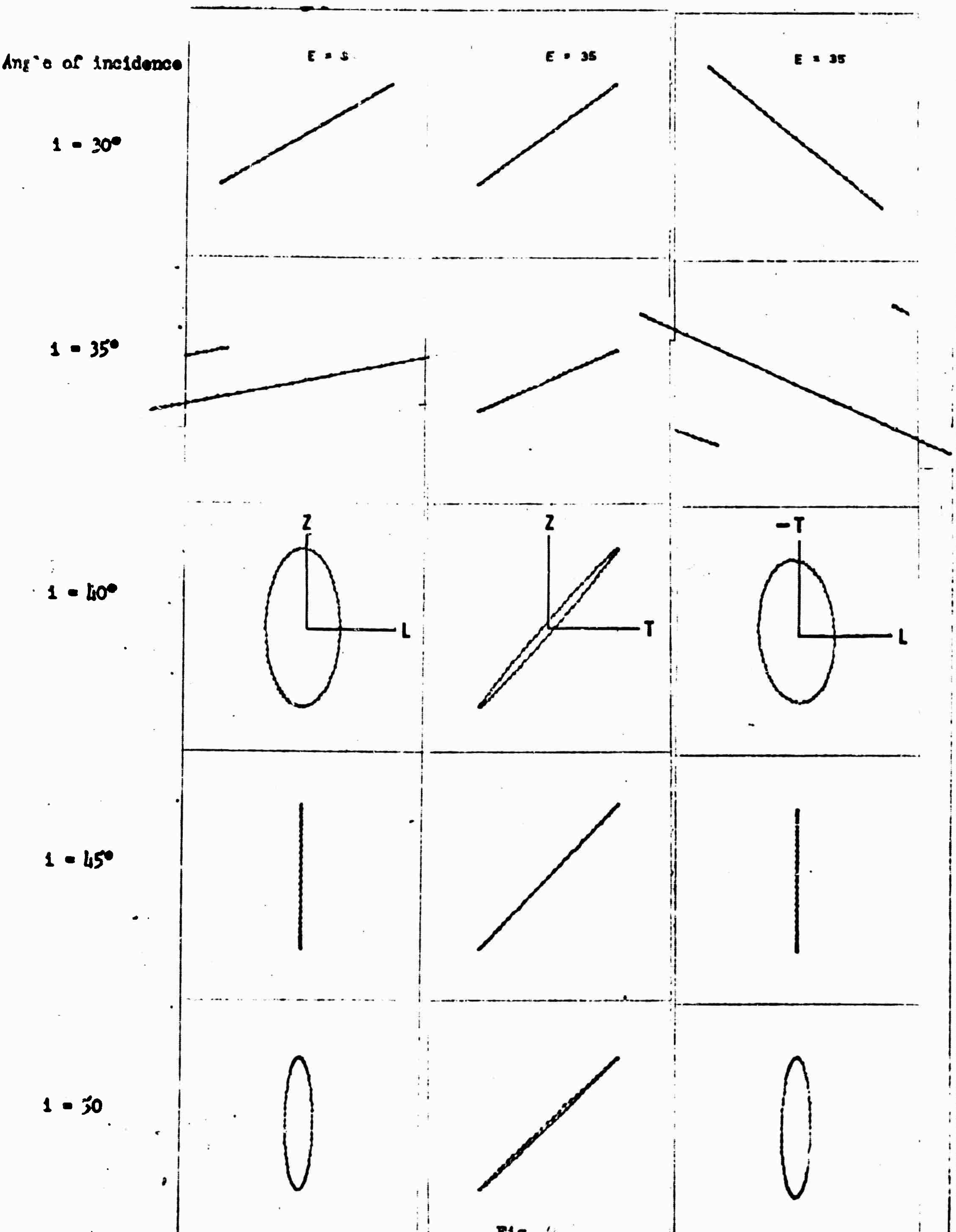


Fig. [illegible]

10. CRUSTAL STRUCTURE ESTIMATION WITHIN THE ARRAY

T.V. McEvilly

The University of California seismic array, located between the western continental margin and the Sierra Nevada range, clearly spans a zone where complex transitions in crust and upper mantle structure should occur. In addition, the array is divided by the San Andreas fault zone through the Coast Ranges, with the resultant lateral discontinuity of granitic rocks to the west and the Franciscan series to the east. It is not surprising that anomalous features of wave propagation are discovered in studies utilizing wave arrivals at stations in this area. Understanding and considering these anomalies, however, is of prime importance in fully utilizing the capabilities of the large-scale array in seismic research; for example, in obtaining maximum accuracy of epicenter location both for local and distant earthquakes. On the other hand, the advantages of array recording can be brought to bear on the problem of resolving the underlying structural variations producing the anomalous propagation.

Seismic studies of several types have produced strong evidence of non-uniform crust and/or upper mantle structure in the array area. Evernden (1953, 1954, 1955) observed variations from great circle paths in directions of approach of Rayleigh waves recorded in central California. Otsuka (1966a, b), working with the array, found cyclic anomalies in apparent velocity and direction of approach for teleseismic P-waves which, in general, were indicative of either very rapid crustal thickening eastward or a low velocity zone in the upper mantle thickening eastward. Bolt and Nuttli (1966) [illegible] similar variations, relative to Berkeley observations, in teleseismic P wave residuals at individual stations of the array in northern California. Refraction studies in central California also suggest that crust-mantle configuration is complex. Interpretations have suffered from a lack of good control on the P_n branch of the travel-time curve. Studies by Byerly (1939), Cameron (1961), Ryall (1962), Healy (1963), Eaton (1963), and Hamilton et al. (1964), have produced P_g velocities from 5.1 to 6.3 km/sec, with indications of up to 1.0 km/sec difference across the San Andreas zone, P_n velocities from 7.8 to 8.0 km/sec, and crustal thicknesses of 20 to 30 km.

During the contract period summarized in this report an effort was made to improve the apparent uncertainty in crustal-upper mantle structural interpretations in central California Coast Ranges. The method devised utilizes the seismic array, implemented by some fifty temporary stations that have been placed in operation over the past four years in various studies, as a two-dimensional refraction array for sources consisting of about twenty accurately timed blasts at three locations and precisely located hypocenters in four aftershock sequences (see another section in this report). The data are a suite of travel times between more than 100 station-source pairs. Distances range up to nearly 300 km.

The interpretation method is a least squares procedure of minimizing residuals in the observed travel times by systematically varying structural parameters. Crustal velocity is approximated by a linear increase with depth. Surface velocity, gradient, crustal thickness, upper mantle velocity, Moho dip and curvature are variable parameters. Preliminary results using only blast data are summarized by McEvilly (1966). This initial work emphasized the difficulty of recording P_n arrivals from explosions in the area. P_g arrivals, however, gave strong evidence for a change of about 0.6 km/sec in shallow crustal velocity across the San Andreas zone, with higher velocities on the southwestern side. Combining all data for upper mantle structure yielded a depth of about 22 km to the Moho in the center of the array with appreciable east dip and a P_n velocity of 7.83 km/sec. This result suffers from the poor quality of P_n arrivals from explosions. The study has been expanded to include large aftershocks in sequences studied in detail using temporary stations at very short distances (~10 km) so that errors in focal depths and origin times are not significant. The required program modifications for variable source depth have been made and the additional P_n data are now being readied for analysis.

Overall general conclusions can be drawn from the various studies related to crust and upper mantle structure in central California. There is strong evidence, as well as geophysical reason, for general inland dip on the Moho. Unfortunately, quantitative determination of dip magnitude is difficult since the effect of the lateral velocity decrease across the San Andreas zone, when viewed through an averaging process using the entire array, is virtually equivalent to that produced by crustal thickening inland, or even seaward dip on the top of a low velocity layer within the mantle. The simplest manner of resolving the ambiguities calls for determining the shallow structural properties and subsequently "stripping" these known effects to investigate deeper features. The indications of a lateral velocity decrease of the order of 0.5 km/sec in the shallow crust northeast of the San Andreas are fairly good and the details can be mapped by refraction studies. P_n arrivals, when known crustal velocities are used, will contribute information on depth and configuration of the Moho. Present interpretations favor a 20- to 25-km crust with several degrees of dip inland and possible crustal thickening to the southeast. Better P_n arrivals within the array are required to clarify this structure. The velocity distribution in the upper mantle must be inferred from the teleseism azimuth and velocity anomalies, taking into account the structure above.

At the present stage of interpretation, it is clear only that the seaward dipping velocity inversion in the upper mantle, when considered in conjunction with a moderately inland dipping Moho, produces velocity and azimuth anomalies similar to these observed. In terms of anomaly the dipping low velocity lid is essentially equivalent to a lateral inland decrease of about 0.5 km/sec in velocity in the upper mantle.

In summary, within the area of the continental margin spanned by the array, it appears that velocities decrease landward in both the crust (where the jump appears associated with the San Andreas fault zone) and the mantle. Total change across the array may be as much as 0.5 km/sec in each case. The Moho appears to exhibit a few degrees of landward dip and lie at an average depth of 20 to 25 km within the array. Systematic studies in combining refraction data, teleseism anomalies, and possibly surface wave dispersion are required for further definition.

References

Bolt, B.A. and O.W. Nuttli (1966). P Wave Residuals as a Function of Azimuth. 1. Observations. J.G.R. 71, 5977-5985.

Byerly, P. (1939). Near Earthquakes in Central California. Bull. Seism. Soc. Am. 29, 427-462.

Cameron, J.B. (1961). Earthquakes in Northern California Coastal Region, (Part 1). Bull. Seism. Soc. Am. 51, 203-221.

Eaton, J.P. (1963). Crustal Structure from San Francisco, California to Eureka, Nevada, from Seismic Refraction Measurements. J.G.R. 5789-5806.

Evernden, J.F. (1953). Direction of Approach of Rayleigh Waves and Related Problems, Part I. Bull. Seism. Soc. Am., 43, 335-374.

Evernden, J.F. (1954). Direction of Approach of Rayleigh Waves, Part II. Ibid., 44, 159-184.

Evernden, J.F. (1955). Tripartite Results for the Kamchatka Earthquake of November 4, 1952. Ibid., 45, 167-178.

Hamilton, R.M., A. Ryall, and E. Berg (1964). Crustal Structure Southwest of the San Andreas Fault from Quarry Blasts. *Bull. Seism. Soc. Am.* *54*, 67-77.

Healy, J.H. (1963). Crustal Structure Along the Coast of California from Seismic Refraction Measurements. *J.G.R.* *68*, 5777-5787.

McEvilly, T.V. (1966). Crustal Structure Estimation within a Large Scale Array, *G. Jour., Roy Astro. Soc.* *11*, 13-17.

Otsuka, Michio (1966a). Azimuth and Slowness Anomalies of Seismic Waves Measured on the Central California Seismographic Array. Part I, Observations. *Bull. Seism. Soc. Am.* *56*, 223-239.

Otsuka, Michio (1966b). Azimuth and Slowness Anomalies of Seismic Waves Measured on the Central California Seismographic Array. Part II, Interpretation. *Ibid.* *56*, 655-675.

Ryall, A. (1962). The Hebgen Lake, Montana, Earthquake of August 18, 1959: P Waves. *Bull. Seism. Soc. Am.* *52*, 235-271.