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Crustal Structure and Surface Wave Dispersion

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by

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INTRODUCTION

A recent seismic refraction profile[1] in 2800 fm. (5.1 km.) at Latitude 34°00' N. Longitude 66°30' W. in the Atlantic Ocean proved that basement rocks having velocity of 7.58 km./sec. for compressional waves were covered by 1.37 km. of sediment. On the basis of this velocity we tentatively identified the layer as P_n, indicating the absence of the granitic and intermediate layers. This velocity is higher than most of the values deduced for the uppermost sub-oceanic rocks from studies of the velocity and the dispersion of earthquake surface waves over oceanic paths. If this refraction measurement is representative of ocean wide conditions, it is evidently in conflict with the crustal layering inferred from previous studies on surface waves. The present study indicates that the observed surface wave dispersion is to be expected if proper account is taken of the influence of the water and sediment over an ocean bottom consisting of a very thick basaltic[2] layer, as indicated by the seismic refraction measurements.

INFERENCES FROM THE AIRY PHASE

In a recent study[3] of the Bermuda records of some West Indian earthquakes, a prominent new phase was investigated with the conclusion that rocks with velocity higher than granite extended practically up to the ocean floor in this area. This conclusion was based on a theory of the normal mode propagation of elastic waves in an ocean of uniform depth with a homogeneous solid bottom. The theory treated the case of an impulsive point source of compressional waves situated beneath the bottom. The theoretical dispersion at large distances from the source could be obtained from the period equation:

$$\tan \left(k_n H\sqrt{c_n^2/v_1^2-1}\right) = \frac{\rho_2 \beta_2^4 \sqrt{c_n^2/v_1^2-1}}{\rho_1 c_n^4 \sqrt{1-c_n^2/\alpha_2^2}} \left[4\sqrt{1-c_n^2/\alpha_2^2}\sqrt{1-c_n^2/\beta_2^2} - (2-c_n^2/\beta_2^2)^2\right] \quad \ldots. \quad (1)$$

(1) Maurice Ewing, J. L. Worzel, J. B. Hersey, Frank Press and G. R. Hamilton, "Refraction Measurements in the Atlantic Ocean Basin, Part I," submitted for publication to Bull. Geol. Soc. Amer., 1949

(2) In this paper the terue basaltic layer refers to P_n, and has no petrographic implications.

(3) Frank Press, Maurice Ewing and Ivan Tolstoy, "The Airy Phase of Shallow Focus Submarine Earthquakes," Bull. Seism. Soc. Amer., 1950

where α_2, β_2 and ρ_2 are the compressional wave velocity, shear wave velocity, and density in the bottom respectively, v_1 and ρ_1 are the compressional wave velocity and density in the water, c is the phase velocity, H the water depth and $2\pi/k$ is the wavelength measured along the horizontal. An equivalent equation was given by Stoneley (4). Since available information indicates that the velocity of sound in the bottom sediments of ocean basins is approximately 10% greater than that for water, we will consider H to be the combined thickness of water and sediment.

It can be seen that $k_n H$ is a multiple valued function of phase velocity, each value belonging to a distinct mode of propagation denoted by the subscript n. Now in a dispersive medium in which an arbitrary initial disturbance occurs, the energy associated with each wavelength is known to propagate with the group velocity given by the familiar formula:

$$U = c + (k_n H) \frac{dc}{d(k_n H)} \qquad (2)$$

The period equation (1) was used to obtain $k_n H$ as a function of c/v_1 and the group velocity was subsequently determined by numerical differentiation according to (2). The results of these computations for $c \geqslant v_1$ in the first mode are shown in Figure 1 where U/v_1 is plotted as a function of the dimensionless parameter $\gamma = H/v_1 T$. $T = 2\pi/ck$ is the period. The computations were carried out for the two cases $\rho_2/\rho_1 = 2.5$, $\alpha_2 = \sqrt{3}\beta_2$, $\beta_2 = 2V_1$ and $\rho_2/\rho_1 = 3.0$, $\alpha_2 = \sqrt{3}\beta_2$, $\beta_2 = 3V_1$ which represent in an approximate way the conditions for a granitic and basaltic bottom. We may easily compute U/v_1 for slightly different values of β_2 than those assumed in Figure 1 in the range $\gamma < .23$, since U is approximately proportional to β_2 for any given value of γ in this interval.

The sequence of arrivals at a point distant from the source can be described with the aid of the group velocity curves. The first arrivals consist of very long period waves ($\gamma \sim 0$) travelling with the speed of Rayleigh waves $.92\ \beta_2$. Subsequent arrivals show a decrease in period, corresponding to increasing γ. At a time corresponding to propagation at the speed of sound in water, a short period wave arrives, riding on the continuing longer period waves. The two simultaneously arriving wave trains thereafter approach each other in period and finally merge into a train of waves of large amplitude, having a discrete period and travelling with

(4) Robert Stoneley, "The Effect of the Ocean on Rayleigh Waves," Mon. Not. Roy. Astron. Soc., Geophys. Suppl., 1:349-356 (1926)

the speed given by the minimum value of group velocity. The term Airy phase was introduced by Pekeris(5) to describe this train of waves.

The dispersion introduced by the layer of water over a thick layer of granit-eor basalt can readily be calculated from the curves in Figure 1. It will be shown that the layer of water, neglected in previous studies, can account for the observed dispersion of sub-oceanic Rayleigh waves, if the ocean bottom is taken to be basalt.

THE DATA OF WILSON AND BAYKAL

Wilson and Baykal(6) studied the earthquake of 25 November 1941 at 37°0 N., 19°0 W. They listed periods and velocities for the Rayleigh waves for 6 stations, some with mostly oceanic paths, others with mostly continental paths. They devised a method for separating out the continental and the oceanic dispersion effects and obtaining "observed" dispersion curves for purely continental and for purely oceanic paths. They endeavored to explain the oceanic dispersion on the assumption of a crustal structure in which the ocean bed was a layer 26 km. thick having a shear wave velocity of 4.0 km./sec. underlain by a thick layer with shear wave velocity 4.43 km./sec. The effect of the water was not considered.

The thickness 26 km. was chosen to make the theoretical dispersion agree with that which was observed. The fit was good for the longer periods, but poor for the shorter ones. Wilson and Baykal reexamined the seismograms and discovered that a pronounced change in character occured for periods below about 18 sec. The change in character apparently consisted mostly of a marked decrease in amplitude and sharp deviation from the computed dispersion curve. The authors state that "at Weston the retrograde elliptical motions typical of Rayleigh waves continues beyond the change in character..."

We have plotted the observed dispersion data for 100% oceanic path as circles in Figure 2. In this Figure the theoretical dispersion curve is drawn for an ocean bottom with shear velocity 4.45 km./sec.

(5) C.L. Pekeris, "Theory of Propagation of Explosive Sounds in Shallow Water," in Propagation of Sound in the Ocean, Mem. No. 27, Geol. Soc. Amer., 1948

(6) J. T. Wilson and Orhan Baykal, "Crustal Structure of the North Atlantic Basin as Determined from Rayleigh Wave Dispersion," Bull. Seism. Soc. Amer., 38:41-53 (1948)

The agreement is excellent taking the water-sediment thickness to be 5.25 km. Approximately 75% of the great circle path to Fordham lies in water deeper than 1500 fathoms, with an average deep water depth of 2200 fms. or 3.7 km. Thus a layer of sediments having an average thickness of 1.5 km. is required in order for the observed and theoretical dispersion to agree. This is not unreasonable in view of the results of the refraction measurements described earlier.

Moreover, the Fordham data (chosen because it comes nearest to an all oceanic path) rejected by Wilson and Baykal and plotted as crosses in Figure 2 appear as a normal continuation of the other data. The observed dispersion of Rayleigh Waves under the Atlantic Ocean is thus accounted for by including the effect of the water and sediment, and assuming an homogeneous ocean bottom with compressional velocity $\alpha_2=\sqrt{3}\beta_2=7.7$ km/sec. , in good agreement with our refraction measurment. The dashed line in Figure 2 is the theoretical curve given by Wilson and Baykal. For periods greater than 20 sec., it cannot be distinguished from our curve. For periods less than 18 sec., the two curves diverge.

The marked decrease in amplitude noted by Wilson and Baykal can be accounted for by the relatively steep slope of our group velocity curve for periods below 18 sec. The relative amplitude of the waves are known to be proportional to the inverse square root of the slope, except near stationary values of the group velocity where large amplitudes occur, but a closer approximation is required. The curve of Wilson and Baykal (dashed line in Figure 2) has a stationary value of group velocity of about 3.43 km./sec. at a period of 16 to 17 sec., which would imply large amplitudes in the Rayleigh Waves. He reports that the seismograms show low aplitudes and small change of period for large changes in travel time in this region, as illustrated by his tables and reproductions of the Weston and Fordham seismograms. As stated in the earlier section on the Airy Phase, large amplitude waves of period 9 to 10 sec. and velocities 1.06 km./sec. have been observed at Bermuda in confirmation of the corresponding stationary value in our dispersion curve.

THE DATA OF BULLEN AND DE LISLE

Bullen(7) discussed the dispersion of Rayleigh waves recorded at Wellington from the earthquake of 10 November 1938 in the North Pacific at 55°6'N., 157°7'W. DeLisle(8) included data from many additional stations for the same earthquake, several of which involved paths which may be considered to be entirely Pacific. These data were interpreted on the basis of Jeffreys(9) dispersion curves (which take no account of the water) for Rayleigh waves. He took two solid layers with the ratio $\rho_2/\rho_1=5/4$ and $\beta_1/\beta_2=.75$. This would include the case in which S waves have a velocity of 3.3 km./sec. in the upper layer and 4.4 km./sec. in the lower. For each observed period they calculated the thickness of the upper layer which would correspond to the observed group velocity. The thickness ranged from about 6 km. for 32 second waves to about 20 km. for 17 second waves.

Observed dispersion obtained from the papers of Bullen and DeLisle are shown by the circles in Figures 3-5. The averaged data for Wellington and Christchurch presented in Figure 3 is in fair agreement with the theoretical dispersion for a layer of water and sediments 5.45 km. deep, overlying a basaltic bottom with shear wave velocity 4.35 km./sec. and density 3.0. Approximately 80% of the great circle path to Wellington was in deep water (depth greater than 1700 fms.) with an average deep water depth of 2600 fms. or 4.7 km. This is to be compared with the value 5.45 km. obtained for the depth of water and sediments from the disperion data.

The dispersion data for Apia shown in Figure 4 agree quite well with the theoretical curve obtained for the same ocean-sediment depth and bottom velocity used in the previous paragraph. About 80% of the great circle path to Apia was in water deeper than 2000 fms., with an average deep water depth of approximately 2800 fms. or 5.1 km.

The dispersion data averaged for the stations at Pasadena, Tinemaha, Santa Barbara and Riverside are shown in Figure 5. The theoretical curve for a layer of water and sediments 4.78 km. thick overlying a basaltic bottom with shear velocity 4.17 km./sec. and density 3.0 agrees reasonably well with the observed data. Approximately sixty per cent of the great circle path lies in water deeper than 1700 fms., the average deep water depth being 2100 fms. or 3.83 km.

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(7) K. E. Bullen, "On Rayleigh Waves Across the Pacific Ocean, Mon. Not. Roy. Astron. Soc., Geophys. Suppl. 4:579-582 (1939)
(8) J. F. DeLisle, "On Dispersion of Rayleigh Waves from the North Pacific Earthquake of November 10, 1938," Bull. Seism. Soc. Amer., 31:303-307 (1941)
(9) Harold Jeffreys, "The Surface Waves of Earthquakes," Mon. Not. Roy. Astron. Soc., Geophys. Suppl. 3:253-261 (1935)

The data for Manila is not presented since only a small portion of the great circle path crosses deep water, and the dispersion introduced by the water would be small or negligible. The character of the dispersion however is unlike that observed for continental paths, so that here might well be a case where the crustal structure assumed by Bullen and DeLisle or Wilson and Baykal can be applied without considering the effect of the ocean.

LOVE WAVES

The fact that the water cannot participate in the propagation of Love waves leads one to expect that the observed dispersion in this type of wave for oceanic paths would be far less than that for Rayleigh waves if the Rayleigh wave dispersion is due to the influence of the water and not to crustal layering. On the other hand, if the Rayleigh wave dispersion is due to crustal layering, the Love wave dispersion should be comparable to it in magnitude under the oceans as it is under the continents. Wilson,[10] in his excellent study of the Love waves of the South Atlantic earthquake of 28 August 1933 had available oceanic paths through the Atlantic, Pacific and Indian Oceans as well as mixed continental and oceanic paths. He found that the dispersion was much less along oceanic paths than along mixed paths, and that the dispersion for the three oceans was about the same. He attributed practically all of the dispersion observed for mixed paths to the continental part. His observed group velocities for oceanic paths varied in a regular way from 4.3 km./sec. at 20 sec. to about 4.5 at 100 sec. This is in marked contrast to the variation of 3.3 km./sec. at 20 sec. to 4.2 at 100 sec. for continental paths.

An attempt will be made in a later paper to make a detailed analysis of the dispersion of Love waves over oceanic paths, but it seems clear that the small magnitude of this effect supports our interpretation of the Rayleigh wave dispersion.

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(10) J. T. Wilson, "the Love Waves of the South Atlantic Earthquake of August 28, 1933," Bull. Seism. Soc. Amer., 30:273-301, (1941)

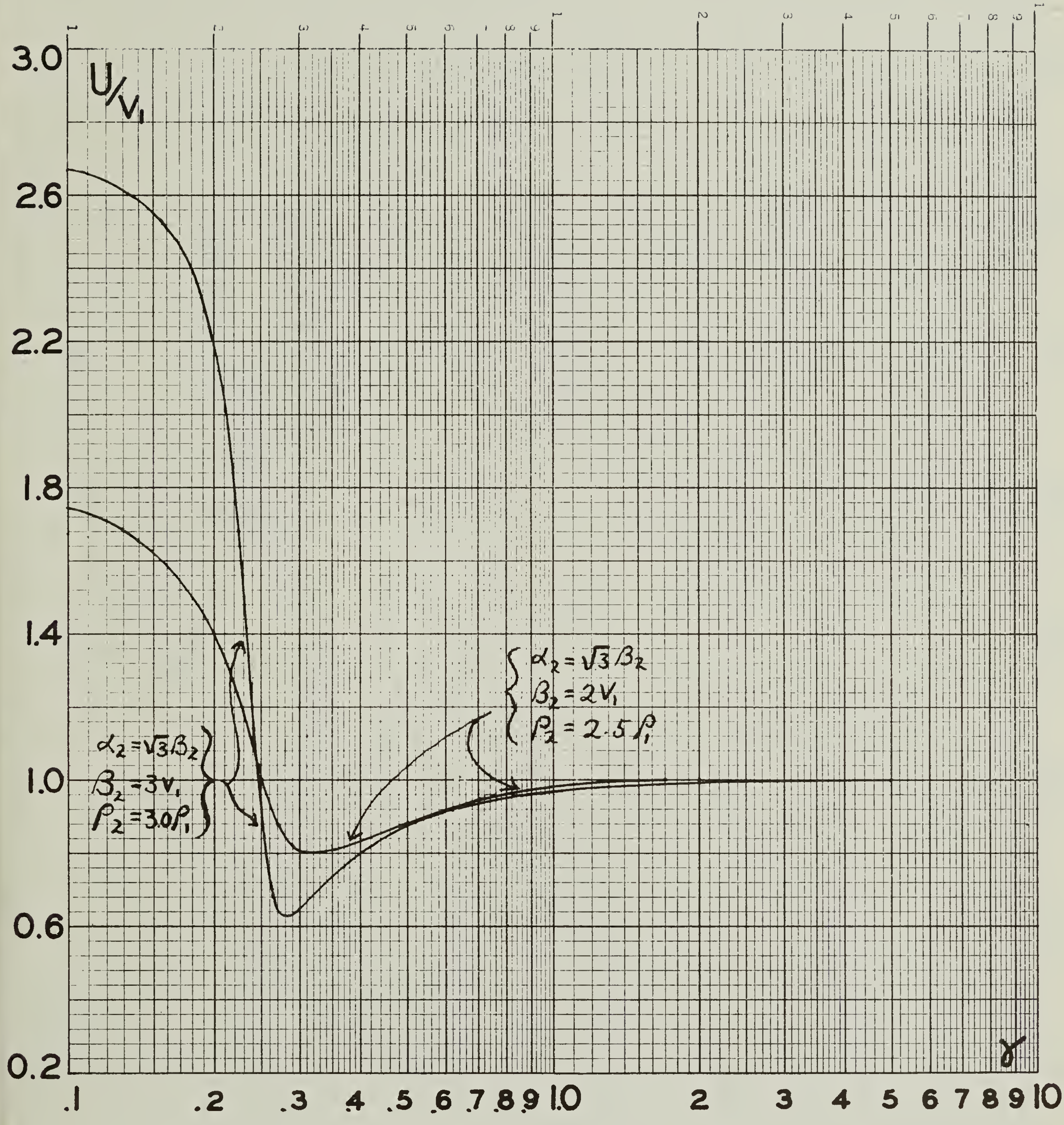

Figure 1. Theoretical dispersion curves of suboceanic Rayleigh Waves for granitic and basaltic bottoms.

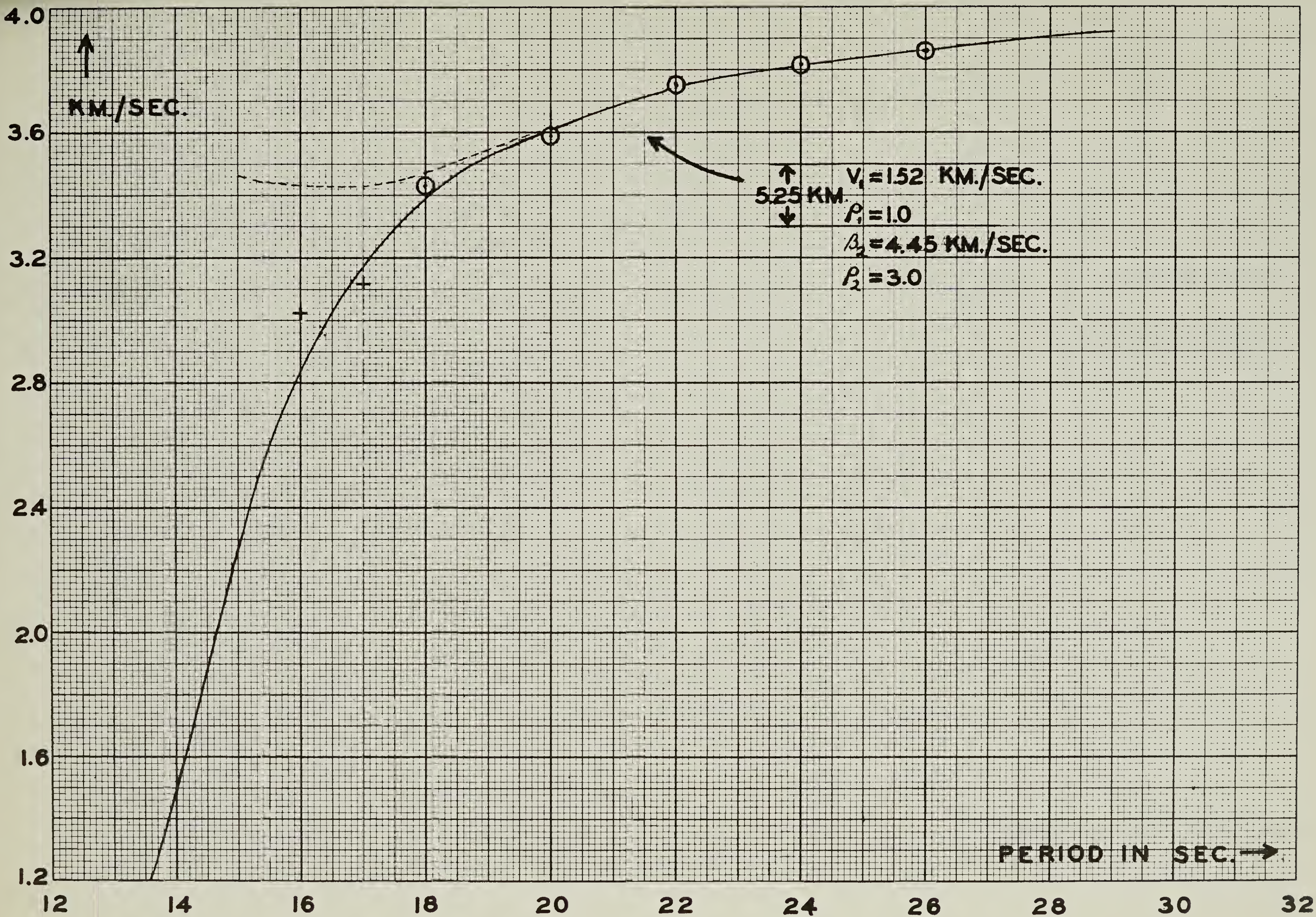

Figure 2. Theoretical and observed dispersion of Rayleigh Waves in the Atlantic Ocean.

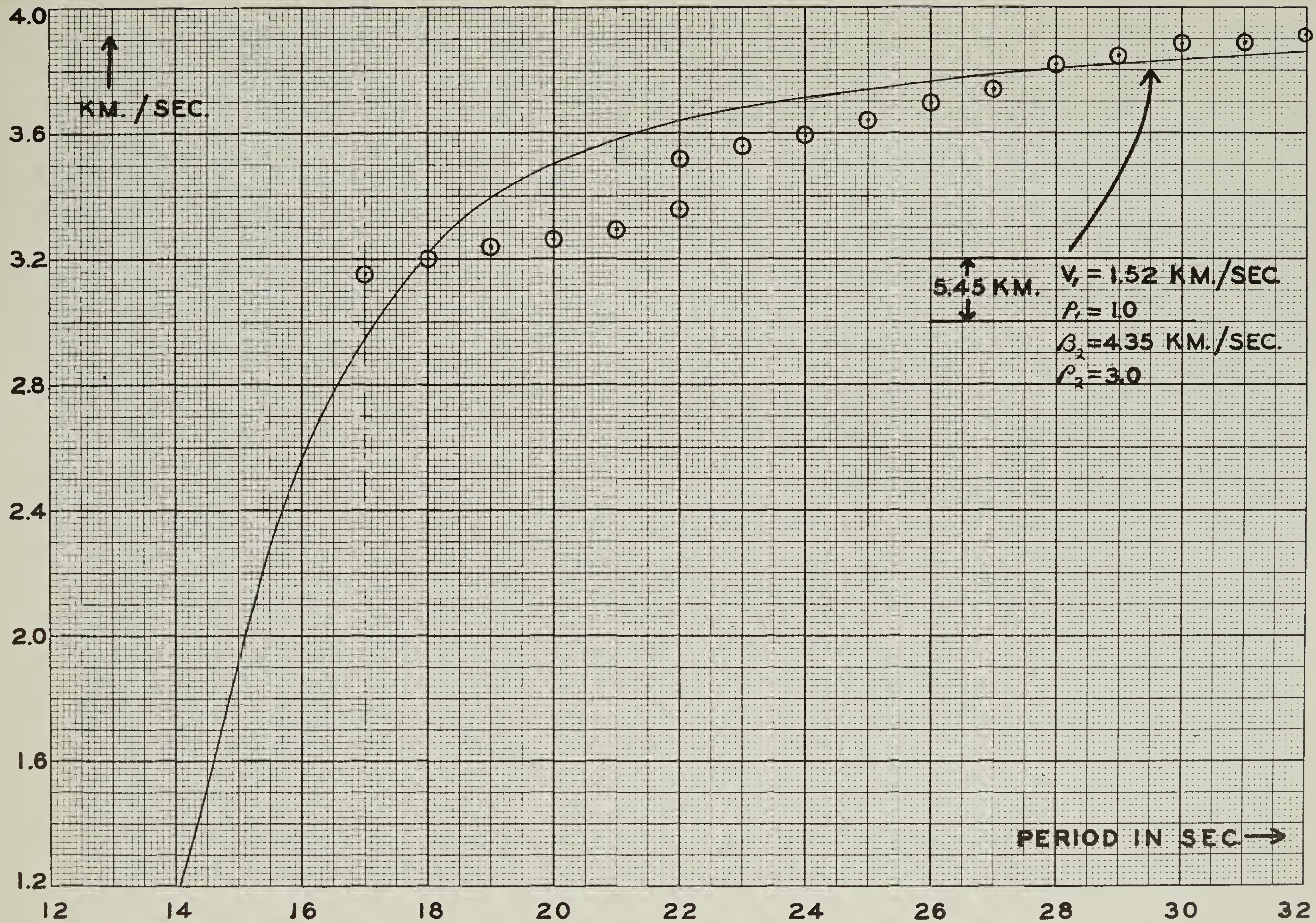

Figure 3. Theoretical and observed dispersion (Wellington and Christ Church) of Rayleigh Waves in the Pacific Ocean.

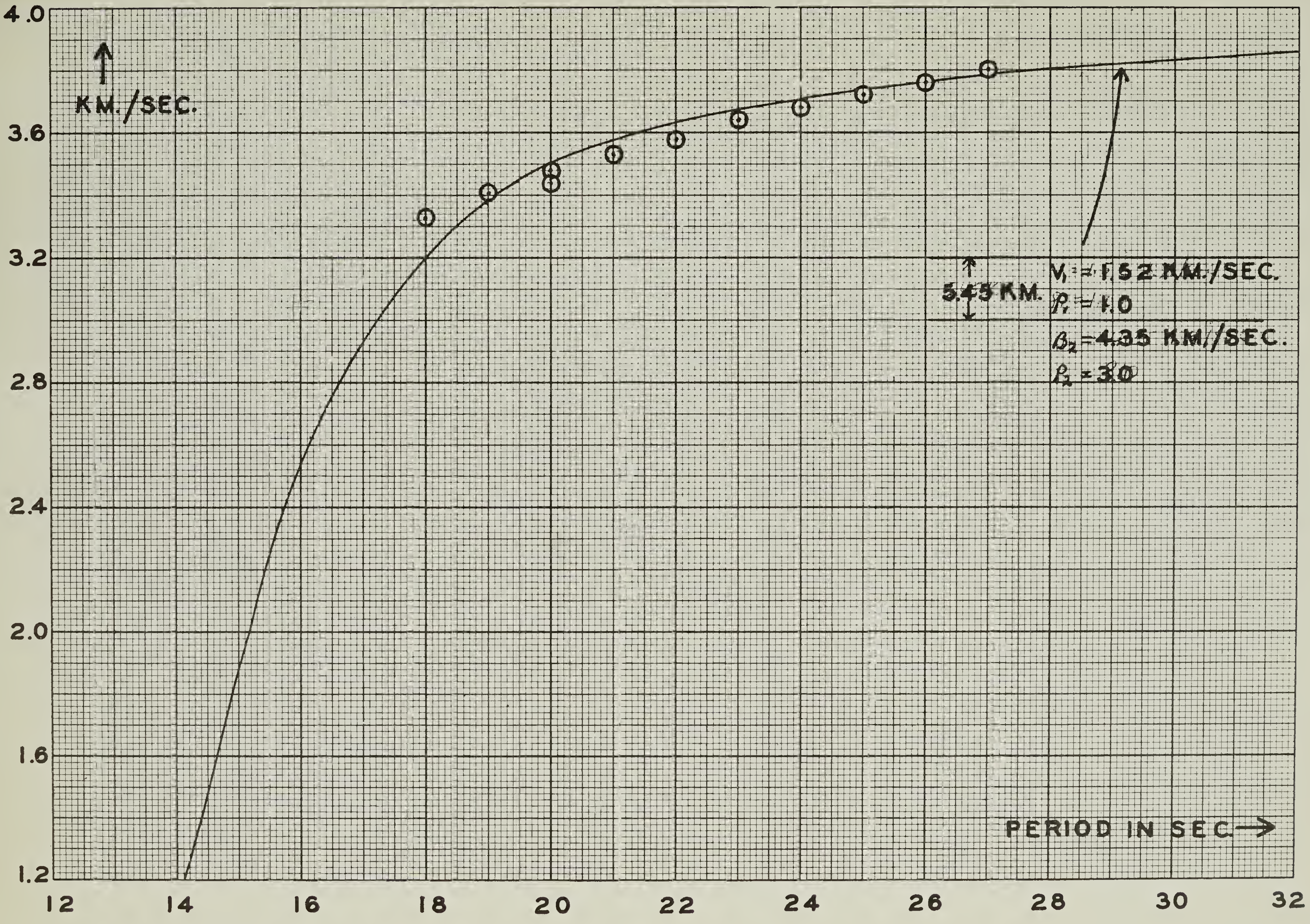

Figure 4. Theoretical and observed dispersion (Apia) of Rayleigh Waves in the Pacific Ocean.

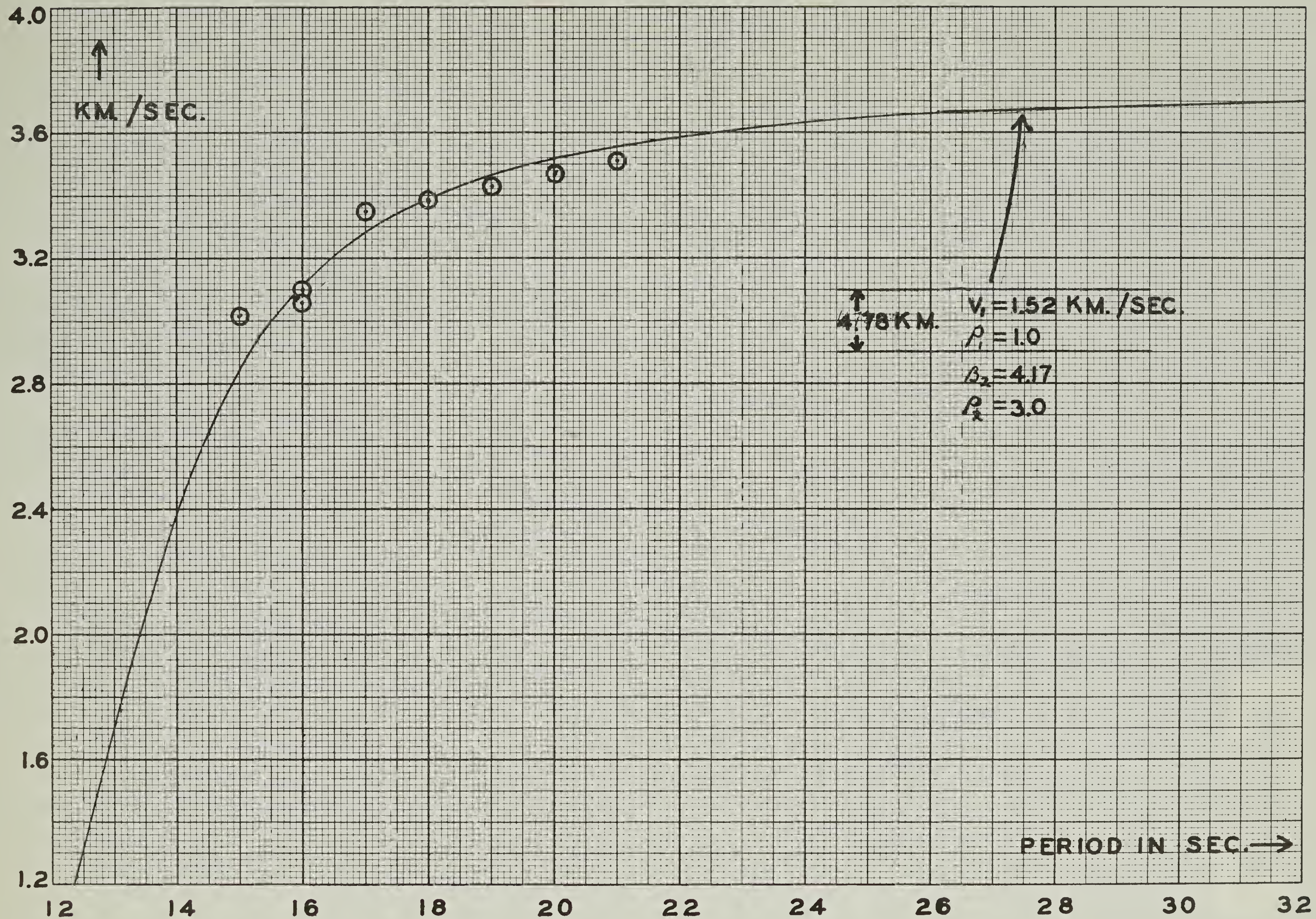

Figure 5. Theoretical and observed (Pasadena, Santa Barbara, Riverside and Tinemaha) dispersion of Rayleigh Waves.