

## Stratigraphy, palaeoenvironmental interpretation and uplift history of Barbados based on foraminiferal and other palaeontological evidence

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**ABSTRACT** – The ages and environments of deposition of the principal mapped units of Barbados, based on foraminiferal and other palaeontological evidence, are discussed, together with the uplift history of the island. The age of the Scotland Formation is demonstrated to be Paleocene to ?early Middle Eocene; that of the Oceanic Formation late Middle Eocene to early Early Miocene; that of the Bissex Hill Formation and Conset Marl late Early to early Late Miocene; and that of the Coral Rock Formation Middle–Late Pleistocene. The environment of deposition of the Scotland Formation is interpreted to be abyssal; that of the Oceanic Formation abyssal to be lower bathyal; that of the Bissex Hill Formation and Conset Marl middle to lower bathyal; and that of the Coral Rock Formation inner neritic. Observed elevation/age relationships imply a mean uplift rate of between  $120 \text{ m Ma}^{-1}$  and  $220 \text{ m Ma}^{-1}$ . *J. Micropalaeontol.* 28(1): 37–44, May 2009.

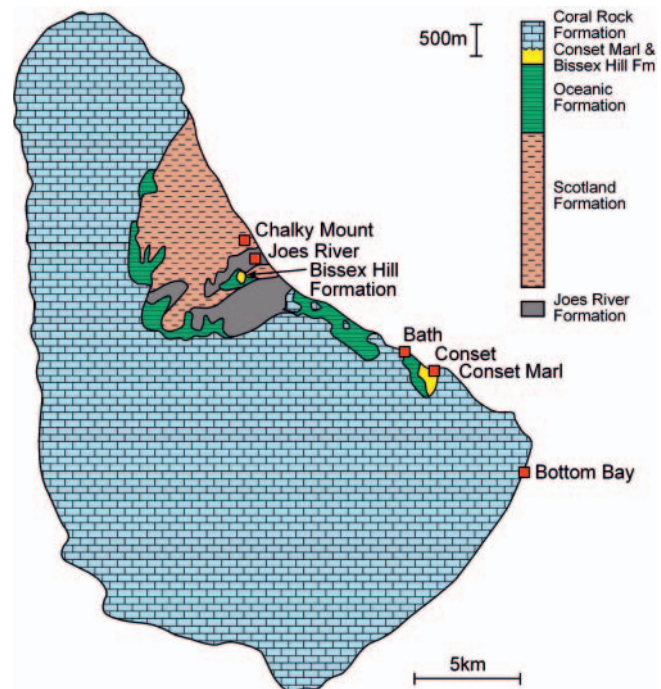
**KEYWORDS:** stratigraphy, palaeoenvironmental interpretation, uplift history, Barbados, Foraminifera

### INTRODUCTION

The island of Barbados is situated atop the Barbados Accretionary Prism formed by the collision between the Caribbean and Atlantic plates (Speed, 1981, 1985, 1988; Speed & Larue, 1982; Torrini *et al.*, 1985; Torrini, 1988; Speed *et al.*, 1991; Driscoll & Diebold, 1999; Machel, 2004; Gill *et al.*, 2005). The geology and petroleum geology of the island has attracted renewed interest from the oil industry recently, following the demonstration that the oils and gases from the onshore Woodbourne Field could be typed back to the prolific ‘Middle’ Cretaceous La Luna-Querecual-Naparima Hill Formation petroleum system of northern South America, and that potential reservoir facies extended offshore (Dolan *et al.*, 2004; Hill & Schenk, 2004).

The most important mapped lithostratigraphical units on the island are, in ascending stratigraphical order: the Scotland Formation or Group or approximately equivalent ‘Accretionary Basal Complex’ and ‘Prism Cover’ (predominantly sandstone and non-calcareous mudstone); the Oceanic Formation or Group (calcareous mudstone and marl, with some volcanic ash bands); the Bissex Hill Formation and Conset Marl (calcareous mudstone and marl, unknown thickness); and the Coral Rock Formation (limestone) (Saunders, 1968; Machel, 2004; Gill *et al.*, 2005; Fig. 1). The Coral Rock forms a protective carapace over most of the island, with the exception of the Scotland District of the Atlantic coast, where it has been eroded, and where the Scotland, Oceanic, Bissex Hill and Conset Marl have become exposed. A further unit, the Joes River Formation (mudstone), is also present, although only in a melange, such that its stratigraphical relationship to the other units is unclear.

The palaeontological content of these lithostratigraphical units has been described in a number of previous studies (Jukes-Browne & Harrison, 1891, 1892; De Cizancourt, 1948; Beckmann, 1953; Saunders & Cordey, 1968; Caudri, 1972; Maurrasse, 1983; Kugler *et al.*, 1984; Saunders *et al.*, 1984;



**Fig. 1.** Geological Map of Barbados. Note that the contact between the Oceanic Formation and the Scotland Formation is thrust tectonic rather than stratigraphical. Note also that the Oceanic is locally overlain by the Coral Rock, with the Bissex Hill and Conset Marl unrepresented.

Steineck *et al.*, 1984; Biju-Duval *et al.*, 1985; Steineck & Murtha, 1985; Wood *et al.*, 1985; Gortner & Larue, 1986; Bolli *et al.*, 1994; Harding, 1996; Gill *et al.*, 2005).

The purpose of the present study is to discuss the palaeontological, in particular the foraminiferal, evidence for the age and environment of deposition of the lithostratigraphical units, and the uplift history of the island.

## DISCUSSION

## Stratigraphy and palaeoenvironmental interpretation

**Palaeoenvironmental interpretation.** In the case of the Scotland Formation, which contains only extinct species, palaeoenvironmental interpretation is based, in part, on the ecological ranges of those species as established by backstripping (van Morkhoven *et al.*, 1986; Kaminski & Gradstein, 2005) and, in part, on analogy between contained extinct and counterpart extant species, on the functional morphology of the contained extinct species, and on associated sedimentary facies (Jones, 2006). In the case of the Oceanic Formation, Bissex Hill Formation and Conset Marl, and Coral Rock Formation, which contain some still extant species, it is based in part on the ecological ranges of those species as established by empirical observation (van Morkhoven *et al.*, 1986; Charnock & Jones, 1990; Jones, 1994, 1998, 1999, 2006; Kaminski & Gradstein, 2005; Tables 1–3).

## Scotland Formation and approximately equivalent ‘Accretionary Basal Complex’ and ‘Prism Cover’

**Stratigraphy.** To summarize, the demonstrable overall age of the Scotland Formation is interpreted as Paleocene–?early Middle Eocene, 65.5–?43 Ma, on the Gradstein *et al.* (2005) timescale. The minimum age is poorly constrained and is not necessarily coincident with the maximum age of the overlying Oceanic Formation (see below), as the contact between the two formations has been interpreted as thrust tectonic rather than stratigraphical (Speed, 1988; Speed *et al.*, 1991; J. Frampton, pers. comm., 2009).

The Scotland Formation contains no planktonic foraminifera or calcareous nannoplankton, and is not directly datable with reference to the global standard calcareous planktonic zonation schemes of the Cenozoic.

However, the Lower Scotland Formation does contain an autochthonous fauna of deep-water arenaceous or agglutinating benthonic foraminifera (Kugler *et al.*, 1984; J. Frampton, pers. comm., 2005). It can be indirectly dated as Paleocene–Early Eocene on the basis of correlation – by means of selected agglutinating benthonic foraminiferal species – with the Lizard Springs Formation of Trinidad, which has been independently dated on planktonic foraminiferal evidence as Paleocene–Early Eocene, P1–P9=P1–E6, approximately 65.5–48.6 Ma.

The Lower and Upper Scotland Formation also contain an allochthonous fauna of shallow-water calcareous larger benthonic foraminifera (De Cizancourt, 1948; Caudri, 1972) that can be interpreted as contemporaneously transported down-slope from the shelf. If this is so, the Walkers Member of the Lower Scotland Formation can be dated as Paleocene on the basis of the presence, and the Morgan Lewis Member as Early Eocene on the absence, of *Actinosiphon barbadiensis*, which appears to be restricted to the Paleocene. The Murphy’s, Chalky Mount and Mount All members of the Upper Scotland Formation can all be dated as early Middle Eocene on the basis of the occurrence of *Asterocyclina barbadiensis*, *Eoconuloides senni* and *Neodiscocyclina anconensis*, which appear to be restricted to the early Middle Eocene, 48.6–43 Ma.

Note, though, that the allochthonous fauna of shallow-water calcareous larger benthonic foraminifera can also be interpreted

Species	IN	MN	ON	UB	MB	LB	AB
<i>Siphogenerina raphanus</i>	X	X	X	X			
<i>Fissurina laevigata</i>	X	X	X	X	X	X	X
<i>Fissurina lagenoides</i>	X	X	X	X	X	X	X
<i>Globocassidulina subglobosa</i>	X	X	X	X	X	X	X
<i>Anomalinoidea bilateralis</i>		X					
<i>Cibicidoides pachyderma</i>		X	X	X	X	X	X
<i>Sphaeroidina bulloides</i>		X	X	X	X	X	X
<i>Lenticulina torrida</i>			X	X	X		
<i>Plectofrondicularia vaughani</i>			X	X	X		
<i>Cibicidoides eoacenus</i>			X	X	X	X	X
<i>Gavelinella micra</i>			X	X	X	X	X
<i>Psammosphaera fusca</i>			X	X	X	X	X
<i>Pullenia quinqueloba</i>			X	X	X	X	X
<i>Saccamina gryzbowskii</i>			X	X	X	X	X
<i>Usbekistania charoides</i>			X	X	X	X	X
<i>Bulimina alazanensis</i>				X			
<i>Pleurostomella brevis</i>				X			
<i>Recurvoidea turbinatus</i>				X			
<i>Orthomorphina consobrina</i>				X	X		
<i>Anmodiscus glabratus</i>				X	X	X	
<i>Buliminella grata</i>				X	X	X	
<i>Hormosina trinitatensis</i>				X	X	X	
<i>Hyperammia friabilis</i>				X	X	X	
<i>Trochammina altiformis</i>				X	X	X	
<i>Alabaminoides exiguus</i>				X	X	X	X
<i>Cyclammina cancellata</i>				X	X	X	X
<i>Eggerella bradyi</i>				X	X	X	X
<i>Hyperammia elongata</i>				X	X	X	X
<i>Karreriella bradyi</i>				X	X	X	X
<i>Laticarinina pauperata</i>				X	X	X	X
<i>Lituotuba lituiformis</i>				X	X	X	X
<i>Oridorsalis umbonatus</i>				X	X	X	X
<i>Planulina renzi</i>				X	X	X	X
<i>Pullenia bulloides</i>				X	X	X	X
<i>Spiroplectammina trinitatensis</i>				X	X	X	X
<i>Stilostomella consobrina</i>				X	X	X	X
<i>Trochamminoides proteus</i>				X	X	X	X
<i>Veleroninoides scitulus</i>				X	X	X	X
<i>Bulimina impendens</i>					X		
<i>Bulimina trinitatensis</i>					X		
<i>Hanzawaia ammophila</i>					X		
<i>Osangularia mexicana</i>					X		
<i>Cibicidoides mexicanus</i>						X	
<i>Uvigerina rippensis</i>					X	X	
<i>Anomalinoidea semicribratus</i>					X	X	X
<i>Cibicidoides laurissae</i>					X	X	X
<i>Cibicidoides havanensis</i>					X	X	X
<i>Duqupsammia cubensis</i>					X	X	X
<i>Gavelinella semicribrata</i>					X	X	X
<i>Plectofrondicularia paucicostata</i>					X	X	X
<i>Cibicidoides haitiensis</i>						X	
<i>Quadriformina profunda</i>						X	
<i>Abyssamina</i> spp.						X	X
<i>Alabamina dissonata</i>						X	X
<i>Bulimina jarvisi</i>						X	X
<i>Cibicidoides grimsdalei</i>						X	X
<i>Cibicidoides havanensis</i>						X	X
<i>Marginulina obesa</i>						X	X
<i>Nuttallides truempyi</i>						X	X
<i>Fissurina alveolata</i>							X
<i>Osangulariella umbonifera</i>							X
<i>Pyrulina extensa</i>							X
<i>Siphonodosaria abyssorum</i>							X
<i>Spirosigmollina tenuis</i>							X

Compiled from various sources (see text). Palaeobathymetric zonation after Charnock & Jones (1990) and Jones (1999). IN, inner neritic (0–50 m); MN, middle neritic (50–100 m); ON, outer neritic (100–200 m); UB, upper bathyal (200–1000 m); MB, middle bathyal (1000–1750 m); LB, lower bathyal (1650–2250 m); AB, abyssal (>2250 m). The occurrences are consistent with a lower bathyal to abyssal environment of deposition (highlighted).

**Table 1.** Bathymetric ranges of benthonic foraminifera from the Oceanic Formation.

Species	IN	MN	ON	UB	MB	LB	AB
<i>Planulina ariminensis</i>		X	X	X	X	X	X
<i>Rectuvigerina transversa</i>				X			
<i>Planulina mexicana</i>				X	X		
<i>Karreriella bradyi</i>				X	X	X	X
<i>Oridorsalis umbonatus</i>				X	X	X	X
<i>Osangularis mexicana</i>					X		

Compiled from various sources (see text). Palaeobathymetric zonation after Charnock & Jones (1990) and Jones (1999). IN, inner neritic (0–50 m); MN, middle neritic (50–100 m); ON, outer neritic (100–200 m); UB, upper bathyal (200–1000 m); MB, middle bathyal (1000–1750 m); LB, lower bathyal (1650–2250 m); AB, abyssal (>2250 m). The occurrences are consistent with a middle bathyal environment of deposition (highlighted).

**Table 2.** Bathymetric ranges of benthonic foraminifera from the Bissex Hill Formation.

Species	IN	MN	ON	UB	MB	LB	AB
<i>Globocassidulina subglobosa</i>	X	X	X	X	X	X	X
<i>Sphaeroidina bulloides</i>		X	X	X	X	X	
<i>Cibicidoides pachyderma</i>		X	X	X	X	X	X
<i>Sigmoilopsis schlumbergeri</i>		X	X	X	X	X	X
<i>Plectofrondicularia vaughani</i>			X	X	X		
<i>Melonis pompilioides</i>			(X)	(X)	(X)	X	X
<i>Rectuvigerina nodifera</i>				X			
<i>Rectuvigerina transversa</i>				X			
<i>Uvigerina hispida</i>				X	X	X	
<i>Laticarinina pauperata</i>				X	X	X	X
<i>Oridorsalis umbonatus</i>				X	X	X	X
<i>Pullenia bulloides</i>				X	X	X	X
<i>Bulimina rostrata</i>					X	X	X
<i>Cibicidoides wuellerstorffi</i>						X	X

Compiled from various sources (see text). Palaeobathymetric zonation after Charnock & Jones (1990) and Jones (1999). IN, inner neritic (0–50 m); MN, middle neritic (50–100 m); ON, outer neritic (100–200 m); UB, upper bathyal (200–1000 m); MB, middle bathyal (1000–1750 m); LB, lower bathyal (1650–2250 m); AB, abyssal (>2250 m). The occurrences are consistent with a lower bathyal environment of deposition (highlighted).

**Table 3.** Bathymetric ranges of benthonic foraminifera from the Conset Marl.

as non-contemporaneously reworked into rocks as young as Late Eocene, as has been demonstrated to be the case in an analogous situation in Trinidad (Caudri, 1996; J. Frampton, pers. comm., 2009), or even younger.

Note also that the so-called ‘Prism Cover’ overlying the ‘Accretionary Basal Complex’ in Woodbourne Field in Barbados, and underlying the Oceanic Formation, has been interpreted as being as young as Miocene in age (Speed *et al.*, 1991; J. Frampton, pers. comm., 2009).

Thus, the top of the Scotland Formation can be interpreted as younger than the base of the Oceanic Formation (see below), supporting the interpretation that the contact between the two formations is thrust tectonic rather than stratigraphical.

**Palaeoenvironmental interpretation.** The overall environment of the Scotland Formation is interpreted as abyssal, with water depths in the range >2250 m (?±4800 m).

As noted above, the Scotland Formation contains an autochthonous fauna of deep-water agglutinating benthonic foraminifera (Kugler *et al.*, 1984; Biju-Duval *et al.*, 1985; J. Frampton, pers. comm., 2005), and an allochthonous fauna of shallow-water calcareous larger benthonic foraminifera (De Cizancourt, 1948; Caudri, 1972). The autochthonous ‘deep-water agglutinating foraminifera’ (DWAF) fauna, also described as a ‘*Rhabdammina*’ fauna or ‘fysch-type’ fauna, is indicative of a deep-marine, bathyal to abyssal, submarine fan environment of deposition (Jones, 1996, 1998, 2006). The development of DWAF faunas, and the effective absence of a calcareous component, has been interpreted as indicative of deposition below the calcite compensation depth (CCD), estimated to have been at approximately 4800 m in the Eocene (Saunders *et al.*, 1984). Note, though, that the development of such faunas appears to be controlled by factors other than depth, and may be related to depth only indirectly. These factors include calcium carbonate dissolution, which favours the sustenance and/or preservation of agglutinating foraminifera over their calcareous counterparts, and which can take place *above* the CCD in submarine fan environments, when acids are liberated by the oxidation of organic material during diagenesis. Note also that the local occurrence of calcareous benthonic foraminifera is indicative of at least local deposition above the CCD. The calcareous benthonic foraminifera are characterized by robust form, large size and small surface area with respect to volume, rendering them resistant both to destruction during transportation and to dissolution.

The dominance of the epifaunal suspension-feeding ‘morphotype’ *Bathysiphon* (‘morphogroup’ A of Jones & Charnock, 1985), and the subordination of epifaunal detritus-feeding ‘morphotypes’ *Glomospira* and *Trochammina* (‘morphogroup’ B) and infaunal detritus-feeding ‘morphotypes’ *Bolivinopsis* and *Hormosina* (‘morphogroup’ C) within the DWAF fauna is strongly suggestive of a dominance of ‘turbiditic’ over ‘hemipelagic’ deposition (Jones, 1999, 2006; Jones *et al.*, 2005).

The Scotland Formation is also characterized by trace fossils, lithologies, sandbody morphologies and sedimentary structures consistent with an abyssal, submarine fan environment (Pudsey & Reading, 1982; Larue & Speed, 1983; Larue, 1985; Pudsey, 1985; Gortner & Larue, 1986; Kasper & Larue, 1986; Chaderton & Wood, 2007). The trace fossils include *Palaeodictyon* (Pudsey & Reading, 1982), consistent with an abyssal environment (Jones, 2006). Interestingly, they also include *Ophiomorpha* (pers. obs.), which is the burrowing trace of a callianassid crustacean characteristic of shallow marine, shoreface environments (Jones *et al.*, 1999), and here evidently transported downslope. The lithologies include a predominance of medium- to coarse-grained sandstones, and the sandbody morphologies include channels, levees and lobes (Chaderton & Wood, 2007). The sedimentary structures include unidirectional current ripples, and graded and inverse-graded bedding. The inverse-graded bedding is interpreted as having formed by ‘dynamic sieving’ in a ‘turbidite’ flow (R. Dixon, pers. comm., 2005).

Incidentally, geochemical and heavy mineral evidence indicates that the sediments of the Scotland Formation and, by inference, those of the equivalent lithostratigraphical unit drilled at ODP Site 672 on the Tiburon Rise (Beck *et al.*, 1990; Dolan *et al.*, 1990), were derived from a provenance area on the

northwestern Venezuelan Shield (Mahabir *et al.*, 2004). Whether they were derived by way of the palaeo-Orinoco or another river system remains unclear. Note in this context, though, that there is an abundance of palaeobiogeographical and other evidence to indicate that the palaeo-Orinoco discharged into the Caribbean until the Miocene, when the uplift of the Merida Andes diverted its course towards the Atlantic (Jones, 2006). In the Eocene, the palaeo-Orinoco discharged into the area around Lake Maracaibo in western Venezuela, depositing the deltaic sediments of the Misoa Formation and the incised valley fills of the Mirador Formation, potentially the up-tract equivalents of the submarine fan sediments of the Scotland Formation.

### Oceanic Formation

**Stratigraphy.** The Oceanic Formation contains planktonic foraminifera indicative of late Middle Eocene–early Early Miocene Zones P12?–N7=E10?–M4 (Saunders *et al.*, 1984; Biju-Duval *et al.*, 1985; Wood *et al.*, 1985; Bolli *et al.*, 1994), approximately 43–17 Ma (Gradstein *et al.*, 2005).

**Palaeoenvironmental interpretation.** The overall environment of the Oceanic Formation is interpreted as lower bathyal to abyssal, with water depths in the range 1650–>2250 m (<4800 m). This interpretation is consistent with those of previous authors, with water depths in the range 500–1000 fm or approximately 900–1800 m according to Jukes-Browne & Harrison (1892), or 2000–>2800 m according to Saunders *et al.* (1984) and Wood *et al.* (1985).

The Oceanic Formation contains the benthonic foraminifera listed in Table 1 (Beckmann, 1953; Saunders & Cordey, 1968; Saunders *et al.*, 1984; Wood *et al.*, 1985; Bolli *et al.*, 1994). The occurrences of virtually all of the species encountered are consistent with a lower bathyal to abyssal environment of deposition, with water depths in the range 1650–>2250 m. The only exceptions are the occurrences of some shallower-water species, which are attributed to downslope transportation. Significantly, most of these species have elongate morphologies that render them hydrodynamically unstable and, therefore, susceptible to entrainment in, and downslope transportation by, ‘turbidite’ flows. The occurrence of calcareous benthonic foraminifera is indicative of deposition above the CCD, estimated to have been at approximately 4800 m in the Eocene (Saunders *et al.*, 1984). Note, though, that there is evidence of dissolution below the lysocline of up to 90% of calcareous foraminifera in the lower part of the Oceanic Formation, although only 50% in the upper part (Saunders *et al.*, 1984). The trend toward decreased dissolution through time is indicative of either a deepening of the lysocline, or uplift and shallowing of relative sea-level (from abyssal to lower bathyal).

It also contains planktonic foraminifera, calcareous nannoplankton, radiolarians and silicoflagellates, and ‘deep-sea’ benthonic ostracods. The abundance of calcareous and siliceous plankton is suggestive of a dominance of (hemi)pelagic deposition. Note, though, that the evidently comparatively high sedimentation rate is suggestive of at least some ‘turbiditic’ influence, or else of enhanced pelagic productivity (Saunders *et al.*, 1984).

In addition, the Oceanic Formation also contains the trace fossil *Zoophycos* (pers. obs.), consistent with a bathyal environment (Jones, 2006).

### Bissex Hill Formation and Conset Marl

**Stratigraphy.** The Bissex Hill Formation contains planktonic foraminifera indicative of late Early–early Middle Miocene Zone N8=M5 (Steineck & Murtha, 1985; Bolli *et al.*, 1994), approximately 17–15 Ma (Gradstein *et al.*, 2005).

The Conset Marl contains planktonic foraminifera indicative of late Middle–early Late Miocene Zones N9–?N15 = M6–?M12 (Steineck & Murtha, 1985; Bolli *et al.*, 1994), approximately 15–10 Ma (Gradstein *et al.*, 2005).

**Palaeoenvironmental interpretation.** The Bissex Hill Formation and Conset Marl contain the benthonic foraminifera listed in Tables 2 and 3, respectively (Steineck & Murtha, 1985). The occurrences of virtually all of these species are consistent with a middle bathyal environment of deposition, with water depths in the range 1000–1650 m, for the Bissex Hill Formation; and a lower bathyal environment, with water depths in the range 1650–2250 m, for the Conset Marl. The only exceptions are those of some shallower-water species, which are attributed to downslope transportation.

These interpretations are deeper than those of previous authors, with water depths in the range 300–500 m for the Bissex Hill Formation, and 1000–1500 m for the Conset Marl (Steineck & Murtha, 1985). The interpretations of previous authors did not take into account the possibility that the observed occurrences of shallower-water species could be attributable to downslope transportation.

### Coral Rock Formation

**Stratigraphy.** Detailed mapping has revealed the presence of a series of up to thirteen terraces within the Coral Rock Formation that record periodic uplift from the locus of deposition effectively at or immediately below sea-level (Mesolella, 1967; Shackleton & Matthews, 1977; Fairbanks & Matthews, 1978; Humphrey & Kimbell, 1990; Schellmann & Radtke, 2004). The highest and oldest terraces (T12–T13), at heights of 110–120 m above sea-level, have been dated on electron spin resonance (ESR) evidence to Middle Pleistocene, 410 000–400 000 years BP, coincident with Marine/Oxygen Isotope Stage (M/OIS) 11 (Schellmann & Radtke, 2004). The intermediate terraces, at heights of 45–90 m above sea-level, have been dated on ESR evidence to Middle Pleistocene, 3325 000–200 000 years BP, M/OISs9–7 (antepenultimate to penultimate interglacials). The youngest and lowest terraces (T1–T5), elevated to <5–40 m above sea-level, have been dated on ESR and other evidence to Late Pleistocene, 1325 000–725 000 years BP, M/OIS5e (last interglacial). The observed elevation/age relationships imply a mean uplift rate, uncorrected for eustatic effects, is approximately 220 m Ma<sup>-1</sup>.

**Palaeoenvironmental interpretation.** Analogy with the modern reef fringing the Caribbean coast of Barbados indicates that the ancient reef terraces of the Coral Rock Formation formed

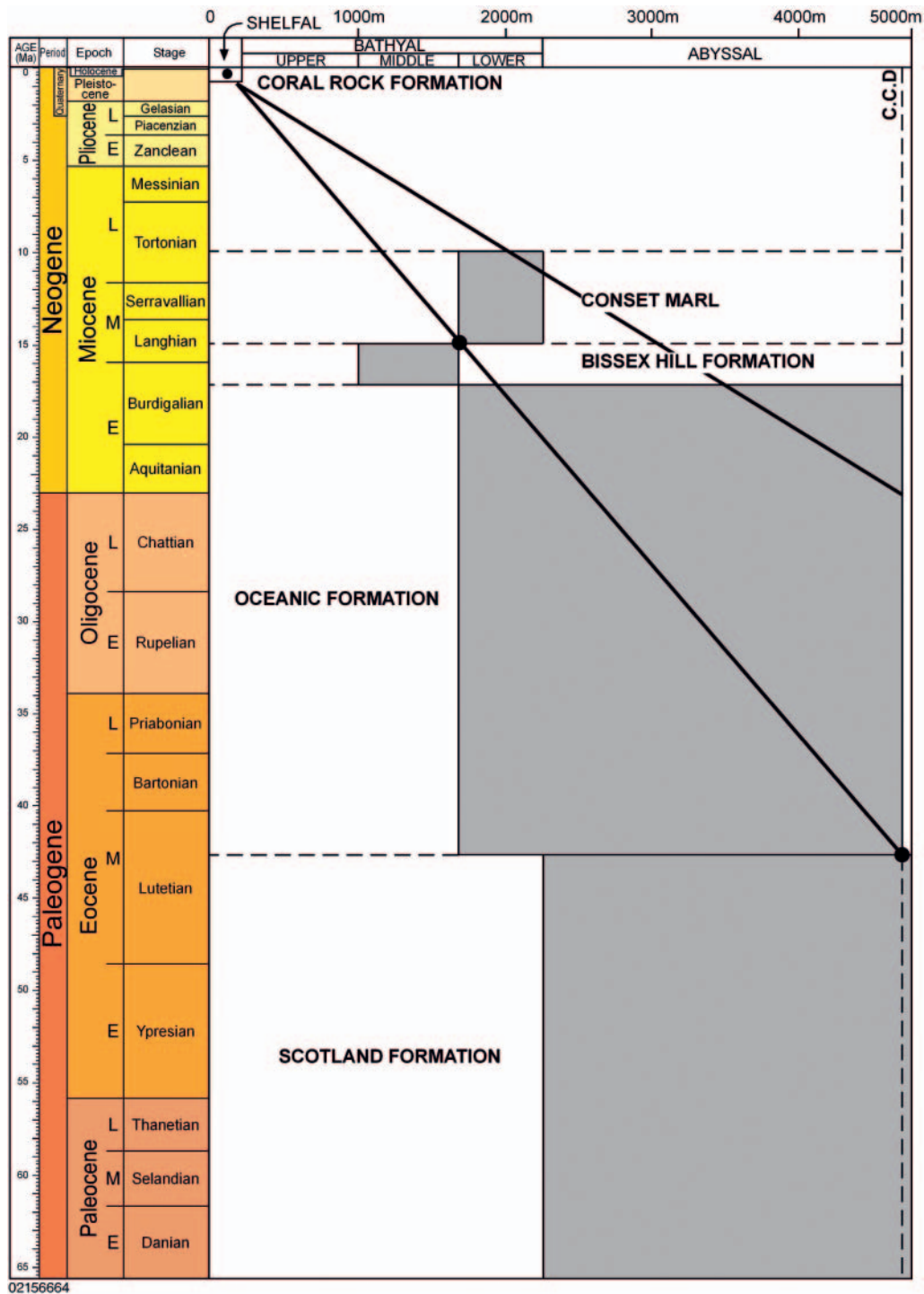


Fig. 2. Uplift history of Barbados.

effectively at or immediately below sea-level (Schellmann & Radtke, 2004, and additional references cited therein). The reef-top, effectively at sea-level, is and was characterized by the ‘Elk’s Horn Coral’ *Acropora palmata*; the reef-front, immediately (<5 m) below, and still well within the euphotic zone, by the ‘Stag’s Horn Coral’ *A. cervicornis*. (The back-reef is and was characterized by the ‘Organ-Pipe Coral’ *Montastrea annularis*,

*Porites* and *Siderastrea*; the fore-reef by the ‘Brain Coral’ *Diploria*, *Montastrea annularis*, *M. cavernosa* and *Siderastrea*).

**Joes River Formation**

**Stratigraphy.** As noted above, the Joes River Formation is only present in a melange, such that its stratigraphical relationship to

the other units is unclear. It has been interpreted as having formed by diapiric extrusion onto the seafloor (Kugler *et al.*, 1984; Gill *et al.*, 2005).

**Palaeoenvironmental interpretation.** The Joes River Formation contains a fauna of benthonic foraminifera and macrofossils (Kugler *et al.*, 1984; Gill *et al.*, 2005).

The benthonic foraminiferal assemblage is similar to that of the Lower Scotland Formation (Kugler *et al.*, 1984). However, it is distinguished from it by the inclusion of a distinctive palmate morphotype of *?Dendrophyra* sp., whose morphology may represent an adaptation to gliding over soft substrates.

The macrofossil assemblage includes *?vestimentiferan* worm tubes, the bivalve molluscs vesicomid sp. A, lucinid sp. A and *Nuculana semmi*, and the gastropods *Calliotropis* sp., *Abyssochrysos* sp. and zygopleurid sp. B (Kugler *et al.*, 1984; Gill *et al.*, 2005). The assemblage is taxonomically similar to that of the living chemosynthetic community associated with 'cold' hydrocarbon seeps on the modern Barbados Accretionary Prism and elsewhere (Jollivet *et al.*, 1990; Jones, 2006). Moreover, the containing carbonate sediments are characterized by a carbon isotope signature indicative of microbially-mediated oxidation of methane (Gill *et al.*, 2005). The Joes River Formation is thus interpreted as having acted as a conduit for advecting methane.

## UPLIFT HISTORY

Taking the palaeobathymetric interpretations discussed above as accurate, there appears to have been elevation or uplift throughout the deposition of the Oceanic Formation, Bissex Hill Formation, Conset Marl and Coral Rock Formation, as indicated on Figure 2.

The lower diagonal line on this figure represents the simplistic interpretation of the trend in elevation with respect to age within allowable ranges (indicated by shaded areas), and indicates uplift of 5000 m over 43 Ma, at a mean uplift rate of 120 m Ma<sup>-1</sup>. The mean uplift rate of 120 m Ma<sup>-1</sup> implied by this interpretation is inconsistent with – half – that of 220 m Ma<sup>-1</sup> inferred for the Coral Rock Formation on the basis of observation (see above).

The upper diagonal line represents an alternative interpretation of the trend in elevation with respect to age based on extrapolation back through time of the mean uplift rate of 220 m Ma<sup>-1</sup> calculated for the Coral Rock Formation, and indicates uplift of 5000 m over a shorter period of 23 Ma (i.e. since the beginning of the Miocene). The abyssal palaeobathymetry for the Bissex Hill Formation implied by this uplift rate interpretation is inconsistent with – significantly deeper than – the middle bathyal palaeobathymetry inferred on the basis of observation (see above).

Another alternative interpretation and, indeed, the only one that would be entirely consistent with all of the existing observations, is that the uplift rate was not constant, but varied through time, perhaps in response to emplacement of the Oceanic nappe(s) (J. Frampton, pers. comm., 2009). The actual uplift rate could at times have significantly exceeded the mean value and, indeed, could have been sufficiently high as to have given rise to emergence and erosion.

## CONCLUSIONS

The age of the Scotland Formation of Barbados, based on foraminiferal evidence, is demonstrated to be Paleocene to ?early Middle Eocene; that of the Oceanic Formation late Middle Eocene to early Early Miocene; and that of the Bissex Hill Formation and Conset Marl late Early to early Late Miocene. The age of the Coral Rock Formation, based on electron spin resonance and other evidence, is demonstrated to be Middle–Late Pleistocene. The Joes River Formation is only present in a melange, such that its stratigraphical relationship to the other units is unclear.

The environment of deposition of the Scotland Formation, based on foraminiferal and other palaeontological evidence, is interpreted to be abyssal; that of the Oceanic Formation abyssal to lower bathyal; and that of the Bissex Hill Formation and Conset Marl middle to lower bathyal; and that of the Coral Rock Formation inner neritic. The Joes River Formation is interpreted as having formed by diapiric extrusion onto the seafloor and as having acted as a conduit for advecting methane.

Observed elevation/age relationships imply a mean uplift rate of between 120 m Ma<sup>-1</sup> and 220 m Ma<sup>-1</sup>.

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