

## Coda $Q$ in the eastern Caribbean, West Indies

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Accepted 1992 August 11. Received 1992 August 4; in original form 1992 February 18

### SUMMARY

Coda  $Q$ ,  $Q_c$ , has been estimated from seismograms of local earthquakes recorded on short-period seismographs on some of the eastern Caribbean islands of the Lesser Antilles arc, West Indies, using the  $S$ - $S$  single-scattering model. The region was subdivided into four distinct subregions in order to investigate lateral variations in  $Q_c$ . The  $Q_c$  values exhibit a strong frequency dependence in the frequency band 1.5 to 16 Hz, with calculated coda  $Q$  at 1 Hz,  $Q_o$ , ranging from a minimum of 97 in the Dominica area to a maximum of 145 in the Leewards. The degree of frequency dependence is also largest in the Dominica area ( $n = 1.09$ ) and smallest in the Leewards ( $n = 0.82$ ). Although there appears to be some lateral and depth variation of both  $Q_o$  and  $n$  in the region, this variation does not seem to be very significant.

**Key words:** Caribbean, coda  $Q$ , earthquakes, seismograms.

### 1 INTRODUCTION

Attenuation of seismic waves, customarily described by the dimensionless parameter  $Q$ , called the specific quality factor, expresses the wave-amplitude decay that occurs when a wave propagates through real media and cannot be attributed to geometrical spreading. Seismic-wave attenuation is a combination of two different loss mechanisms: anelastic absorption, the loss of elastic energy to heat or other forms of energy, and scattering, the deflection and/or mode conversion of seismic energy due to randomly distributed inhomogeneities in the transmitting medium (Dainty 1981). However, according to Dainty (1981), the effects of intrinsic and scattering attenuation cannot be directly separated because of similarity in their mathematical form.

Seismic-wave attenuation varies spatially (e.g. Sutton, Mitronovas & Pomeroy 1967; Cheng & Mitchell 1981; Singh & Herrmann 1983; Jin & Aki 1988) and may also be frequency dependent (Mitchell 1980; Rovelli 1984; Kvamme & Havskov 1989), with the degree of frequency dependence varying from region to region (Mitchell 1981; Pulli & Aki 1981). Consequently, the degree of spatial variation of both attenuation and its frequency dependence may be used to infer the nature of the material conditions in the earth.

Although seismic-wave attenuation is an important parameter, knowledge of which is, for example, essential for the prediction of earthquake ground motion in seismic-hazard analyses, its nature is not well understood. Furthermore, it is difficult to measure, especially in the frequency band 1 to 30 Hz, frequencies of interest in short-period seismology and structural engineering. Hough *et al.* (1988), following the categories recognized by Cormier

(1982) in teleseismic studies, classified methods used to study high-frequency attenuation at near and regional distances into four broad classes. These include methods which cancel the seismic source, methods which make assumptions about the source, coda methods and time-domain methods. Many recent determinations of attenuation using local earthquakes have involved the use of coda methods because of their simplicity and ease of application.

Coda waves comprise the latter part of seismograms, the part after all the direct waves such as  $P$ ,  $S$  and surface waves have arrived (Herraiz & Espinosa 1987). Theoretical and observational studies on coda waves generally seem to suggest that the coda is produced by the interaction between primary waves and small-scale lithospheric heterogeneities. Scattered body waves can also be generated by topography (Spudich & Bostwick 1987) while an irregular low-velocity surface layer will convert and scatter body waves to surface waves (Levander & Hill 1985).

The most widely applied coda method is that formulated by Aki (1969) and extended by Aki & Chouet (1975) and Sato (1977). It considers the  $S$ -wave coda as consisting of single, backscattered  $S$ -waves from randomly distributed heterogeneities in the lithosphere. The envelopes of the codas of narrow, bandpass-filtered seismograms can then be used to determine the average  $Q$  for the medium for the particular frequency bands. The single-scattering model has been used to determine attenuation in many regions of the world (e.g. Rautian & Khalturin 1978; Roecker *et al.* 1982; Pulli 1984; Havskov *et al.* 1989; Ambeh & Fairhead 1989) and to investigate temporal changes in coda attenuation as a possible tool for earthquake prediction (e.g. Jin & Aki 1986; Lee *et al.* 1986; Novelo-Casanova, Berg & Helsley 1990).

Although this simple model seems to explain much of the

character of observed coda, there are still significant disagreements, especially in the details of the modelling process. For example, a point of great contention is how the coda  $Q$  should be interpreted. Coda  $Q$  as originally formulated was thought to be a reflection of the scattering effect only (Aki 1969). Aki (1980a) and many others, from comparisons of coda  $Q$  and shear wave  $Q$ , have suggested that coda  $Q$  is more closely related to intrinsic rather than scattering attenuation. This view has been supported by results of analyses by Wu (1985) and Frankel & Wennerberg (1987) using energy flux models. Langston (1989) has, however, shown in the analysis of long-period Rayleigh waves in western North America that coda decay with time, which is used to obtain  $Q$ , cannot be used to discriminate between coda mechanisms, i.e. scattering or anelastic absorption.

The eastern Caribbean is a tectonically complex area which includes a subduction zone, island arc and active volcanoes. Earthquakes occurring in the area have focal depths from near surface to about 200 km and are monitored by short-period seismographs operated by the Seismic Research Unit of the University of the West Indies, Trinidad, and the 'observatoires Volcanologiques' in Guadeloupe and Martinique. No quantitative studies of seismic-wave attenuation in the eastern Caribbean have been made to date. In this paper, we investigate the spatial variation of seismic-wave attenuation and its frequency dependence in the eastern Caribbean using the Sato (1977) extension to the  $S$ - $S$  single scattering coda model of Aki & Chouet (1975).

## 2 MODEL, DATA AND ANALYSIS

### 2.1 The model

In the single, backscattering model of Aki & Chouet (1975), coda waves are considered as being composed of the superposition of backscattered body waves from numerous randomly distributed heterogeneities in the lithosphere. The model assumes that the earthquake and the station are coincident, i.e. the scatterers are at large distances compared to the source-receiver distance. According to Aki & Chouet (1975), coda amplitude,  $A(f|t)$ , at frequency,  $f$ , and lapse time (traveltime),  $t$ , is given by

$$A(f|t) = C(f)t^{-\alpha} \exp(-\pi ft/Q_c) \quad (1)$$

where  $C(f)$  represents the coda source factor,  $\alpha$  is a constant that depends on geometrical spreading and takes values of 1.0, 0.5 and 0.75 for body wave, surface wave and diffusion scattering respectively, and  $Q_c$  is the coda quality factor.

Aki (1980b), based on reported results of good agreement between coda  $Q$  and shear wave  $Q$  (e.g. Rautian & Khalturin 1978; Aki 1980a), concluded that coda waves are made up primarily of backscattered  $S$  waves. This close agreement between  $S$ -wave  $Q$  and coda  $Q$  has been confirmed by other workers (e.g. Roecker *et al.* 1982; Del Pezzo *et al.* 1985; Rebollar, Traslosheros & Alvarez 1985; Kvanne & Havskov 1989). Consequently, we assume a spreading parameter of  $\alpha = 1$ . It must, however, be mentioned that Herrmann (1980) also found good

agreement at 1 Hz between coda  $Q$  and  $Q$  from  $Lg$  waves.

The assumption in the model of Aki & Chouet (1975) that the source and the receiver are located at the same point is acceptable for coda waves recorded long after the passage of the primary waves. In fact, Rautian & Khalturin (1978) state that eq. (1) is valid only for lapse times greater than twice the  $S$ -wave traveltime. However, analysis in this region of the coda is often difficult because of an inadequate signal-to-noise ratio or short recording times. Sato (1977) extended the above single-scattering model to incorporate source-receiver offset, thus allowing one to begin coda analysis immediately after the shear wave arrival. The coda-wave relationship in the case of non-coincident source and receiver may be stated as

$$A(r, f|t) = C(f)K(r, a) \exp(-\pi ft/Q_c) \quad (2)$$

where  $a = t/t_s$ ,  $t_s$  is the  $S$ -wave lapse time,  $r$  is the source-receiver distance,  $K(r, a) = (1/r)\{(1/a) \ln[(a+1)/(a-1)]\}^{0.5}$  and all the other symbols have the same meaning as in eq. (1). Taking natural logarithms of eq. (2) and rearranging terms, we obtain

$$\ln[A(r, f|t)/k(r, a)] = \ln C(f) - (\pi f/Q_c)t. \quad (3)$$

For narrow-bandpass filtered seismograms,  $C(f)$  is a constant and hence by performing a linear regression of the term on the left-hand side of eq. (3) versus  $t$ ,  $Q_c$  can be determined from the slope which is equal to  $-\pi f/Q_c$ .

### 2.2 Data

In order to make a regional comparison of coda  $Q$  in the eastern Caribbean, we searched the data base of the Seismic Research Unit (SRU) of the University of the West Indies, Trinidad, for suitable events/seismograms recorded during the period May 1989 to June 1991. The SRU has operated a telemetered network of short-period (1 s) vertical component seismic stations in the English-speaking eastern Caribbean islands since 1987. Data digitized at a rate of 100 samples per/s and 12-bit resolution has been recorded on personal computers. Events/seismograms were selected on the basis of such factors as spatial distribution, absence of spikes, good signal-to-noise ratio characteristics, and epicentral distances less than about 70 km.

The final data set used in this study consists of 73 earthquakes with signal duration magnitudes,  $MD$ , ranging from 2.3 to 3.7 and focal depths from 1 km to 183 km. The earthquake epicentres and station locations are plotted in Fig. 1 while detailed information on the events and stations are listed in Tables 1 and 2 respectively. Ideally, we would have liked the epicentres to be distributed uniformly along the island arc but, unfortunately, this is not the case. Events are concentrated at the northern and southern ends and this, to a certain extent, is a reflection of the contemporary seismicity pattern in the eastern Caribbean. The lack of data in the Guadeloupe and Martinique areas is due to the unavailability of seismograms for stations on these islands while fewer earthquakes occur in the region from Grenada to St Lucia. Using the available earthquake and station data, we subdivided the eastern Caribbean into four subregions as shown in Fig. 1 and Table 1.

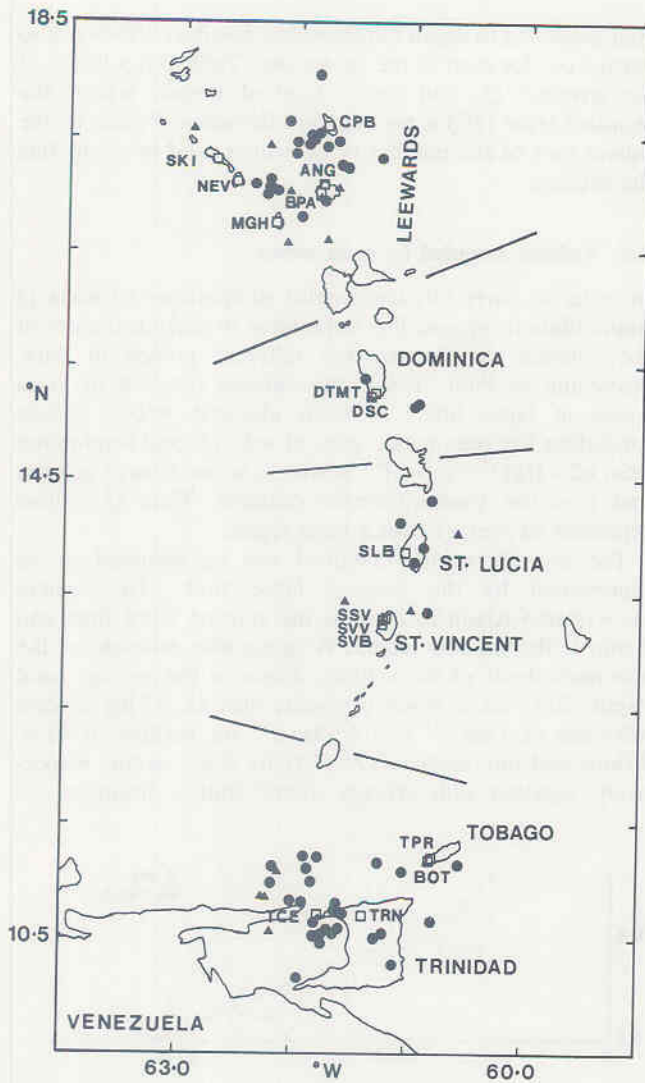


Figure 1. Map showing the earthquake epicentres and stations used in this study. Dots are shallow earthquakes ( $0 \leq Z \leq 70$  km), triangles are intermediate depth earthquakes ( $70 < Z < 200$  km) and squares are seismic stations. Approximate boundaries of the four subregions are also shown.

### 2.3 Analysis

Each seismogram time series was first bandpass filtered over eight frequency bands centred at 1.5, 2, 3, 4, 6, 8, 12 and 16 Hz, with bandwidths of 1, 2, 2, 4, 4, 8, 8, and 16 Hz respectively, using an eight-pole, phase-free Butterworth filter. Starting at the *S* arrival, the root-mean-square (rms) amplitudes in each window were determined for the data in each frequency band, with the window sliding across the time series at 1 s intervals. Time-window lengths for the rms averaging of 8 s (for centre frequencies of 1.5, 2, 3, 4 and 6 Hz) and 5 s (for centre frequencies 8, 12 and 16 Hz) were chosen so as to smooth out as much as possible irregularities in the amplitudes of the arrivals. The left-hand side of eq. (3) was then evaluated and plotted against lapse time. From the plot, the linear portion, which had to be at least 30 s long, was visually selected and a straight line fitted to it

Table 1. Parameters of events used in the coda-*Q* analysis.

Trinidad/Tobago (TT) Region							
Date	Time	Lat.	Lon.	Depth	Md	Stations	
DDMM-YY-	HRMN SEC	(°N)	(°W)	(km)			
01061989	0757 48.17	10.55	61.63	34	3.8	TRN	
27061989	1952 52.14	10.56	62.17	76	3.2	TRN	TCE
04071989	0716 35.90	10.86	62.25	91	3.8	TCE	
10071989	1230 03.46	10.65	60.78	55	3.0	TRN	
31071989	0820 13.03	10.75	61.62	39	3.1	TRN	TCE
03101989	1903 42.47	10.49	61.27	44	2.9	TRN	
20111989	2307 38.70	11.14	60.55	44	3.5	BOT	
29111989	1020 00.44	11.10	61.86	69	2.9	TCE	
20121989	1030 04.89	10.85	62.21	87	3.1	TCE	
20121989	1815 43.38	10.83	62.00	48	3.2	TRN	TCE
21121989	1516 13.02	11.21	61.89	15	3.0	TCE	
23121989	0355 29.52	10.16	61.93	5	3.7	TCE	
19011990	0742 23.21	10.72	61.55	41	3.2	TRN	TCE
31011990	2214 59.73	10.28	61.11	46	2.6	TRN	
08041990	0915 35.79	11.12	62.16	9	2.9	TCE	
14041990	2232 34.37	10.99	61.82	8	3.0	TRN	TCE
26041990	0453 22.27	11.20	61.77	29	3.1	TCE	
04051990	0043 26.06	10.59	61.58	39	2.5	TRN	
22071990	0350 27.40	10.51	61.28	44	2.4	TRN	
05081990	1103 54.29	10.46	61.73	10	2.9	TRN	
07091990	0749 36.07	10.80	61.60	61	3.4	TRN	TCE
17091990	1207 43.97	10.81	61.90	44	3.5	TRN	
22091990	0058 16.85	11.08	61.04	33	2.4	TRN	TPR
20111990	1240 57.35	10.52	61.80	26	3.1	TRN	
29111990	1635 22.81	10.64	61.79	49	3.0	TRN	
17121990	0725 29.46	11.08	62.11	76	3.1	TCE	
15011991	1555 14.62	10.54	61.73	8	3.0	TRN	
03021991	0311 57.97	10.55	61.20	40	3.0	TRN	
13031991	1146 07.16	10.98	62.17	68	3.0	TCE	
30041991	2224 08.79	11.16	61.25	32	3.3	TRN	
14061991	0155 46.82	10.58	61.68	33	3.5	TRN	
St. Vincent/St. Lucia (SVL) Region							
09081989	2207 23.63	14.32	60.83	9	3.4	SLB	
21091989	1656 55.85	13.44	61.56	145	3.7	SVV	SSV SVB
19071990	0624 28.30	13.37	60.99	128	3.1	SVB	
25081990	0509 31.78	14.04	60.59	71	3.4	SLB	
30091990	0632 22.90	13.92	60.89	39	3.2	SLB	
02101990	0358 42.67	13.79	60.97	20	2.9	SLB	
25121990	2108 44.84	13.36	60.85	27	3.0	SLB	
10021991	1834 39.75	14.13	61.10	10	2.4	SLB	
Dominica Region							
26051989	0216 17.85	15.39	61.42	2	2.7	DTMT	DSC
05121989	2324 09.88	15.14	60.98	15	3.1	DTMT	
12121989	0256 09.39	15.17	60.95	15	2.7	DTMT	
Leewardwards Region							
12051989	0607 25.17	17.00	62.30	19	3.2	NEV	SKI
26051989	0124 23.59	17.05	62.26	1	3.7	BPA	ANG
07061989	0525 41.79	16.56	62.11	146	3.4	MGH	BPA
20061989	1638 38.46	17.64	62.11	38	2.9	NEV	BPA
23061989	0708 23.66	17.13	62.27	18	3.1	NEV	
01071989	1321 50.33	17.03	62.21	11	3.1	BPA	
16071989	0801 15.59	17.09	62.40	3	2.4	NEV	
17071989	1034 15.30	17.02	62.09	105	3.7	MGH	BPA
17071989	2102 56.96	17.32	61.30	13	3.1	BPA	
21071989	0538 09.36	17.57	62.94	183	3.2	SKI	
03081989	1753 15.53	16.99	62.29	14	3.0	MGH	
06081989	0248 27.92	17.44	61.94	40	3.2	BPA	
09081989	1906 29.15	17.05	62.24	96	2.8	BPA	
14081989	0213 21.45	16.80	61.99	19	3.1	BPA	
30081989	1032 06.96	17.54	61.85	64	3.5	BPA	
07111989	1305 14.79	17.43	62.27	78	3.2	BPA	
30111989	1435 57.28	17.47	61.68	26	3.2	BPA	
06011990	1630 47.15	16.95	61.79	20	2.9	BPA	ANG
09011990	0021 35.06	16.59	61.76	128	2.7	ANG	
06021990	1126 08.91	17.48	61.90	13	3.5	BPA	
06021990	1133 17.28	17.37	61.71	8	3.0	BPA	
17021990	1630 47.70	17.05	61.67	71	3.2	BPA	
25041990	0625 28.03	16.98	61.82	83	3.2	MGH	BPA
03061990	0951 39.59	17.42	61.78	20	2.3	CPB	
22071990	0847 56.65	18.05	61.85	25	2.9	CPB	
26071990	0648 17.53	17.52	61.92	29	3.5	BPA	
03091990	0022 54.44	17.46	62.04	28	3.4	BPA	
11091990	0848 28.68	17.26	61.65	35	3.3	BPA	
17091990	0336 40.76	17.23	61.59	46	2.9	BPA	
24101990	1002 23.23	17.36	62.05	25	2.9	BPA	
27101990	1952 42.51	17.10	62.26	24	3.0	BPA	

**Table 2.** Listings of stations used in the coda- $Q$  analysis.

Code	Name	Lat. ( $^{\circ}$ N)	Lon. ( $^{\circ}$ W)	Alt. (m)
TRN	St. Augustine, Trinidad	10.65	61.40	24
TCE	Chacaachacare, Trinidad	10.70	61.75	240
BOT	Bacolet, Tobago	11.16	60.72	30
TPR	Prospect, Tobago	11.18	60.78	245
SVB	Belmont, St. Vincent	13.27	61.25	282
SVV	Wallibou, St. Vincent	13.32	61.21	243
SSV	Summit, St. Vincent	13.33	61.19	824
SLB	Belfond, St. Lucia	13.82	61.04	600
DSC	Scott's Head, Dominica	15.21	61.36	50
DTMT	Tete Morne, Dominica	15.23	61.35	496
MGH	St. George's Hill, Monserrat	16.72	62.21	351
NEV	Gingerland, Nevis	17.13	62.57	244
SKI	Bayfords, St. Kitts	17.33	62.74	306
BPA	Boggy Peak, Antigua	17.04	61.86	396
ANG	Frias Hill, Antigua	17.15	61.83	27
CPB	Codrington, Barbuda	17.64	61.82	5

by least squares. From the slope of the line,  $Q_c$  was calculated. By using only linear windows which were at least 30 s long, we hope to minimize the contribution of temporal small-scale variations in coda amplitude which may be caused by interference effects, secondary arrivals, or site conditions.

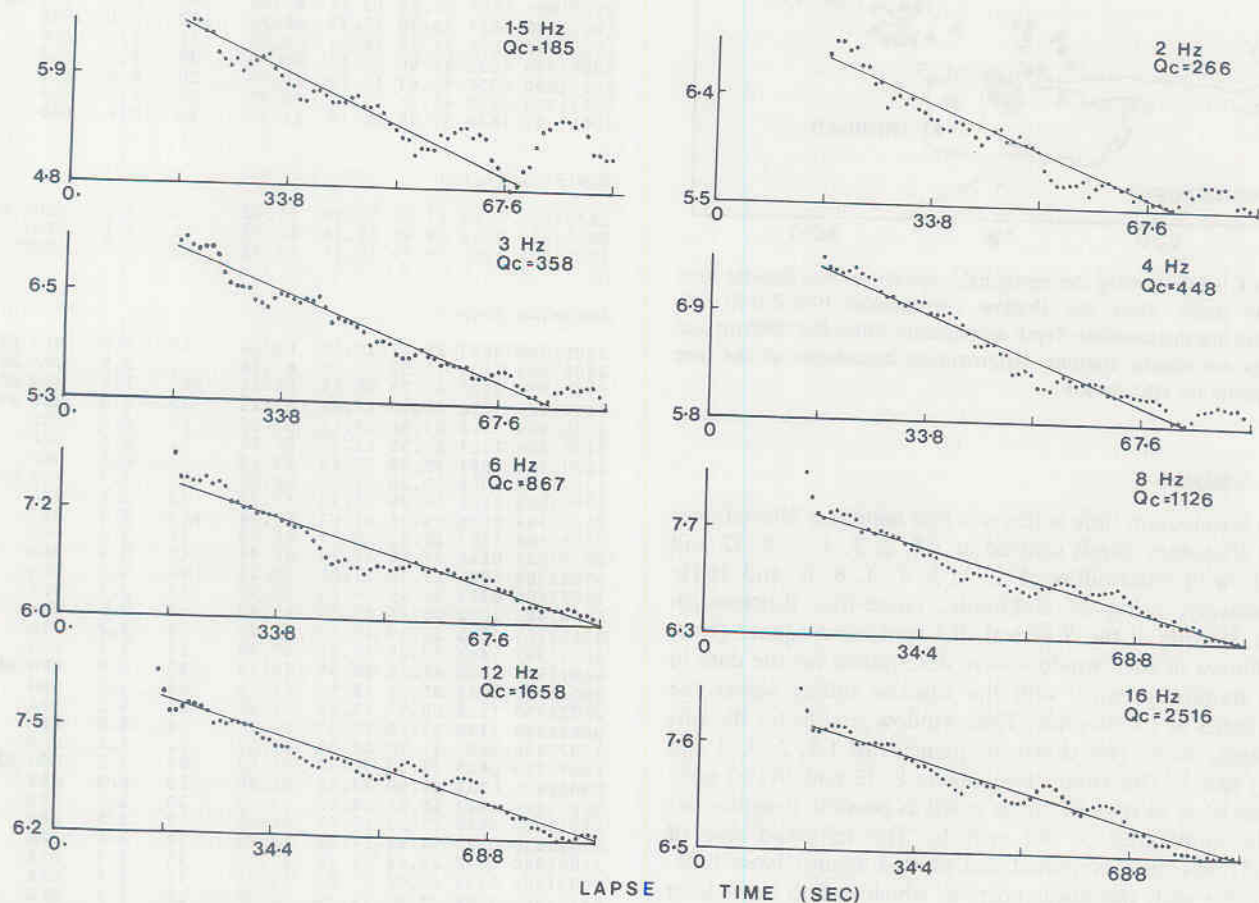
Fig. 2 is an example of the application of this analysis procedure. Only  $Q_c$  values obtained from least-squares fits with correlation coefficients greater than or equal to 0.95 were retained. The arbitrary value of 0.95 seems to represent an acceptable compromise between rejecting too much data and obtaining a high scatter in individual  $Q$  values for a particular region. For each station, an average coda- $Q$  value was calculated at each frequency for the data,

split according to depth ranges where possible. This was also carried out for each of the subregions. Table 3 is a listing of the average  $Q_c$  and their standard errors, where the standard error (SE) is the standard deviation divided by the square root of the number of  $Q_c$  values used in calculating the average.

## 2.4 Volume sampled by coda waves

In order to carry out meaningful comparisons of coda  $Q$  from different regions, it is imperative to make estimates of the volumes sampled by the different groups of data. According to Pulli (1984), the volume sampled by coda waves at lapse time,  $t$ , is an ellipsoid whose surface projection has semi-major axis,  $a_1 = V_s t/2$ , and semi-minor axis,  $a_2 = [(a_1)^2 - (r^2/4)]^{0.5}$  where  $V_s$  is the  $S$ -wave velocity and  $r$  is the source-receiver distance. Thus  $Q_c$  values represent an average over a large region.

The average volume sampled can be assumed to be represented by the average lapse time,  $T_{av}$ , where  $t_{av} = t_{start} + \Delta t_{win}/2$ ;  $t_{start}$  is the starting lapse time and  $\Delta t_{win}$  is the window length. A reasonable estimate of the maximum depth of the volume,  $Z_{max}$ , is the average focal depth,  $Z_{av}$ , for a group of events plus  $a_2$ . Using  $S$ -wave velocities of  $4 \text{ km s}^{-1}$  and  $4.5 \text{ km s}^{-1}$  for shallow ( $0 \leq z \leq 70 \text{ km}$ ) and intermediate ( $Z > 70 \text{ km}$ ) depth events respectively, together with average source-station distances and



**Figure 2.** Example of coda- $Q$  analysis as applied to station TRN seismogram for event of 22071990 0350 UTC. The plot is for the quantity  $\ln [A(r, f | t)/k(r, a)]$  versus lapse time,  $t$ . The straight lines show the portions chosen to determine  $Q_c$ .

**Table 3.** Average  $Q_c$  values and their standard errors. Values in brackets represent the number of  $Q$  used in averaging. T.T—Trinidad/Tobago; St Vt—St Vincent; DOM—Dominica; Lwds—Leewards. S: shallow events; I: intermediate depth events; A: all events.

Station	FREQUENCY							
	1.5	2.0	3.0	4.0	6.0	8.0	12.0	16.0
Region								
TRN(S)	194±16 (4)	259±13 (15)	321±17 (16)	398±15 (20)	548±26 (20)	750±38 (19)	1037±72 (14)	1484±122 (13)
TRN(I)	-	-	-	362 (1)	449 (1)	-	-	-
TRN(A)	194±16 (4)	259±13 (15)	321±17 (16)	396±14 (21)	544±25 (21)	750±38 (19)	1037±72 (14)	1484±122 (13)
TCE(S)	-	211±7 (2)	369±21 (7)	442±19 (9)	664±25 (10)	822±42 (10)	1137±148 (3)	1524±174 (3)
TCE(I)	152 (1)	298±106 (2)	358±39 (3)	404±5 (3)	576±45 (4)	805±69 (4)	1247±294 (4)	1659±534 (3)
TCE(A)	152 (1)	255±50 (4)	366±18 (10)	433±15 (12)	639±24 (14)	817±35 (14)	1200±168 (7)	1592±253 (6)
BOT(S)	176 (1)	163 (1)	243 (1)	294 (1)	304 (1)	-	-	-
TPR(S)	-	142 (1)	207 (1)	331 (1)	522 (1)	814 (1)	1268 (1)	1675 (1)
T.T(S)	190±13 (5)	243±13 (19)	327±14 (25)	405±12 (31)	576±22 (32)	776±28 (30)	1067±61 (18)	1502±97 (17)
T.T(I)	152 (1)	298±106 (2)	358±39 (3)	394±11 (4)	551±43 (5)	805±69 (4)	1247±294 (4)	1659±534 (3)
T.T(A)	184±12 (6)	248±14 (21)	330±13 (28)	404±11 (35)	573±20 (37)	779±26 (34)	1099±70 (22)	1526±107 (20)
SVV(I)	-	350 (1)	436 (1)	463 (1)	631 (1)	855 (1)	1022 (1)	1381 (1)
SSV(I)	-	-	386 (1)	433 (1)	523 (1)	718 (1)	1064 (1)	1506 (1)
SVB(I)	-	-	351±74 (2)	450±88 (2)	546±68 (2)	741±80 (2)	1367 (1)	2150 (1)
SLV(A)	-	350 (1)	381±36 (4)	449±36 (4)	561±36 (4)	764±45 (4)	1144±112 (3)	1679±238 (3)
SLB(S)	-	210±16 (2)	296±20 (4)	369±29 (4)	638±21 (2)	754±33 (3)	1072±145 (3)	1484±192 (4)
SLB(I)	157 (1)	197 (1)	344 (1)	467 (1)	762 (1)	849 (1)	1162 (1)	1964 (1)
SLB(A)	157 (1)	206±10 (3)	306±18 (5)	389±30 (5)	679±43 (3)	777±33 (4)	1095±105 (3)	1564±179 (5)
SVL(A)	157 (1)	242±37 (4)	339±22 (9)	415±24 (9)	612±35 (7)	771±26 (8)	1116±71 (7)	1607±134 (8)
DSC(S)	-	207 (1)	295 (1)	368 (1)	-	-	-	-
DTMT(S)	-	236 (1)	270 (1)	469±81 (2)	757±209 (2)	1023±140 (3)	1354 (1)	1870 (1)
DOM(A)	-	221±14 (2)	282±13 (2)	435±58 (3)	757±209 (2)	1023±140 (3)	1354 (1)	1870 (1)
MGH(S)	-	-	398 (1)	400 (1)	752 (1)	1039 (1)	1641 (1)	-
MGH(I)	207±53 (2)	306±1 (3)	373±33 (3)	486±42 (3)	730±79 (3)	1104±156 (3)	1818±872 (2)	2325±1019 (2)
MGH(A)	207±53 (2)	306±1 (3)	380±24 (4)	465±37 (4)	735±56 (4)	1088±111 (4)	1759±507 (3)	2325±1019 (2)
NEV(S)	-	269 (1)	273±27 (4)	345±34 (4)	423±111 (2)	1058±341 (2)	984 (1)	1236 (1)
SKI(S)	-	-	-	615 (1)	828 (1)	1255 (1)	-	-
SKI(I)	-	-	-	521 (1)	872 (1)	1225 (1)	2884 (1)	3455 (1)
SKI(A)	-	-	-	568±47 (2)	850±22 (2)	1240±15 (2)	2884 (1)	3455 (1)
BPA(S)	216±30 (5)	296±31 (8)	352±19 (11)	480±22 (15)	655±48 (16)	805±38 (16)	1121±51 (17)	1482±88 (15)
BPA(I)	239±36 (2)	301±69 (4)	351±59 (6)	454±69 (6)	630±84 (6)	853±118 (6)	1176±119 (6)	1624±133 (6)
BPA(A)	223±23 (7)	298±29 (12)	352±23 (17)	473±24 (21)	648±41 (22)	818±41 (22)	1135±47 (23)	1523±73 (21)
ANG(S)	-	377 (1)	450±26 (2)	599±0 (2)	820±78 (2)	983±86 (2)	1274±290 (2)	1736±396 (2)
ANG(I)	-	-	-	583 (1)	580 (1)	849 (1)	-	-
ANG(A)	-	377 (1)	450±26 (2)	593±5 (3)	740±92 (3)	938±67 (3)	1274±290 (2)	1736±396 (2)

Table 3. (Continued.)

Station	FREQUENCY							
	1.5	2.0	3.0	4.0	6.0	8.0	12.0	16.0
CPB(S)			238 (1)	302 (1)	387±33 (2)	588±25 (2)	873±158 (2)	1294 (1)
L'wards(S)	216±30 (5)	301±26 (10)	342±18 (19)	463±22 (24)	638±41 (24)	851±44 (24)	1129±52 (23)	1486±80 (19)
L'wards(I)	223±28 (4)	303±37 (7)	359±40 (9)	481±39 (11)	674±54 (11)	955±84 (11)	1508±255 (9)	1983±283 (9)
L'wards(A)	219±19 (9)	302±21 (17)	348±17 (28)					

lapse times, the parameters, which are a reflection of the volume sampled by coda waves in each subregion, were calculated. For example, for the shallow earthquakes in the Trinidad and Tobago region,  $Q_c$  estimates at an average lapse time of 52 s correspond to sampling volumes of about 208 km in lateral extent, 137 km in depth and 16 500 km<sup>2</sup> in surface area. Sampling volumes for shallow earthquakes in the other subregions are similar to those for the Trinidad and Tobago area. We deduce that the volumes sampled by the coda waves from shallow events in each subregion appear to be distinct, with little or no overlap. This may, however, not be the case for the coda waves of intermediate depth events which sample larger volumes.

### 3 RESULTS

Our results show that average  $Q_c$  values in the eastern Caribbean at a frequency of 1.5 Hz, range from 152 for intermediate depth earthquakes recorded at TCE, to about 239 for intermediate depth events recorded at BPA. At 16 Hz, the variation in  $Q_c$  is from about 1236 (NEV) to 3455 (SKI). Looking at the  $Q_c$  values listed in Table 3, there seems to be some variation within particular subregions, i.e. among stations, and between the different subregions. However, before examining the coda  $Q$  in detail for station-to-station or regional variations, we checked for other possible causes of fluctuations in  $Q_c$  values, such as window length, average lapse time, epicentral distance, focal depth and magnitude.

#### 3.1 Variation of $Q_c$ with window length, average lapse time, epicentral distance, focal depth and magnitude

It has been observed in many coda- $Q$  studies that  $Q_c$  increases with increased lapse time and consequently, increased window length (e.g. Rautian & Khalturnin 1978; Rovelli 1984; Lee *et al.* 1986; Kvamme & Havskov 1989). Taking into consideration the volumes sampled by coda waves as postulated by Pulli (1984), increasing coda  $Q$  with increasing lapse times has been interpreted to be due to increasing  $Q$  with depth (Roecker *et al.* 1982; Rovelli 1984). But Gao *et al.* (1983a) have suggested that multiple scattering might be responsible for the observed increase in  $Q_c$  while others have attributed it to incorrect coda-model parameterization [e.g. the use of an inappropriate geometrical spreading factor,  $\alpha$ , in eq. (1)]. We note, however, that Havskov *et al.* (1989) and Canas *et al.* (1991) did not observe any significant variation in  $Q_c$  with lapse time and window length for studies in Washington State, USA, and southern Spain respectively.

$Q_c$  values for stations TRN and BPA were plotted, for each frequency, against each of the following variables:

window length, average lapse time, epicentral distance, focal depth and magnitude. TRN and BPA were chosen because they had relatively more data compared to the other stations. We found no obvious dependence of  $Q_c$  values at TRN or BPA on any of the above variables. Selected examples of these plots are shown in Fig. 3.

#### 3.2 $Q_c$ variation and frequency dependence

In most regions where coda- $Q$  measurements have been made, a positive correlation between  $Q_c$  and frequency has been noted (e.g. Aki & Chouet 1975; Rautian & Khalturnin 1978; Roecker *et al.* 1982; Pulli 1984; Havskov *et al.* 1989; Ambeh & Fairhead 1989). Frequency-dependent  $Q$  has also been observed in studies of shear wave  $Q$  using the single-station method (Aki 1980a), in an inversion of  $P$ -wave data for  $Q$  (e.g. Thouvenot 1983), and in shear wave spectral analysis (e.g. Singh *et al.* 1982; Rebollar *et al.* 1985; Kvamme & Havskov 1989). The form of this frequency dependence is generally

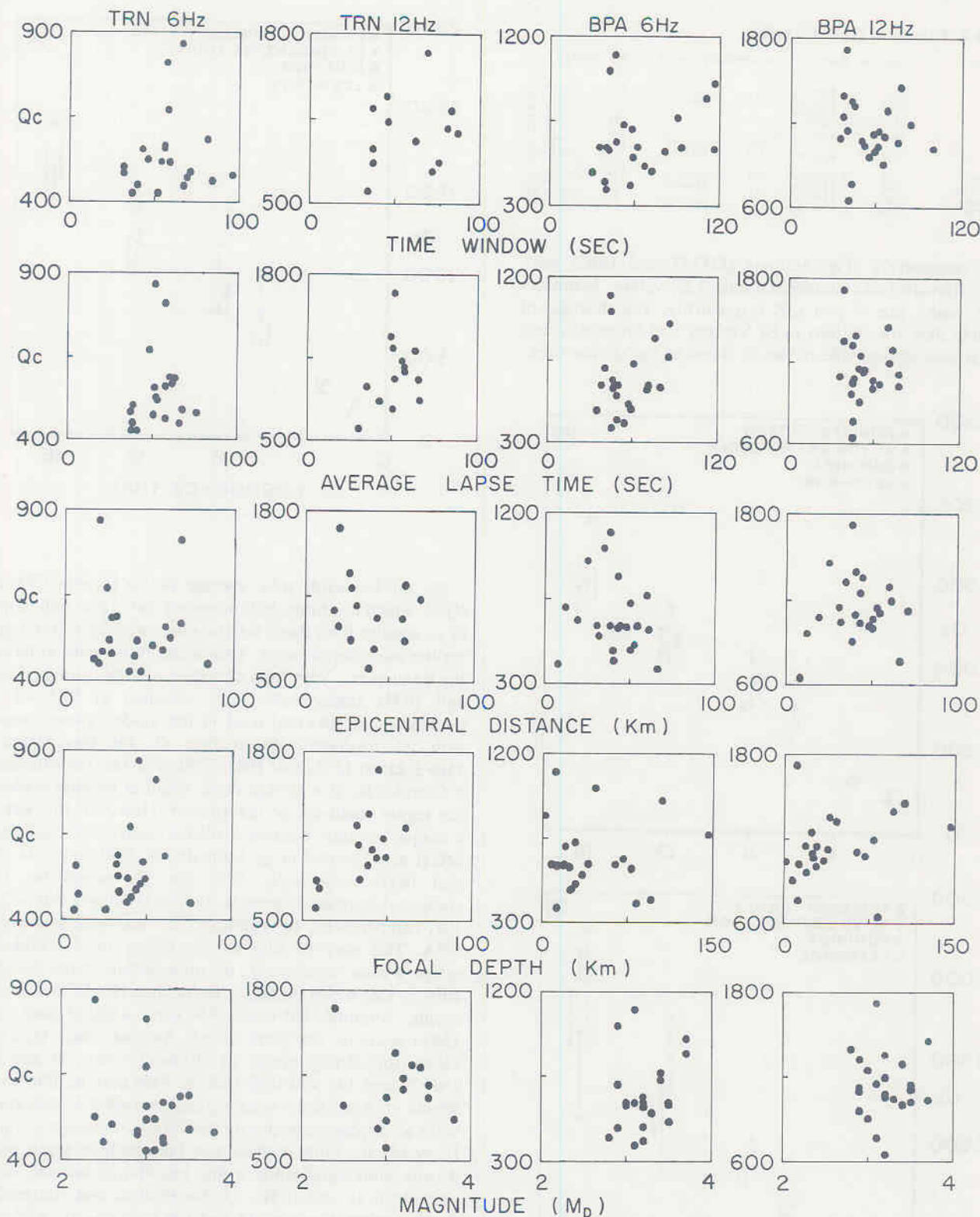
$$Q_c = Q_o f^n \quad (4)$$

where  $n$  has been found to lie mainly in the range 0.5 to 1.1. Stations and regions with  $Q_c$  values from at least three events were fitted to eq. (4) and the results are listed in Table 4.

In the Trinidad and Tobago region, there seems to be no significant difference between average  $Q_c$  at all frequencies for stations TRN and TCE within error limits for both shallow and intermediate depth earthquakes. This is confirmed by calculated  $Q_o$  values which lie in the narrow range 128 to 132. The variation in the index,  $n$ , is also very small: 0.83 for TRN shallow events and 0.88 for TCE shallow and intermediate depth earthquakes. This is not totally surprising since both TCE and TRN sample almost the same volume. It may also suggest that the influence of receiver site effects are minimal. A similar comparison could not be extended to the two Tobago stations, TPR and BOT, because their  $Q_c$  values are from a single earthquake only.

$Q_c$  at St Vincent stations (SVV, SSV, SVB) were estimated from two intermediate-depth earthquakes and are generally consistent with each other. No  $Q_c$  values from shallow earthquakes are available for these stations.

For SLB (St Lucia), average  $Q_c$  from four shallow earthquakes at 3 to 16 Hz appear to be slightly lower (by ~100) than those for a single intermediate depth event.  $Q_o = 105$  and  $n = 0.94$  were obtained for these shallow events. Although none of the earthquakes used for SLB was recorded at any of the St Vincent stations and vice versa, we decided, because of the paucity of suitable earthquake data in the St Vincent and St Lucia area and the overlapping coda volumes involved, to treat this area as a single



**Figure 3.** Selected examples of plots of the variation of  $Q_c$  at TRN and BPA as a function of window length, average lapse time, epicentral distance, focal depth and magnitude.

subregion. A  $Q_c$  of 129 was obtained for the St Vincent/St Lucia intermediate depth events compared to the 105 for the shallow events. Again, considering the uncertainties involved in determining  $Q$  and the different depths of penetration of the coda waves, this difference does not

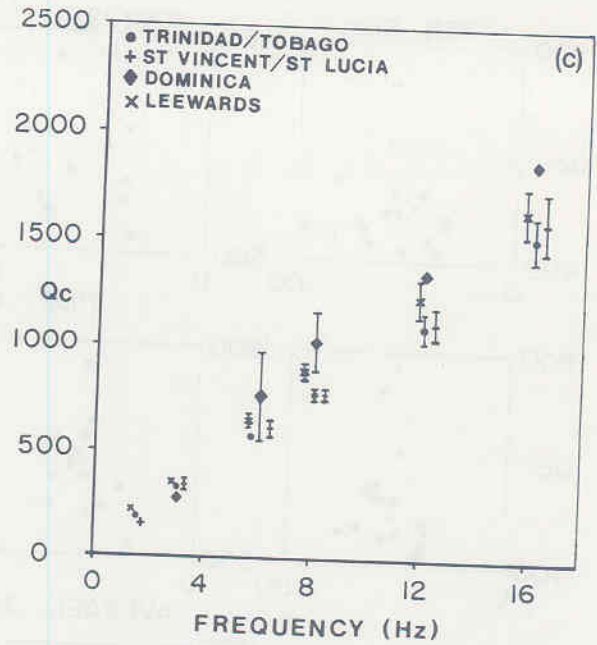
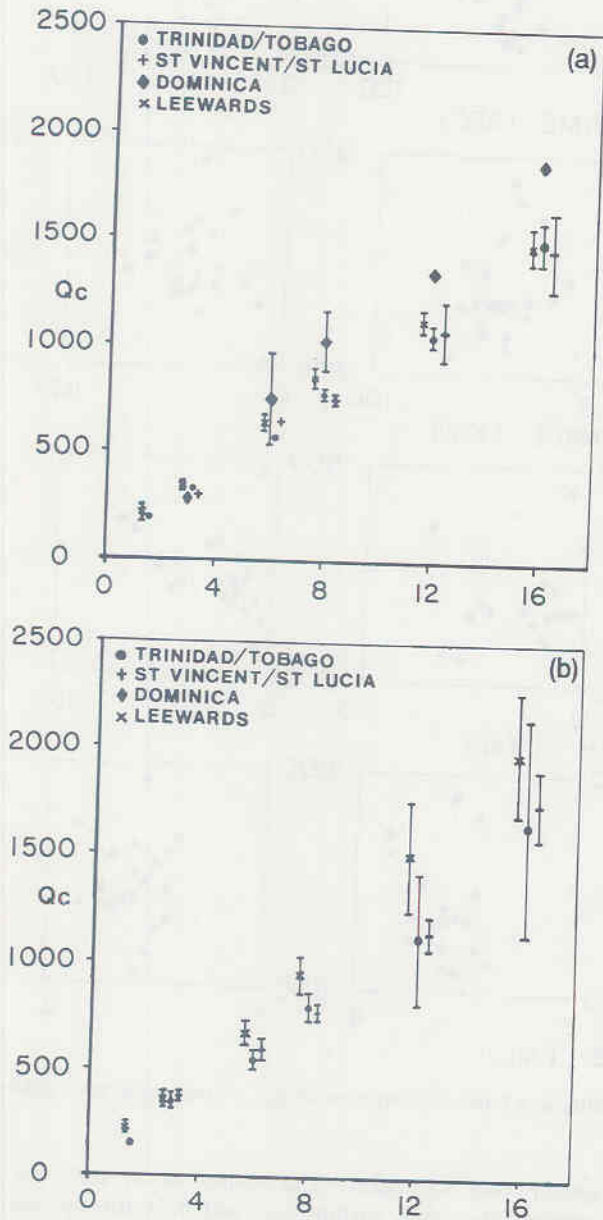
appear very significant. The values of  $n$ , 0.89 for the intermediate depth earthquakes and 0.94 for the shallow events, are also not much different within error limits.

The three earthquakes used in the Dominica region are shallow and average  $Q_c$  at 2 and 16 Hz are  $221 \pm 14$  and

Table 4. Calculated  $Q_0$  and  $n$  values

Station/ Region	Shallow Events		Intermediate Events		All Events	
	$Q_0$	$n$	$Q_0$	$n$	$Q_0$	$n$
TRN	131	0.83±0.03			130	0.83±0.03
TCE	132	0.88±0.04	128	0.88±0.08	131	0.88±0.04
SLB	105	0.94±0.05			106	0.96±0.04
DTMT	105	1.06±0.11			105	1.06±0.11
NEV	101	0.92±0.14			101	0.92±0.14
MGH			136	0.97±0.08	133	0.98±0.07
BPA	152	0.80±0.03	137	0.85±0.07	147	0.82±0.03
ANG					209	0.73±0.07
TR region	124	0.86±0.02	124	0.88±0.08	124	0.87±0.02
SVL region	105	0.94±0.05	129	0.89±0.05	119	0.91±0.04
Dominica	97	1.09±0.09			97	1.09±0.09
Leewards	145	0.82±0.03	134	0.92±0.06	141	0.85±0.03

1870 respectively. Two stations (DTMT and DSC) were used although DSC contributed only 3  $Q_c$  values. Estimates of  $Q_0$  and  $n$  are 97 and 1.09 respectively. The shortage of suitable data for stations in St Vincent and Dominica may be partially attributable to the noisiness of the station sites.



For the Leewards area, average  $Q_c$  for stations CPB and NEV, which are from shallow events only, generally appear to be smaller than those for the other stations in the region for the same depth range. This seems to be valid at most of the frequencies. Very high  $Q_c$  values of 2884, and 3455 at 12 and 16 Hz respectively, were obtained at SKI for the deepest event (183 km) used in this study. These compare with intermediate-depth average  $Q_c$  for this region of  $1508 \pm 255$  at 12 Hz and  $1983 \pm 283$  at 16 Hz. Unfortunately, a  $Q_c$  value for this 183 km depth event at another station in the region could not be determined. However, this was not a unique situation because a 105 km deep event recorded at MGH also resulted in  $Q_c$  estimates of 2690 and 3344 at 12 and 16 Hz respectively. The low  $Q_c$  values for NEV compared to other Leewards stations is reflected in a  $Q_0$  of 101, compared to, for example, 152 for shallow events at BPA. This may be due to site effects or differences in sampled coda volumes.  $Q_0$  for intermediate depth events at BPA is 138, which is slightly lower than the 152 for shallow events. Although BPA and ANG are situated only about 13 km apart on the same island, Antigua, their  $Q_0$  and  $n$  values considering events at all depths are 209 and 0.73 (ANG) and 147 and 0.82 (BPA). This may be due to site effects at ANG since seismograms recorded at this station seem to display anomalously long codas. Average  $Q_c$  in the Leewards for both shallow and intermediate-depth events do not differ significantly within uncertainty bounds, except perhaps at 12 and 16 Hz.  $Q_0$  for shallow and intermediate depth earthquakes are 145 and 134 respectively, while  $n$  is 0.82 for shallow and 0.92 for intermediate events.

Average  $Q_c$  for shallow, intermediate and all earthquakes for the four subregions are plotted as a function of frequency in Fig. 4. For the shallow events (Fig. 4a), the main feature is the fact that  $Q_c$  for the Dominica region seems generally to be higher than those for the other regions at frequencies greater than or equal to 6 Hz. This is in spite of the fact that events in the Dominica region sample a

Figure 4. Average  $Q_c$  versus frequency for the different subregions (A: shallow events; B: intermediate depth events; C: all events). Error bars represent  $\pm 1$  standard error.



shallower coda volume compared to those in the other regions. Attenuation of waves with frequencies greater than about 6 Hz may, therefore, be greater in the Dominica region compared to the other areas in the eastern Caribbean. It must be stated once more that the number of events used in the Dominica region is small and consequently some caution has to be exercised in the interpretation and conclusions. For the intermediate depth earthquakes (Fig. 4b), average  $Q_c$  for the Leewards are larger than those for the Trinidad and Tobago region at all frequencies although there is a significant overlap of error bars at higher frequencies. Fig. 4(c), which shows data for all events, seems to reflect on average trends already described for the shallow and intermediate depth events.

#### 4 DISCUSSION AND CONCLUSIONS

A comprehensive review of coda studies and the problems associated with the interpretation of  $Q_c$  was made by Herraiz & Espinosa (1987). While there seems to be no doubt that coda originates from waves scattered from lithospheric heterogeneities, there is still no commonly accepted view as to what  $Q_c$  represents. In this study, we used the extension of Sato (1977) to the single  $S$ - $S$  backscattering model of Aki & Chouet (1975) and consequently, our interpretation of the results are ultimately constrained by the assumptions and limitations of this model.

Several studies have questioned the validity of the single-scattering approach in coda studies. According to Gao *et al.* (1983a, b), the effects of multiple scattering are dominant at lapse times greater than about 100 s, but Spudich & Bostwick (1987), in an analysis of Morgan Hill, California, local earthquakes, found that the early portions of their coda were dominated by multiple scattering from near-site heterogeneities.  $Q_c$  as originally formulated by Aki (1969) was thought to reflect a predominantly scattering contribution. However, Frankel & Wennerberg (1987), using an energy-flux model, suggest that  $Q_c$  is a measure of intrinsic rather than scattering attenuation. The physical significance of the frequency dependence of  $Q_c$  is also a point of contention. Dainty (1981) suggested that the frequency dependence of  $Q_c$  between 1 and 20 Hz is mainly due to scattering, with anelastic attenuation being relatively frequency independent. Richards & Menke (1983) and Frankel & Clayton (1986), however, conclude that frequency dependence observed in coda analysis using the single scattering approach may be due to multiple scattering.

Empirical correlations between the coda  $Q$  at 1 Hz,  $Q_o$ , in an area, and the level of current tectonic activity in the area, have been made. Seismically active regions, or areas with a high intensity of tectonic activity, seem to be associated with low  $Q_o$  values (e.g. Aki 1980b; Roecker *et al.* 1982; Singh & Herrmann 1983; Van Eck 1988; Jin & Aki 1988; Canas *et al.* 1991). Correlations between the degree of frequency dependence of  $Q_c$  and the level of tectonic activity in the area of measurement have also been made in compilations of  $Q_c$  measurements by several workers (e.g. Aki 1980b; Pulli & Aki 1981; Jin, Cao & Aki 1985). In general, tectonically stable regions were found to exhibit almost no frequency dependence while active areas in which processes

such as folding, faulting or subduction are likely to introduce strong heterogeneity, show significant frequency dependence of  $Q_c$ . We note that reservations as to the validity of these correlations exist. For example, coda  $Q$  measurements in New England, USA (Pulli 1984), which is a non-tectonic region, show a very strong frequency dependence at lapse times less than 100 s.

The  $Q_c$  measurements in the eastern Caribbean exhibit a strong frequency dependence ( $n = 0.8$ – $1.1$ ), which if we assume the validity of the above correlation, would not be surprising because of the presence of a subduction zone. However, within the eastern Caribbean, there seems to be no obvious correlation between the level of seismic activity and  $Q_o/n$  since the most seismically active subregions (Leewards and the Trinidad/Tobago areas) have about the same  $n$  and slightly higher  $Q_o$  than the St Vincent/St Lucia area where seismic activity is significantly less. The Dominica region which may be slightly less seismically active than the Leewards and Trinidad/Tobago areas has a lower  $Q_o$  and higher  $n$ . The frequency dependence of  $Q_c$  in three subduction-zone environments in other parts of the world: Adak Islands, Aleutians (Scherbaum & Kisslinger 1985, 1987), Washington State, USA (Havskov *et al.* 1989) and Hindu Kush (Roecker *et al.* 1982), average about 60 for  $Q_o$  and 1 for  $n$ . The  $Q_o$  values in these areas are lower than those obtained in the eastern Caribbean.

Coda  $Q$  of local earthquakes recorded by short-period seismic stations on some eastern Caribbean islands was determined using the single-scattering model. The lateral and depth variation of  $Q_c$  in the region seems to be relatively small.  $Q_o$  is a minimum in the Dominica region ( $Q_o = 97$ ) and a maximum in the Leewards ( $Q_o = 145$ ) while the degree of frequency dependence is largest in the Dominica area ( $n = 1.09$ ) and smallest in the Leewards ( $n = 0.82$ ). The possibility of the existence of site effects at stations such as ANG and NEV cannot be totally discounted. The use of shorter lapse times with the consequent sampling of shallower structures may have yielded larger regional variations. However, the similarity in average  $Q_c$  may be an indication that average attenuation properties in the crust and uppermost mantle in the eastern Caribbean are similar.

#### ACKNOWLEDGMENTS

We are grateful to the staff of the Seismic Research Unit of the University of the West Indies, Trinidad, for help in the data acquisition. Thanks to Mrs Yvonne Joseph for typing the manuscript and Mr Godfrey Almorales for help in drafting the diagrams.

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