Bulletin of the Seismological Society of America. Vol. 66, No. 6, pp. 1905–1920. December 1976

SEISMIC-WAVE TRANSMISSION ACROSS THE CARIBBEAN PLATE: HIGH ATTENUATION ON CONCAVE SIDE OF LESSER ANTILLES ISLAND ARC.

BY J. A. RIAL*

ABSTRACT

High attenuation of short-period body waves and extremely low surface-wave group velocities have been found for seismic paths that traverse the crust and upper mantle beneath the concave side of the Lesser Antilles island arc (eastern Caribbean). The observations can be explained in terms of the currently accepted models of lithospheric plate subduction at other island arcs such as Fiji-Tonga, Marianas and the Aegean, a characteristic of which is the existence of an abnormally low Q zone in the crust and upper mantle above the down-going slab. The Greater Antilles island arc appears to be tectonically distinct, as subduction is not evident there and no anomalous low-Q zone exists south of Puerto Rico and Hispaniola. The Aves swell is probably not related tectonically to the low-Q zone, or to the subduction process, at least presently.

INTRODUCTION

Tectonic processes in the neighborhood of the Antilles island arc in the eastern Caribbean sea are currently understood in terms of the modern ideas of plate tectonics according to which the Caribbean plate is moving eastward with respect to North and South America while the Atlantic lithosphere is being subducted at its eastern margin, (e.g., Le Pichon, 1968; Vine, 1969; Molnar and Sykes, 1969; MacDonald, 1972).

Seismological studies of the Caribbean crust and upper mantle structure are numerous; seismic reflection and refraction profiling, seismicity, and focal mechanisms are among the most used methods of investigation (e.g., Officer *et al.*, 1959; Edgar *et al.*, 1971; Chase and Bunce, 1969; Sykes and Ewing, 1965; Molnar and Sykes, 1969). On the basis of these and many other investigations, the Caribbean crust is known to possess a seismic velocity structure that corresponds to the transitional type described by Menard (1967); the crustal column to mantle is 2.5 times thicker than in normal oceans; a substantial part of the Caribbean comprising Venezuela and Colombia basins is underlain by a second layer of compressional-wave velocity between 6.0 and 6.4 km/sec and a thick (5 to 10 km) lower layer with velocities between 7.0 and 7.4 km/sec.

Studies on the character of the transmission of seismic body and surface waves across the Caribbean plate however are not numerous. Molnar and Oliver (1969) for instance, investigated the attenuation of high-frequency shear body waves traveling across the concave side of the Antilles arc in a search for anomalous, low-rigidity zones in the crust and upper mantle rocks that could be related to the subduction process. Although observations were not conclusive, their "limited data" showed "somewhat anomalous propagation" of shear waves near Lesser Antilles (Molnar and Oliver, 1969, p. 2659). Papazachos (1964) and Tarr (1968) have studied Rayleigh-wave dispersion characteristics specially in the western Caribbean and Gulf of Mexico.

*Present address: Seismological Laboratory, California Institute of Technology, Pasadena, California 91109.

In this paper, lateral variations in the attenuation of high-frequency shear body waves that travel across the Caribbean lithosphere are examined along with the dispersive character of the fundamental mode of Rayleigh and *PL* waves, in an effort to compile and compare data about the deeper crust and uppermost mantle beneath the eastern Caribbean, specially under those zones for which reflection and refraction methods give no precise information. The data come largely from seismic waves generated along

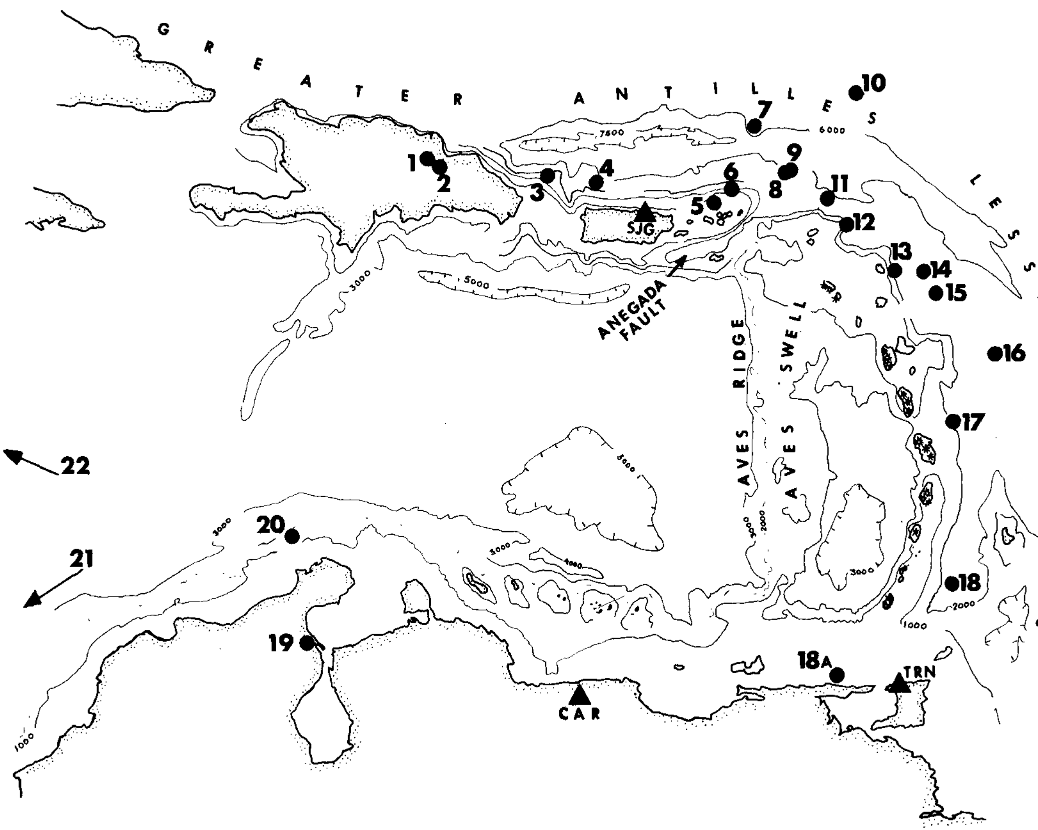

FIG. 1. Studied area. Earthquake epicenters are numbered in clockwise sequence beginning at Hispaniola Island. Caribbean seismological stations are represented by solid triangles. See Table 1 for epicentral location of events 21 and 22.

the Caribbean seismic belt and recorded at local seismological stations. By analyzing short- and long-period seismograms of over 22 seismic events (see Figure 1 and Table 1) recorded at WWSSN stations CAR (Caracas, Venezuela), SJG (San Juan, Puerto Rico), and TRN (Port Spain, Trinidad), it has been possible to detect and locate an anomalous region in the concave side of the Lesser Antilles arc, east of Aves ridge, in which high-frequency shear waves are strongly attenuated along the ray path.

Attenuation of Body Waves

The evidence shown here, which demonstrates that attenuation of shear body waves is high in the concave side of the Lesser Antilles arc, is based on a semi-quantitative visual comparison of different short-period seismograms of waves traversing the crust and uppermost mantle. Gross differences in the frequency content of the *Sn* (or *S*) phase were used as evidence of variations in the efficiency of a given zone in transmitting high-frequency shear waves. The differences found are obvious, even to a visual inspection, so that more precise analyses such as spectral variation by Fourier methods were not used. The procedure followed is largely that implemented by Oliver and Isacks (1967) and later adapted by Molnar and Oliver (1969) and Barazangi and Isacks (1971) to define anomalous, low-rigidity, low-Q regions in the upper mantle in various parts of the world.

TABLE 1

LIST OF EARTHQUAKES USED IN THE ANALYSIS*

No.	Date			Origin Time		Epicenter °N	Epicenter °W	Depth	Magnitude
1	67	MAY	06	1400	41.4	19.3	70.0	(39)	5.3
2	68	OCT	16	0155	32.7	19.2	69.8	(36)	5.2
3	67	FEB	21	0416	21.7	19.1	67.9	(49)	4.9
4	68	APR	13	0115	32.3	19.0	66.9	(51)	5.1
5	68	APR	15	0150	33.0	18.7	64.8	(65)	4.8
6	69	AUG	01	1306	50.1	18.8	64.52	(53)	5.0
7	69	JUN	30	1836	24.2	20.0	64.1	(17)	5.3
8	67	APR	10	2055	21.0	19.3	63.6	(33)	4.8
9	67	APR	12	0440	53.7	19.31	63.64	(41)	4.8
10	68	SEP	03	1537	00.2	20.6	62.2	(33)	5.5
11	67	APR	11	1242	47.7	18.8	62.7	(49)	5.2
12	67	NOV	29	0123	34.5	18.4	62.4	(58)	5.1
13	67	SEP	25	0851	49.4	17.7	61.6	(48)	4.8
14	67	OCT	26	1344	45.1	17.6	61.0	(37)	5.3
15	67	OCT	14	0331	04.5	17.3	60.8	(29)	5.3
16	69	DEC	29	0051	49.9	16.18	59.7	(17)	5.6
17	68	MAR	19	0219	13.1	15.1	60.5	(55)	5.1
18	67	MAY	31	1138	39.0	12.5	60.3	(60)	5.1
18A	67	JAN	04	2015	57.2	10.9	62.5	(68)	5.4
19	69	OCT	20	1311	37.0	10.8	72.5	(40)	5.7
20	68	MAR	12	0932	07.4	13.0	72.6	(11)	5.3
21	67	JUL	12	2100	22.2	5.73	82.72	(30)	5.3
22	67	NOV	08	0310	53.3	16.8	85.9	(28)	5.4

*To avoid unnecessary repetitions several events which occurred in the time interval studied are not listed here as they belong to the same epicenters as those in Table 1. All events for which dispersion curves were calculated are listed. Earthquake numbers are those referred to in Figure 1.

All shallow ($h \leq 70$ km) earthquakes of body-wave magnitudes ranging between 4.8 and 5.7, which occurred along the Antilles island arc during the years 1967, 1968, and part of 1969 and were recorded by the short-period instruments of stations CAR, TRN, and by SJG, were considered in the study (see Table 1). Instrumental response is the same for all stations, the only difference being in the particular magnification factor of each recording instrument (20 K at 1 sec for CAR, TRN; 50 K at 1 sec for SJG). Hypocentral locations and magnitudes were taken directly from USCGS and ISC reports. All seismic-wave arrivals were examined and J-B seismological tables used to check the epicentral distances calculated on the basis of USCGS and ISC data. Whenever the locations did not coincide within reasonable values, hypocenters were relocated or in extreme cases the seismograms were not used. At the epicentral distances concerned (700 to 1300 km for body-wave studies) the ray paths bottom out within 120 km below the surface, so that deeper anomalies, if any exist, are not detected by this analysis.

The phase Sn (or S) was selected for study mainly because the striking results obtained by Molnar and Oliver (1969), Barazangi and Isacks (1971), etc, in defining anomalous attenuating zones in the upper mantle near island arcs. The character of Sn at the epicentral distances concerned has been extensively discussed by Molnar and Oliver (1969). Along with the study of Sn, its dilatational counterpart, Pn, was also taken into account although it served mainly as a confirmation of the attenuated character of Sn in some instances and as a useful tool in determining possible radiation pattern effects in others.

In order to establish when a seismogram shows attenuated phases, a semi-quantitative criteria, similar to that described by Molnar and Oliver (1969) has been used. To characterize the different types of seismograms analyzed the following classes are considered:

Class O. No Sn phase present at or within 20 sec of the expected time. Pn may be weak in all components, showing predominant periods longer than 1 sec.

Class 1. Predominant period of Sn greater than 1.5 sec. Pn may be present with amplitudes comparable to those of Sn and periods about or slightly less than 1 sec.

Class 2. Clear Sn with predominant periods between 1 and 1.5 sec. Pn may be strong and impulsive with periods less than 1 sec.

Class 3. Strong, well-defined Sn with periods shorter than 1 sec. Long trains of both Pn and Sn with high frequencies predominant along the train.

Classes 0 and 1 characterize inefficient transmission (high attenuation) of the seismic wave. Classes 2 and 3 characterize efficient transmission (Figures 2 through 6).

This classification has been adapted to this study because of its simplicity and clarity and in order to be able to compare the results here obtained with those of the previously mentioned investigators. Seismograms with characteristics of both classes 1 and 2 were found for paths lying between regions of well-defined efficient and inefficient transmission.

Once the events are classified, direct comparison of extreme cases shows obvious differences (Figure 2). Figures 7 and 8 summarize the observed data, which delineates a region in the concave side of the Lesser Antilles arc in which the shear-wave transmission is inefficient and attenuation high, suggesting either lack of rigidity, reduced strength, or partial fusion of the rocks within the lithosphere.

The highly attenuating zone appears in a horizontal projection as a 700-km long, 200-km wide, sausage-like region, parallel to the arc and limited on the east by the line of volcanoes, on the north by the Anegada fault zone, on the west by Aves ridge and part of Aves swell, and on the south by the 14°N parallel (Figure 8). This southern boundary is only suggested, as class 3 transmission was observed on seismograms of events 17 and 18 (Figure 1). The diffuse seismic activity between 13°N and 15°N did not provide sufficiently good recorded events so as to properly define the structure in this region.

Q values. $Q\beta$, the dimensionless quality factor for shear waves, can be estimated from the relation $f_c = \langle Q\beta \rangle / \pi t$, where $\langle Q\beta \rangle$ is defined as $t / \int_{\text{path}} ds / Q(h)\, \beta(h)$, or average $Q\beta$ along the ray path, t is the travel time, f_c the path cut-off frequency for the attenuated wave spectrum, and ds a differential element of ray path. $Q(h)$ and $\beta(h)$ are the values of $Q\beta$ and the shear-wave velocity as a function of depth. The predominant frequency of the observed signal is an upper limit for f_c (Molnar and Oliver, 1969). For events with characteristics of efficient transmission, predominant frequencies of earthquakes analyzed in this study give values of $\langle Q\beta \rangle$ of about 2500, whereas for those events that cross the anomalous zone showing periods of 2 sec or longer, the calculated $\langle Q\beta \rangle$ values are about 400 for the entire path. As the anomalous zone represents approximately one fifth of the total path, $\langle Q\beta \rangle$ can be as low as 80 within it. These $\langle Q\beta \rangle$ values are in good agreement with those reported by Molnar and Oliver (1969, p. 2657).

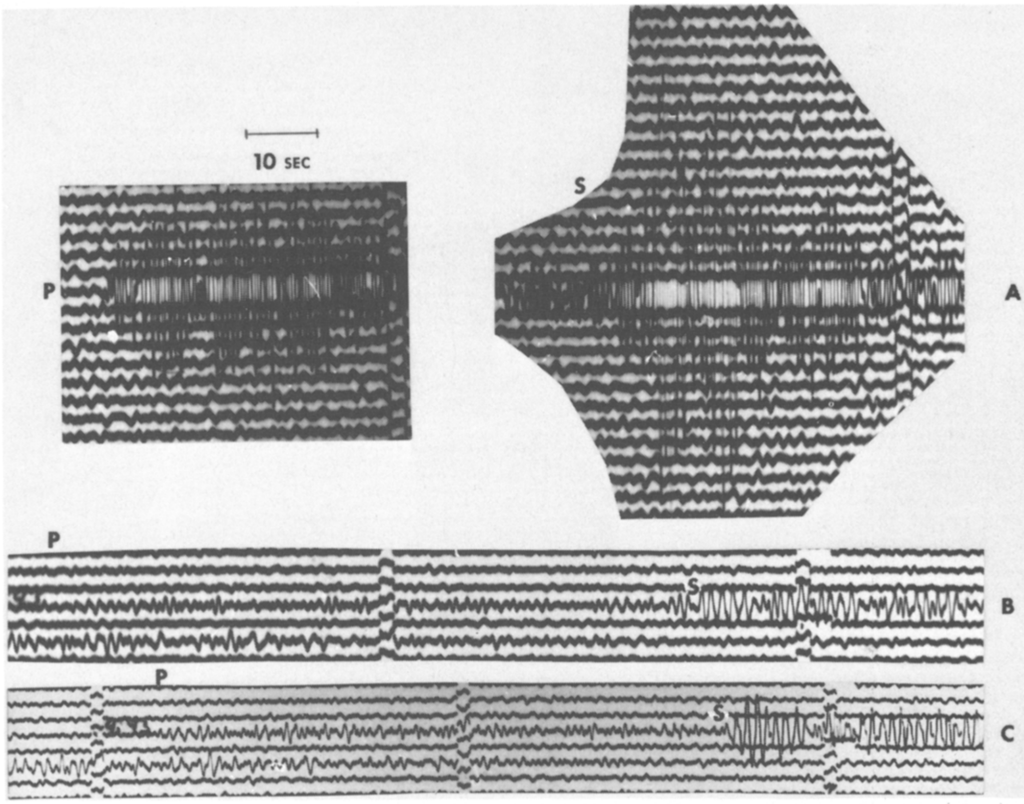

FIG. 2. Short-period seismograms (WWSSN): (A) path 2 (TRN), N-S component, class 3; (B) path 9 (CAR), E-W component, class 1; (C) path 9 (CAR), N-S component, class 1. Event numbers are those of Figure 1 and Table 1.

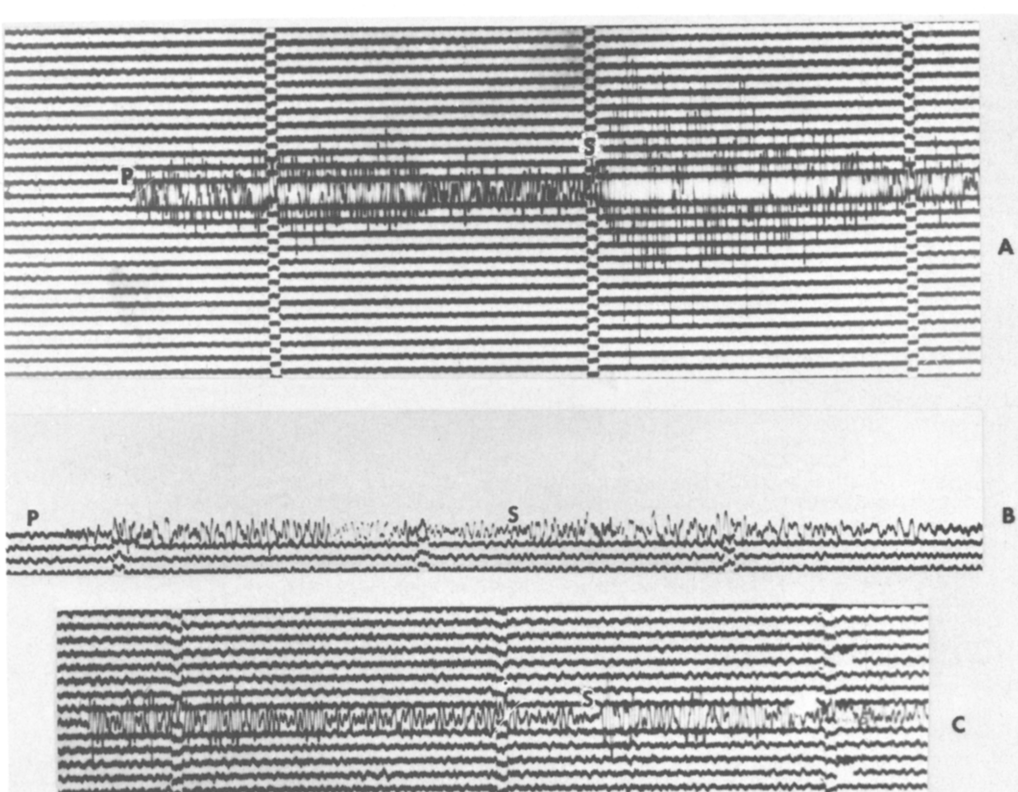

FIG. 3. Short-period seismograms (WWSSN): (A) path 4 (CAR), N-S component, class 3; (B) path 11 (TRN), E-W component, class 0; (C) path 16 (CAR), N-S component, class 1. Event numbers are those of Figure 1 and Table 1.

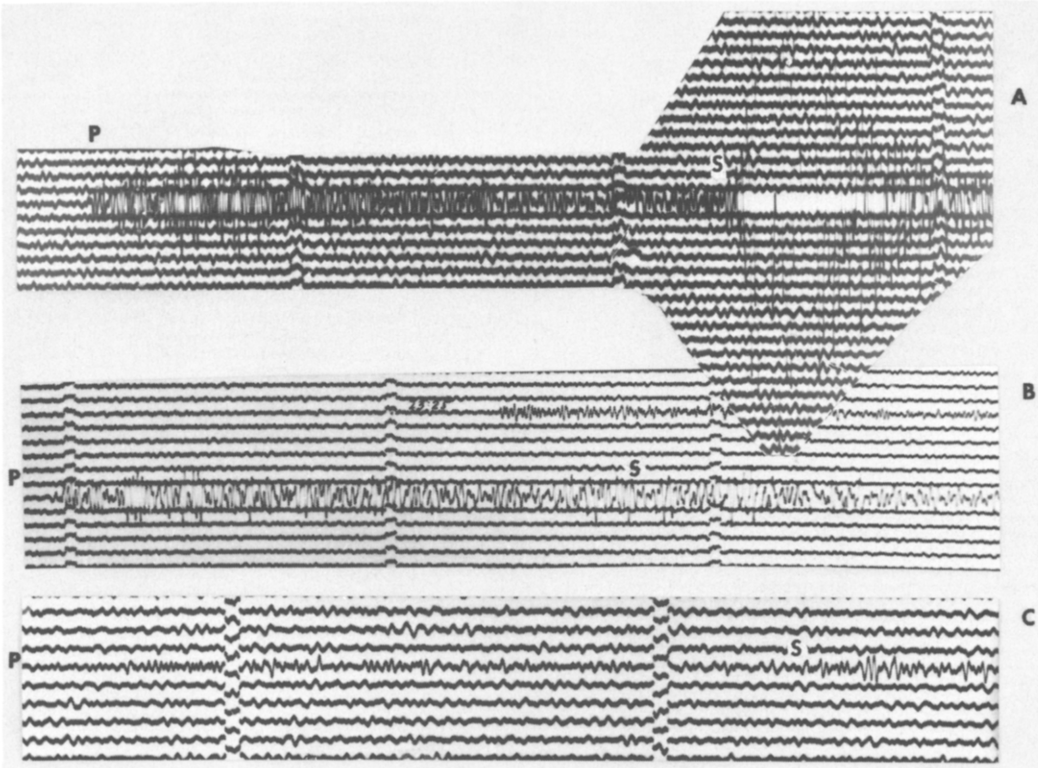

Fig. 4. Short-period seismograms (WWSSN): (A) path 2 (TRN), E-W component, class 3; (B) path 16 (CAR), E-W component, class 0; (C) path 12 (CAR), Z component class 0. Event numbers are those of Figure 1 and Table 1.

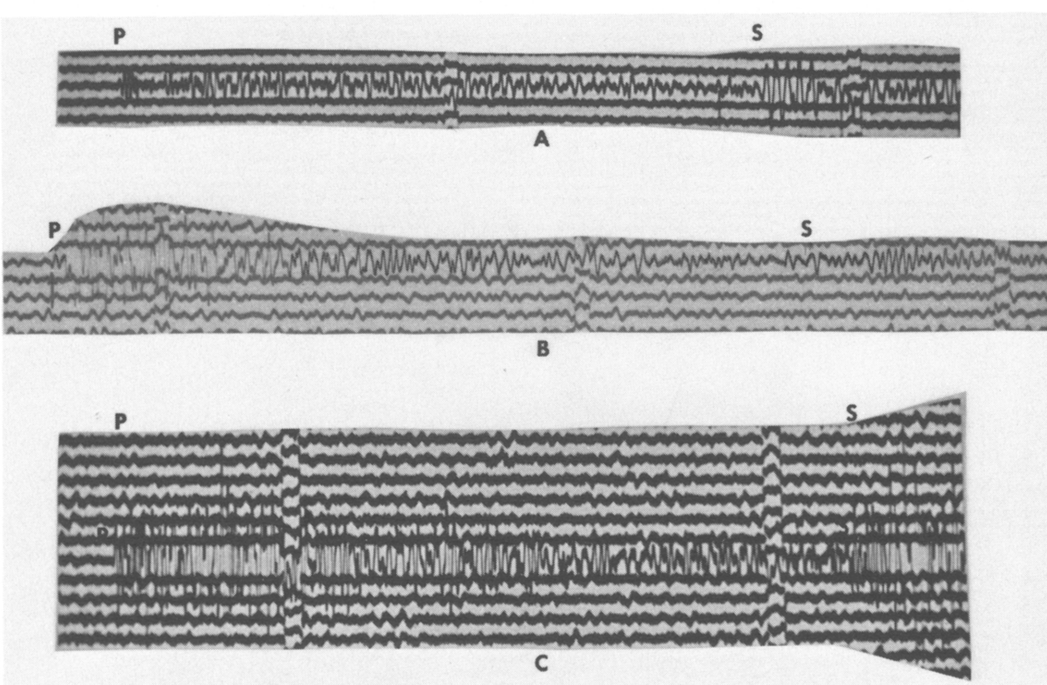

Fig. 5. Short-period seismograms (WWSSN): (A) path 16 (CAR), Z component, class 1; (B) path 7 (TRN), Z component, class 0; (C) path 3 (CAR), Z component class 3. Event numbers are those of Figure 1 and Table 1.

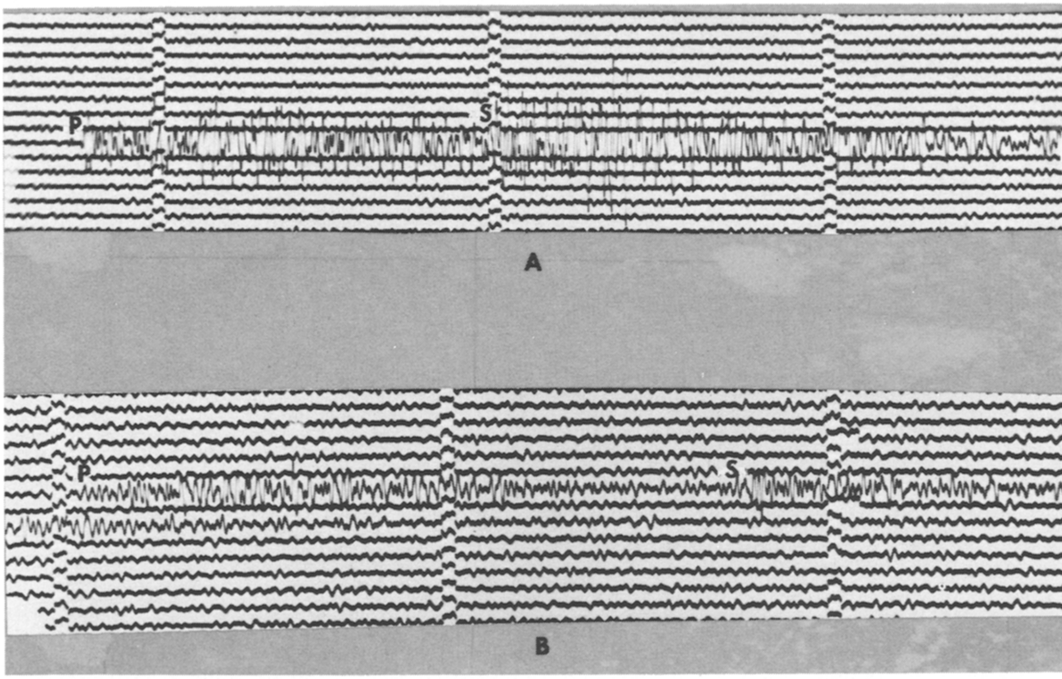

FIG. 6. Short-period seismograms (WWSSN): (A) path 15 (TRN), E-W component, class 2; (B) path 9 (TRN), E-W component, class 0. Event numbers are those of Figure 1 and Table 1.

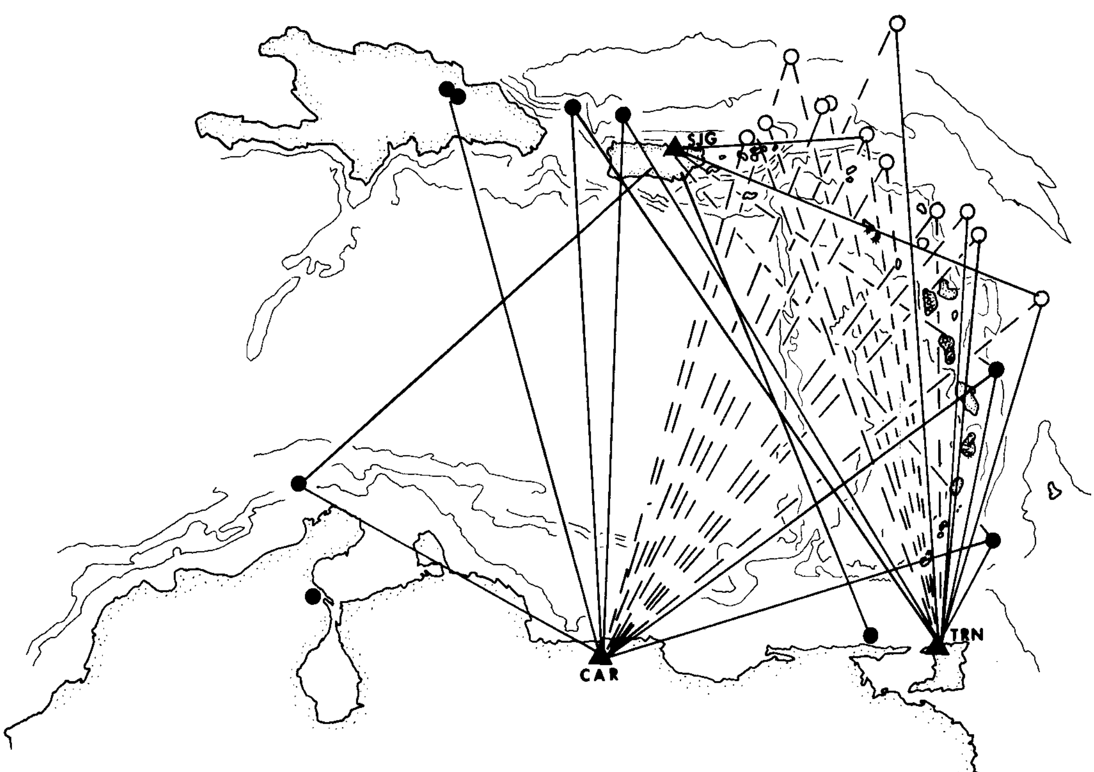

FIG. 7. Shear body-wave transmission character. Solid lines represent efficient (low attenuation) transmission. Dashed lines represent inefficient (high attenuation) transmission.

The pattern of efficient and inefficient transmission shown in Figure 7 and $Q\beta$ values can be easily explained in terms of a plate subduction model similar to that proposed by Barazangi and Isacks (1971, Figure 17) in which it is shown that the zone of the crust and upper mantle beneath Lau basin (Fiji-Tonga island arc), strongly attenuates high-frequency shear waves. This is a region of about 300 km wide, characterized by extremely low Q values and sharply limited to the east by the line of volcanoes. A similar situation

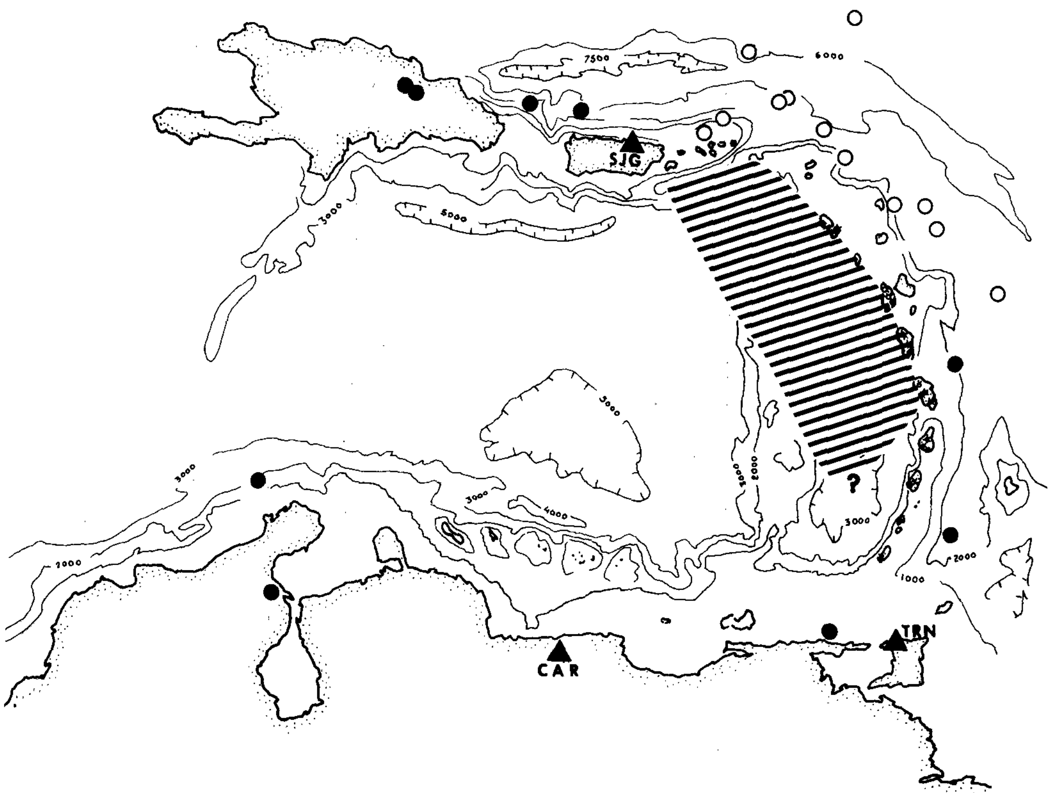

FIG. 8. The Anomalous zone in the concave side of the Lesser Antilles arc is shown as the hatched area.

seems then to hold for the eastern Caribbean. In the Lesser Antilles the anomalous zone crosses obliquely the topographic expression of Aves swell, thus suggesting that this latter feature is tectonically independent of the recent episodes of plate subduction. The seismically active Anegada fault, on the other hand, appears as a well-defined northern limit of the anomalous zone, suggesting a tectonic transition from subduction along the Lesser Antilles to shear, strike-slip or transform fault movements along the Greater Antilles.

Validity of the results. The consistency of the results plus the fact that the same type of anomalous regions has been extensively reported as occurring in typical island arcs, strengthens the belief that the observations are related exclusively to the elastodynamic character of the rocks along the propagation path. However, the possibility exists that local structure near the recording stations, focal spectrum variations, and the radiation pattern at the focus might produce effects in the waves that could be confused with attenuation along the path. The following discussion attempts to demonstrate that in this study the mentioned effects can be properly counted.

Local structure at the recording site. At all stations used, high-frequency *S* waves were observed for either local or distant events. This rules out the possibility that the local geological setting of the stations causes the attenuation observed.

Focal spectrum variations. The focal spectrum varies essentially with focal depth and magnitude. The first effect is not important in this case as focal depths are reasonably close for all events (17 to 65 km). The effect of magnitude is essentially a broadening of the bandwidth and an increase of low-frequency content with increasing magnitude. In the frequency range used and for the limited range of magnitudes, this effect can be neglected.

Radiation pattern. This is by far the most important factor that may affect the observed seismogram in such a way as to produce the impression of inefficient transmission. It is possible that a recording station lies on a nodal line of a particular focal mechanism. However, in this study the following observed features make such possibility a rather remote one:

(a) Clear, low-frequency (0.3 to 0.5 Hz) *Sn* phases are commonly recorded (Figures 2B, 2C, 5A). As the radiation pattern is probably frequency-independent, the absence of higher frequencies in the signal is interpreted as attenuation (high-cut filtering) along the ray path. The effect of relative attenuation is readily noticed when events showing classes 1 and 3 characteristics are compared (Figure 2).

(b) In general, the relative location of station to epicenter allows the same *Sn* signal to be inspected from well-spaced points around the source. The use of records from the three mentioned stations and WWSSN station BEC (Bermudas), and the comparison of many different paths, makes it difficult to explain the absence or weakness of *Sn* phases as an effect of a particular radiation pattern.

Radiation pattern effects are generally ruled out in similar studies (Oliver and Isacks, 1967; Molnar and Oliver, 1969; Barazangi and Isacks, 1971; Barazangi *et al.*, 1972) on the basis of similar arguments. A further check can be given here that comes from the observed regional character of seismic-wave transmissibility. It is well known to many seismologists that seismic events from the Antilles islands arc recorded at eastern North American stations and BEC show long *Pn* and *Sn* wave trains with predominant frequencies as high as 5 to 7 Hz (Shurbet, 1962; Isacks and Oliver, 1964). In this study it is observed that whereas high-frequency *Pn* and *Sn* waves are recorded at BEC for events in the Antilles, the same phases of the same earthquakes are seen consistently attenuated at CAR and TRN whenever their ray paths cross through the region of Aves ridge. Otherwise their frequency content is similar to that found in BEC seismograms.

Analysis of Surface-Wave Transmission

Fundamental-mode group-velocity dispersion curves in the period range 10 to 50 sec of Rayleigh waves for 14 earthquakes and of *PL* waves for 9 earthquakes, a total of 21 paths in the Caribbean region, have been calculated by the usual method of obtaining period as a function of arrival time from the slope of the graph of peak, trough and zero-crossing order number versus time of arrival. Corrections due to time delay of the instruments were applied throughout. To avoid major errors in the calculated velocities, epicentral distances were checked as before. Errors in the calculated velocities are estimated small, within the range of 0.04 km/sec for Rayleigh waves and 0.08 km/sec for *PL* waves. The consistency of results gives confidence that those ranges may be narrower. In Figure 1 the earthquake locations are shown, and in Figures 9, 10, 11 and 15 the observed dispersion curves are presented along with those for various theoretical models.

Rayleigh waves. The general behavior of Rayleigh-wave dispersion shows a systematic decrease in group velocity toward the eastern end of the Caribbean. From Figures 1, 9, 10 and 11 it is seen that when the Caribbean paths of Rayleigh waves are swept from west to east the group velocity diminishes accordingly in the period range from 15 to 40 sec. The numbers assigned to the different events increase clockwise along the island arc from Hispaniola to Trinidad. For a given station, CAR or TRN, it is easy to observe that an increase in the event's order number (path closer to the island arc) generally implies that the corresponding group velocity decreases (Figures 9, 10 and 11).

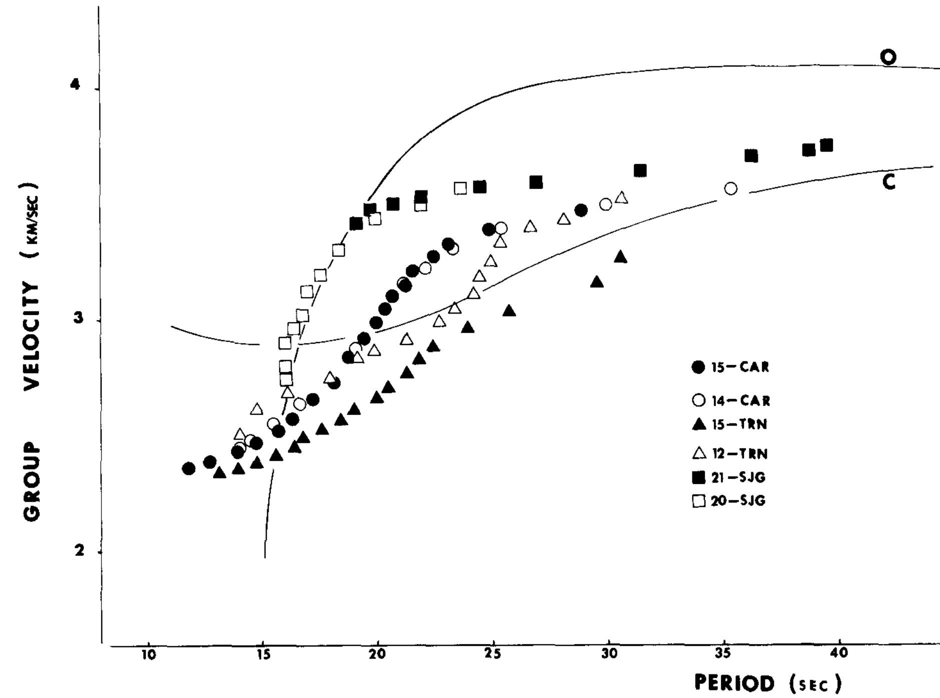

FIG. 9. Rayleigh-wave dispersion curves. Event numbers are those of Figure 1 and Table 1. Curves O and C correspond to the theoretical dispersion for typical ocean and typical continent, respectively.

In Figure 9 curves 20 and 21 (SJG) correspond to paths that cross the middle Caribbean plate from Panama to Puerto Rico, thus being representative of that sector of the plate far from the influence of the complicated structure underneath Aves swell and Lesser Antilles arc. Thus it has been assumed that paths 20 and 21 (SJG) represent the characteristic dispersion imposed by the plate itself. All other paths in this study correspond to regions closer to the island arc.

Figure 9 alone shows the basic findings of this study: Paths 20 and 21 (SJG) represent the average plate. Paths 14 and 15 (CAR) include the effect of the thickening of the crust at Aves swell. Path 12 (TRN) includes the effect of the anomalous zone previously discussed and the Grenada trough and path 15 (TRN) includes the effect of the island arc itself. The two extremal curves in Figure 9 thus represent the total range of variation of group velocities in the studied area. Figures 10 and 11 show the rest of the data for detailed comparison. As expected, the general behavior of Rayleigh-wave dispersion is in agreement with the fact already discussed by many investigators that the average Caribbean crust is of intermediate nature, between continental and oceanic. This is clearly observed when the data used in this study are compared with dispersion curves typical

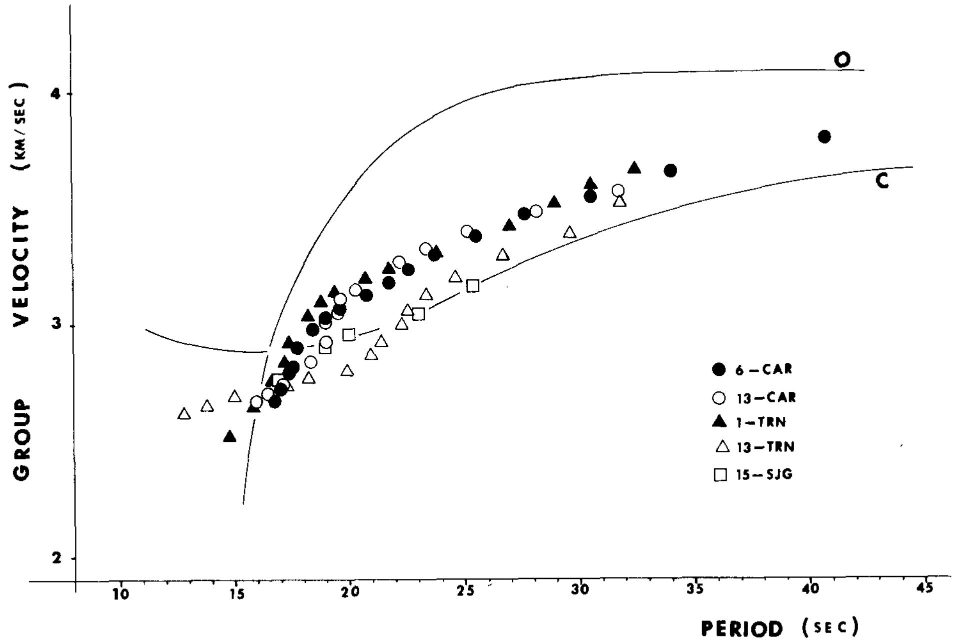

FIG. 10. Rayleigh-wave dispersion curves. Event numbers are those of Figure 1 and Table 1. Curves O and C correspond to the theoretical dispersion for typical ocean and continent, respectively.

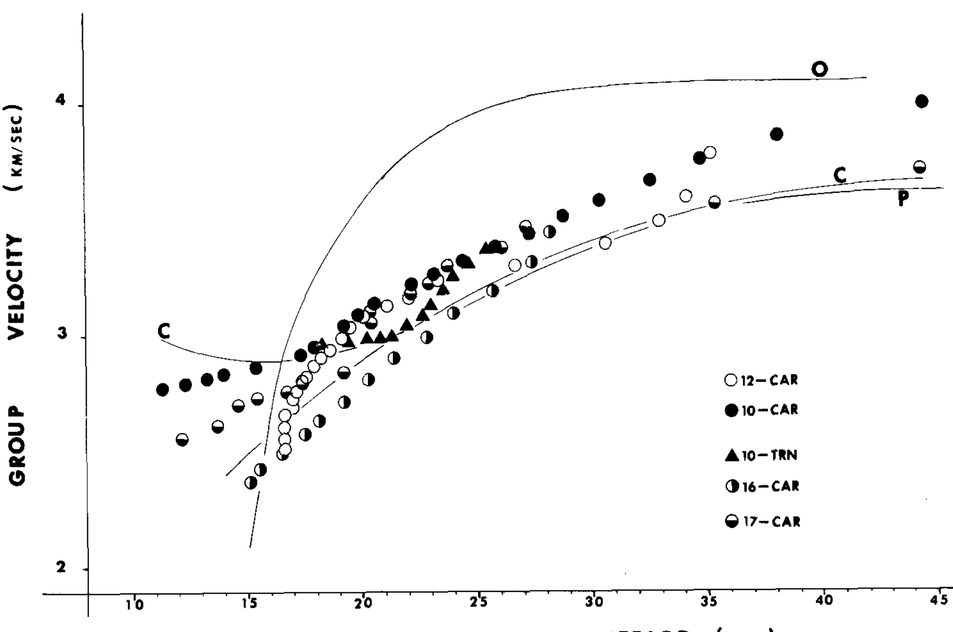

FIG. 11. Rayleigh-wave dispersion curves. Event numbers are those of Figure 1 and Table 1. Curves O and C correspond to the theoretical dispersion for typical ocean and continent, respectively. Curve P is from Papazachos (1964) model with the following structure.

H (km)	α (km/sec)	β (km/sec)	ρ
3.0	2.0	1.0	2.0
8.0	4.9	3.0	2.6
14.0	6.5	3.7	2.8
40.0	8.1	4.6	3.3
160.0	8.15	4.3	3.4
	8.7	4.8	3.6

of oceanic and continental crusts. To emphasize the "continental" character of some of the data, a model dispersion curve for a continent which includes a 160-km-thick low shear-velocity layer is included in Figure 11.

Aves swell has been recognized as representing a major thickening of the Caribbean crust (Chase and Bunce, 1969). This fact is indeed reflected in the lower group velocities found for paths that cross this feature with respect to those which do not, as can be interpreted from Figure 9 if 14 (CAR) or 15 (CAR) are compared with 20 (SJG). However, when this effect of crustal thickening is taken into account, still further indications of anomalously low velocities are found. In fact, in Figures 9, 10, and 11, the paths 12 (TRN), 13 (TRN) and 10 (TRN) all of which cross the anomalous zone previously discussed along its longest dimension, clearly show "embayments" of lower group velocities in the period range of about 18 to 25 sec. This feature may represent the effect of the anomalous zone which, this being the case, extends down to a depth of about 70 km.

Another interesting feature on Figures 9, 10 and 11 is the fact that for periods close to 40 sec all dispersion curves tend to coalesce, therefore behaving as those that correspond to the average Caribbean crust. An interpretation of this fact may be that the thickening represented by Aves swell disappears at depths of the order of 140 km.

It is relevant now to take under consideration the effects that thick sedimentary layers and the water depths along the paths may have on the observed dispersion curves. Station TRN and CAR were the most used in the determination of dispersion curves here reported. It can be shown that the differences found in Rayleigh-wave group velocities cannot be accounted for in terms of great thicknesses of sediments along the path. In fact, according to the isopach map of layers of velocity less than 5 km/sec given by Edgar *et al.* (1971) for the Caribbean, equivalent thicknesses of sediments (4 to 6 km) exist in the Grenada and Curacao troughs through which surface waves have to pass before reaching either station. On the other hand, seismic paths from the Windward Islands and Puerto Rico to TRN cross a region along which average ocean depths are about 2 km. In contrast, to reach CAR surface waves travel along paths with average ocean depths of 3.5 to 4 km (Figure 1). It is well known that the effect of shallow waters is to increase group velocities on the high-frequency side of the dispersion curve, therefore the water layer in the present case would tend to diminish the existent differences rather than to increase them.

PL waves. A remarkable fact about the transmission of seismic waves across the Caribbean plate is the extremely clear long-period *PL* waves detected specially at CAR and SJG from earthquakes in the Antilles (Figures 12 through 14). To the author's knowledge, this is the first time that such clear *PL* waves have been reported for a water-covered path. Oliver and Major (1960) describe extensively those waves that appear on the long-period seismograms beginning at or near the initial *P* arrival and continue sometimes to the arrival of the Rayleigh group. *PL* waves here reported show unusually large amplitudes (0.5 to 1.1 times that of the Rayleigh phase of the same period). Dispersion curves for *PL* waves are shown in Figure 15. Again, it is observed that crustal velocities decrease toward the eastern end of the plate. In fact, it is observed that sweeping of paths across the Caribbean from west to east provide lower and lower group velocities of the *PL* phase. Again too, the general character of the curves shows the intermediate nature of the plate between a pure oceanic and a pure continental crustal structure.

It has been recognized by observation of seismograms around the Caribbean that *PL* phases are a common feature except perhaps for those recordings at TRN, which either do not show the phase at all or its character is masked by much higher frequencies. As it is shown in Figures 12 through 14, *PL* phases are well defined, of large amplitude and relative low frequencies when recorded at CAR. The same features are observed in seismograms recorded at SJG and BHP. However, when the same events or similar station-epicenter paths are seen at TRN no appreciable *PL* phases are found with the character of those described at the above stations. This circumstance points to a near-station effect. If this is indeed the case, the complicated tectonic structure of northeastern Venezuela may be responsible for these differences inasmuch as the recording instruments are supposedly identical.

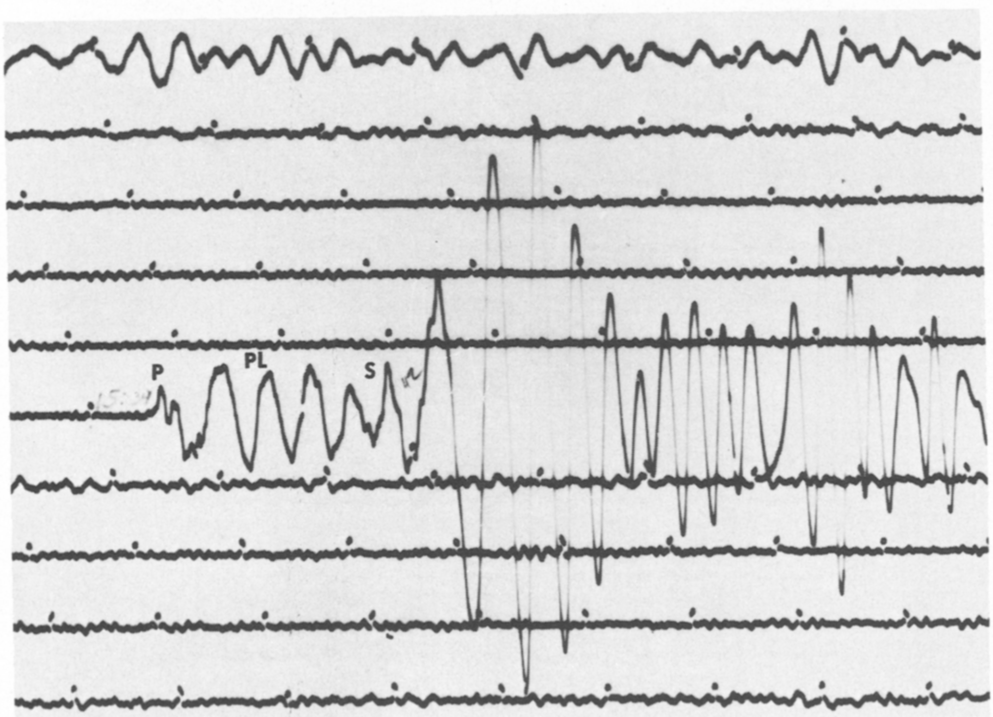

FIG. 12. *PL* and Rayleigh waves for path 10 (CAR), *Z* component.

The existence of so well-defined *PL* phases is an indication that the Caribbean crust is well developed and the velocity contrast with the underlying mantle must be large and well defined for most of the plate west of Aves ridge.

Discussion and Conclusions

High attenuation of short-period body waves and extremely low surface-wave group velocities have been found for seismic paths that traverse the crust and upper mantle beneath the concave side of the Lesser Antilles islands arc. The observations can be explained in terms of the currently accepted models of lithospheric plate subduction at several island arcs like Fiji-Tonga, Marianas, Aegean, etc., and characteristic of which is the existence of an abnormally low *Q* zone in the crust and upper mantle above the subducted plate (Barazangi and Isacks, 1971).

On the basis of the evidence here presented there appears to be a close relationship between the region determined as anomalous and the present period of plate convergence and subduction at the Lesser Antilles arc. The Greater Antilles arc appears to be tectonically different. Subduction is not evident there, and no anomalous zone exists south of Puerto Rico and Hispaniola. The two arcs are sharply separated at the Anegada fault zone, which marks the northern limit of both the anomalous zone and the historically active volcanoes (Robson and Tomblin, 1966). This suggests that tectonic processes at Greater Antilles do not include subduction but, possibly, east-west shear movements along the strike of the north Caribbean fault zone.

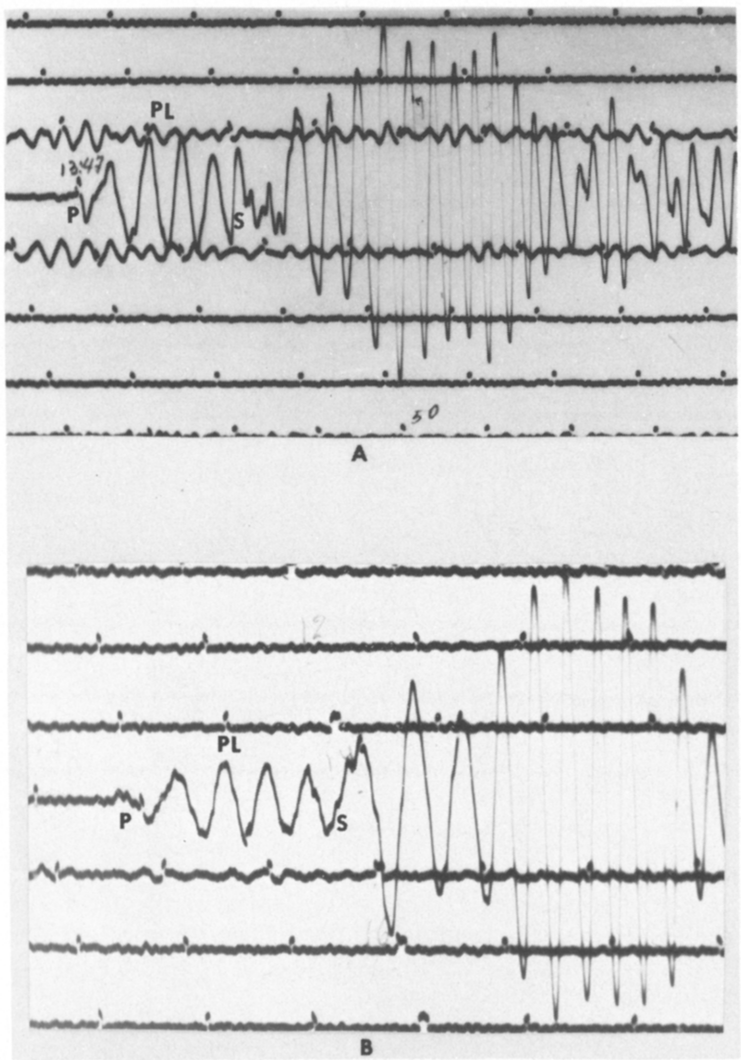

FIG. 13. (A)*PL* and Rayleigh waves for path 14 (CAR), Z component; (B) *PL* and Rayleigh waves for path 16 (CAR), Z component.

Aves swell is probably not related tectonically to the anomalous zone, at least presently. Nevertheless, it has certainly been active in the past, likely as the easternmost boundary of the Caribbean plate, acting as a rigid tongue against the oncoming Atlantic plate.

A further, more complete analysis of seismic-wave transmission in the eastern Caribbean is necessary to define with more accuracy the anomalous zone. In this study 2 years of seismic data were used, and no events deeper than 70 km were found such that their study might provide more detail in the results here presented. Therefore, an anomalous, highly attenuating zone in the eastern Caribbean has been identified, although its exact limits are still to be determined.

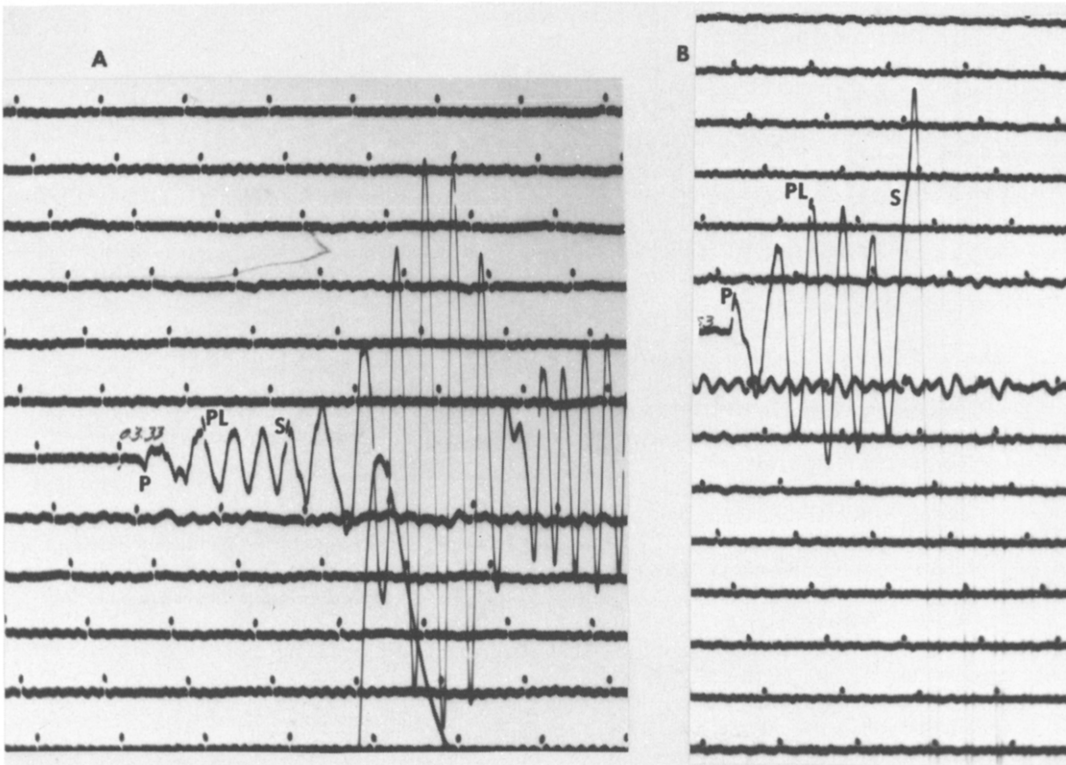

FIG 14. (A) NS component of *PL* waves for path 15 (CAR); (B) *PL* wave for path 16 (CAR), Z component.

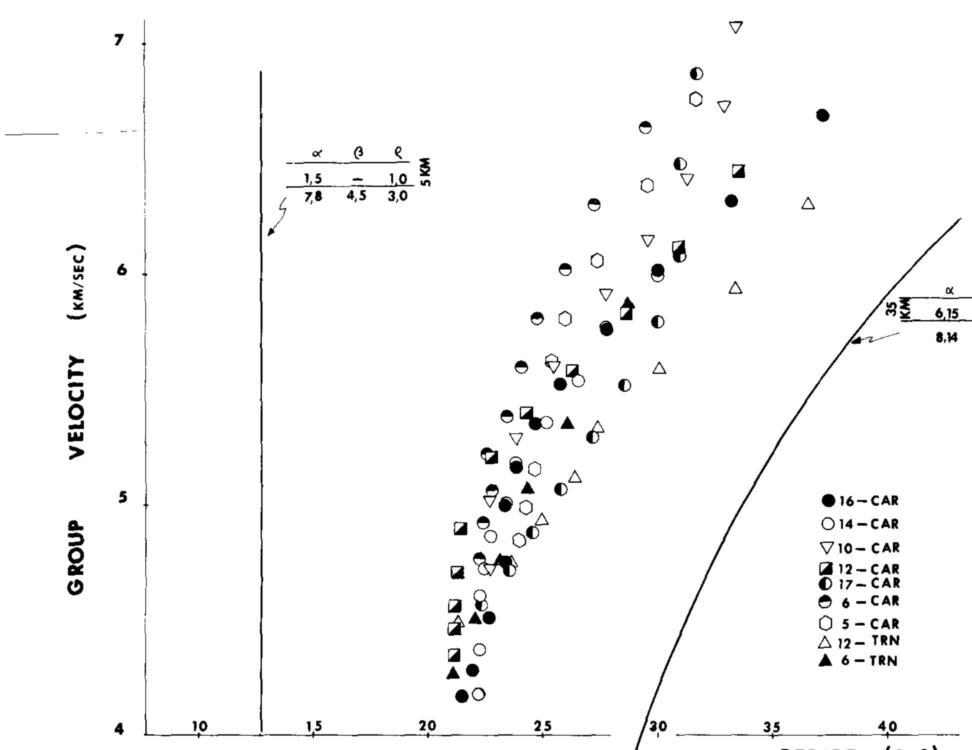

FIG. 15. *PL*-wave dispersion curves. Event numbers are those of Figure 1 and Table 1. The two theoretical curves are taken from Oliver and Major (1964).

Acknowledgments

This study was entirely supported by the Consejo de Desarrollo Cientifico y Humanistico, Universidad Central de Venezuela, Caracas. The investigation was carried out at the Department of Geology and Mineralogy of the University of Michigan. The author is indebted to Dr. H. N. Pollack, whose constant help and advice made this study possible, and to Dr. R. Chander, whose valuable suggestions are gratefully acknowledged.

References

Barazangi, M. and B. Isacks (1971). Lateral variations of seismic wave attenuation in the upper mantle above the inclined earthquake zone of the Tonga Island Arc: Deep anomaly in the upper mantle, *J. Geophys. Res.* **76,** 8493–8516.

Barazangi, M., B. Isacks, and J. Oliver (1972). Propagation of seismic waves through and beneath the lithosphere that descend under the Tonga Island Arc, *J. Geophys. Res.* **77,** 952–958.

Chase, R. L. and E. T. Bunce (1969). Underthrusting of the eastern margin of the Antilles by the floor of the western Atlantic Ocean, and origin of the Barbados Ridge. *J. Geophys. Res.* **74,** 1913–1920.

Edgar, T., J. Ewing, and J. Hennion (1971). Seismic refraction and reflection in the Caribbean Sea, *Bull. Am. Assoc. Petrol. Geologists* **55,** 833–870.

Harkrider, D. G., A. L. Hales, and F. Press (1963). On detecting soft layers in the mantle with Rayleigh waves, *Bull. Seism. Soc. Am.* **53,** 539–548.

Isacks, B. and J. Oliver (1964). Seismic waves with frequencies from 1 to 100 cycles recorded in a deep mine in northern New Jersey, *Bull. Seism. Soc. Am.* **54,** 1941.

Le Pichon, X. (1968). Sea floor spreading and continental drift, *J. Geophys. Res.* **73,** 3661–3697.

MacDonald, W. D. (1972). Continental crust, crustal evolution, and the Caribbean, In *Geol. Soc. of Am. Memoir 132, The Hess Volume* 351–362.

Menard, H. W. (1967). Transitional types of crust under small ocean basins, *J. Geophys. Res.* **72,** 3061–3073.

Molnar, P. and J. Oliver (1969). Lateral variations of attenuation in the upper mantle and discontinuities in the lithosphere, *J. Geophys. Res.* **74,** 2648–2682.

Molnar, P. and L. R. Sykes (1969). Tectonics of the Caribbean and Middle American regions from focal mechanisms and seismicity, *Bull. Geol. Soc. of Am.* **80,** 1639–1684.

Officer, C., J. Ewing, J. Hennion, D. Harkrider, and D. Miller (1959). Geophysical investigations in the eastern Caribbean in *Summary of the 1955 and 1956 cruises*, L. M. Ahrens, F. Press, K. Rankama and S. K. Runcorn, Editors, *Phys. Chem. Earth*, **3,** 17–109.

Oliver, J. and B. Isacks (1967). Deep earthquake zones, anomalous structures in the upper mantle and the lithosphere, *J. Geophys. Res.* **72.**

Oliver, J. and M. Major (1960). Leaking modes and the *PL* phase. *Bull. Seism. Soc. Am.* **50,** 165–180.

Papazachos, B. C. (1964). Dispersion of Rayleigh waves in the Gulf of Mexico and Caribbean Sea. *Bull. Seism. Soc. Am.* **54,** 909–926.

Robson, G. R. and J. F. Tomblin (1966). Catalogue of the active volcanoes and solfatara fields of the West Indies, Part XX, *Intern. Assoc. Volcanol.*

Shubert, D. H. (1962). The high-frequency *P* and *S* phases from the West Indies, *Bull. Seism. Soc. Am.* **52,** 957–962.

Sykes, L. R. and M. Ewing (1965). The seismicity of the Caribbean region, *J. Geophys. Res.* **70,** 5065–5074.

Tarr, A. C. (1968). The dispersion of Rayleigh waves in the crust and upper mantle under the western north Atlantic ocean, Gulf of Mexico and Caribbean Sea, *Ph.D. thesis* (unpublished). University of Pittsburgh.

Vine, F. G. (1966). Spreading of the ocean floor: New evidence, *Science*, **154,** 1405–1415.

Department of Geology
and Mineralogy
The University of Michigan
Ann Arbor, Michigan 48104

Seismological Laboratory
California Institute of Technology
Pasadena, California 91125
Contribution No. 2828

Manuscript received September 22, 1975