2. GEOPHYSICS AND THE STRUCTURE OF THE LESSER ANTILLES FOREARC[1]

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ABSTRACT

The Barbados Ridge complex lies east of the Lesser Antilles volcanic arc along the eastern margin of the Caribbean Plate. The complex dates in part from the Eocene, and elements of the arc system have been dated as Late Cretaceous and Late Jurassic, although most of the volcanic rocks date from the Tertiary, particularly the latter part. It is probable that the arc system was moved a considerable distance eastward with respect to North and South America during the Tertiary.

The accretionary complex can be divided into zones running parallel to the arc, starting with a zone of initial accretion at the front of the complex where sediment is stripped from the ocean floor and the rate of deformation is greatest. This zone passes into one of stabilization where the deformation rate is generally lower, although there are localized zones of more active tectonics where the generally mildly deformed overlying blanket of sediment is significant disturbed. Supracomplex sedimentary basins that are locally very thick are developed in the southern part of the complex. The Barbados Ridge Uplift containing the island of Barbados lies at the western edge of the complex; between it and the volcanic arc lies a large forearc basin comprising the Tobago Trough and Lesser Antilles Trough.

There are major longitudinal variations in the complex that are broadly related to the northward decrease in sediment thickness away from terrigenous sources in South America and that are locally controlled by ridges in the oceanic igneous crust passing beneath the complex.

An important feature of the complex is the underthrusting of undeformed sedimentary horizons at least 80 km westward beneath the accretionary wedge. This underthrusting is facilitated by very high pore fluid pressures, which are presumably also related to the large number of mud diapirs in the southern part of the complex. The style of deformation is dominantly one of thrusting, although folding occurs in association. The size of deformational structures is directly related to the thickness of the accreted layer lying above the décollement, which separates it from the undeformed sediment beneath.

The geology of Barbados and seismic stratigraphy show that the complex has had an episodic rather than a smoothly evolutionary or steady-state history.

INTRODUCTION

The Lesser Antilles island arc lies along the eastern margin of the Caribbean Plate. Between the volcanic arc and the Atlantic ocean floor lies a broad and complex forearc region, 450 km wide at its southern extremity and still over 100 km wide north of Barbuda (Fig. 1).

The arc and the island of Barbados have been of geological interest since the latter part of the nineteenth century, but although the presence of the large negative gravity anomaly east of the arc and the seismicity of the Benioff zone had been known since the 1930s (Field et al., 1933; Ewing and Worzel, 1954; Gutenberg and Richter, 1954), it was not until the 1950s that widespread geophysical investigations were undertaken (see Case, 1975, for an historical account). Seismic refraction data and crustal sections were published by Ewing et al. (1957) and Officer et al. (1959). These data gave the first broad picture of crustal structure, which was supplemented by Edgar et al. (1971). This information, with the results of a large-scale seismic refraction experiment, and gravity, magnetic, and seismic reflection data, was used to derive cross-sectional models of the crustal structure of the arc and forearc at the latitude of Barbados (Westbrook et al., 1973; Westbrook, 1975; Boynton et al., 1979) and elsewhere (Bowin, 1976; Westbrook, 1982).

Gravity, magnetic, and seismic reflection investigations had continued concurrently with the seismic refraction experiments (Bunce et al., 1970; Bowin, 1972; Marlow et al., 1974; Kearery et al., 1975; Westbrook, 1975; Peter and Westbrook, 1976; Bowin, 1976), so that by the late 1970s the broad picture of the region's structure had emerged.

Seismic reflection profiles showing deformation and overthrusting at the eastern margin of the accretionary forearc complex (Barbados Ridge complex) were first published by Chase and Bunce (1969), with further data and accretion models published by Westbrook et al. (1973), Marlow et al. (1974), and Westbrook (1975). The Barbados Ridge complex was one of the first accretionary complexes to be identified as such. Further data and analyses of the tectonics of the complex, drawing attention to the influence of transverse structures in the Atlantic oceanic basement and forearc, were published by Peter and Westbrook (1976).

In recent years multichannel seismic reflection surveys in addition to those of oil companies have been carried out by the Comité d'Etude Pétroliere Marine (CEPM) of France (Biju-Duval et al., 1978; Mascle et al., in

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[1] Biju-Duval, B., Moore, J. C., et al., *Init. Repts. DSDP*, 78A: Washington (U.S. Govt. Printing Office).

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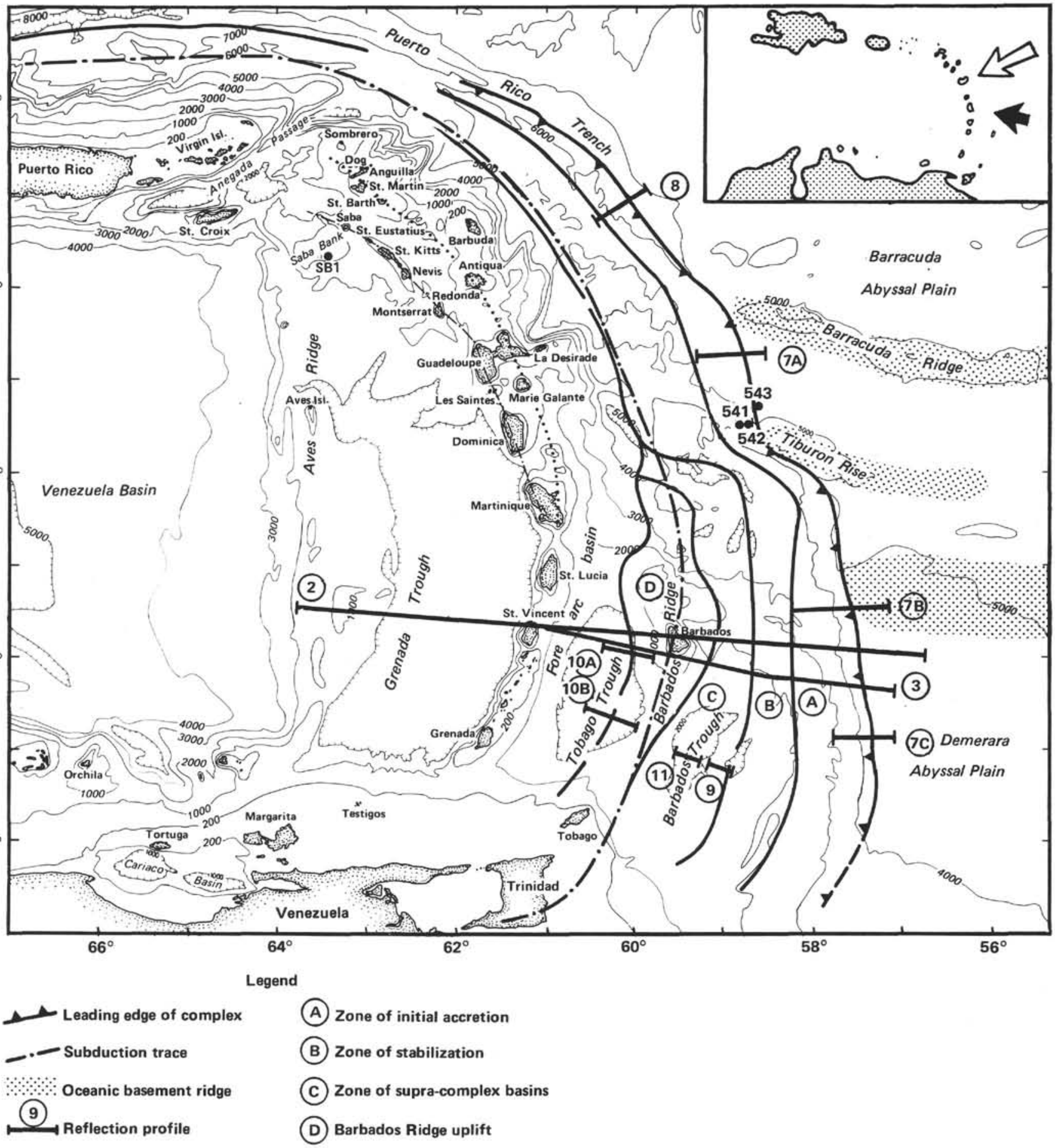

Figure 1. Map of the eastern Caribbean showing the major divisions of the Barbados Ridge accretionary complex and the locations of sections in Figures 2, 3, 7, 8, 9, 10, and 11. Also shown are prominent ridges in the oceanic basement, and the subduction trace of oceanic lithosphere beneath the crystalline crust of the Caribbean Plate. Bathymetric contours are in meters. (Inset: the directions of convergence between the Caribbean and North American plates, after Minster and Jordan, 1978 [solid arrow] and after Sykes et al., 1982 [open arrow].)

press; Biju-Duval et al., 1982), the University of Durham (Westbrook et al., 1982), Lamont-Doherty Geological Observatory, and University of Texas Marine Science Institute. The aim of these surveys was to provide a better cross-sectional picture of the structure of the forearc by improving penetration and resolution.

In conjunction with the Durham and CEPM seismic work, modern bottom surveys have been conducted by the Institute of Oceanographic Sciences (IOS), Wormley, using the long-range side scan sonar GLORIA (Belderson, et al., this volume; Stride et al., 1982), and by CEPM-CNEXO using the multi-narrow-beam sonar system SEABEAM (Biju-Duval et al., 1982; Fontas et al., this volume). The former method gives continuous sonograph images of the seafloor, and the latter provides high-resolution swath mapping. Both methods were used to provide a third dimension to the cross-sectional structure shown on the seismic reflection sections, because in this currently tectonically active region many of the structures have a morphological expression that can be imaged and mapped by GLORIA and SEABEAM.

Some of these studies are still in progress, and they provide an effective technique for examining the structure of the forearc complex that combines well with mathematical analyses of the stress distribution for the forearc (Park, 1981; Ngokwey, 1983), as well as with reexaminations and further investigations of the seismicity associated with the subduction of the oceanic lithosphere (Pérez and Aggrawal, 1981; Stein et al., 1982; W. R. McCann, personal communication, 1982), and with recent geological investigations such as those in the Lesser Antilles (Bouysse et al., this volume) and Barbados (Speed, 1981; Poole and Barker, in press; Pudsey and Reading, 1982).

A great part of, if not all, the geophysical and geological information related to the forearc region has been assembled in maps and sections that compose the synthesis study of the eastern Caribbean (Area 10). (Sponsored by J.O.I. for the Ocean Margin Drilling Program, and completed in June 1982, this study should be published in late 1983 or early 1984. The coordinator for the synthesis was R. C. Speed; Speed et al., in press).

At present, the Lesser Antilles forearc is one of the most intensely investigated examples of an active plate margin.

THE LESSER ANTILLES SUBDUCTION ZONE

The subduction zone of the Lesser Antilles forms the eastern boundary of the Caribbean Plate, where Atlantic oceanic lithosphere of the North and South American plates passes beneath it. The predominantly easterly direction of plate convergence at the boundary has been inferred primarily from the northern boundary of the Caribbean Plate (Jordan, 1975; Minster and Jordan, 1978). The rate of convergence has been calculated from spreading rates in the Cayman Trough (MacDonald and Holcombe, 1978) as 20 km/Ma for the past 2.4 Ma and 40 km/Ma for the period 8.3 to 2.4 Ma. Relative motion between the North and South American plates has been roughly constant for the past 38 Ma, so it is probable that the direction of motion of the Caribbean Plate, but perhaps not the rate, was much the same for most of the Tertiary. The direction and rate of motion of the Caribbean with respect to North America has been recently questioned by Sykes et al. (1982), who suggest that convergence at the Lesser Antilles has been ENE at 37 km/Ma for the past 7 Ma.

The Benioff zone extends to a depth of 200 km and passes beneath the active volcanic islands uniformly at a depth of 100 km. The dip of the deeper portion is about 45°. The arc is not strongly seismically active, and the southern part of the arc is noticeably less active than the northern part. Slip rates calculated from seismicity (Molnar and Sykes, 1969; Westbrook, 1975) indicate a rate of subduction of 5 km/Ma, which is much less than that predicted by plate motion models just mentioned. This difference suggests that a large proportion of motion in the subduction zone may be aseismic (Stein et al., 1982). Activity in the upper and outer part of the Benioff zone is sparse, and those earthquakes that have had their focal mechanisms determined arise from normal and strike slip faults in the oceanic lithosphere, probably along old fracture zones (Stein et al., 1982).

THE VOLCANIC ARC

The Lesser Antilles volcanic arc can be shown from isotopic and stratigraphic dating to have been in existence since the middle Eocene (Lewis and Robinson, 1976; Briden et al., 1979; Nagle et al., 1976; Westercamp, in press; Andreiff et al., 1981).

Indirect evidence, such as the age of some La Desirade and Tobago volcanic sequences (Early Cretaceous), the continuity of the southwestern extension of the arc into Margarita (where intrusive rocks have been dated Late Cretaceous), the origin and age of the Aves Ridge, and the necessity of a convergent boundary in most plate models for the evolution of the Caribbean area, suggest that a "proto" Lesser Antilles existed in the Cretaceous (Bouysse et al., this volume; Girard and Maury, 1980).

The volcanic islands of the arc diverge north of Martinique into an outer arc extinct since the middle Miocene, and an inner arc, active since about 5 or 6 Ma (Martin-Kaye, 1969; Tomblin, 1975; Westercamp and Tazieff, 1980). This divergence is gradual, and on the eastern margins of the southern islands the complexity of gravity and magnetic anomalies compared with the western margin also suggests a westward shift in activity, although it was not sufficiently large to create new islands.

The crust beneath the arc is approximately 30 km thick (Fig. 2), and beneath the uppermost few kilometers is composed of an upper and a lower crustal layer (seismic velocities 6.2 and 6.9 km s^{-1}, respectively). The relative thicknesses of these layers varies considerably along the arc (Boynton et al., 1979). The upper layer is almost certainly a product of the arc, whereas the lower layer is probably the original ocean crust on which the arc was built, with additional intrusive, probably cumulate, igneous material added to it. In the north, where the arc divides, the crustal root lies beneath the old arc.

Between the arc and the boundary between Caribbean and Atlantic igneous crust lies a segment of oceanic-type crust 100 km wide overlain by a thick sequence of sediments in a forearc basin (Figs. 2 and 3)—the Tobago Trough and its northern extension, sometimes called the Lesser Antilles Trough. North of Guadeloupe, this segment of crust is narrower, 40 km, and less thickly covered by sediment.

THE BACK ARC

The Grenada Trough lies behind the Lesser Antilles and is underlain by an anomalously thick two-layer crust of oceanic type (at least south of 16°N) similar to much

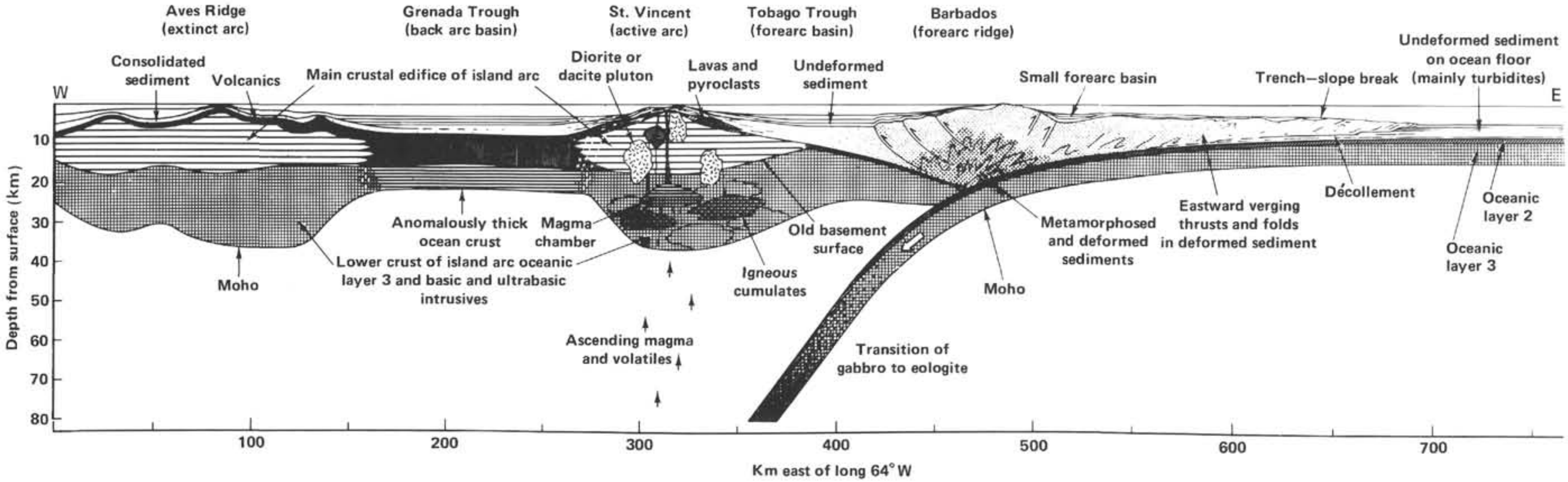

Figure 2. Cross-sectional model of the Lesser Antilles arc system through Barbados and St. Vincent, derived from all geophysical data, but primarily gravity and seismic refraction. Location is shown in Figure 1.

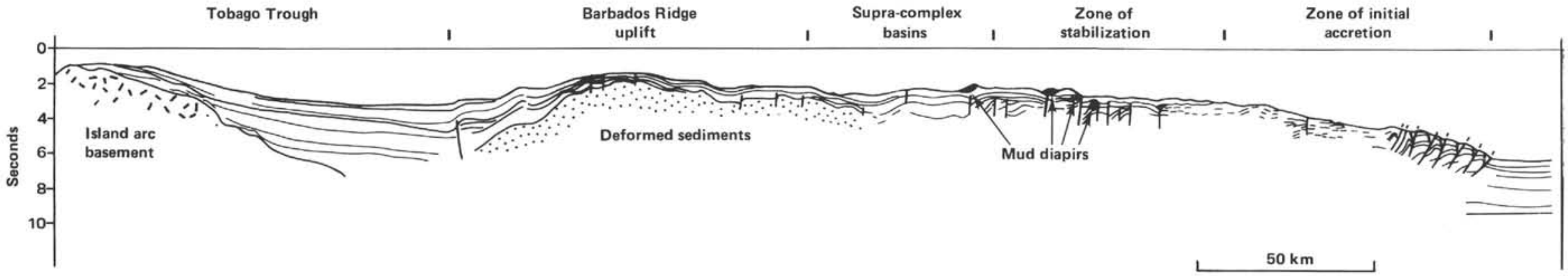

Figure 3. Line drawing of a seismic reflection section across the accretionary complex and forearc basin (Tobago Trough). Dashes show island arc basement. Stippling shows deformed rock beneath the Barbados Ridge. Black regions show mud diapirs. The section shows well the folds and thrusts at the front of the complex and undeformed sedimentary horizons overlying deformed rocks in the stabilized parts of the complex.

of the crust of the Venezuela Basin. The Grenada Trough has a thick fill (>6 km) of horizontally stratified sediment, most of which appears to have come from the arc. The Grenada Trough probably has an extensional origin, splitting the Lesser Antilles from the Aves Ridge, in which case its age is Late Cretaceous or early Tertiary (Boynton et al., 1979).

The Aves Ridge, which is separated from the Lesser Antilles by the Grenada Trough, is generally thought to be an extinct, volcanic arc because of its crustal thickness (35 km), the calc–alkaline affinities of rocks dredged from it (Fox et al,. 1971; Nagle, 1972), the morphology of its basement surface, and the similarity in style of the magnetic and gravity anomalies to those of the Lesser Antilles. The Aves Ridge, however, is wider than the volcanic arc. This width and the straightness of the western flank of ridge have yet to be explained.

THE ATLANTIC OCEAN FLOOR

As defined by its thickness and seismic structure (Ewing et al., 1957; Peter and Westbrook, 1976), the oceanic crust being subducted beneath the Caribbean is typical of oceanic crust elsewhere in the Atlantic and other oceans. It does, however, have two important characteristics that have had a major influence on the development of the accretionary sediment complex east of the Lesser Antilles. These are the presence of many ridges and troughs in the igneous basement, and the great variation from south to north of the thickness and type of sediment lying on the ocean floor.

Most of the oceanic crust east of the Lesser Antilles was produced at the Mid-Atlantic Ridge where it is successively offset to the west by several transform faults, of which two of the currently most notable are the Vema Fracture Zone and the Fifteen Twenty Fracture Zone. The transform faults generate troughs and asymmetrical flanking ridges. Two of these that can be seen near the Lesser Antilles are the Barracuda Ridge and Tiburon Rise; another farther east is the Researcher Ridge. The troughs and the ridges farther south are not shown by the bathymetry, because they are filled and covered by sediment, but they can be traced from seismic reflection profiles and gravity anomalies. The ridges and troughs near the arc were not created at the transform faults that currently displace the Mid-Atlantic Ridge, but they were presumably similar in character (Peter and Westbrook, 1976). Sediment thickness on the Atlantic ocean floor increases from 200 m at 19°N to >7 km south of 11°N (Ewing et al., 1973; Peter and Westbrook, 1976; Westbrook and Ladd, in press; Westbrook et al., in press), thickening and thinning locally over the ridges and troughs just mentioned.

In the north, the sedimentation is essentially pelagic, but in the south it is dominated by turbidites (Fig. 4), with large input from the Orinoco and Amazon rivers. Individual turbidites have been observed as far north as DSDP Hole 27 on the southern flank of the Barracuda Ridge. Sediment thicknesses immediately in front of the accretionary sediment complex of the Lesser Antilles and beneath the toe of the complex are shown in Figure 5.

The pattern of oceanic magnetic anomalies (Fig. 6) indicates that the ocean crust being subducted beneath the northern part of the arc was generated at the Mid-Atlantic Ridge. Although positive identification of some anomalies was rather tenuous, because of their low amplitude, the pattern shown by Peter and Westbrook (1976) gave a good qualitative representation of spreading history close to the Mid-Atlantic Ridge, although the positions of major fracture zones were not accurately identified (Collette et al., 1974). As part of the synthesis study of Area 10 of the Ocean Margin Drilling Project, a magnetic map of the area east of the Lesser Antilles

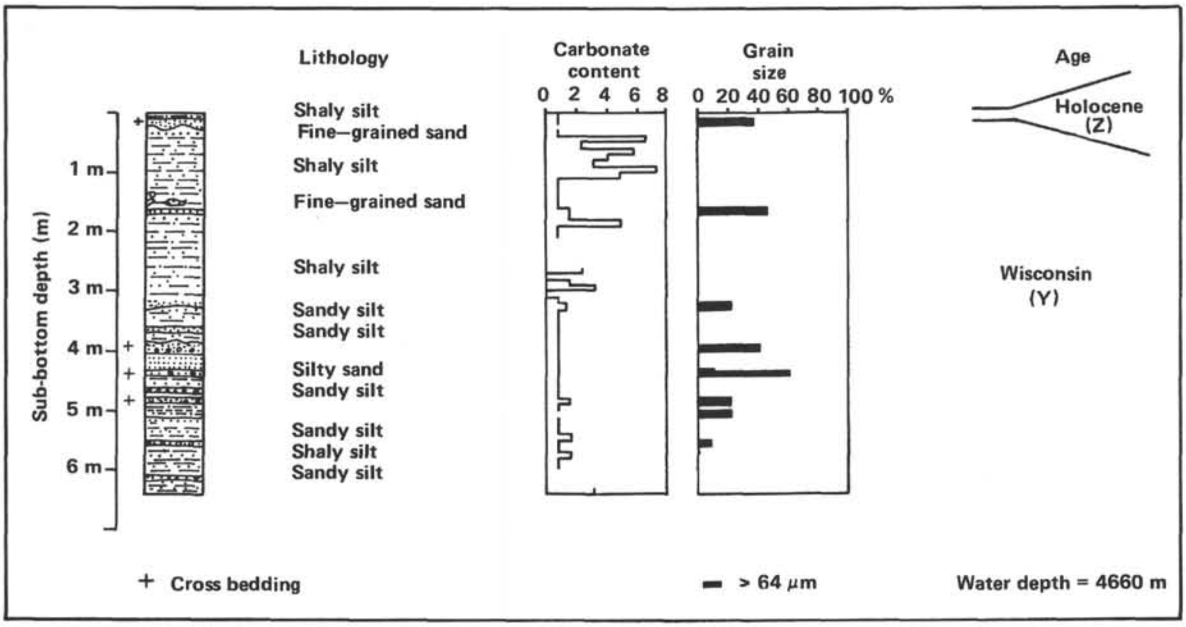

Figure 4. Details of Core KS5 taken from the Demerara Abyssal Plain at 10°59′N54°00′W, showing lithologies and age of the uppermost 6.5 m of sediment, interpreted as interbedded turbidites and hemipelagic layers (Moyes et al., 1978).

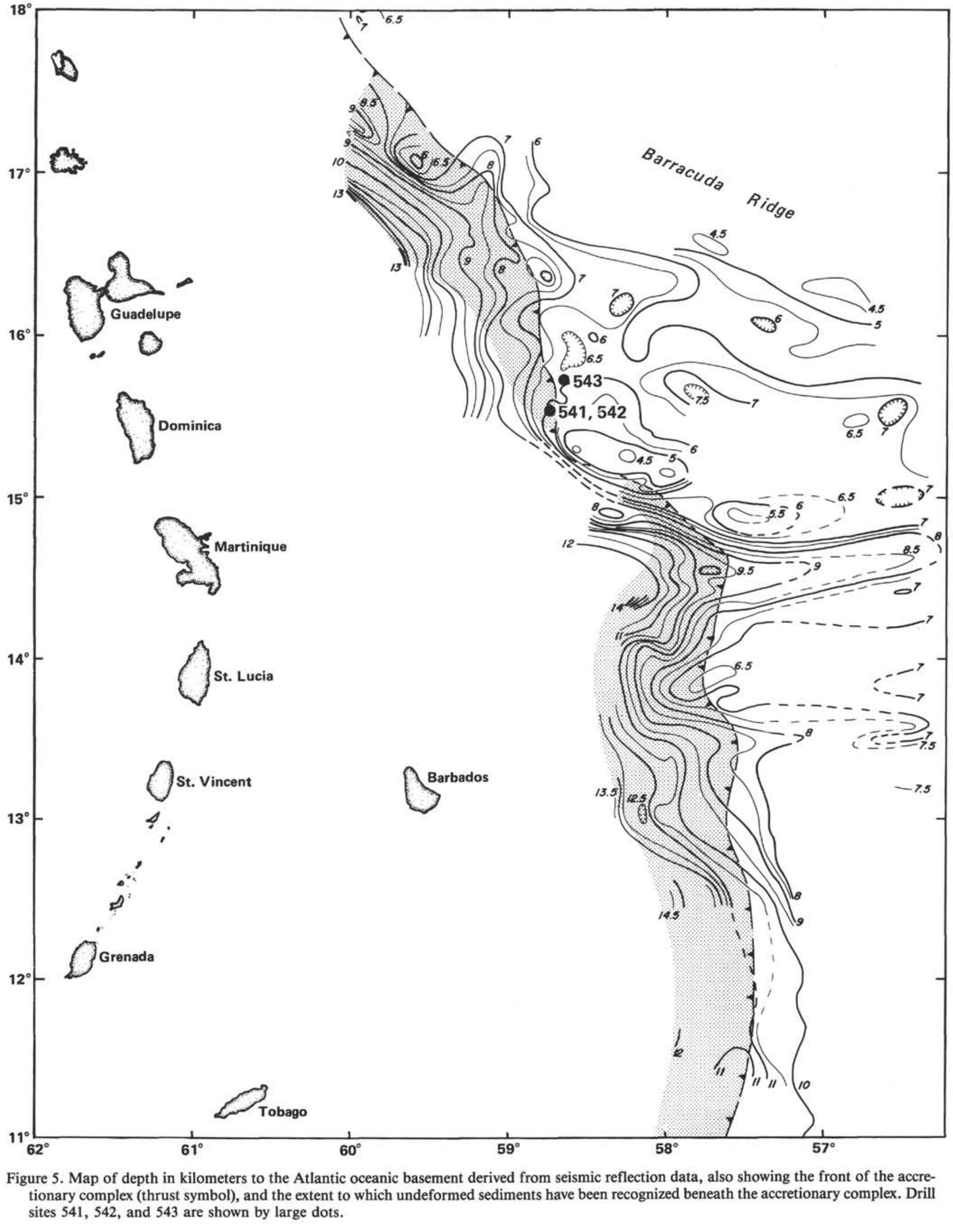

Figure 5. Map of depth in kilometers to the Atlantic oceanic basement derived from seismic reflection data, also showing the front of the accretionary complex (thrust symbol), and the extent to which undeformed sediments have been recognized beneath the accretionary complex. Drill sites 541, 542, and 543 are shown by large dots.

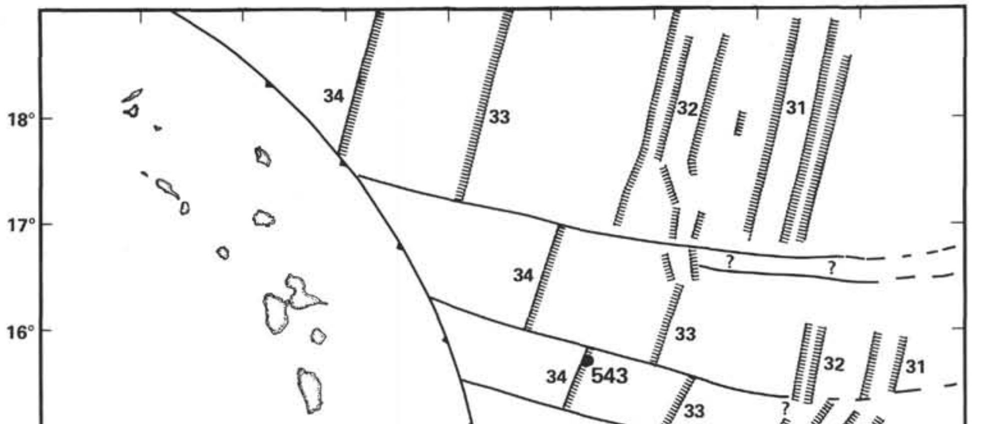

Figure 6. Oceanic magnetic anomalies and fracture zones in the Atlantic east of the Lesser Antilles. Solid lines are fracture zones. Dashed lines mark boundaries between positively and negatively magnetized ocean crust with shading on the negative side. Numbers indicate the identification of magnetic anomalies. Drill Site 543 is indicated by a large dot. East of the arc and parallel to it lies the line along which the magnetic anomalies of the ocean floor are truncated against those of the island arc, and which shows where the Atlantic ocean crust is subducted beneath the crystalline crust of the Caribbean. In the south of the map lies a boundary marked by linear gravity and magnetic anomalies that truncates the anomalies produced by fracture zones. From models of the opening of the Atlantic it is expected that the crust south of this boundary was formed during an early phase before the South Atlantic began to open and its age is therefore Late Jurassic to Early Cretaceous.

was compiled. From this and the along-track magnetic profiles the anomalies and fracture zones shown in Figure 6 were identified (G. K. Westbrook, unpublished data). Particularly prominent and easy to identify is Anomaly 34 (the end of the long Cretaceous normal polarity interval), which is dated at around 84 Ma (Lowrie and Alvarez, 1981). This anomaly is successively offset left laterally by fracture zones so that it is found along a trend running southeasterly across the map, although its actual trend is NNE. Anomaly 34 occurs just to the east of Site 543 and places that ocean crust in the lower Campanian, which is compatible with paleontology of the deepest cores from that site.

Running southeast from Barbados the edge of the Demerara Plateau is a boundary, shown by gravity and magnetic anomalies, which truncates the anomalies associated with the fracture zones. Models of the early opening history of the Atlantic, particularly that of Klitgord and Schouten (1982), suggest that the crust south of this boundary is Jurassic or Early Cretaceous, formed before the South Atlantic began to open. One would expect the age of this crust to decrease from SE to NW, because the western edge of the Demerara Plateau was on the eastern Atlantic margin before the South Atlantic opened.

THE FOREARC

The region east of the Lesser Antilles island arc is occupied by a large and complicated accretionary complex with a markedly deformed eastern margin, first noted by Chase and Bunce (1969), and some large forearc basins. The distance between the arc and the front of the complex ranges from 450 km in the south near Tobago, to 150 km in the north, off Antigua. There is no bathymetric trench in front of the complex south of 17°N.

The position of the subduction trace (Fig. 1), where igneous ocean crust passes beneath the crystalline crust of the Caribbean, is shown by the axis of the negative Bouguer gravity anomaly, the increase in intensity of seismicity, and the truncation of magnetic anomalies from the ocean crust.

Modelling of the crustal structure from gravity and seismic refraction data shows that the thickness of the accretionary complex increases to greater than 20 km beneath Barbados. The greatest part of the accretionary complex overlies the Atlantic ocean crust, but part overlies the Caribbean crust where it is bounded on its western boundary by a large forearc basin—the Tobago Trough and its northern extension (Fig. 1). The western boundary of the complex is tectonic, and the eastern part of the forearc basin has been deformed and thereby incorporated into the accretionary complex.

The strong negative isostatic gravity anomaly over the subduction trace shows that the complex is held down dynamically out of equilibrium by the subduction process. There is a positive anomaly 150 km seaward of the subduction trace (Westbrook, 1975); this anomaly corresponds to the outer trench rise of most island arcs (Watts and Talwani, 1974) and is buried beneath the accretionary complex south of 15°N.

PROVINCES OF THE ACCRETIONARY COMPLEX

The major part of the accretionary complex, which lies between 11°N and 15°N, can be divided laterally into four main zones (Fig. 1).

1. Initial Accretion

This zone forms the eastern margin of the complex, where it slopes markedly down to the ocean floor. It is generally about 50 km wide, although its width increases in the south. In this zone most of the sediments of the ocean floor undergo initial deformation and become transferred from the Atlantic ocean floor to the accretionary complex. The style of this initial deformation varies along the complex (see back pocket Plate 1A–C), and falls broadly into three main types that can be seen on seismic reflection sections:

Broad, asymmetrical, eastward-verging folds with westward-dipping listric thrusts running up into the synclinal troughs (Fig. 7C) comprise the first type; this style of deformation is characteristic of the southern part of the complex where the sediment thickness is great, and is also locally developed at 14°30′N where thick sediment fills a basement trough. Bathymetric ridges and troughs are formed over the anticlines and synclines, and mapping of these features using SEABEAM (Biju-Duval et al., 1982) and GLORIA (Stride et al., 1982) has shown that they have very great continuity along strike, generally exceeding 50 km.

Westward-dipping reflectors typify the middle part of the province, and are developed where the sediment is moderately thick (2 or 3 km). Whether or not some of the dipping reflectors represent thrusts is not always easy to determine, but most appear to be westward tilted strata from the ocean-floor sequence (Fig. 7B). This style of deformation was the first to be identified with accretion by successive thrusting of the ocean-floor sediments along décollement surfaces (Westbrook et al., 1973).

A seismically irresolvable deformation occurs north of 15°N, and is the style seen at the Leg 78A drill sites. Diffraction hyperbolas are often all that can be seen within the deformed material, and the surface of the zone is also very rough. A striking aspect of this region, between Tiburon Rise and Barracuda Ridge, is the contrast between the deformed material and the undeformed sequence of ocean-floor sediments that pass beneath it for several tens of kilometers (Fig. 7A). This underthrusting of undeformed sediment occurs elsewhere in the complex and is discussed later. North of the Barracuda Ridge the intrasediment décollement is often poorly developed or absent, but is sometimes well developed (Fig. 8). As the drilling results show, on a small scale the sediments in this zone of deformation are not strongly deformed. To have any significant continuity on a seismic section a reflector must be easily traced over ten or more traces. Typical trace spacing on multichannel seismic sections is 50 m, so it would appear that planar structures in this zone lack significant continuity on a scale greater than 0.5 km. In this regard, it should also be borne in mind that the rough seabed will reduce the apparent continuity of reflectors beneath it. If the topography is directly related to deformation, as it can be shown to be elsewhere, then the scale of the topography is also a measure of the size of deformational structure. The wavelength of the topography as seen on seismic profiles and by GLORIA (Belderson et al., this volume) is typically between 0.5 and 1.0 km.

Although it is probable that more accretion may take place farther beneath the accretionary complex, it is in the zone of initial accretion that the rate of accretion and shortening in the sedimentary cover appear to be greatest. Where the sediment entering the complex is thick, horizons in the undeformed sequence are progressively truncated with increasing depth and increasing distance of underthrusting beneath the toe of the complex. The rate of change of thickness of the complex with distance from the leading edge is greatest in the zone of initial accretion, and it is likely that most of the dewatering and compaction of the accreted sediment takes place when it is in this zone.

2. Stabilization

This zone lies behind that of initial accretion, and although it has no clear boundary, it is taken to commence at the break of the initial slope. The bathymetric topography is undulatory, rises only gently to the west, and in some areas actually slopes back down toward the west. The rate of increase in thickness of the complex over this zone is small, and it would appear that through this zone the material in the complex undergoes only slight further deformation.

In the south, the open folds of the zone of initial accretion have passed into westward-dipping reflectors before the zone of stabilization is reached. A few westward-dipping reflectors are all that can be resolved on seismic sections through this zone, which mostly show only incoherent reflections. The surface of this zone is covered with modest thicknesses of slope sediments that show generally mild deformation, with some locally intense deformation.

It would appear that in the zone a state of equilibrium is being approached between the shear stresses applied at the base of the complex, on the one hand, which tend to increase the angle of slope and drive the complex backward, and the gravitational body forces, which tend to reduce the angle of slope and drive the complex forward, and the strength of the sediments to resist the stresses in the complex on the other. Consequently, strain rates in this zone probably are far lower than in the zone of initial accretion.

3. Supracomplex Basins

Extending from 11°30′N to 15°N is a wide zone occupied by sedimentary basins, the largest of which is the Barbados Trough. These basins are filled with up to 2 km of generally undeformed sediment (Mascle et al., in press; Biju-Duval et al., 1982). Deformation is confined to widely spaced fault zones. On the eastern margin of Barbados Trough, these faults downthrow to the west (Fig. 9), but the true nature of the faults is undetermined. In the region between 14°N and 15°N the basins appear to have undergone some recent broad movement, such that a sequence of undeformed sediment over 1 km thick is now uplifted on a ridge between two basins that contain little sediment younger than the uplifted sequence.

Apart from the cover of sediment and evidence of even less deformation, there is probably no essential difference between this zone and that of stabilization, although there is evidence of westward vergence in structures affecting the sediment cover.

4. Barbados Ridge Uplift

Running between Tobago and Barbados is the Barbados Ridge (*sensu stricto*), which extends north of Barbados as far as 15°, where it is truncated by the Dominica Transverse Valley (Peter and Westbrook, 1976). The principal fact concerning the Ridge is that is has been uplifted considerably, by as much as 3 km with respect to the Tobago Trough. This fact is shown most clearly by the uplift and folding of sedimentary horizons in the Tobago Trough forearc basin (Fig. 10A). Along most of the ridge this uplift appears to be currently active, but on the flank of the most southwesterly part of the Ridge, this uplift feature is covered by recent sedimentation that shows no disturbance (Fig. 10B). Undeformed sediment covers the Ridge south of Barbados, but north of Barbados the cover of undeformed sediment is not continuous, and deformed sediment crops out at the surface in many places.

It is not clear from the available reflection profiles whether the deformed material in the ridge corresponds to the Eocene Scotland Formation of Barbados or the Eocene–Miocene Oceanic Formation (Saunders, 1979). It is probable that both formations are present, because although the Oceanic Formation is by no means as strongly deformed as the Scotland Formation, it is probably sufficiently disturbed (Speed, 1981; Speed and Larue, 1982) to lack significant continuity on a seismic section.

THE FOREARC BASIN

A major forearc basin, the Tobago Trough, occupies the region between the arc and the accretionary complex. The crystalline basement dips eastward beneath the whole of the basin (Fig. 2), so it is clear that the eastern margin of the basin has been formed dynamically by the accretionary complex. The basin can be traced northward to Guadeloupe and southward beneath the continental shelf almost as far as Margarita (Feo-Codecido, 1977). Bathymetrically, the forearc basin is interrupted east of St. Lucia by the St. Lucia–Barbados Transverse Ridge. Although there is a spur of basement beneath this Ridge, it is not of sufficient size to be the principal cause of the Ridge, and the forearc basin sequence passes through into the region called the Lesser Antilles Trench. The thickness of sediments decreased northward and the basin becomes increasingly more asymmetric as the relief of the Barbados Ridge decreases.

As discussed earlier, the eastern margin of the basin is formed dynamically by the creation and uplift of the accretionary complex. Horizons in the basin are uplifted and deformed on the eastern flank of the basin into a series of westward-verging folds, and lower horizons passing into the complex lose their coherence (Fig. 10A). For most of its length the basin is being encroached upon by the accretionary complex. At its southernmost end, however, this process is reversed, and the sedimentary horizons overstep the western margin of the accretionary complex near Tobago (Fig. 10B). It is possible that there has been an alternation of sequences of uplift and deformation of the margin followed by overstep and burial of the deformed sediments, but is seems that in this particular case the southeastern margin of the trough has been protected since the beginning of the Pliocene by a spur of metamorphic basement rock, of which the island of Tobago is a part.

THE SUBCOMPLEX DÉCOLLEMENT

One of the most striking features seen on seismic reflection sections across the eastern margin of the accretionary complex, and especially those east of Guadaloupe, is a strong reflector passing beneath the seismically incoherent material forming the accretionary complex and overlying undisturbed reflectors between it and the oceanic basement (Peter and Westbrook, 1976; Biju-Duval et al., 1978; Westbrook et al., 1982; Westbrook and Smith, 1983). This reflector has been interpreted as representing a décollement surface between the accretionary complex and an underlying sequence of ocean-floor sediments; the principal objective of Leg 78A was to drill through the décollement and into the underlying undeformed sediment.

A multichannel line run by Durham University 70 km to the north of the 78A drill sites (Fig. 7A, and back pocket Plate 1A) demonstrates that the décollement can be followed uninterruptedly 45 km from the leading

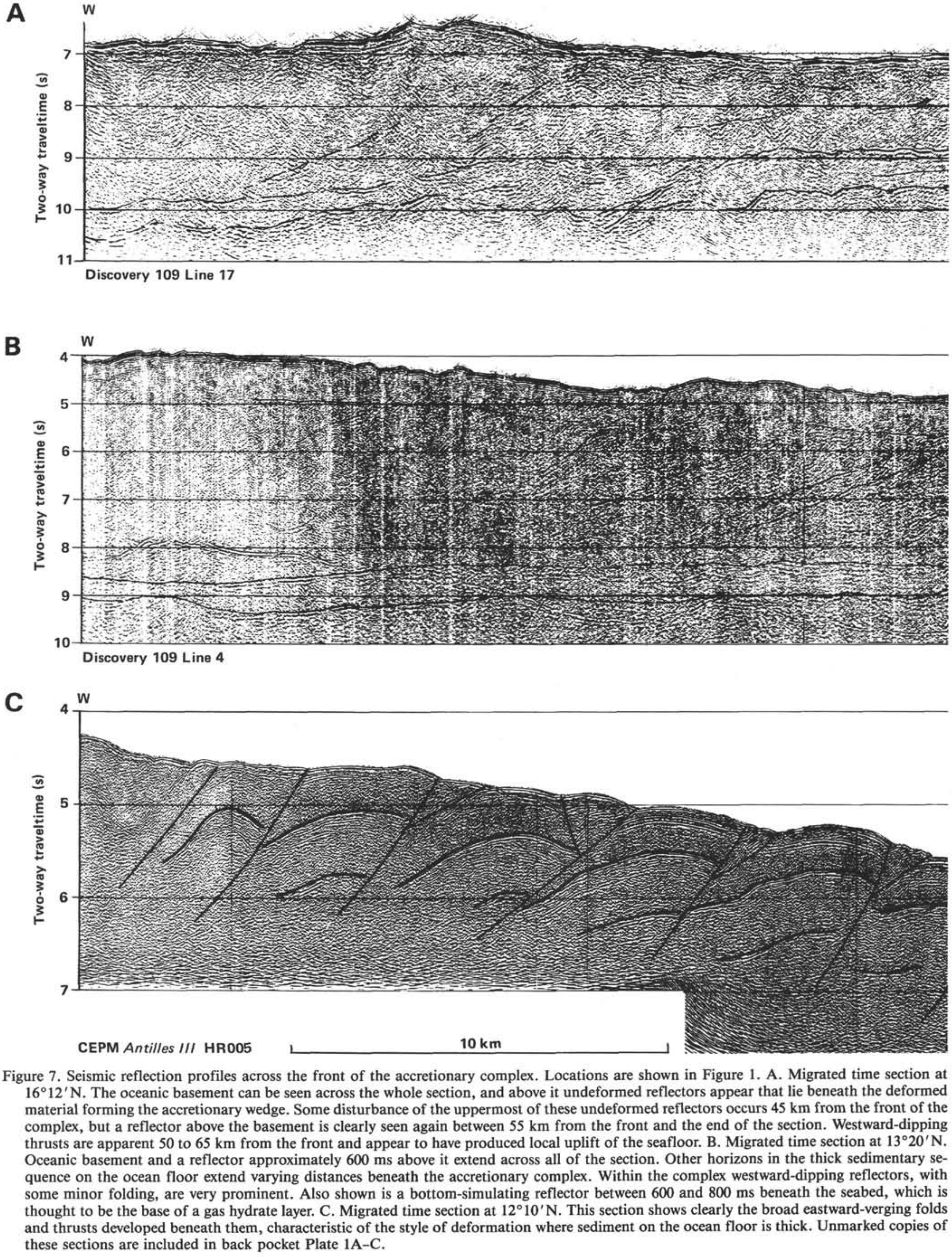

Figure 7. Seismic reflection profiles across the front of the accretionary complex. Locations are shown in Figure 1. A. Migrated time section at 16°12′N. The oceanic basement can be seen across the whole section, and above it undeformed reflectors appear that lie beneath the deformed material forming the accretionary wedge. Some disturbance of the uppermost of these undeformed reflectors occurs 45 km from the front of the complex, but a reflector above the basement is clearly seen again between 55 km from the front and the end of the section. Westward-dipping thrusts are apparent 50 to 65 km from the front and appear to have produced local uplift of the seafloor. B. Migrated time section at 13°20′N. Oceanic basement and a reflector approximately 600 ms above it extend across all of the section. Other horizons in the thick sedimentary sequence on the ocean floor extend varying distances beneath the accretionary complex. Within the complex westward-dipping reflectors, with some minor folding, are very prominent. Also shown is a bottom-simulating reflector between 600 and 800 ms beneath the seabed, which is thought to be the base of a gas hydrate layer. C. Migrated time section at 12°10′N. This section shows clearly the broad eastward-verging folds and thrusts developed beneath them, characteristic of the style of deformation where sediment on the ocean floor is thick. Unmarked copies of these sections are included in back pocket Plate 1A–C.

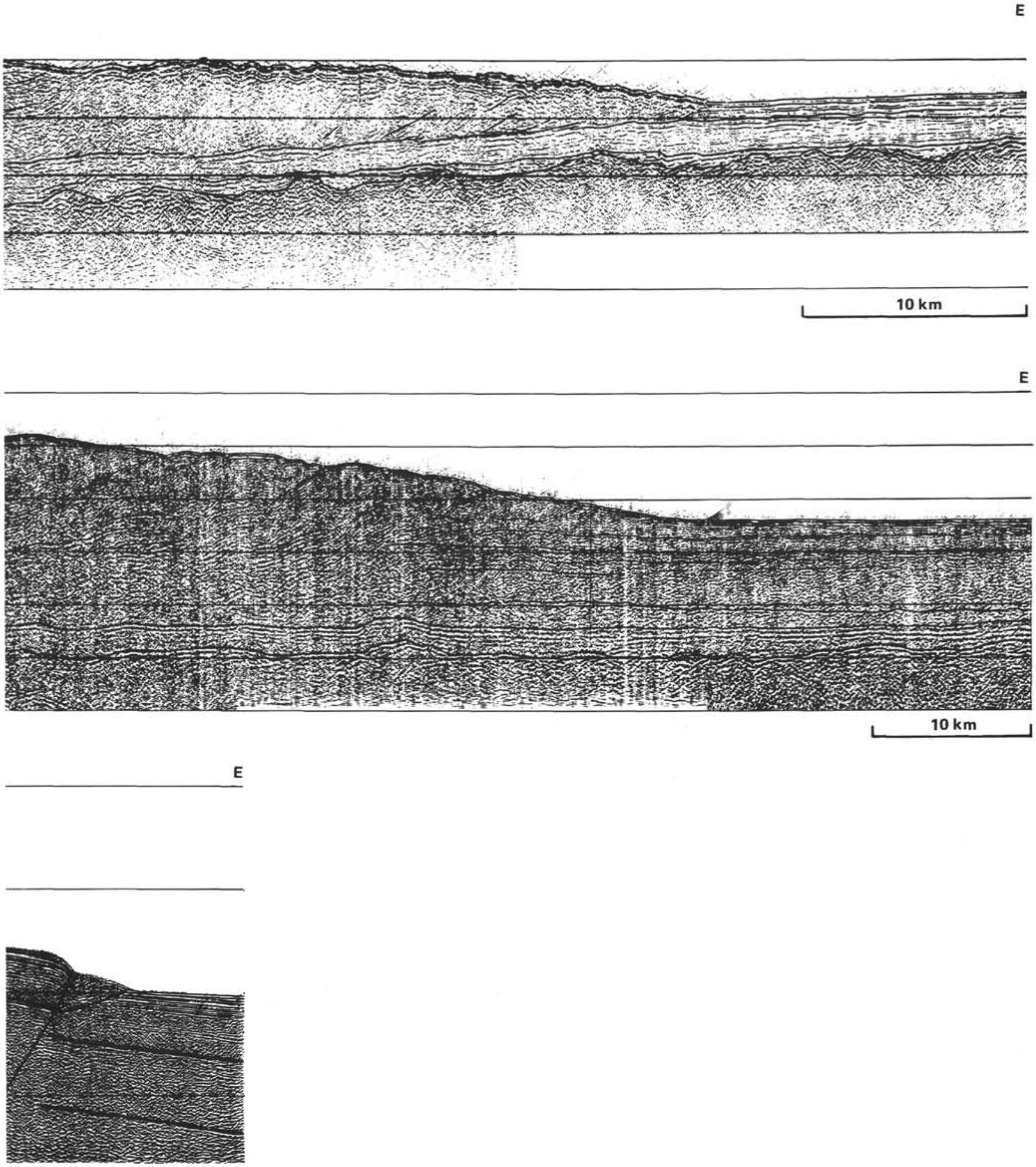

Figure 7. (Continued).

edge of the complex. Also, although there is some intervening disruption, the oceanic basement and an overlying reflector, which is presumably the décollement, can be traced farther from 55 to 74 km from the edge of the complex, where the section ends.

A synthesis of multichannel seismic reflection data from the area, carried out for J.O.I. as part of the Ocean Margin Drilling Project, has shown that the décollement is widespread beneath the frontal part of the accretionary complex. The extent to which it has been mapped is shown in Figure 5. The development of the décollement farther south, where the sediment is thicker, is somewhat different from that in the vicinity of the Leg 78A sites. In the north, the sediment lying above

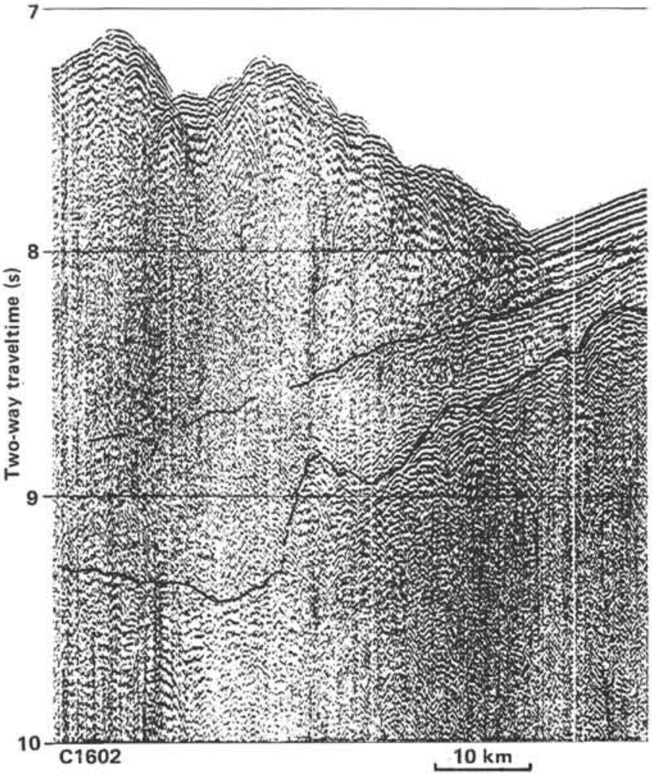

Figure 8. Single-channel reflection record at 18°N from *Conrad* Cruise 1602. A sequence of sediment on the ocean floor 500 ms thick is brought into the complex where the top 150 ms is immediately stripped off. The next 150 ms penetrates 10 km before being disrupted. The bottom 200 ms or more, above an undulating basement surface, extends at least 35 km beneath the complex. Location is shown in Figure 1.

the reflector that becomes the décollement surface appears to become deformed very rapidly at the leading edge of the complex; this rapid deformation is probably a consequence of the thinness and weak properties of this sediment. In the south, the horizons in the undeformed sequence extend increasingly farther beneath the complex with increasing depth, until the final décollement surface is reached, between a 0.5 and 1 s two-way traveltime above the basement. The décollement then continues uninterruptedly a few tens of kilometers farther beneath the complex to a distance of over 80 km from the leading edge of the complex (Fig. 7B). The final thickness of undeformed sediment beneath the décollement appears to be only loosely dependent upon the total thickness of ocean-floor sediment.

The limit of the extent of the décollement shown in Figure 5 is essentially the limit of seismic reflection coverage or the limit of visibility of the feature on seismic sections, so the feature continues an unknown distance farther west than shown. The underthrusting of a sequence of sediment so far beneath the complex without disruption and at such a low angle indicates very low shear stresses along the décollement (Chapple, 1978; Park, 1981; Davis et al., 1983). This situation is only possible if very high pore fluid pressure exists within rocks in contact along the décollement.

DIAPIRISM

Mud diapirism has long been identified in Trinidad (Higgins and Saunders, 1974) and offshore to the east (Michelson, 1976). It is also possible that the *Joes River Formation* on Barbados represents a *mud diapir* (Poole and Barker, in press). In the southern part of the complex, in the sedimentary basins, and to some extent in the stabilization zone, diapirs have been identified on seismic sections and bathymetric maps (Mascle et al., in press; Biju-Duval et al., 1982; Fontas et al., this volume) and are seen to be more widespread on GLORIA sonographs (Stride et al., 1982). The total extent of the diapirism is not known, but diapirs have not been identified north of the latitude of the Tiburon Rise, where turbidites form only a small proportion of the ocean-floor sediments. The distribution of diapirs is not completely random; there is a concentration of them along some fault lines, particularly at the margins of the sedimentary basins. Recent mud extrusions have created cir-

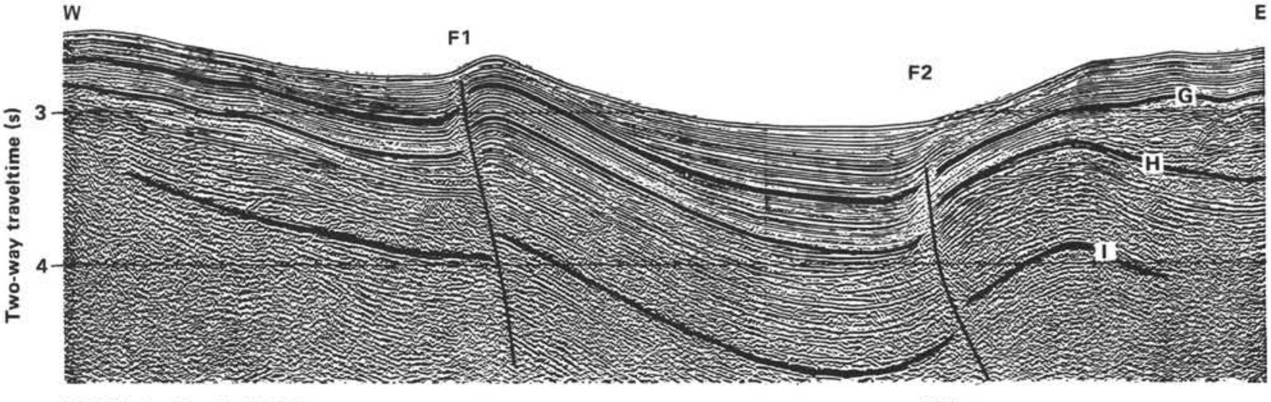

Figure 9. Seismic section from the central part of the accretionary complex in the transition from the zone of stabilization to the zone of supracomplex basins. A thick sequence of essentially undeformed sediment overlying the accreted rocks shows local disturbance along two prominent faults with some associated folding. Fault F1 appears to be no older than horizon G, and Fault F2 appears to be no older than horizon H. The age of the whole sequence is believed to be Neogene–Quaternary. Location is depicted in Figure 1.

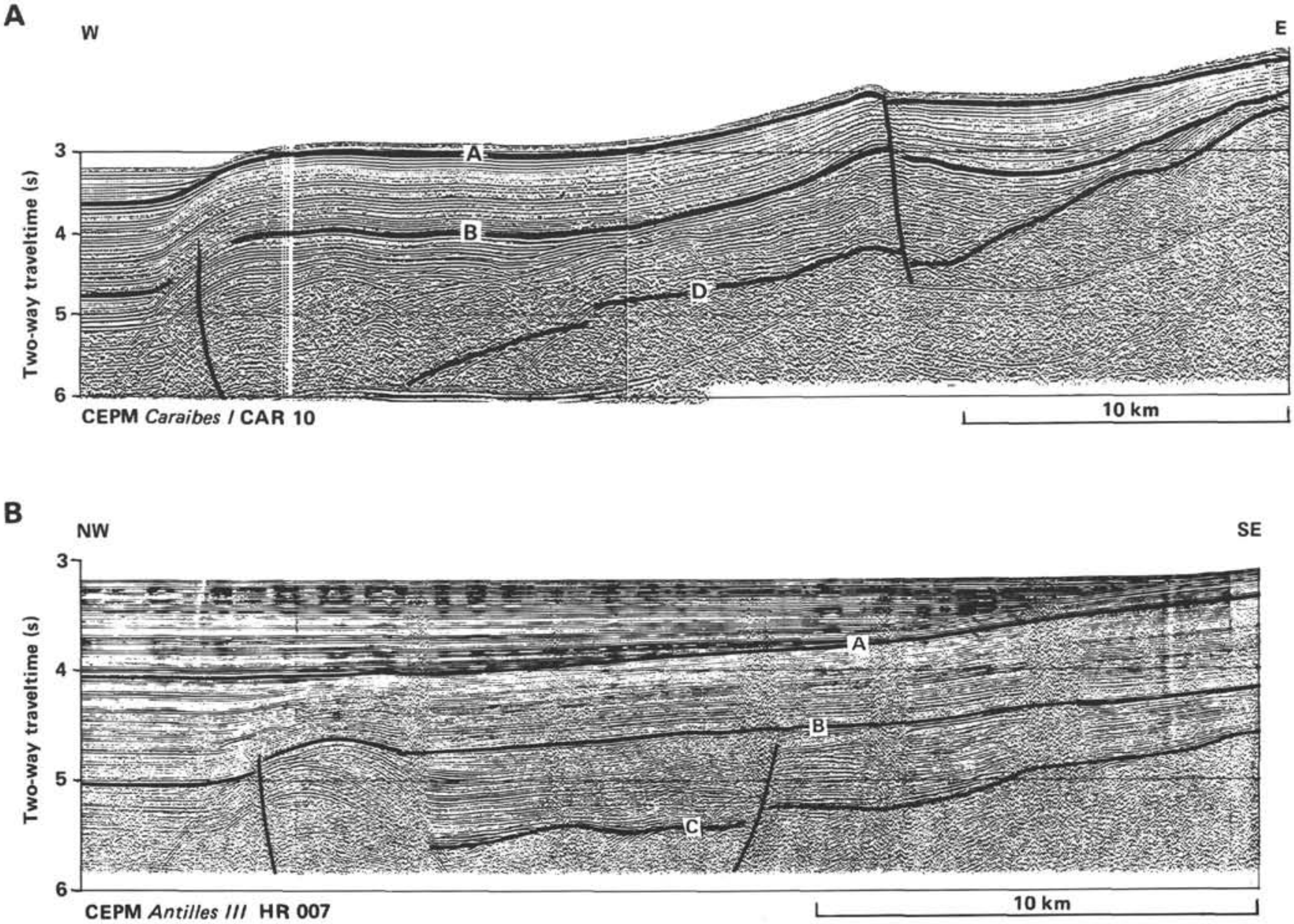

Figure 10. Seismic sections across the eastern margin of the Tobago Trough (western flank of the Barbados Ridge). Locations are shown in Figure 1. A. The section shows the youngest horizons flexed upward to the east over what is thought to be an eastward-dipping fault in the lower horizons. The sequence A to B is undeformed except for gentle flexure and faulting. The sequence B to D shows more disturbance from faulting and perhaps some folding. Beneath D the rocks appear to be significantly deformed. Horizon B is a lower Pliocene unconformity. B. This section from farther south in the Trough shows that horizons above A overstep the flexure–fault without any disturbance, although many of them pinch out against the slope of the Barbados Ridge farther east, showing that some uplift of the Ridge continued without significant movement on the fault.

cular hills on the seafloor, and seismic reflector geometry suggests older extrusions now covered by recent deposits (Fig. 11). The age of the source beds of the incompetent extruded clays is unknown. In Trinidad to the south, such uncompacted clays are especially prevalent in the lower and middle Miocene (Higgins and Saunders, 1974).

Two mud diapirs have been identified east of the front of the accretionary complex, where their presence is attributed to raised pore water pressure in ocean-floor sediments arising from loading produced by the accretionary wedge (Westbrook and Smith, 1983).

VARIATIONS IN STRUCTURE ALONG THE FOREARC

The most obvious changes along the forearc are the decrease in width and elevation of the accretionary complex from south to north. This decrease is related principally to the northward decrease of the thickness of sediment on the ocean floor, but important local control is exerted by the ridges and troughs in the oceanic basement (Westbrook, 1982). Two pronounced changes in width occur at the Barracuda Ridge and the Tiburon Rise, and a smaller one occurs at 14°N where a buried ridge runs beneath the complex. Major changes in elevation along the complex also occur at these ridges, the steepest part of the slope lying over the along-strike continuation of the ridges beneath the complex.

The main way in which the ridges and troughs influence the accretionary complex is that, by damming and collecting turbidite sedimentation, they control the thickness of sediment on the ocean floor and hence the volume of sediment added to the complex. Also, they directly deform and pile up sediment in snowplow fashion as they move obliquely into the complex (Westbrook, 1982). This latter effect is most noticeable on the southwestern side of the Tiburon Rise.

The ridges can also directly uplift the accretionary complex above them, and it appears that this is the reason for the especially enhanced elevation of the island of Barbados, and the St. Lucia–Barbados Transverse Ridge, which lies above a prominent east-west trending

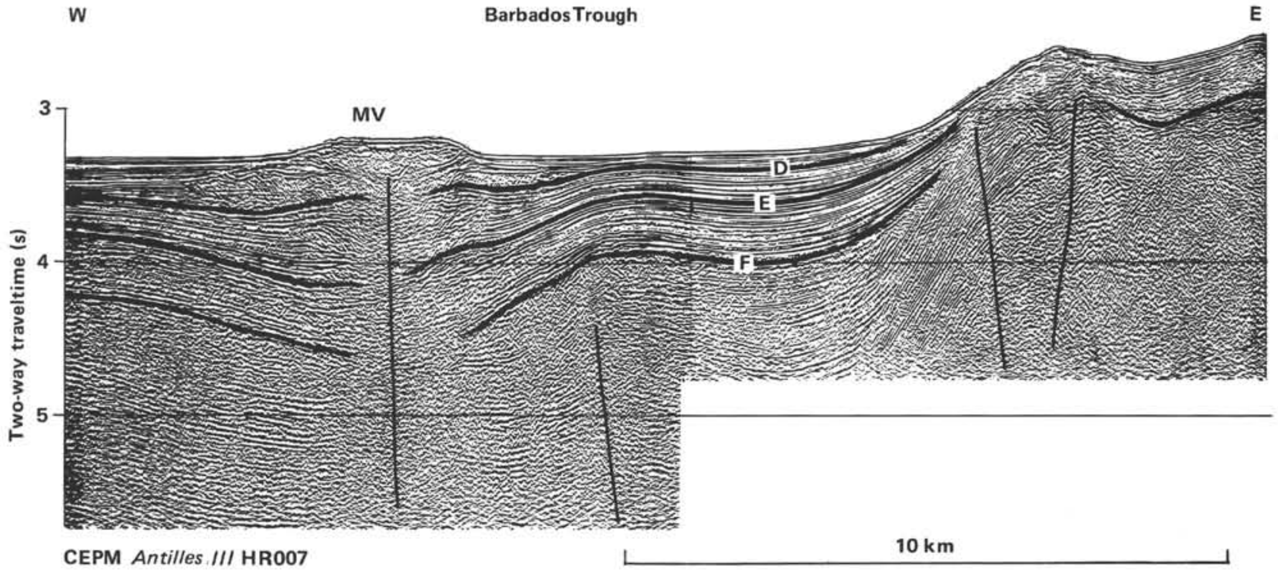

Figure 11. Migrated seismic section from the eastern side of the Barbados Trough, a supracomplex basin. Location is shown in Figure 1. Piercing the sedimentary sequence filling the trough, and forming a mound 2 km across and 80 m high on the seafloor, is a mud diapir (MV, mud volcano), which also has intruded laterally into sediments to some extent. Uplift of the margin of the Trough is clearly demonstrated by the thinning and upwarping of the sedimentary horizons D, E, and F.

gravity high that in the eastern part of the complex is known to be caused by a ridge in the oceanic basement, identified from seismic reflection profiles (Fig. 5).

The northward narrowing of the complex is accompanied by the absence of supracomplex sedimentary basins and the Barbados Ridge uplift north of the intersection of the arc with the Tiburon Rise. Also, the forearc basin is lost, except for a few isolated pockets north of Guadeloupe, but this is in part at least a result of a change in elevation, and perhaps structure, of the forearc basement.

North of the Barracuda Ridge, the amount of undeformed sediment underthrust beneath the accretionary complex becomes much less, and the deformation is increasingly incoherent and seismically opaque (Fig. 8).

There is a direct relationship between the spacing of thrusts and the thickness of the deformed layer above the décollement. The spacing of thrusts is about three times the thickness of the layer along the whole of the complex despite the great changes in the thickness of the thrust layer.

Another factor of possible importance in controlling the style of deformation in the accretionary complex, in addition to sediment thickness, is the ratio of terrigenous to pelagic sediment. It could be that thick and comparatively coarse-grained turbidites in the south have more rigidity, giving rise to broader open structures than the thinly bedded fine-grained pelagic sediments of the north, although it has been argued elsewhere (Moore, 1975) that, because of their greater organic content and greater age, the pelagic sediments are likely to be more lithified and stronger than recent turbidite fill in a trench. Perhaps an essential difference here from many circum-Pacific situations is that much of the sequence of sediments in the south is as old as or older than the pelagic sediments in the north, and as the turbidites are in a very thick sequence the deeper units will be far more consolidated and lithified than the "typical" fill of some circum-Pacific trenches, such as the Middle America Trench (Watkins, Moore, et al., 1982).

CONCLUSION

The accretionary complex of the Lesser Antilles shows a mature development in that it is wide, thick, complicated, and exhibits a great range of deformation styles. The variations in structure along it are in some respects of more interest than the variations across it, in that they show changes related to variation in sediment thickness and type uncomplicated by changes in rate and age of subduction, which are nearly constant along the arc.

Important controlling factors in the forearc's development are that the subduction is fairly old; the rate of subduction is comparatively low; there is a nearby source of terrigenous sediment to the south that has provided a gradient in sediment thickness and sediment type across the incoming Atlantic ocean floor and has also provided sediment fill in the southern supracomplex sedimentary basins and, to some extent, the Tobago Trough forearc basin (Keller, et al. 1972); the gradient in sediment thickness is modified by ridges and troughs in the oceanic basement, which also have some direct tectonic effect on the accretionary complex.

It cannot be assumed that the development of the complex has been a continuous process. The geology of Barbados (Saunders, 1979; Speed, 1981), and the geology of the complex as seen on seismic reflection profiles, provide evidence of considerable episodic development. The great thickness of sediment on the ocean floor may only have been encountered by the arc late in its history, when it had migrated into the region of the mouth of some proto-Orinoco. There have probably also been changes in the rate and perhaps direction of subduction, such as that related to the inward shift of volcanism and the creation of the young inner arc in the north at the beginning of the Pliocene.

Finally, it is worth pointing out that although the major component of the Lesser Antilles forearc complex is accreted material transferred from the Atlantic ocean floor, an important proportion of the complex comes from sediments deposited directly upon or behind the complex in several different environments. These sediments may also be subsequently deformed in a variety of ways. The geology of Barbados bears witness to the diversity of material forming the complex with lithologies from various paleoenvironments and different tectonic histories (Saunders, 1979; Poole and Barker, in press; Speed, 1981; Pudsey and Reading, 1982; Speed and Larue, 1982; Speed, 1983).

ACKNOWLEDGMENTS

Figure 7 seismic profiles were acquired from the *Discovery* through the support of the Natural Environment Research Council (research grant GR3/3551). Compilation of some of the geological and geophysical data used in this paper was supported by a research contract from J.O.I., Inc.

REFERENCES

Andreieff, P., Bizon, G., and Bouysse, P., 1981. Revision de l'âge des formations sédimentaires de l'île de St. Martin: implication sur la chronologie du volcanisme de l'arc insulaire des Petites Antilles. *C.R. Acad. Sci. Ser. II*, 79–82.

Biju-Duval, B., Le Quellec, P., Mascle, A., Renard, V., and Valery, P., 1982. Multibeam bathymetric survey and high resolution seismic investigations on the Barbados Ridge Complex (Eastern Caribbean): a key to the knowledge and interpretation of an accretionary wedge. *Tectonophysics*, 80:275–304.

Biju-Duval, B., Mascle, A., Montadert, L., and Wannesson, J., 1978. Seismic investigations in the Colombia, Venezuela and Grenada basins, and on the Barbados Ridge for future IPOD drilling. *Geol. Mijnbouw*, 57:105–116.

Boynton, C. H., Westbrook, G. K., Bott, M. H. P., and Long, R. E., 1979. A seismic refraction investigation of crustal structure beneath the Lesser Antilles Island Arc. *Geophys. J. R., Astron. Soc.*, 58: 371–393.

Bowin, C. O., 1972. Puerto Rico trench negative gravity anomaly belt. *In* Shagam, R., Hargraves, R., Morgan, W., et al. (Eds.), *Studies in Earth and Space Sciences*, Geol. Soc. Am. Mem., 132:339–350.

________, 1976. Caribbean gravity field and Plate tectonic. *Geol. Soc. Am., Spec. Pap.*, 169:1–79.

Briden, J. C., Rex, D. C., Faller, A. M., and Tomblin, J. F., 1979. K-Ar geochronology and palaeomagnetism of volcanic rocks in the Lesser Antilles Island Arc. *Phil. Trans. R. Soc. London*, 291(1383): 485–528.

Bunce, E. T., Phillips, J. D., Chase, R. L., and Bowin, C. O., 1970. The Lesser Antilles Arc and the Eastern Margin of the Caribbean Sea. *In* Maxwell, A. E. (Ed.), *The Sea* (Vol. 4, Pt. 2): New York (Wiley-Interscience), 359–385.

Case, J. E., 1975. Geophysical studies in the Caribbean Sea *In* Nairn, A., and Stehli, F. (Eds.), *The Ocean Basins and Margins, The Gulf of Mexico and the Caribbean* (Vol. 3): New York (Plenum Press), 107–180.

Chapple, W. M., 1978. Mechanics of thin-skinned fold-and-thrust belts. *Geol. Soc. Am. Bull.*, 89:1189–1198.

Chase, R. L., and Bunce, E. T., 1969. Underthrusting of the eastern margin of the Antilles by the floor of the western North Atlantic Ocean, and origin of the Barbados Ridge. *J. Geophys. Res.*, 74: 1414–1420.

Collette, B. J., Schouten, H., Rutten, K., and Slootweg, A. P., 1974. Structure of the Mid-Atlantic Ridge province between 12° and 18°N. *Mar. Geophys. Res.*, 2:143–179.

Davis, D., Suppe, J., and Dahlen, F. A., 1983. Mechanics of fold-and-thrust belts and accretionary wedges. *J. Geophys. Res.*, 88:1153–1172.

Dorel, J., 1979. Seismicité et structure de l'Arc des Petites Antilles et du bassin atlantique [Ph.D. dissert.]. Université Pierre et Marie Curie, Paris.

Edgar, N. T., Ewing, J. I., and Hennion, J., 1971. Seismic refraction and reflection in Caribbean Sea. *Bull. Am. Assoc. Pet. Geol.*, 55: 833–870.

Ewing, M., Carpenter, G., Windisch, C., and Ewing, J., 1973. Sediment distribution in the oceans: the Atlantic. *Geol. Soc. Am. Bull.*, 84:71–88.

Ewing, J. I., Officer, C. B., Johnson, H. R., and Edwards, R. S., 1957. Geophysical investigations in the Eastern Caribbean: Trinidad Shelf, Tobago Trough, Barbados Ridge, Atlantic Ocean. *Geol. Soc. Am. Bull.*, 68:897–912.

Ewing, M., and Worzel, J. L., 1954. Gravity anomalies and the structure of the West Indies, Pt. 1. *Geol. Soc. Am. Bull.*, 65:165–174.

Feo-Codecido, G., 1977. Un esbozo geologico de la plataforma continental Margarita-Tobago (a geological outline of the Margarite-Tobago continental shelf). *Bol. Geol.* (*Venezuela*), 3:1923–1946.

Field, R. M., Brown, T. T., Townsend, T., Collins, B., and Hess, H. H., 1933. *The Navy-Princeton Gravity Expedition to the West Indies.* U.S. Hydrog. Office.

Fox, P. J., Schreiber, E., and Heezen, B. C., 1971. The geology of the Caribbean crust: tertiary sediments, granitic and basic rocks from the Aves Ridge. *Tectonophysics*, 12:89–109.

Girard, D., and Maury, R., 1980. Affinité choleïtique d'arc insulaire des spilites de l'île de Tobago (Petites Antilles). *C.R. Acad. Sci. Ser. D.*, 935–938.

Gutenberg, B., and Richter, C. F., 1954. *Seismicity of the Earth* (2nd ed.): Princeton, New Jersey (Princeton University Press).

Higgins, G. E., and Saunders, J. B., 1974. Mud volcanoes, their nature and origin. *Contributions to the Geology and Paleobiology of the Caribbean and Adjacent Areas*, Verhandlungen der Naturforschenden Gesellschaft in Basel, 84:101–152.

Jordan, T. H., 1975. The present-day motion of the Caribbean Plate. *J. Geophys. Res.*, 80:4433–4439.

Kearey, P., Peter, G., and Westbrook, G. K., 1975. Geophysics maps of the eastern Caribbean. *J. Geol. Soc. London*, 131:311–321.

Keller, G. H., Lambert, D. N., Bennet, R. H, and Rucker, J. B., 1972. Mass physical properties of Tobago Trough sediments. *Trans. VI Caribbean Geol. Conf.*, Margarita, Venezuela, pp. 405–408.

Klitgord, K. D., and Schouten, H., 1982. Early Mesozoic Atlantic reconstruction from sea-floor-spreading data. *E.O.S.*, 63(18):307.

Lewis, J., and Robinson, E., 1976. A revised stratigraphy and geological history of the Lesser Antilles. *Trans. VII Conférence Géologique des Caraïbes*, St. Francois, Guadeloupe, pp. 339–344.

Lowrie, W., and Alvarez, W., 1981. One hundred million years of geomagnetic polarity history. *Geology*, 9:392–397.

MacDonald, K., and Holcombe, T., 1978. Inversion of magnetic anomalies and seafloor spreading in the Cayman Trough. *Earth Planet. Sci. Lett.*, 40:407–414.

Marlow, M. S., Garrison, L. E., Martin, R. G., Trumbull, J. U. A., and Cooper, A. K., 1974. Tectonic transition in the north eastern Caribbean. *J. Res. U.S. Geol. Surv.*, 2:289–302.

Martin-Kaye, P. H. A., 1969. A summary of the geology of the Lesser Antilles. *Overseas Geol. Miner. Resour.*, 10:172–206.

Mascle, A., Lajat, D., and Nelly, G., in press. Sediment deformation linked to subduction and to argilokinesis in the southern Barbados Ridge from multichannel seismic surveys. *Trans. 4th Latin American Geol. Congr.*

Michelson, J. E., 1976. Miocene deltaic oil habitat, Trinidad. *Bull. Am. Assoc. Pet. Geol.*, 60:1502–1519.

Minster, J. B., and Jordan, T. H., 1978. Present-day plate motions. *J. Geophys. Res.*, 83:5331–5354.

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

Moore, J. C., 1975. Selective subduction. *Geology*, 3:530–532.

Moyes, J., Gayet, J., Poutiers, J., Pulol, C., and Pujos-Lany, A., 1978. Orgon II, étude stratigraphique et sédimentologique. In *Geochimie organique des sédiments marins profonds, Orgon II, Atlantique—Nord-Est Brésil.* (Edition du CNRS), pp. 105–106.

Nagle, F., 1972. Rocks from seamounts and escarpments of the Aves Ridge. In *Trans. VI Caribbean Geol. Conf.*, Margarita, Venezuela, pp. 409–413.

Nagle, F., Stipp, J. J., and Fisher, D. E., 1976. K-Ar geochronology of the Limestone Caribbean and Martinique, Lesser Antilles, West Indies. *Earth Planet. Sci. Lett*, 29:401–412.

Ngokwey, K., 1983. *Application de la méthode des éléments finis à la connaissance des contraintes et déformations au front d'une marge active* [thèse du Docteur Ingenieur]. Institut Français du Pétrole, Rueil Malmaison, France.

Officer, C. B., Ewing, J. I., Hennion, J. F., Harkrider, D. G., and Miller, D. E., 1959. Geophysical investigation in the Eastern Caribbean: summary of 1955 and 1956 cruises. *In* Ahrens, L. H., Press, F., Rankama, K., et al. (Eds.), *Physics and Chemistry of the Earth* (Vol. 3): New York (Pergamon Press), 17–109.

Park, M. J. M., 1981. *Numerical analysis of deformation in the upper part of subduction zones* [Ph.D. dissert.] University of Durham, Durham, England.

Pérez, O. J., and Aggrawal, Y. P., 1981. Present-day tectonics of the southeastern Caribbean and northwestern Venezuela. *J. Geophys. Res.*, 86:10791–10804.

Peter, G., and Westbrook, G. K., 1976. Tectonics of southwestern north Atlantic and Barbados Ridge Complex. *Bull. Am. Assoc. Pet. Geol.*, 60:1078–1106.

Poole, C. J., and Barker, L., in press. The Geology of the Scotland district, Barbados. *9th Caribbean Geol. Conf.*, Santo Domingo, Dominican Republic.

Pudsey, C. J., and Reading, H. G., 1982. Sedimentology and structure of the Scotland Group, Barbados. *In* Leggett, J. K. (Ed), *Trench and Forearc Geology: Sedimentation and Tectonics in Ancient and Modern Active Plate Margins*. Spec. Publ. Geol. Soc. London, 10: 291–308.

Robson, G. R., 1958. Seismological and volcanological work in the eastern Caribbean, 1952–1955, abstract and map. *1st Caribbean Geol. Conf.*, Antigua, 1955.

Saunders, J. B., 1979. Field Trip 1, Barbados. *4th Latin American Geol. Congr.* Field Guide, pp. 71–88.

Speed, R. C., 1981. Geology of Barbados: implication for an accretionary origin. International Geological Congress, Paris, *Oceanol. Acta* (Supple. to Vol. 4), pp. 259–265.

________, 1983. Structure of the accretionary complex of Barbados, I. Chalky Mount. *Geol. Soc. Am. Bull.*, 94:92–115.

Speed, R. C., Biju-Duval, B., Ladd, J. W., Mascle, A., Moore, J. C., Saunders, J. B., Schoonmaker, J. E., Stein, S., and Westbrook, G. K., in press. *Atlas of Geology and Geophysics of the Lesser Antilles and Surrounding Terrains* (J. Thompson and Co.).

Speed, R. C., and Larue, D. K., 1982. Barbados: architecture and implications for accretion. *J. Geophys. Res.*, 87:3633–3643.

Stein, S., Engeln, J. F., Wiens, D. A., Speed, R. C., and Fujita, K., 1982. Subduction seismicity and tectonics in the Lesser Antilles Arc. *J. Geophys. Res.*, 87:8642–8664.

Stride, A. H., Belderson, R. H., and Kenyon, N. H., 1982. Structural grain, mud volcanoes and other features on the Barbados Ridge Complex revealed by GLORIA long range side-scan sonar. *Mar. Geol.*, 49:187–196.

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

Sykes, R., McCann, W. R., and Kafka, A. L., 1982. Motion of Caribbean plate during last 7 million years and implications for earlier Cenozoic movements. *J. Geophys. Res.*, 87:10656–10676.

Tomblin, J. F., 1975. The Lesser Antilles and Aves Ridge, *In* Nairn, A., and Stehli, F. (Eds.), *The Ocean Basins and Margins, The Gulf of Mexico and the Caribbean.* (Vol. 3): New York (Plenum Press), 467–500.

Watkins, J. S., Moore, J. C., et al., 1982. *Init. Repts. DSDP*, 66: Washington (U.S. Govt. Printing Office).

Watts, A. B., and Talwani, M., 1974. Gravity anomalies seaward of deep-sea trenches and their tectonic implications. *Geophys. J. R. Astron. Soc.*, 36:57–90.

Westbrook, G. K., 1975. The structure of the crust and upper mantle in the region of Barbados and the Lesser Antilles. *Geophys. J. R. Astron. Soc.*, 43:210–242.

________, 1982. The Barbados Ridge Complex: tectonics of a mature forearc system. *In* Leggett, J. K. (Ed.), *Trench and Forearc Geology: Sedimentation and Tectonics in Ancient and Modern Active Plate Margins.* Spec. Publ. Geol. Soc. London, 10:275–290.

Westbrook, G. K., Bott, M. H. P., and Peacock, J. H., 1973. The Lesser Antilles subduction zone in the region of Barbados. *Nature Phys. Sci.*, 244:18–20.

Westbrook, G. K., and Ladd, J. W., in press. Seismic refraction. *In* Speed, R. C., Biju-Duval, B., Ladd, J. W., et al., *Atlas of Geology and Geophysics of the Lesser Antilles Arc System and Surrounding Terrains* (J. Thompson and Co.)

Westbrook, G. K., Mauffret, A., Munschy, M., Jackson, R., Biju-Duval, B., Mascle, A., and Ladd, J. W., in press. Seismic reflection maps. *In* Speed, R. C., Biju-Duval, B., Ladd, J. W., et al., *Atlas of Geology and Geophysics of the Lesser Antilles Arc System and Surrounding Terrains* (J. Thompson and Co.)

Westbrook, G. K., and Smith, M. J., 1983. Long décollements and mud volcanoes: evidence from the Barbados Ridge Complex for the role of high pore-fluid pressure in the development of an accretionary complex. *Geology*, 11:279–283.

Westbrook, G. K., Smith, M. J., Peacock, J. H., and Poulter, M. J., 1982. Extensive underthrusting of undeformed sediment beneath the accretionary complex of the Lesser Antilles subduction zone. *Nature*, 300:625–628.

Westercamp, D., in press. Carte Géologique de l'île de St. Barthélémy. BRGM, Orléans, France.

Westercamp, D., and Tazieff, A., 1980. *Guides Géologiques Régionaux, Martinique, Guadeloupe, St. Martin, La Desirade:* Paris (Masson Ed.).

Date of Initial Receipt: August 18, 1982
Date of Acceptance: September 20, 1983