VELOCITY AND RAY PATHS OF SOUND WAVES IN SEA WATER.

by

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Radio Acoustic Ranging is the best method available for obtaining positions at considerable distances off shore, or when the land objects are obscured by weather conditions. The desire to improve this method and increase the limits of accuracy led to the following experiments and study of the propagation of sound waves in sea water. With the existing methods and knowledge of the ray paths the position of the vessel is obtained with an error usually less than fifty meters for distances up to fifty miles and a maximum error of four hundred meters up to two hundred miles. The main cause of errors is intervening irregularities of the sea bottom.

In all our present hydrographic surveying using R A R the apparent horizontal velocity — that is, the horizontal distance divided by the travel time of the sound wave — to each of the hydrophones is determined experimentally in various portions of the area, and as far off shore as possible, by firing bombs simultaneously with obtaining the true position by visual fixes on land objects. This method provides a close approximation to the apparent horizontal velocity at greater distances. The fundamental purpose of these experiments was to provide a practical method for obtaining the apparent velocity in deep water, and to determine the actual path over which the energy usually is transmitted. With such knowledge a satisfactory adjustment of apparent discrepancies can be made.

The first experiments for the study of the propagation of sound waves in sea water were made in November, 1933 by the surveying vessels *Pioneer* and *Guide*. (See report, "Velocity and Ray Path of Sound Waves in Sea Water" of April, 1934). These experiments definitely indicated the refraction and reflection theory. Consequently, the same two vessels conducted additional experiments in January, 1935. The general program was the same as before with numerous refinements introduced as a result of the knowledge gained at that time. One of the most important differences was that during the latter experiments accurate distances between the bomb and hydrophone were determined.

The site of the experiments was the same as for the previous work. (Fig. 1). In the deep water tests (1000 fathoms over the entire distance between bombs and hydrophones) electric bombs were fired near the surface and at depths for distances from the hydrophone varying from 4 to 75 km. with the bombing vessel stationary, and the fuse bombs from 4 to 86 km. with the bombing vessel underway. In the deep to shoal water tests the program was similar but tests were made over a maximum distance of about 46 km. Shoal to deep water tests, that is bombing in shoal water (20 fathoms) with hydrophone at 30 fathoms where the water was 1000 fathoms deep, were carried out with distances varying from 3 to 36 km.

During the deep water tests one hydrophone was lowered to 30 fathoms and one to 390 fathoms. A supplementary test was made where bombs were fired at various depths to 800 fathoms with the deep hydrophone at the same depth as the bomb. Positions of the bombs and hydrophones were obtained by four observers with theodolites and radio transmitters and receivers stationed on Santa Barbara, San Nicolas, and Santa Cruz Islands.

For those who do not care to go into the detailed discussion of the experiments and the results, the Summary, Interpretation, and Recommendations as applied to R A R are given in the first part of the report as follows :

SUMMARY

The velocities as given in the British Admiralty tables are correct (or less than 0.2% in error). Fig. 6.

The sound wave traveling through sea water is refracted and reflected and for short distances may suffer diffraction. See Fig. 31.

The sound traveled direct from the bomb to the hydrophone for only a very short distance. Its amplitude faded out rapidly with distance. Figs. 7, 16, 26, 27, 32.

Sound arriving at the surface hydrophone at distances greater than 20 km. (through a constant depth of water of 1000 fathoms) had been reflected one or more times from the sea floor. Sound reflected once from the bottom was observed to a maximum distance of 73 km. in the all deep water tests, but the last 35 or 40 km. of travel depended on diffraction. Improvements in the reliability and accuracy of R A R in deep water rests on a full knowledge of this effect. Figs. 7, 8, 26.

Some energy from a bomb fired at 30 fathoms traveled along a narrow constant velocity layer at 100 fathoms and reached a near the surface hydrophone at distances up to 17½ km. Fig. 12. A similar wave from the near the surface bomb along the 400 fathom layer was not observed at the surface hydrophone. With bomb and hydrophone at 100 fathoms a wave that apparently traveled along the 100 fathom layer was recorded at 26½ km. The first arrivals at a hydrophone 400 fathoms deep, from bombs exploded at that depth may have traveled along the 400 fathom layer as far as 56 km., but other interpretations also satisfy these data.

The apparent horizontal velocity (See definition above) of sound in the open sea is a discontinuous function of the distance, the magnitude of the discontinuities depending on the bottom profile, depth and size of the bombs, and sensitivity of the hydrophone. With decreasing depth of bottom, or, increasing bomb size the magnitude of the discontinuities decreases and may become negligible under certain conditions. With a uniform depth of about 1000 fathoms between the bombs and hydrophone, a drop of 14 meters per second in the apparent velocity occurred at a distance of 45 km. with 4 ounce bombs (Figure 27); when the bomb charge was doubled, (½ pint bombs), a change of 11 meters per second was observed at 57 km. The two types of bombs were not fired at exactly the same depth, which may have had a small effect. A more spectacular discontinuity occurred at short distances where direct waves died out. See Figures 24, 26, 27.

The mean velocity between 30 and 1020 fathoms obtained in the experiments agrees within a few meters per second with the theoretical. A wave was observed with an instantaneous velocity practically equal to the theoretical velocity at about 100 fathoms. The instantaneous velocity of the direct waves is practically equal to the average theoretical velocity from the surface to 25 or 30 fathoms.

A high initial velocity is indicated. (By the travel time curve of the direct wave not going through the origin. Fig. 11, 13, 22).

The underwater explosions acted as a multiple source, that is there seemed to be several impulses sent out. The reason was not established by the experimental data. The first impulse generated was as strong as the later ones.

Frequencies from 100 to 2000 hertz were observed with the 100, 200, 450, and 550 predominating. These frequencies may have been inherent in the apparatus although there is a suggestion that 200 was actually present in the bomb noises. (Blasts set off in rock are said to set up a very narrow range of rather low frequencies). The ability of the bomb noises to induce or set up the higher frequencies in the recordings showed a marked decrease with distance, the tendency being greater for the smaller bombs. Fig. 33 and 33A.

There is good evidence for dispersion of frequencies since the direction of the first motion of several waves showed a gradual change in sign. This would necessitate the presence of more than one frequency in the wave trains. Fig. 15. (See also Trace Amplitudes — Deep Water Tests).

The trace amplitude curves of the reflected impulses show a maximum at the distance at which the tangent ray is received due to the focusing action of the vertical velocity distribution. Fig. 17, 18.

The maximum distance diffraction as detected for direct waves was much less than that for the reflections (about 12 and 40 km. respectively). The only reasonable explanation is that the energy was carried mainly by high frequencies near the source and by lower frequencies at a distance. It has already been remarked that the tendency of the higher frequencies to record decreased with increasing distance. Diffraction effects are theoretically more pronounced at low frequencies than at high frequencies.

With the hydrophone at the head of a steep slope, zones of silence were observed. Fig. 32, 21, 22, 23, 24, 29. The area at the foot of the slope was flat and the horizontal distance along the slope was about the same as for one leg of the tangent ray, (i. e., the distance between grazing the surface and reflecting from the bottom). Fig. 3. This profile gave rise to a travel time curve that was not affected appreciably by the presence of the slope.

A variable increase in the travel time as much as 0.2 second was observed several times at one distance in the deep to shoal water tests, apparently due to irregularity of the bottom.

Plotting of log readings against chronograph times is of value in determining sharp changes in apparent velocity when the vessel is holding a straight course cutting sharply across the distance arcs.

The R A R chronograph had a negligible small daily rate but showed a variation as high as .04 second in 10 seconds. It was not determined whether this was periodic.

The velocity of sound in the water soaked mud floor of the Santa Barbara Islands Basin may be about 1580 meters per second.

The travel time curves of the impulses that operated the chronograph can be represented by the equation.

$$t = \frac{s}{v} + c; \quad \text{or } s = v\ (t - c)$$

when t = travel time

s = distance

v = the surface velocity

c = parameter (time interval between the arrival of PD, PR_1, PR_2, etc.)

The theoretical velocity computed from bottom temperature and salinity can be used for the apparent horizontal velocity down to depths of 250 fathoms.

INTERPRETATION

Any method of utilizing R A R travel times for the plotting of fixes must be simple and rapid to be of practical value. A variable increasing and decreasing velocity must be taken into account, the amount and rate of variation depending on the temperature and salinity curves, and the depth and uniformity of the bottom. It must also be borne in mind that occasional discrepancies which cannot be evaluated will occur (as for example at 35 km. in the deep to shoal water tests where a delay of 0.2 second was observed in the arrival of PR-1.).

From the standpoint of R A R the first arrival that has sufficient amplitude to operate the shore station transmitter is the most important. The change in path of the first arrival with distance is shown in Fig. 31. The bottom is assumed to be level, and the numerical values that follow were obtained from the deep water tests which were carried to a much greater distance than were the deep to shoal water experiments. A wave that traveled a more or less direct path from bomb to hydrophone was observed to a maximum distance of 20 km. Its amplitude dropped sharply at about 8 km. showing that it reached greater distances by diffraction. After it faded out, PR-1, the next first sound to arrive, had been reflected once from the bottom. To a distance of 35 to 40 km. this was a true reflection, but its transmission to greater distances depended on diffraction, and the diffracted PR-1 was observed to a distance of approximately 73 km. but recorded on the chronograph to only 56 km. PR-2 was a true reflection to 61 km. after which it was also diffracted. The attenuation of the reflections is due to the curvature of the ray paths which was discussed in some detail in the report of the November, 1933 experiments in Santa Barbara basin.

In the deep to shoal water tests where bombs were fired in deep water and the hydrophone was in shallow water (as in actual R A R) the general results were the same, but a zone of silence was introduced by the presence of the slope. (See Fig. 19). It is thought that the zone of silence could have been crossed successfully by diffraction through the use of more powerful bombs. It is important to note that outside of the zone of silence the travel times were unaffected by the presence of the slope. If the horizontal travel of the tangent ray between grazing the surface and reflection from the level part of the bottom approximates the distance from the foot of the slope to the hydrophone, as was the case in Santa Barbara Basin, the travel time curves along the profiles should have the same general characteristics as those of the experiments.

The chronograph travel time curves are approximately parallel lines, excepting the interval between the fading out of the direct (PD-1) and the beginning of diffraction effects in PR-1. (Figs. 7, 8, and 19). The reciprocal slope of the straight lines is the velocity of the direct wave. The reason for this is evident in that the diffracted portion of the path is the same regardless of number of reflections that have occurred. (Fig. 31). It is proposed to utilize this parallelism in the plotting of R A R positions.

The equation of the straight portion of the travel time curve may be written : (See Figs. 7, 8, 19).

$$t = \frac{s}{v} + c, \text{ or } s = v\,(t-c).$$

Where *t* is the travel time;

s is the horizontal distance;

v is the velocity of the direct wave;

c is a parameter.

v usually can be obtained experimentally by measuring the velocity to short distances from the hydrophone; however, the accuracy in timing ordinarily available renders such determinations somewhat uncertain. An empirical rule for *v* suggested by the experiments is to use the average theoretical velocity of the upper 25 or 30 fathoms. The times arcs on the hydrographic sheets would of course be drawn with this *v* velocity, and then *c* subtracted from *t* in plotting the positions. (Using each hydrophone as a center, arcs are drawn on the sheet at regular intervals equal to the distance the sound wave will travel in five seconds assuming a certain velocity).

Under favorable conditions, *c* for the change from first reflection to second reflection can be determined experimentally if a visual fix can be obtained in the PR-1 diffraction interval. *c* is then the measured travel time less the quotient $\frac{s}{v}$

If the bottom is reasonably level, *c* for PR-2 will be twice *c* for PR-1. Therefore if both PR-1 diffracted, and PR-2 are recorded on the chronograph tape in the region in which PR-1 fades out, the time interval between is *c* for PR-1 and ½*c* for PR-2 It is strongly recommended that the apparatus be arranged so that second arrivals can be recorded and this is one of the reasons why a hydrophone with high damping is desirable. The amount to be added to *c* as the various reflections fade out then can be measured.

c can be computed to a good degree of accuracy if the vertical velocity distribution is known. It is (for PR-1) the travel time along the tangent ray between two successive intersections of the surface less the travel time along a horizontal path at the near surface velocity *v*. A method of computing the travel time along a refraction path was given in the report of the November 1933 experiments. This method assumes a spherical earth but the computations are not simplified nor lessened by assuming a flat earth. The value of *c* is not materially affected by small errors in the near surface velocity distribution.

Computing *c* in this way using Table III of the 1933 report and 1500 m/sec for the velocity of the direct wave as observed in the deep to shoal water experiments of January 1935 (Fig. 24) gives a value for *c* (PR-1) of 0.35 second for a depth of 1020 fathoms, within .01 or .02 second of the observed average value. The same computation for the deep water tests of January 1935 (using the observed velocity of the direct of 1495 m/sec), gives 0.28 second against an observed 0.24 second. (Fig. 26).

The foregoing discussion applies when the velocity-depth curve has a minimum below the surface. It is only in this event that the rays are bent downward at depths above the velocity minimum. With the velocity minimum at the surface the rays would be bent upward by refraction but the distance to which a given reflection could be observed would still be limited by refraction curvature. It is very likely that if the velocity increased steadily with depth from the surface down, the travel time curve of the first arrivals would be quite smooth and continuous and that no sudden large changes in apparent velocity would occur. In high latitudes the velocity depth curves might have a minimum at the surface during the winter months and this should be considered when sound ranging in deep water in such areas is contemplated. It has already been observed * that the range of under water signals is greater during the winter months than during the summer which is another reason for preferring the colder seasons for R A R when other factors are favorable.

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* See *Unterwasserschalltechnik,* F. Aigner (Berlin, 1922).

The reason why a constant velocity is successful in sound ranging in shallow water may be seen from the following rough calculations.

A horizontal bottom is assumed and a decrease of velocity with depth.

The equation of the travel time of the first arrivals is taken as

$$t = \frac{s}{v} + nc$$

c, being the constant for PR-1 and n the number of reflections that the first arrival has undergone from the bottom. The numerical values are taken from Table III of the November 1933 report and a depth of 150 fathoms is assumed. c, then is 0.04 second. The tangent ray travels 5.6 km. between grazings at the surface so n may be written $n = \frac{s}{5.6}$ with a maximum error of .04 second.

$$\text{Then } t = \frac{s}{v} + \frac{.04\,s}{5.6} = s\left(\frac{1}{v} + \frac{.04}{5.6}\right)$$

$\frac{ds}{dt} = \frac{5.6\ v}{5.6 + 0.04\ v}$ = 1.484 Km/sec since v is approximately 1.500 Km/sec.

Using a velocity of 1484 m/sec introduces a maximum error of .04 second or a displacement of the distance arc of 60 meters in this particular case.

It appears that R A R will always have slight errors which it may be impracticable to determine in areas of rough sea bottom, and if the velocity of sound decreases with depth near the surface. In special cases, when there is a constant velocity layer, good results may be obtained to comparatively short distances by utilizing the propagation along such a layer. Bomb and hydrophone would need to be lowered to this depth to obtain the best results. The possibility of constructing bombs that would explode at a predetermined depth opens the way for bombing of this type if the need arises. It is not known how general the distribution of such constant velocity channels is, but it could be easily determined from the temperature and salinity data available.

It also can be shown why the theoretical velocity for bottom temperature and salinity for depths less than 250 fathoms approximates the observed apparent velocity. For a depth of 150 fathoms the horizontal distance between two successive surface tangents of the ray as given in Table III of the November 1933 report, is 5.60 km. The theoretical travel time, same table, was 3.78 seconds. 5,600 m/3.78 sec = 1,482 m/sec. The theoretical velocity for bottom temperature and salinity (Figure 11 of same report) was 1483 meters per second.

For 225 fathoms the theoretical bottom velocity was 1482 and the theoretical apparent velocity 1478. For 400 fathoms the theoretical bottom velocity was 1480 and the theoretical apparent velocity was 1471. This shows why the bottom velocity does not apply for the greater depths, which is consistent with actual field experience.

Distance and Travel Time to Point of Reflection of Ray Horizontal at the Surface (From Table III and Fig. 11 of 1933 Report)

Depth (Fms)	Travel Time (Sec)	Horizontal Distance (Km)	Velocity at Depth Indicated
0	0	0	1502
15	.7690	1.1553	1501
30	.9611	1.4413	1489
50	1.1250	1.682	1485
90	1.433	2.134	1483
150	1.888	2.799	1483
225	2.445	3.613	1482
400	3.699	5.442	1480
500	4.403	6.469	1480
930	8.067	11.846	1494
1000	8.873	13.057	1496
1233	14.576	21.606	——

RECOMMENDATIONS FOR R A R

When there is a choice, the hydrophone should be situated at the head of the steepest slope available. It is also desirable to have the hydrophone as far out as possible, preferably on the shoulder of the slope, if steep, (unless, of course, this introduces an undesirable bottom profile between the hydrophone and the area to be surveyed, such as ridges or submarine valleys, which can be avoided by a different location of the hydrophone).

The data suggest that there may be a decided advantage in having a hydrophone and amplifier particularly sensitive to the lower frequencies. Hydrophones with low frequency diaphragms are undesirable because of the persistence of the diaphragm vibrations, especially when loaded with a unit. A hydrophone with rigid walls and lighter than the water it displaces may be a satisfactory solution. Such a hydrophone would move with the water and there would be no dependence on diaphragm vibrations. In fact it would not be necessary to mount the unit on a diaphragm face. It is very difficult to damp low frequency hydrophones successfully, but comparatively easy to damp the units. A light body hydrophone, say an ebonite sphere, with rigid walls and large enough to be buoyant is suggested. The body of the hydrophone would move with the water and diaphragm vibration could be eliminated by the design. The unit should not have pronounced directional qualities because of the difficulty of keeping a submerged buoyant hydrophone oriented. Further investigation of the frequency characteristics of bomb noises is necessary and may indicate the desirability of a narrow band pass filter in the amplifier circuit.

It is very desirable to arrange that radio returns of the second and later arrivals be recorded instead of having the radio dash, started by the initial impulse, continue until stopped manually. This would furnish a direct measurement of corrections to be applied at the fading out of the previous first arrival.

Chronometers should be tested for uniformity of rate over short intervals of time by comparison with radio time signals on the chronograph.

The shore station equipment should be so designed that the lag is reduced to a negligible quantity.

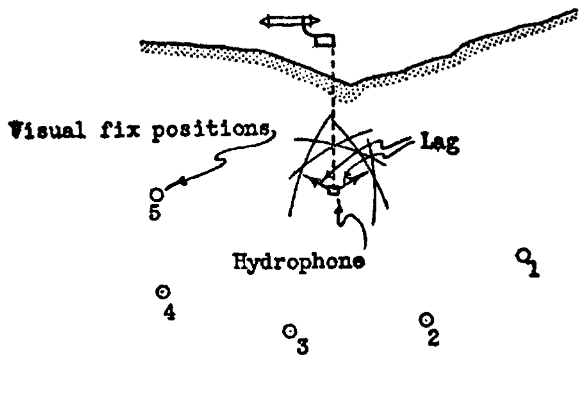
No less than three shore stations should be used in order that good intersections may be obtained as well as a check or a triangle of error. If only two stations are established, the intersections of their arcs may be in error as much as one mile.

A long area of shoal water between the hydrophone and bomb will materially decrease the effective distance R A R can be carried from that station.

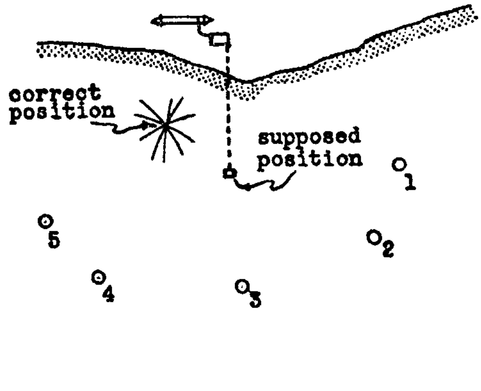
The operators should report after each bomb whether the first of the sound train actuated his transmitter; that is, if he heard the sound before it operated his transmitter; or, in other words, if there was a build-up in the amplitude before his transmitter operated. This will give the hydrographer valuable information on the velocity to be used. When the operator can hear the sound coming, so to speak, it means that there is a change taking place in the path of the first arrival at the hydrophone. The diffracted wave is fading out before the arrival of the reflected wave. This lag should be from two to four tenths of a second depending upon the distance and the depth of the intervening water. When the operator reports a short interval during which amplitude increases, a larger bomb may often overcome the difficulty.

The surveying vessel should obtain good velocity tests three or four miles distant from the hydrophone to measure the velocity of the direct ray. The hydrophone should be encircled with a series of velocity tests at a distance of about one mile. If R A R distance arcs drawn from the visual fixes as centers, pass behind the position of the hydrophone, using the theoretical velocity for the 10 or 15 fathom layer, the distance from the hydrophone to the arc will be a measure of the total instrumental lags. (See Sketch A). If the arcs intersect at a point other than the plotted position of the hydrophone, the point of intersection will be the true position of the hydrophone. (Sketch B).

During R A R hydrography the run between bomb positions should be plotted as accurately as possible by course and log or engine revolutions. When the R A R arcs do not check the dead reckoning between bomb positions, a change in the apparent horizontal velocity should be suspected for one of the distances.



Sketch "A"



Sketch "B"

GENERAL DESCRIPTION OF THE EXPERIMENTS

APPARATUS USED

The underwater sounds were received by non-directional hydrophones having Utah loud speaker units attached to the inside center of one diaphragm. After vacuum tube amplification, the sounds were photographically recorded by a two string oscillograph, one string connected to the shoal hydrophone and the other to a deep type hydrophone as described in the report covering the November, 1933 experiments.

Two amplifiers were used, one connected to each string of the oscillograph. The amplifiers were calibrated in decibels and full amplification was seldom necessary. Unfortunately it is not known whether the connections in the electrical circuit between the hydrophones and oscillograph were always made in the same way, so it is not possible to correlate the diaphragm motion with the direction of trace motion throughout the experiments. It is almost certain that the "direction" of the electrical connection was different at various times. The amplitudes on the oscillograph records can, however, be reduced to a common standard for direct comparison due to the calibration of the amplifiers. It was found that the A amplifier had about 2.5 decibels more gain than the B amplifier. The A amplifier recordings are the lower traces on the oscillograms; the B amplifier recordings are the upper traces.

Travel times were measured by an R A R chronograph and surface hydrophone, with time marks every second on the chronograph and with time marks every .01 second on the oscillograph.

The oscillograph time units were marked by a synchronous motor operated from a tuning fork. The apparatus is the same as that used last year with the exception of the amplifiers. During part of the deep water tests the spool of sensitive paper in the oscillograph was turned by a small motor. Usually, only fractional seconds were measured on the oscillograph, i. e. it was turned off between the arrival of the initial and the onset of the bomb noises to save photographic paper.

HYDROPHONES

During the experiments in the Santa Barbara Islands Basin three hydrophones were used, all equipped with small Utah units.

The near surface hydrophone was a cast aluminum pot. It has a 7-3/4" (diameter) diaphragm, 1/4" in thickness. The fundamental frequency as measured in air with the Utah unit in place is about 1250 hertz. The theoretical frequency* in air without the unit is 1700 hertz. Considering the entire weight of the unit as effective in reducing the fundamental frequency, it is theoretically 840 hertz with the unit in place. It is concluded that the entire weight of the unit is not effective. This is not surprising because of the flexible connection between the diaphragm and the main mass of the unit.

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* *Wood, A. B., A Textbook of Sound, p.* 158 (*Macmillan Co.,* 1930).

If the frequency of the diaphragm is very high in comparison with that of the Utah unit when the latter is clamped by the pin, the effective mass of that part of the unit not connected rigidly to the diaphragm would be expected to be very small. The entire weight of the unit should be effective when the diaphragm frequency is low in comparison with that of the unit. The frequency of the aluminum pot in water was not measured. As the frequency is lowered by immersion, the effective mass of the unit is increased by an unknown amount. Since the effective mass of the unit will have a value between that in air and the total mass of the unit, an upper and lower value of the frequency in water can be set. Therefore, the fundamental underwater frequency of the aluminum pot hydrophone with unit should be between 640 and 675 hertz.

The characteristics of the deep sea hydrophone used for bombs Nos. 437 to 465 inclusive were not determined. The deep sea hydrophone used the rest of the time was identical with the one described in the report of the November, 1933, work. Its fundamental frequency in air with the unit is 300. Low frequency diaphragms are probably seriously distorted by the turning moment of the suspended unit so that the theory would not apply. The fundamental frequency is lowered by immersion in water. The underwater fundamental is estimated to be, very approximately, 230 hertz. (See also "observed frequencies" this report).

PROCEDURE

The following procedure is typical for electric bombs :

The changes for fuse bombs are sufficiently obvious to need no comment.

Wireless signals were sent by the Guide 60, 30 and 15 seconds before the explosion. About ten seconds before the firing switch was thrown, the chronographs on the Guide and Pioneer and the oscillograph on the Pioneer were started. At the firing dash the observers at the triangulation stations cut in the Guide. The oscillograph was stopped after a firing dash recorded and started again about 5 to 10 seconds before the arrival of the sound at the hydrophones, the approximate travel time being known. The arrival of the sound operated the Pioneer's radio transmitter which was recorded on the Guide and also served as a signal for the triangulation observers to cut in the Pioneer. As previously stated the instant of the explosion was thus recorded on the Guide's chronograph and on the chronograph and oscillograph on the Pioneer, and the arrival at the surface hydrophone was recorded on all three instruments, and the arrival at the deep hydrophone on the oscillograph. No manœuvering of the Pioneer occurred from 30 seconds before the explosion until after the oscillograph was finally stopped.

TESTS OF EQUIPMENT

The following results of the tests of the equipment are reported by Dr. C. G. McIlwraith :

1. There is no lag larger than .001 second between recording of sound on oscillograph and start of plate current in ship's transmitter.

2. There is a time of about .003 to .004 second during which the current through the coil of the Pioneer's chronograph builds up. The pen marks some time towards the end of that period, usually about .002 to .003 second after start of current in coil.

3. The A amplifier has about 2.5 decibels more gain than the B amplifier.

4. The two contacts of the Guide's Leach relay close within .002 second of each other, the left one being the later. The left contact opens about .006 second before the right contact. Right contact of Leach firing relay to Guide's transmitter; left to bomb.

5. The marking pen of the Guide's chronograph is operated by application of 67 volts across the magnets, takes .04 to .06 second to make its mark, the mean being .05 second. It returns in about .002 second after the current is off.

6. Two measurements on electric detonators give lags of .004 and .006 second between the application of 110 DC to the detonator and the rupture of a wire wrapped around the detonator.

7. The aluminum hydrophone in air has a resonant frequency of about 1300 hertz.

8. The diaphragm and small unit for the deep hydrophone have a frequency in air of about 240 hertz; with the hydrophone head clamped on the frequency is 300 hertz.

9. The Pioneer's transmitter shows a lag of .024 to .028 second between start of plate current and start of radio frequency current when tuned for maximum output. When slightly detuned the lag is .017 to .020 second. With another crystal the lag was .003 to .005 second.

10. The shore station transmitter used at Laguna and Santa Cruz has a lag not more than .003 second in radio frequency output.

11 *. When clamped by the pin and tapped on the body the small unit has a frequency of about 160 hertz, and the large unit 150 hertz. The small unit also has another frequency of about 850 hertz.

CALIBRATION OF TUNING FORK

The tuning fork was compared with the R A R chronometers and the chronometer with the radio time signals from Mare Island. In both cases comparisons were made on the chronograph, over a period of 4 to 9 minutes. The daily chronometer rate was also determined and found to be very nearly zero. However, the rate over small intervals was found to be quite variable as the following table shows.

Comparison of Timing Chronometer With Mare Island Time Signals

2 / 7 / 35		1 / 8 / 35		3 / 8 / 35	
Chronometer (seconds)	M.I. Signal (seconds)	Chronometer (seconds)	M.I. Signal (seconds)	Chronometer (seconds)	M.I. Signal (seconds)
0	0.52	30	30.42	0	0.77
15	15.515	35	35.41	60	60.77
31	31.515	40	40.40	70	70.765
45	45.515	41	41.40	80	80.765
54	54.51	42	42.39	90	90.76
60	60.51	43	43.39	100	100.76
61	61.497	44	44.385	109	109.745
62	62.495	45	45.385	110	110.75
63	63.49	46	46.38	113	113.74
64	64.49	47	47.38	114	114.74
65	65.485	48	48.38	120	120.735
66	66.485	75	75.375	121	121.735
67	67.485	90	90.38	122	122.735
68	68.48	150	150.39	123	123.735
69	69.475	210	210.41	180	180.73
70	70.47			240	240.73
80	80.47			250	250.73
91	91.47			260	260.725
100	100.47			280	280.73
120	120.47			285	285.73
140	140.465			286	286 725
160	160.465			287	287.725
180	180.46			288	288.73
200	200.46			289	289.73
220	220.46				
240	240.46				
260	260.46				
289	289.46				

The above readings were made on the chronograph tapes starting from an arbitrary zero.

* *Dr. Dyk made the following measurements of this test of the small unit — The dominant frequencies were* 150 *to* 500 *hertz.* 1100 *was generally superposed, particularly on the* 150. 600 *occurred in one place.*

The maximum rate over a time interval comparable with the time intervals used during the tuning fork calibration is 22 seconds per day or .00025 second per second. A rate of .004 second per second does occur in one ten second interval but this is not sustained nor frequent and the sign apparently changes with time.

The tuning fork calibration curve is probably correct to .0002 second per second but errors in the chronograph tape time of around $\pm$ .004 may be expected.

THEORETICAL VELOCITIES

Since one purpose of the experiments was to check the theoretical velocities, complete serial temperatures and salinities were obtained. One hundred forty eight temperatures and forty one salinity observations were made by the two vessels during the course of the work, affording excellent material for the calculation of the theoretical vertical velocity distribution. The temperature and salinity curves are shown in Figures 4 and 5 and the theoretical velocities taken from the British Admiralty Table * in Figure 6. The full line curve was used for the computation of theoretical ray paths. The distribution has the same characteristics as that obtained in 1933, with constant velocity layers at 100 and 450 fathoms and, in the present case, at the surface. Although the near surface temperatures are subject to variations, it is probable that the theoretical velocity was very nearly a constant in the upper 15 fathoms throughout the experiments.

DEPTH OF WATER

Two lines of soundings were run to supplement the depths obtained by previous hydrographic surveys. The profiles of these lines are shown in Figures 2 and 3. Slightly greater depths were found than are indicated by the chart of the area.

TRAVEL TIMES — DEEP WATER TESTS NEAR SURFACE BOMBS AND HYDROPHONES

The travel time curves obtained on the deep water tests are shown in Figures 7 and 8. On all the diagrams the points plotted vertically over each other are arrivals from the same bomb, and the curves are observational. The nomenclature is the same as previously used with the exception of PD which was not observed in 1933. The P indicates a compressional wave, D a direct path, and R reflection. When the bomb and hydrophone are near the surface, only one numeral follows "PR" and it indicates the number of times reflection from the bottom has occurred. When either or both bomb and hydrophone are at an appreciable distance below the surface two numerals follow the "PR"; the first indicates the number of reflections from the bottom, and the second the number from the surface.

The identification of reflection paths rests on the travel times. The travel time of PR-1 at any distance should be about half that of PR-2 at twice the distance, about one-third that of PR-3 at three times the distance, etc. The same holds for the reduced travel times. By reduced travel time is meant the travel time in seconds minus the quotient, distance in km. divided by 1.5. This is a device to secure a more open time scale for the diagrams. It has the advantage that impulses separated by only a few thousandths of a second can be shown. It should be noted that straight lines on the travel time curve are also straight lines on the reduced travel time curve. In Figure 9 the reduced travel times of PR-1 are compared with one half the reduced travel time of PR-2 at twice the distance and the comparable times of the other observed reflections. The comparison is not carried beyond 30 km. for PR-1 or much beyond 60 km. for the other reflections to avoid serious complications due to curved ray paths or changing depth of the bottom. The check is excellent considering the variations in the depth of the bottom and the fact that the bombs and hydrophones were not directly at the surface, and the probable high velocity near the bombs. (To be discussed later).

A striking feature of the travel time curves is the absence of the multiple reflections at the shorter distances. Very often the oscillograph was stopped too early to record the later reflections even if they were strong enough to record. Records 431 to 434 inclusive,

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* *Table of the Velocity of Sound, etc., HD 282 Hydrographic Department (British) Admiralty* 1927.

at distances of 20.9 and 23.3 km. show no trace of PR-4 at the expected time. At 26.9 km. one record, shows no evidence of a PR-4 while it was feebly recorded on another. All were electric four ounce bombs. At greater distances PR-4 was always recorded when the oscillograph was run for the necessary length of time. PR-5 was not very well recorded at any distance. The shortest distance at which it was observed is 37.5 km. but it does not appear on many of the records even at greater distances.

The absence of PR-4 and PR-5 at the shorter distances must be due to the transmission of a large percentage of energy into the material at the ocean bottom. Since they were recorded at some distances, they should have been recorded at all distances at which total reflection occurred. The minimum distance at which they were recorded should give an emergence angle equal to or greater than that for total reflection, in other words a maximum value of the velocity of compressional waves in the material on the ocean floor. Since PR-4 was observed first at 26.9 km.

$$\text{Tan } e_{max} = 1/3$$

$$\text{or} \quad e_{max} = 18^\circ$$

which by Snell's law gives a maximum velocity of 1580 m/sec. in the material underlying the water. This is the value at the boundary. Velocities of this order have been reported for water soaked sand.

More important from the standpoint of R A R is the failure of PR-1 to record beyond certain distances due to the curvature of the ray paths. It was observed on the oscillograph to 51.6 km. with four ounce bombs and to 73 km. with 1/2 pint bombs. (Four ounce bomb contained about one half the amount of TNT of the 1/2 pint bomb). In both cases PR-1 becomes very weak and the duration on the record is reduced from the order of tenths of seconds to about a hundredth of a second. The greatest distance at which it recorded on the chronograph is 45 km. and 55 km., respectively.

The maximum distance to which PR-1 should travel without diffraction effects is difficult to predict even though the theoretical velocity distribution is known for any particular condition since this distance depends very greatly on the near surface velocities which are constantly changing during the day. For example, if the velocity in the upper fifteen fathoms were constant, due to the earth's curvature a ray starting horizontally at a depth of 15 fathoms would travel approximately 18 km. before reaching the surface; if the velocity decreased 2 m/sec. from the surface to 15 fathoms, the maximum horizontal travel between the surface and the fifteen fathom level would be only 1 km.

The data of Figs. 7 and 8 are plotted on a more open time scale in Figure 10 where the ordinates are travel time less distance in km.: 1.500. The early arrivals at distances less than 21 km. are not shown in Fig. 10 but are shown separately in Fig. 11.

There is a clearly marked tendency for the waves from the 1/2 pint bombs to occur in groups of three, the intervals between being very nearly .10 second. (See Fig. 10). For example they were observed in the first reflection at 9.3 km. and in the second and fifth reflections at 59.5 km.

In addition a beginning was often observed at .03 second after the first one in the groups of three. The intervals are independent of the distances and the number of reflections that have occurred and of the depth of the hydrophone. The latter fact can be seen in Fig. 13 and is the final proof that the source of the multiplicity is in the explosion and not due to difference in paths. The repetition of the intervals from bomb to bomb indicates a very striking uniformity in the mechanics of the explosion. The deep-to-shoal-water tests check the observations.

The small electric bombs show the multiplicity to a much lesser extent. The presence of two waves in the "directs" separated by a time interval of .03 second is shown in Fig. 11. The same interval appears sufficiently often in the reflections to prove its origin at the explosion. (Discussed more fully later).

The PR-1 points beyond 25 km. lie on a straight line practically parallel to the PR-2 curve at distances greater than 50 km., the instantaneous velocity (reciprocal slope of travel time curve) being 1498 m/sec. and the time separation .27 second. The travel time for both curves is given by an equation of the form :

$$t = s/1498 + c$$

when t is time, s is distance, and c is a parameter. In R A R this type of relation between the distance and time would be convenient if the distance arcs are laid off according to the instantaneous velocity. (See discussion of application to R A R).

In order to study the multiplicity of the impulses in the directs, the reduced travel times are drawn on a rather large time scale (Fig. 11). The points show considerable scattering due to small errors in time and distance measurements, as is to be expected. Before attempting to draw curves it is necessary to be reasonably certain that the impulses can be definitely correlated from record to record. This was done by plotting the travel time of PR-1 less the travel time of the earlier arrivals as a function of the distance (Fig. 12). It suppresses the errors of observation and it should be possible to draw smooth curves through the earlier arrivals as presumably PR-1 should lie on a smooth curve. This is simply a method of correlating beginnings.

Fig. 12 establishes the validity of the lower two curves of Fig. 11 and offers an excellent justification for drawing the third, P100. The existence of the third curve is better established than some of the curves in seismic travel times. The shape of the curves at once suggests that they can be represented as straight lines on a reduced travel time graph. The points on the lower curve of Fig. 12 are shown as X's in Fig. 11, those on the middle curve as circles and those on the upper curve as Greek crosses. The unexplained points appear as squares in Fig. 11. The fact that the two upper curves intersect the time axis at about the same place was established by drawing a third curve with travel time later arrivals less travel time PD-1 as ordinate. The lower curve of Fig. 11 is designated PD-1 the middle PD-2, and the upper P-100 for reasons that will appear directly.

The data are insufficient to justify a least square analysis. Rectilinear curves are indicated. Fig. 12 shows that the lower curves should be approximately parallel and .03 second apart. As has been stated, the upper curves should intersect the time axis at approximately the same height. With this information as a guide, the curves were drawn in by eye.

Parallelism in the travel time curves of the P waves in earthquakes has been observed and Byerly * suggests it is due to change of type upon incidence at a discontinuity. This explanation is, of course, of no help in the present instance. It seems necessary to look to the mechanics of the explosion for an explanation. The first impulse no doubt is due to the displacement of the water by the expanding gases and the second could be due to inrush of the displaced medium. The two impulses have about the same maximum amplitude which is consistent. A difference in sign of the first motion between the two impulses was observed in the three instances (Bombs Nos. 422, 423 and 536) when the direction of first motion of both impulses could be determined from the oscillograms. This is weakened as a supporting evidence by the probability of the existence of dispersion as discussed elsewhere. (Direction and trace amplitude of first motion). The fact that two phases, one about .03 second later than the other, are also observed in the reflections, is also evidence of a multiple source. Since the path associated with the two lower curves (Fig. 11) is undoubtedly more or less direct from bomb to hydrophone these arrivals are called PD-1 and PD-2. It is not intended to imply that the paths are right lines since there must be refraction curvature, and beyond 8 km. diffraction probably plays a part in the transmission. The lower curve does not pass through the origin. This might be due to errors in observation but is very likely due, in part, to an abnormally high velocity near the source. The high velocity of waves of finite amplitude is well known and very recently has been observed in air by Partlo and Service **.

It is worthy of note that two bombs at 17.5 km. show arrival on the upper curve and the direct waves are absent.

Jeffreys *** found it necessary to explain the amplitudes of indirect compressional waves in near earthquakes by diffraction. He considered diffraction at a first order discontinuity. It is extremely interesting and possibly significant that here we have evidence of this type of diffraction at a second order discontinuity under the special condition that there is a constant velocity layer with second order discontinuity above and below. Possibly the fact that we have waves of finite amplitude near the source facilitates getting energy into the constant velocity layer.

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* *Byerly, Bull. S.S.A. Vol.* 28, *N°* 1, *Jan.,* 1935.

** *Partlo & Service, Physics,* 6. *pp.* 1-5, *Jan.,* 1935.

*** *Jeffreys, H., Camb. Phil. Soc.,* 23 *pp.* 472-481, 1926.

The intercept at zero distance is .03 second above that of PD-1. Hence the ray path from bomb to the 100 fathom layer could not have been straight down. An emergence angle of about 30 degrees would give an intercept of about .03 second.

REDUCED TRAVEL TIMES
DEEP BOMBS AND DEEP HYDROPHONES

The results from the firing of the few deep bombs were insufficient to allow definite conclusions to be made. Four bombs were exploded at a depth of four hundred fathoms with a hydrophone at the same depth, and another hydrophone at the surface, for which distances and travel times were obtained. The observations at the deep hydrophone are shown in Fig. 14. The lines PR-1.1, PR-2.2, PR-3.3 and PR-4.4 are the observed PR-1, PR-2, PR-3 and PR-4 curves of Fig. 10 (surface hydrophone and bomb); it can be seen at once that the travel time of PR-n.n with bombs and hydrophone at the same depth are independent of this depth and equal to the travel time of PR-n with bombs and hydrophone at the surface, assuming a level bottom. In the present case it is true to a first approximation only. It should be noted that there are two paths n.n — one being first reflected from the bottom and the other from the surface. Between the curves n.n and (n+1). (n+1) there are the possible curves for PR-(n+1). n and PR-n. (n+1), which are not shown in Fig. 14. In addition PR-1.0 and PR-0.1 should be observed ahead of PR-1.1 at short distances.

Observations at depth are subject to a rather large uncertainty due to the errors possible in the location of the bomb and hydrophone. If a maximum error of 5° lead in the supporting cables is assumed, a maximum error of 65 meters in each position at a depth of 400 fathoms can occur or a .08 second error in the travel time due to this cause. This is the main source of error. It seems extremely unlikely that the error was this large in most cases since a great deal of care was taken to keep the visible part of the cable vertical.

Returning to Fig. 14, the first arrival can be interpreted as having traveled in practically a straight line from bomb to hydrophone, allowing for errors of .05 second, as evidenced by the straight line indicating a velocity of 1483 m/sec. at a depth of about 400 fathoms. However, the points can be explained otherwise. The first arrival at 56 km. may be PR-1.2, at 43 km. and 36 km., PR-1.1, and at 6 and 8 km. PR-0.1; the one at 26 km. may be PR-1.0 diffracted. There is very good a priori reason to expect the transmission of energy along the constant velocity layer at 400 fathoms. To verify this beyond doubt the observations would need to be spaced much more closely and the amplification should be low enough to avoid the loss of impulses in recording due to large amplitudes and faintness in the records *.

Simultaneous observations were made with a near surface hydrophone. The first arrivals could have traveled along the four hundred fathom layer and reached the surface by a least times path from that depth but here again alternative explanations can be found without good reasons apparent for preference.

The later arrivals in each case are the expected reflections and nothing unusual appears that warrants discussion.

There is insufficient data with bombs at other depths to yield definite information. A more detailed study of the properties of constant velocity layers may be of value for special problems in R A R and coast defense. As an example of the first, it may help to fix the position of dangers to navigation in areas where the irregularities of the bottom render reflection R A R inaccurate and the importance of a good fix justifies the expense of firing bombs at depth.

CHECK OF THEORETICAL VELOCITIES

With the possible exception of the velocity at about 100 fathoms, the data yield only the average vertical velocity between certain depths. (The instantaneous velocity of PD-1 and PD-2 cannot be attributed to any one depth because of the uncertainty regarding the path).

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* *It might be said in this connection that in this type of work it would be desirable to have an oscillograph with enough strings so that each hydrophone can produce two records at different amplifcations side by side. In view of the large range of amplitudes in the various impulses it was usually desirable to have the amplification high enough to record the weaker impulses, which lessened the value of other portions of the record.*

During the Guide's fuse-bomb run, a sounding line was run taking soundings every minute (Fig. 2). All the deep water tests were carried out near this line or its extension. The slope of the bottom is quite steep until a depth of 1020 fathoms is attained after which it is extremely gentle for some distance. The steep slope ends at about 5 km. from the average position of the Pioneer. There is little error in taking the depth of bottom from the profile at distances greater than 6 or 7 km.

The average velocities from a depth of 30 fathoms to the bottom were computed from the travel time of PR-1 taking the depths from the profile for the bombs when it was certain that the point of reflection was on the level part of the profile. Bombs Nos. 424, 425 and 426 at 10.4 km. were included since the position of the Pioneer for these bombs was about a mile south of the average position assuring the reflection from the level part. Bombs Nos. 535, 536 and 538 were also included since it appears extremely likely that the reflection occurred on the level part of the profile at a depth of about 980 fathoms. Only electric bombs at distances less than 21 km. were used so that it can be assumed reflection from the bottom actually occurred, and the ray paths approximate straight lines. The bombs and hydrophones were all at depth of 30 fathoms.

The average experimental velocities from 30 fathoms to 1020 fathoms were obtained as follows:

Bomb Number	Average Velocity	Residuals
424	1491 m/sec.	— 2.8
425	1491	— 2.8
426	(1500) Rejected	
427	1487	+ 1.2
428	1486	+ 2.2
429	1488	+ 0.2
430	1487	+ 1.2
431	1485	+ 3.2
432	(1482) Rejected	
542	1491	— 2.8
543	1489	— 0.8
544	1490	— 1.8
546	1491	— 2.8
547	1487	+ 1.2
548	1487	+ 1.2
549	1488	+ 0.2
550	1486	+ 2.2
	Mean 1488.2	

Mean Experimental Average Velocity between 30 and 1020 fathoms 1488 m/sec.

Mean Theoretical Average Velocity between 30 and 1020 fathoms 1486 m/sec. (computed from British Admiralty Tables).

TRACE AMPLITUDE — DEEP WATER TESTS

In the majority of instances, the direction and amplitude of first motion at hydrophone cannot be ascertained because either the oscillograph string motion was too rapid to record or strays or motion of earlier arrivals obscure the beginning. The relation between the direction of first trace motion and the water motion is not known since it is not certain that the electrical connections between the hydrophones and the oscillograph were always made in the same way. Hence, the graphs for different bomb series cannot be compared for actual direction of motion. In Fig. 15 only those measurements are grouped together for which it is quite certain no change in the connections was made.

It is seen that for a given path the direction of first motion depends on the distance. This is contrary to views that have been expressed in this connection*. The front of the advancing wave train is a changing thing, the wave train itself being then, of necessity, oscillatory in character. The changing front could come about either through dispersion or loss of complete half waves at the front.

Consider a simple oscillatory wave train advancing into an undisturbed medium. The first crest AB will lose energy more rapidly than the succeeding one since the later ones encounter a medium already disturbed, and BC eventually will become the front of the train.

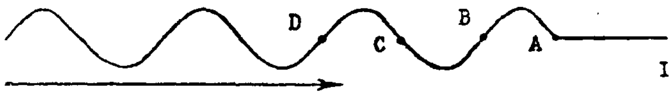

Illustration "A"

On this argument, BC will have its maximum amplitude (as first arrival) when it first appears at the front of the train and the distance — amplitude curve of first motion should have the general characteristics of illustration B.

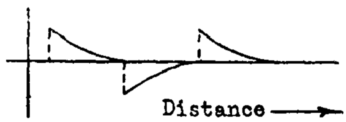

Illustration "B"

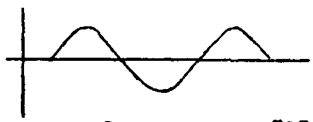

Illustration "C"

In contrast, the curve, if due to dispersion should tend to be of the character of illustration C. The latter type of curve is observed and this is considered very strong evidence of dispersion. It is felt that change of direction of motion with distances along a given path is by itself, not conclusive evidence of dispersion.

Boyle and Taylor ** found no change in wave velocity of sound in water from 29,000 to 570,000 hertz and this has been verified by other workers ***. No experimental work of this nature has been done, however, for the range of frequencies observed in the present work.

On theoretical grounds, velocities between the Newtonian $\sqrt{\frac{p}{\rho}}$ and the Laplacian $\sqrt{\frac{p}{\gamma\rho}}$ could be expected, depending on the completeness of the adiabatic state, the lower frequencies having the higher velocity, according to Herzfield and Rice (1). Since $\sqrt{\gamma}$ is approximately 1.005 for sea water, the expected dispersion due to this cause would be very small and it is not surprising that it has not been observed in measurements of wave velocity, if indeed it exists.

The maximum trace amplitude of any impulse was taken as the maximum occurring within the first .1 second or less of that impulse. The trace amplitudes were all reduced to a uniform amplification. The amplification was varied by known amounts during the experiments by the introduction of a potentiometer bridge on the plate circuit of the output.

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* *See for example Jeffreys, H., The Earth, p. 94. Cambridge University Press, 1929, and Dorsey's comments on p. 73 of the U.S.C. & G.S. Field Engrs. Bulletin, December, 1934.*

** *R. W. Boyle and G. B. Taylor. Trans. Royal Society of Canada., Vol. 211 Sec. 3, p. 79, 1927.*

*** *Wood, Loomis and Hubbard. Nature, Aug. 6,. 1927.*

(1) *Herzfield and Rice. Phys. Rev. 31, p. 691, 1928.*

Due to fast motion or lack of contrast in the oscillograms it was often impossible to measure the maximum amplitude. This is shown by up and down arrows on the graphs. Usually, but not always, this indicates a large amplitude.

Other than surprisingly large amplitudes in P-100, the directs show nothing unexpected. If the suggested path of P-100 is correct, one would expect an amplitude small in comparison with that of PD, particularly at short distances. However, in near earthquakes, where ray paths are better established than that of P-100, similar difficulties are encountered in the explanation of observed amplitudes so this cannot be regarded as a serious objection.

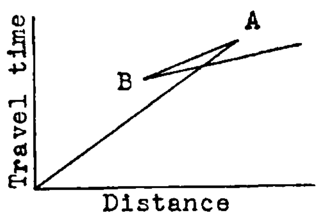
The amplitudes of bombs 532-550 inclusive appear to be considerably larger than those found on other days for the same size bombs at the same distances. In Fig. 17 the observations for these bombs (532-550) are set apart by surrounding them by a dotted line. Apart from these, the trace amplitudes of PR-1 show the same characteristics with distance for both the fuse and the electric bombs. The PR-1 curve shows a maximum at 35 km., PR-2 at 60 km., and PR-3 at 80+ km. The observations of November, 1933, indicated the same sort of thing but were rendered uncertain by unknown variations in the amplification.

The theoretical relation between trace amplitudes and amplitude of the passing waves is very difficult to determine because of the complex nature of the instrumental system and the fact that both diaphragm motion and motion of the hydrophone as a whole excite the Utah unit.

One possible explanation of the maximum was advanced in the report of the 1933 work. If the hydrophones have directional properties, the maximum could be caused by the decrease of the emergence angle of the incident rays with distance. The hydrophones supposedly respond to pressure variations and should thus be non-directional, but a study of the frequencies recorded suggests that the motion of the hydrophones as a whole is recorded, in which case directional properties may exist.

The hydrophone was suspended from its cable and hence free to turn. Consequently if there was any directional effect there would be a variation in the sound amplitude due to the direction of the hydrophone diaphragm when the sound arrived.

A more likely cause lies in the theoretical existence of reversed segments in the travel time curves, with the consequent focusing effect. Slichter * has shown that with the type of velocity depth curves normally found off the coast of Southern California (i. e. velocity first decreasing and then increasing with depth) the travel time curve must have a reversed segmet if the depth is great enough. A travel time curve with reversed segment is shown thus :



Slichter shows that if the quantity

$$\frac{(dZ/dV)_o}{(V_m^2 - V_o^2)^{\frac{1}{2}}} + \int_{V_o}^{V_m} \frac{\frac{d^2Z}{dV^2}}{(V_m^2 - V_o^2)^{\frac{1}{2}}} < O$$

the travel time curve will have a reversed segment, where

Z = depth

Vo = velocity at $Z = 0$

Vm = velocity at the maximum depth attained.

It is assumed that the ray returns to the surface by refraction, i. e. the emergence angle is zero at the lowest point reached. For his case (1) he gives :

" When the slope at the surface $\left(\frac{dZ}{dv}\right)$ is negative, the ray paths will be

* *Slichter, L., Physics, Vol. 3, N° 6, pp. 273-295. Dec., 1932.*

concave downwards initially, and the shallowest ray will penetrate to such a depth that the velocity at its apex is equal to the surface velocity, $v_m = v_0$. With this value for v_0, the first term..... is negatively infinite. Furthermore, if the velocity function has a curvature of constant negative sign the integral

$$\int_{V_0}^{V_m} \frac{d^2 Z / dV^2}{(V_m^2 - V_0^2)^{\frac{1}{2}}} dv$$

will also be negative and the existence of a reversed segment is assured".

Considering the velocity curve as represented by a series of straight lines as in Fig. 6, the integral is zero for any depth range. For a source below 10 fathoms depth, the first term is negative and a reversed segment occurs if the bottom is deep enough so that the rays are refracted back to the surface which was certainly the case for the electric bombs and probably for the fused ones.

The reason for increased amplitude in the vicinity of the ends of the reversed segments lies in the large value of $\frac{de}{d\Delta}$ in these regions; e being emergence angle and Δ distance along the earth's surface measured as an angle (with the vertex at the earth's center). Jeffreys * has shown that the measure of the energy in the wave front is given by

$$E = \frac{\cot e}{\sin \Delta} \frac{de}{d \Delta}$$

The emergence angles were plotted as a function of the travel distance for a depth of source of 15 fathoms and a depth of bottom of 1072 fathoms. When $e = 0° 30'$ the rays were reflected from the bottom. A large increase in intensity occurs at 2°. The same result will hold even if the theoretical velocities are somewhat in error since the shape of the velocity curve is undoubtedly correct.

Amplitude peaks due to this cause obviously should broaden with each reflection but the observations do not show this. Unfortunately fuse bomb records between 36 and 44 km. were not obtained to better delineate the PR-1 maximum.

The distance to which PR-1 diffracted is observed is rather surprising. Presumably all the PR-1's beyond the diminishing amplitude drop at 40 km. were diffracted. The extension of the diffraction interval with increasing size of bombs is particularly apparent in PR-1 and explains why large bombs often give good R A R intersections from three or more stations when smaller ones give large triangles. In such cases a later reflection with a low apparent velocity records from the smaller bomb. The importance of diffraction in deep water sound ranging must be fully recognized since it is the prime reason that R A R is so successful.

The diffraction interval of PR-1 extends over 30 km. and yet the direct wave is observed to only 20 km. It is not clear why diffraction effects should be the more pronounced after reflection.

The only previous measurements of variation of intensity of under water signals with distance that have been published to our knowledge are those of Aigner ** and Barkhauser and Lichte *** in shallow water. The measurements were made by having a variable resistance in series or parallel with the underwater detector and adjusting the resistance so that the signal was just audible through earphones. The source of the signals was a Fessenden oscillator or underwater sirens. Barkhauser and Lichte found the decrease in amplitude with distance to be exponential and independent of the frequency and the depth of water (under 100 fathoms). It is not known whether the source was sustained or intermittent but presumably it was sustained. Certainly the results are quite different in deep water with a source of short duration. Their curves are reproduced below, illustrations D, E and F.

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* *Jeffries, H., M.N.R.A.S. Geoph. Sup., June* 1926.

** *Aigner, F. Unterwasserschalltechnik.*

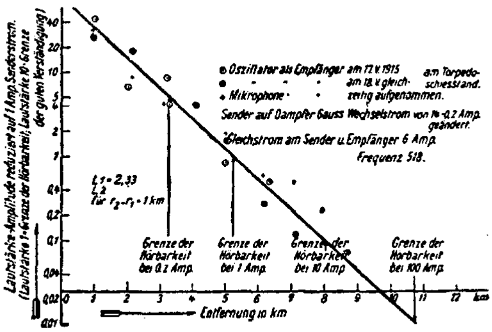
*** *Barkhauser and Lichte. Ann. d. Physik.*

Aigner shows a very interesting result, the illustration G being self-explanatory.

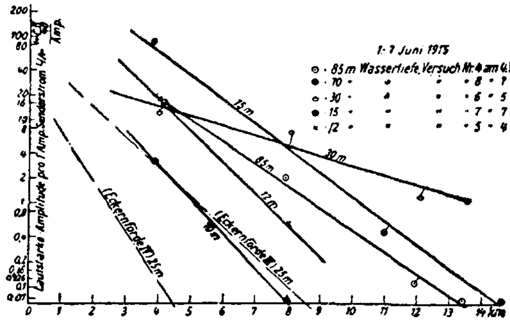
The amplitude drops very sharply just inshore of the steeper portion of the slope which he thinks is due to the depth of bottom becoming equal to the wave length of the sound which was generated by a Fessenden oscillator. It is quite likely that the slope was an important factor, as indicated in Fig. 3.

DEEP TO SHOAL WATER EXPERIMENTS

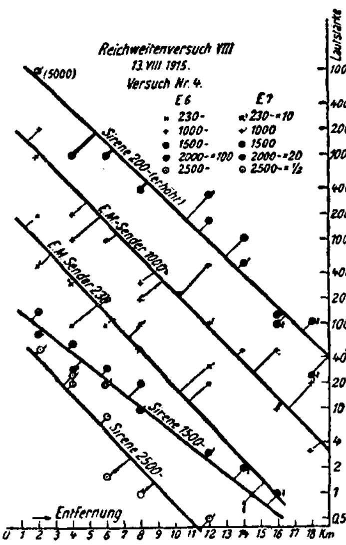
The simplified conditions of the deep water tests were necessary to determine experimentally the acoustic properties of sea water. The purpose of the deep to shoal water experiments was to develop practical rules of general use in R A R under conditions found on the Pacific Coast where the sea bottom slopes rather steeply from the beach.



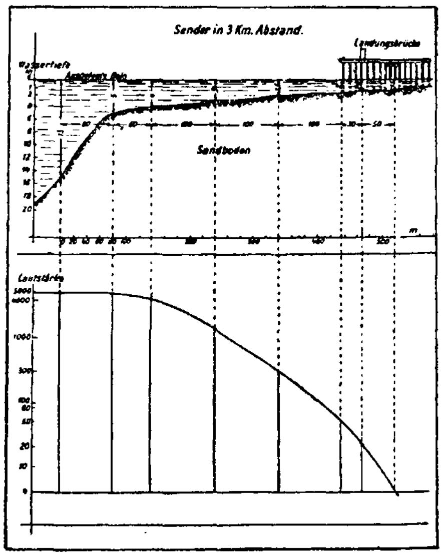
D



E



F



G

The bottom profile of the experimental area is shown in Fig. 3. The vertical scale is exaggerated, but the average slope of the bottom is about 10° at the steep part. Since the emergence angle is increased by an amount equal to twice the angle of slope upon reflection, it can be seen that the conditions are not favorable for sound propagation. At large emergence angles over 90% of the incident energy is transmitted into the underlying material, and the small amount of energy reflected may start seaward after a few reflections from the bottom.

The travel time curves are shown in Figs. 19, 20, 21 and 22. Reference to the profile, (Fig. 3) shows that the horizontal distance along the slope is practically the same as that along one leg of the tangent ray. In other words, the average slope of the bottom is about the same as the average slope of the tangent ray. The bottom, at the foot of the slope, is quite level. With this combination of conditions, the travel time curve of the first arrivals outside of the zones of silence was not affected by the presence of the slope. This is an important observation for sound ranging; when there is a choice, the hydrophones should be situated at the head of the steepest slope available *. It is also desirable to have the hydrophones as far out as possible, preferably directly at the peak of the slope.

The direct impulse was not observed beyond 8 ½ km. It had an instantaneous velocity of 1500 m/sec. and a negative time intercept. The instantaneous velocity is 5 m/sec. higher than observed in the deep water tests, the near surface temperatures having been slightly higher inshore than offshore. The intercept below the origin was also observed in the deep water tests and could be due to a higher velocity near the source.

There is some doubt as to the accuracy of the timing of the electric bombs in this series. The crystal in the ship's transmitter was set into oscillation when the firing switch was thrown. It was found on testing the equipment after finishing the experiments that a lag of .026 second occurred between the start of the plate current and the oscillation of the crystal when the transmitter was tuned for maximum output. The lag was small when the transmitter was slightly detuned. The travel times of the fuse and electric bombs agree when no lag is assumed, showing that if there was a lag in actual operation, it was small. Many of the oscillograph initials (i. e. time of the explosion) of electric bombs show a double beginning separated by from .01 to .02 second, the first being a single complete wave, the second the usual continuous oscillation. The indications are that the first should be used as the initial and the magnitude of the interval between the two leads to the belief that it is a measure of the time between the start of the plate current and the oscillation of the transmitter crystal. Presumably the preliminary initial was absent when no lag occurred.

From 13 to 20 km. the arriving sounds were too weak to operate the radio return but they did record weakly on the oscillograph. (Fig. 23). This was the region in which only multiple reflections from the slope were recorded. As the distance is approached at which a tangent ray is reflected at the foot of the steep slope, the slope no longer acts as a barrier (See Fig. 3) and the intensity at the hydrophone increases. As the distance is further increased PR-1 diffracted dies out before a PR-2 reflected the second time at the foot of the slope comes through, and hence another zone of quiet is observed at about 42 km. Of course, the transition from multiple reflections involving the slope to the tangent rays reflected from the level bottom is gradual; the points on the PR-2 curve (Fig. 19) are not true PR-2's and the bombing was not carried to the distance at which the tangent PR-2 should have been observed.

At 35 km. both the fuse and electric bombs (which were fired under different conditions) came in from .05 to .22 second late (Figs. 21 and 22), no doubt because of an irregularity in the bottom. It is very fortunate that this observation is so clearly substantiated since it illustrates admirably the limitations of the accuracy of R A R over irregular bottom.

OBSERVED FREQUENCIES

The major frequencies present in each impulses were recorded. However, no effort was made to evaluate their relative durations. Frequencies ranging from 100 to 1600 hertz were observed, but for a given experimental set-up two or three frequencies predominated heavily. The frequency statistics are shown in tables. It is stressed that the numbers are not intended to indicate relative duration of the frequencies as they occur, simply the number of times they are observed to occur, ordinarily only one occurrence per frequency being recorded per impulse.

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* *Unless, of course, this introduces an undesirable bottom profile between the hydrophones and the area to be surveyed, such as ridges or submarine valleys, which can be avoided by a different location of the hydrophones.*

The frequencies observed during preliminary experiments at Laguna Beach are included in the table. The hydrophone had a steel diaphragm 21 inches in diameter and 3/16 inch thick. The fundamental frequency measured in air is 88 with an overtone of 204, the latter presumably being vibration with one nodal diameter. The corresponding under water frequencies are probably around 50 and 100. A large Utah unit (weight 2 pounds) was used in this hydrophone.

Neither the hydrophones (See " Hydrophones ") nor oscillograph were satisfactory means of determining actual frequencies present in the bomb noises. The hydrophones with the units comprised a complex vibrating system with a number of inherent vibration frequencies of somewhat doubtful magnitudes, and the oscillograph string itself is a vibrating system with an infinite number of modes of vibration. None of the vibrating elements were particularly well damped, making it practically certain that the inherent frequencies would predominate in the records.

A few supplemental records were obtained with a Rochelle salt crystal hydrophone which should respond to all frequencies the oscillograph will record. It showed frequencies of from 205 to 260 with 220 hertz ca. being the most prominent. Since strays of frequency 1900 hertz were present throughout the records, it seems extremely likely that no considerable portion of the energy resided in frequencies between 260 and 1900 hertz. These records were obtained at ten miles in comparatively shoal water.

For a given hydrophone combination the frequency distribution was not affected by a change in bomb size from 4-ounce bottles to 1/2 pints, having a charge ratio of roughly 1 to 2. The depth of the explosion also does not affect the frequency distribution.

Segregating the frequency statistics into groups according to travel time shows that the ability of the bomb noise to induce the higher frequencies decreases with the distance. (See tables at end of report). This, of course, would be expected.

There is a tendency for the higher frequencies to persist to greater distances with the larger size bomb than with the smaller. Pint size bombs still excited a rather high percentage of high frequencies even at a travel time of sixty seconds, particularly in the first arrivals. The high frequencies are present in the first arrivals in practically all cases in the deep water tests. This is not true in the deep to shoal water tests which is important from the standpoint of R A R. The Laguna Beach statistics are particularly significant in this regard since at distances greater than 40 km. (25 seconds), the highest frequencies (about 900 hertz) do not appear on the records. The low frequency of this particular hydrophone no doubt has some bearing on this, but the higher frequency hydrophone showed similar tendencies in the deep to shoal water tests off Santa Cruz Island.

The data suggest that there may be an advantage in having a hydrophone and amplifier particularly sensitive to the lower frequencies. Hydrophones with low frequency diaphragms are undesirable because of the persistence of the diaphragm vibrations, especially when loaded with a unit. A hydrophone with rigid walls and lighter than the water it displaces may be a satisfactory solution. Such a hydrophone would move with the water and there would be no dependence on diaphragm vibrations. In fact it would not be necessary to mount the unit on a diaphragm face.

RELATIVE DISTRIBUTION OF MAJOR FREQUENCIES

(*Note:* The first column is the unit of measure).

Deep water Tests	Frequencies		200	450	900
Santa Barbara Ids. Basin Electrically fired bombs at 30 fms.; Aluminum Pot hydrophone at 30 fms.	Travel time	0-15 sec	1	0.2	7.4
		15-30 »	1	1.2	3.3
	over	30 »	1	0.2	1.3

Deep water Tests					
Santa Barbara Ids. Basin ½ Pt. Fuse Bombs; Aluminum Pot hydrophone at 30 fms.	Travel time	0-20 sec	1	0.5	3.4
	over	20 »	1	0.1	2.0

Deep to Shoal Water Tests	Frequencies		200 to 600 inc.	over 600
Santa Barbara Ids. Basin Electrically fired bombs at 30 fms.; Aluminum Pot hydrophone at about 10 fathoms.	Travel time	0-15 sec	1	0.4
	over	15 »	1	0.1

Deep to Shoal Water Tests Santa Barbara Ids. Basin ½ pint fuse bombs; Aluminum Pot hydrophone at about 10 fathoms.	Frequencies	300 to 600 inc.		over 600
	Travel time 0-15 sec	1		0.3
	over 15 »	1		0.4
Deep to Shoal Water Tests Laguna Beach. ½ pint fuse bombs; Kettle Drum hydrophone at about 10 fathoms.	Frequencies	100	500	950
	Travel time 0-12 sec	1	1.3	1.6
	12-25 »	1	1.3	0.1
	over 25 »	1	0.6	0
Deep to Shoal Water Tests Laguna Beach. Electrically fired bombs at 30 fms.; Kettle Drum hydrophone at about 10 fms.	Frequencies	100	450	950
	Travel time 0-10 sec	1	1.6	2.0
	10-20 »	1	0.7	0.2
	over 20 »	1	0.7	0.0

See also the Table of Frequencies.

COMPARISON OF TIME INTERVALS MEASURED BY THE CHRONOGRAPH AND THE OSCILLOGRAPH

During the deep to shoal water tests the oscillograph was ashore and only one hydrophone was used, it being in 15 fathoms of water ½ mile offshore (depth of bottom 20 fathoms). The B string of the oscillograph was used to record the start of the plate current in the shore radio transmitter upon the arrival of the sound at the hydrophone. The radio signal was received at the Pioneer and operated the ship's chronograph. During the all deep water tests an auxiliary electromagnetic shutter was employed to cut out a small band of light at the top edge of the oscillograms when the chronograph marked the receipt of the bomb noise. This time mark is called a return in this discussion. A check of the chronograph times is thus possible regardless of what portion of the bomb noise operated the chronograph. Instrumental lags should introduce a difference of less than .01 second in the time intervals measured by the two separate devices as can be seen by reference to the lag determinations. There is excellent reason to believe that the lag in the ship's transmitter was negligible in actual operation as shown elsewhere. (Paragraph of Deep to Shoal Water Tests).

In the tables, the columns headed Chrono. Time and Osc. Return are, apart from minor lags, measurements of the same interval of time. In the columns of Tables A and B headed Osc. Time, the time of the first arrival is also entered in the event that a later arrival operated the chronograph.

In table B a number of the differences " Chrono. minus Return " are rejected since the character of the return made it uncertain which portion recorded on the chronograph tape. Ordinarily, this occurs when the beginning is weak, i. e., the amplitude of the first arrival is small and its duration short. The algebraic sum of the differences between the Osc. Return and the Chrono. Times is so small that it can be assumed that the differences are due to accidental errors. However, an inspection of the differences is disconcerting since it shows absolute values of the differences greater than .03 second in a number of instances, involving a displacement of an R A R intersection line of more than 50 m. If a large percentage of errors of this magnitude are to be expected due to a faulty chronograph, the application of intelligent analysis of radio acoustic data is rendered exceedingly difficult. It seems that some estimation of velocities is necessary in deep water areas with an uneven bottom, but it would seem that satisfactory results can be obtained if the equipment is reliable.

The most obvious source of part of this error is in the apparent variable rate of the chronometer which has been discussed. It is probable that this is built into the mechanical arrangement of time marking in the chronometer and is unavoidable. If break second (or make second) chronometers are commonly subject to apparent irregularities in rate of this order, it may be desirable to replace them with tuning forks or vibrating reeds.

During the deep water experiments with fused bombs, very few oscillograph returns were recorded so the chonograph times are compared directly with the oscillograph times in Table B. This is legitimate since Table A shows that the return was usually sent a very few thousands of a second after the onset of an impulse which is the magnitude of the measured lag in the relay recording the return. The same comments that were made about Table A apply to these results. A correlation between the measured time and the difference (Chrono minus Osc.) is not noticeable in either case.

The differences, Table C, for the deep to shoal water tests show an indisputable relation to the length of the time interval measured indicative of a difference in rate between the chronometer and tuning fork of 3½ minutes per day, the tuning fork being the faster. There was no such discrepancy in the deep water tests. Evidence that the assumed tuning fork rate may have been four minutes per day too high during the deep water tests has already been given in the discussion of the theoretical velocities. However, Table A and B do not substantiate it unless it be assumed that the chronometer rate was also high at that time and lower during the experiments conducted during the work of the previous week. It is contrary to experience with chronometers that the rate should change by the required amount in such a short time under proper treatment. The same is true of tuning forks. No explanation of the apparent change in rate (or frequency) seems reasonable unless the tuning fork was mounted in a different manner on the ship than ashore on Santa Cruz Island. The tuning fork was calibrated on the ship after the deep water tests.

DEEP WATER TESTS

Electric Bombs

Table A.

Bomb N°	Chronograph Time	Chronograph Time	Oscillograph Return	Chronograph Return
404	35.03	35.026		
405	35.00	35.017		
406	28.64	28.654		
409	24.25	24.253		
410	24.32	24.319		
411	24.33	24.329		
412	20.06	20.066		
413	20.08	20.095		
415	4.22 ?	4.235		
416	4.15	4.149		
417	3.95	3.960	3.962	—0.01
418	3.91	3.913	3.915	—0.01
423	4.28	3.552 & 4.269	3.553 & 4.270	+ 0.01
426	7.33	7.294	7.297	+ 0.03
427	9.78	9.520 & 9.790	9.790	—0.01
428	9.80	9.547 & 9.803	9.804	0
429	11.99	11.79 & 11.981	11.982	+ 0.01
430	12.01	11.813 & 12.008	12.010	0
431	14.29	14.285	14.286	0
432	14.29	14.276	14.278	+ 0.01
434	15.88	15.867	15.868	+ 0.01
435	18.27	18.272	18.267	0
436	18.26	18.253	18.255	0
437	18.05	18.062	— —	
438	17.86	17.859	17.860	0
439	17.62	17.537 & 17.624	17.624	0
441	21.25	21.230	21.231	+ 0.02
442	21.22	21.207	21.209	+ 0.01
443	25.32	25.319	25.321	0
444	25.30	25.314	25.315	—0.02
445	25.29	25.301	25.303	—0.01
446	30.30	30.252	30.254	+ 0.05

Bomb N°	Chronograph Time	Chronograph Time	Oscillograph Return	Chronograph Return
447	30.22	30.220	30.220	0
448	30.18	30.203	30.202	—0.02
450	33.06	32.84 & 33.081	33.082	—0.02
451	33.04	32.81 & 33.038	33.039	0
452	37.79	37.795	37.772	+ 0.02
453	37.78	37.782	37.712 ?	+ 0.07-R
454	37.77	37.786	37.776	0
455	37.60	37.477 & 37.618	37.617	—0.02
456	37.49	37.522	— —	
457	37.46	37.459	37.460	0
458	37.24	37.217	37.219	+ 0.02
459	37.14	37.134	37.136	0
460	53.44	53.407	— —	
461	53.35	53.344	53.358	—0.01
463	59.12	59.14	— —	
464	59.35	59.32		
470	67.55	67.56 ±	67.559	—0.01
471	67.78	67.762	67.776	0
532	2.73	2.728	2.730	0
	3.59	3.577		
533	2.71	2.712	2.714	0
	3.56	3.562		
534	2.70	2.709	2.711	—0.01
	3.56	3.559		
535	4.80	4.810	4.811	—0.01
	5.37	5.369		
536	4.81	4.813	4.814	0
	5.34	5.371		
538	5.16	5.156	5.158	0
	5.69	5.685		
539	5.24	5.227	5.228	+ 0.01
	5.55			
542	8.10	7.997	7.997 Sputtery	+ 0.10-R
	8.39	8.383		
543	8.09	8.014	8.016 Sputtery	+ 0.07-R
	8.40	8.40		
544	8.11	8.023	— —	
	8.40	8.41		
545	9.61, 9.78	9.518 and others		
546	9.64, 9.90	9.520, 9.604 and others.		
547	9.91	9.559	9.560	0
		9.905	9.906	
548	14.10	14.045	14.047	+ 0.05
549	14.05	14.031	14.032	+ 0.02
550	14.08	14.073	14.074	+ 0.01
551	14.05	13.879	13.880	+ 0.17-R
552	24.28	24.292	24.293	+ 0.01
554	29.14	29.089	29.090 Sputtery	+ 0.05-R

Sum of negative difference —0.16
Sum of positive difference + 0.29
Average difference ± .01 sec.

COMPARISON OF TIME INTERVALS MEASURED BY THE OSCILLOGRAPH AND THE CHRONOGRAPH

DEEP WATER TESTS

Fuse Bombs

Table B.

Bomb N°	Chronograph Time	Oscillograph Time	Oscillograph Return	Chronograph Return	Chronograph Oscillograph
481	57.85	57.902	57.903	— 0.05	— 0.05
486	52.58	52.580	52.573	+ 0.01	0
488	50.37	50.38	— —		— 0.01
489	49.23	49.25			— 0.02
491	46.96	46.963			
495	42.55	42.219	42.461	— 0.09	+ 0.06
		42.493			
496	41.82 ?	41.101	41.340		— —
		41.394			
497	40.28	40.289	— —		— 0.01
500	36.58	36.586			— 0.01
502	34.35	34.347	— —		0
503	32.86	32.838	— —		+ 0.02
506	29.87	29.867	29.869	0	0
510	24.35	24.327			+ 0.02
511	23.22	23.208	— —		+ 0.01
512	22.11	22.095	— —		+ 0.01
517	17.20	17.177	— —		+ 0.02
525	7.81	7.470	— —		0
		7.807			
526	6.73	6.286	— —		0
		6.742			
				Algebraic sum	+ 0.03

Note : Oscillograph and Chronograph aboard Pioneer.
Bombs fired at Guide.

DEEP TO SHOAL WATER TESTS

Table C.

Bomb N°	Chronograph Time: Sec.	Oscillograph Time: Sec.	Oscillograph Return	Chronograph Return
202	3.85	3.769		
203	3.16	3.124		
204	3.14	3.106		
206	5.33	5.260		
207	5.27	5.212		
222	14.73	14.685	14.817	— 0.09
223	17.05	17.043		
224	17.08	17.087		
225	19.38	19.382		
229	20.12	20.112	20.138	— 0.02

Bomb N°	Chronograph Time: Sec.	Oscillograph Time: Sec.	Oscillograph Return	Chronograph Return
230	24.58	24.603	24.622	— 0.04
231	24.61	24.631	24.652	— 0.04
236	27.56	27.620		
238	30.79	30.745	30.783	+ 0.01
242	9.60	9.589	9.608	— 0.01
243	9.675	9.627	9.680	0
245	9.00	8.908	8.961	— 0.04
246	9.01	8.915	8.963	— 0.05
247	7.41	7.363	7.411	0
248	7.41	7.385	7.409	0
249	5.76	5.726	5.747	+ 0.01
250	5.76	5.711	5.746	+ 0.01
251	4.14	4.112	4.140	0
252	4.16	4.128	4.141	+ 0.02
253	2.48	2.438	2.459	+ 0.02
254	2.46	2.438	2.455	0
255	1.49	1.469	1.481	+ 0.01
256	—	1.464	1.481	
257	0.80	0.760		
258	1.73	1.729		
259	2.82	2.799	2.817	0
261	4.07	3.985	4.067	0
262	5.04	4.915	5.033	+ 0.01
263	6.01	5.944	6.022	— 0.01
272	13.78	13.461	13.813	— 0.03
274	15.65	15.637	15.685	— 0.03
275	16.57	16.563	16.578	— 0.01
278	19.58		19.625	— 0.04
279	20.64	20.659	20.675	— 0.04
280	21.74	21.756	21.782	— 0.04
283	24.71	24.757	25.773	— 0.06
286	28.05	28.104	28.117	— 0.07
291	26.41	26.444	26.47	— 0.06
292	26.62	26.660	— —	
293	23.75	23.758	— —	
294	23.71	23.755	— —	
298	34.05	33.096	34.101	— 0.05
301	36.88	36.69 ±		
302	38.94	38.908	39.094	— 0.15
304	39.28	39.16	39.361	— 0.08
306	27.79	27.831	27.845	— 0.06
307	27.72	27.732	27.777	— 0.06
309	22.57	22.583	22.627	— 0.06
310	22.79	22.798	22.830	— 0.04
311	17.50	17.478	17.495	0
313	17.49	17.54	— —	

Oscillograph ashore; Chronograph on *Pioneer*. Bombs fired at *Pioneer*.

COMPARISON OF LOG READINGS AND REVOLUTION COUNTER WITH CHRONOGRAPH TIMES

In order to detect marked changes in the apparent velocity of bomb sounds in actual R A R through the use of log reading (L.R.) or revolution counter reading (R.C.R.), the ship's course must be quite constant and the instruments must be reliable. The taffrail log and the R.C. might be expected to measure distances with sufficient accuracy to indicate sudden changes in the apparent velocity, if the ship's course cuts the distance circles at an appreciable angle. If this is not appreciable then a bomb distance that plots off line would indicate the change in apparent velocity.

R A R conditions were simulated to a certain extent during the fuse bomb runs in both deep and deep to shoal water tests with the special condition that the lines were run directly toward or away from the hydrophones.

During the deep water tests a line was run toward the hydrophone and the course was not changed during the entire run. The log readings plotted against travel time should then be equivalent to a travel time curve. In Fig. 28 the travel times were measured by the chronograph. From 5 to 31 seconds the points fall on a smooth curve the upper end of which is a straight line, and those from 37 to 57 seconds fall on a straight line nearly parallel to the first and 0.30 seconds above. Comparison of the chronograph and oscillograph times indicate that the first reflection tripped the chronograph pen to a distance equivalent to 31 seconds travel time after which the second reflection tripped the pen. The sudden change in apparent velocity is very clearly indicated and is of the order of 12 m/sec. which is in good agreement with the facts. Another jump of about 150 m/sec. is indicated at 5 seconds where the direct waves ceased to record on the chronograph, again in agreement with the oscillograms. The jumps in the R.C. curves agree with the facts better than do the log readings.

In actual R A R the sounding lines do not radiate from the hydrophone stations and the relation between the log readings and bomb distances is not linear. In this case, a linear travel time curve would mean a log time curve of varying curvature. The log time curves should, however, be smooth and show sudden large changes in the apparent velocity if the ship's course cuts the distance arcs at a favorable angle. To properly evaluate the magnitude of the change, every effort should be made to record and measure on the chronograph tapes the second arrivals at the hydrophones.

The effect of changing course is readily seen in Fig. 30 where the log-times for the deep to shoal water tests are shown. The course was gradually changed to the left during the early part of the run and then gradually to the right during the latter part of the run, thus making a curved instead of a straight line on the graph. The effect is probably more striking in Fig. 29 where log readings are plotted against actual distance. Fig. 30 could not be successfully interpreted to assist materially in obtaining good distance arcs from the chronograph times as it stands.

Since this latter type of data is probably more typical of R A R it would be of interest to determine if the changes in course can be conveniently taken into account. If an average course is assumed, the difference in L.R. between successive bombs multiplied by the cosine of the angle between the actual course and the assumed average gives the difference in L.R. that would be observed along the projection of the actual course on the assumed average. If the data were plotted in this manner it might be more consistent with the travel time curves.

Another way of handling the data is to divide the difference of successive log readings by the difference in chronograph time when sudden changes in the radio would indicate breaks in the travel time curve. However, this method is probably not as satisfactory as the other since in the graphical method the interpretation is more obvious.

As stated elsewhere, the best method of detecting when there is an abrupt change in velocity is when the distance arc does not go through the approximate dead reckoning point, and when the shore station operator first reports hearing a wave arrive before the one that trips the transmitter.

Perhaps it is fortunate that in the first R A R work the full complexity of underwater-sound-wave travel was not supsected, for if it had been known this valuable and accurate method might not have been developed. However, the empirical relations used in earlier work have been explained and justified by the recent experiments, and it is believed that this new knowledge will improve the accuracy of R A R even beyond the present limits, which now give the most accurate control known for offshore hydrography.

There are many problems and investigations (which are purely of academic interest) suggested by these recent experiments. Although it is not within the province of this investigation to analyze thoroughly all the suggested possibilities, numerous ones have been noted in this study, and it is hoped that sufficient data are given herein to enable those who pursue some particular branch of this work to study it further in the light of knowledge gained.

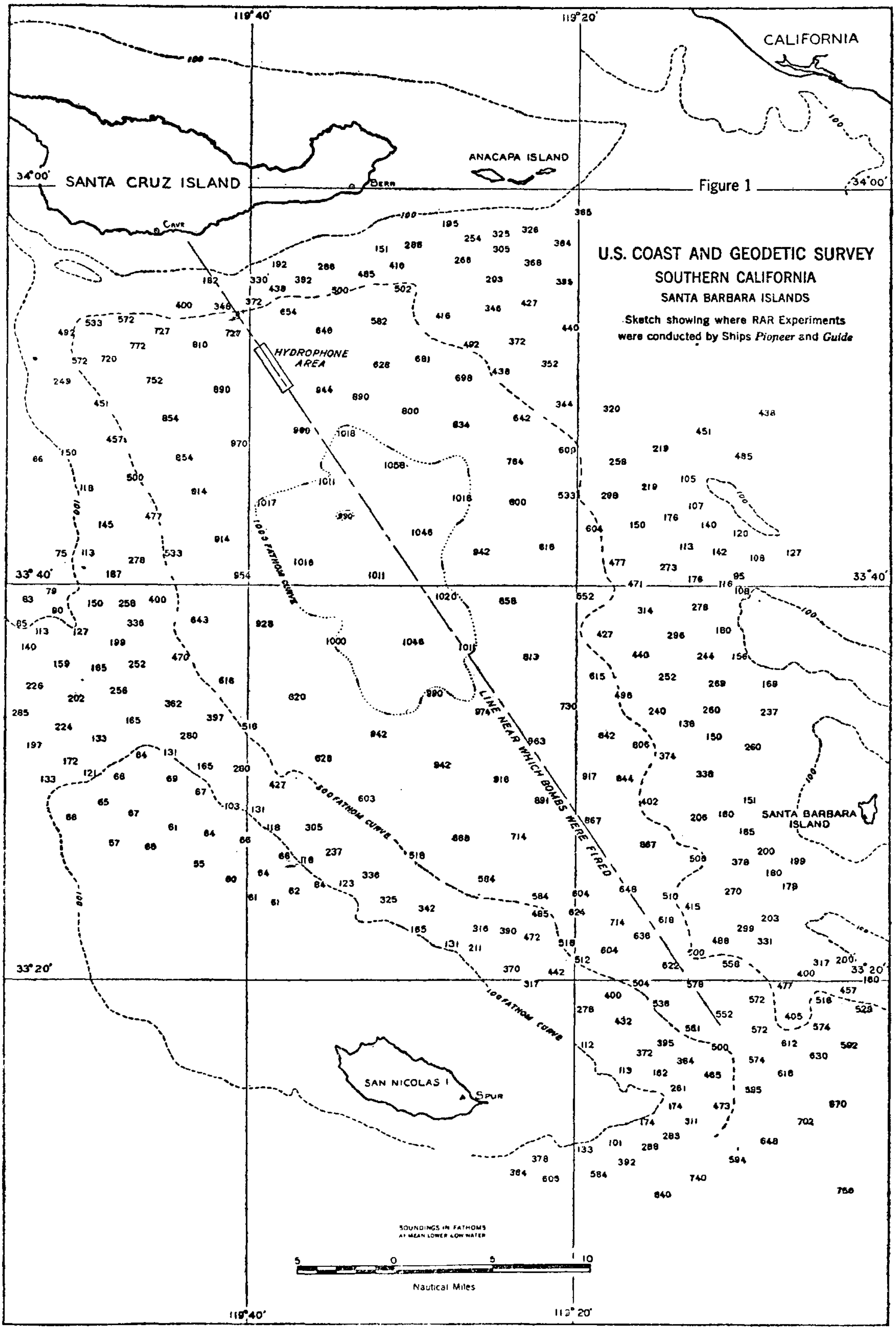
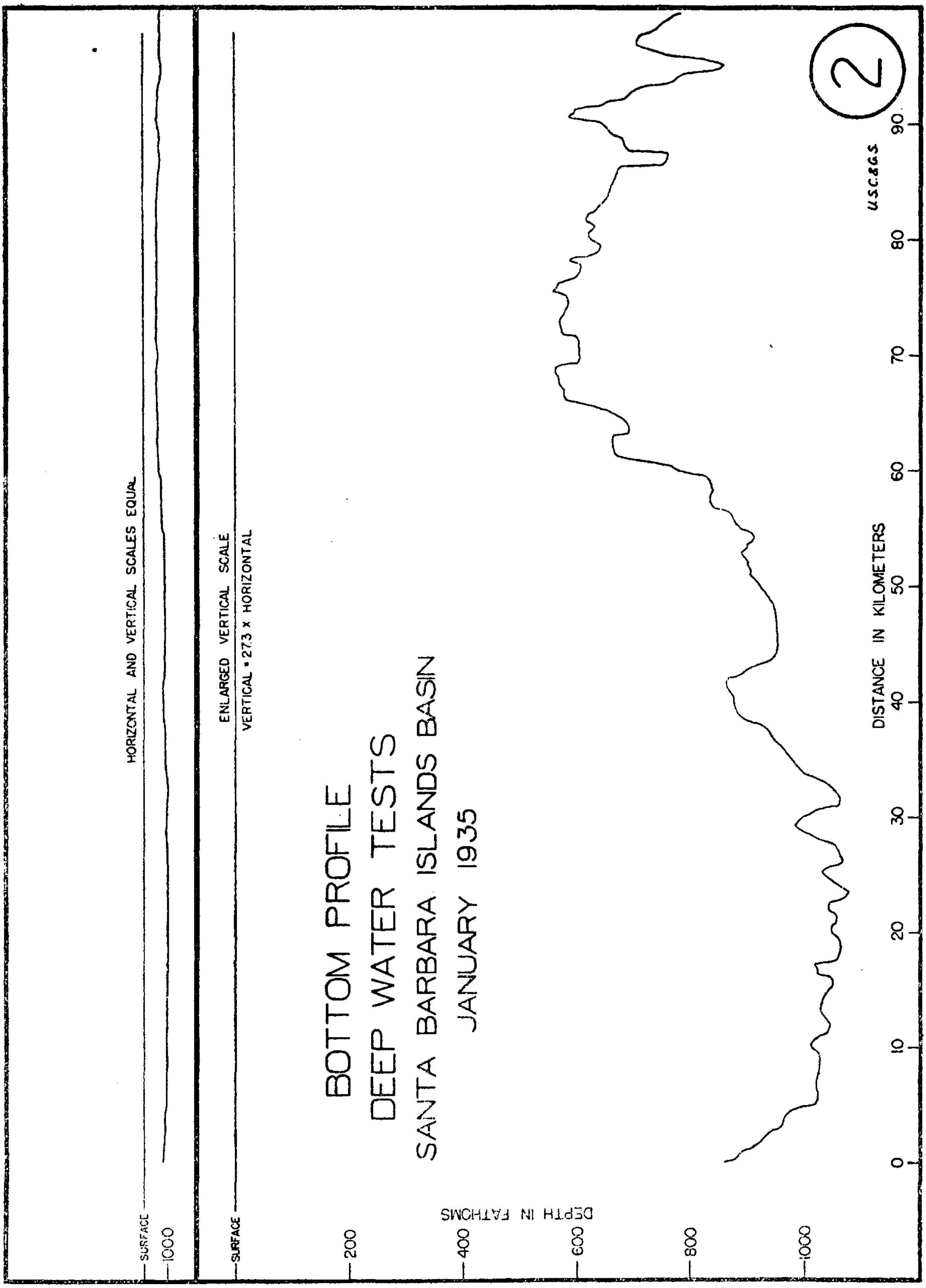
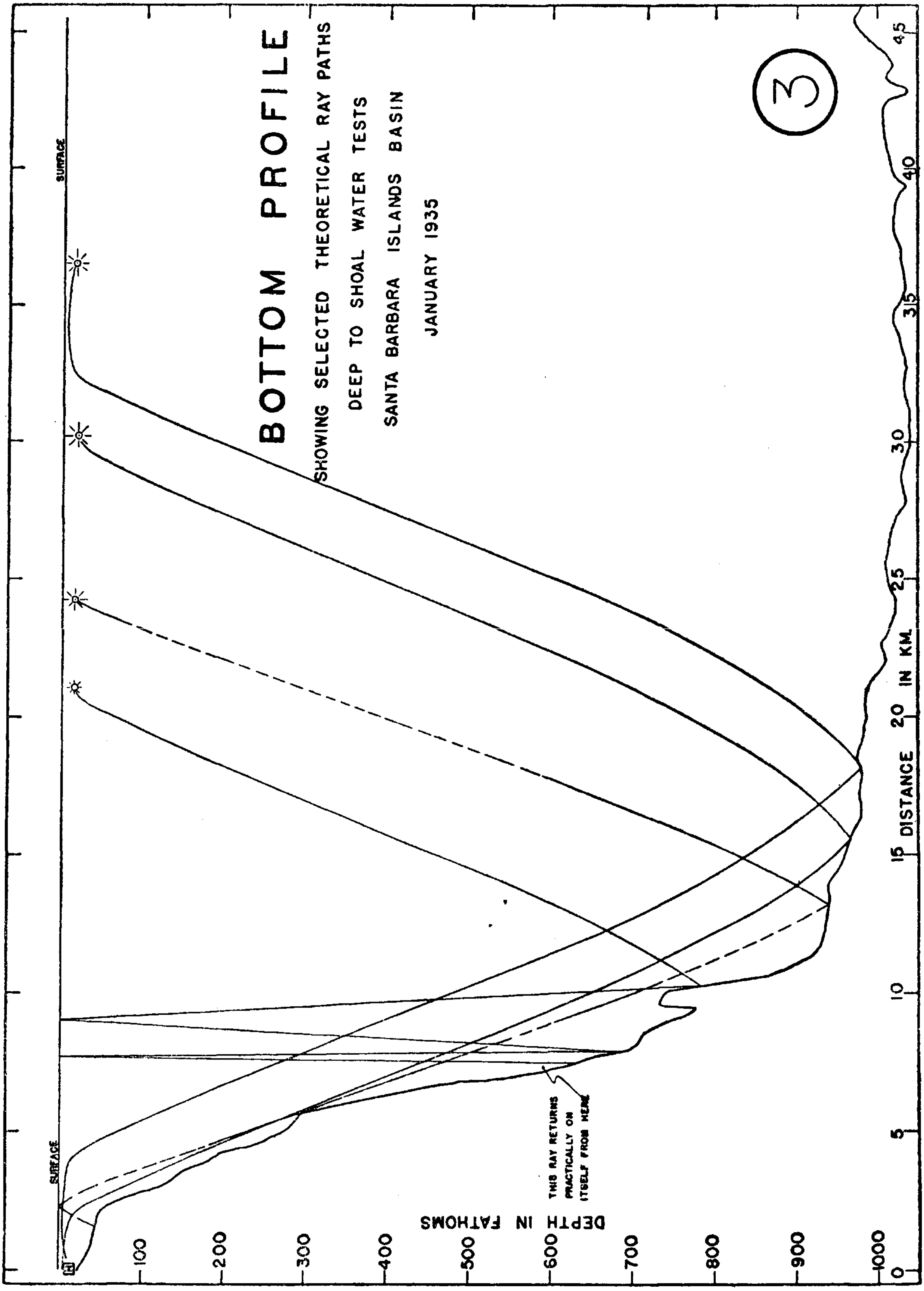
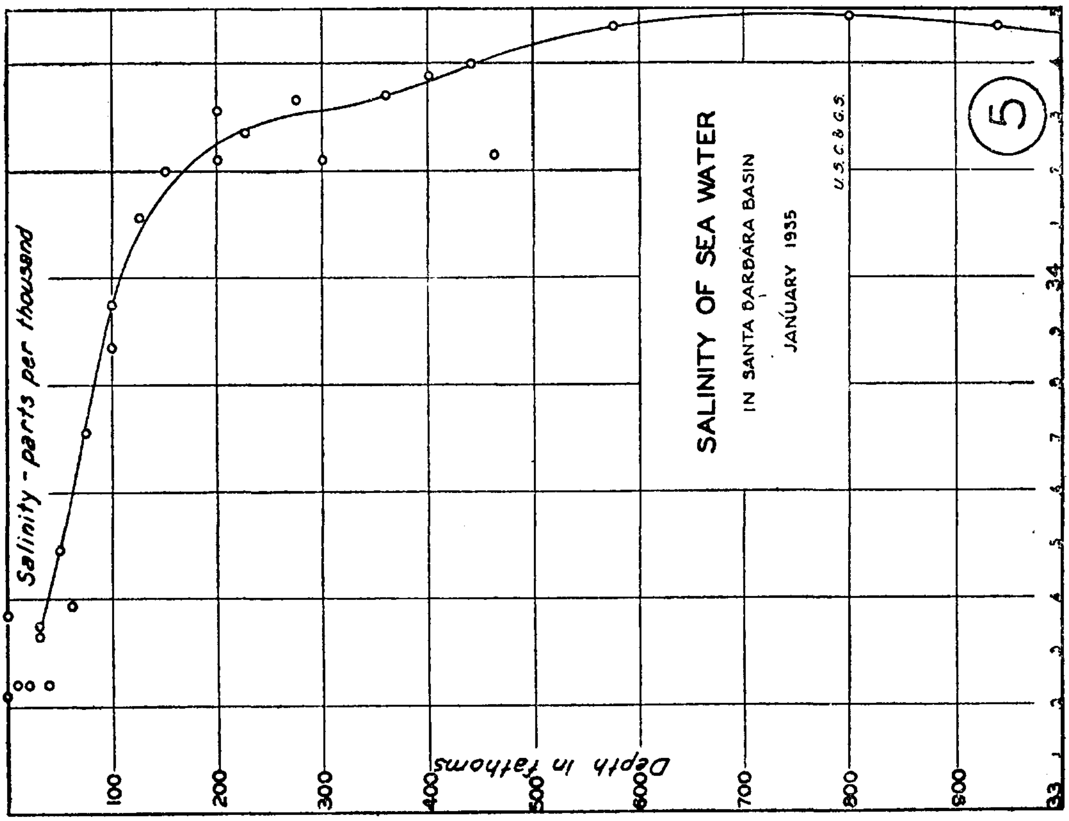
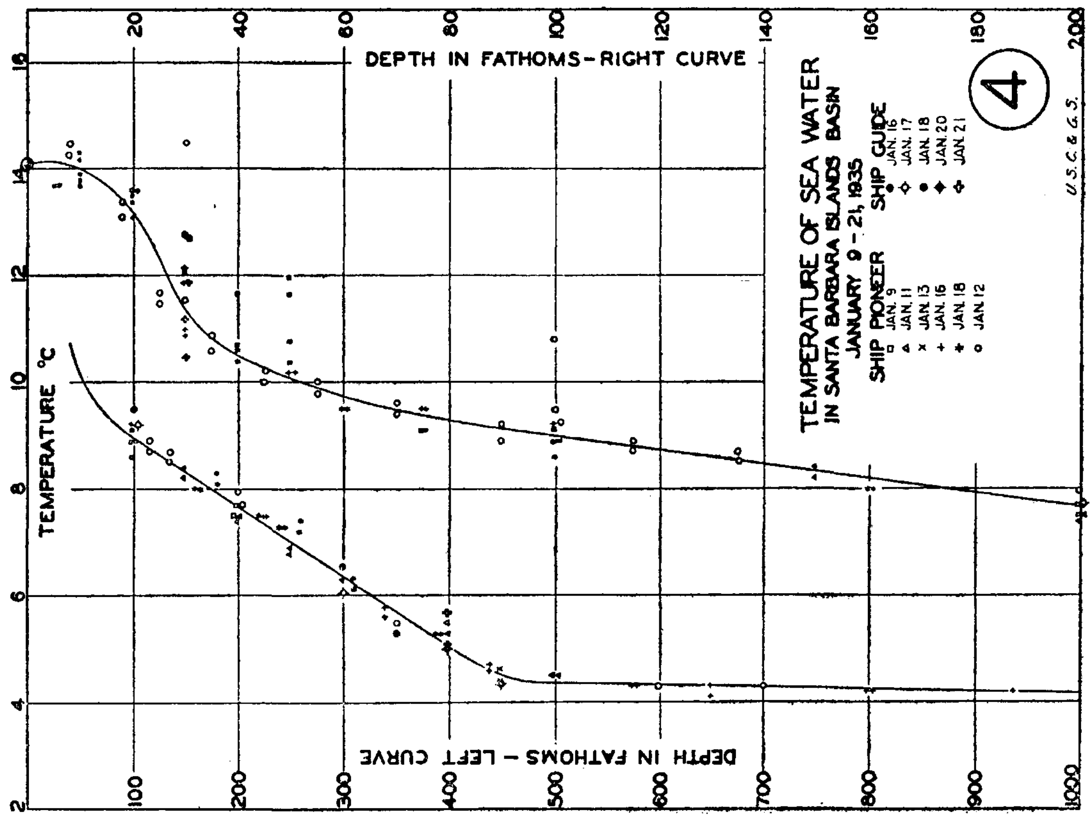


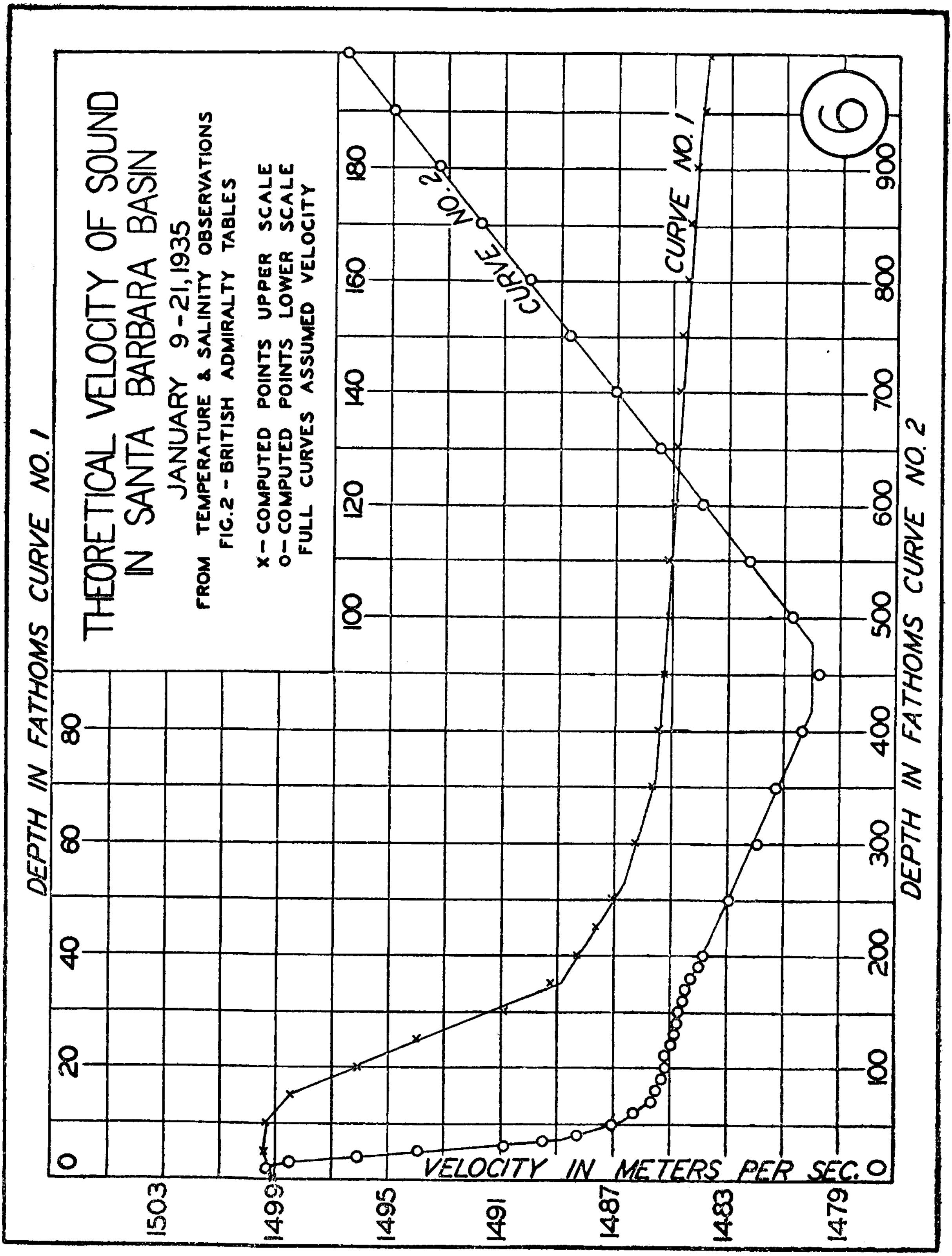
Figure 1
U.S. COAST AND GEODETIC SURVEY
SOUTHERN CALIFORNIA
SANTA BARBARA ISLANDS
Sketch showing where RAR Experiments were conducted by Ships *Pioneer* and *Guide*
CALIFORNIA
SANTA CRUZ ISLAND
ANACAPA ISLAND
SANTA BARBARA ISLAND
SAN NICOLAS I
HYDROPHONE AREA
LINE NEAR WHICH BOMBS WERE FIRED
1000 FATHOM CURVE
500 FATHOM CURVE
100 FATHOM CURVE
Cave
Bern
Spur
119°40'
119°20'
34°00'
33°40'
33°20'
SOUNDINGS IN FATHOMS AT MEAN LOWER LOW WATER
5 0 5 10
Nautical Miles

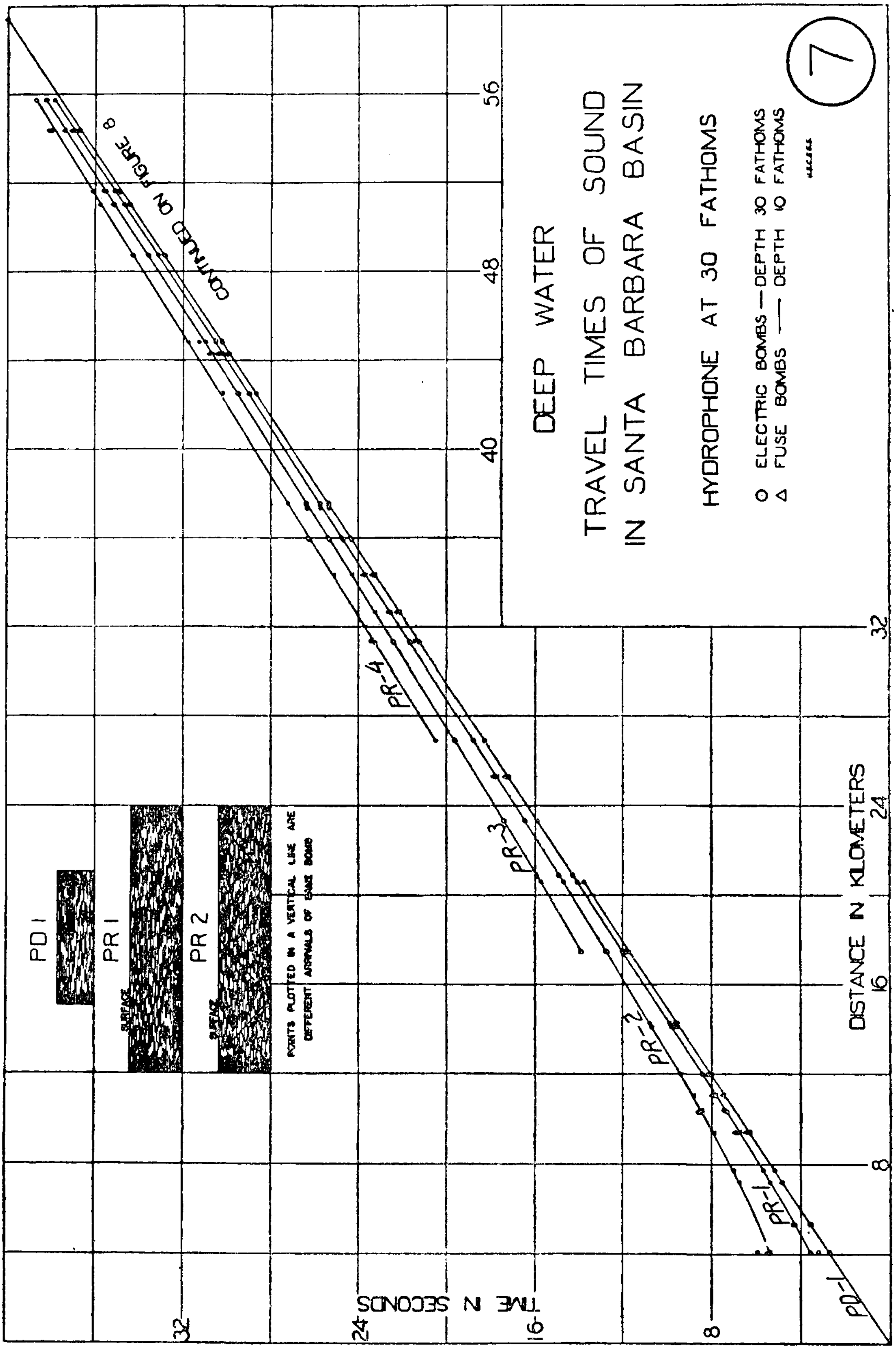

HORIZONTAL AND VERTICAL SCALES EQUAL
SURFACE
1000
ENLARGED VERTICAL SCALE
VERTICAL = 27.3 x HORIZONTAL
SURFACE
BOTTOM PROFILE
DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
DEPTH IN FATHOMS
200
400
600
800
1000
DISTANCE IN KILOMETERS
0
10
20
30
40
50
60
70
80
90
U.S.C.&G.S.
2

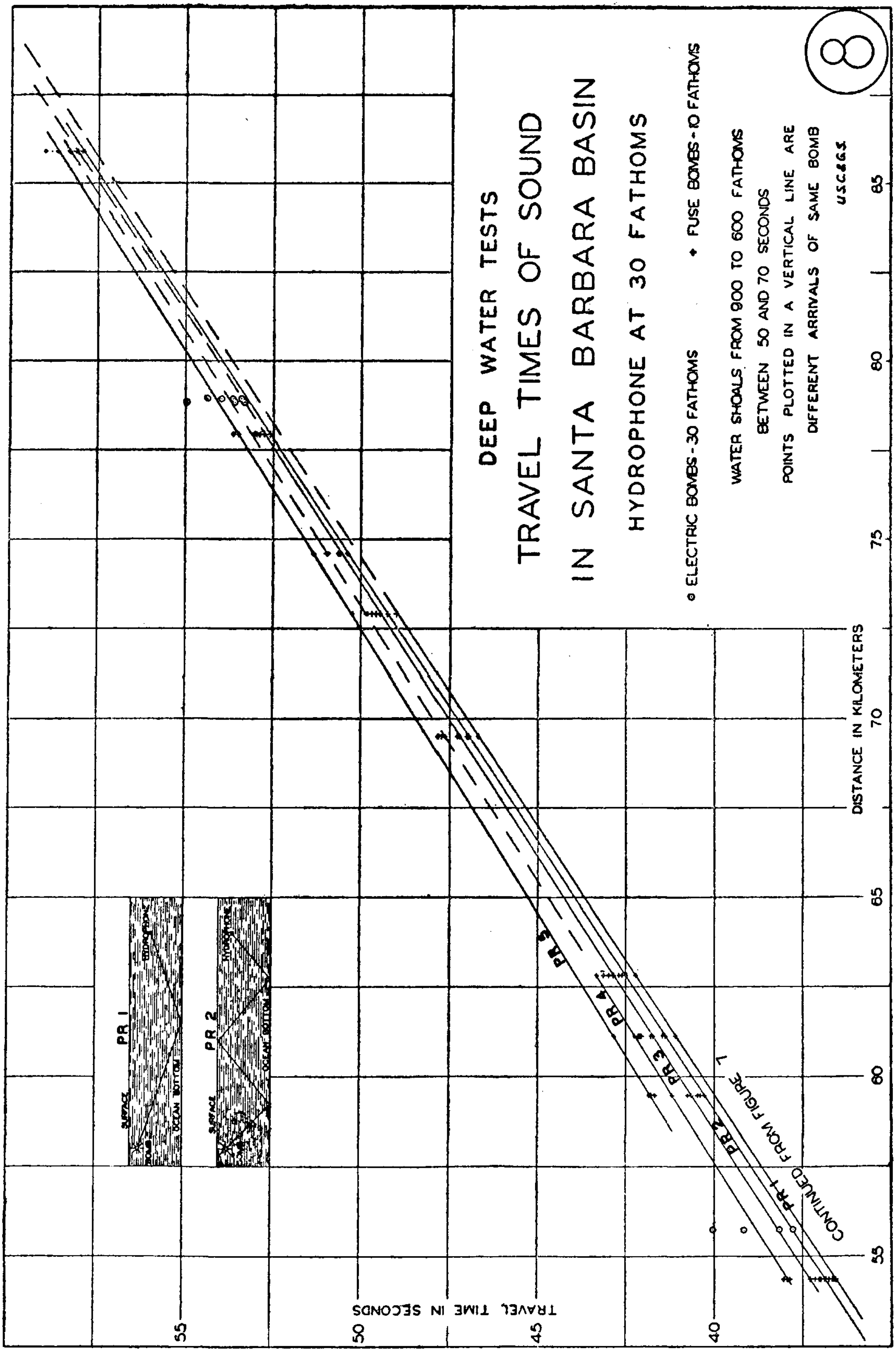

BOTTOM PROFILE
SHOWING SELECTED THEORETICAL RAY PATHS
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
3
SURFACE
SURFACE
THIS RAY RETURNS PRACTICALLY ON ITSELF FROM HERE
DEPTH IN FATHOMS
DISTANCE IN KM.
0 5 10 15 20 25 30 35 40 45
100 200 300 400 500 600 700 800 900 1000

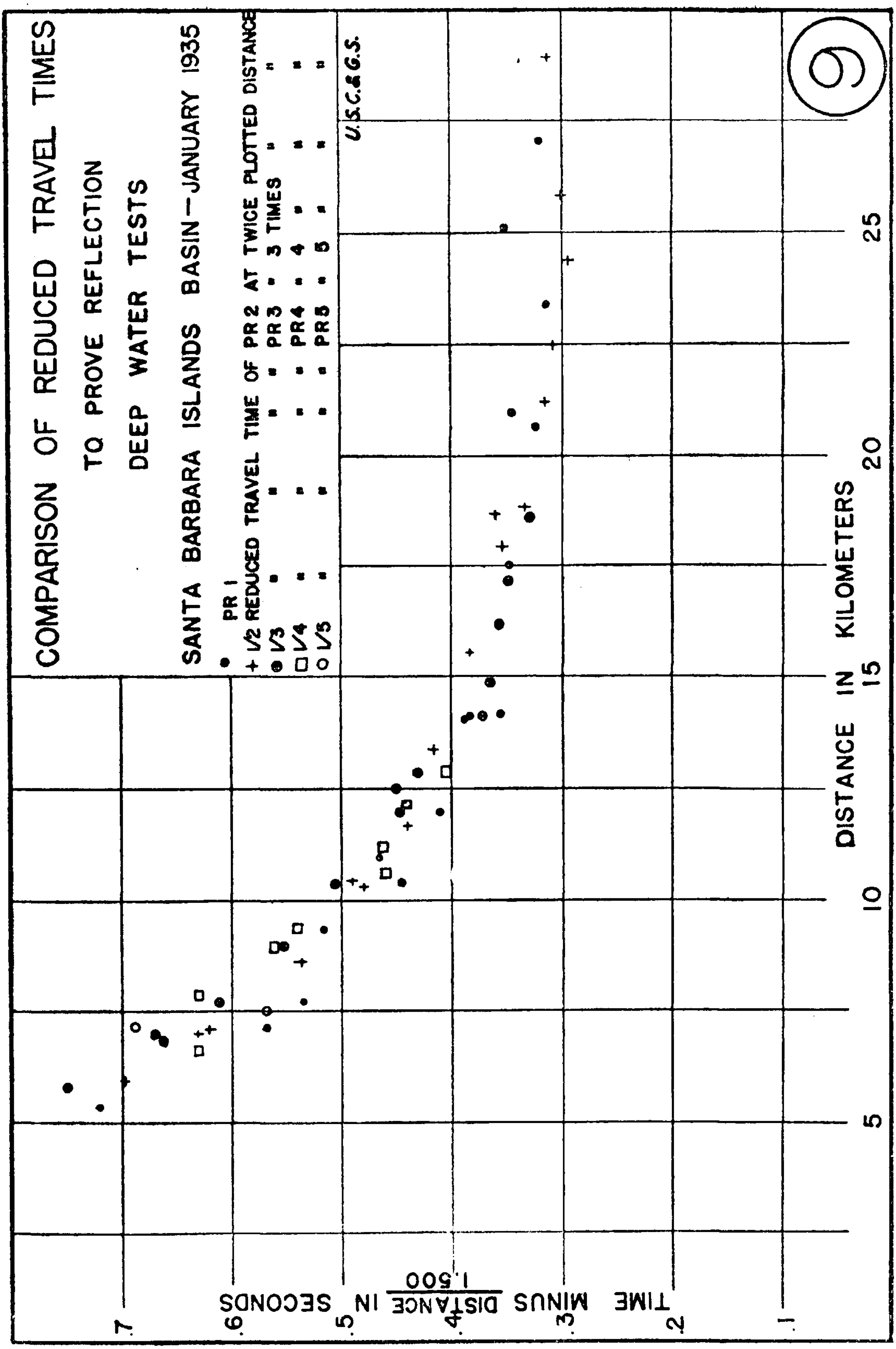

SALINITY OF SEA WATER
IN SANTA BARBARA BASIN
JANUARY 1935
U.S.C.&G.S.
5
Salinity - parts per thousand
Depth in fathoms

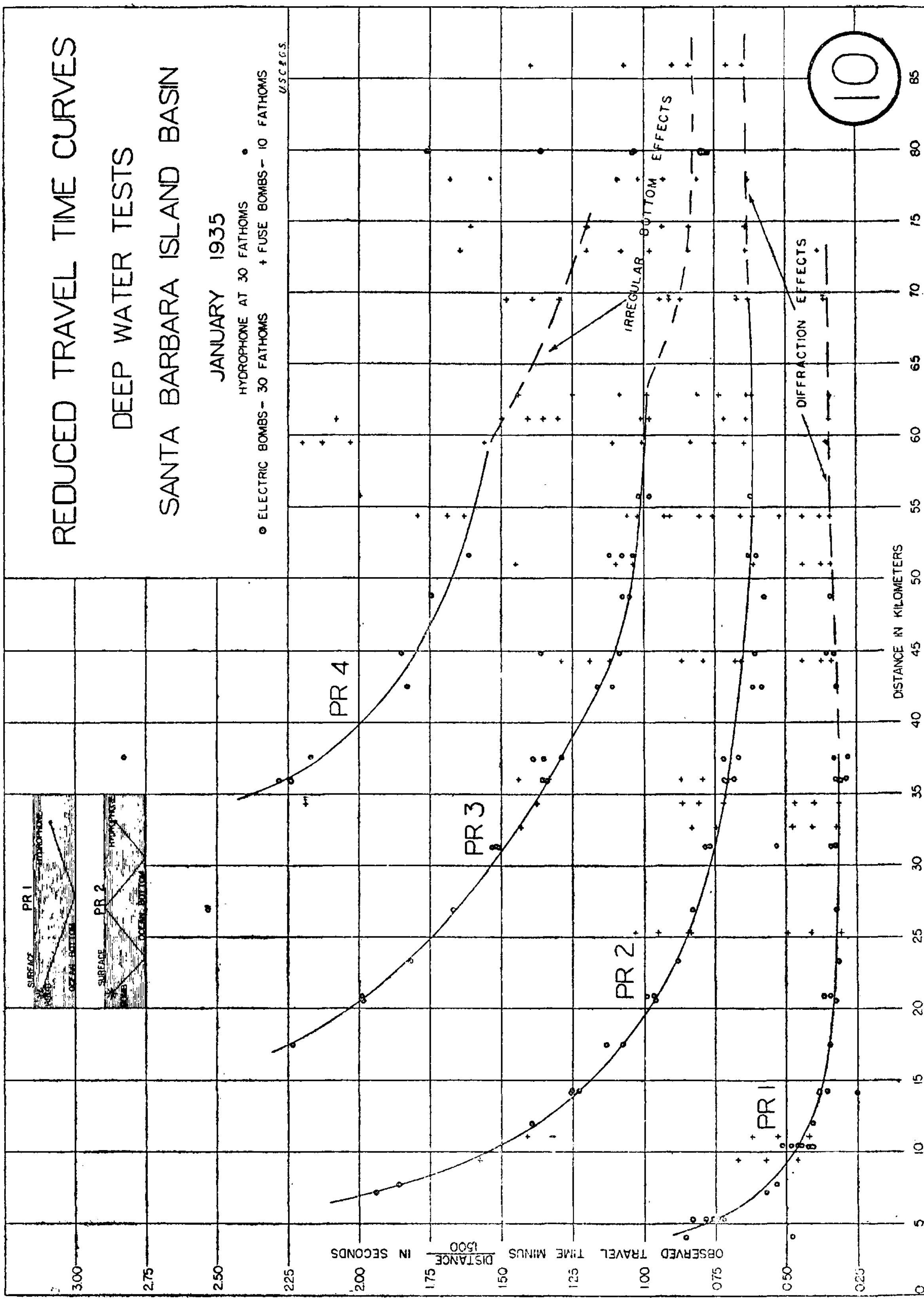

TEMPERATURE OF SEA WATER
IN SANTA BARBARA ISLANDS BASIN
JANUARY 9 - 21, 1935
SHIP PIONEER
JAN. 9
JAN. 11
JAN. 13
JAN. 16
JAN. 18
JAN. 12
SHIP GUIDE
JAN. 16
JAN. 17
JAN. 18
JAN. 20
JAN. 21
U.S.C.&G.S.
4
TEMPERATURE °C
DEPTH IN FATHOMS - RIGHT CURVE
DEPTH IN FATHOMS - LEFT CURVE

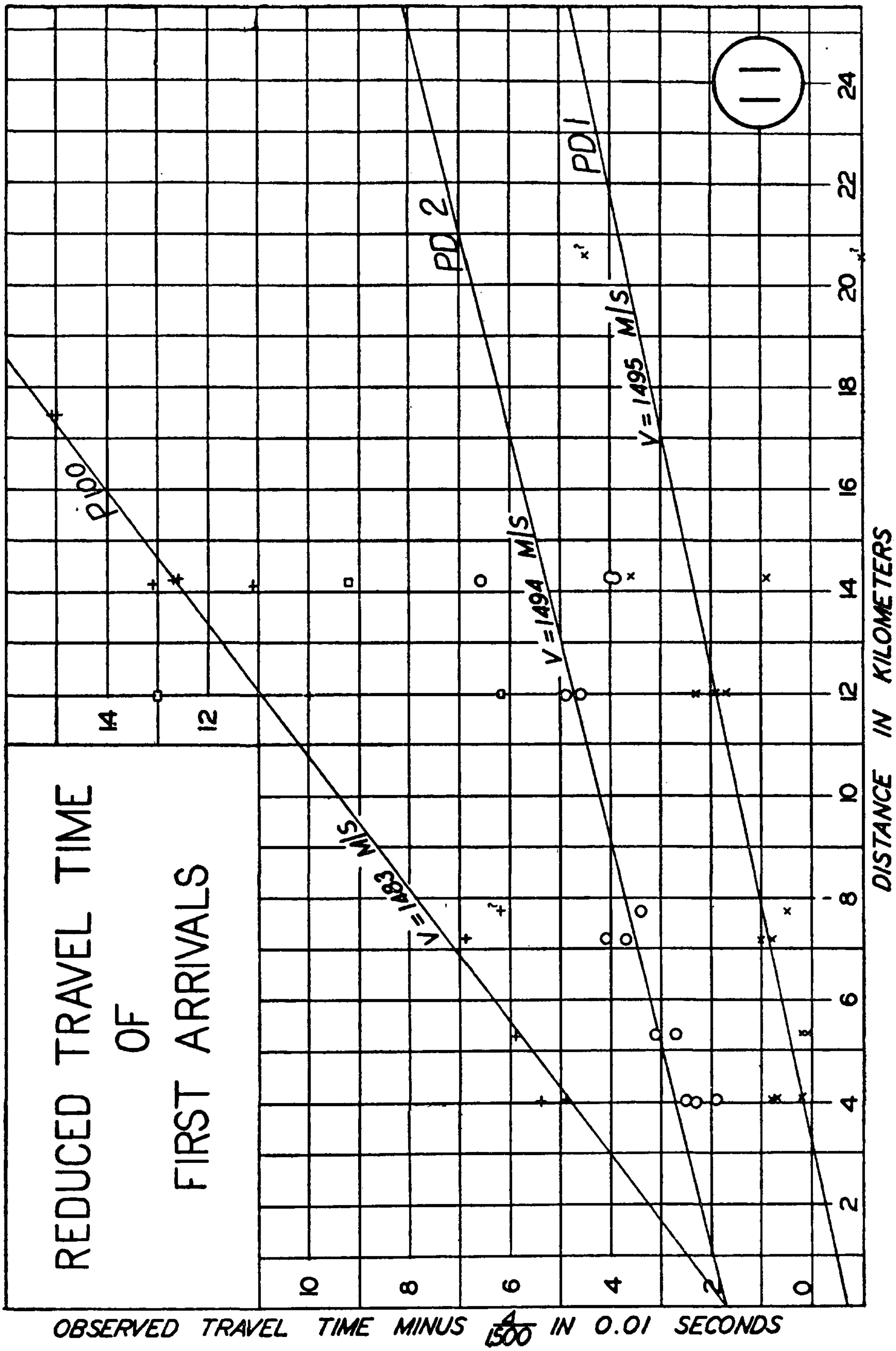

THEORETICAL VELOCITY OF SOUND
IN SANTA BARBARA BASIN
JANUARY 9-21,1935
FROM TEMPERATURE & SALINITY OBSERVATIONS
FIG.2 - BRITISH ADMIRALTY TABLES
X - COMPUTED POINTS UPPER SCALE
O - COMPUTED POINTS LOWER SCALE
FULL CURVES ASSUMED VELOCITY
DEPTH IN FATHOMS CURVE NO. 1
0
20
40
60
80
100
120
140
160
180
DEPTH IN FATHOMS CURVE NO. 2
0
100
200
300
400
500
600
700
800
900
VELOCITY IN METERS PER SEC.
1503
1499
1495
1491
1487
1483
1479
CURVE NO. 1
CURVE NO. 2
6

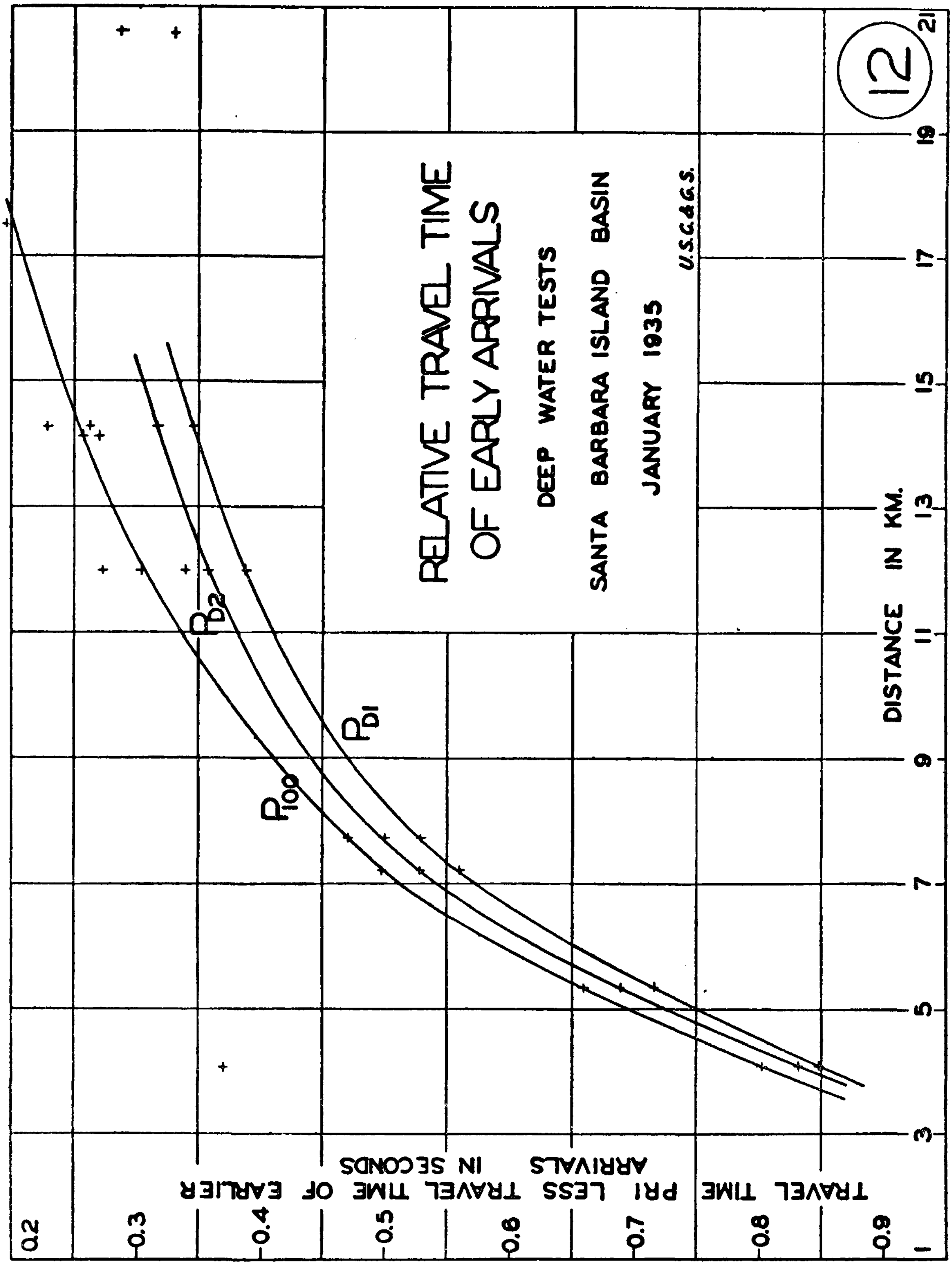

DEEP WATER
TRAVEL TIMES OF SOUND
IN SANTA BARBARA BASIN
HYDROPHONE AT 30 FATHOMS
○ ELECTRIC BOMBS — DEPTH 30 FATHOMS
△ FUSE BOMBS —— DEPTH 10 FATHOMS
7
CONTINUED ON FIGURE 8
PD 1
PR 1
PR 2
SURFACE
POINTS PLOTTED IN A VERTICAL LINE ARE DIFFERENT ARRIVALS OF SAME BOMB
PD-1
PR-1
PR-2
PR-3
PR-4
DISTANCE IN KILOMETERS
8
16
24
32
40
48
56
TIME IN SECONDS
8
16
24
32

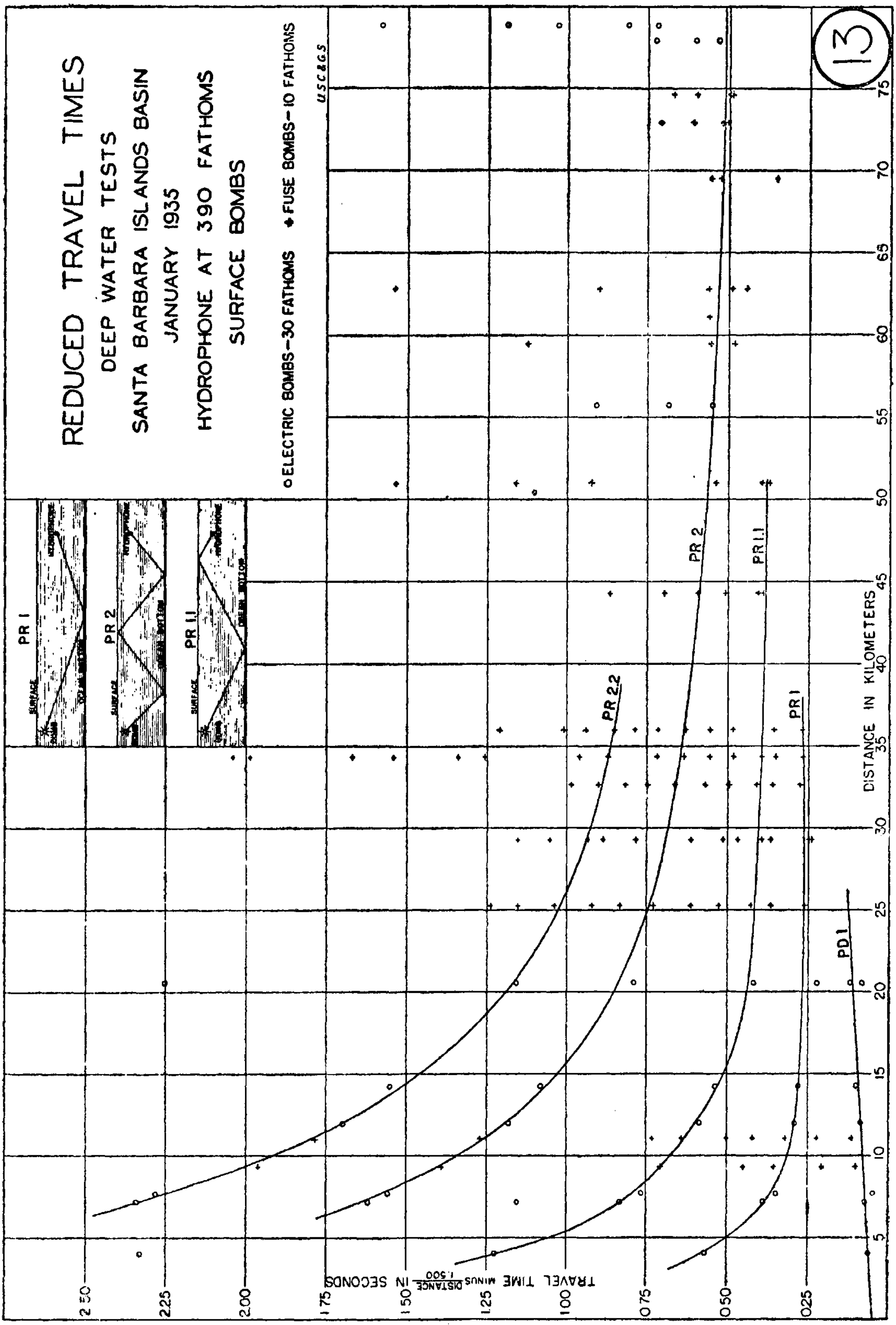

DEEP WATER TESTS
TRAVEL TIMES OF SOUND
IN SANTA BARBARA BASIN
HYDROPHONE AT 30 FATHOMS
○ ELECTRIC BOMBS - 30 FATHOMS
+ FUSE BOMBS - 10 FATHOMS
WATER SHOALS FROM 900 TO 600 FATHOMS
BETWEEN 50 AND 70 SECONDS
POINTS PLOTTED IN A VERTICAL LINE ARE
DIFFERENT ARRIVALS OF SAME BOMB
U.S.C.&G.S.
8
DISTANCE IN KILOMETERS
TRAVEL TIME IN SECONDS
PR 1
PR 2
PR 3
PR 4
PR 5
SURFACE
OCEAN BOTTOM
HYDROPHONE
CONTINUED FROM FIGURE 7

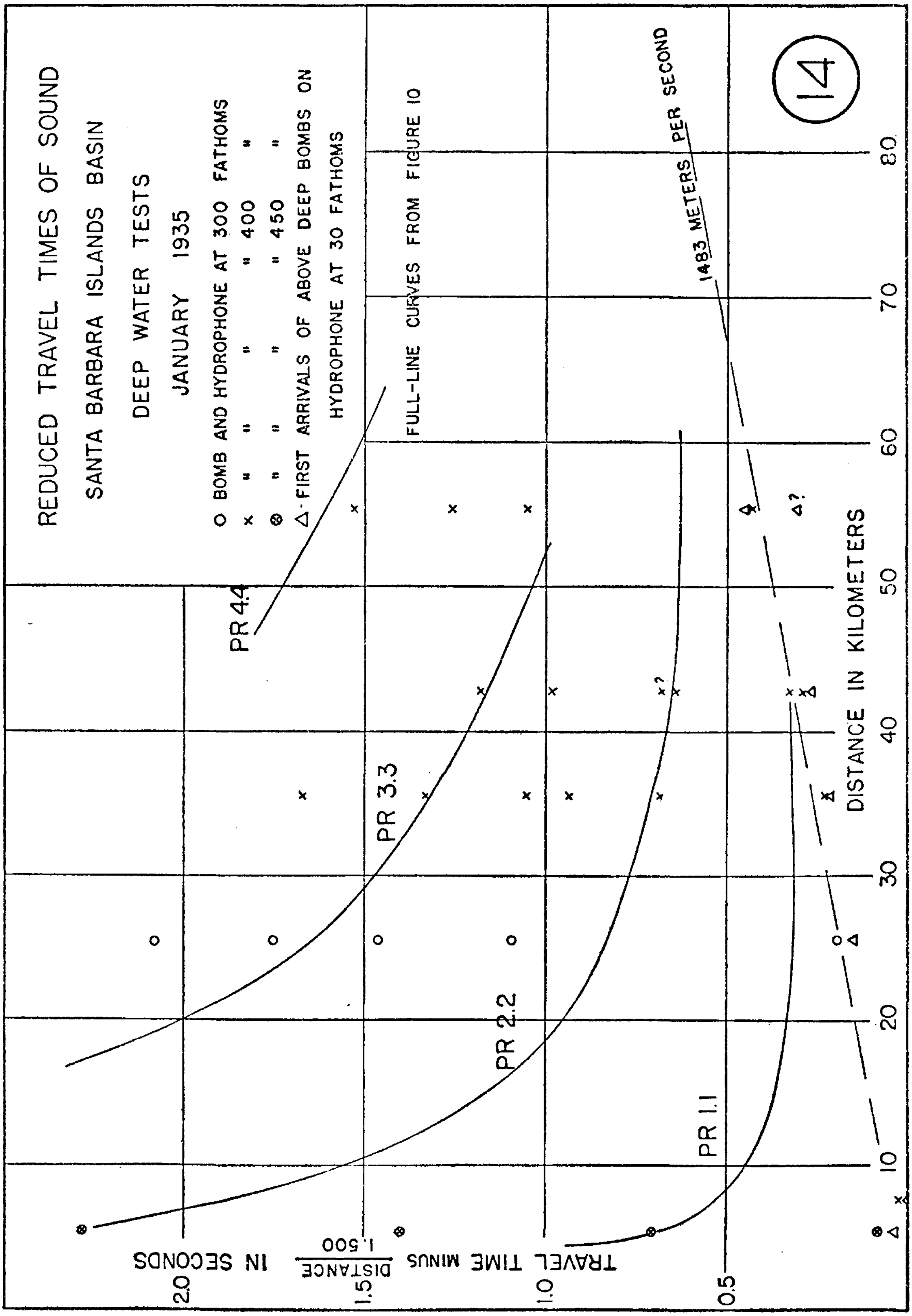

COMPARISON OF REDUCED TRAVEL TIMES
TO PROVE REFLECTION
DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN—JANUARY 1935
● PR 1
+ 1/2 REDUCED TRAVEL TIME OF PR 2 AT TWICE PLOTTED DISTANCE
● 1/3 " " " " PR 3 " 3 TIMES "
□ 1/4 " " " " PR 4 " 4 " "
○ 1/5 " " " " PR 5 " 5 " "
U.S.C.&G.S.
9
DISTANCE IN KILOMETERS
5
10
15
20
25
TIME MINUS DISTANCE/1.500 IN SECONDS
.1
.2
.3
.4
.5
.6
.7

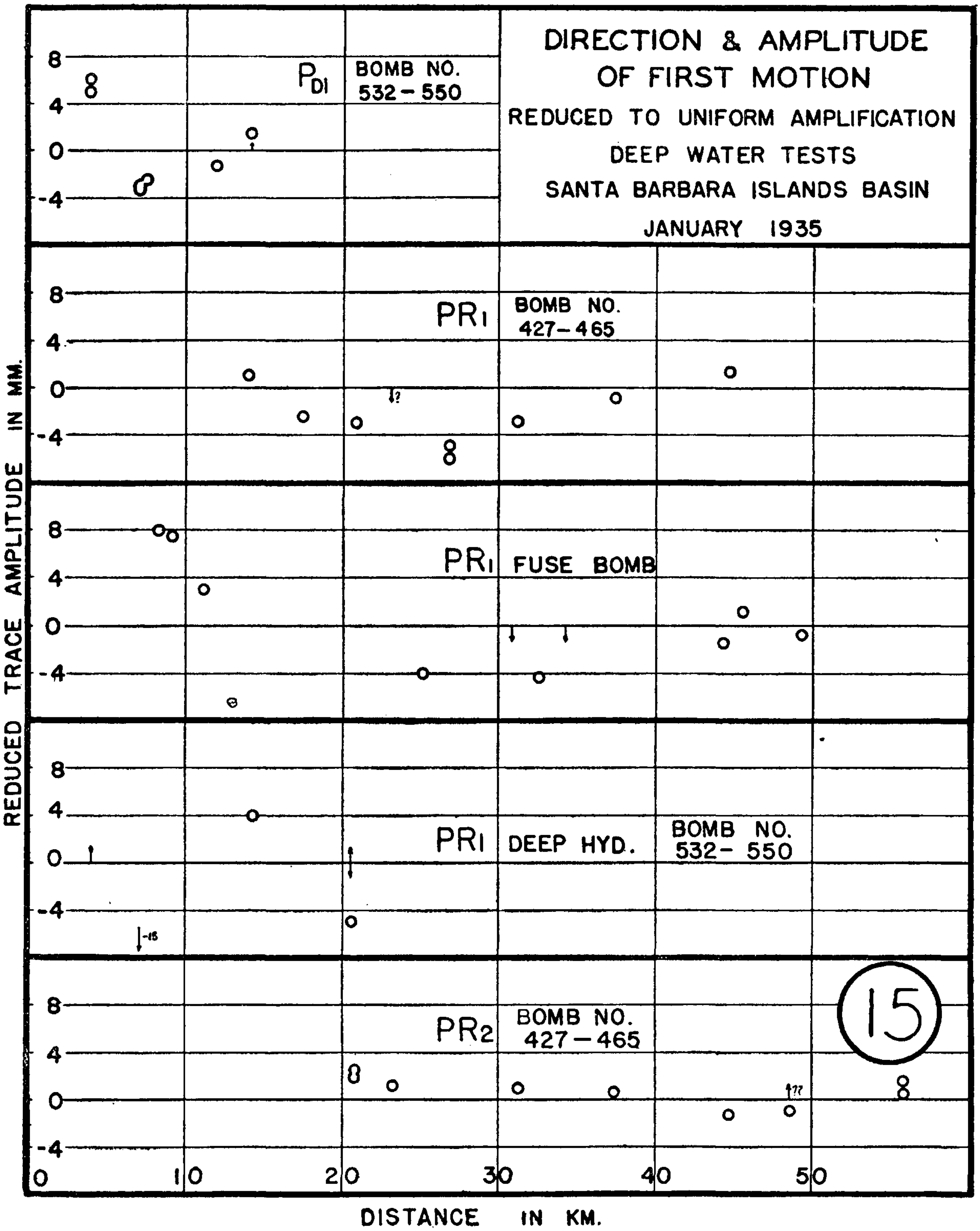

REDUCED TRAVEL TIME CURVES
DEEP WATER TESTS
SANTA BARBARA ISLAND BASIN
JANUARY 1935
HYDROPHONE AT 30 FATHOMS
⊙ ELECTRIC BOMBS - 30 FATHOMS
+ FUSE BOMBS - 10 FATHOMS
U.S.C.&G.S.
10
PR 1
PR 2
PR 3
PR 4
SURFACE
HYDROPHONE
OCEAN BOTTOM
IRREGULAR BOTTOM EFFECTS
DIFFRACTION EFFECTS
DISTANCE IN KILOMETERS
OBSERVED TRAVEL TIME MINUS DISTANCE/1500 IN SECONDS
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85
0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00

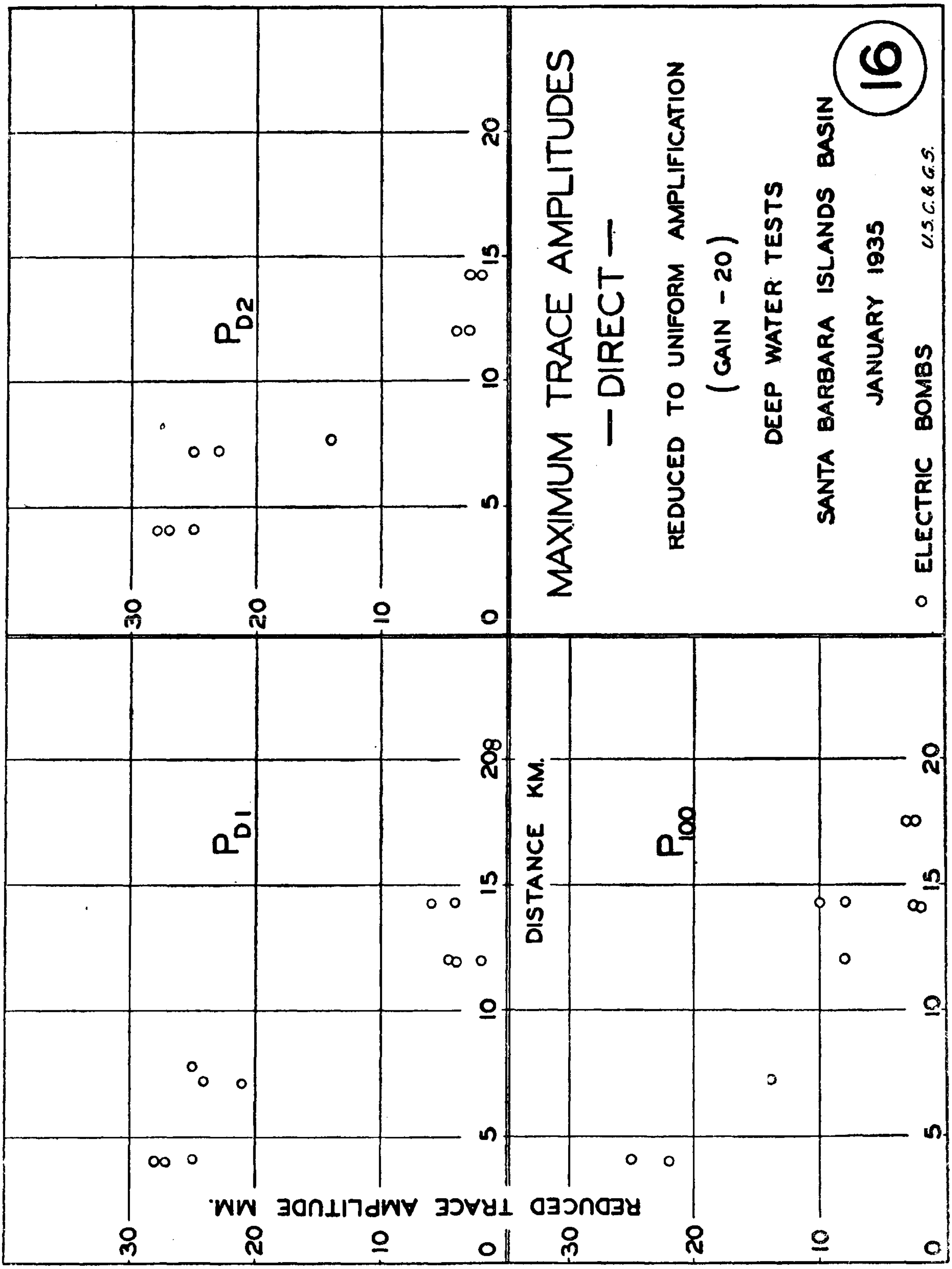

REDUCED TRAVEL TIME
OF
FIRST ARRIVALS
11
P100
V = 1483 M/S
PD 2
V = 1494 M/S
PD 1
V = 1495 M/S
DISTANCE IN KILOMETERS
OBSERVED TRAVEL TIME MINUS Δ/1500 IN 0.01 SECONDS


RELATIVE TRAVEL TIME
OF EARLY ARRIVALS
DEEP WATER TESTS
SANTA BARBARA ISLAND BASIN
JANUARY 1935
U.S.C.&G.S.
12
DISTANCE IN KM.
1
3
5
7
9
11
13
15
17
19
21
TRAVEL TIME PRI LESS TRAVEL TIME OF EARLIER
ARRIVALS IN SECONDS
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
P100
PD1
PD2

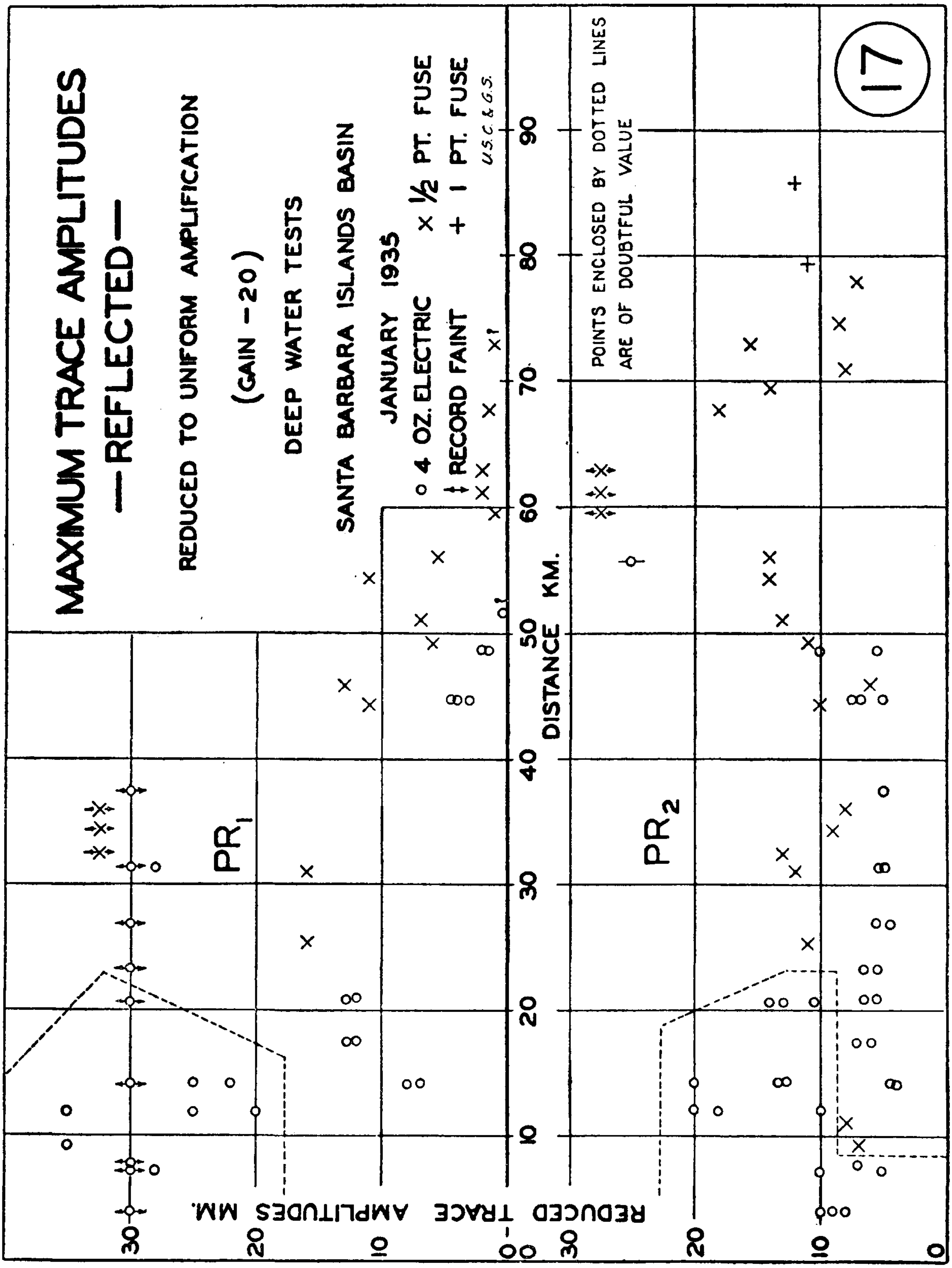

REDUCED TRAVEL TIMES
DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
HYDROPHONE AT 390 FATHOMS
SURFACE BOMBS
o ELECTRIC BOMBS—30 FATHOMS
+ FUSE BOMBS—10 FATHOMS
U.S.C.&G.S.
13
PR 1
PR 2
PR 1.1
SURFACE
OCEAN BOTTOM
PR 2.2
PD 1
DISTANCE IN KILOMETERS
TRAVEL TIME MINUS DISTANCE/1.500 IN SECONDS
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
2.50
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75

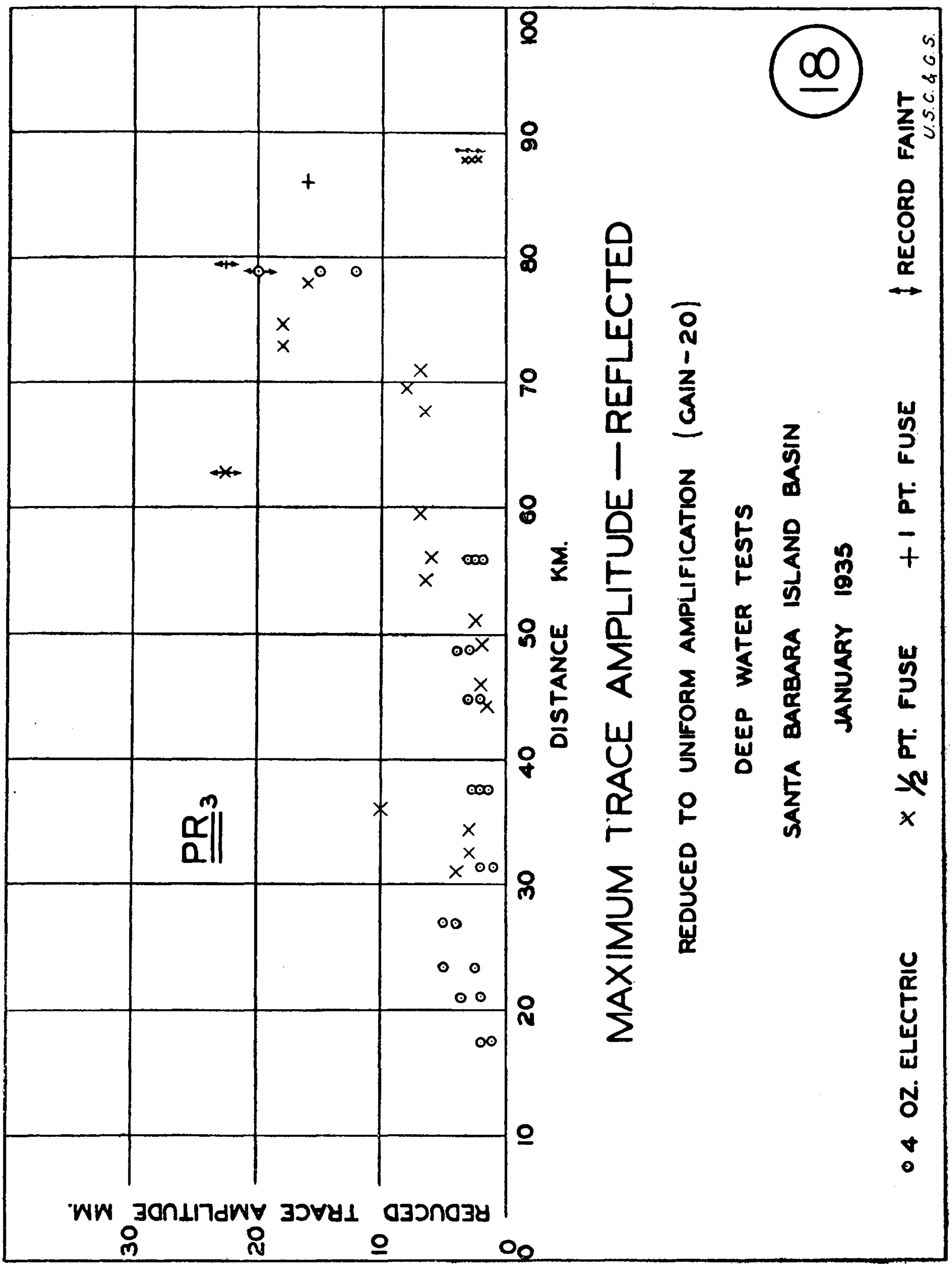

REDUCED TRAVEL TIMES OF SOUND
SANTA BARBARA ISLANDS BASIN
DEEP WATER TESTS
JANUARY 1935
O BOMB AND HYDROPHONE AT 300 FATHOMS
× " " " " 400 "
⊗ " " " " 450 "
Δ - FIRST ARRIVALS OF ABOVE DEEP BOMBS ON HYDROPHONE AT 30 FATHOMS
FULL-LINE CURVES FROM FIGURE 10
1483 METERS PER SECOND
14
PR 4.4
PR 3.3
PR 2.2
PR 1.1
10
20
30
40
50
60
70
80
DISTANCE IN KILOMETERS
0.5
1.0
1.5
2.0
TRAVEL TIME MINUS DISTANCE/1,500 IN SECONDS

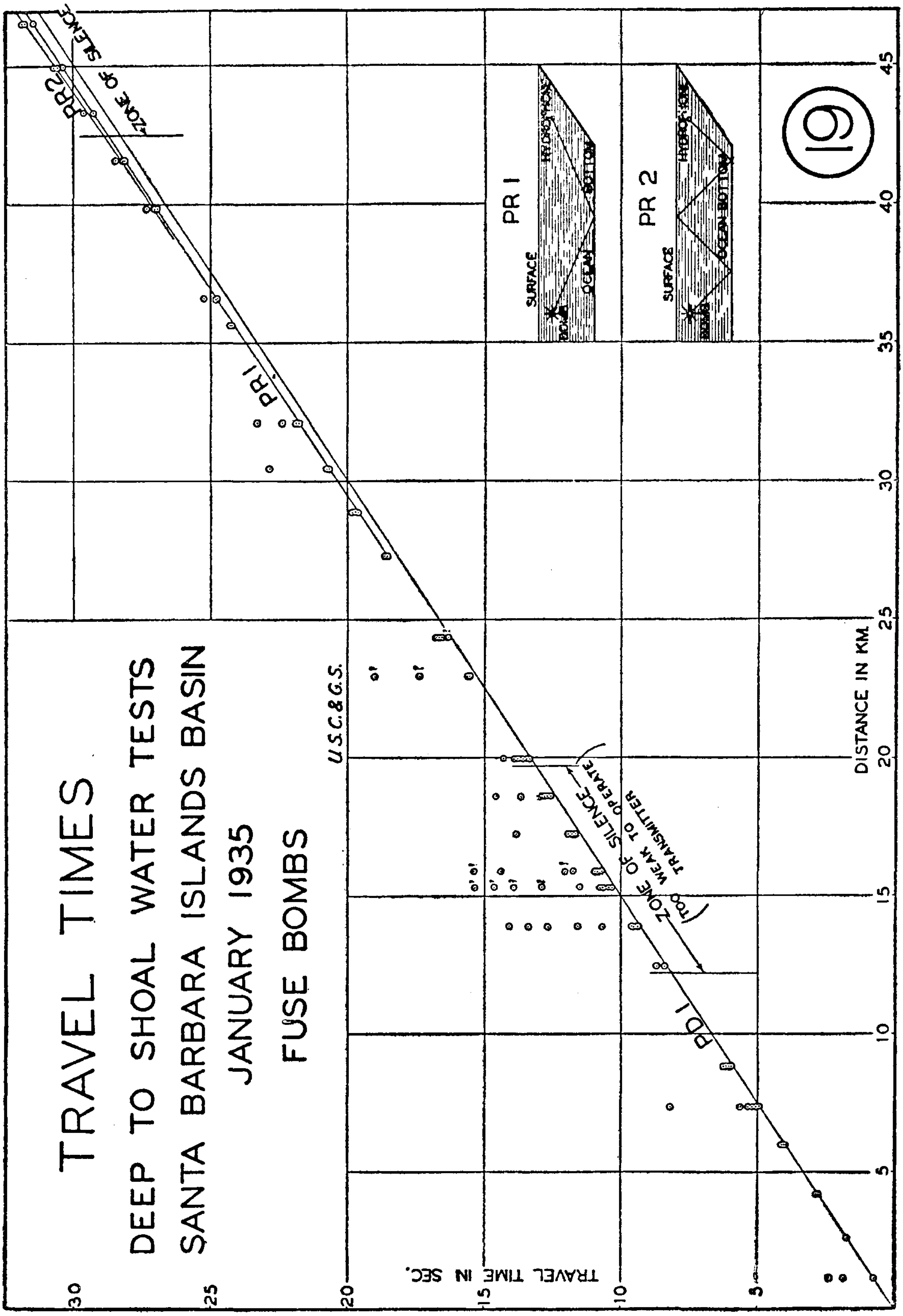

DIRECTION & AMPLITUDE OF FIRST MOTION
REDUCED TO UNIFORM AMPLIFICATION
DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
P_{D1}
BOMB NO. 532 – 550
PR_1
BOMB NO. 427 – 465
PR_1
FUSE BOMB
PR_1
DEEP HYD.
BOMB NO. 532 – 550
PR_2
BOMB NO. 427 – 465
15
REDUCED TRACE AMPLITUDE IN MM.
DISTANCE IN KM.
0
10
20
30
40
50
8
4
0
-4

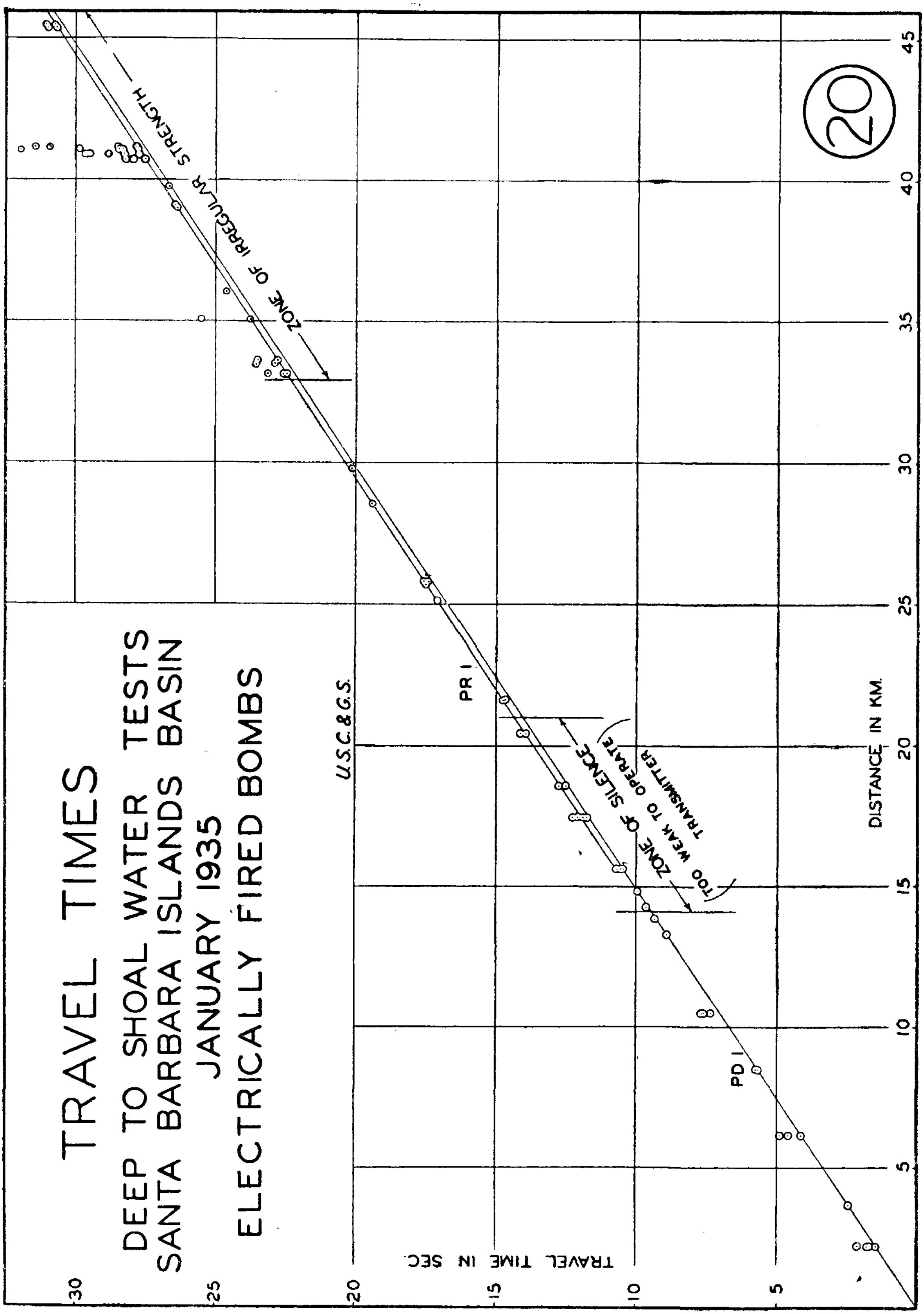


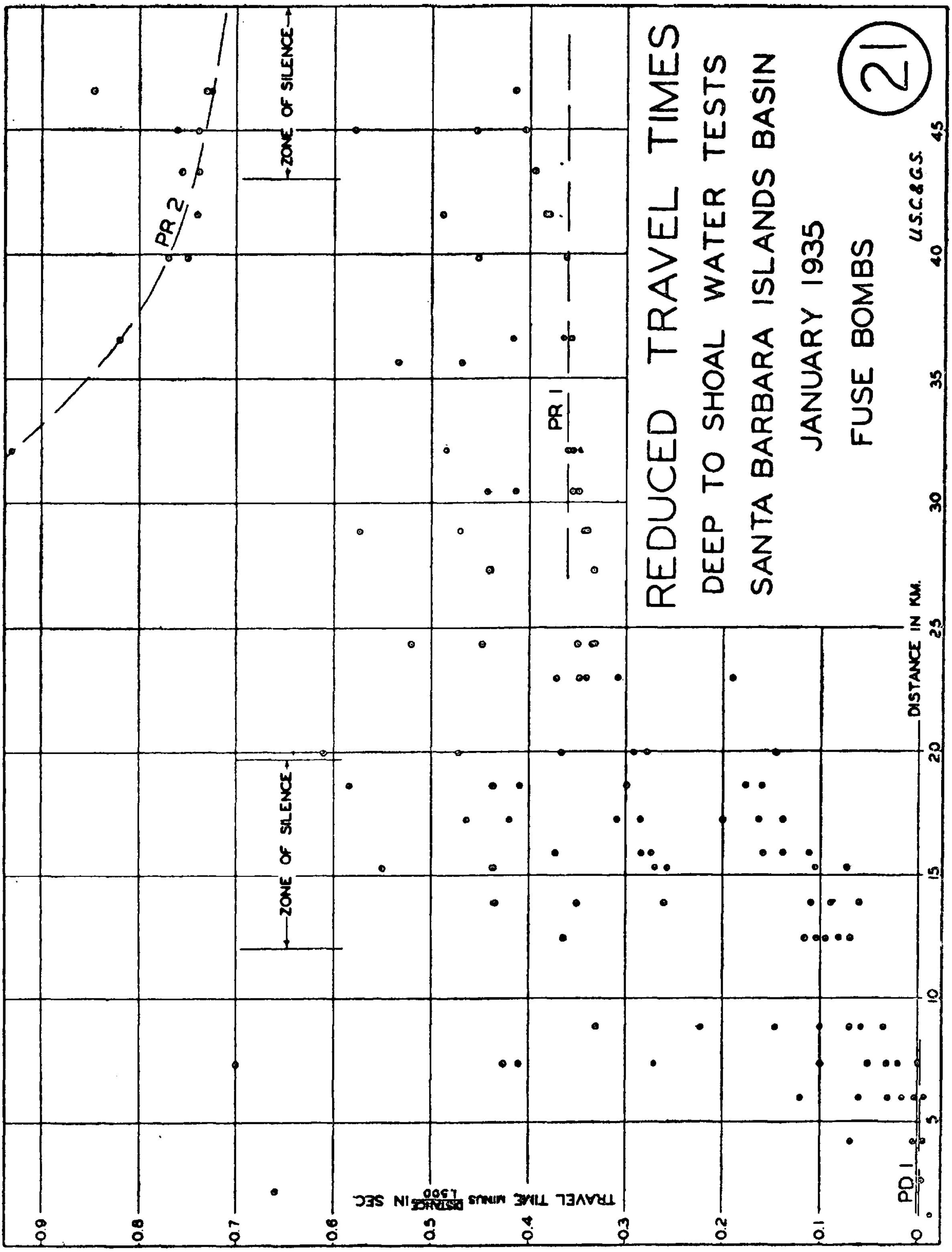
MAXIMUM TRACE AMPLITUDES
— DIRECT —
REDUCED TO UNIFORM AMPLIFICATION
(GAIN - 20)
DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
○ ELECTRIC BOMBS
U.S.C.&G.S.
16
P D2
P D1
P 100
DISTANCE KM.
REDUCED TRACE AMPLITUDE MM.

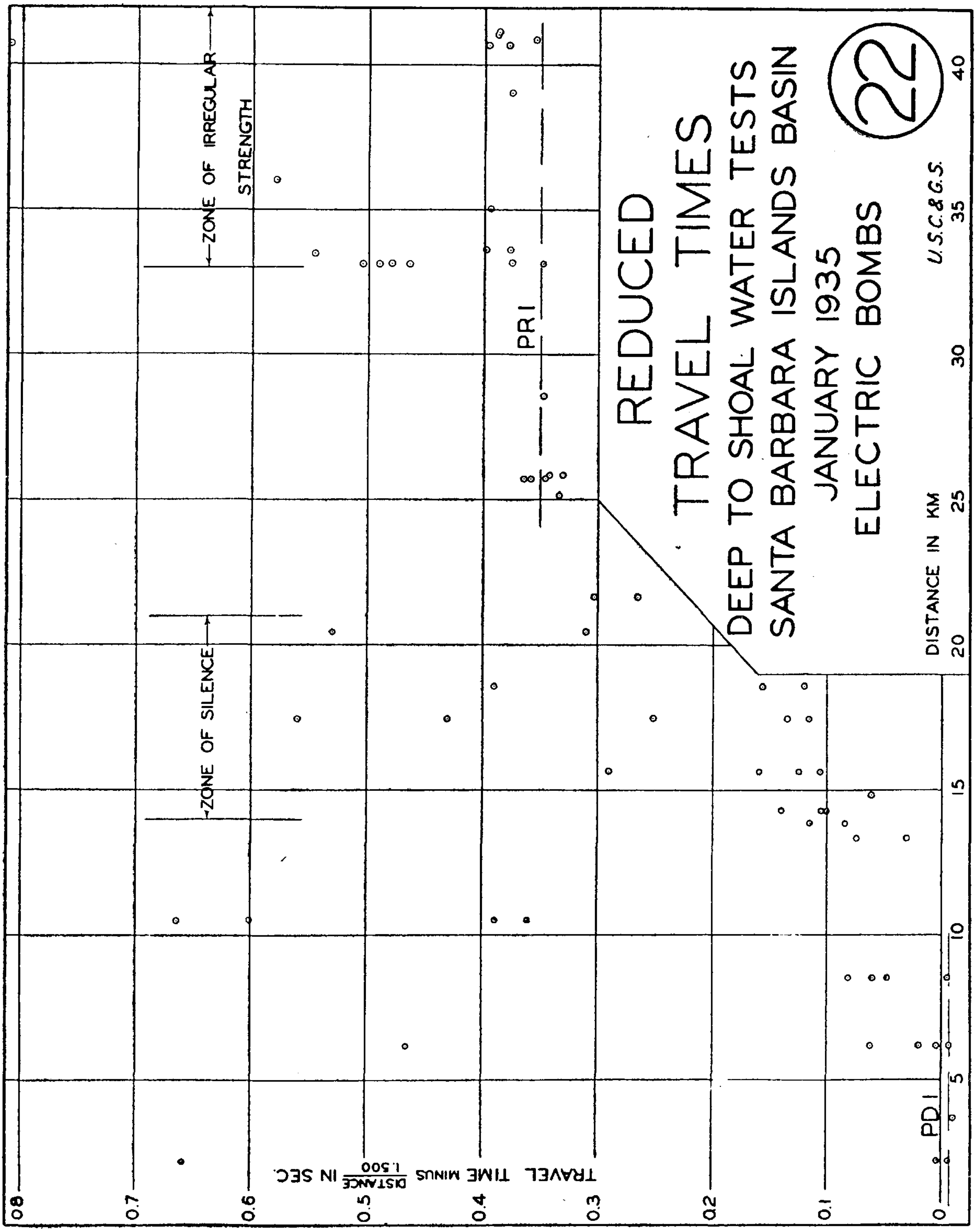

MAXIMUM TRACE AMPLITUDES
—REFLECTED—
REDUCED TO UNIFORM AMPLIFICATION
(GAIN -20)
DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
○ 4 OZ. ELECTRIC
× 1/2 PT. FUSE
↕ RECORD FAINT
+ 1 PT. FUSE
U.S.C.&G.S.
POINTS ENCLOSED BY DOTTED LINES ARE OF DOUBTFUL VALUE
17
PR1
PR2
DISTANCE KM.
REDUCED TRACE AMPLITUDES MM.
10 20 30 40 50 60 70 80 90
0 10 20 30

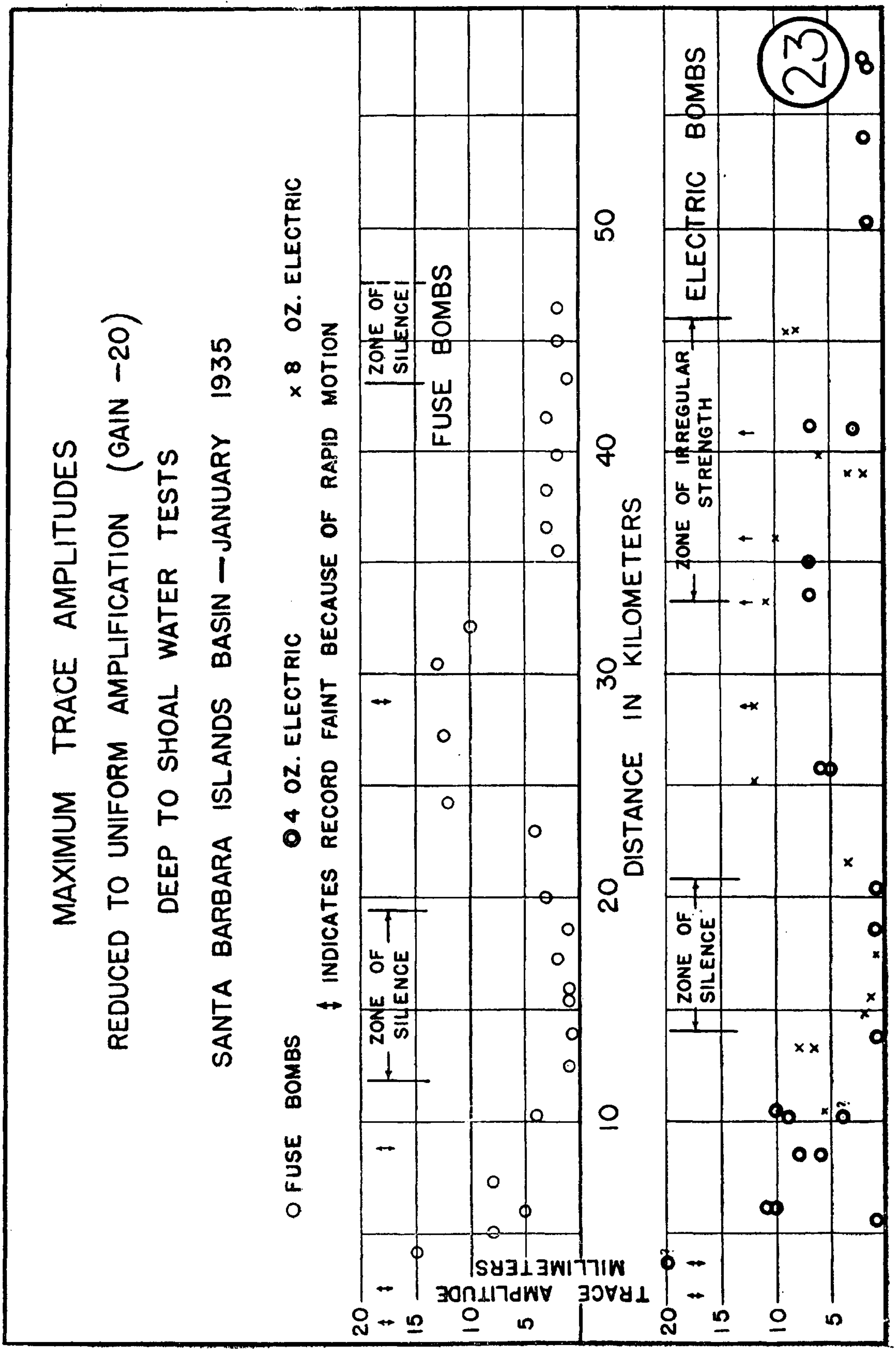

MAXIMUM TRACE AMPLITUDE — REFLECTED
REDUCED TO UNIFORM AMPLIFICATION (GAIN-20)
DEEP WATER TESTS
SANTA BARBARA ISLAND BASIN
JANUARY 1935
18
PR3
DISTANCE KM.
REDUCED TRACE AMPLITUDE MM.
0 10 20 30 40 50 60 70 80 90 100
0 10 20 30
○ 4 OZ. ELECTRIC × ½ PT. FUSE + 1 PT. FUSE ↕ RECORD FAINT
U.S.C.&G.S.

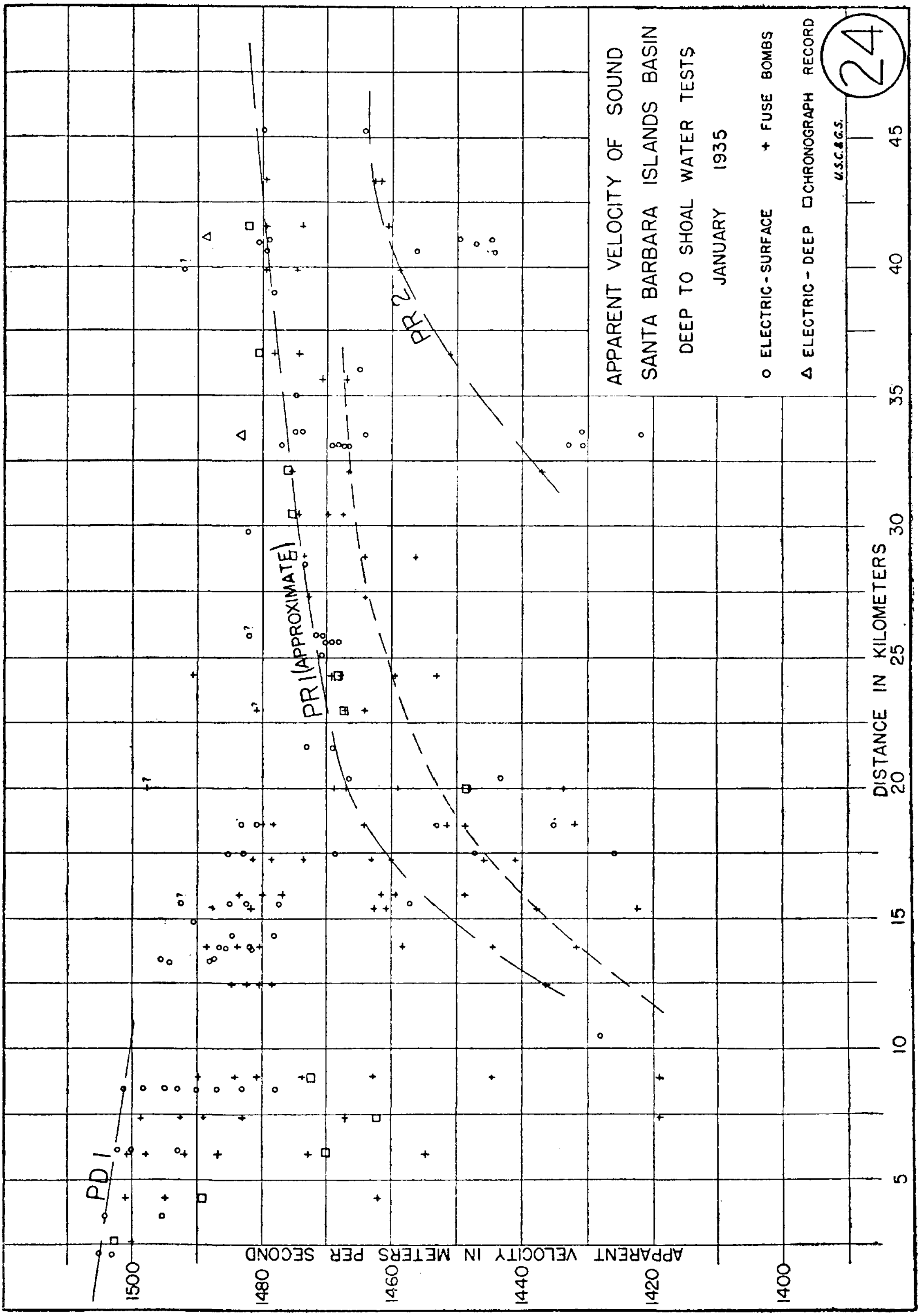

TRAVEL TIMES
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
FUSE BOMBS
U.S.C.&G.S.
PR 1
PR 2
PD 1
ZONE OF SILENCE
TOO WEAK TO OPERATE TRANSMITTER
SURFACE
OCEAN BOTTOM
HYDROPHONE
BOMB
19
DISTANCE IN KM.
TRAVEL TIME IN SEC.

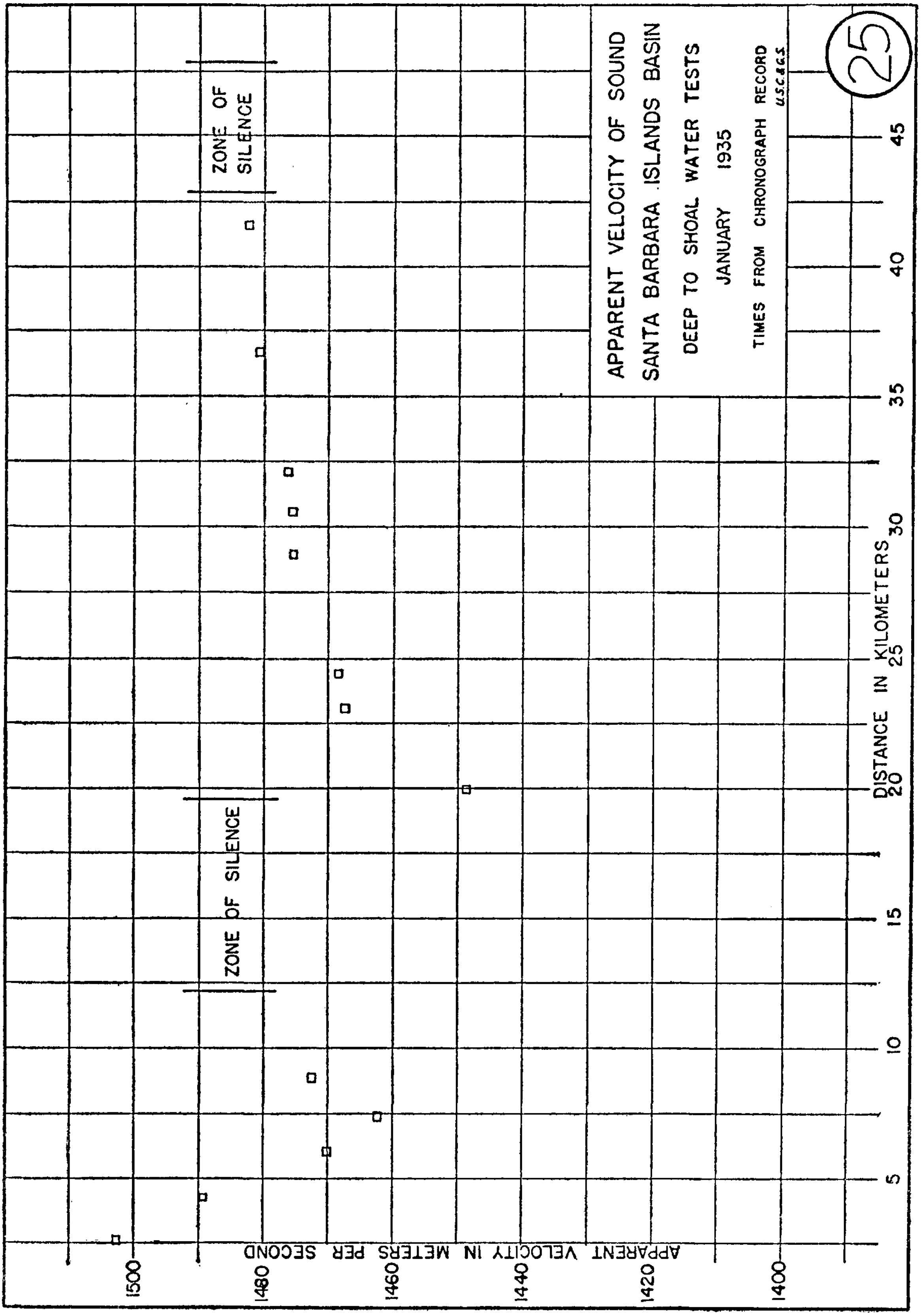

TRAVEL TIMES
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
ELECTRICALLY FIRED BOMBS
ZONE OF IRREGULAR STRENGTH
ZONE OF SILENCE
TOO WEAK TO OPERATE TRANSMITTER
U.S.C.&G.S.
PR I
PD I
20
DISTANCE IN KM.
5
10
15
20
25
30
35
40
45
TRAVEL TIME IN SEC.
5
10
15
20
25
30

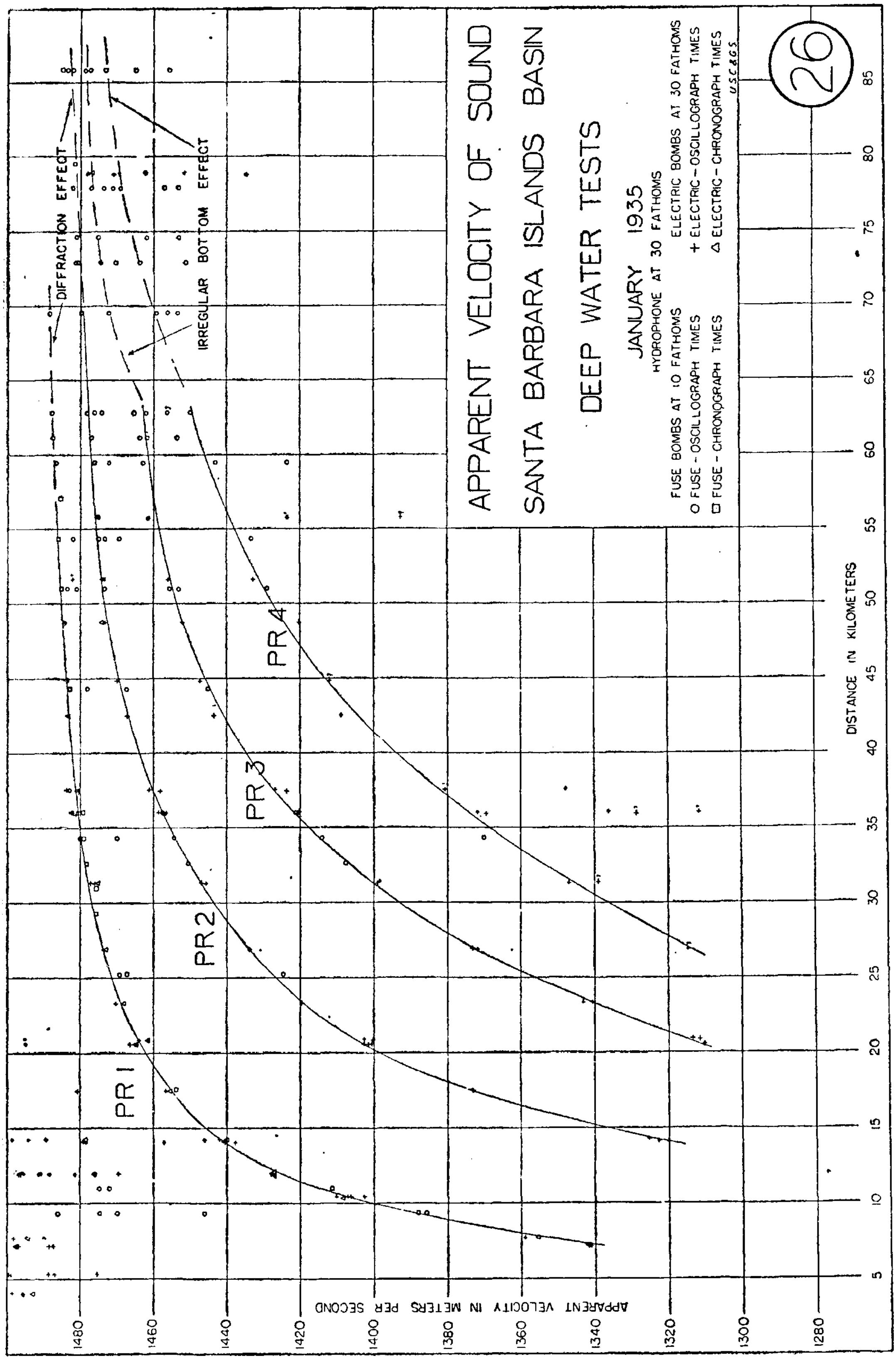

REDUCED TRAVEL TIMES
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
FUSE BOMBS
21
U.S.C.&G.S.
ZONE OF SILENCE
ZONE OF SILENCE
PR 2
PR 1
PD 1
DISTANCE IN KM.
TRAVEL TIME MINUS DISTANCE/1500 IN SEC.

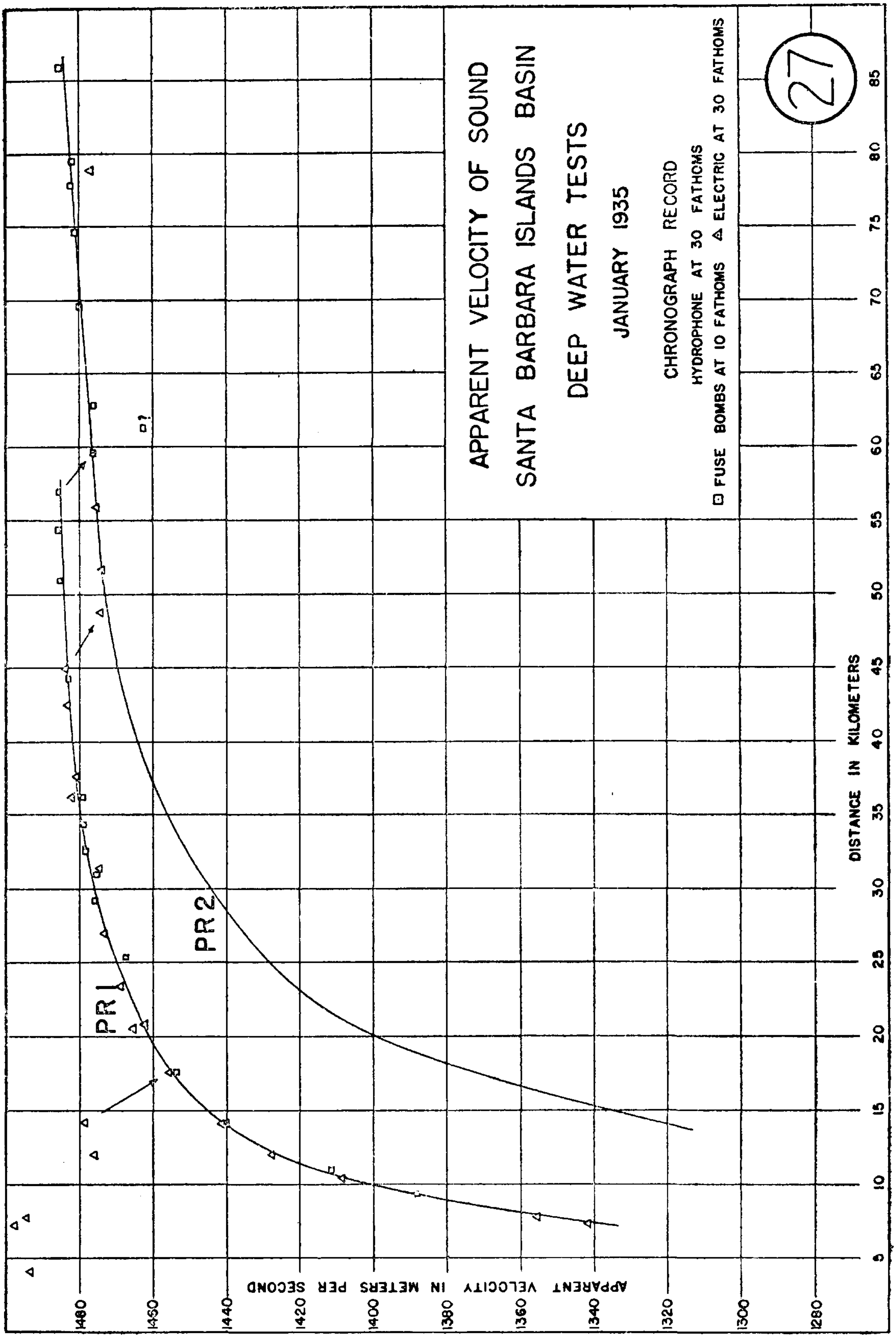

REDUCED
TRAVEL TIMES
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
ELECTRIC BOMBS
22
U.S.C.&G.S.
DISTANCE IN KM
0 5 10 15 20 25 30 35 40
TRAVEL TIME MINUS DISTANCE/1.500 IN SEC.
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
ZONE OF IRREGULAR STRENGTH
ZONE OF SILENCE
PR I
PD I

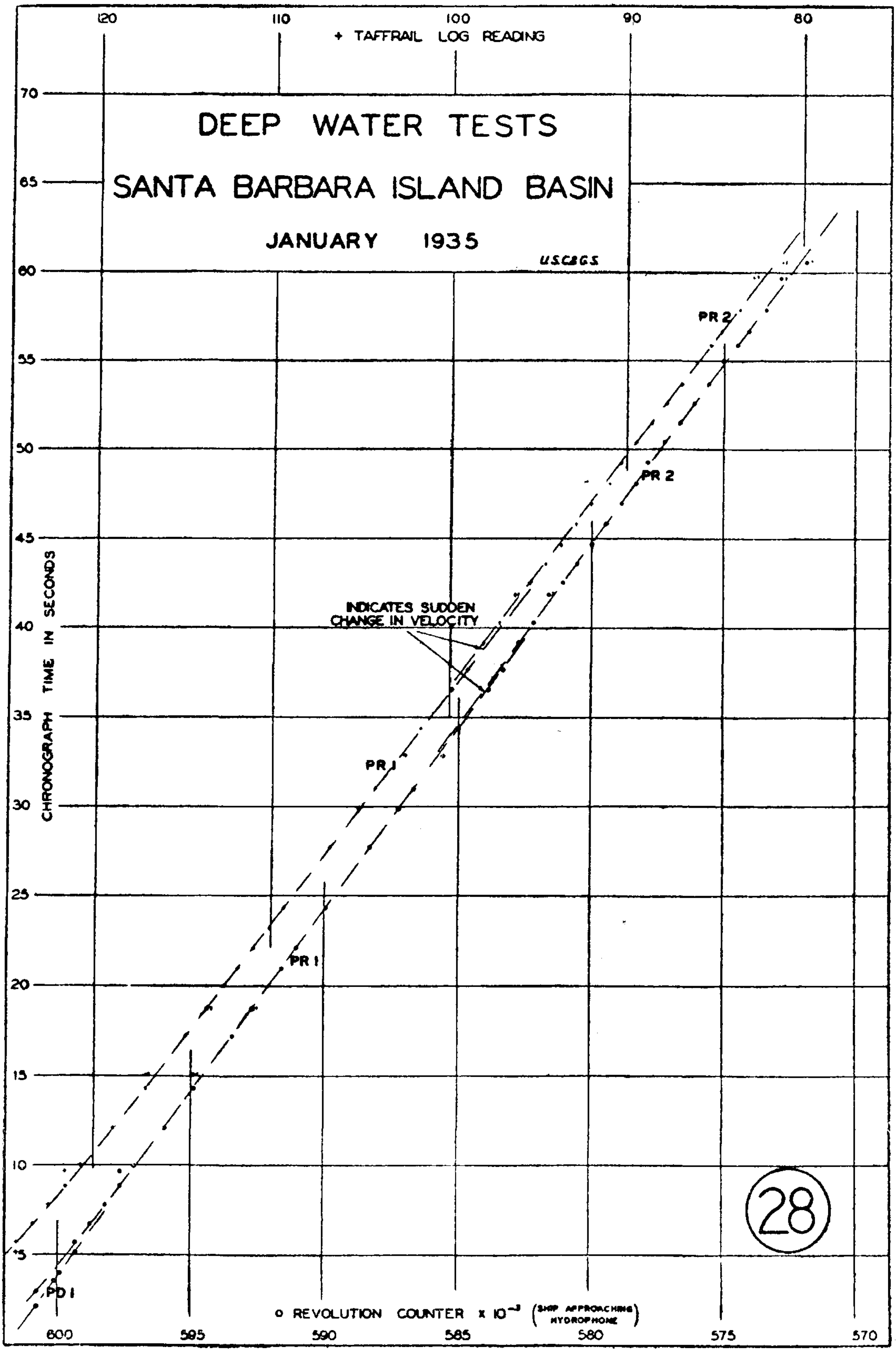

MAXIMUM TRACE AMPLITUDES
REDUCED TO UNIFORM AMPLIFICATION (GAIN −20)
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN—JANUARY 1935
O FUSE BOMBS
4 OZ. ELECTRIC
× 8 OZ. ELECTRIC
↕ INDICATES RECORD FAINT BECAUSE OF RAPID MOTION
ZONE OF SILENCE
ZONE OF SILENCE
FUSE BOMBS
ZONE OF SILENCE
ZONE OF IRREGULAR STRENGTH
ELECTRIC BOMBS
DISTANCE IN KILOMETERS
10
20
30
40
50
TRACE AMPLITUDE MILLIMETERS
20
15
10
5
20
15
10
5
23

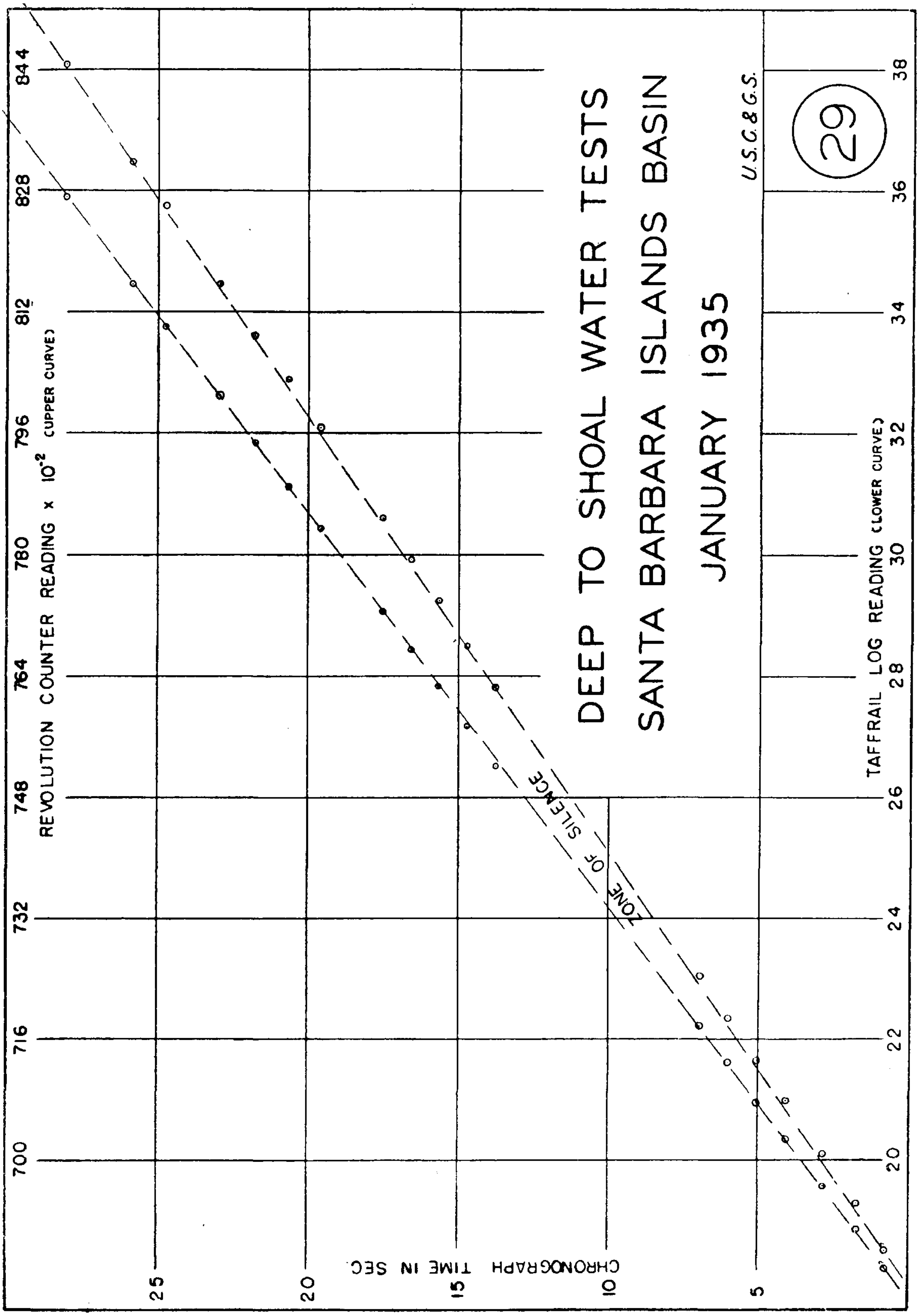

APPARENT VELOCITY OF SOUND
SANTA BARBARA ISLANDS BASIN
DEEP TO SHOAL WATER TESTS
JANUARY 1935
o ELECTRIC-SURFACE
+ FUSE BOMBS
Δ ELECTRIC-DEEP
□ CHRONOGRAPH RECORD
U.S.C.&G.S.
24
PD I
PR I (APPROXIMATE)
PR 2
DISTANCE IN KILOMETERS
5
10
15
20
25
30
35
40
45
APPARENT VELOCITY IN METERS PER SECOND
1500
1480
1460
1440
1420
1400

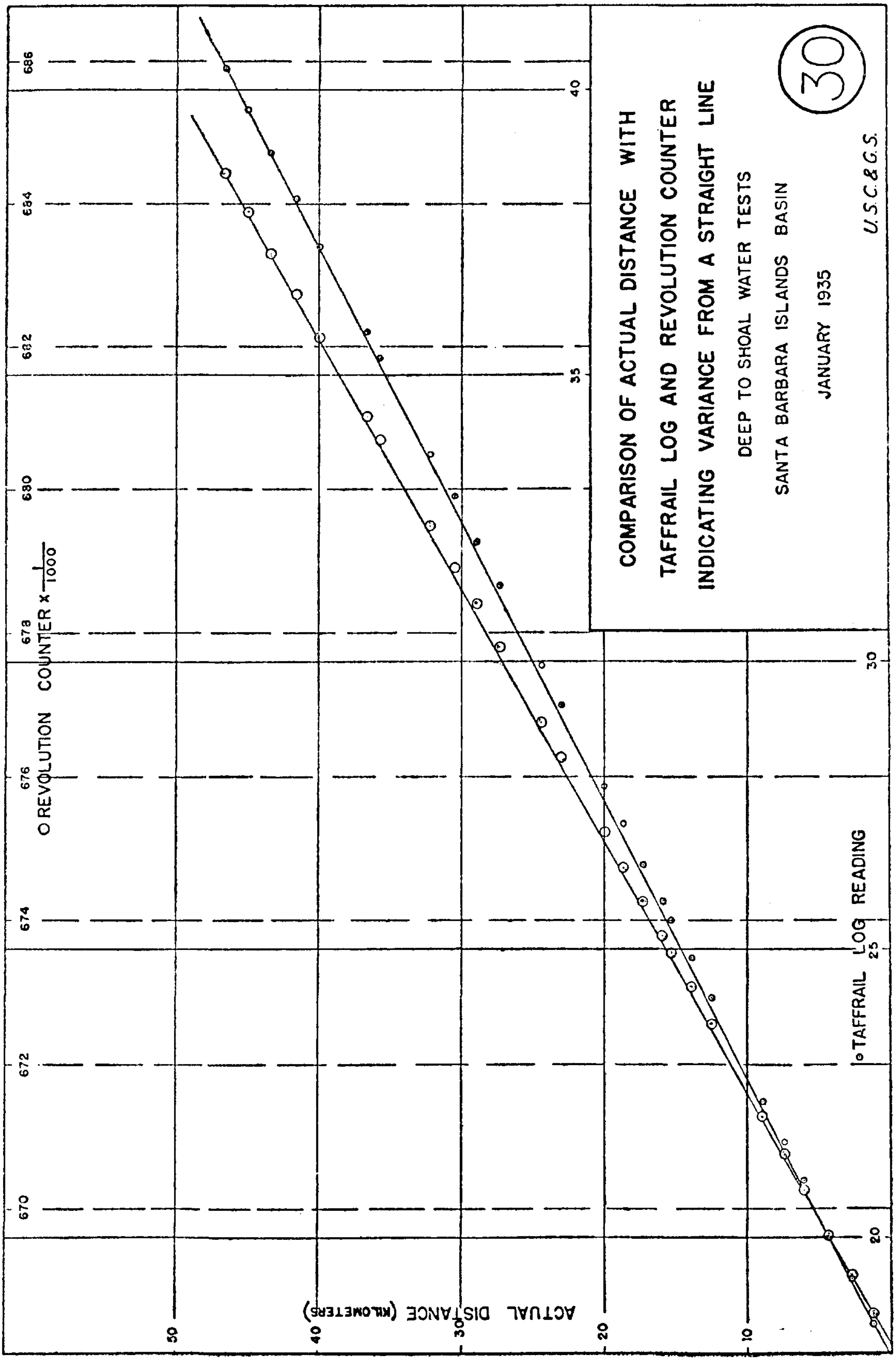

25
APPARENT VELOCITY OF SOUND
SANTA BARBARA ISLANDS BASIN
DEEP TO SHOAL WATER TESTS
JANUARY 1935
TIMES FROM CHRONOGRAPH RECORD
U.S.C.&G.S.
ZONE OF SILENCE
ZONE OF SILENCE
DISTANCE IN KILOMETERS
5
10
15
20
25
30
35
40
45
APPARENT VELOCITY IN METERS PER SECOND
1500
1480
1460
1440
1420
1400

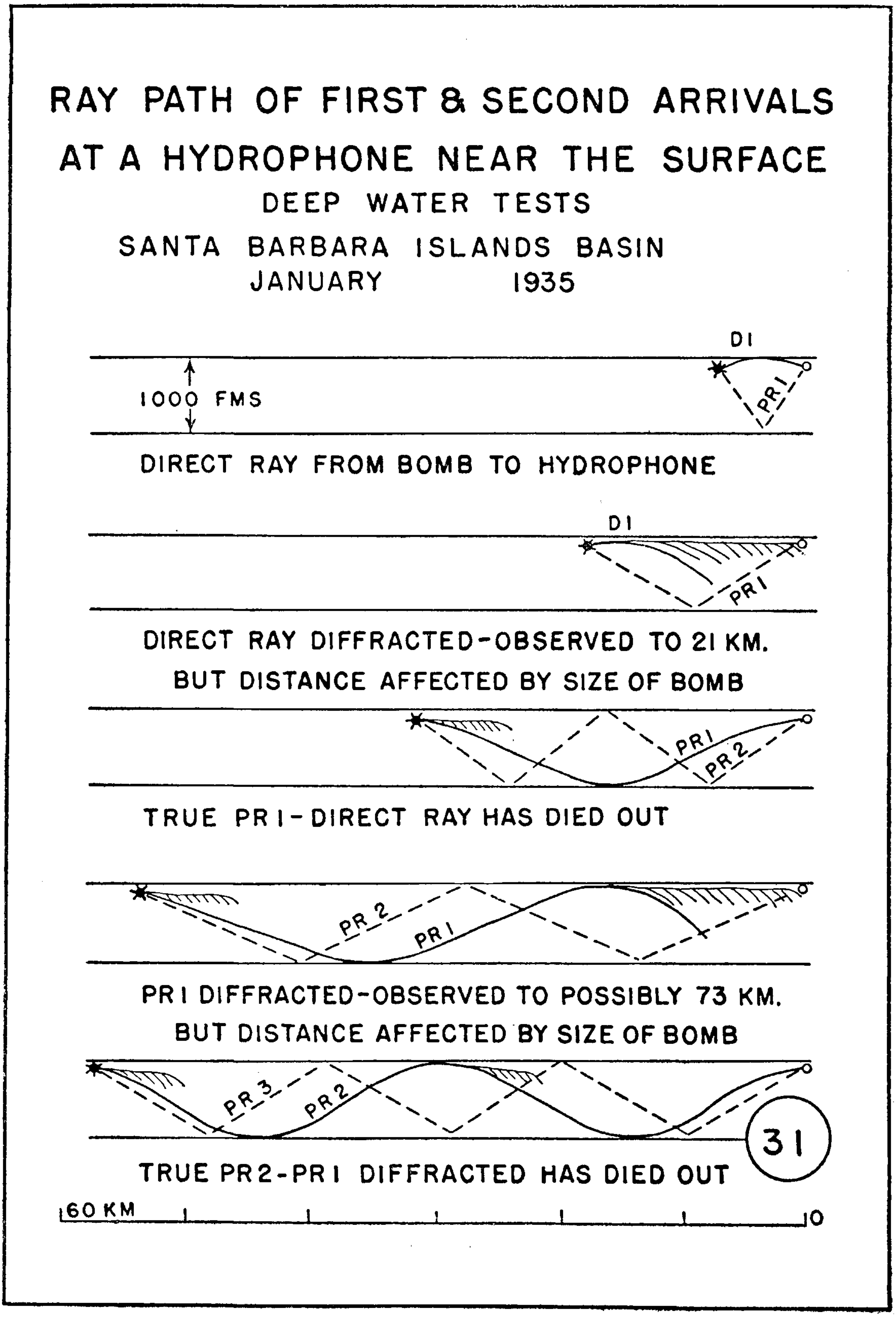

APPARENT VELOCITY OF SOUND
SANTA BARBARA ISLANDS BASIN
DEEP WATER TESTS
JANUARY 1935
HYDROPHONE AT 10 FATHOMS
HYDROPHONE AT 30 FATHOMS
FUSE BOMBS AT 10 FATHOMS
O FUSE - OSCILLOGRAPH TIMES
◻ FUSE - CHRONOGRAPH TIMES
ELECTRIC BOMBS AT 30 FATHOMS
+ ELECTRIC - OSCILLOGRAPH TIMES
Δ ELECTRIC - CHRONOGRAPH TIMES
USC&GS
26
DIFFRACTION EFFECT
IRREGULAR BOTTOM EFFECT
PR 1
PR 2
PR 3
PR 4
DISTANCE IN KILOMETERS
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
APPARENT VELOCITY IN METERS PER SECOND
1480
1460
1440
1420
1400
1380
1360
1340
1320
1300
1280

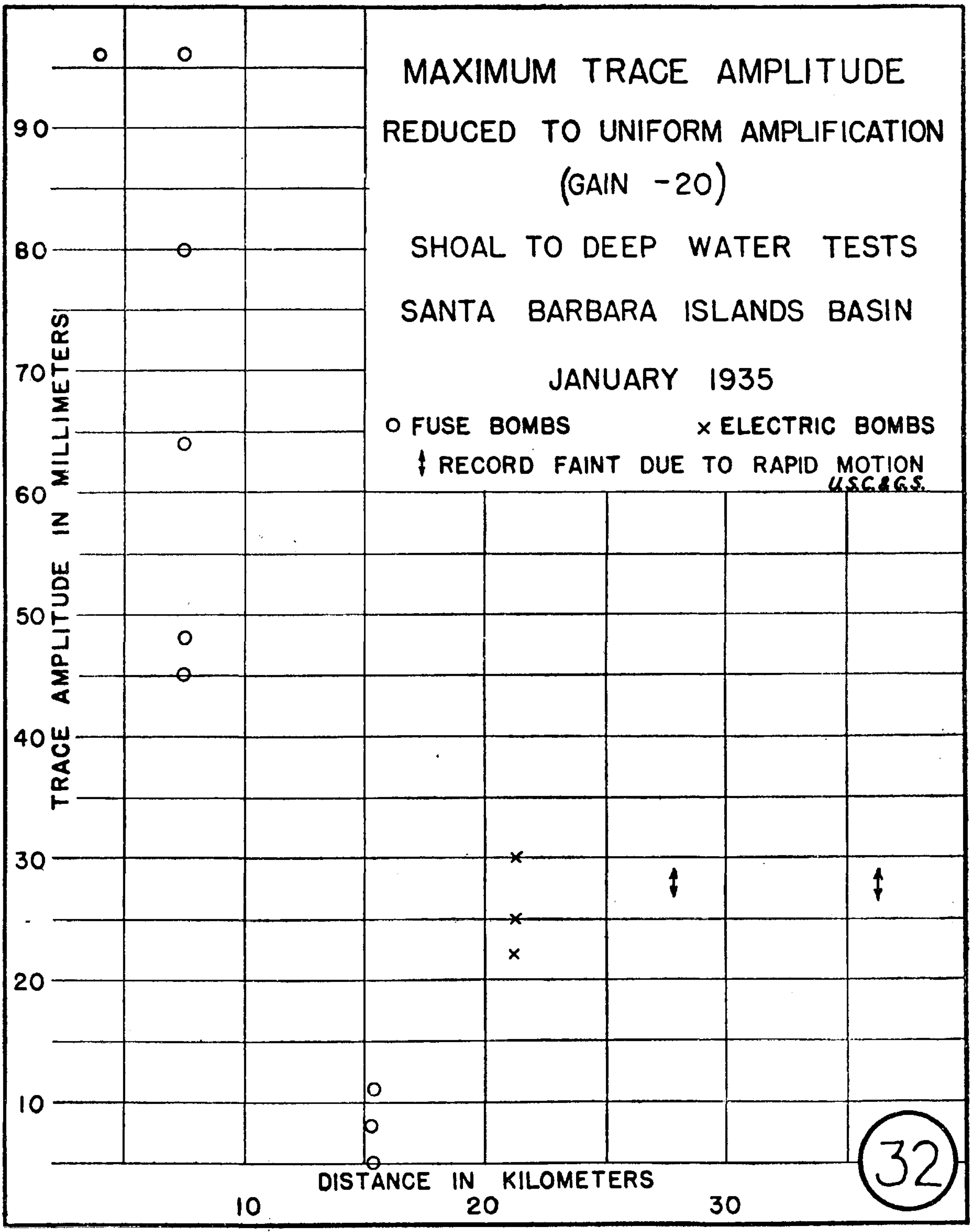

APPARENT VELOCITY OF SOUND
SANTA BARBARA ISLANDS BASIN
DEEP WATER TESTS
JANUARY 1935
CHRONOGRAPH RECORD
HYDROPHONE AT 30 FATHOMS
FUSE BOMBS AT 10 FATHOMS
ELECTRIC AT 30 FATHOMS
27
PR 1
PR 2
DISTANCE IN KILOMETERS
APPARENT VELOCITY IN METERS PER SECOND


DEEP WATER TESTS
SANTA BARBARA ISLAND BASIN
JANUARY 1935
U.S.C.&G.S.
+ TAFFRAIL LOG READING
120
110
100
90
80
CHRONOGRAPH TIME IN SECONDS
70
65
60
55
50
45
40
35
30
25
20
15
10
5
INDICATES SUDDEN CHANGE IN VELOCITY
PR 2
PR 2
PR 1
PR 1
PD 1
○ REVOLUTION COUNTER x 10⁻³ (SHIP APPROACHING HYDROPHONE)
600
595
590
585
580
575
570
28


DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
U.S.C.&G.S.
29
REVOLUTION COUNTER READING x 10^2 (UPPER CURVE)
700 716 732 748 764 780 796 812 828 844
TAFFRAIL LOG READING (LOWER CURVE)
20 22 24 26 28 30 32 34 36 38
CHRONOGRAPH TIME IN SEC.
5 10 15 20 25
ZONE OF SILENCE


COMPARISON OF ACTUAL DISTANCE WITH
TAFFRAIL LOG AND REVOLUTION COUNTER
INDICATING VARIANCE FROM A STRAIGHT LINE
DEEP TO SHOAL WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
30
U.S.C.&G.S.
O REVOLUTION COUNTER x 1/1000
• TAFFRAIL LOG READING
ACTUAL DISTANCE (KILOMETERS)
670
672
674
676
678
680
682
684
686
20
25
30
35
40
10
20
30
40
50


RAY PATH OF FIRST & SECOND ARRIVALS
AT A HYDROPHONE NEAR THE SURFACE
DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
D1
1000 FMS
PR1
DIRECT RAY FROM BOMB TO HYDROPHONE
D1
PR1
DIRECT RAY DIFFRACTED-OBSERVED TO 21 KM.
BUT DISTANCE AFFECTED BY SIZE OF BOMB
PR1
PR2
TRUE PR1-DIRECT RAY HAS DIED OUT
PR 2
PR1
PR1 DIFFRACTED-OBSERVED TO POSSIBLY 73 KM.
BUT DISTANCE AFFECTED BY SIZE OF BOMB
PR 3
PR 2
TRUE PR2-PR1 DIFFRACTED HAS DIED OUT
31
60 KM
0

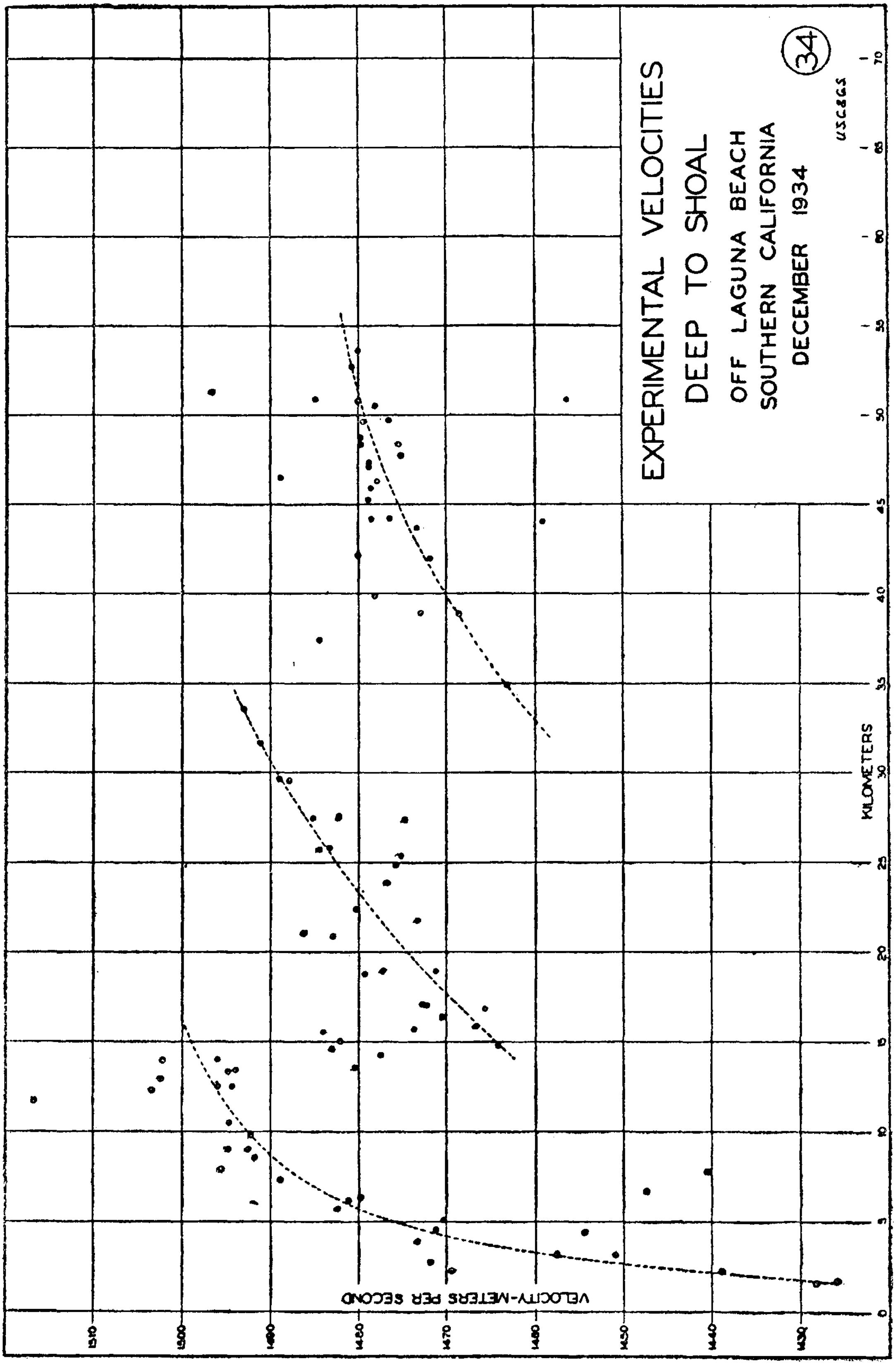

MAXIMUM TRACE AMPLITUDE
REDUCED TO UNIFORM AMPLIFICATION
(GAIN -20)
SHOAL TO DEEP WATER TESTS
SANTA BARBARA ISLANDS BASIN
JANUARY 1935
o FUSE BOMBS
× ELECTRIC BOMBS
RECORD FAINT DUE TO RAPID MOTION
U.S.C.&G.S.
TRACE AMPLITUDE IN MILLIMETERS
90
80
70
60
50
40
30
20
10
DISTANCE IN KILOMETERS
10
20
30
32

TYPE OF TEST LOCATION	TYPE OF BOMB AND HYDROPHONE DEPTH AND TRAVEL TIME	
DEEP WATER TESTS SANTA BARBARA ISLANDS BASIN	Fuse bombs - one half pint Aluminum pot hydrophone at 30 fathoms	
	Electric bombs at 30 fathoms Aluminum pot hydrophone at 30 fathoms	
	Electric bombs at 100 fathoms and over Aluminum pot hydrophone at 30 fathoms	
	Fuse bombs - one half pint Deep hydrophone 4 at 390 fathoms	
	Electric bombs at 30 fathoms Deep hydrophone 1 at 30 fathoms	
	Electric bombs at 30 fathoms Aluminum pot hydrophone at 30 fathoms	Travel time, 0-15 seconds
		Travel time, 15-30 seconds
		Travel time, over 30 seconds
	Fuse bombs - ½ pint Aluminum pot hydrophone at 30 fathoms	Travel time, 0-20 seconds
		Travel time, over 20 seconds
DEEP TO SHOAL WATER TESTS SANTA BARBARA ISLANDS BASIN	Fuse bombs - one half pint Aluminum pot hydrophone at 10 fathoms	
	Electric bombs at 30 fathoms Aluminum pot hydrophone at 10 fathoms	
	Electric bombs-30 fathoms Aluminum pot hydrophone at 10 fathoms	Travel time, 0-15 seconds
		Travel time, over 15 seconds
	Fuse bombs ½ pint Aluminum pot hydrophone at 10 fathoms	Travel time, 0-15 seconds
		Travel time, over 15 seconds
DEEP TO SHOAL WATER TESTS LAGUNA BEACH	Fuse bombs - one half pint Kettle-drum hydrophone at 10 fathoms	
	Electric bombs at 30 fathoms Kettle-drum hydrophone at 10 fathoms	
	Electric bombs at 30 fathoms Kettle-drum hydrophone at 10 fathoms	Travel time, 0-10 seconds
		Travel time, 10-20 seconds
		Travel time, over 20 seconds
	Fuse bombs one half pint Kettle-drum hydrophone at 10 fathoms	Travel time, 0-12 seconds
		Travel time, 12-25 seconds
		Travel time, over 25 seconds
SIGNAL CORPS HYDROPHONE		

U.S.C.&G.S. 33A

MEASURED FREQUENCIES																				
100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1200	1500
		76	11	2	1	5	6	1		1	1	1	1	7	20	154	7	1		
	2	41	18	14	3	4	13	10	4		1	2	1	4	25	124	18	16	1	
1		28	3	4			4	2		3	3			5	15	41	8			
	5	7	2	3	84	76	7	5	6			1								
4	4	7	27	6					5	7	3	5	2	1	1			1	1	
		8	3	3			1	1		1		1		3	11	62	8	7	1	
•		12	2	3	2	1	9	6	4						10	29	5	8		
	2	21	13	8	2	2	3	3		3	1	2	1	1	4	33	3	1		
		7	1				4					1			5	18	2			
		68	11	2	1	5	2	1		1	1		1	7	16	135	3	1		
		1	1		1	16	40	54	11	4	1			2		1	1	21	15	3
				2	3	32	54	53	9	10				1	1	2		16	5	13
				1	1	11	28	20	4	9					1	2		6	4	13
				1	2	20	27	33	5	1				1				10	1	
		2			1	6	20	36	7	3	1					1	1	9	10	2
		1				7	18	20	3	1								12	5	1
93			1			3	42	63		1		1		1		11	47	6		
56						2	34	17								12	16	3	2	
14						2	17	4								11	15	1	2	
19							8	6								1	1	1		
23							9	7										1		
38			1			2	38	10		1						10	47	3		
32						1	2	41				1		1				3		
23							1	13												
	8	29	6	4	5	1	1	6	3	3	1		1			1		5	2	3

U.S.C.&G.S. 33B


EXPERIMENTAL VELOCITIES
DEEP TO SHOAL
OFF LAGUNA BEACH
SOUTHERN CALIFORNIA
DECEMBER 1934
34
USC&GS
KILOMETERS
VELOCITY-METERS PER SECOND