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No. 14

Further Study of the T Phase

Lamont Geological Observatory
(Columbia University)
Palisades, New York

Further Study of the T Phase

Technical Report No.14

by

Maurice Ewing, Frank Press, J. L. Worzel

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ABSTRACT

New data are presented in support of the conclusion that the T phase is propagated across oceans as compressional waves in the water. T phases from many circum - Pacific belt shocks were recorded at the Honolulu seismograph station and at the Kaneohe and Point Sur Sofar Stations, permitting the determination of oceanic velocity by simple division of epicential distance by travel time since correction for land travel was unnecessary. The signals were much sharper and less prolonged than those previously studied. Very little scatter in the velocity was observed. Divergent views on the nature of T reported by other investigators are due to complications in path, travel time, land correction introduced by the relatively large proportion of land (or shallow water) paths involved in the shocks which they have studied.

INTRODUCTION

The T phase is a train of waves of period between about ½ and possibly 1/100 second propagated across ocean basins from earthquakes having epicenters in the ocean basin or very near its margin, and received on seismographs on islands or near the coast. In an earlier paper[1] it was concluded that the T phase represents sound energy introduced into the ocean near the epicenter and transmitted as compressional waves in the water over the oceanic part of the path. In the first paper two approximations were made: (1) the velocity in the continental part of each path was taken as that of

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[1] Ivan Tolstoy and Maurice Ewing, "The T phase of Shallow Focus Earthquakes", Bull. Seism. Soc. of Am., vol. 40, pp. 25-51,(1950).

compressional waves in typical continental rock; (2) refraction effects, both lateral and vertical, at the continental margins were ignored. The build-up and decay times varied from a few tens of seconds to several minutes, being greater where considerable continental travel was involved, and also greater for large shocks than for small ones. Any determination of the velocity of T across the ocean depends on the correction applied for travel across land. This correction is extremely difficult to ascertain because of the complex layering of the continental crust and the multiple refraction paths resulting from propagation across an irregular continental margin. The gradual buildup of T for paths with considerable continental travel introduces uncertainty in the true travel time of the phase.

In view of these approximations it is clear that the best way to determine the velocity of T across the ocean is to select epicenters and detector locations such that the correction for the continental part of the path is negligible or very small and the signal duration is brief. We now present new material chosen with this purpose in mind. Many shocks from the circum-Pacific belt produced T phases at the Honolulu seismograph station and at the Kaneche and Point Sur Sofar stations, all of which required no correction for land travel, and permitted determination of velocity by simple division of epicentral distance by travel time. These signals were much sharper and less prolonged than those previously studied, the maximum could be picked with an uncertainty less than 10 seconds, the duration was usually under one minute, and the distances were sufficiently large that a change in velocity of one percent or less would have been introduced by using the arrival time of the first detectable signal. A small amount of additional material was available for Atlantic shocks recorded by seismographs on Bermuda.

For 27 circum-Pacific shocks recorded on the Honolulu or Brisbane seismographs the mean velocity was 1.49 ± .02 km/sec. For 15 shocks with reasonably good preliminary epicenters recorded at the Sofar stations the mean velocity was 1.47 ± .01 km/sec. All other observations reported below are consistent with these velocities. These velocities agree well with 1.48 km/sec. given by Anderson[2] for Sofar propagation in the Pacific and 1.49 to 1.52 km/sec. given by Ewing and Worzel[3] for Sofar in the Atlantic; there is now no reason to doubt that the T phase is propagated as compressional waves in water.

T PHASES RECORDED BY SEISMOGRAPHS

Figure 1 shows typical T phase seismograms. "A" was recorded on the Brisbane Benioff Vertical from the Queen Charlotte Islands shock of 22 August 1949, at an epicentral distance of 11,550 km. "B" was recorded on a Sprengnether Horizontal of the Bermuda tripartite microseism station from the Dominican Republic shock of 25 July 1950, at a distance of about 1430 km. "C" was recorded on the Honolulu Neuman-Labarre from the Solomon Islands shock of 29 July 1950 at a distance of about 5,960 km.

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[2] E. R. Anderson, "Distribution of Sound Velocity in a Section of the Eastern North Pacific", Trans. Am. Geophys. Union, vol.31, pp. 221-228, 1950.

[3] Maurice Ewing and J. L. Worzel, "Long Range Sound Transmission", in Memoir 27, Geol. Soc. Amer., 1948.

Table 1 gives the relevant data about all T phases found in a search of the Honolulu seismograms for a two year period. Additional material from Brisbane is included as well as a summary of results previously reported. The mean T phase velocity for the shocks recorded at Honolulu and Brisbane is 1.49 ± .02 km/sec. The propagation paths are indicated in Figure 2. Several T phases from Atlantic shocks recorded on Bermuda seismographs are listed in Table II. Velocities computed for the first three shocks are uncertain since epicenters and origin times for these tremors are poorly determined because of their small size. In fact, it would be more logical to use the T phase for epicenter location than for velocity determination in these cases. A more complete study of Atlantic T phases recorded on Bermuda will be presented at a later date.

T PHASES RECORDED BY SOFAR STATION

Sofar[3] is the name which has been coined by the U.S. Navy for the long distance transmission of sound between a source and a receiver in the ocean at the depth of minimum sound velocity. A typical Sofar signal from the explosion of a small bomb at a depth of 4,000 feet received by a hydrophone at a depth of 3,600 feet 300 miles away is shown in Figure 3. It is seen that the intensity increases gradually for about four seconds to a sharp maximum and ends abruptly. This maximum corresponds to sound which has traveled horizontally at the depth of minimum sound velocity, and it is standard practice to read the travel time of this maximum rather than the beginning of the signal for use in calculations of distance.

TABLE I.

PACIFIC T-PHASES RECORDED ON SEISMOGRAPHS

Station	No.	Date	G.C.T. Origin Time	Lat.°	Long.°	Magn.	Focal Depth	Δ km	Travel Time sec.	Veloc. km sec.
Honolulu	1	9 Sept. 50	10-21-40	4S	153E	6¼		6033	4090	1.48
"	2	31 Oct. 49	17-55-35	5S	152½E		100	6125	4055	1.51
"	3	4 Dec. 50	16-28-01	5S	153½E	7	100	6044	4049 4119	1.49 1.47
"	4	20 Oct. 49	12-44-54	5½S	154E	6½		6025	4067 4136	1.48 1.46
"	5	20 Oct. 49	21-00-11	5½S	154E	6 3/4		6025	4099 4154	1.47 1.45
"	6	24 Sept. 49	04-17-38	6S	154E	7		6055	4027	1.50
"	7	29 July 50	23-48-58	6S	155E	7		5956	4012	1.48
"	8	8 Nov. 50	02-18-09	9½S	159½E	7¼-7½		5764	3751 3821	1.54 1.51
"	9	28 Oct. 49	06-31-51	10S	160E			5755	3794	1.52
"	10	15 Oct. 50	15-54-53	10S	160E	6½		5755	3817	1.51
"	11	28 July 50	05-23-21	13S	167E			5391	3639	1.48
"	12	28 July 50	04-55-13	13S	167E			5391	3637	1.48
"	13	7 Nov. 49	05-59-35	14S	166½E	6 3/4		5517	3705	1.49
"	14	10 Sept. 50	15-15-57	14S	167E	7		5469	3763	1.45
"	15	21 July 50	20-32-01	15½S	168E			5513	3749	1.47
"	16	2 Dec. 50	19-51-45	18S	167E	7½-8		5786	3815	1.52
"	17	20 July 50	09-30-48	17S	174E			5225	3600 ±	1.45
"	18	6 Aug. 49	00-35-27	19S	174½W	7½		4805	3223	1.49
"	19	22 Nov. 49	00-51-32	29S	178W	7¼-7½		5962	3998	1.49

TABLE I.
(continued)

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PACIFIC T-PHASES RECORDED ON SEISMOGRAPHS

Station	No.	Date	G.C.T. Origin Time	Lat.°	Long.°	Magn.	Focal Depth	Δ km	Travel Time sec.	Veloc. km sec.
Honolulu	20	27 Nov. 49	08-42-16	18S	173W			4642	2914	1.59
"	21	23 Aug. 49	20-24-32	53N	132W	6¼		4150	2808	1.48
"	22	22 Aug. 49	04-01-12	54N	133W	8		4190	2823	1.48
Brisbane	22a	22 Aug. 49	04-01-12	54N	133W	8		11,550	7768	1.49
Honolulu	23	31 Oct. 49	01-39-32	56N	135W	6 3/4		4288	2903	1.48
"	24	25 Aug. 49	04-14-15	52½N	178W	6½	deeper than normal	3869	2585 2630	1.45 1.47
"	25	3 Nov. 49	01-12-37	48½N	154E	6 3/4-7	200	5211	3533	1.47
"	29a*	14 May 48	22-31-42	54½N	161W	8		3692	2456	1.50
Pasadena, Cal.	26*	23 Jan. 38	08-32-43	21N	156W	6 3/4		3975	2591	1.53
Riverside, Cal.	27*	20 Dec. 46	19-19-05	32½N	134½E	8.2		9469	6191	1.53
Tinemaha, Cal.	28*	10 Nov. 38	20-18-42	55½N	158W	8¼		3600	2125	1.69
Mineral, Cal.	29*	14 May 48	22-31-42	54½N	161W	8		3295	2245	1.47
Tinemaha, Cal.	30*	7 Dec. 44	04-35-42	33N	136E	8		9058	5943	1.52
Tinemaha, Cal.	31*	2 Mar. 33	17-31-00	39N	144½E	8¼		8049	5331	1.51

* From published paper Tolstoy and Ewing.

TABLE II.

SOME RECENT ATLANTIC T-PHASES RECORDED ON BERMUDA SEISMOGRAPHS

No.	Date	G.C.T. Origin Time	Lat.°	Long.°	Magn.	Focal Depth km.	Δ km	Travel Time sec.	Veloc. km/sec.
1	26 July 50	08-31-28	19N	68W			1430	1002	1.43
2	6 Oct. 50	11-20-05	17N	68W			1622	1095	1.50
3	6 Oct. 50	12-43-03	17N	68W			1622	1047	1.57
4	1 Dec. 50	14-51-00	14.3N	47.6W	7¼	50	2650	1770	1.50

Sofar records covering intermittent monitoring by the Sofar stations at Point Sur and Kaneohe were examined for signals generated by earthquakes, and 21 signals were found as listed in Table III. The paths of these T phases are shown in Figure 4. (The dashed lines indicate uncertain epicenters.) In addition numerous signals were observed which could not be correlated with any reported earthquakes and may have originated in tremors too small for observation by seismographs.

Figure 5, A, B, C, D shows typical T phase records recorded at the Kaneohe, Oahu Sofar Station from earthquakes off the Aleutian Islands, California, Mexico, Queen Charlotte Islands. Figure 6, A, B, C shows T phases recorded at the Point Sur, California Sofar Station for shocks in New Hebrides, Solomon Islands and off California. These records give a measure of the sound intensity as detected by a hydrophone at a depth of several hundred fathoms. The deflection of the trace is proportional to the logarithm of the intensity.

In determining the average velocity we have not used the data for shocks 6, 11, 12, 21, since accurate epicenter determinations are not available. Here again, it would be better to use the signal travel time to determine the epicenter than to use it to determine the velocity of propagation. The mean velocity for the remaining 17 signals is 1.46 ± .02 km/sec. It is to be noted that shocks 13 and 14 which occurred on the same day at the same place gave velocities significantly lower than all others and in particular lower than other shocks in the same area. It is believed that these low velocities are due to an error (which we have been

TABLE III.

PACIFIC T-PHASES RECORDED AT SOFAR STATIONS

Recording Station	No.	Date	G.C.T. Origin Time	Lat°	Long.°	Magn.	Focal Depth Km.	Signal Duration Sec.	Δ in Km.	Travel Time sec.	Veloc. km/sec.
Pt. Sur	1	10 Sept. 50	15-15-57	14S	167E	7		105	9260	6353	1.46
" "	2	29 July 50	23-48-58	6S	155E	7		50	9751	6590	1.48
" "	3	4 Dec. 50	16-28-01	5S	153½E	7	100	145	9819	6665	1.47
Kaneohe	4	18 Jan. 51	21-15-50	52N	177W	6¼-6½		45	3770	2551	1.48
"	5	28 Sept. 50	21-47-01	54½N	134½W			25	4144	2888	1.43
"	6	1 Oct. 50	13-06-14	Queen Charlotte Region				30		2780	
"	7	29 Jan. 51	05-02-03	43N	128W			45	3636	2515	1.45
"	8	29 Jan. 51	05-43-47	43N	128W			85	3636	2485	1.46
"	9	24 Aug. 50	17-45-34	42½N	126W			30	3750	2508	1.50
"	10	8 Oct. 50	12-24-17	40½N	125W			60	3724	2542	1.46
Pt. Sur	11	6 Feb. 51	16-33-10	Off Cape Mendocino				30		432	
" "	12	6 Feb. 51	17-06-33	"	"			30		437	
Kaneohe	13	29 Sept. 50	06-32-14	19N	107W	7		60	5268	3781	1.39
"	14	29 Sept. 50	07-54-22	19N	107W	6.2		55	5268	3788	1.39
"	15	3 Jan. 51	12-21-31	18N	106W	6¼-6½		45	5394	3653	1.48
"	16	3 Jan. 51	13-04-24	18N	106W	6¼		25	5394	3659	1.47
"	17	21 Oct. 50	08-27-13	17½N	106W			45	5409	3698	1.46
"	18	21 Oct. 50	08-57-10	17½N	106W	5 3/4		55	5409	3702	1.46
"	19	21 Oct. 50	09-42-58	17½N	106W	6 3/4		60	5409	3701	1.46

TABLE III.
(continued)

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PACIFIC T-PHASES RECORDED AT SOFAR STATIONS

Recording Station	No.	Date	G.C.T. Origin Time	Lat.°	Long.°	Magn.	Focal Depth Km.	Signal Duration Sec.	Δ in Km.	Travel Time sec.	Veloc. km/sec.
Pt. Sur	20	19 Feb. 51	22-11-54	25S	117W	6½		70	6825	4664	1.46
" "	21	20 Feb. 51	15-24-18	22S	114W	6		45		4959	

unable to locate) either in epicenter or more probably in the timing at the Sofar station. Excluding these values we obtain a mean velocity of 1.47 ± .01 km/sec. for the T phase from the remaining 15 shocks.

It is interesting to note that earthquakes southwest of Honolulu which produced T phases on the seismographs there, did not produce signals on the Sofar hydrophone which is situated a short distance northeast of the same island. Thus the island of Oahu casts a shadow for the T phase from earthquakes exactly like that cast by Bermuda for Sofar signals, as described by Ewing et al[4]. This is additional evidence in support of the view that the T phase is propagated as a compressional wave in the water.

It has been shown theoretically[5] that the efficiency of an earthquake in exciting the T phase decreases rapidly as the depth of focus increases if the ocean floor at the epicenter is level, but that an ocean floor which deepens in the direction of propagation of the T phase can permit entry of the sound waves into the water with travel along near-horizontal rays as required for wave guide propagation[1] (analogous to use of a prism to introduce light into a plate in the Lummer-Gehrcke interferometer). As is well known, the precise depth of focus of an earthquake is difficult to obtain from seismological evidence, particularly for oceanic epicenters, where data from an enclosing network of nearby seismographic stations are not available. Hence it is not surprising

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[4] Maurice Ewing, G. P. Woollard, A.C.Vine and J.L.Worzel, "Recent Results in Submarine Geophysics", Bull. Seism. Soc. of Am., vol. 57, pp. 909-934, 1946.

[5] Frank Press, Maurice Ewing and Ivan Tolstoy, "The Airy Phase of Shallow Focus Submarine Earthquakes", Bull. Seism. Soc. of Am., vol. 40, pp. 111-148, 1950.

that the intensity of the T phase is not determined by the magnitude of the earthquake alone. For example, some small shocks which are only barely detectable by the Berkeley Seismographs give much stronger T phases on the Kaneohe Sofar hydrophone than shocks of magnitude 6¼ - 6½ in other regions at comparable distances (e.g. shocks 4 and 6 Table III). This illustrates the potentialities of the T phase as an effective tool for investigating details of the action at the focus, in addition to its value for precise location of epicenters[1,4]. Over almost all of the circum-Pacific belt earthquakes of this magnitude are undetected, being beyond the range of the small number of sensitive seismographs located near it, yet their T phase could be detected almost anywhere in the Pacific Ocean.

Little is known about the spectrum of the energy released by an earthquake in the higher frequencies, due to the high attenuation in rock at high frequency. Since this limitation is less severe for water. study of T phase reception by hydrophones can provide important information on this point. The fact that T is readily detected at Sofar stations is evidence that considerable energy is propogated through the water with periods much shorter than 0.1 sec.

Assuming the origin times determined by seismograph data for the shocks off the California coast of 6 February 1951 163310 and 6 February 1951 170633 fall respectively along arcs 635 km and 642 km from the Point Sur station.

DISCUSSION

The early history of the T phase was discussed in an earlier paper[1]. While that paper was in press Coulomb & Molard[6] published an account of a short period phase observed on the seismograms of Martinique from Caribbean shocks. They calculated the velocity of propagation as epicentral distance divided by total travel time. Their velocities showed a considerable scatter, which they attributed to the use of approximate epicenters, and ranged between 1.58 and 2.36 km/sec.,averaging 1.854 km/sec. They considered that this rather low velocity phase was transmitted as shear waves (SH) in the layer of sediments on the floor of the Caribbean, and that the velocities were definitely greater than the speed of sound in water. They expressed the opinion that submarine volcanism might generate this motion, realizing that theoretical difficulties were involved. We believe it significant that the great circle paths from the epicenters to Martinique for all of these earthquakes included considerable land or shallow water portions averaging 25% of the total path. A recalculation of velocities from data given by Coulomb and Molard in which a correction for propagation over land or shallow water (1000 fm) at 5 or 6 km/sec. results in a mean velocity for the oceanic portion of the path close to the speed of sound in water.

More recently Leet, Linehan and Berger[7] have presented a

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6. J. Coulomb & Molard, "Ondes Seismiques au Fond de La Mer des Antilles", Ann.de Geophysique, T.S.,fasc.3 pp.1-2,1949.
7. L.Don Leet, Daniel Linehan, S.J., and P.R. Berger, "Investigation of the T Phase", Bull. Seism. Soc. Amer., vol. 41, pp.123-141,1951.

paper in which they also assign propagation of shear waves through the ocean bottom sediments as the mechanism for transmission of the T phases from Atlantic and West Indian earthquakes. These phases had been reported since 1935, without explanation of the mechanism of propagation, in the Harvard and Weston bulletins. Byerly (personal communication May 17, 1951) recently identified T on the Berkeley record of the earthquake of June 28, 1935 in Hawaii.

It is clear that the divergent views expressed by these authors are mainly due to the complications in path, travel time, land correction introduced by the relatively large proportion of land (or shallow water) paths involved in the shocks which they have studied. These complications require corrections which at best are only approximate. The results of Leet, Linehan and Berger on the land velocity of T are not convincing in that they depend on questionable correlations of events on the Harvard and Ottawa and Harvard and Weston seismograms. The new data presented in the present study were selected to eliminate these difficulties and to provide an accurate determination of the velocity of T. The consistency of our results as shown by this small scatter and the excellent agreement of our results with the speed of sound in water leaves little room to doubt that T is propagated as compressional waves in water, and the similarity between reception by Sofar hydrophones of the T phase and of signals from bombs exploded at the sound channel axis is additional strong evidence. Moreover the hypothesis that T is transmitted as SH waves in ocean bottom sediments is immediately ruled out as such waves could not enter the water for detection by the hydrophones.

No destructive tsunamis have been produced by the shocks studied here. Although there has been no opportunity for systematic examination of tide gauge records to correlate the excitation of T with that of tsunamis, Capt. E. B. Roberts of the U.S. Coast & Geodetic Survey has advised us that the Queen Charlotte Islands shock of 22 August 1949, which produced a large T phase, did produce a small tsunami. The correlation between T phase and tsunami excitation for shocks of magnitude about 7 or greater, previously pointed out[8], can be carried much further when a system for determining the magnitudes of T phases is devised. It is clear that seismographs in most locations have orders of magnitude less sensitive for this purpose than Sofar hydrophones. It is also clear that the sensitivity of each seismograph installation as a T phase detector depends greatly upon the direction of approach of the disturbance, being subject to acoustical shadows to almost the same degree as Sofar hydrophones. Thus Berkeley and Pasadena are far more sensitive to shocks from the Hawaiian Islands, the Solomon Islands, etc., than from the remainder of the circum-Pacific belt, particularly Central America and the Aleutians, and Honolulu almost certainly has a maximum of sensitivity to the north and a maximum to the southwest with orders of magnitude difference in the two sensitivities. It appears highly probable that the correlation between T phase and tsunami generation will be greatly improved when proper account is

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[8] Maurice Ewing, Ivan Tolstoy and Frank Press, "Proposed Use of the T Phase in Tsunami Warning Systems", Bull. Seism. Soc. Amer., vol. 40, pp. 53-58, 1950.

taken of the intensities of the T phase.

CONCLUSIONS

1. The T phase is propagated as compressional waves in water.

2. It provides an important tool for epicenter location and study of depth and mechanism at the focus.

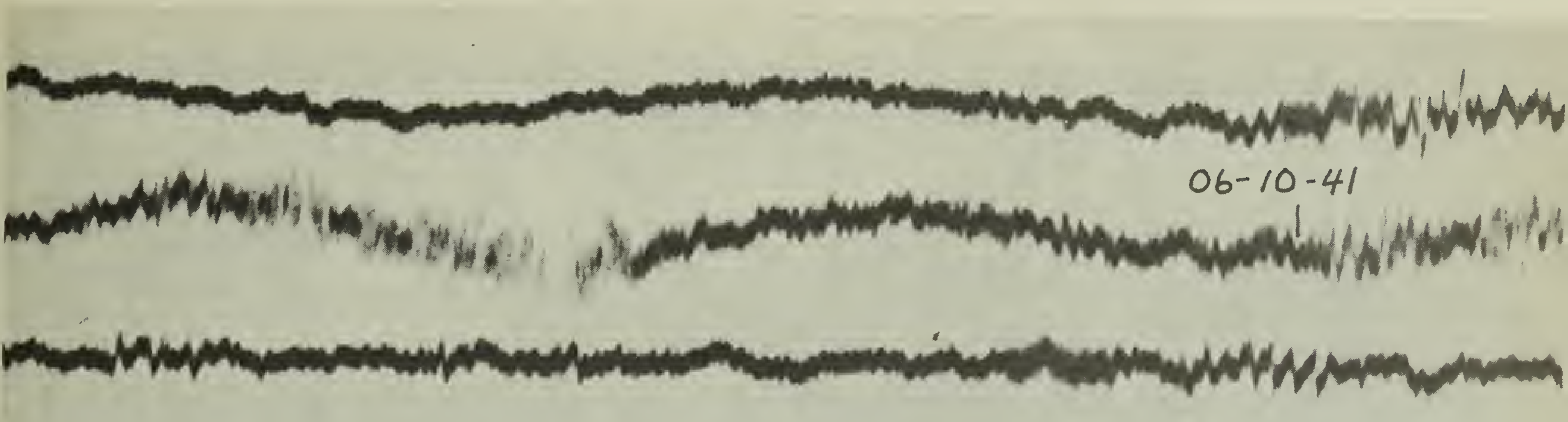
3. Sofar stations can provide seismologists with an abundant supply of very precise data for investigations involving the T phase.

4. A sofar network could form an extremely useful adjunct to the Pacific tsunami warning system.

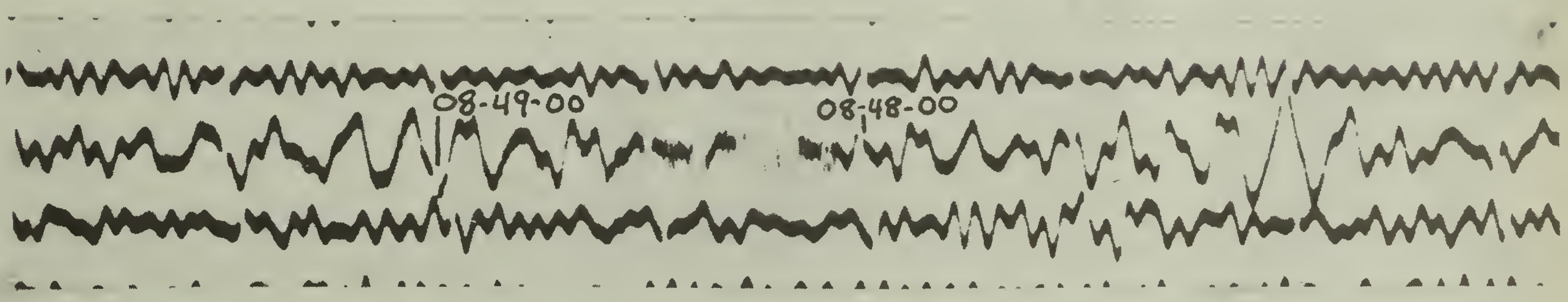
5. A T phase magnitude scale, which must take into account the directionality of each detector, and the enormous differences in sensitivity of sofar hydrophones and the various types of seismometers is necessary for seismological applications of the T phase (except epicenter and origin time determinations) and is urgently needed for direct correlation with tsunami.

ACKNOWLEDGMENTS

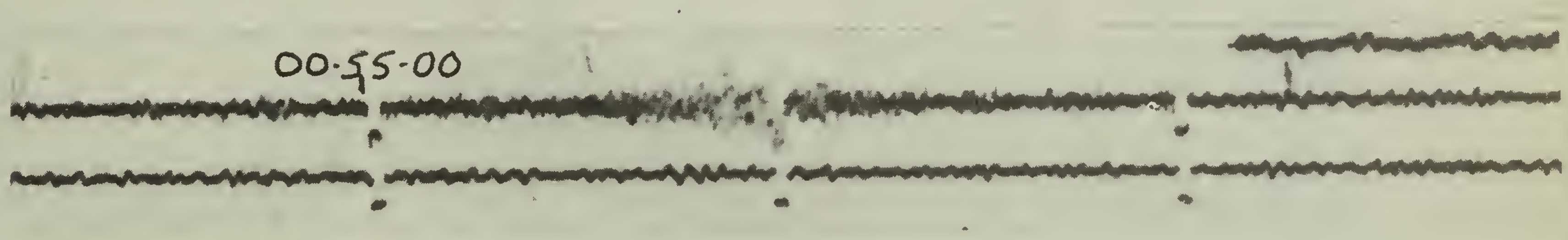
We are indebted to the Commanding Officer and members of the staff of the Naval Electronics Laboratory, San Diego for their cooperation in making the Sofar records available to us and to the United States Coast and Geodetic Survey for the use of the Honolulu seismograms.



A. Queen Charlotte Islands Earthquake of 22 Aug, 1949 04:01:12
Recorded at Brisbane

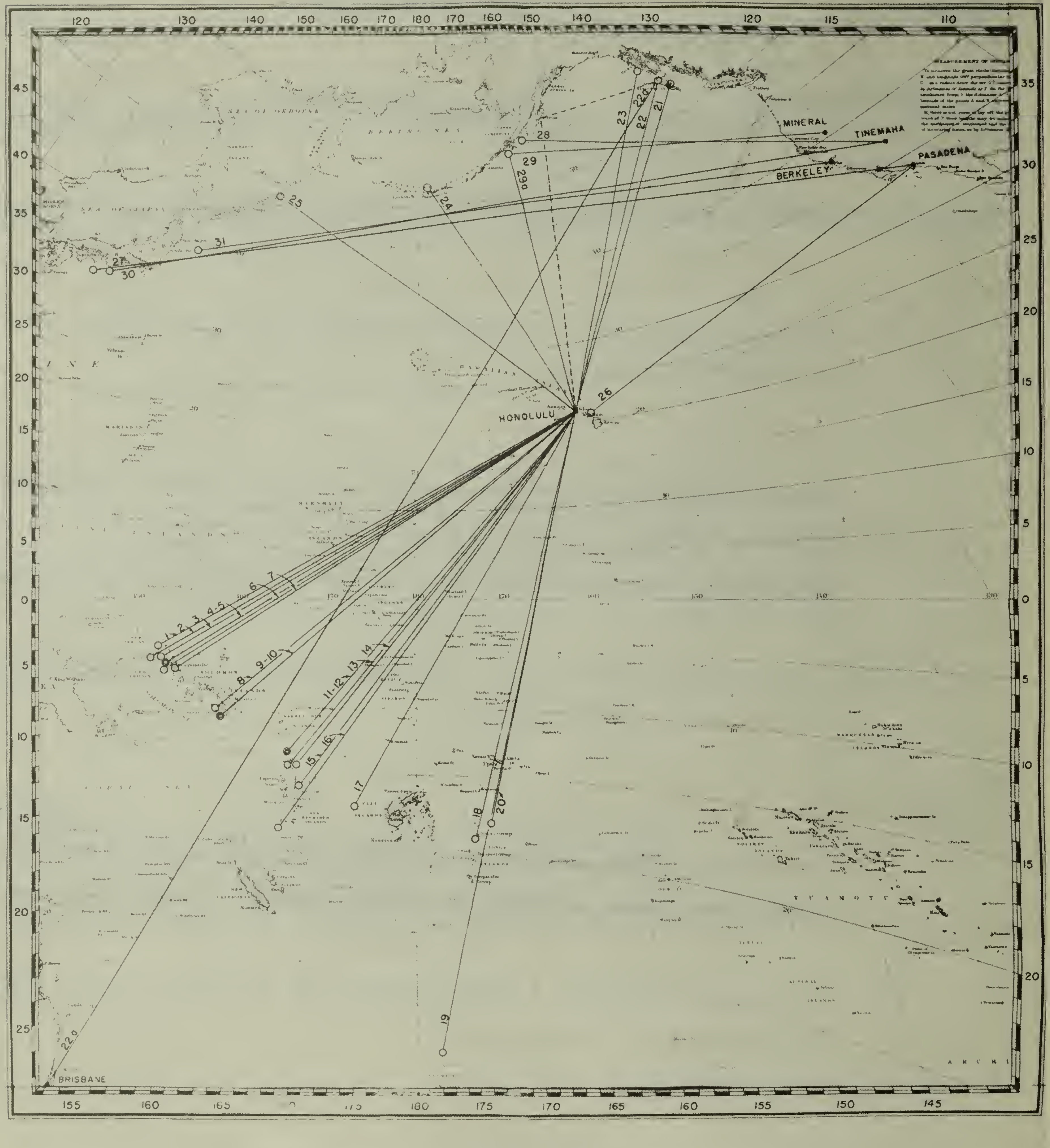


B. Dominican Republic Earthquake of 26 July 1950 08:31:28
Recorded at Bermuda



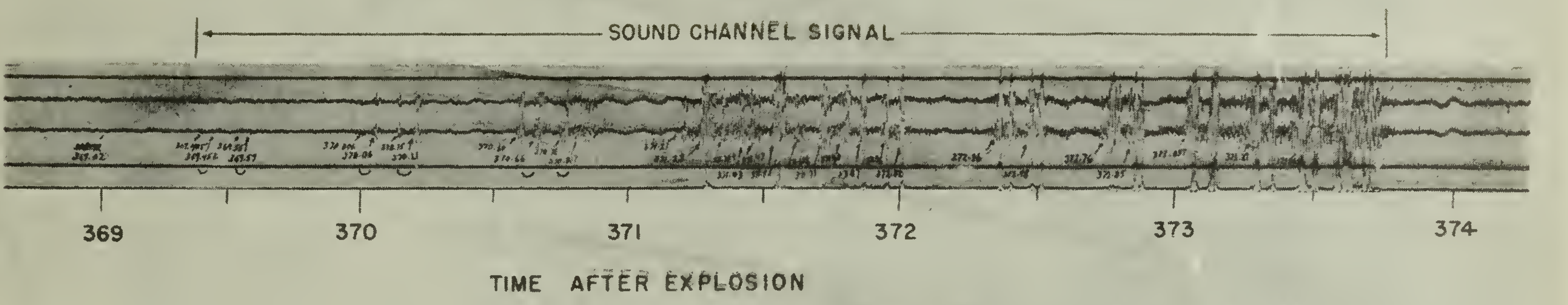
C. Solomon Islands Earthquake of 29 July 1950 23:48:58
Recorded at Honolulu

Figure 1. Typical T-Phases recorded on Seismographs



Pacific T - Phase
Recorded on Seismograph

FIGURE 2



SHOT 43° 1601 4/3/44
RECEIVED AT 25° 40' N
75° 10' W

SEISMOGRAM OF SOUND-CHANNEL TRANSMISSION AT 300 MILES
4 lb. bomb; bomb depth 4000 ft.; hydrophone depth 3600 ft.

FIGURE 3

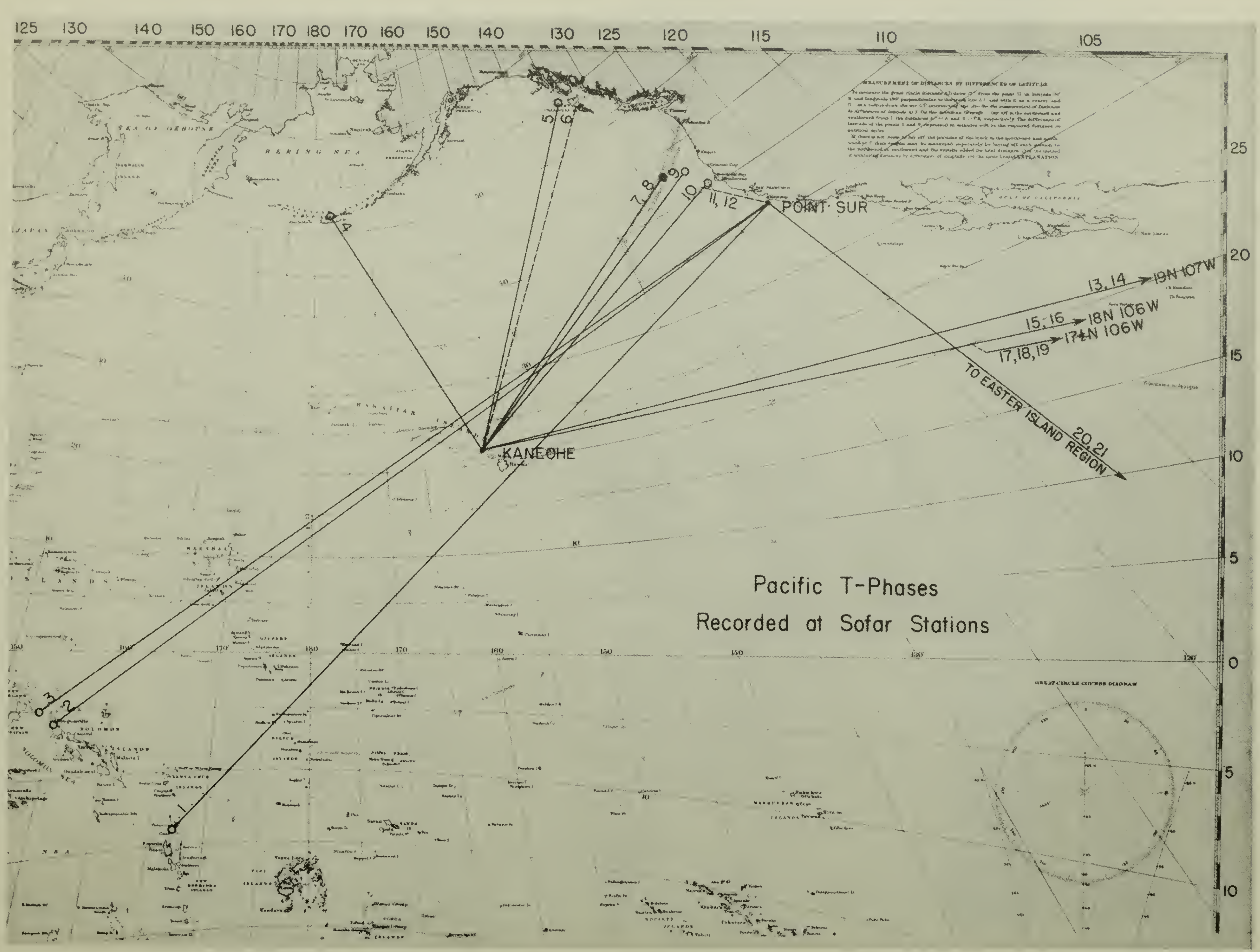
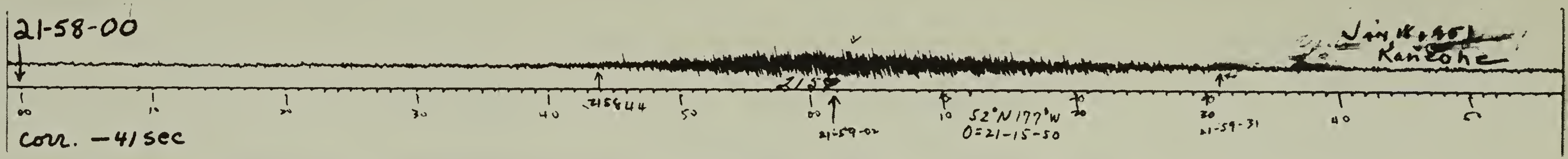
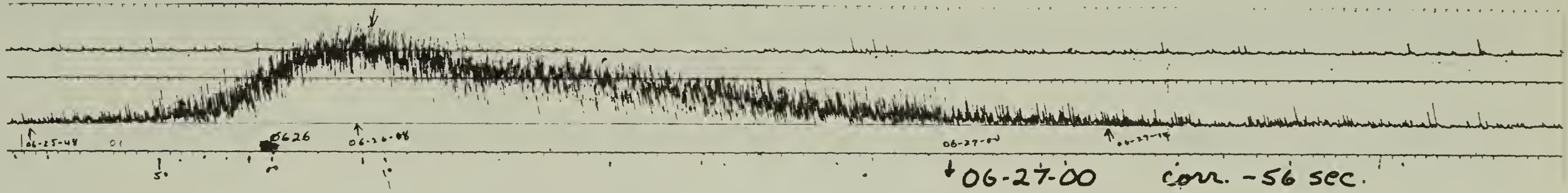

Pacific T-Phases
Recorded at Sofar Stations
KANEOHE
POINT SUR
TO EASTER ISLAND REGION
20,21
13,14
19N 107W
15,16
18N 106W
17,18,19
17½N 106W
1
2
3
4
5
6
7,8
9
10
11,12
BERING SEA
SEA OF OKHOTSK
HAWAIIAN IS.
MARSHALL
SOLOMON
SAMOA
GREAT CIRCLE COURSE DIAGRAM
125
130
140
150
160
170
180
170
160
150
140
130
125
120
115
110
105
25
20
15
10
5
0
5
10

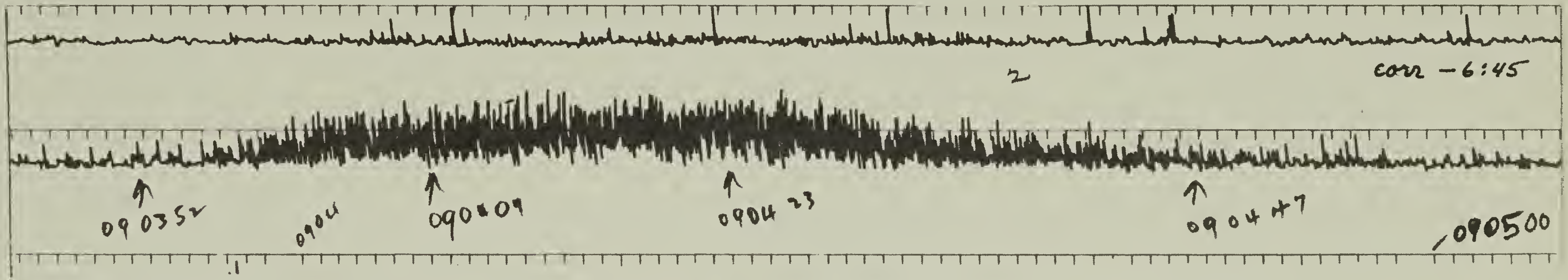
FIGURE 4



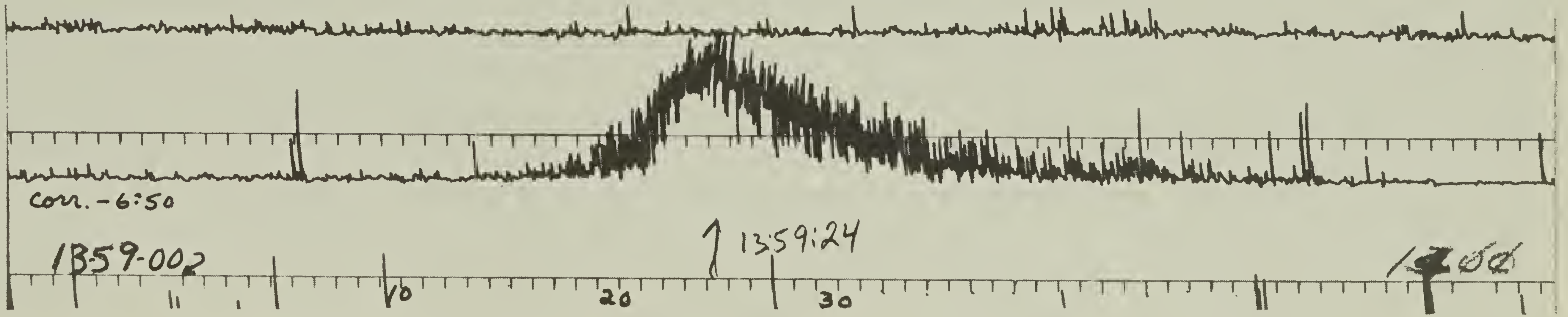
A. ALEUTIAN ISLANDS EARTHQUAKE 18 JAN. 1951 21:15:50.



B. EARTHQUAKE OFF CAPE MENDOCINO 29 JAN. 1951 05:43:47

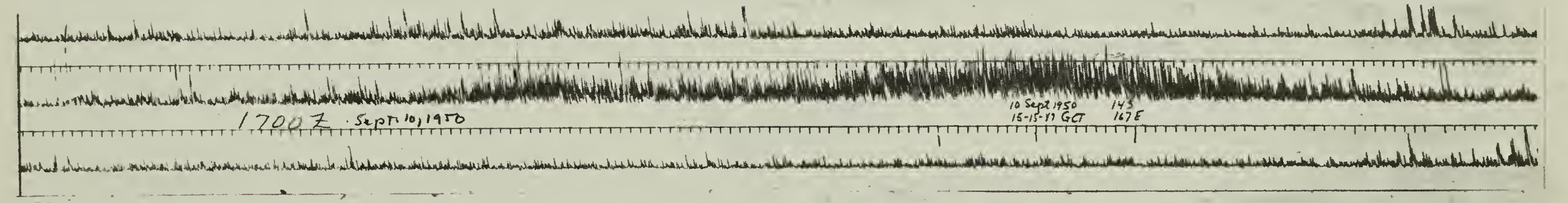


C. EARTHQUAKE OFF COLIMA, MEXICO 29 SEPT. 1950 07:54:22

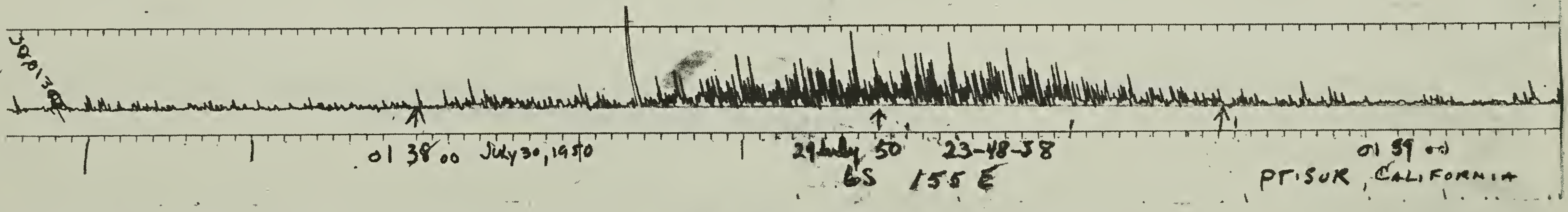


D. QUEEN CHARLOTTE ISLANDS EARTHQUAKE 1 OCT. 1950 13:06:14

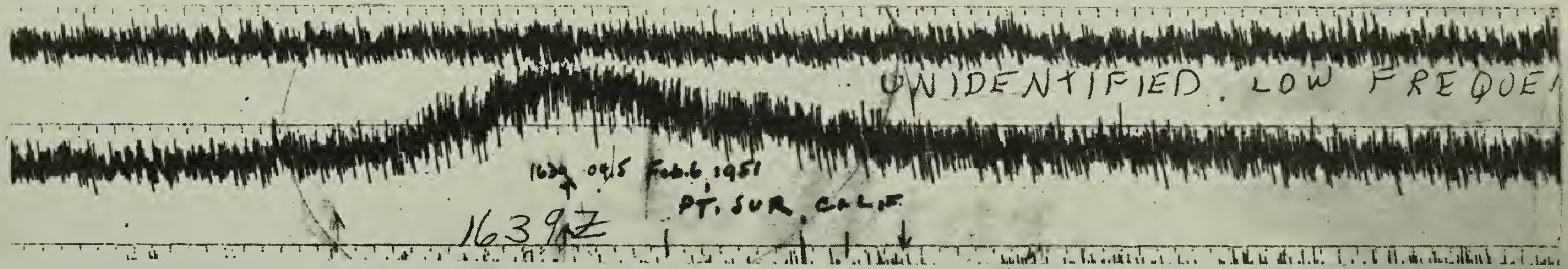
FIGURE 5. T-PHASES RECORDED AT SOFAR STATION, KANEOHE, OAHU.



A. NEW HEBRIDES EARTHQUAKE 10 SEPT. 1950 15: 15: 47



B. SOLOMON ISLANDS EARTHQUAKE 29 JULY 1950 23: 48: 58



C. CAPE MENDOCINO EARTHQUAKE 6 FEB. 1951 16:33:10

FIGURE 6. T-PHASES RECORDED AT SOFAR STATION, PT. SUR, CALIFORNIA