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SHEAR WAVE Q STRUCTURE FOR THE LITHOSPHERE IN THE LÜTZOW-HOLM BAY REGION, EAST ANTARCTICA

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Abstract: Seismic wave attenuation in the lithosphere has been studied in various regions by the analysis of coda amplitudes of S-waves for local earthquakes. On the basis of the observed facts, the attenuation factor of coda waves (Q_c) is assumed to reflect the averaged Q for S-waves (Q_s) in an area within the ellipsoid of the scattering medium in the lithosphere. In this study, layered models of Q_s for the lithosphere in two tectonically different regions of shield and island arc were estimated from the observed Q_c at the various lapse times defined as 'time from origin of earthquake'. As for the representative of stable shield regions, five shallow earthquakes observed with a local telemetry seismic network around the Lützow-Holm Bay region, East Antarctica, were re-analyzed to calculate Q_c for the lapse time ranging from 20 s to 70 s in the 4, 8 and 16 Hz frequency bands. As for the tectonic active island arc region, Q_c for intra-plate earthquakes observed by the telemetered network in the middle and northern Kinki district, Japan was found in eight lapse time ranges from 20 s to 85 s at the same three frequency bands. From the resultant Q_s structure in both regions, it is remarkable that (1) Q_s for each layer of the same depth in the Lützow-Holm Bay region takes larger values than those of the Kinki district, particularly in high frequency range; (2) Q_s for the Lützow-Holm Bay region has a stronger frequency dependency than in the Kinki district. Another noticeable point is that Q_s for both regions has a rapid increase near the surface layer, which is attributed to the dependence of Q_c on lapse time in the short lapse time range. This is predominant in the Kinki district where Q_s is characterized by low values in the surface layer and a noticeable increase with depth in the upper 5 km of the crust.

1. Introduction

Attenuation properties of seismic waves in the lithosphere have been studied by the analysis of decay of coda amplitudes with time. The coda part of S-waves for local earthquakes is considered to consist mainly of S-waves scattered (reflected, refracted and diffracted) by random inhomogeneities in the lithosphere (AKI, 1969; AKI and CHOUET, 1975). The attenuation factor determined by the time decay of coda amplitude is called the coda Q (Q_c). On the basis of the observed Q_c and attenuation factor for the S-wave (Q_s), Q_c is assumed to reflect the averaged Q_s within an ellipsoid of the scattering medium in the lithosphere.

Q_c has been determined in various regions in the world (AKAMATSU, 1980; PULLI, 1984; SATO, 1986; ECK, 1988; CORREIG *et al*., 1990; NISHIGAMI *et al*., 1990; KANAO and

ITO, 1992). Regional differences in Q_c have also been revealed in relation to the determination of the frequency exponent n in the formula $Q=Q_0 f^n$, where f is frequency in Hz. The relationship of tectonic features, seismicity with Q_c and n has also been pointed out. For example, JIN *et al.* (1985) investigated the regional variations in Q_c for the oceanic lithosphere, finding that the younger oceanic lithosphere has a higher n value than the older one, which is similar to the active continental regions with higher n values. Thus the Q_c and n values provide an efficient way to determine the attenuation characteristics and their relation to seismo-tectonics in the studied area.

It is also known that Q_c depends on the lapse time, defined as 'time from origin of earthquake' (*e.g.*, ROECKER *et al.*, 1982; IBÁÑEZ *et al.*, 1990). For large lapse time range, the scattering ellipsoid is approximately a sphere. The radius r of the scattering area (sphere) is roughly estimated as $r=V_s t/2$, where V_s is S-wave velocity and t is lapse time. Q_c increases rapidly in the short lapse time range and gradually increases in the large lapse time range. We interpret this observation as an indication of the depth variation for Q_s in the lithosphere.

In this study, a one-dimensional layered model of Q_s for the lithosphere was estimated from the observed Q_c at various lapse times. Q_s structures correlating to the lapse time dependence of Q_c had already been obtained in some tectonic active regions, such as the western Pyrenees, France (GAGNEPAIN-BEYNEIX, 1987) and in the western Nagano region, Japan (KOSUGA, 1992) by use of micro-seismic data. As a representative of the shield regions, the Q_s structure of the Lützow-Holm Bay region, East Antarctica was compared to that of the tectonic active region of the island arc, Japan. Thus the obtained structures of the two regions were compared to each other concerning their seismicity, tectonics and crustal evolution.

2. Data and Regions

For the Lützow-Holm Bay region, AKAMATSU (1991) estimated Q_c based on the single isotropic scattering model applying to the coda part of S-waves for six shallow earthquakes observed with a local telemetry seismic network along the Sôya Coast from June 1987 to October 1989. Details of the seismic observations and their results are described in the papers by AKAMATSU *et al.* (1989) and AKAMATSU *et al.* (1990). The network consists of a large array of spacing about 15 km along the Sôya Coast (SYO, TOT and LAN) and a smaller tripartite array of spacing about 1 km on East Ongul Island (E, S and W) (See Fig. 1a). Q_c was estimated in the frequency range from 1 Hz to 24 Hz for the lapse time windows from 20 s to 210 s. The considerably smaller Q_c toward 1 Hz and extremely large values towards high frequency are the resulting strong frequency dependence of Q_c in this region.

In this study, five earthquakes (in Table 1) observed by the local telemetry network from 1987 to 1989 were re-analyzed by varying the lapse time from 20 s to 70 s for each waveform trace. The starting point of the time window, adopting the single scattering model, was set at twice the travel time of S-wave for all waveforms. Figure 1a shows the locations of earthquakes and stations used in this study in the Lützow-Holm Bay area. An example of band-pass filtered seismograms for six frequency bands and coda decay in logarithmic amplitudes with predicted curves by a single scattering model are presented in

Table 1. List of earthquakes used in this study for the Lützow-Holm Bay region.

No.	Date	Time	M	Region	Stations for analysis
1	Nov. 7, 1987	0623	1.5	Eastern part of Lützow-Holm Bay 50 km NW of Syowa Station	SYO, LAN, TOT
2	Dec. 22, 1987	1136	1.0	Mouth of Tama Glacier 50 km NE of Syowa Station	SYO, TOT
3	Dec. 23, 1987	0654	0.9	Mouth of Tama Glacier 50 km NE of Syowa Station	SYO, TOT
4	May 24, 1988	2303	0.2	Mouth of Langhovde Glacier 20 km S of Syowa Station	SYO, TOT, E, S, W
5	May 26, 1988	2303	−0.8	Mouth of Langhovde Glacier 20 km S of Syowa Station	SYO, TOT, E, S, W

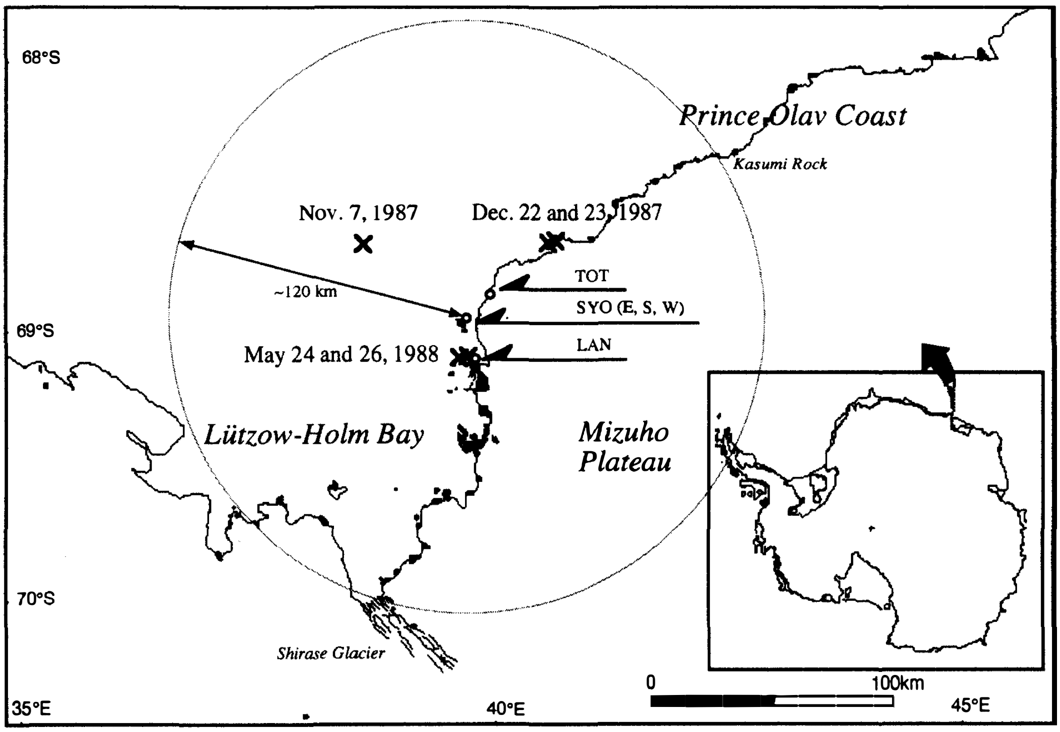

Fig. 1a. Location of local earthquakes (×) and seismic stations (SYO, TOT and LAN: 1-s three-component seismometers; E, S and W: 1-s vertical component array) used in this study in the Lützow-Holm Bay region, East Antarctica. A circle with radius about 120 km indicates the scattering area (sphere) affecting the coda wave generation corresponding to the maximum lapse time of 70 s.

Figs. 2a–b. Less than one hundred waveform traces recorded on six stations (SYO, TOT, LAN, E, S and W) were analyzed to obtain Q_c. Then the frequency dependent Q_c were determined for three frequency bands; the averaged values are listed in Table 2 for each lapse time window.

Q_c in the middle and northern Kinki district had already been determined (AKA-MATSU, 1980; AKAMATSU, 1986; KANAO and ITO, 1990, 1991). Frequency dependent

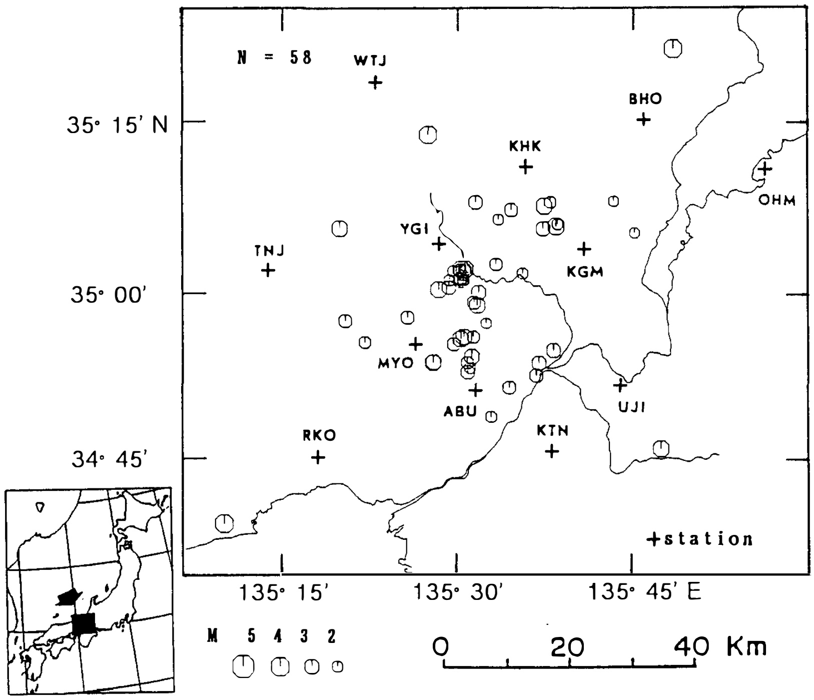

Fig. 1b. Location of local earthquakes (○) and seismic stations of Abuyama Observatory (+) in the middle and northern part of the Kinki district, Japan (after KANAO and ITO, 1990). Records of seismometer with the natural period of 1-s are used for all stations. The radius of a circle for each earthquake is proportional to the degree of magnitude (M).

Q_c with eight lapse times ranging from 20 to 85 s (KANAO and ITO, 1990) were adopted in order to estimate the Q_s structure in this region. They determined Q_c in five frequency bands from 2 to 32 Hz by applying the single scattering model to band-pass filtered coda decay curves for the vertical component seismogram from intra-plate earthquakes recorded by the Abuyama observatory telemetered network. Sets of Q_c with lapse times for three frequency bands used in this study are listed in Table 2, and the locations of earthquakes and seismic stations are presented in Fig. 1b (modified after KANAO and ITO, 1990), respectively.

The monotonous increase of Q_c in relation to the increase of lapse time has been pointed out in both regions in previous papers. The frequency dependent Q_c averaged over twelve stations in the Kinki district were fitted to the regression formula $Q_c = a + bt$, where t is lapse time (KANAO and ITO, 1990). For the Q_c in the Lützow-Holm Bay region, two windows, for short and long lapse times, were taken into account for the calculation of Q_c (AKAMATSU, 1991). In this study, the radius of the scattering sphere affecting the coda wave generation for the maximum lapse time of 70 s is estimated to be about 120 km, which is indicated by the circle with its center on the station 'SYO' in Fig. 1a. The scattering sphere covers almost all of the Lützow-Holm Bay region, from Kasumi Rock on the Prince Olav Coast in the north to the Shirase Glacier in the south. The maximum depth of about 120 km of the scattering medium indicates that the area which affects coda generation is restricted to the lithosphere.

In the following analysis, we discuss the results for the three frequency bands 4, 8 and

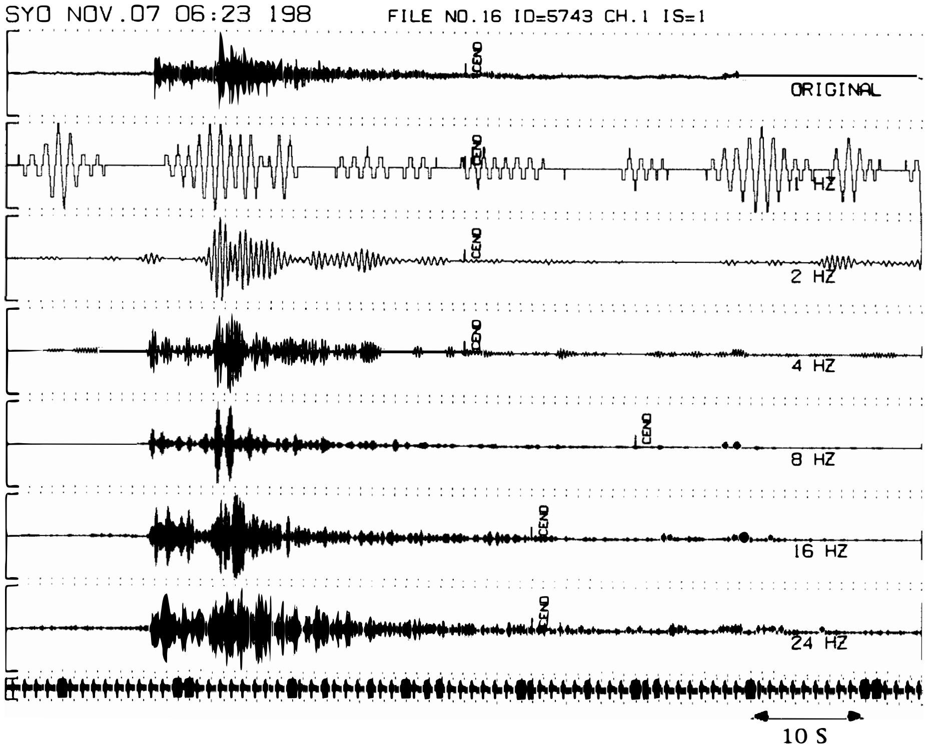

Fig. 2a. Example of band-pass filtered seismogram for six frequency bands of the event No. 1 (Table 1) at the station SYO. The label 'CEND' for each waveform indicates the point for three-times the coda amplitude compared with the noise level before P-wave arrival.

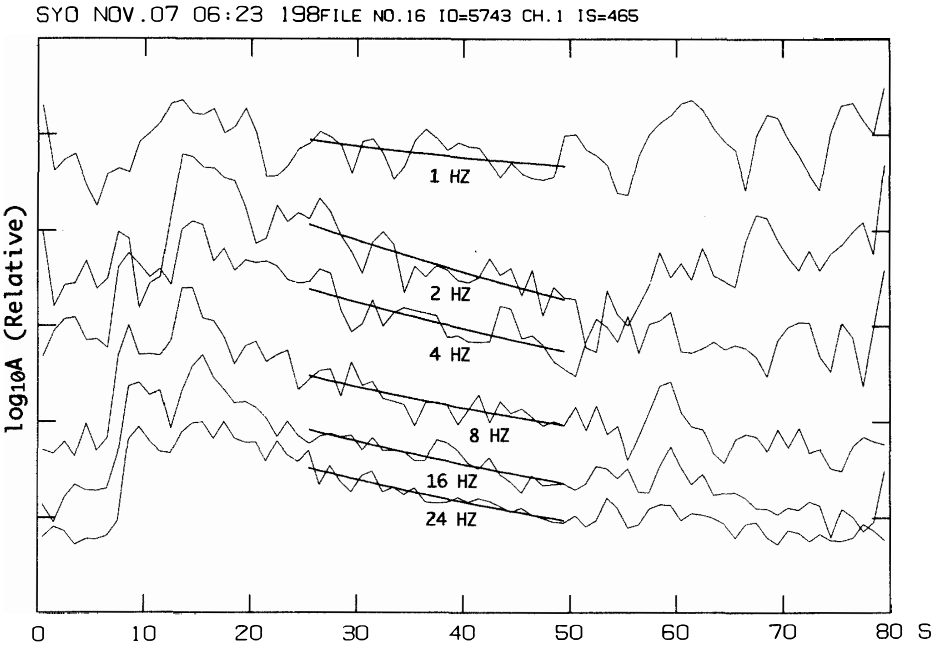

Fig. 2b. Example of coda decay in logarithmic amplitudes with curves predicted by a single scattering model in the same event as shown in Fig. 2a. Time was measured from earthquake origin time (lapse time). The predicted curves were fitted from 25 s to 50 s in this example.

Table 2. Averaged Q_C as a function of lapse time for three frequency bands in the Lützow-Holm Bay region (in this study) and Kinki district, Japan (after KANAO and ITO, 1990).

Lapse time	Averaged Q_C				Number of traces		
	4 Hz	8 Hz	16 Hz		4 Hz	8 Hz	16 Hz
Lützow-Holm Bay, Antarctica							
20	216	446	659		2	7	4
25	313	466	1075		11	13	12
30	182	439	1152		14	15	14
35	225	425	1924		16	16	16
40	242	588	2436		16	16	12
45	492	886	2960		7	6	6
50	356	1044	3242		10	9	6
55	1168	1437	6536		2	2	1
60	2147	1682	4710		4	4	3
70	1469	2246	4348		3	4	·2
				total	85	92	76
Kinki, Japan							
20	175	336	700		17	17	17
25	244	445	769		8	8	8
30	274	459	807		8	8	8
35	301	510	878		9	9	9
42.5	346	571	987		6	6	6
55	328	550	915		3	3	3
70	442	704	1201		4	4	4
85	479	711	1217		3	3	3
				total	58	58	58

16 Hz, because these frequency bands were accurately evaluated in both regions with enough datasets of Q_c and lapse time for the inversion analysis.

3. Estimation of Q_s Structure

For calculation of the layered Q_s structure in the lithosphere, single isotropic scattering and spatially uniform distribution of scattering strength were assumed. The Q_s structure was estimated by the inversion technique developed by KOSUGA (1992). In the following analysis, Q_c is considered to be the averaged Q_s within the scattering ellipsoid whose dimension is determined by the lapse time. For a large lapse time range, the scattering ellipsoid is approximated by a sphere.

The earth medium of the scattering sphere was assumed to be divided into n layers with constant Q_s for each layer. If the coda wave spends a time t_j in the j-th layer with an attenuation coefficient of Q_{s_j}, Q_c is related to Q_{s_j} by the following expression:

$$\frac{1}{Q_c}=\sum_{j=1}^{n}\frac{t_j}{Q_{s_j}}, \tag{1}$$

where the summation is taken over the number of layers sampled by coda waves. t_j was assumed to be normalized by the summation for all the layers such as $\sum t_j=\text{const}=1$.

Since it is difficult to evaluate t_j correctly in the practical analysis, the formula (1) can be reformed into the following expression:

$$\frac{1}{Q_C}=\sum_{j=1}^{n}\frac{\nu_j}{Q_{s_j}}, \tag{2}$$

where ν_j is the volume of the j-th layer and the summation is taken over the number of layers. ν_j is evaluated by travel times from the source to scatterers and return to receiver, and normalized by the formula $\sum\nu_j=\text{const}=1$. A schematic illustration for the calculation of Q_{s_j} is shown in Fig. 3.

Q_C is determined by the Marquardt method expressed by the following formula:

$$f_i=\log\left[\frac{1}{Q_{Ci}^{\mathrm{obs}}}\right]-\log\left[\frac{1}{Q_{Ci}^{\mathrm{cal}}}\right], \tag{3}$$

where i is the dataset number, and f is the residual function. If we take m as the maximum dataset number, the Q_{s_j} are determined after some iterations to minimize the square of the residual (S values) for the observed and calculated Q_C in the following expression:

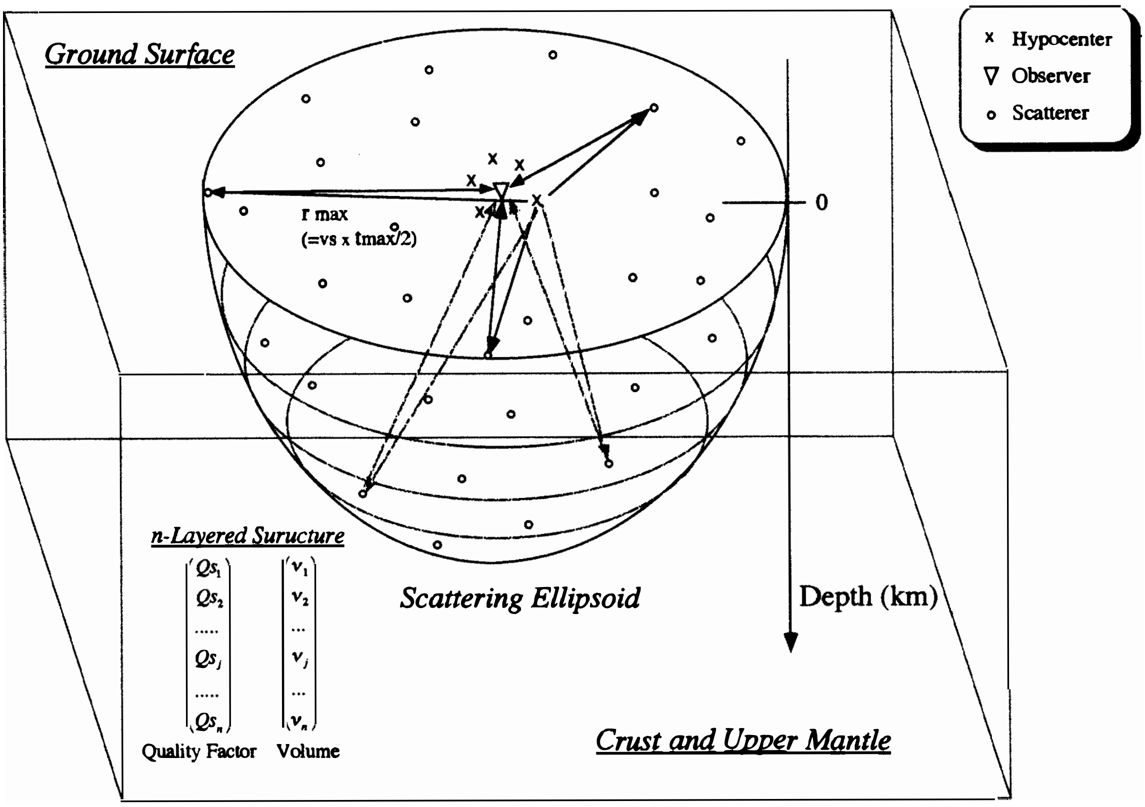

Fig. 3. Schematic illustration for calculation of the Q_s structure. S-coda waves are considered to consist of scattered S-waves from the scattering sphere in the lithosphere. The scattering sphere was divided into n layers with constant Q_s value in each layer with volume ν. The maximum radius of the scattering sphere is roughly estimated as $r_{max}=V_s t_{max}/2$, where V_s is S-wave velocity and t_{max} is the maximum lapse time.

$$S=\sum_{i=1}^{m} f_i^2. \tag{4}$$

Moreover, we assume that the S-wave velocity is constant at 3.5 km/s within the scattering area.

In order to minimize the estimation errors, the solution is constrained to not deviate significantly from the initial values. The initial values of Q_{s_j} were determined by forward modeling for trial-and-error estimation. The velocity model was adopted to constrain the layer thickness. The adopted velocity model shown in Fig. 4 is based on explosive refraction experiments conducted in the regions from Lützow-Holm Bay to the Mizuho Plateau (IKAMI *et al.*, 1984; ITO and IKAMI, 1984), and on apparent velocities of P-arrivals after crustal earthquakes according to teleseismic data of Abuyama Observatory (OKANO and KUROISO, 1986). The depths of discontinuities between the lower crust and upper mantle (Moho) are 40 km and 36 km, respectively. It is noticed that there are no sedimentary layers in the velocity model of the Lützow-Holm Bay region.

The maximum radius of the sphere in this analysis was estimated to be about 120 km (70 s lapse time) for the Lützow-Holm Bay region and to be 150 km (85 s lapse time) for the Kinki district. We considered the depth distribution of the volume ratio ($\nu_j/\sum\nu_j$) for each layer to the total scattering sphere. For the short lapse time range of 20 s, the volume within the crust has the maximum contribution to Q_c calculation. On the contrary, the volume of the uppermost mantle affects mostly Q_c for a long lapse time of 70 s and 85 s.

The results of calculation in the Lützow-Holm Bay region are shown in Fig. 5. Observed and calculated Q_c are plotted as a function of lapse time for three frequency bands. Observed Q_c are after the values in Table 2 for all obtained data and the mean values for each lapse time window are linked by broken lines. On the other hand, the calculated ones were determined on the assumption of a one-dimensional Q_s structure. The calculated Q_c have larger values in the short lapse time range less than 50 s and take smaller values in longer lapse times than the averaged Q_c for all observed data in the three frequency bands.

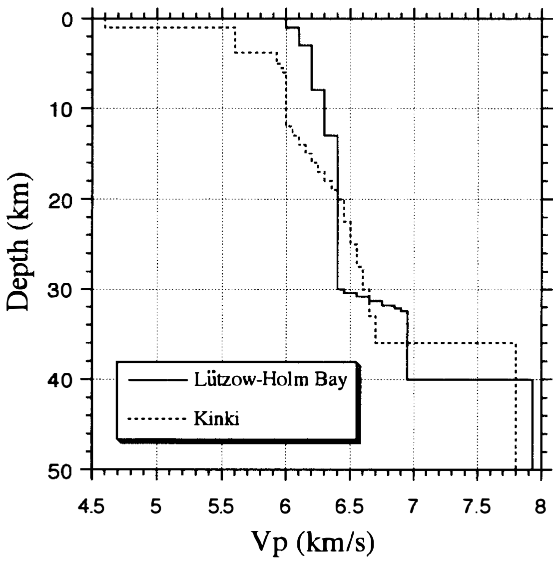

Fig. 4. P-wave velocity models for the crust and the uppermost mantle. (solid line) Lützow-Holm Bay region to Mizuho Plateau, East Antarctica derived from seismic refraction experiments (after IKAMI et al., 1984). (broken line) Kinki district, Japan, derived from apparent velocities of P-arrivals for intra-plate earthquakes (after OKANO and KUROISO, 1986).

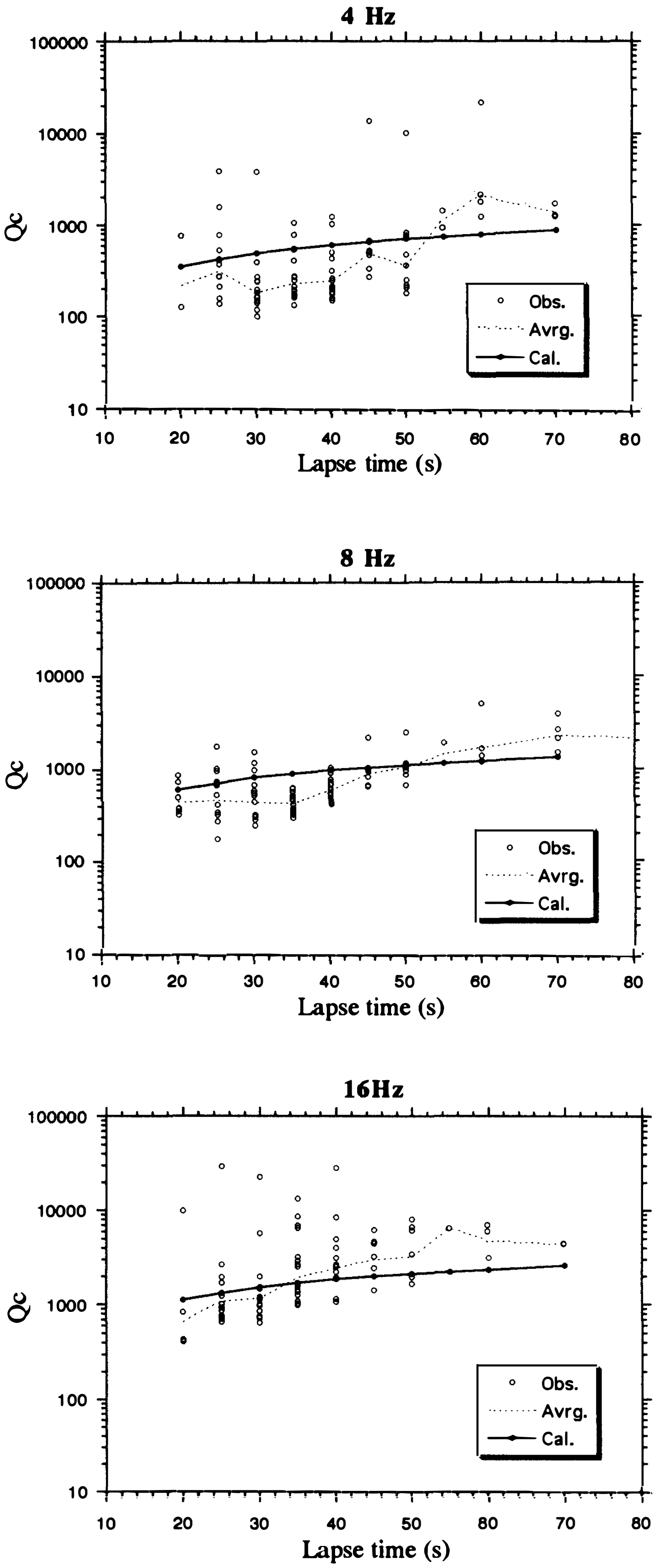

Fig. 5. Comparison between observed Q_C (Obs.; open circles) and calculated Q_C (Cal.; solid lines and circles) as a function of lapse time for the three frequency bands 4, 8 and 16 Hz in the Lützow-Holm Bay region. Averaged values (Avrg.; broken lines) for the observed Q_C (in Table 2) are linked for each lapse time. The calculated ones were obtained after the inversion of Q_S structure.

4. Results and Discussion

Figure 6 shows the inverted one-dimensional Q_s model in both regions from the surface layer to the depth of 50 km. Although Q_s for the depth range from 50 km to 120 km are not displayed in this figure, they were assumed to have constant values beneath 40 km depth for each frequency band in this calculation. Comparing Q_s of two regions to each other at the same depth, the Q_s in the Lützow-Holm bay region are larger than those of the Kinki district for all frequency bands. Lützow-Holm Bay, in a tectonically stable shield region, has a higher Q_s lithosphere for the propagation of S-waves than an island arc, tectonic active subduction zone such as Japanese islands.

The second noticeable point is that the frequency dependence of Q_s is stronger in the Lützow-Holm Bay region than in the Kinki district. This is because of the large n values of 0.776 for the shallow lithosphere with a short lapse time from 20 s to 40 s in this region (AKAMATSU, 1991). Large n values are correlated with high tectonic activity; however, the weak attenuation in high frequency band and rather strong attenuation at lower frequency in the Lützow-Holm Bay region indicate the existence of the scattering loss by heterogeneities such as the perturbation of velocities and/or density, particularly in lower frequency bands. At frequency higher than 4 Hz, there seem to be scarcely any faults or micro-cracks that cause strong scattering effects in the lithosphere.

It is known that the velocity change is large at the Moho discontinuity. On the other hand, Q_s increase rapidly near the surface layers. This depth distribution of Q_s is attributed to the dependence of Q_c in the short lapse time range. Particularly, in the Kinki district, the Q_s structure is characterized by low values in the surface layers and a noticeable increase with depth in the upper 5 km of the crust. In the Lützow-Holm Bay region, the temperature profile, and P- and S-wave velocities of the upper crust calculated from the laboratory data (after YUKUTAKE and ITO, 1984), are shown in Fig. 7a. The P-wave velocity from the explosion seismic experiments on the Mizuho Plateau (IKAMI *et al*., 1984) is also given in the figure. These observations of no sedimentary layer with low velocity support the existence of a high Q_s zone near the surface in this region.

Figure 7b shows the depth variation of Q_s from the inversion analysis in the upper crust from the surface to 20 km at three frequency bands in both regions. The regressive curves are drawn as a mean Q_s for each dataset in Fig. 6. From the result, the increasing ratio of Q_s with depth is about 1.5 times larger in the Kinki district rather than in the Lützow-Holm Bay region for the higher frequency bands of 8 Hz and 16 Hz. On the other hand, the increasing ratios of Q_s in the 4 Hz band are the same in both regions. These facts suggest that the spatial distribution of the heterogeneities corresponding to 16 Hz might be different between the two regions. The attenuation of the shallow crust is large in the Kinki district in high frequency bands. This is interpreted as due to the fact that the density of small-scale heterogeneities such as micro-cracks and sub faults seems to be large in the high frequency range in the Kinki district. On the other hand, attenuation near the surface layer is small in the Lützow-Holm Bay region.

The non-uniform distribution of the scattering strength affects the lapse time dependence on Q_c (HOSHIBA, 1994). The multiple scattering model can also explain the increase of Q_c with lapse time (GAO *et al*., 1983), the influence of multiple scattering on the coda generation should be taken into consideration. Even when we take that effect into

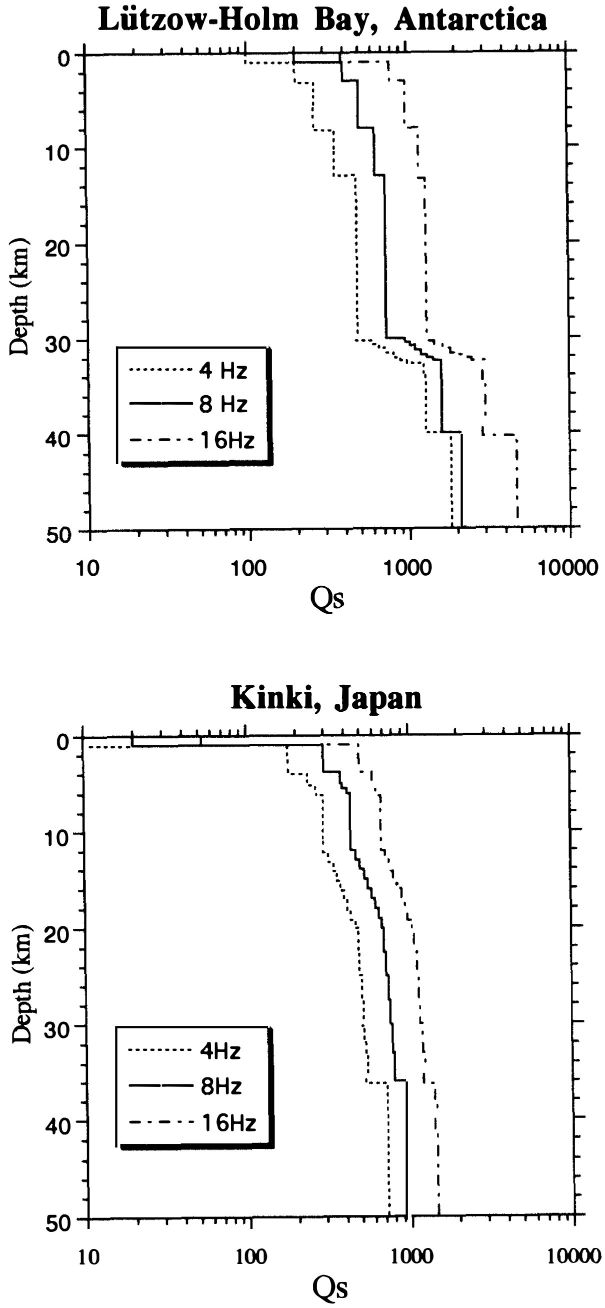

Fig. 6. One-dimensional Q_S structure for the crust and the uppermost mantle derived from the observed Q_C at various lapse times for the three frequency bands 4, 8 and 16 Hz. Depths of interfaces between two layers with constant Q_S were assumed to exist at the depths of velocity discontinuities from the P-wave velocity model in Fig. 4. (upper) Lützow-Holm Bay region, (lower) Kinki district, Japan.

consideration, however, the features discussed in this chapter, such as comparison of Q_S values, frequency dependence and the depth variations in the both regions, still hold true.

Further investigation of the precise structure in the crust and the uppermost mantle is needed, particularly in the Antarctic region. A more detailed Q_S model for the lithosphere will be obtained by advanced study of the velocity structure analysis by use of body/surface waves and explosion experiments. The possibility of multiple scattering should also be taken into consideration in the future study of the Q_S structure in the long lapse time range.

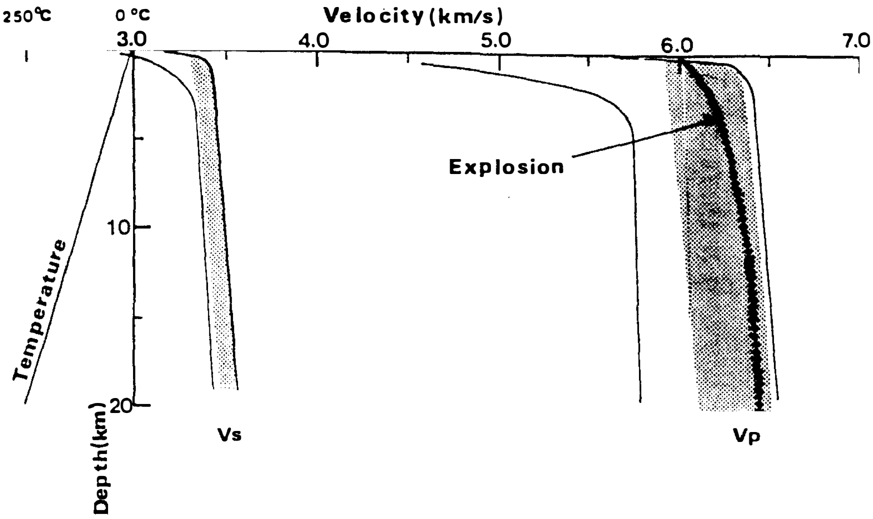

Fig. 7a. *Temperature profile, and P- and S-wave velocities of the upper crust calculated from the laboratory data. The P-wave velocity from explosion seismic experiments on the Mizuho Plateau is also given (after* YUKUTAKE *and* ITO, *1984)*

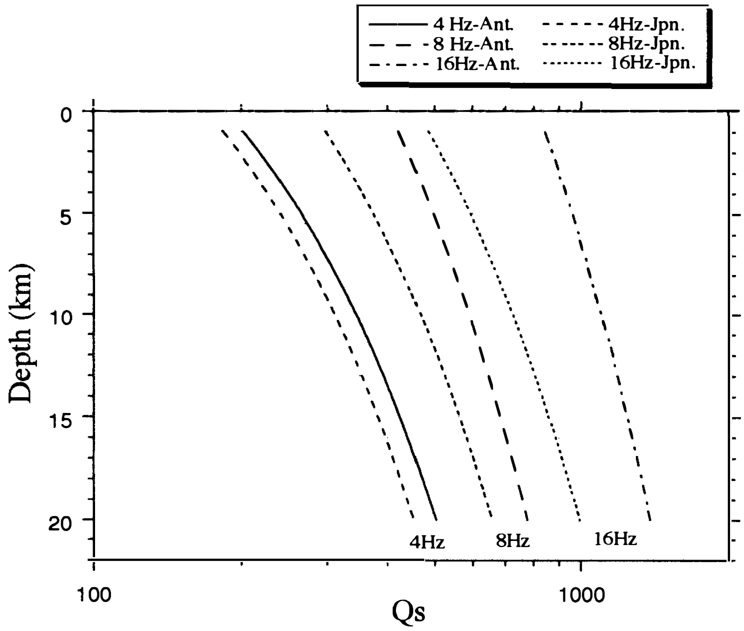

Fig. 7b. *Depth variations of Q_S in the upper crustal range from the surface to depth 20 km in three frequency bands in both regions. The regressive curves are drawn with linearlized fitting for each Q_S. The depth gradient for Q_S is steeper in the Lützow-Holm Bay region than in the Kinki district, particularly in the high frequency band.*

5. Concluding Remarks

One-dimensional Q_S models for the lithosphere were derived by inversion of the observed Q_C in the Lützow-Holm Bay, East Antarctica and the Kinki district, Japan. The detailed depth structures of Q_S in the 4, 8 and 16 Hz frequency ranges have been discussed; the results are summarized as follows.

(1) Compared at the same depth, Q_S in the Lützow-Holm Bay region is larger than that in the Kinki district, particular in high frequency bands.

(2) The frequency dependence of Q_S is larger in the Lützow-Holm Bay region than in the Kinki district. This noticeable high n in Lützow-Holm Bay is considered to be related to the weakness of the small scale heterogeneities corresponding to the wavelength of the high frequency band.

(3) Q_S increases rapidly near the surface layer, particularly in the Kinki district. This might be caused by the strong scattering effect in the upper crust. High Q_S near the surface in the Lützow-Holm Bay region is due to the lack of sedimentary layer with low velocity. There is a difference of Q_S and increasing ratio with depth between the two regions, particularly in the high frequency bands of 8 and 16 Hz.

(4) All these characteristics (1) to (3) indicate that Lützow-Holm Bay, representative of stable shield region, has a more homogeneous lithosphere for the propagation of S-waves, particularly in the high frequency range, than in the tectonically active island arc region, Japan.

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