Group and Phase Velocities for Rayleigh Waves of Period Greater than 380 Seconds

Abstract. Recent theoretical and experimental investigations of the periods of free spheroidal oscillation of the earth have shown good agreement. These data are used to determine group and phase velocities for Rayleigh waves of period greater than 380 seconds. The velocities so obtained are compared with those determined from analysis of progressive waves. It is concluded that group and phase velocities determined by either of the two methods are in agreement.

Phase velocity, *C*, and group velocity, *U*, may be determined from periods of free oscillation according to Jeans' formula (*1*):

$$C = 2\pi a/(n + \tfrac{1}{2})T$$

where *a* is the radius of the earth, *n* is the mode number of the oscillation, and *T* is the period. Periods of free oscillation of the earth have been determined by spectral analysis of the following records: Los Angeles gravimeter records (*2*), the Isabella (*3*) and Ogdensburg (*4*) strain seismograms, and the Chester (*5*), Palisades (*4*), and Pasadena (*3*) long-period pendulum seismograms. The theoretical periods for spheroidal (*6, 7*) and torsional (*8*) oscillations were used to identify peaks of the spectra. The different measurements show good agreement with each other and with theoretical calculations. Phase velocity points derived from the period of each free spheroidal mode from $n = 27$ to $n = 6$ are shown in Fig. 1 as a function of wavelength,

$$2\pi a/(n + \tfrac{1}{2})$$

It has been shown that this definition of wavelength is consistent with analysis of progressive wave trains provided a $\pi/2$ phase advance at each polar or antipodal crossing is taken into account (*9*). Two phase velocity points derived by such analysis (*9, 10*) are shown as open triangles in Fig. 1. The phase velocity curve reaches a maximum of 6.67 km/sec at a period of 700 seconds and then decreases because of the effect of the earth's fluid core.

The phase velocity curve shown in Fig. 1 was differentiated to give group velocity, *U*. This group velocity curve rises steadily from 4.0 km/sec at a wavelength of 2000 km ($T = 354$ seconds) to 7.83 km/sec at a wavelength of 6200 km ($T = 967$ seconds), giving velocities much higher than those previously reported (*11, 12*), and denying a flattening of the Rayleigh wave group velocity curve beyond a period of 380 seconds. The previously reported flattening of the group velocity curve resulted from attributing certain observed long-period Rayleigh waves to the wrong wave trains. Thus a wave of period 480 seconds was previously identified as part of the wave train R10, giving a group velocity of 4.12 km/sec (*11*), but it gives a velocity of 4.97 km/sec when assigned to the train R12 (Fig. 1). Similarly, a velocity of 4.13 km/sec for a wave of period 630 seconds (*12*) identified with R18 increases to 6.02 km/sec when the wave is assigned to R26. A wave of period 530 seconds on the Chester, New Jersey, record of the Chilean earthquake gives a velocity of 5.24 km/sec when assigned to the train R18 (*13*).

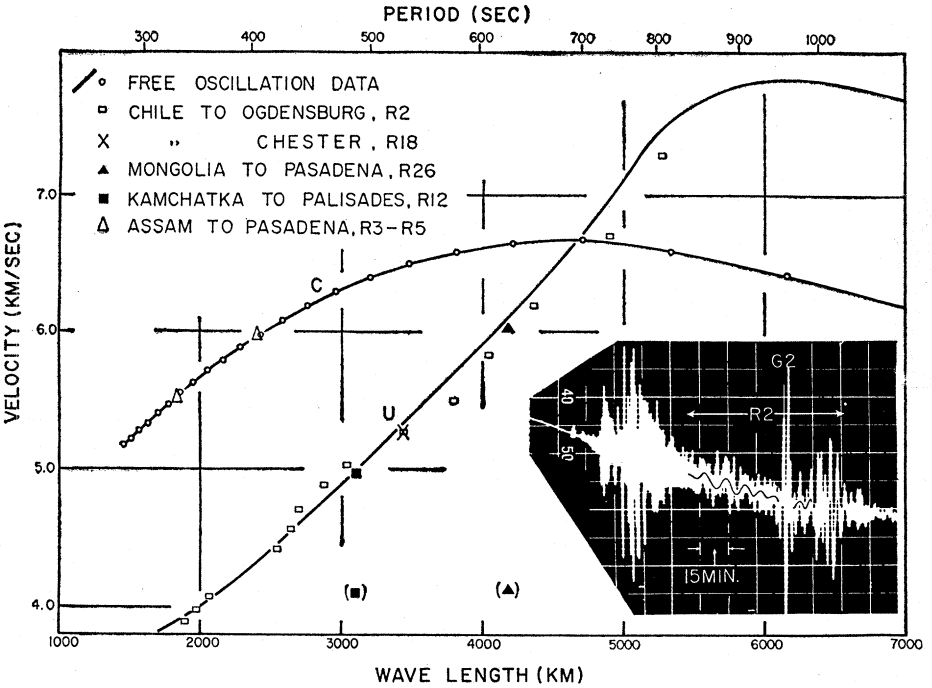

Fig. 1. Phase and group velocity data for mantle Rayleigh waves plotted as a function of wavelength with variable period scale at the top. Previous results, in error because of wrong identification of wave train, are shown in parentheses. The insert shows the Ogdensburg strain seismogram of the Chilean earthquake. The arrival time of the first clear event on the record, the *S* wave from a foreshock, is 19 18 00, 22 May, GMT.

Static load (*14*) and particle motion (*7*) calculations indicate that the supposed flattening could not be due to the earth's fluid core as had been suggested (*11, 12*). Jeffreys (*15*) also maintained that the core could not cause the flattening.

The Ogdensburg strain seismogram of the Chilean earthquake (Fig. 1, inset) recorded waves of periods near 700 seconds, preceding the *G* wave. These waves are interpreted as part of the train R2 with an epicentral distance of 31,280 km and give group velocities ranging up to 7.30 km/sec; these group velocities are in good agreement with those determined from periods of the free oscillations. Because of the high group velocities, this train had been tentatively identified as a higher torsional or spheroidal mode (overtone) of oscillation (*4*), but spectrum analysis of the strain seismogram for several days after the Chilean earthquake showed that the fundamental spheroidal type of motion with periods from 400 to 800 seconds was present with high amplitude on this record and therefore the long period waves shown in Fig. 1 are almost certainly due to this type of motion.

Thus analysis of seismograms in terms of standing waves or progressive waves gives comparable results. Progressive waves yield information which may be more readily associated with a given part of the earth than that from standing waves (*16*).

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Pressure Sensitivity of an Amphipod

Abstract. The responses of an intertidal amphipod indicate an ability to perceive rapid pressure changes of less than 0.01 atm. The interaction of rate of change of pressure and total difference in pressure implies a rapid accommodation as well as a threshold. Evidence suggests that the sensory mechanism may not involve compressibility of a gas.

It has long been recognized that changes in hydrostatic pressure, in the range of hundreds of atmospheres, can have marked, and often lethal, effects on organisms (*1*). Recently, Hardy and Bainbridge (*2*) described controlled experiments in which decapod larvae slowly swam upward after much smaller increases of hydrostatic pressure: 500 to 2000 mb (*3*). The response continued for more than an hour. Two other recent papers have claimed that planktonic invertebrates, including representatives of several phyla, may be sensitive to changes in hydrostatic pressure as small as 10 mb. Knight-Jones and Qasim (*4*) described a "negative geotaxis" associated with pressure increase, and a general decrease in activity associated with pressure decrease. Baylor and Smith (*5*) stated that the organisms they examined swam upward the appropriate distance to compensate for pressure increase, and downward to compensate for pressure decrease. Neither of these reports described the experimental methods used to determine the presumed thresholds.

This preliminary report (*6*) deals with the brief but sharp increase in activity shown by a benthic intertidal amphipod, *Synchelidium* n. sp. (*7*), in response to small changes in hydrostatic pressure. The experimental equipment consisted of: a 250-cm^3 observation flask, containing about 300 amphipods, attached to a 50-cm^3 syringe by 6 m of 3-mm (inside diameter) plastic tubing, the entire system being filled with seawater, except for a 5-cm^3 airspace in the flask; a transducer-type pressure gauge (Statham model PM 6 TC, ± 1 lb/in.^{2} full range) connected directly to the flask by a glass Y-tube; a 30-cy/sec amplifying recorder (Gilson Medical Electronics, "Mini-polygraph") with one pen connected to the transducer and a second pen to an event-recording line leading from near the flask. The observation chamber, pressure gauge, and an observer were in a room where a high noise level was maintained; the recorder and the syringe through which pressure changes were applied were in a separate, adjacent room. The observer thus had no auditory or visual cue to the timing of pressure changes, other than the behavior of the animals. The large number of amphipods was used in order to allow more precise differentiation between the normal, average activity pattern of the animals and the increased activity associated with pressure changes.

Pressure on the system was changed either by placing (or removing) small weights on a platform atop the syringe plunger, producing an almost instantaneous pressure change; or by mechanically raising the open syringe up an inclined ramp at a rate that could be adjusted as desired. The air space in the flask is not essential to the response of the amphipods; they reacted similarly when the system was completely filled with water. It did serve, however, to considerably cushion the pressure change, eliminating large overshoot and rebound with the first method, and producing a much smoother pressure record with the second method.

The observer was notified that a recording had been started; at sometime within the next 60 seconds, the timing being determined by a number selected from a table of random numbers, the operator changed the pressure on the system. When, and if, the observer noted a marked change in the behavior of the amphipods, his signal depressed the event-recording pen of the recorder.

Several considerations make it appear unlikely that the observed response was due to a pressure-correlated sound stimulus: (i) The behavior of the animals when subjected to a wide variety of shock and noise stimuli, in the absence of pressure changes, indicates that this species is relatively unresponsive to all sounds tested, including loud, strong blows on the syringe. (ii) The absence of the air space in the experimental system, which should have altered the sound transmissive characteristics, had no noticeable effect on the response. (iii) The same type of response was obtained when the open syringe was raised carefully by hand, either with or without the airspace in the flask, a procedure presumably avoiding any high-frequency mechanical shocks associated with other methods. (iv) There is no known mechanical peculiarity of the system which could account for a sound stimulus present during prolonged linear pressure increases and absent during briefer increases (Table 1).

Table 1. Responses to slow, linear pressure increases: av. rate, 2.8 mb/sec (2.6 to 3.1); percentage of time at atmospheric pressure, 61 and 77; three "spontaneous activity" records. For $\triangle P$, $\triangle P_T$, and T, see Fig. 1*B*.

$\triangle P$ (mb)		Responses		T (sec)	
Av.	Range	Positive	None	Av.	Range
		Large increases (final $\triangle P > 35$ mb)			
41.8*	27–51*	19	1	14.4	9.4–17.7
		Small increases (final $\triangle P < 25$ mb)			
18.7	18–21	0	19		

* $\triangle P_T$

The system has been carefully examined for the possibility of some pressure-correlated visual cue to the animals; none has been found.

The most evident response to pressure change is the sudden onset of a rapid scrambling and darting by the amphipods, which are otherwise far less active, predominantly resting on the bottom of the flask. The reaction occurs whether the pressure is increased or decreased, but is much stronger after pressure increase. With slow rates of pressure increase, the sudden burst of activity is preceded by a brief reduction of the slight normal movements of the animals. This decreased activity is less easily discerned, however, and the criterion for pressure response will here be restricted to the sudden pronounced increased activity. Rough estimates of the duration of increased activity associated with pressure change ranged from about 5 seconds for an increase of 10 mb, to about 15 seconds for an increase of 100 mb.

Small bursts of spontaneous activity occasionally occurred in the observation flask; signals denoting an apparent response to pressure at a time prior to

Table 2. Threshold for observable reaction to rapid pressure increases: t, 0.6–0.9 sec; percentage of time at atmospheric pressure, 86 and 92; one "spontaneous activity" record. For $\triangle P$, T, and t, see Fig. 1*A*.

$\triangle P$ (mb)	Responses		T (sec)	
	Positive	None	Av.	Range
	Initial threshold			
6–8	6	4	1.7	1.0–2.3
8–15	5	1	1.3	1.0–1.7
15–20	4	0	1.1	1.1–1.2
	Final threshold			
6–8	0	5		
8–10	1	4	2.0	
10–15	8	4	1.9	1.5–3.0
15–20	5	0	1.6	1.4–1.8