RAYLEIGH WAVE ATTENUATION ACROSS THE ATLANTIC-INDIAN RIDGE

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(Received April 6, 1987; Revised February 13, 1988)

The regionalization method has been applied to the attenuation coefficients of the vertical components of Rayleigh waves for the Southern Atlantic-Indian Ocean to obtain the attenuation across the ridge region.

The obtained ridge attenuation coefficients are similar to those for the North Atlantic ridge and much lower than the values for the East Pacific Rise.

Inversion theory, in its stochastic form, shows that the low- Q zone under the ridge seems to be located between 50 km and 200 km depth, with the maximum Q^{-1} value ($\approx 15 \times 10^{-3}$) at a depth of about 140 km.

Comparison of the ridge model in this study with models for the North Atlantic ridge and East Pacific Rise, obtained by others, indicates that the attenuation coefficients for the study region are similar to those for the North Atlantic ridge, and much weaker than those for the East Pacific Rise. Since the spreading rate in the southern part of the Atlantic-Indian Ocean is similar to that in the North Atlantic, and lower than the corresponding rate in the Pacific, it seems that there is a close relation between spreading rates and low- Q regions under the ridges, with the Q values being higher in the region where the spreading rates are lower.

The above results suggest that the creep rate under the ridge of the Southern Atlantic-Indian Ocean may be similar to that for the Atlantic, and much lower than for the Pacific Ocean for regions of comparable ages.

1. Introduction

Surface-wave attenuation studies for the Pacific and Atlantic Oceans have provided a good knowledge of the Q structure under both oceans (e.g., ANDERSON *et al.*, 1965; TSAI and AKI, 1969; MITCHELL, 1976; MITCHELL *et al.*, 1976). Local and regionalized studies in these oceans (e.g., SOLOMON, 1973; CANAS and MITCHELL, 1978; CANAS *et al.*, 1980; CANAS and MITCHELL, 1981; CANAS, 1982) have shown that the Q structure is a function of the oceanic sea floor age, the Q values being lower as the oceanic regions become younger. This result is in general agreement with the results of NAKANISHI and ANDERSON (1984), who found that young oceanic regions have lower Q values than older ones. Comparison of the Q structures under the Pacific and Atlantic suggests that the Q values and the spreading rates of the

lithospheric plates are closely related to long-term creep in the mantle (CANAS and MITCHELL, 1981).

The principal purpose of this study is to determine the Q distribution under the Southern Atlantic-Indian ridge. Since the spreading rates in the southern part of the Indian ridge are similar to those in the North Atlantic Ocean (e.g., LE PICHON, 1968; MCKENZIE and SCLATER, 1971; MINSTER *et al.*, 1974), the Q values under the Atlantic-Indian ridge are expected to be similar to those beneath the ridge of the North Atlantic Ocean, in agreement with the idea that Q values are associated with spreading rates (CANAS and MITCHELL, 1981).

2. Data

The earthquakes in this study (Table 1, Fig. 1) were selected so that great circle

Table 1. List of earthquakes used in the present study.

Date	H_0	Locations	h	m_b	Stations
5-Apr.-69	06:53:39.2	— 54.7, 143.8	33	5.2	SPA-NAT
27-Oct.-69	08:10:58.3	44.9, 17.2	33	5.3	SPA-WIN
9-Aug.-70	10:16:04.6	— 62.8, —160.5	33	5.2	SPA-WIN
10-Aug.-70	02:01:53.1	41.1, 19.8	33	5.2	SPA-WIN
23-Oct.-71	01:41:12.7	— 54.7, 146.3	33	5.5	SPA-NAT
14-Aug.-72	22:29:27.6	— 6.3, 144.4	44	5.6	SPA-NAT
26-Sep.-73	16:27:47.2	— 55.4, 146.3	33	5.5	SPA-NAT
13-Aug.-74	14:45:42.0	— 55.5, 146.3	33	5.6	SPA-NAT
23-Oct.-74	11:26:36.2	— 54.2, 143.7	33	5.6	SPA-NAT

Fig. 1. Location of the WWSSN stations (●). The earthquakes are located outside the figure limits. The ×'s represent the schematic situation of the earthquakes. The dashed line indicates the 0-23 m.y. old region of the ridge. The 0-23 m.y. old region is determined from HEEZEN *et al.* (1978).

Table 2. Average group velocity, average and regionalized ridge-region attenuation coefficients of Rayleigh waves.

T	$U(\text{km/s}) \pm \text{S.D.}$	Average $\gamma * 10^{-4}(\text{km}^{-1}) \pm \text{S.D.}$	Ridge-region $\gamma * 10^{-4}(\text{km}^{-1}) \pm \text{S.D.}$
15	3.355 ± 0.170	2.04 ± 0.94	5.03 ± 1.72
16	3.351 ± 0.167	1.66 ± 0.98	4.63 ± 1.58
18	3.420 ± 0.135	1.62 ± 0.95	3.26 ± 1.65
20	3.536 ± 0.144	1.07 ± 0.90	2.83 ± 1.52
22	3.564 ± 0.112	0.70 ± 0.82	2.61 ± 1.20
24	3.696 ± 0.155	0.74 ± 0.91	2.40 ± 1.18
26	3.764 ± 0.119	0.78 ± 1.00	2.11 ± 1.17
28	3.809 ± 0.170	1.09 ± 1.04	1.95 ± 1.19
30	3.771 ± 0.095	1.56 ± 0.92	1.80 ± 1.15
35	3.947 ± 0.101	1.47 ± 0.81	1.72 ± 1.23
40	3.956 ± 0.089	1.04 ± 0.51	1.73 ± 1.12
45	3.954 ± 0.056	0.85 ± 0.58	1.40 ± 1.11
50	3.970 ± 0.096	0.94 ± 0.86	1.26 ± 1.17
60	3.900 ± 0.104	0.92 ± 0.72	0.87 ± 1.14
70	3.849 ± 0.148	1.00 ± 0.72	1.02 ± 1.13
80	3.915 ± 0.145	0.92 ± 0.95	0.93 ± 1.12
90	3.789 ± 0.105	0.85 ± 1.10	0.88 ± 1.37
100	3.672 ± 0.145	1.04 ± 1.28	0.66 ± 1.52

paths between pairs of seismographic stations were close to being common. The maximum separation between stations on a common great circle path is no more than 3 deg of arc. In Fig. 1 are also shown the seismographic stations used in this study. All the stations belong to the World Wide Standard Seismograph Network (WWSSN); therefore, their instrument constants are reasonably well known. Departures from expected amplitudes were checked using the method of MITCHELL and LANDISMAN (1969).

The multiple filter method (DZIEWONSKI *et al.*, 1969; HERRMANN, 1973) has been applied to the digitized long-period, vertical component Rayleigh-wave data sampled at intervals of 1 s, yielding amplitudes and group velocities. The resulting interstation group velocities, despite some contamination due to the Antarctic block, are in close agreement with those obtained for the Atlantic Ocean (CANAS, 1981). The average interstation group velocities are listed in Table 2 together with their standard deviations.

3. Rayleigh-Wave Attenuation Coefficients

Applying the two-station method (TSAI and AKI, 1969), the attenuation coefficients (γ), are given by:

$$\gamma(\omega) = \ln \frac{A_1(\omega, r_1) I_2(\omega) (\sin \Delta_2)^{1/2}}{A_2(\omega, r_2) I_1(\omega) (\sin \Delta_1)^{1/2}}, \quad (1)$$

where $A_1(\omega, r_1)$ and $A_2(\omega, r_2)$ are the spectral amplitudes at distances r_1 and r_2 in kilometers; $I_1(\omega)$ and $I_2(\omega)$ are the amplitude responses of the instruments, ω is the angular frequency, and $(\sin \Delta_1)^{1/2}$ and $(\sin \Delta_2)^{1/2}$ correct for the geometrical spreading of the energy; Δ_1 and Δ_2 are the epicentral distances in degrees to stations 1 and 2, respectively.

The main goal of this study is to determine the Q distribution under the southern part of the Atlantic-Indian ridge. Therefore, to obtain the attenuation coefficients for the ridge region, the following scheme has been applied:

$$\gamma(\omega) = \sum_{i=1}^M \alpha_i \gamma_i(\omega) \quad (2)$$

where $\gamma_i(\omega)$ represents the value of the attenuation coefficient for a portion of a particular path, α_i equals r_i/r , where r_i represents the portion of the path in kilometers, for which $\gamma = \gamma_i(\omega)$ and r is the length of the particular path. M is the number of different segments that make up the path.

If N is the number of observations, such that $N > M$, a least-squares method can be applied to obtain $\gamma_i(\omega)$, $i = 1, \dots, M$. Because this study is concerned with the determination of the Q distribution under the ridge, two regions will be considered. The first one is the region close to the ridge, in which the lithospheric ages are 0–23 m.y. old (Fig. 1). Selecting this range of ages allows us to compare the results obtained in this study to the results obtained in the North Atlantic Ocean for a region of the same range of ages (CANAS and MITCHELL, 1981).

Contamination of the average attenuation data by the Antarctic block becomes unimportant after the regionalization scheme has been applied, since the effect of the continental portion of the different paths between seismographic stations is confined to the region older than 23 m.y.

The average attenuation coefficients and the regionalized coefficients for the ridge region are listed in Table 2, and shown in Fig. 2. As can be seen in Table 2, the attenuation coefficients for the ridge region are larger than those corresponding to the average mixed paths studied. The average values are close to the average values obtained by CANAS (1981) for the Atlantic Ocean.

The fact that the average attenuation coefficients in this study are similar to those for the North Atlantic Ocean may indicate similar average Q distributions under both oceans, but no definite conclusions can be made, since the average attenuation coefficients obtained in this study may be contaminated by the continental portion of the Antarctic block.

The ridge attenuation coefficients obtained in this study and those obtained for the Pacific ridge (MITCHELL *et al.*, 1976) and for the Atlantic ridge (CANAS and MITCHELL, 1981) are shown in Fig. 3. It is clear that the attenuation coefficients obtained in this study for the ridge region are much lower than those for the Pacific ridge and somewhat lower than those for the Atlantic ridge. Because of the standard deviations of the regionalized attenuation coefficients for the ridge region in this study (Table 2), we avoid any speculation about differences between the attenuation

Fig. 2. Average South Atlantic-Indian Ocean (●) and South Atlantic-Indian ridge (▲) attenuation coefficients obtained in this study.

Fig. 3. Comparison of Rayleigh wave attenuation coefficients corresponding to the Pacific ridge (···) (Correig and Mitchell, 1981), the North Atlantic ridge (-·-) (CANAS and MITCHELL, 1981), and the Atlantic-Indian ridge (---).

Fig. 4

Fig. 5

Fig. 4. Shear-wave friction model for the ridge region obtained in the present study. The standard deviations are included in the representation.

Fig. 5. Resolving kernels at selected depths corresponding to the Q_β^{-1} in Fig. 4.

coefficients for the North Atlantic and Southern Atlantic-Indian ridges.

4. Inversion of the Attenuation Coefficients

The generalized inversion method in stochastic form, which has been applied in several previous studies (e.g., CANAS and MITCHELL, 1981; CANAS, 1982) is also used in the present paper. In the inversion procedure it is assumed that the values of the internal friction, Q_β^{-1} , are frequency-independent in the period range from 15 to 110 s. This assumption, as a first approximation, seems to be most likely true for this period range (e.g., KANAMORI and ANDERSON, 1977; MINSTER, 1978; SIPKIN and JORDAN, 1979). Q_α^{-1} is assumed to be a function of Q_β^{-1} in the sense obtained by ANDERSON *et al.* (1965). The velocity model used to compute the partial derivatives for performing the inversion is that of the 0–23 m.y. old region for the North Atlantic (CANAS and MITCHELL, 1981).

Figure 4 presents the internal friction model for the Atlantic-Indian ridge, together with the standard deviations, and the resolving kernels at several selected depths are shown in Fig. 5. The kernels indicate that the low- Q zone in the model is

Fig. 6. Comparison between regionalized attenuation coefficients for the ridge region and theoretical ones obtained from the Q_{β}^{-1} model in Fig. 4.

well resolved. The model in Fig. 4 presents a well-developed low- Q region located between about 50 km depth and 200 km depth with maximum Q_{β}^{-1} value ($\approx 15 \times 10^{-3}$) at about 140 km depth.

Figure 6 presents a comparison between the theoretical attenuation coefficient values for the model in Fig. 4 and the regionalized attenuation coefficients for the Southern Atlantic-Indian ridge. Matching between theoretical and regionalized attenuation coefficients for the ridge indicates that the model in Fig. 4 represents adequately the ridge region.

The ridge Q_{β}^{-1} models for the Pacific (CANAS *et al.*, 1980) and for the Atlantic (CANAS and MITCHELL, 1981), and the model obtained in the present study for the Atlantic-Indian ridge are compared in Fig. 7. The Q values of the model obtained in the present study are somewhat lower than those for the North Atlantic ridge model and much lower than those for the Pacific. It seems clear that as the relative plate velocity decreases (≈ 10 cm/year for the Pacific, ≈ 2 cm/year for the North Atlantic and the southern part of the Atlantic-Indian ridge), the low- Q regions under the ridges become weaker.

5. Conclusions

Attenuation coefficients of Rayleigh waves across the Southern Atlantic-Indian ridge are somewhat lower than the corresponding values for the North Atlantic ridge, and much lower than those for the East Pacific Rise.

A well-constrained Q_{β}^{-1} model is found for the region under the Southern Atlantic-Indian ridge, extending from about 50 to 200 km depth, with the depth of

Fig. 7. Comparison between the Q_{β}^{-1} models corresponding to the East Pacific Rise (E.P.R.), the North Atlantic ridge (N.A.R.), and the southern Atlantic-Indian Ridge (A.I.R.).

the maximum Q_{β}^{-1} value ($\approx 15 \times 10^{-3}$) being about 140 km.

Comparison of the Q_{β}^{-1} model in this study to the corresponding models for the Atlantic ridge and East Pacific Rise, obtained by others, shows that the model obtained in this study is similar to the one for the North Atlantic ridge and it is extremely different from the Q model for the East Pacific Rise. This agrees with the suggestion of CANAS and MITCHELL (1981) that low spreading rates correspond to less-developed low- Q zones under the ridge. The Q distribution determined in this study may indicate a similar creep rate under the South Atlantic ridge and the North Atlantic ridge, which is much lower than that under the East Pacific Rise.

I thank Brian J. Mitchell for a critical review of the manuscript.

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