The Barbados Ridge Complex: tectonics of a mature forearc system

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SUMMARY: The Barbados Ridge Complex is the wide accretionary sediment pile associated with the Lesser Antilles island arc. Its width is so great (>200 km) that a trench no longer exists on the oceanward side of it. This development is a product of the age of the system (>50 Ma) and the thickness of sediment on the ocean floor (0.8 km in the north, >4 km in the south). The northward decrease in elevation of the sediment pile and the variation in the style of initial deformation at the leading edge of the pile are related to the northward change in sediment thickness and type. The region in which deformation is prevalent has a westward limit just west of the axis of the minimum negative Bouguer gravity anomaly. In the south the axis of this minimum is coincident with the Barbados Ridge (an outer 'sedimentary arc'). The deformed rocks of the accretionary pile are overlain by later sediments, which show varying degrees of deformation, and often occupy small basins.

In the northern part of the complex, the relief and structure of the accretionary pile are complicated by ridges and troughs running east-west across the general trend of structures. These appear to be related to variations in the relief of the subducted oceanic basement.

The Barbados Ridge Complex is a region with complicated bathymetry lying along the eastern margin of the Lesser Antilles Island arc in the eastern Caribbean (Fig. 1). It takes its name from the northerly trending Barbados Ridge which lies 150 km east of the arc. The island of Barbados is its most elevated part. The complex generally deepens towards the east, and most bathymetric features have a northerly trend, except between latitudes 13°30′N and 15°30′N where easterly trending ridges and troughs occur. The complex becomes broader and more elevated towards the south (Fig. 2).

The considerable quantity of geophysical information obtained in the region shows that the complex is composed of sedimentary rocks above a linear depression in the igneous basement (Fig. 3). The axis of this depression, which reaches a depth of 20 km beneath Barbados, lies up to 50 km west of the eastern limit of seismicity associated with the subduction zone beneath the Lesser Antilles, and is where the crystalline crust of the Atlantic Plate passes beneath the crystalline crust of the Caribbean Plate. The axis is strongly out of isostatic equilibrium, being depressed beneath its equilibrium position. The eastern part of the complex is above its equilibrium position and corresponds to the outer trench rise of most island arcs which do not have such a broad sediment complex. The existence of metamorphosed sediments beneath the Barbados Ridge (7–10 km beneath Barbados) is indicated by seismic velocities of around 5.0 km sec^{-1} and magnetic anomalies (Westbrook 1975). Another possible contributory cause of the magnetic anomalies in the vicinity of Barbados may be diagenetic magnetite formed in sediments from reduction of hydrated ferric oxides by petroleum microseepage (Donovan *et al.* 1980); hydrocarbons are found in Barbados.

The overall thickness of the complex increases towards the south, and broadly reflects a similar southward thickening of undeformed sediment on the Atlantic ocean floor. Along the eastern margin of the complex, the sediments of the Atlantic ocean floor are progressively deformed as they pass into the complex, eventually losing any structure that can be recognized from those seismic reflection sections that are currently available. The deformed sediment is overlain by more recent sediment which thickens towards the west, and is absent in the easternmost part of the complex. North of 14°N this overlying layer shows gentle deformation. South of 14°N, the Tobago Trough, a well-developed basin containing a thickness of at least 3 km of undeformed sediment, lies between the Barbados Ridge and the volcanic island arc. Similar, but smaller, basins lie to the east of the Barbados Ridge. On the island of Barbados, strongly folded and faulted Eocene flysch (the Scotland Group) is overlain by pelagic sediments of upper Eocene to Miocene age (Saunders 1979). Pleistocene to recent coral rock covers most of the island. The trend of deformational structures on Barbados is generally NE.

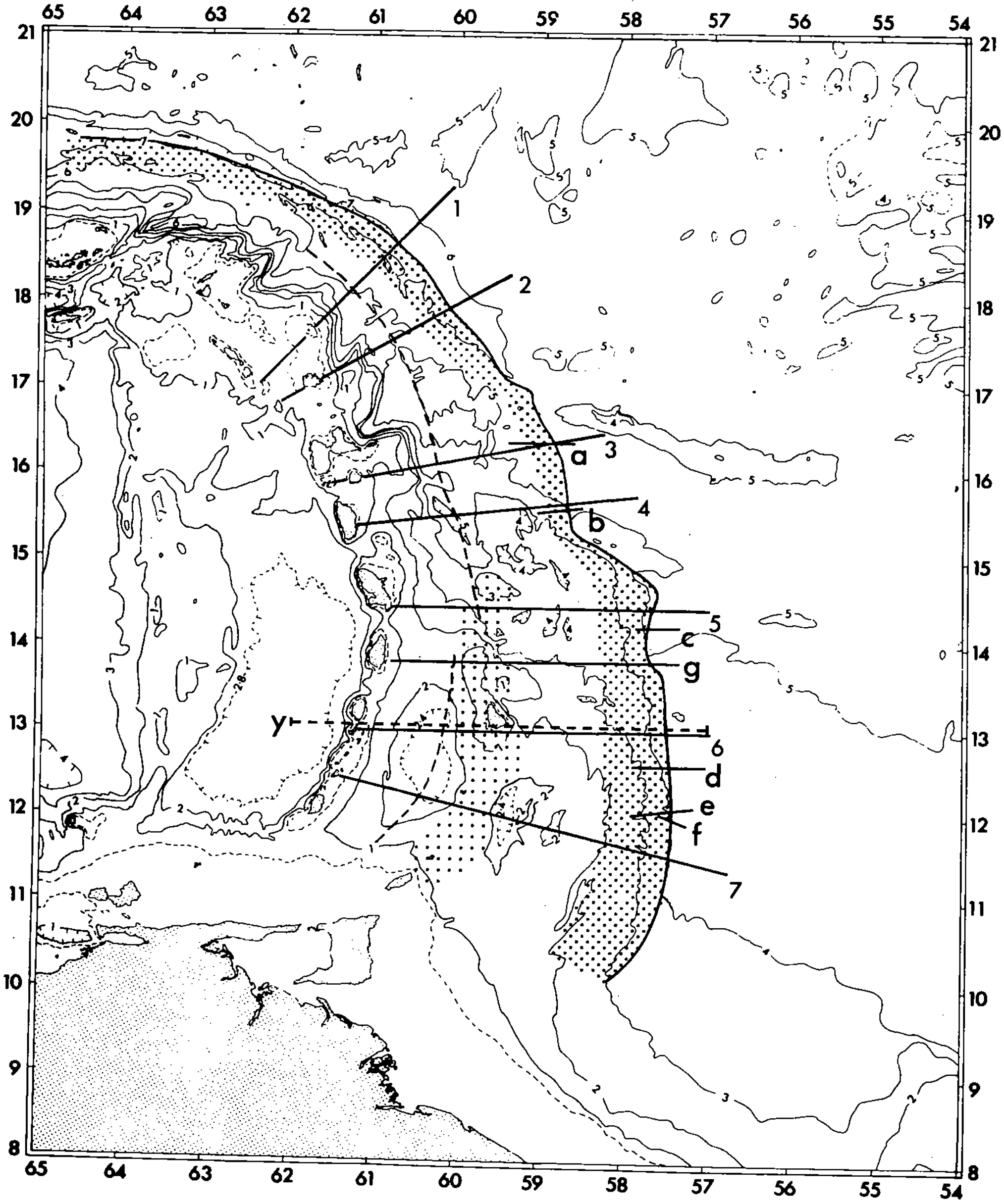
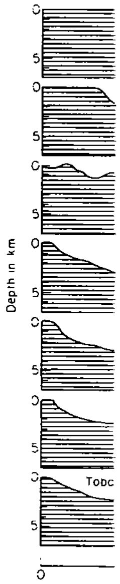


Fig. 1. Eastern Caribbean showing: bathymetry from U.S.G.S. Geologic-Tectonic Map of the Caribbean Open File 75–146, & Kearey *et al.* (1975) (isobaths at 1 km intervals); lines of profiles 1–7 of Fig. 2; the eastern limit of the Barbados Ridge Complex (solid black line); the region of the initial slope of the complex (close stipple); the western limit of deformation (dashed line); the Barbados Ridge (open stipple); the line of section for Fig. 3 (y); the lines of the seismic reflection sections of Fig. 5 (g) and Fig. 6 (a,b,c,d,e,f).



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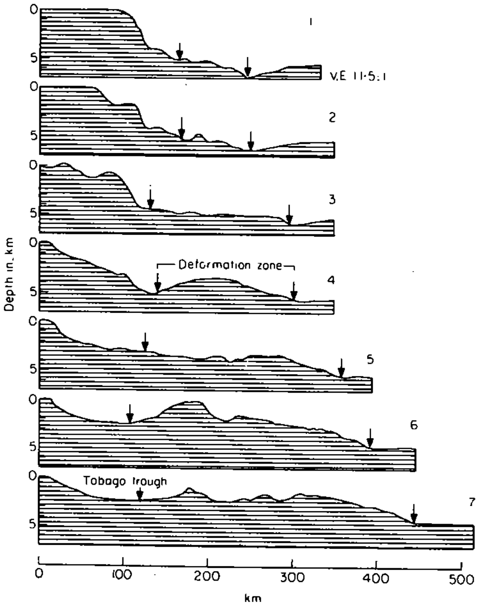

FIG. 2. Bathymetric profiles across the Barbados Ridge Complex showing the variation in its width and shape. The left edge of each profile ends at the active volcanic island arc. The arrows mark the limits of the region in which deformation can be seen on seismic reflection sections. The positions of the profiles are shown on Fig. 1.

Eastern margin

Between 17°30′N and 12°N the distance of the eastern edge of the complex from the Lesser Antilles increases from 200 to 450 km. Similarly the distance between the axis of the Bouguer gravity anomaly minimum (lying over the line of subduction of the Atlantic crystalline crust) beneath the Caribbean crystalline crust) and the eastern edge increases from 95 to 265 km. The increase in width of the complex is gradual, except at 15°N where the edge runs WNW for about 90 km because of the influence of a ridge in the oceanic basement. South of this change in strike of the edge of the complex, the margin is typically in the form of a slope rising from the Atlantic ocean floor by about 1.5 km in 50 km then flattening off or becoming less steep. North of the change in strike, the slope is more gentle, 0.5 km in 50 km, until the Puerto Rico Trench is reached, where it becomes steeper again (Fig. 2).

The deformation of the sedimentary horizons of the Atlantic ocean floor at the eastern margin of the Barbados Ridge Complex was first reported by Chase & Bunce (1969), who drew an analogy with the sandbox experiment of Hubbert (1951) to explain the mechanism of thrusting and folding. Westbrook *et al.* (1973) subsequently suggested that the deformation was brought about by successive thrusts emanating from a master décollement close to the sediment/basement interface accompanied by shearing parallel to bedding planes, and producing a reverse stratigraphy of thrust slices in the complex which is characteristic of models published for other forearc regions (Seely *et al.* 1974; Karig & Sharman 1975). This was incorporated later into an evolutionary model for the whole of the complex by Westbrook (1975).

The style of deformation varies considerably along the eastern margin (Peter & Westbrook 1976; Mascle *et al.* 1977; Biju-Duval *et al.* 1978). In the south it takes the form of gently asymmetric east-facing folds (amplitude 0.5 km; wavelength 8 or 9 km) riding on thrusts dipping westward at 20° which probably have a listric form at depth, presumably becoming parallel to the basement as they run into a major décollement (Fig. 6d,e,f). North of 15°30′N the deformation of sediment is so intense and/or chaotic that no structure can be recognized in it from seismic reflection sections. This deformed material, however, overlies undeformed bedded sediment on a plane of discontinuity (probably a décollement) which lies at shallow depth within the undeformed sedimentary section (Fig. 6a,b). A much smaller part of the ocean sediments is involved in the initial deformation (a layer 0.2 km thick as opposed to 1.5–2 km in the south). The plane of discontinuity extends at least 30 km beneath the deformed sediment, and how it does so without being deformed does pose some problems (Peter & Westbrook 1976; Mascle *et al.* 1977). If the deformed material was essentially a submarine slide formed by the gravitational collapse of the frontal slope of the complex it would explain the lack of disruption beneath the discontinuity and the gentler gradient of the frontal slope in the region where this discontinuity exists. However, reflection profiles run by Lamont-Doherty (Ewing *et al.* 1974) and NOAA (Peter & Westbrook 1976 and unpublished data) show that this discontinuity exists over such a wide area (between 15°30′N and 16°40′N) that a submarine slide, although possible, is an unlikely explanation. Given that the plane of discontinuity is likely to be a décollement, then the presence of a particularly weak horizon above the décollement, probably with a more competent (more lithified) sequence of sediments lying beneath it, is re-

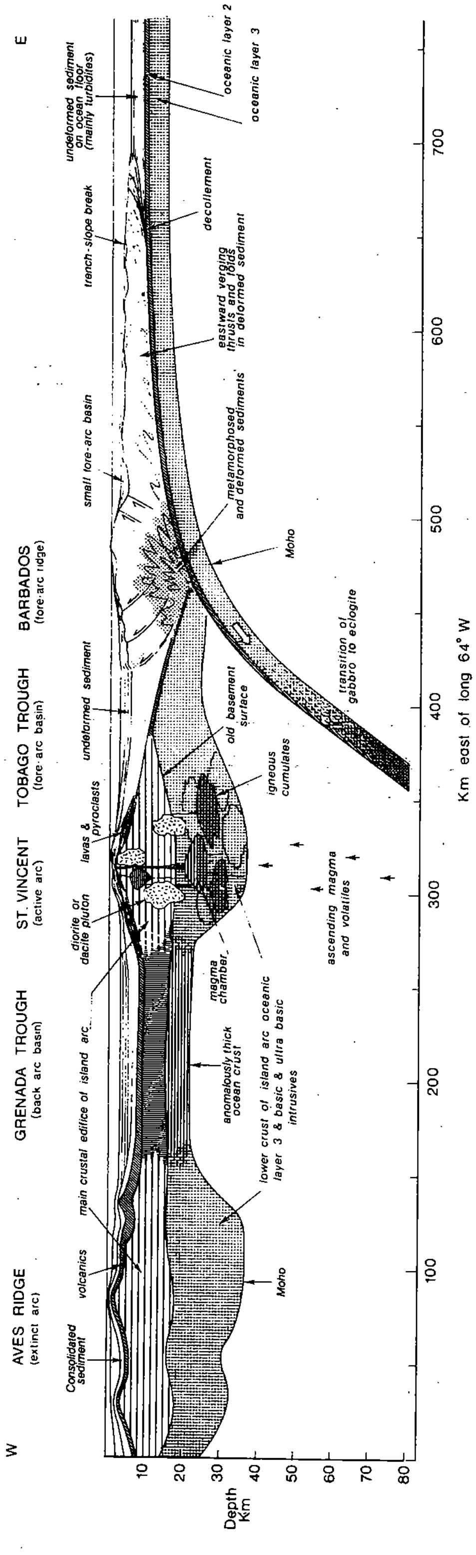

Fig. 3. Interpretative cross-section of the Lesser Antilles and the Barbados Ridge Complex; from Westbrook (1975) and Boynton *et al.* (1979). Position of section is shown in Fig. 1 (line y).

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There is a general correlation between the thickness of sediment on the Atlantic Ocean floor and style of deformation. The thinner the sediment the more intense is the deformation, because the stresses are distributed in a smaller volume of material. This feature of the Barbados Ridge Complex has been used by Moore (1979) in developing a model for deformation in forearc sediments, but thickness is not the only factor. Lithological variation also plays a part, as discussed above for the region north of 15°30′N where the development of a décollement high in the sedimentary column results in only one-quarter of the sediment being involved in the deformation at the front of the sediment pile. The sediments in the north are further from continental sources than those in the south (Bunce *et al.* 1971; Peter & Westbrook 1976) and likely to have a higher clay content. Consequently they may deform in a far less competent fashion, especially if pore water is trapped in them, causing them to become overpresssured.

Western margin

The sediments of the forearc region wedge out against the Lesser Antilles island arc. Up to 120 km from the active arc the sediments are completely undeformed except for some occasional slumping. South of 14°N this zone of undeformed sediments exists in the Tobago Trough which can be followed round to the south-west passing beneath the Venezuelan continental margin as far as the island of Margarita (Feo-Codecido 1977). The thickness of undeformed sediment exceeds 6 km to the east of Grenada. North of 14° the undeformed sediment does not occupy a bathymetric basin except opposite Dominica where the so-called Lesser Antilles Trench lies at the foot of the slope down from the arc. Much of the sediment comes from the island arc, but a proportion of clay and silt size material comes from the Amazon and Orinoco (Keller *et al.* 1972). The sediments become deformed as they pass eastward into the Barbados Ridge Complex. The limit of deformation lies just to the west of the axis of the negative Bouguer gravity anomaly (Fig. 4). In the east of the Tobago Trough the deformation has been accompanied by considerable uplift to form the Barbados Ridge. The deformation is in the form of gentle westward facing folds, although on the western flank of the Barbados Ridge there is the implication that they are the near surface expression of westward directed thrusts (Westbrook 1975; Mascle *et al.* 1981). Almost without exception, the youngest sedimentary horizons are affected by this deformation.

Southern margin

In the south the Barbados Ridge Complex abuts the continental margin of South America. Although much of it has been explored for petroleum, the structure of the region where the two provinces merge is not well known.

East of Trinidad, the deformed margin of the Barbados Ridge Complex passes into the undeformed passive margin of eastern South America. The area of transition is characterized by diapiric structures, which can be seen on reflection profiles (Lowrie & Escowitz 1969; Ewing *et al.* 1974; Mascle *et al.* 1981). Whether these result from salt as on parts of the African Margin or from overpressured shales, such as those producing mud volcanoes on Trinidad (Arnold & Macready 1956) is not known, but the latter seems more likely.

In the west, as mentioned above, the forearc basin beneath the Tobago Trough continues south-westward until it pinches out between the metamorphic rocks of the Venezuelan Coast Range and the south-westward extension of the volcanic arc.

In the region of Tobago there is a sharp drop in bathymetry from the continental shelf down to the Barbados Ridge and the continuity of structure from the Barbados Ridge into the shelf is very unclear, although some authors claim it exists (Weeks *et al.* 1971). Seismic refraction and reflection show that rocks with a high seismic velocity occur close to the surface at the southern end of the Barbados Ridge (Ewing *et al.* 1957; Edgar *et al.* 1971); these could be the Cretaceous metamorphic rocks that crop out on Tobago and Trinidad. These rocks deepen towards the north. The trend of structures in Trinidad suggest that even if there is no direct continuity of structures between the Barbados Ridge Complex and the South American margin, then they have been produced in a similar tectonic situation. There is no very obvious evidence for any significant transcurrent faulting along the northern margin of the present continental shelf.

Variation in structure along the Barbados Ridge Complex

The overall elevation of the complex decreases towards the north and the Barbados Ridge does

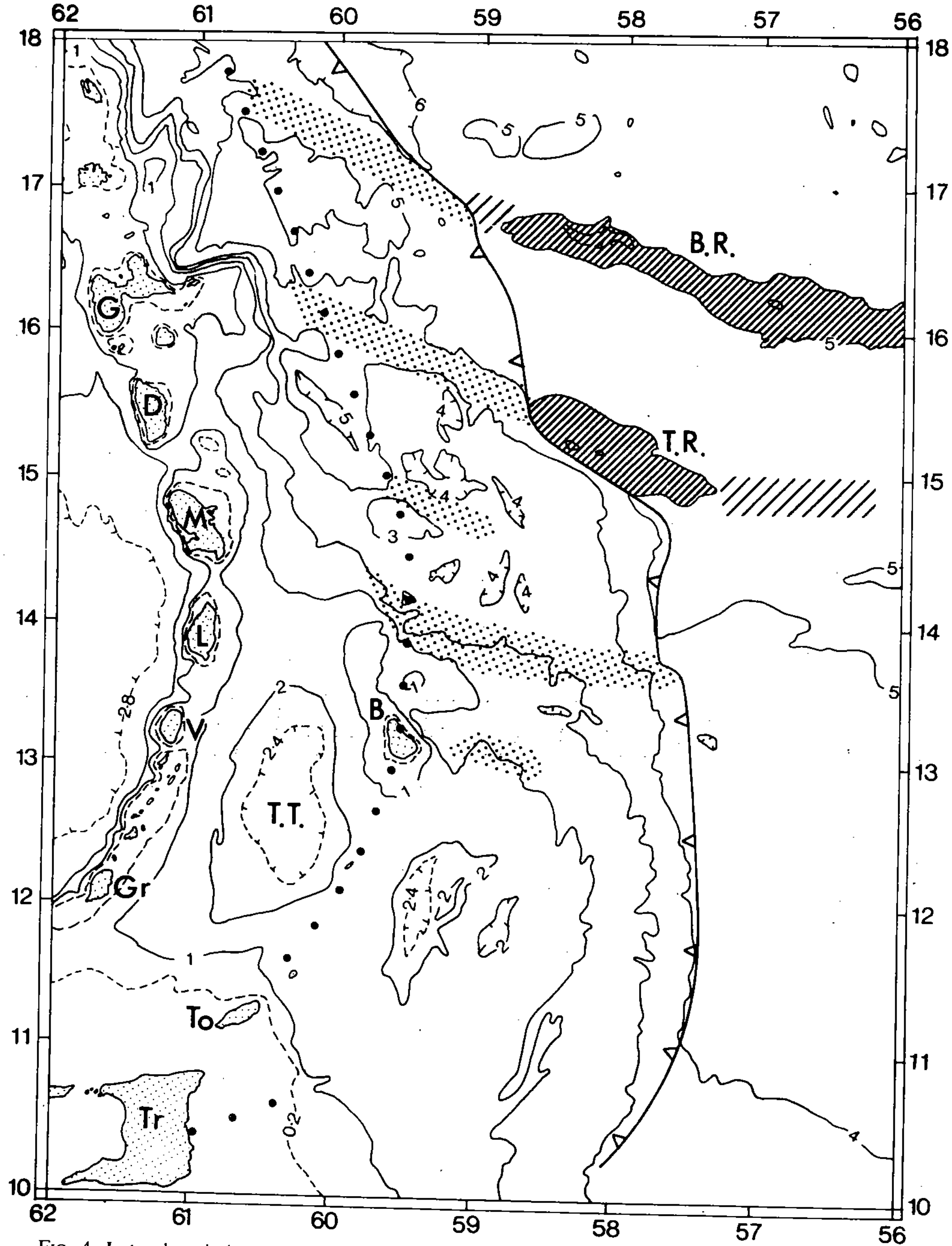

FIG. 4. Lateral variations in the Barbados Ridge Complex. Northward facing slopes ('steps') are stippled. Ridges in the oceanic basement are shown in close diagonal hatching where they form bathymetric features and in open hatching where they are known from seismic profiles to exist beneath the ocean floor. Hatching is not continued where the ridges extend beneath the Barbados Ridge Complex, as these areas are already stippled. The eastern margin of the complex is shown by the solid line with triangles on the overthrusting side. The large dots mark the axis of the negative Bouguer gravity anomaly. B.R.—Barracuda Ridge; T.R.—Tiburon Rise; G—Guadeloupe; D—Dominica; M—Martinique; L—St Lucia; B—Barbados; V—St Vincent; T.T.—Tobago Trough; Gr—Grenada; To—Tobago; Tr—Trinidad.

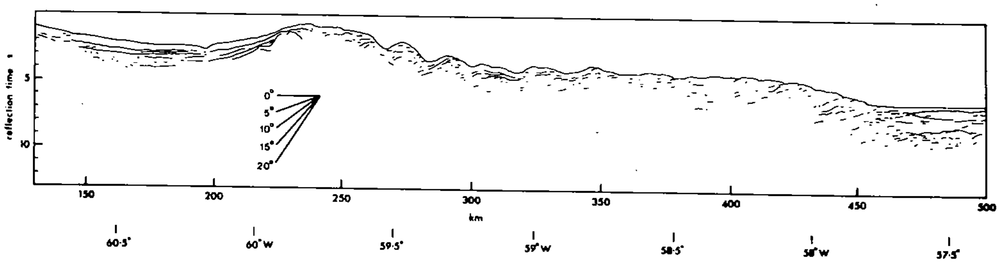

FIG. 5. Line drawing of seismic reflection section across the Barbados Ridge Complex (g in Fig. 1) from Westbrook (1975).

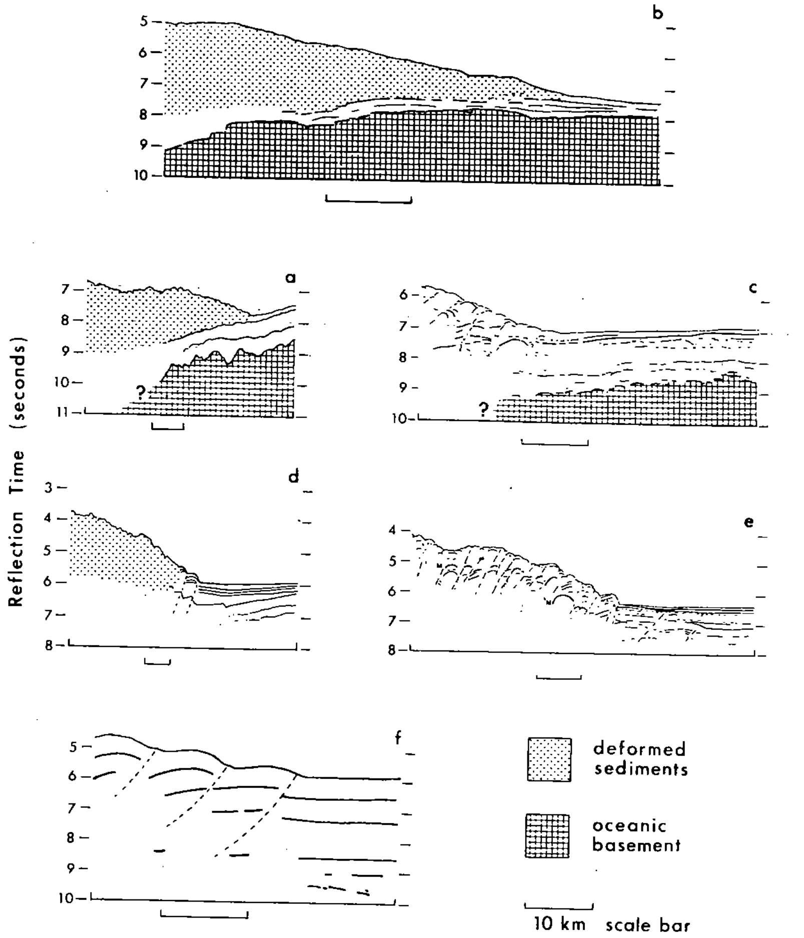

FIG. 6. Line drawings of seismic reflection sections across the eastern margin of the Barbados Ridge Complex. (a) and (d) from Peter & Westbrook (1976), (b) and (f) from Biju-Duval *et al.* (1978), (c) and (e) from Chase & Bunce (1969). The zones which are stippled on sections (a), (b) and (d) strongly reflect seismic energy, but the pattern of reflections lacks coherency. Pecked lines show the interpreted positions of thrusts.

not continue further north than 14°50′N (Fig. 2). This appears to be principally related to the northward decrease in thickness of the ocean floor sediments (>4 km at 12°N; 1 km at 16°N). This northward decrease in elevation is not uniform however (Fig. 4). South of 13°N the elevation of the complex is fairly uniform at around 2000 m, east of the Barbados Ridge, it then descends at 13°N and 13°50′N to 3500 m, the biggest drop coming at 13°50′N. It descends again at 15°50′N to around 5000 m and at 17°10′N to 5600 m. These 'steps' which all have a WNW trend are associated with ridges in the oceanic basement (Peter & Westbrook 1976). The northernmost of these is the Barracuda Ridge which extends at least 100 km beneath the complex (Schubert 1974), the next south is the Tiburon Rise at 15°20′N. Both these ridges have a parallel trend (WNW) and run beneath the 'steps' in the complex, which have the same trend. At 13°55′N the ridge is not expressed as a bathymetric feature on the seafloor east of the arc, but its presence is shown on seismic reflection profiles and by a linear positive gravity anomaly (Westbrook 1975).

The ridges can influence the complex in various way. (Fig. 7). They control the thickness of sediment on the ocean floor and consequently provide lateral control on the amount of accreted sediment in the complex. When the ridges first encounter the complex, their effect must be to uplift material above them.

After some time this initial effect will be reversed by the accretion of thicker sediment from the troughs flanking the ridges. With turbidite sediments coming from the south, sediment thickness south of each ridge will tend to be greater than to the north, and this would lead to a northward decrease in accreted sediment across each ridge.

Another important effect is produced by the difference between the trend of the ridge and the direction of convergence of the ridge with the complex. As the ridge moves obliquely into the complex the sediment will tend to be swept to one side by its 'plough' action. Earthquake first motions and the orientation of Caribbean plate boundaries indicate that the direction of convergence between the Caribbean and the Atlantic is easterly (Jordan 1975; Tomblin, pers. comm.). The trend of the ridges is 290°, which give a difference in angle of 20°. This produces a southward sweeping action which builds up material to the south of the ridge producing compressional structures semi-parallel to the ridge (Fig. 8). The cross-stress produced by the ridge comes from the reaction normal to its surface, which depends on the angle of slope of the ridge and the angle between the strike of the ridge and the direction of convergence.

A significant aspect of this process is that structures with a trend oblique to the main structural trend are produced without any change in the overall geotectonic setting. No north-south regional stresses are required other than the reaction to the stresses produced at the ridges. Between 13°50′N and 15°20′N the complex is dominated by WNW to west trending ridges and troughs superimposed upon the northerly trending features characteristic of the southern part of the complex. The northernmost ridge is that associated with the Tiburon Rise. The sediment in this ridge shows no clear reflecting horizons by comparison with the ridges and troughs south of it, implying recent deformation by the oblique convergence of the Tiburon rise (Peter & Westbrook 1976, line M). The ridge east of Martinique may also be associated with a basement ridge, but there is no clear geophysical evidence to support its existence, except that the NW flank of this ridge is the site of a positive gravity anomaly which locally modifies the form of the main negative gravity anomaly. The blanket of undeformed sediment which overlies the tectonized rocks of the complex in this region of cross-trends is displaced vertically by topography (Peter & Westbrook 1976). The troughs are not filled by more recent sediment and the displaced sediment layer shows no variations in thickness related to topography, implying fairly recent movement. By contrast, in the area south of 13°30′N, the blanket of overlying sediment is undisturbed and the troughs are sites of recent sedimentation.

The buried basement ridge at 13°55′N is probably responsible for the relatively high elevation of Barbados and the portion of the Barbados Ridge just north of it, compared with the southern part of the ridge. It is possible that it has been a significant feature since the late Eocene producing the southward dipping palaeoslope on which the Oceanic Formation of Barbados was deposited (Lohmann 1973).

Development of the Barbados Ridge Complex

The Barbados Ridge Complex is the widest example of an accretionary sediment pile associated with an island arc. This implies that some features of accretionary sediment piles, which may only be nascent in many arcs, should

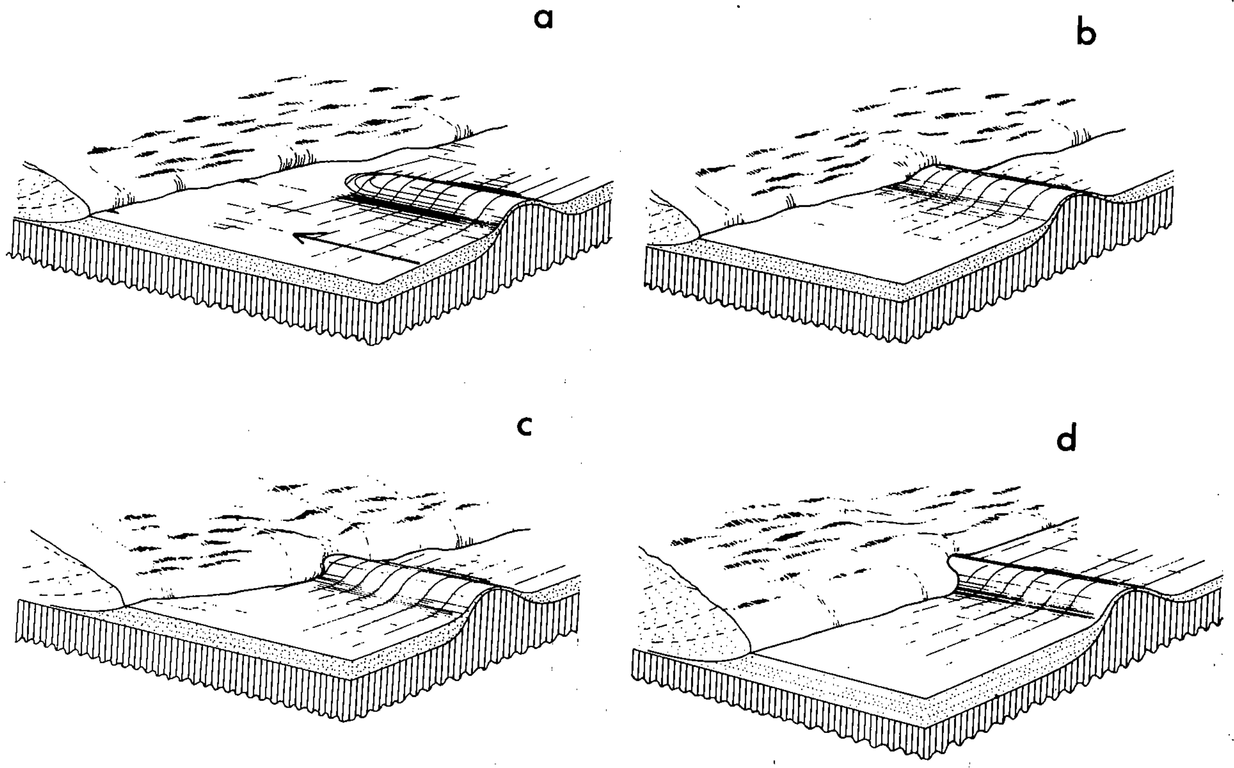

FIG. 7. The influence of a ridge in oceanic basement upon a forearc complex:
(a) Ridge approaching the edge of the forearc complex. The direction of convergence is the same as the strike of the ridge.
(b) After coming beneath the edge of the complex the ridge locally uplifts the part of the complex above its crest.
(c) After further subduction the effect of the relief of the ridge is outweighed by the greater contribution of sediment to the complex from either side of the ridge which builds the complex further out than over the ridge, where little sediment is added.
(d) If there is a greater thickness of sediment on one side of the ridge than the other, because of its acting as a barrier to turbidites, then one side of the complex will grow out further than the other, leading to a change in strike of the front across the ridge.

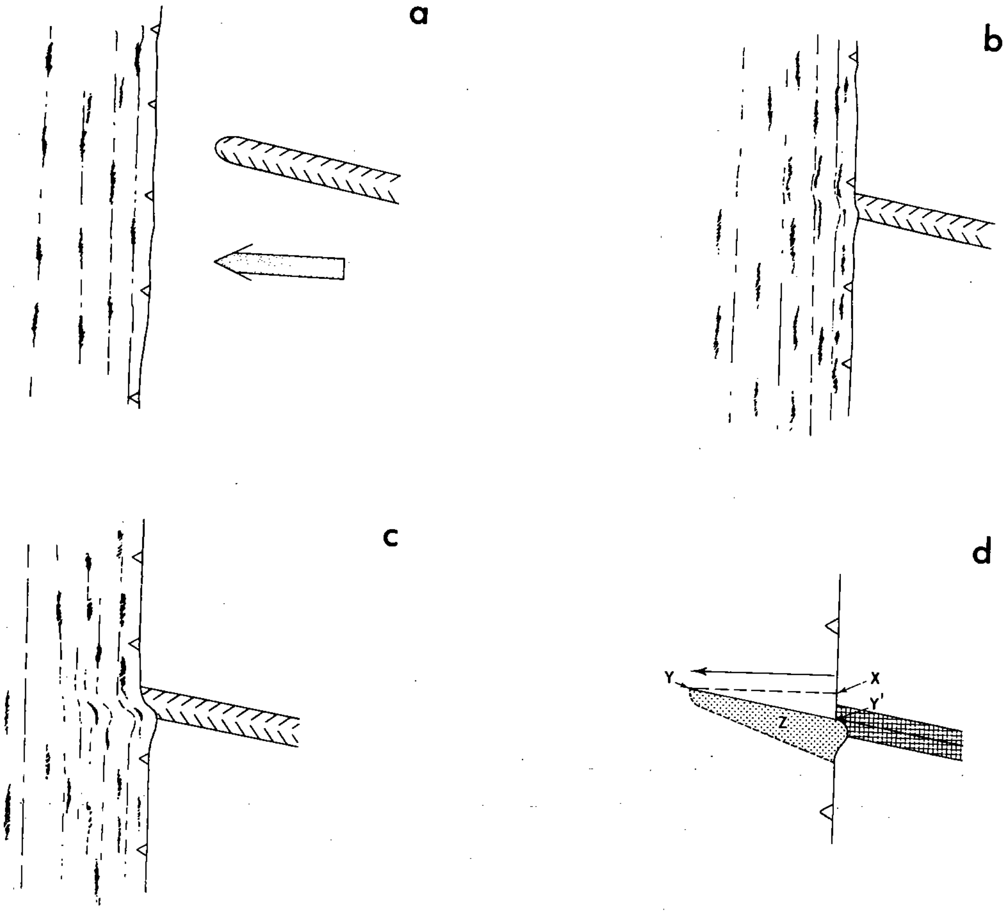

FIG. 8. The effect of a ridge in oceanic basement converging obliquely with a forearc complex:
(a) Ridge approaching the edge of the complex in a direction oblique to that of the strike of the ridge.
(b) Shortly after passing into the complex the ridge begins to distort the form of the leading edge as the point of entry of the ridge migrates along it.
(c) After further subduction, the southward sweeping action of the ridge has built up material on its southern side. There should also be some depletion on the northern side, but this would not produce such an obvious change in strike in the leading edge of the complex.
(d) Diagram showing the main elements of the situation. Y marks the end of the ridge. Y′ marks the point at which the crest of the ridge passes under the leading edge of the complex. This has migrated along the leading edge, from X, the point at which the ridge entered the complex. Z is the zone in which most of the compressional structures produced by the ridge exist.

be fully developed in the Barbados Ridge Complex. One of these is the trench-slope break, the break of slope at the top of the inner trench-wall which is very often the highest point of an accretionary sediment pile. The outer sedimentary ridges of arcs such as the Java-Sumatra, have also been described as the trench-slope break (Karig *et al.* 1980). The Barbados Ridge, however, is clearly not the equivalent of a trench-slope break, since it only exists in the southern part of the complex, and even in the region where it exists the topography and structure of the area between it and the front of the complex is so varied that it is conceptually difficult to identify the whole of it as the inner trench wall. The 'trench-slope break' of the Barbados Ridge complex lies 50–60 km west of its eastern edge (Figs 1 & 2). It is interpreted as representing the maximum elevation attained by material involved in the

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initial accretion process before gravitational forces nullify the upward movement of material caused by the horizontal convergence. The opposition of gravitational body forces to tectonically induced forces allows the complex to build forward rather than be pushed upward and backward. On a large scale the deformation of the pile can be considered as a viscous or plastic process and therefore the position of the trench slope break and the angle of the trench slope will be a function of gravitational body forces, tectonically induced stresses and the rheology of the rocks. This last is the most difficult to assess, because it varies with lithology, and the amount of deformation and metamorphism. Following from this, one can speculate that variations in the angle of the trench slope on the eastern margin of the complex are related to lithological variations in the material being accreted. Between the Tiburon Rise and the Barracuda Ridge where only the topmost sediment has been stripped away from the undeformed sedimentary column and intensely deformed, the angle of the trench slope is less steep than it is further south.

The Barbados Ridge has been formed by the uplift produced by the horizontal compressional forces in the complex. These arise principally from shear stresses applied to the base of the sediment pile by the subducting ocean crust which are opposed by the reaction of the island arc and consequently achieve a maximum value immediately above the line along which the ocean crust of the Atlantic is subducted beneath the crystalline crust of the Caribbean. A wide accretionary pile is subject to more horizontal compression than a narrow one, because shear stress has been applied over a greater surface area. Also, a purely frictional model for imparting the shear stress at the base of the accretionary complex is probably inadequate, as some shear stress will be transmitted by viscous shear through deforming sediment. This time-dependent element in the deformational process implies that an increase in subduction rate would increase the amount of compressional stress acting on the accretionary complex.

Comparison with other arcs

If the Barbados Ridge Complex is taken as a model, then which other forearc systems possess a sedimentary ridge that is a separate feature from the trench-slope break? Off Sumatra a major break of slope lies 30 km from Nias Island and 50 km from the trench (Karig *et al.* 1980), and further north along the same arc system, the break of slope is 80 km from the Nicobar Islands and again 50 km from the trench (Weeks *et al.* 1967). The Nicobar Islands and Nias are the equivalents of Barbados. In the eastern Aleutians where the major break of slope occurs 50–70 km from the trench, the position of Barbados is analagous with that of Kodiak Island 100 km from the break of slope. The presence of a large forearc basin between Kodiak Island and the break of slope does not detract from the comparison. Forearc basins occur between the Barbados Ridge and the eastern edge of the complex. Although in Dickinson & Seely's (1979) classification of forearcs, the Barbados Ridge Complex is cited as an example of a narrow ridged forearc, it should be classed as a broad ridged forearc. It is implicit in the evolutionary model of Westbrook (1975) that narrow ridged forearcs evolve into broad ridged forearcs.

It is common for geological models of forearc ridges (e.g. Dickinson & Seely 1979; Seely 1979) to include rises of oceanic crust beneath the ridges. The geophysical evidence is strongly against the existence of a rise of oceanic crust beneath the Barbados Ridge (Westbrook 1975; Boynton *et al.* 1979), and is ambivalent for its existence beneath the forearc ridge of the Java Sumatra arc system (Curray *et al.* 1977; Karig *et al.* 1980; Kieckhefer *et al.* 1980).

Barbados and history of the complex

Barbados, the geology of which is succinctly summarized by Saunders (1979) is an important source of information on the nature of the rocks comprising the Barbados Ridge Complex, but is also a source of problems. The Scotland Formation (Pudsey & Reading 1981) comprises a group of sediments of early Eocene (perhaps Palaeocene) to middle Eocene age which can be generally described by flysch. Current opinion is that these rocks were deposited in deep water. Pudsey & Reading propose that they were deposited as a deep sea fan in the former trench of the Lesser Antilles arc. While there is a strong likelihood of this, it is also possible that the fan was formed on the ocean floor and engulfed later by the subduction complex. The very small amount of material in the formation derived from a volcanic source lends some support to the latter view.

The Scotland Formation is quite strongly deformed. Most of this deformation is tectonic, but some synsedimentary gravity-driven deformation has been recognized. Exploration wells show that there is tectonic repetition of the Scotland Formation, at least four times to a depth of at least 4.5 km (Baadsgaard 1960).

The strike of this deformation is NE, rather than the northerly trend expected from general consideration of the shape of the arc and the direction of subduction. Herrera & Spence (1964) suggested that this trend was the result of emplacement of the Scotland Formation as gravity slides from the south. The difficulty with this explanation is that after sliding into the trench the material underwent relatively little deformation. The possibility that the deformation reflects a southerly component in the direction of subduction since the Cretaceous is supported by some plate tectonic reconstructions of the area (Malfait & Dinkleman 1972; Ladd 1976) for the period from Late Cretaceous until late Eocene. Subsequent tectonic rotation of the small area of Barbados is a possible explanation which could be tested palaeomagnetically. The Oceanic Formation (middle Eocene to Oligocene) and the Bissex Hill Formation (early Miocene) which overlie the Scotland Formation are also deformed, although by no means to the same extent as the Scotlands. They show the continuing influence of tectonism, comparatively far from the leading edge of the complex.

Reconstructions of plate motions and the stratigraphy of Trinidad suggest that Jurassic and Cretaceous rocks should have been present on the ocean floor during the early history of the arc, but they are not present in Barbados as might be expected from many models of subduction complexes. Maybe these older sediments were not scraped off, but taken further down the subduction zone in the initial stages of its formation, or exist further west in the complex.

Barbados has undergone considerable vertical movement since the late Eocene when the Oceanic Formation began to be deposited on the Scotlands at a depth of 3500 m (Saunders 1979). In the early Miocene during the deposition of the Bissex Hill Formation the water depth can have been as little as 300 m (Steineck & Murtha 1981). In the middle Miocene during deposition of the Conset Marl the water depth was between 1000 and 1500 m (Steineck & Murtha 1981). The seismic stratigraphy of the Tobago Trough suggests that Barbados has risen about 3 km relative to the trough's centre since the Miocene. The vertical displacements are controlled by the subduction process, which over a long term would tend to increase the elevation of Barbados. On a shorter term a slowing of subduction would result in a rise of the complex as the negative isostatic imbalance was reduced, whereas an increase in rate would initially depress the surface. A possible scenario for the history of these movements is shown in Fig. 9.

The great volume of material in the Barbados Ridge Complex is undoubtedly a consequence of the proximity of the Lesser Antilles to sources of terrigenous sediment from the South American continent. How much was directly deposited in a trench in front of the arc earlier in its history and how much was deposited on the ocean floor can only be conjectured. A considerable proportion, however, must be continental slope and rise deposits from the northern margin of South America, incorporated as the Lesser Antilles moved eastward along the margin (Fig. 10) (Chase & Bunce 1969). How far the Lesser Antilles have migrated past South America is undetermined, but if one follows Jordan (1975) this could be virtually the whole length of the Caribbean. (This is illustrated by Pudsey & Reading 1981.) The tectonic history of northern Venezuela suggests that it might not have moved as far as this, however (Bell 1972; Maresch 1974). In the region currently occupied by the Barbados Ridge Complex, there must once have existed a thick sedimentary cone built in front of a proto-Orinoco River system. The collision of the complex with this cone must have had a significant influence on the development of the complex. This collision could have begun at any time between the end of the Eocene and the middle of the Miocene, depending on the model chosen for the development of the eastern Caribbean (Fig. 9f).

Maturity of the Barbados Ridge Complex

Can the Barbados Ridge Complex be considered to be a mature member of a sequence of forearc evolution? Listed below are variables which can influence the development of forearc complexes.

(1) Age of the subduction zone.
(2) Rate of subduction.
(3) Thickness of sediment:
    (a) on ocean plate to be subducted,
    (b) in trench at the foot of the forearc.
(4) Lithologies of sediments on (a) and in (b).
(5) Shape of the basement surface.
(6) Sedimentation directly on to the forearc complex.

It is implicit in most models of accretionary complexes that there will be growth but will this growth always proceed in the same way? Looked at in simple terms the volume of sediment in the complex should be the product of

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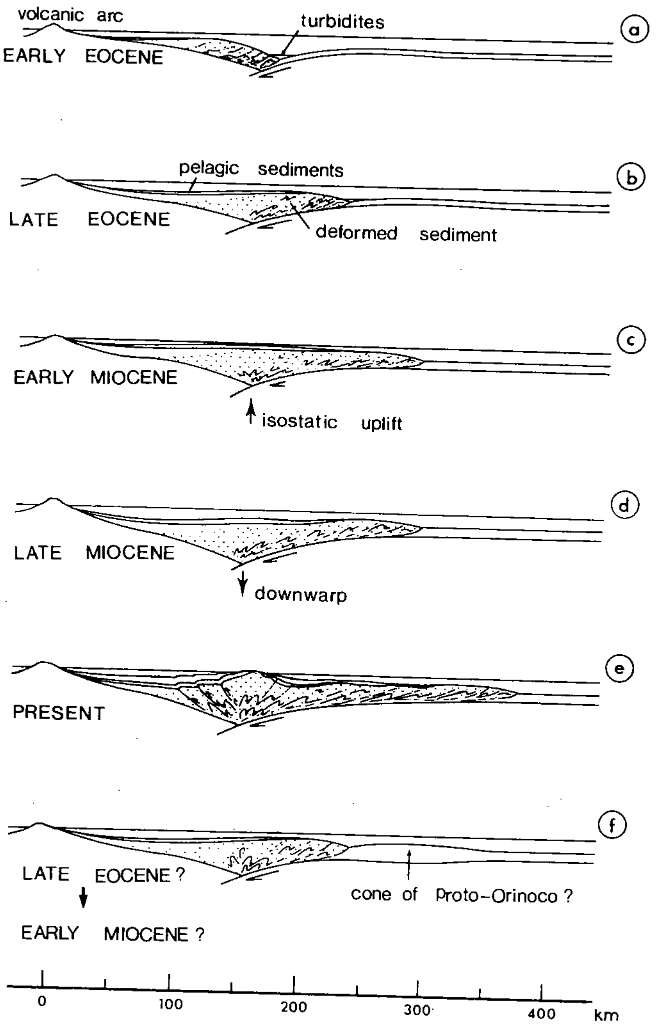

FIG. 9. Evolution of Barbados Ridge Complex.
(a) Early Eocene: youthful stage in the evolution of the forearc which had a trench possibly with direct deposition of Scotland Formation sediments into it.
(b) Late Eocene: region in which Barbados now is, no longer in active accretionary zone and receiving pelagic sedimentation of Oceanic Formation. Elevated position keeps it free of terrigenous sediments. The forearc may also have been far from a source of continentally derived material at this time. This stage of development began in the mid-Eocene.
(c) Early Miocene: a hiatus in subduction has allowed the central part of the forearc complex to rise by isostatic rebound. During this stage the Bissex Hill Formation of Barbados was laid down.
(d) Late Miocene: following the recommencement of subduction in the middle Miocene the central part of the forearc has become depressed by the reimposition of the negative isostatic imbalance. Some of the Conset Marl of Barbados was probably laid down at the beginning of this stage, as the water began deepening.
(e) Present: continued accretion and consequent widening of the forearc have imposed more stress on the centre, and caused it to rise forming the Barbados Ridge and Tobago Trough. Present rate of uplift is about 400 m Ma^{-1}.
(f) End Eocene—early Miocene?: at some time during the period, the Barbados Ridge Complex encountered what was probably quite a thick cone of sediment produced by some proto-Orinoco delta. This must have produced a rapid widening of the complex.
Note: The hiatus in subduction referred to in (c) and (d) may have been a considerable slowing rather than a cessation.

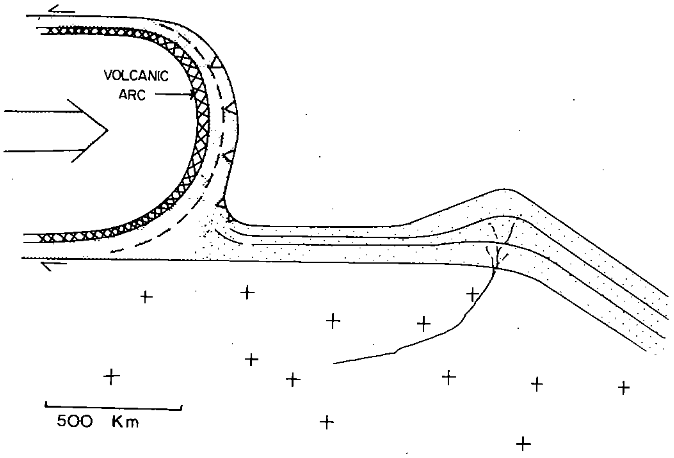

FIG. 10. Migration of the Lesser Antilles island are eastward along the northern margin of South America during the Tertiary. The continental slope deposits of the South American margin become assimilated in the forearc complex. Eventually the sediment cone of the proto-Orinoco becomes incorporated in the complex. The front of the complex is shown by a solid line with triangle. The line of subduction of crystalline ocean crust beneath crystalline crust of Caribbean Plate is shown by a dashed line.

variables (1), (2) and (3), plus (6), but other effects complicate this. Dewatering and compaction of accreted sediment will reduce its volume. If the mean density of the Barbados Ridge Complex is taken to be 2.35 Mg m^{-3} and the mean density of sediment before addition is 1.9 Mg m^{-3}, then the volume of sediment in the complex is 0.66 of its original volume. Only part of the sedimentary section on the subducted oceanic lithosphere may be accreted in the forearc complex, the remainder being taken down further into the crust and mantle. This is probably strongly dependent on lithology; mature lithified rocks of biogenic origin being far more likely to remain attached to the oceanic lithosphere than overlying terrigenous sediments which were probably only added to the section close to the subduction zone, under most circumstances (Moore 1975). In some situations such as Peru-Chile it is possible that the forearc complex has been 'eroded' at its base by the subducting lithosphere (Karig 1974a). As well as governing the rate at which sediment enters the complex, subduction rate is also important in controlling stress imparted to a forearc complex, and consequently affecting its shape and strain within it.

The shape of the basement must have a strong influence particularly on the early development of the complex. The upthrusting of a slice of oceanic crust beneath which accreted sediment is 'understuffed' (Seely 1979) produces quite a different evolution, with a fixed position of the outer structural high, from that proposed by Karig (1974b) in which sediment accretes in a depression above the oceanic basement and the trench slope break migrates outward. Evidence for Seely's model exists from forearcs associated with continental margins, e.g. Middle America, but not for intra-oceanic arcs. The Barbados Ridge Complex does not follow Seely's model.

Given the variety of situations in which arcs occur and the episodic nature of geological history it is obvious that the development of a universal model for the evolution of forearcs which will predict what will occur under any circumstances during the evolution of forearcs may be an intractable problem. However, in a situation where there is a plentiful supply of terrigenous sediment and a moderate rate of subduction, growth of the forearc complex is a well-established consequence of continued subduction, it is reasonable to suppose that the Barbados Ridge Complex is a mature forearc complex, representing a state towards which forearcs will evolve, given sufficient time.

Conclusions

(1) The Barbados Ridge Complex is an accretionary forearc complex of broad ridged type. Its width and thickness are a consequence of its long history (50 Ma)

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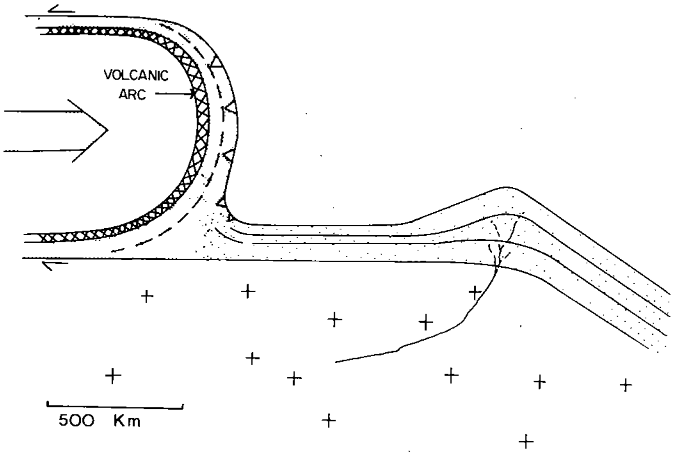

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(2) The changes in elevation along the complex are broadly related to variation in sediment thickness on the ocean floor, and are locally controlled by ridges in the oceanic basement.

(3) Oceanic basement ridges influence the position of the leading edge of the complex and its thickness by laterally controlling the amount of sediment accreted, and by deforming accreted material when they pass into the complex at an angle oblique to their strike.

(4) Style of deformation and accretion at the leading edge of the complex are dependent upon sediment thickness and lithology. Thicker sediment gives a more open style of deformation. More competent lithologies in the lower part of the sedimentary section can restrict the amount of sediment accreted, and confine significant deformation to the upper part of the section.

(5) Increase in the width of the complex, and also perhaps, an increase in subduction rate, has increased the horizontal stress in the complex. This has produced the uplift of the Barbados Ridge and the westward verging structures on its western flank.

(6) Isostatic response to variations in subduction rate has superimposed changes in the elevation of the Barbados Ridge upon the long-term uplift produced tectonically.

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