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HIGHER-MODE RAYLEIGH WAVES STUDIED AS INDIVIDUAL SEISMIC PHASES

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We study a set of very high-quality records of first-order overtone Rayleigh waves from the deep-focus earthquake of September 29, 1973, in the Japan Sea. Standard surface wave techniques are used with these overtones, treated as individual seismic phases, to retrieve radiation pattern, Q, moment and phase velocity. A figure of $M_0 = (6.7 \pm 1.4) \times 10^{27}$ dyn-cm is obtained, in total agreement with published values computed from either P waves, or fundamental Rayleigh waves. We also demonstrate the feasibility of using overtones as individual seismic phases in order to investigate their dispersion and attenuation properties.

1. Introduction

Much of our present knowledge of the long-period mechanism of seismic sources, and of the seismic properties of the upper mantle has come from the study of mantle surface waves. These studies have usually been restricted to their fundamental modes (e.g. [1–4]), and only recently have they involved greater depths, by a systematic use of all of the Earth's normal modes, most often through inversion techniques [5,6]. Only very rarely has information been sought and obtained on any single overtone branch, such as the first higher Rayleigh mode ${}_1$R. One reason for this may be the relatively low excitation of overtones by most seismic sources, and the difficulty of retrieving their signals from a seismic trace, which has necessitated the use of sophisticated processing techniques [7].

However, under favorable source conditions, it is possible to observe Rayleigh overtones of remarkable quality, clearly separated in the time domain, and behaving as individual seismic phases (Fig. 1a). The purpose of this letter is to show that the seismic moment of the source, and the attenuation and dispersion properties of the overtones, can all be easily and reliably retrieved from such records. By studying an earthquake whose focal mechanism, moment and source function are well documented [8,9], we carry out a case study of the feasibility of applying standard methods of data processing to these phases, as a promising way of investigating deeper the properties of the mantle.

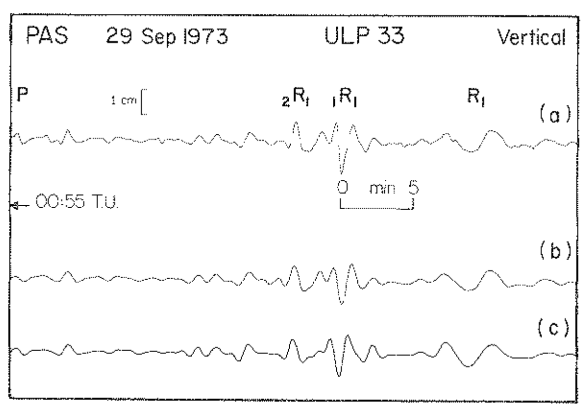

Fig. 1. (a) Pasadena ultra-long period record of the Japan Sea event of 1973. Note the clearly individualized overtones ${}_2R_1$ and ${}_1R_1$ preceded the longer period fundamental R_1. (b) Observed trace filtered at $T \geq 45$ s. (c) Synthetic obtained from models 1066A and SL2.

2. Data

We use records of the deep-focus Japan Sea earthquake (also known as the Vladivostok earthquake) of September 29, 1973 (origin time 00:44:00.8 GMT). The mechanism of this earthquake has been described by Furumuto and Fukao [8], and by Koyama [9]. It consists of a nearly pure vertical dip-slip along a quasi north-south fault plane (strike 186°, dip 83°, rake 90° [8]). For such a simple geometry, the Rayleigh wave radiation pattern is basically two-lobed at all frequencies and for all overtones.

The investigation of the behavior of the eigenfunctions of the first higher Rayleigh modes at the depth of the event (575 km) reveals that the excitation coefficient K_1 characteristic of dip-slip geometry is maximum around 100 seconds. It is therefore best to use records from instruments having a good response at very long periods, such as broad-band instruments (Press Ewing) or ultra-long period systems (such as the Pasadena ultra-long periods). Records used in the present study are summarized in Table 1, the layout of the stations being shown on Fig. 2. Figs. 1 and 3 show the PAS record on the "ULP 33" low-gain system, and the PPT record on the LDG broad-band instrument.

The strong arrival present at PAS around 01:18 with a maximum of energy at a period of 80 s (and at PPT around 01:23), which corresponds to a group velocity of 4.5 km/s, can be identified as the first passage of the first higher mode Rayleigh wave (we

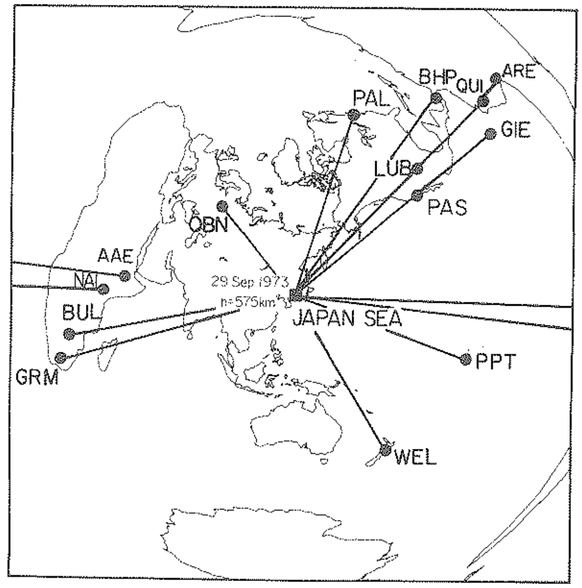

Fig. 2. Map of the stations used in this study, on an azimuthal equidistant projection centered on the epicenter. ${}_1R_2$ was used at AAE and NAI.

TABLE 1

Seismic records used in this study

Code	Station	Instrument	Distance (°)	Azimuth to station (°)
OBN	Obninsk, U.S.S.R.	K.P. Tcha. 100	59.08	318.3
PAS	Pasadena, California	ULP 33	81.28	51.4
LUB	Lubbock, Texas	WWSSN 15-100	90.53	41.5
WEL	Wellington, New Zealand	WWSSN 15-100	91.86	148.4
PPT	Papeete, Tahiti	LDG broad-band	94.09	109.7
PAL	Palisades, New York	Press Ewing 30-90	94.34	18.5
BUL	Bulawayo, Rhodesia	WWSSN 15-100	112.22	262.7
GRM	Grahamstown, South Africa	WWSSN 15-100	121.30	251.9
BHP	Balboa Heights, Canal Zone	WWSSN 15-100	122.11	36.1
GIE	Galapagos Islands, Ecuador	WWSSN 15-100	124.73	53.0
QUI	Quito, Ecuador	WWSSN 15-100	130.69	40.1
ARE	Arequipa, Peru	WWSSN 15-100	148.15	43.4
AAE	Addis-Ababa, Ethiopia	WWSSN 15-100	85.63 *	278.3
NAI	Nairobi, Kenya	WWSSN 15-100	93.93 *	272.0

* This station recorded ${}_1R_2$.

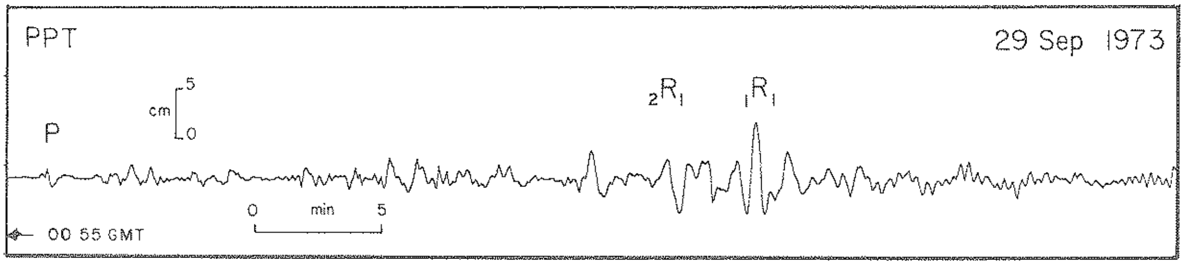

Fig. 3. Papeete record of the Japan Sea event on the LDG broad-band system.

will write this $_1R_1$). This phase can be followed continuously at various stations, up to a distance of 148° (at ARE). The phase $_1R_2$ (second passage of the first higher mode) gives a distinct signal at some stations (AAE, NAI) in the lobes of the radiation pattern. This phase was also identified (but only qualitatively) by Okal and Geller [10], on a PAS record of the Colombian 1970 earthquake.

3. Radiation pattern of $_1R_1$.

Records were digitized, filtered at $T \geqslant 45$ s, and equalized to a common instrument (in view of the long-period nature of the signal, the PAS ultra-long period system was chosen), and a common distance (90°), following the technique of Kanamori [11,12]. The phase and group velocities used in the equalization were derived from Gilbert and Dziewonski's [5] model 1066A; the Q model used was the SL2 model of Anderson and Hart [13]. The equalization was performed only on the portion of record corresponding to the first higher mode. Given that most of the energy in the records is concentrated around 70–80 s, and since the group velocities of the various overtone branches are well separated in this range of periods, it was not necessary to use the "variable filtering" techniques described by Cara [7].

Results are presented in Fig. 4. The data point relative to OBN is only tentative, since the phase response of the instrument was unknown to us, as was its overall magnification (the relative frequency response, or shape of the response curve was available, and very similar to the response of the LDG system at PPT). We used a comparison of the amplitudes of the overtone and fundamental Rayleigh waves at both stations, and assumed a phase response similar to that of the LDG instrument. The resulting equalized amplitude for OBN is probably accurate to ±50%.

The observed radiation pattern is in excellent agreement with the previously published focal mechanism. It is interesting to note that the departure of the observed radiation pattern from the theoretical one compares favorably with that of fundamental Rayleigh waves for the present earthquake [8,9], or other events of recent study [14,15]. The fact that the agreement between observed and theoretical radiation patterns of overtones is somewhat better than for fundamental Rayleigh waves might be due to lateral heterogeneities playing a lesser role in the propagation of overtones.

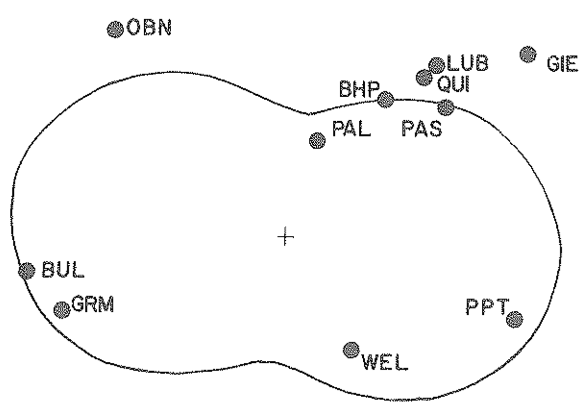

Fig. 4. Radiation pattern obtained from time-domain amplitudes of equalized records of the $_1R_1$ overtones. The full line is the theoretical radiation pattern for a moment of 6.7×10^{27} dyn-cm. The data point at OBN is only tentative.

4. Q and moment

In order to investigate the overtones quantitatively, our next step was to build a synthetic seismogram of the PAS record for a perfectly elastic model ($Q = \infty$) by adding all normal modes with $T \geqslant 45$ s. Since Koyama [9] has shown that the rupture time of the source was approximately 30 s, we use a step-function source, as our results deal exclusively with periods of 70 s or greater. By artificially "switching off" the overtones ${}_1S_l$ from the computation, we lost the phase observed experimentally, and were thus able to confirm its interpretation as ${}_1R_1$.

Q. Since the moment of this earthquake is well documented [8,9], it is possible to use a comparison of this synthetic with the observed record filtered at 45 s, to investigate directly the overtone Q at the predominant frequency involved. Using a moment of 6.7×10^{27} dyn-cm, we obtain $Q = 160$ for the first overtone at $T = 80$ s. Previous direct measurements of the Q's of overtones have usually been constrained to lower frequencies [16,17]. Jobert and Roult [17] obtained values of $Q = 150$–220 in the range ${}_1S_{55}$ to ${}_1S_{69}$, corresponding to periods of 100–120 s. We also computed values of Q by applying the same technique to the phase ${}_1R_2$, well recorded at the two African stations of AAE and NAI (Fig. 5), and obtained $Q = 140$ (NAI) and 145 (AAE) at 70 s. Since the travel time of the phase is about three times that of ${}_1R_1$, anelastic attenuation plays a greater role on the amplitude of the recorded phase, and these values are probably accurate to ±10%. This puts our results in good agreement with Anderson and Hart's [13] models SL1 and SL2 (Fig. 6) which give Q's of respectively 154 and 137 for ${}_1S_{90}$ ($T = 80$ s).

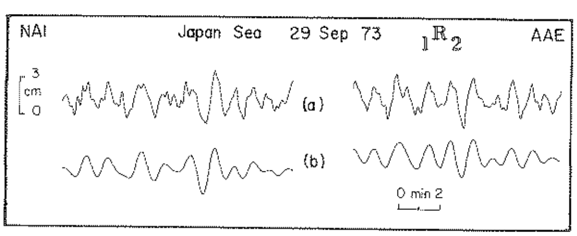

Fig. 5. Records of ${}_1R_2$ at NAI and AAE: (a) original traces; (b) filtered at $T \geqslant 45$ s.

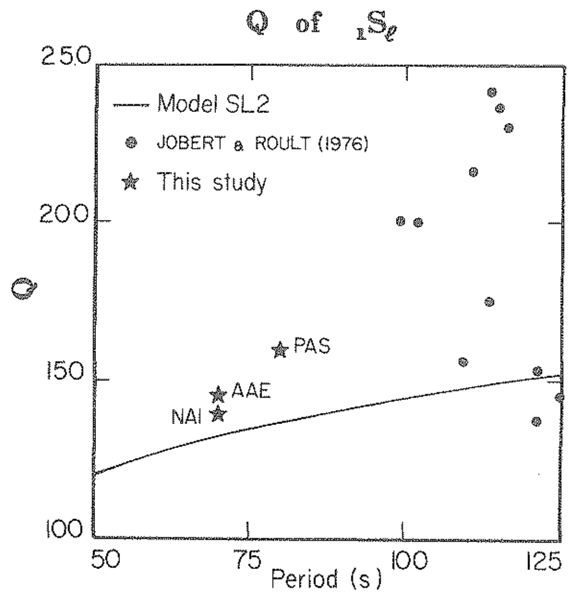

Fig. 6. Values of Q for the first higher modes obtained in this study, compared to theoretical values computed from SL2 [13], and to Jobert and Roult's [17] experimental results at longer periods.

For the second overtone (${}_2R_1$), present in the PAS record around 01:15 GMT, a tentative value of $Q = 230$ at 80 s is proposed. This is somewhat higher than expected from SL2 ($Q = 155$). However, our signal is much smaller, and this value is probably much less accurate than for the first higher overtone. Nevertheless, it is worth noting (see [13, table VII]) that the theoretical values obtained from SL2 (and SL1 as well) are all low compared to experimental results (available only at lower frequencies). Our tentative data seem to confirm this point.

Seismic moment. If, on the other hand, we now assume that a Q model of the Earth is known, synthetic seismograms including the effect of attenuation can be used to compute the moment of the event. We will now use model SL2 [13] to build synthetics of ${}_1R_1$ and ${}_0R_1$, at a number of stations. The excellent agreement of the entire trace of the record with synthetics is demonstrated for PAS in Fig. 1. No synthetic was built for OBN, since the instrument's characteristics were not known accurately, and the LUB fundamental, of very low quality, was omitted from this study.

We computed the moment values resulting from

TABLE 2

Values of seismic moment obtained from overtone and fundamental Rayleigh waves

Station	Overtone moment (10^{27} dyn-cm)	Fundamental moment (10^{27} dyn-cm)	Ratio overtone/ fundamental
PAS	6.7	5.45	1.23
LUB	8.32	N/A	
WEL	4.78	5.58	0.86
PPT	6.14	6.05	1.01
PAL	4.72	5.37	0.88
BHP	6.70	9.31	0.72
BUL	6.52	6.99	0.93
GRM	6.20	8.25	0.75
GIE	9.36	7.71	1.21
QUI	7.76	7.55	1.03
Average value and standard deviation			
	6.72 ± 1.4	6.92 ± 1.32	0.96 ± 0.17

comparison between synthetic and observed seismograms, both for overtones and fundamentals, as listed in Table 2. The fourth column lists the ratio of overtone to fundamental moment at the various stations. This ratio remains very close to 1, which expresses the reliability of overtone determinations with respect to the ones using fundamentals. The standard deviation of the overtone moments is also totally comparable to its counterpart for fundamental waves. The fact that overtone values are usually slightly lower than fundamental ones is certainly not significant, since Koyama [9] reported a value of only 5.2×10^{27} dyn-cm from a different set of long-period fundamental surface waves. The average overtone value is also in full agreement with Furumoto and Fukao's [8] value, obtained from still a third set of fundamental waves.

5. Phase velocity

Finally, because of a favorable layout of stations, it was possible to obtain a direct measurement of the overtone's phase velocity. As shown in Table 1 and Fig. 2, the three stations LUB, QUI and ARE are virtually aligned on a common great circle with the epicenter, which makes it possible to use the two-station method [4,18]. In order to maximize the distance between the two stations, we used LUB and

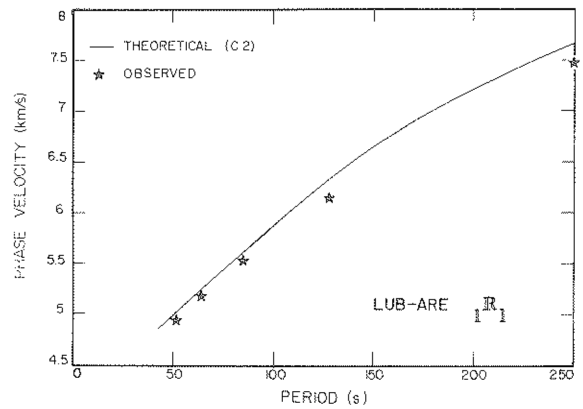

Fig. 7. Experimental phase velocity obtained by the two-station method applied to $_1R_1$ between LUB and ARE. The full line represents the dispersion curve computed from model C2.

ARE. Results are shown in Fig. 7. The agreement with model C2 is excellent and again demonstrates the feasibility of using overtones as individual seismic phases. The fact that the observed values are slightly, but consistently, lower than predicted by C2, may be due to a path of highly tectonic nature. However, this interpretation will have to wait until more data on the regional dispersion of $_1R$ becomes available.

6. Conclusion

A case study of overtones generated by the Japan Sea earthquake of 1973 shows that, when treated as individual seismic phases, overtones can be reliably used to determine focal characteristics, such as radiation pattern and moment. Estimates of Q for the $_1S_l$ branch at 70 and 80 s yield values of 140–160, in good agreement with the latest published models. With the development of the IDA network of accelerometers, it should be possible to gather a large amount of overtone data, and by making use of standard dispersion techniques (such as the two-station method, positively tested over one path), to gain new insight into the properties of the deep upper mantle.

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