Late Eocene deep-water clastics in Grenada, West Indies

Autor(en): **Saunders, John B. / Bernoulli, Daniel / Martin-Kaye, Peter H.A.**

Objekttyp: **Article**

Zeitschrift: **Eclogae Geologicae Helvetiae**

Band (Jahr): **78 (1985)**

Heft 3

PDF erstellt am: **16.08.2024**

Persistenter Link: https://doi.org/10.5169/seals-165666

Eclogae geol. Helv.	Vol. 78	Nr. 3	Pages 469–485	Basel, December 1985

Late Eocene deep-water clastics in Grenada, West Indies[1])

By JOHN B. SAUNDERS[2]), DANIEL BERNOULLI[3]) and PETER H. A. MARTIN-KAYE[4])

ABSTRACT

Sediments of Late Eocene age are exposed in a number of inliers below younger tuffs and lavas across the northern half of the island of Grenada; they constitute the Tufton Hall Formation.

Fine-grained rudites, arenites and siltites are composed mainly of volcanic lithic fragments of andesitic or basaltic composition and abundant plagioclase and pyroxene mineral grains. Cyclically interbedded with these are mudstones and marlstones which show burrowing and occasional trace fossils such as *Chondrites* indicative of deeper water. Considerable variation in bed geometry, sandstone/mudstone ratio and sedimentary structures exists between the various inliers. However, all features are in accordance with gravity and turbidity flow deposition in a submarine fan environment.

The mudstones and marlstones contain an autochthonous fauna of planktonic and benthonic foraminifera and radiolaria and a flora of coccoliths and discoasters. A water depth greater than 2000 m but less than 4800 m is indicated.

The planktonic foraminifera give a correlation with the *Globorotalia cerroazulensis cunialensis* Zone of topmost Eocene age. If a small inlier at Bylands is included, the formation could extend up into the Early Oligocene.

Radiolaria from the Tufton Hall Estate provide confirmation of a latest Eocene age with a determination of the *Cryptoprora ornata* Zone.

The volcanic arenites contain an allochthonous fauna of larger foraminifera together with coralline algae and other minor constituents. The larger foraminifera prove to be also of Late Eocene age and therefore were penecontemporaneously displaced.

In the volcanic arenites much of the pyroxene is very fresh suggesting penecontemporaneous volcanicity. In Barbados, thin ash beds occur plentifully in the chalks and indurated oozes of the Late Eocene part of the Oceanic Formation providing confirmation of volcanicity in the region at this time.

RÉSUMÉ

Dans la moitié nord de l'île de Grenade, on trouve des sédiments d'âge Eocène supérieur qui affleurent dans un certain nombre d'affleurements situées au-dessous de tufs et de laves plus récents: ces dépôts constituent la Formation de Tufton Hall. Les rudites à grains fins, les arénites et les siltites de cette formation sont principalement composées de fragments de roches volcaniques de composition andésitique ou basaltique et de minéraux parmi lesquels le plagioclase et le pyroxène prédominent. Les schistes argileux et les marnes régulièrement intercalés entre ces niveaux sont bioturbés et livrent de rares traces de *Chondrites* qui indiquent un environnement d'eau profonde.

---

[1]) This paper was read at the Fourth Latin American Geological Congress held in Trinidad in 1979. The manuscript was given for publication in the Transactions at that time. Unfortunately these have never appeared. The paper is essentially as completed in 1979 but account has been taken of relevant later work and publications.

[2]) Natural History Museum, Augustinergasse 2, CH–4051 Basel.

[3]) Geological Institute of the University, Bernoullistrasse 32, CH–4056 Basel.

[4]) Hunting Geology and Geophysics Ltd., Boreham Wood, WD6 1SB, England.

D'un affleurement à l'autre, on observe des variations considérables dans la géométrie des couches, dans le rapport sable/vase et dans les structures sédimentaires. Toutes les caractéristiques de ces sédiments parlent toutefois en faveur d'un environnement sédimentaire de type cône sous-marin profond.

Les vases et les marnes contiennent une faune autochtone de foraminifères planctoniques et benthiques, de radiolaires, ainsi qu'une flore de coccolithes et de discoasters. Nous supposons que ces sédiments se sont déposés sous une tranche d'eau de au moins 2000 mais pas plus que 4800 m. Les foraminifères planctoniques permettent de corréler ces terrains avec la zone à *Globorotalia cerroazulensis cunialensis* (Eocène terminal). La Formation de Tufton Hall pourrait cependant recouvrir aussi l'Oligocène inférieur si l'on y inclut l'affleurement de Bylands.

Les radiolaires provenant de Tufton Hall Estate confirment également un âge Eocène terminal (zone à *Cryptoprora ornata*) des principaux affleurements.

Les arénites volcaniques contiennent une faune allochtone de grands foraminifères accompagnés par des algues corallines et d'autres constituants mineurs. Ces foraminifères ont également un âge Eocène supérieur: ils ont donc subi un transport latéral pénécontemporain des dépôts autochtones.

La majeure partie du pyroxène de ces arénites est très fraîche, ce qui suggère que le volcanisme fut également subcontemporain de ces dépôts. A l'île de Barbade, de fines couches de cinérites se trouvent en abondance dans les craies et dans les vases indurées de l'Eocène supérieur de l'Oceanic Formation: cela confirme l'existence d'une activité volcanique dans la région et à la même époque.

Introduction

Grenada is the southernmost island in the volcanic arc of the Lesser Antilles. The continental mass of South America lies 140 km to the south while northwards the island chain continues through the Grenadine Islands, St. Vincent and St. Lucia (Fig. 1).

The islands of the chain are formed largely of volcanic rocks of Late Tertiary age but datable sediments do occur and a study of these is important for the documentation of the early geologic history of the arc which is still poorly known.

The Late Eocene Tufton Hall Formation of Grenada underlies the volcanic pile probably throughout the northern half of the island and constitutes the largest area of datable sediments known from the southern end of the West Indian Arc.

The first mention of fossiliferous beds in Grenada was made by EARLE (1924). He noted folded, stratified, clastic rocks outcropping among the volcanics. Only poor plant remains were recorded. On general comparison of strike with Trinidad rocks they were thought to be pre-Pliocene. Later study has shown that the plant-bearing beds are relatively unimportant and are probably young – maybe as young as Pleistocene. On the other hand, the folded series is a marine deposit of relatively large extent and thickness.

The Reverend K. Clarke of Gouyave was the first to note marine fossils in the folded series when he collected larger foraminifera from boulders in the Brothers Estate River and subsequently found their source. This is now known to be within the Tufton Hall Formation.

In the late 1950's one of the present authors (P.M.-K.) served as Government Geologist, Windward Islands. During his reconnaissance mapping of Grenada he examined the various inliers of the folded sedimentary sequence which he originally named the Levera Formation after one of its coastal localities. The name Levera Formation was mentioned briefly in a paper on Carriacou (MARTIN-KAYE 1958). By this time, however, study of the microfaunas by one of us (J.B.S.) had shown that the best location for a type section would be the inlier in the Tufton Hall Estate and it was decided to use this locality as the name of the Formation. The combined study by Martin-Kaye and Saunders led to a paper being read but unpublished at the Third Caribbean Geological Conference in 1962. A short account of the sedimentary formations of Grenada was given by MARTIN-KAYE

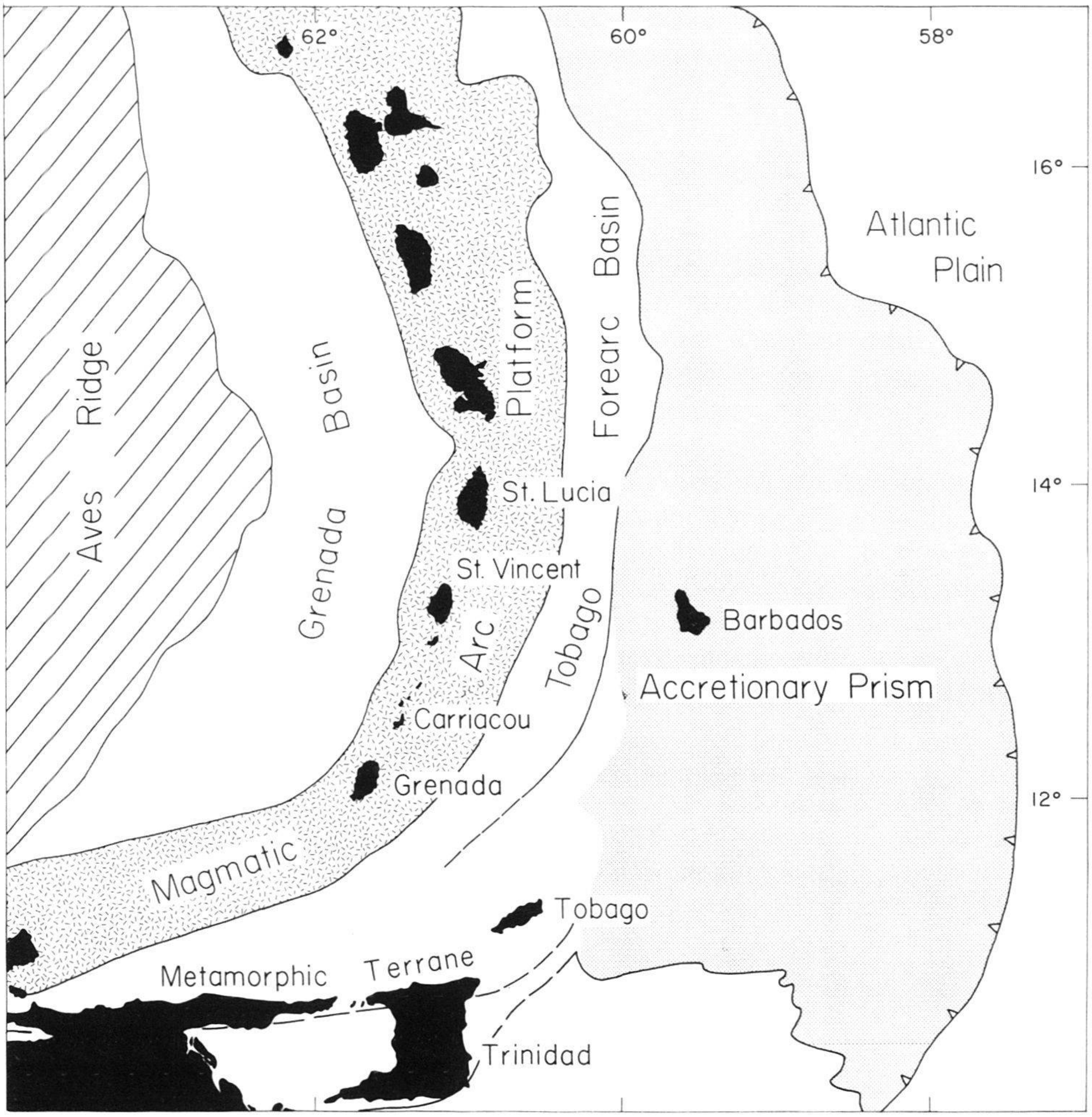


Fig. 1. Location and tectonic setting of the island of Grenada. After SPEED et al. (1984).

(1969). The present paper is partly based on the earlier observations by the authors together with sedimentological results obtained during a further visit to the island in 1978.

Apart from the Tufton Hall Formation, a few other datable levels are known from Grenada:

At Tempe-Parnassus, foraminiferal-algal limestones are found interbedded with a 4.5 m thick marl bed. The latter has yielded a rich foraminiferal fauna of Middle Oligocene, *Globorotalia opima opima* Zone age.

At Hope Vale, a small patch of limestone has yielded a poor foraminiferal fauna indicating an age between Middle Oligocene and Middle Miocene.

Limestone blocks in tuff at Brison south of Halifax Harbour have been dated as Oligocene on larger foraminifera.

Reef limestone patches found amongst the volcanics in various parts of the island are thought to be of Plio-Pleistocene age.

Field relations

The Tufton Hall Formation has been mapped in a number of inliers in river valleys and along the coast in the north and northwestern part of Grenada. It also occurs on the eastern side of Sandy Island off the northeastern coast (Fig. 2).

The beds have a general E–W strike and are often steeply dipping to overturned. The base of the formation has not been seen. In a recent paper, SPEED & LARUE (1985) have published details of structures observed at Levera Bay and La Mabouya Point. According to SPEED & LARUE these imply an earlier phase of N–S-compression with north-verging thrusts followed by N–S-extension.

Volcanic tuffs and agglomerates overlie the Tufton Hall beds with marked unconformity. The volcanic rocks of Grenada have been dated from 20 m.y. to less than 1 m.y. b.p. (BRIDEN et al. 1979; MAURY & WESTERCAMP 1985) and represent a number of different eruptive centres. Topographically the relief on the Tufton Hall surface is at least 350 m. The thickness is unknown but it would seem to be well over 250 m and probably a great deal more. However, the probability of stacking of fault-bounded packages (SPEED & LARUE 1985) makes an estimate of outcropping thickness impossible.

Sedimentological observations

Most of the outcrops of the Tufton Hall Formation are deeply weathered and overgrown by tropical vegetation. In most cases, sedimentary structures are difficult to

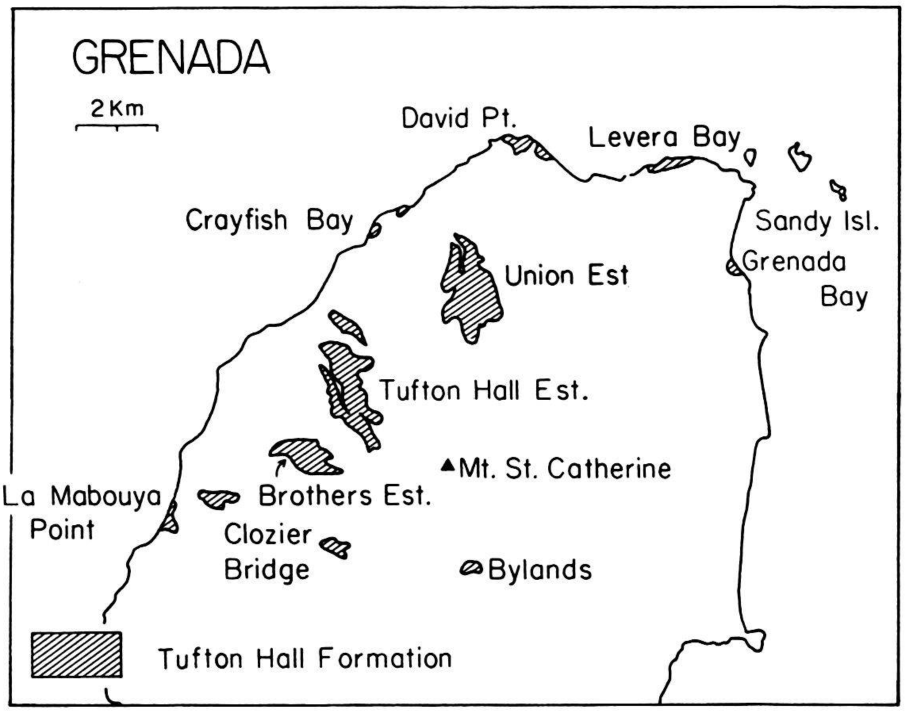


Fig. 2. Outcrop locations of the Tufton Hall Formation, northern Grenada.

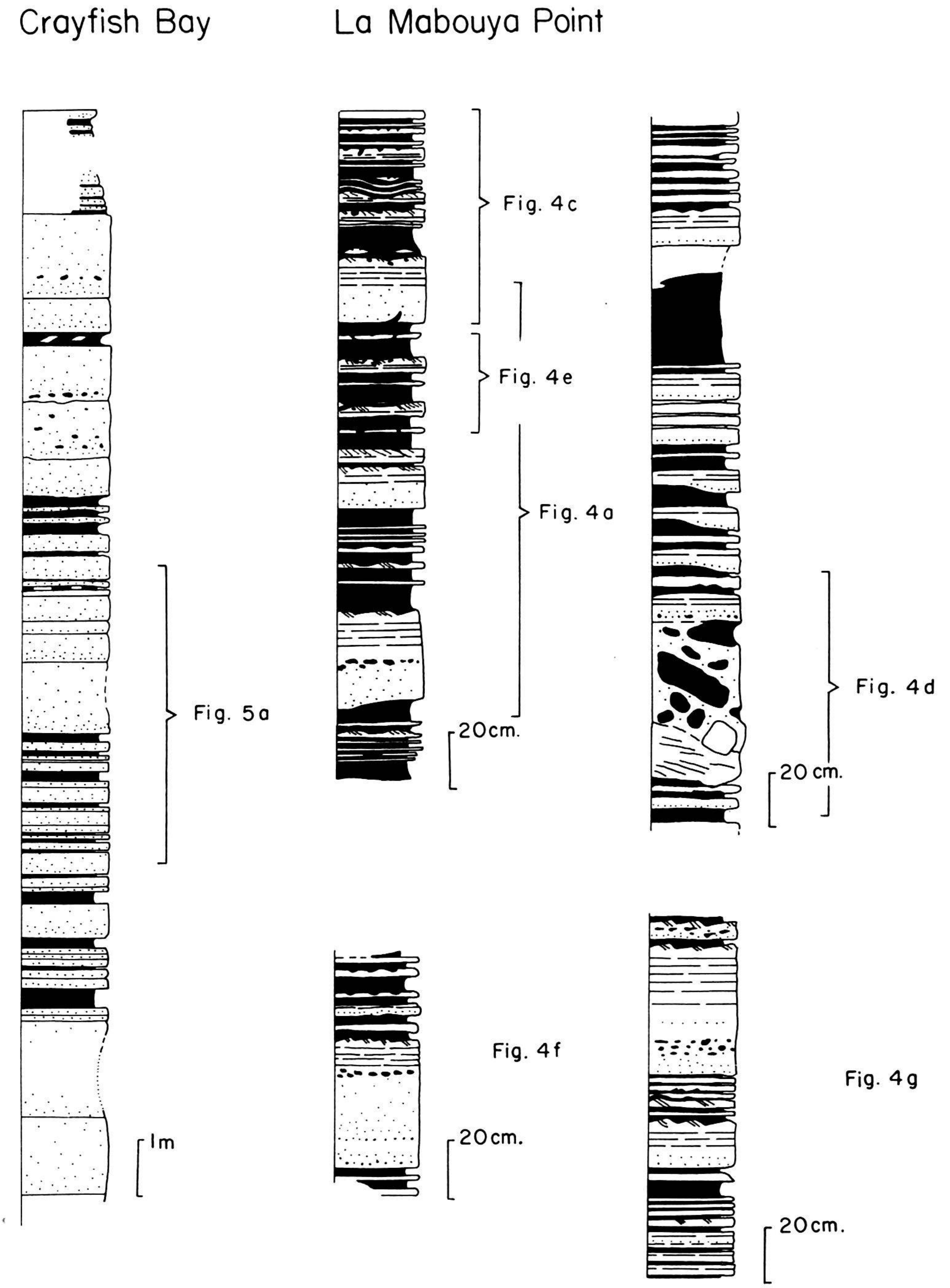


Fig. 3. Typical lithological sequences in the Tufton Hall Formation, Crayfish Bay (left) and La Mabouya Point (centre and right), Grenada. White: volcanic arenites (T_a–T_d intervals). Black: turbiditic mudstones (T_e) and hemipelagites.

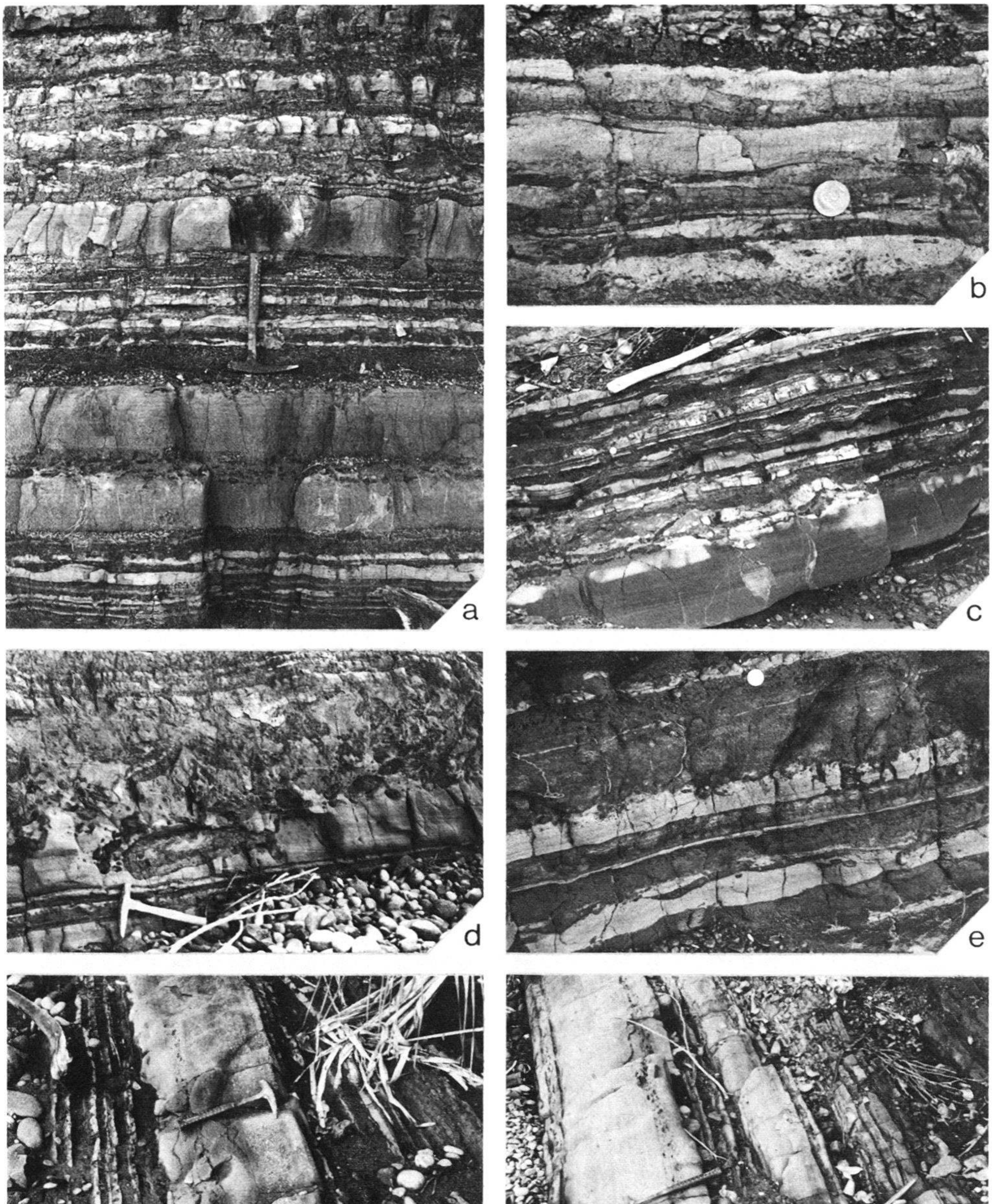
observe and it is only in the coastal outcrops (La Mabouya Point, Levera Bay) that sedimentary structures are readily visible in small but well exposed sections.

At La Mabouya Point a discontinuous, folded and faulted sequence of not more than 10 m total thickness is exposed. It consists of an association of thick-bedded fine rudites to arenites, cm-bedded arenites, mudstones and hemipelagic marlstones (Fig. 3). The thick-bedded rudites to arenites are between 15 and 60 cm thick and distinctly graded with well-developed plane and ripple laminations (T_{a-c}, Fig. 4f and 4g). They often display distinctly rippled surfaces (facies C_1 of MUTTI & RICCI LUCCHI 1972, and in MUTTI et al. 1975). They also contain trains of mud pebbles in the uppermost part of the graded interval (Fig. 4a, 4f and 4g). The outcrop is not large enough to observe distinct channels. However, some variations in thickness and lensing is seen in thinner beds. Amalgamation of coarse sandstones is observed in a 60 cm-thick bed. In this amalgamated layer the presence of large mudstone slabs and lithic pebbles is particularly conspicuous (Fig. 4d).

The thin-bedded arenites are only a few centimeters thick. They are often laterally discontinuous and show ripples with wavelengths of 10 cm and amplitudes of 2 to 3 cm. Some of these beds show a plane lamination in the lower part with superposed ripples (Fig. 4e), while some show only plane or ripple lamination (Fig. 4b). Many exhibit reworking by intense bioturbation from their tops with *Chondrites* type burrows filled with marl or mudstone derived from above (Fig. 4e). The thinner beds most probably correspond to facies E of MUTTI & RICCI LUCCHI (1972). In a few cases, however, incomplete Bouma cycles (T_{c-e}, facies D) are observed. Fine, cm and less thick laminae of arenites and siltites often follow the relief of the underlying rippled arenites (Fig. 4c). Thicker bedded, brown coloured, non-calcareous mudstone layers (Fig. 4e) are interpreted as turbiditic mudstones: they are homogeneous and only burrowed from above along their upper surface, whereas light coloured hemipelagic coccolith marlstones are intensely burrowed by *Chondrites* (cf. Fig. 5e).

In the section along the west coast road at Crayfish Bay, about 19 m of thick-bedded, brown, feldspar-rich volcanic arenites associated with thin-bedded grey and brown turbiditic arenites, siltites and mudstones are exposed (Fig. 3 and Fig. 5a). The thick-bedded lithologies are of a massive and "tuffaceous" appearance, they typically contain sparse pebbles of siltstone or mudstone and are speckled with carbonaceous fragments and white granules and are probably deposits of debris or highly concentrated turbidity flow.

Fig. 4. Turbiditic facies of Tufton Hall Formation at La Mabouya Point, for location of the different figures see Textfigure 3. At La Mabouya Point, the Tufton Hall Formation consists of an association of brown coloured fine lithic rudites to arenites between 15 and 60 cm thick, thin-bedded white feldspar-rich volcanic arenites, brown to olive mudstones and light-coloured hemipelagic marlstones (Fig. 4a). The thicker bedded rudites to arenites (T_{a-c}) are distinctly graded (Fig. 4a, 4e and 4f) and above the massive graded interval a parallel laminated interval is well developed whilst the tops of the beds are distinctly rippled (left in Fig. 4f and 4g, see also Fig. 3). In some of the thick-bedded turbidites a layer of mud pebbles which often has little continuity along the bedding can be observed (Fig. 4a, 4f and 4g). No obvious channeling has been observed in the outcrop but some thinner beds vary in thickness laterally and one amalgamated bed was observed that carries large mudstone slabs and pebbles in a matrix of fine ruditic material (Fig. 4d). The thicker beds have been deposited by highly concentrated turbidity flows. The thin-bedded arenites are only a few centimeters thick (Fig. 4a–4c, 4e), they are plane laminated at their base with ripple lamination at their tops (Fig. 4e) or rippled throughout (Fig. 4b). These beds show exclusively indications of tractive current deposition and correspond to facies E of MUTTI & RICCI LUCCHI (1972 and in MUTTI et al. 1975). Many of the arenites are heavily burrowed from their tops with brown mudstone introduced from above (Fig. 4e).


a
b
c
d
e
f
g

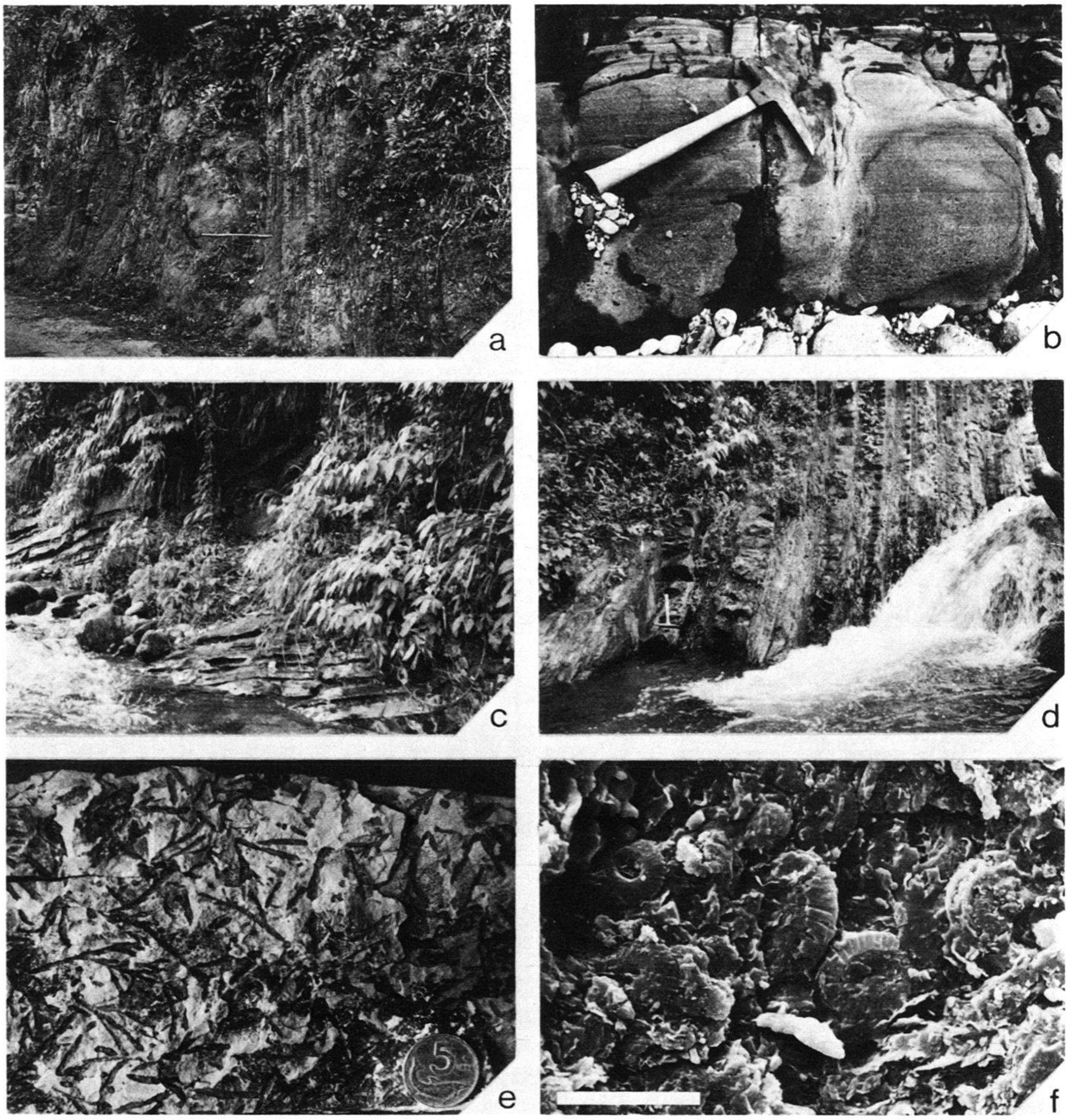


Fig. 5. a: Alternation of thick-bedded volcanic arenites (debris or highly concentrated turbidity flow deposits), thin-bedded turbiditic arenites and mudstones. Crayfish Bay. Scale is 1 m. b: Graded and laminated volcanic arenite (T_{a-c}). St. Marks River, Tufton Hall Estate. Locality Mk 7346. c: Typical outcrop in the Tufton Hall Formation with alternating graded arenites and mudstones. St. Marks River, Tufton Hall Estate. d: Alternation of dm- to cm-bedded arenites and mudstones. The sequence is younging towards the north (left) and shows a thickening-upward cyclic development. St. Marks River, Tufton Hall Estate. The hammer rests on a volcanic arenite rich in larger foraminifera (Mk 7349). e: Hemipelagic marlstone with burrows of *Chondrites*. Tufton Hall Estate. Mk 7348. Diameter of coin is 2 cm. f: Scanning electron micrograph of hemipelagic marlstone illustrated in Figure 5e. The fine sediment is composed of coccoliths and clay minerals. Scale bar is 10 μm.

The thin-bedded arenites and siltites are graded and laminated, and the mudstones occasionally show burrows of *Chondrites* type.

In the Tufton Hall Estate the river course is badly overgrown at the moment with consequent poor exposure of the type section. Generally the formation consists of parallel-bedded sequences of non-channelized dm- to cm-bedded arenites and lutites. The sandstone/shale ratio is around one or slightly higher, and a general tendency towards cyclic development with thickening upwards cycles can be observed (Fig. 5d). Thicker beds occasionally present are graded and laminated with mudstone inclusions in the T_a-interval (Fig. 5b). Intercalated hemipelagic coccolith marlstones are riddled with burrows of *Chondrites* type (Fig. 5e and 5f).

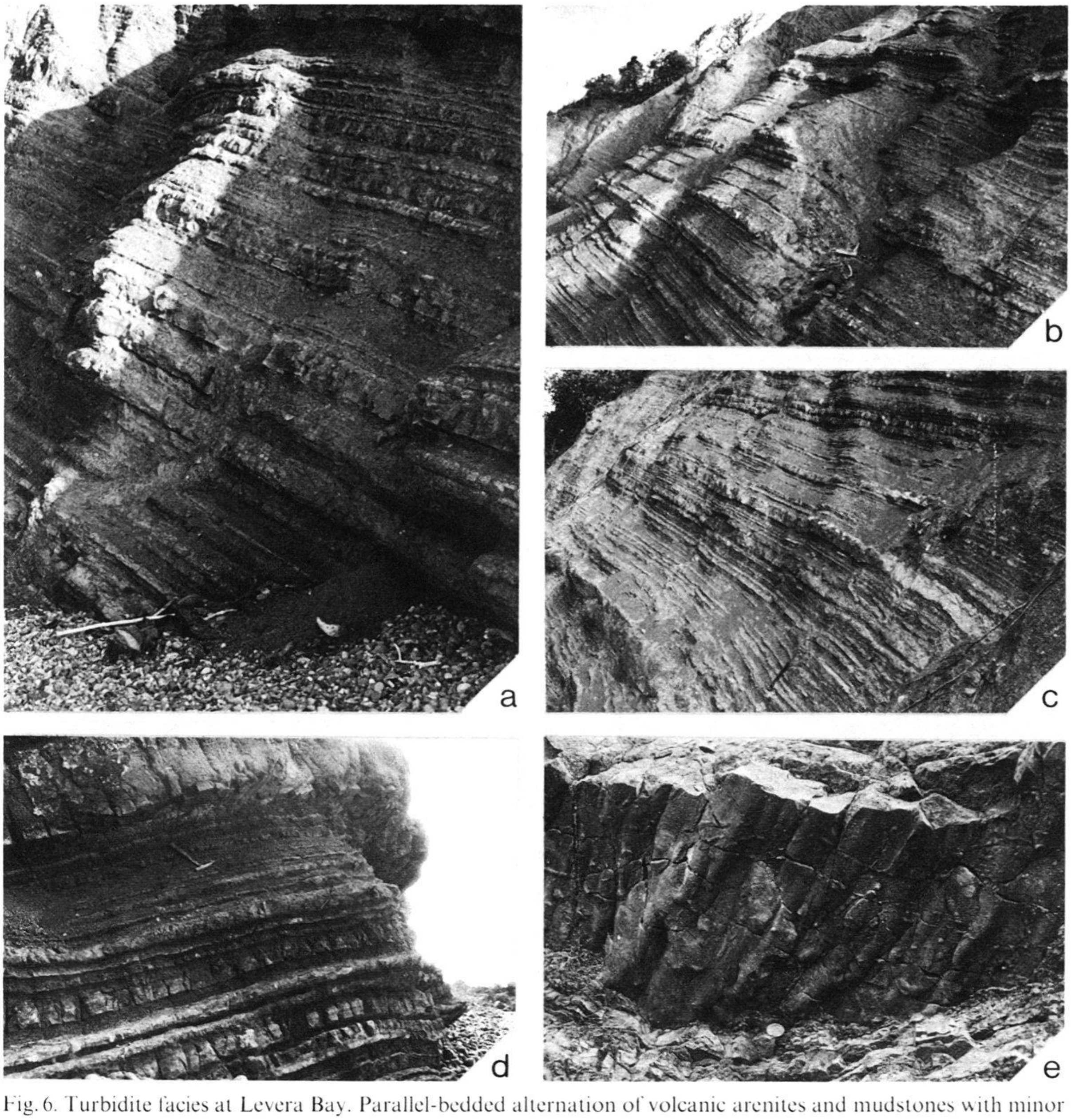


Fig. 6. Turbidite facies at Levera Bay. Parallel-bedded alternation of volcanic arenites and mudstones with minor hemipelagic marlstone intercalations. In the upper part of the sequence (Fig. 6b and 6c) thickening-upward sequences suggest deposition in a prograding sand lobe. Flute casts (Fig. 6e) at the base of a 60 cm thick arenite bed (Fig. 6d, top of photograph) indicate a current direction from south to north.

In the Levera Bay section (Fig. 6), the sequence consists of an alternation of well-bedded turbiditic arenites, mudstones and marlstones. The sequence is parallel-bedded and no channelized deposits have been observed. Though the arenites may be up to 30 cm thick, usually they are in the order of a few to 15 cm and show complete or incomplete Bouma cycles (facies C_2 and D of MUTTI & RICCI LUCCHI 1972, and in MUTTI et al. 1975). One larger bed of 60 cm thickness was observed; flute casts at its base indicate a current direction from south to north (Fig. 6e). Intercalated hemipelagic marlstones are clearly distinct from the turbiditic mudstones (T_e). They are light yellow with darker burrows of *Chondrites*-type and contain abundant coccoliths, whereas the turbiditic mudstones are olive to grey and finely laminated. There is no distinct cyclic development in this section: sets of thicker bedded arenites with high sandstone/shale ratio alternate with shale-rich sets of thinner strata in the lower part of the section (Fig. 6a), and thickening-upward sequences may be recognized only in the upper part (Fig. 6b and 6c).

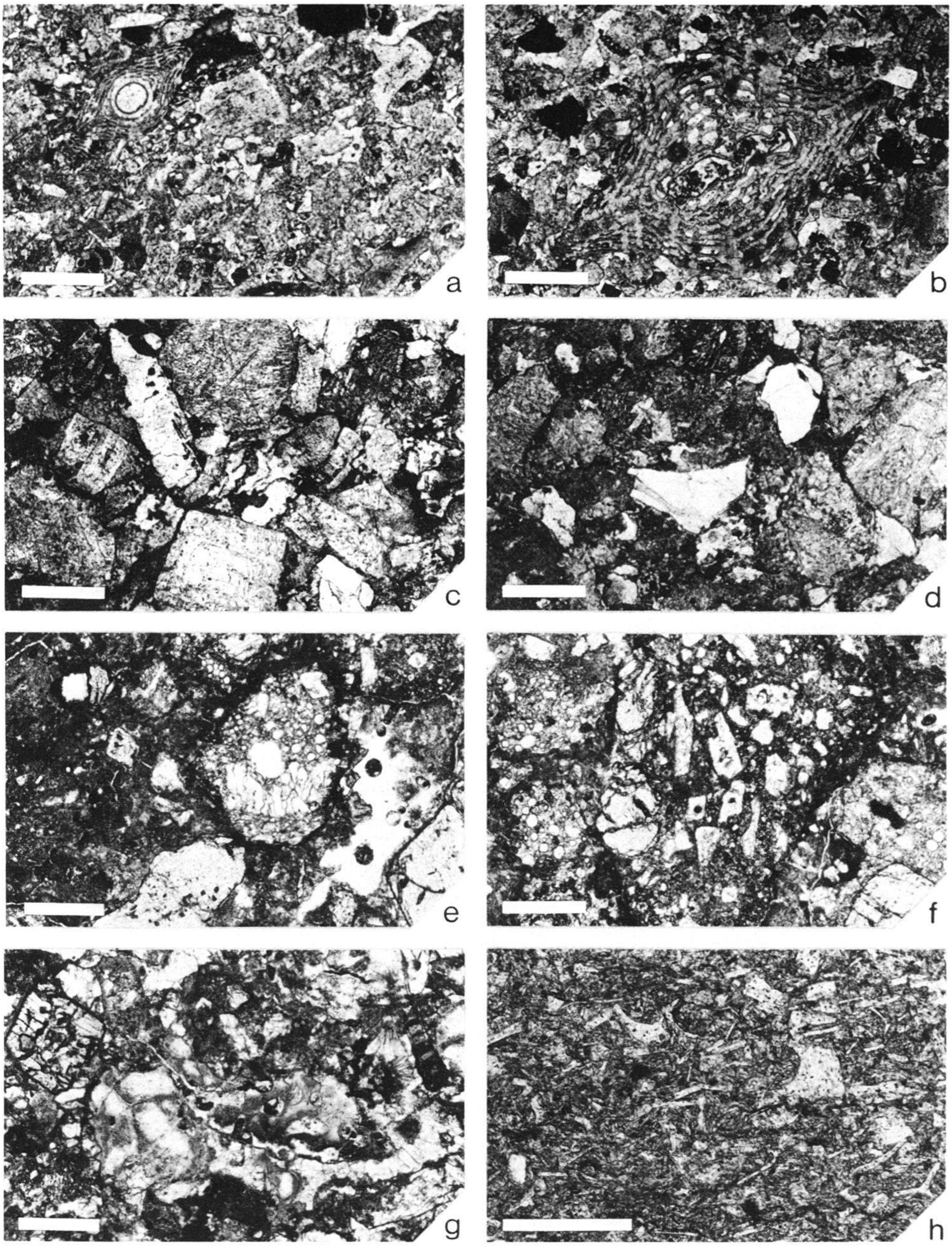
Petrology

In all the rudites and arenites of the Tufton Hall Formation more or less altered volcanic material dominates the clastic fraction. In the Mabouya Point section, the clastic material seems to be exclusively volcanic, whereas in the Crayfish Bay section and in the Tufton Hall area there is an admixture of skeletal carbonate material particularly in the coarser grained lithologies. The skeletal material is primarily composed of larger foraminifera (Fig. 7a–b), spines and plates of echinoids, coralline algae, planktonic foraminifera and a few bivalve fragments. In the Levera Bay section, fossils are particularly frequent and there is also some detrital quartz (< 5%) present. Compositionally the arenites have to be classified as feldspathic volcanic arenites (FOLK 1968).

The rudites and coarse arenites contain granule-sized, angular lithic fragments of andesitic to basaltic composition, plagioclase and pyroxene mineral grains in a fine-grained muddy matrix. The lava fragments commonly show a phyric texture with large phenocrysts of plagioclase and pyroxene; in part they also display a vesicular texture (Fig. 7e). The finer-grained, often lighter coloured arenites contain variable amounts of strongly altered volcanic fragments, the composition of which can no longer be recognized, and of plagioclase and pyroxene (Fig. 7c). Relics of volcanic glass fragments

---

Fig. 7. Photomicrographs of thin sections. Tufton Hall Formation. Grenada. a: Lithic to feldspathic volcanic arenite rich in altered volcanic debris and altered (zoned) plagioclase. Admixed skeletal carbonate consists mainly of displaced larger foraminifera (*Lepidocyclina* sp. in upper left), coralline algae, and some planktonic foraminifera. Levera Bay, DB 5122, scale bar is 0.5 mm. b: Displaced larger foraminifer, *Lepidocyclina pustulosa* forma *tobleri*, in lithic to feldspathic volcanic arenite. Levera Bay, DB 5122, scale bar is 0.5 mm. c: Lithic arenite with volcanic debris and altered zoned plagioclase (e.g. lower centre). Levera Bay, DB 5121, scale bar is 0.5 mm. d: Lithic arenite with volcanic debris, altered plagioclase and some detrital quartz. Levera Bay, DB 5121, scale bar is 0.5 mm. e: Lithic fine rudite to arenite with a clayey (smectitic) matrix containing lithic fragments of vesicular lava (centre) and of phyric lava with altered plagioclase and fresh pyroxene (lower centre and lower right corner). La Mabouya Point, DB 5112, scale bar is 0.5 mm. f: Lithic fine rudite to arenite with debris of phyric (centre) and vesicular lava. Plagioclase is strongly altered whereas pyroxenes are relatively fresh. La Mabouya Point, DB 5112, scale bar is 0.5 mm. g: Lithic rudite to arenite with fragments of volcanic rocks, plagioclase and pyroxene in a clayey (smectitic) matrix. Newly formed rosettes (upper right) are presumably zeolites. Crayfish Bay, DB 5116, scale bar is 0.5 mm. h: Laminated siltstone with devitrified glass shards. Crayfish Bay, DB 5117, scale bar is 0.2 mm.


a
b
c
d
e
f
g
h

can be recognized in many of the rocks, but are particularly abundant in laminated siltites and mudstones (Fig. 7h).

Plagioclase is by far the most abundant mineral. Much of it is strongly altered to albite or sericite, but a primary zonation can be recognized in many crystals. Amongst the pyroxenes, which are remarkably fresh, clinopyroxene dominates. Additionally, small amounts of olivine and hornblende occur. The glass fragments are generally altered to albite, chlorite and iron oxides. Other secondary minerals include clay minerals and zeolites.

At La Mabouya Point, the clay fraction smaller than 2 μm consists exclusively of smectites, whereas at Levera Beach small amounts of detrital kaolinite are also found. At this latter locality smectites appear to be largely altered to corrensite, an ordered mixed-layer clay mineral composed of montmorillonite and chlorite layers. At the same time, plagioclase is altered to albite with the formation of heulandite which obviously represents a sink for the released Ca-ions. We interpret these newly formed minerals as related to somewhat more advanced diagenesis. However, as also noted by SPEED & LARUE (1985), the environment of deformation was clearly non-metamorphic and at shallow depth.

The primary composition of the volcanic material could not be deduced from our samples, and, more specifically, we are unable to decide if the volcanics are of andesitic or basaltic composition. However, FERRAGNE et al. (1985) noted a shift from calc-alkaline to intermediate andesitic-tholeiitic composition in the volcanic ashes of the Oceanic Formation on Barbados between the Middle and the Late Eocene.

Although there is plenty of evidence that the volcanic arenites are not primary deposits (tuffs) but reworked and current deposited, there is little doubt about the penecontemporaneous redeposition of the volcanic material. The almost exclusively volcanic composition of the volcanic arenites points to an almost pure volcanic source area and the angularity and freshness of the pyroxene crystals and the plentiful occurrence of glass fragments point to rapid redeposition.

Fauna and flora

Megafossils, other than larger foraminifera, are practically non-existent. A small coral and a small bivalve were found in one volcanic arenite and coralline algae and echinoid remains have been noted in thin sections.

Certain of the mudstones and, more commonly, the marlstones show branching burrows of *Chondrites* (Fig. 5e). This form genus has a worldwide distribution and a range from Paleozoic to Tertiary. There have been various views on the origin of these trace fossils but the concensus seems to be that the burrows represent the feeding tunnels of sipunculid worms working downwards and then in a horizontal fan system from the seafloor (SIMPSON 1957, OSGOOD 1970).

Some arenites contain larger foraminifera and these are often broken and eroded (Fig. 7a and 7b). The following species have been identified by W. Storrs Cole:

Asterocyclina asterisca (GUPPY)
Helicostegina soldadoensis GRIMSDALE
Lepidocyclina macdonaldi CUSHMAN
Lepidocyclina pustulosa tobleri H. DOUVILLÉ (cf. Fig. 7b)
Fabiania cubensis (CUSHMAN & BERMUDEZ)

The smaller foraminiferal assemblages found in the mudstones and marlstones are relatively rich in agglutinating and calcareous benthonic species with varying numbers of planktonics. Preservation is often not good and many of the tests are crushed and distorted. The type section was originally chosen in the Tufton Hall Estate because of the relative richness of the faunas.

Planktonic species found here include:

Catapsydrax unicavus BOLLI, LOEBLICH & TAPPAN
Globorotalia centralis CUSHMAN & BERMUDEZ
Globorotalia cerroazulensis cunialensis TOUMARKINE & BOLLI
Globorotalia opima nana BOLLI
Hantkenina alabamensis CUSHMAN
Hantkenina suprasuturalis BRÖNNIMANN
Cribrohantkenina danvillensis (HOWE & WALLACE)
Pseudohastigerina micra (COLE)

The common benthonic species are:

Bathysiphon spp.
Ammodiscus incertus (D'ORBIGNY)
Cyclammina garcilassoi FRIZZELL
Karreriella chilostoma (REUSS)
Vulvulina jarvisi CUSHMAN
Spiroplectammina trinitatensis CUSHMAN & RENZ
Chilostomella czizeki REUSS
Anomalina pompilioides GALLOWAY & HEMINWAY

Many of the assemblages are rich in radiolaria though these are often poorly preserved. SANFILIPPO & RIEDEL (1976) listed species from one sample in the Tufton Hall Estate. The re-evaluation of this sample is discussed on pages 482–483.

Some of the mudstones and marlstones contain calcareous nannofossils. Preliminary studies by K. Perch-Nielsen indicate Late Eocene but with a few samples suggesting Oligocene on negative evidence.

Environment of deposition

a) Sedimentological evidence

As shown by their sedimentary structures, all the ruditic and arenitic beds of the Tufton Hall Formation have been deposited by turbidity currents and related mechanisms, and all the features are in accordance with deposition in a submarine fan environment. However, the lack of any lithologic correlation between the small observable sections which certainly make up only a minor part of a formation that could be several hundred meters or more thick prevents the reconstruction of the depositional geometry. At La Mabouya Point a close association of thick-bedded turbidites (T_{a-c}; facies C_1 of MUTTI & RICCI LUCCHI 1972, and in MUTTI et al. 1975) with thin-bedded, laminated and rippled sand (facies E) and minor incomplete Bouma cycles has been noted. This association could be tentatively interpreted as a final phase of channel filling and a transition to open fan deposition. In the Crayfish Bay section, the close association of massive and sometimes nongraded arenites with thin-bedded turbidites and mudstones points to a relatively proximal site of deposition. Finally the occurrence of parallel-bedded and thickening-upward sequences in the Tufton Hall Estate area and in the Levera Bay section could be in accordance with deposition on a prograding sand lobe in an outer fan environment.

b) Faunal evidence

Information on depth ranges of benthonic foraminifera is still somewhat ambiguous because factors other than depth are of considerable importance. Based on the composition of the benthonic foraminiferal fauna, an estimate would suggest a depth greater than 2000 m but above the calcium carbonate compensation depth. Taking the results of RAMSEY (1974), the CCD for this time and this geographic area was at approximately 4000 m water depth. Additional evidence towards the placement of the CCD has come from the results of Site 543 drilled 200 km north of Barbados during Leg 78A of the Deep Sea Drilling Project (BIJU-DUVAL, MOORE et al. 1984). The paleodepth for the site in the Late Eocene can be estimated by back-tracking to be approximately 4800 m. The site was below the CCD at that time on the evidence of the total lack of calcareous component in the fauna and flora.

SAUNDERS et al. (1984) discuss the problems of assigning a paleodepth for the deposition of the age-equivalent Oceanic Formation exposed in the Bath Cliffs on Barbados. These rocks contain a rather similar smaller foraminiferal fauna though without the "flysch-type" agglutinated elements that are common in the Tufton Hall Formation. In both cases, the possible range in depth would seem to be between 2000 m and 4800 m but with the Grenada faunas suggesting perhaps a shallower situation than those of Barbados.

Age of the formation

The first indication of age was obtained from the larger foraminifera submitted to W. Storrs Cole. He gave a Late Eocene age but allowance had to be made for the allochthonous nature of the fauna. However, it is now recognized that the larger foraminifera must have been penecontemporaneously displaced from shallow marine banks.

The latest study of the planktonic foraminifera shows that, wherever a good age determination can be achieved, this proves the presence of the uppermost Eocene zone of *Globorotalia cerroazulensis cunialensis* established by TOUMARKINE & BOLLI (1970). In BLOW's (1969) terminology this would be upper part P16 or lowest part P17. It was once considered that the outcrops at Clozier Bridge might be as young as Early Oligocene but the same Late Eocene zone has now been proved here also. However, the small inlier at Bylands has a specialized planktonic foraminiferal fauna that, according to M. Toumarkine (personal communication), is more likely to be Early Oligocene than Late Eocene though this is on rather negative evidence. The relationship between this inlier and the main outcrops of the Tufton Hall Formation is in some doubt.

An assemblage of radiolaria reported by SANFILIPPO & RIEDEL (1976) from sample Mk 6639 in the Tufton Hall Estate provides confirmation of youngest Late Eocene age. Their determination was "*Thyrsocyrtis bromia* Zone near the boundary with *Theocyrtis* *tuberosa* Zone". Later work on the Eocene/Oligocene boundary in Barbados (SAUNDERS et al. 1984) has resulted in a refined radiolarian zonation and A. Sanfilippo (personal communication) now places this sample in the topmost Eocene, *Cryptoprora ornata* Zone.

Summary of the geologic history of the area

Dating of volcanic rocks from a number of islands in the southern part of the West Indian Arc has produced almost nothing older than 20 m.y. with most results being younger than 10 m.y. (BRIDEN et al. 1979, MAURY & WESTERCAMP 1985). However, datable sediments occur as isolated outcrops on a number of southern islands and these extend the history back certainly to 50 m.y. and perhaps to 80 m.y.

St. Lucia has minor limestone lenses of probable Early Miocene age while St. Vincent has produced no datable fossils so far (MARTIN-KAYE 1969).

From the Grenadine islands, situated between St. Vincent and Grenada, MARTIN-KAYE (1969) reported Lower or Middle Eocene silicified limestone from Mayreau and fossiliferous marlstone of *Globorotalia fohsi lobata* Zone, Middle Miocene age from Petite Martinique.

From Carriacou (MARTIN-KAYE 1958), Upper Eocene rocks have been grouped together as the Anse la Roche Formation (ROBINSON & JUNG 1972). At the type section, 45 m of poorly sorted, graded, foraminiferal volcanic conglomerates in beds ranging from 3 to 7 m thick are overlain by 7 m of hard algal/larger foraminiferal limestone. Planktonic faunas from Petit Carenage in the north of the island are of definite Late Eocene age and probably of the *Globorotalia cerroazulensis cunialensis* Zone. This makes the beds the time equivalent of the Tufton Hall Formation. Younger limestones, tuffs and conglomerates have been dated as upper part Oligocene and lower part Miocene.

Recent field work by a French team has produced important new information from the Grenadines (WESTERCAMP et al. 1985). The most surprising result is the report of hyaloclastites, marls and silicified limestones on Union island dated by nannofossils as Senonian (in the range Santonian to Campanian). This is the first pre-Tertiary date from the southern half of the Lesser Antilles. WESTERCAMP et al. (1985) also document a considerable number of datable sediments in the age range from Middle Eocene to Middle Miocene.

From all studies so far, the oldest island arc material in the southern half of the Lesser Antilles appears to be of Middle Eocene age (BOUYSSE 1984) so earlier island arc volcanism in the southern part of the present West Indian Arc has yet to be proved. However, a Mesozoic substratum for the arc is suggested by the occurrence of Senonian rocks. As WESTERCAMP et al. (1985) point out, such a basement had already been suggested to them by G. Westbrook from geophysical considerations.

In Barbados, which today forms a part of the accretionary prism (Fig. 1), submarine fan deposits are widespread in the Scotland Formation but they are composed of continent-derived detritus and have not been proved to be younger than Middle Eocene on present evidence. A time equivalent of the Tufton Hall Formation is developed in the Oceanic Formation where it is well exposed in the Bath Cliff section (SAUNDERS & CORDEY 1968; SAUNDERS et al. 1984). Beds dated as Late Eocene on a combination of radiolaria, calcareous nannofossils and foraminifera are in the order of 100 m thick here. In the lower part they consist of indurated, coccolith radiolarian ooze with, higher up, an increasing calcareous percentage represented mainly by the tests of coccoliths and foraminifera producing a chalk. More than 30 thin but well marked ash beds have been counted in this thickness and the number must be considerably greater.

The evidence from Grenada itself would suggest the following history:

During the Late Eocene (± 38 m.y. b.p.), sedimentation took place in a deep basin or trough associated with the volcanic arc and close enough to it to receive large quantities of volcanic debris in the form of lithic fragments, sand size volcanic minerals and glass shards. Shallow water bioclastic debris was also introduced from fringing shoal areas. A presumed extension of the Tufton Hall Formation has come from a dredge haul taken 5 km offshore on the steep northwestern slope of Grenada in 1500–1000 m water depth (Westercamp et al. 1985).

By Middle Oligocene time sedimentation was active with shallow water bioclastic debris and volcanic debris being introduced into a bathyal environment. The relationship between the Oligocene sediments and the Tufton Hall Formation is still uncertain but evidence is strong that the folding and planation of the Late Eocene beds took place before the Miocene. This history is, in a general way, comparable to that of part of the Paleogene outer arc of the northern Lesser Antilles (Andreieff et al. 1981; Bonneton & Vila 1983) where Late Eocene volcaniclastic turbidites are unconformably overlain by Late Miocene bioclastic and marly sediments.

During the Miocene, shallowing was strongly evident with the build up of volcanic debris and by Late Miocene time subaerial volcanoes were probably already active on the present site of the island. The oldest date published for the volcanics is 21.2 ± 1 m.y. b.p. (Briden et al. 1979) and from this time in the Miocene until Late Pleistocene, volcanic centres were particularly active. The Holocene has been a period of lesser activity in this southernmost part of the arc.

The geological history outlined above can be compared with the scenario proposed by Speed & Larue (1985) who conclude that the Eocene turbidites were most likely deposited on the arcward flank and base of slope of a forearc basin partly represented by the present Tobago Trough. The N–S compression with northward overriding that they reconstructed in the field is seen by them to be a possible effect of a mid-Tertiary collision of the southern Lesser Antilles magmatic arc platform with continental South America.

Acknowledgments

The fieldwork of one of us (D.B.) was made possible by a contribution from the Shell Grants Committee in London.

K. Perch-Nielsen and M. Toumarkine of Zürich and M. Frey, W. Stern and W. Winkler of Basel provided welcome assistance during the preparation of this paper. A. Sanfilippo of Scripps Institution kindly restudied a radiolarian sample.

Useful comments by A. Matter have been incorporated.

REFERENCES

Andreieff, P., Bizon, G., & Bouysse, P. (1981): Révision de l'âge des formations sédimentaires de l'île de Saint-Martin: implications sur la chronologie du volcanisme de l'arc insulaire des Petites Antilles. – C.R. Acad. Sci. Paris (D) *292*, 79–82.

Biju-Duval, B., Moore, J.C., et al. (1984): Init. Rep. Deep Sea Drill. Proj. *78A*. – U.S. Gov. Print. Office, Washington.

BLOW, W. H. (1969): Late Middle Eocene to Recent Planktonic Foraminiferal Biostratigraphy. – Proc. First int. Conf. on Planktonic Microfossils, Geneva 1967, p. 199–422.

BONNETON, J.-R., & VILA, J.-M. (1983): Données géologiques nouvelles à l'île de Saint-Martin (Petites Antilles). – Bull. Soc. géol. France (7), *25*, 867–871.

BOUYSSE, P. (1984): The Lesser Antilles island arc: structure and geodynamic evolution. In: BIJU-DUVAL, B., MOORE, J. C., et al.: Init. Rep. Deep Sea Drill. Proj. *78A* (p. 83–103). – U.S. Gov. Print. Office, Washington.

BRIDEN, J. C., REX, D. C., FALLER, A. M., & TOMBLIN, J. F. (1979): K–Ar geochronology and paleomagnetism of volcanic rocks in the Lesser Antilles island arc. – Phil. Trans. r. Soc. London (A) *291*, 485–528.

EARLE, K. W. (1924): Geological Survey of Grenada and the (Grenada) Grenadines. – Grenada Gvt. Print. Office.

FERRAGNE, A., PARRA, M., BARDINTZEFF, J. M., DESPRAIRIES, A., MORIN, J. C., & CADET, J. P. (1985): Les cendres de l'île de Barbade: témoins du volcanisme cénozoïque et quaternaire de l'arc des Petites Antilles. In: MASCLE, A. (Ed.): Géodynamique des Caraïbes (p. 199–219). – Technip, Paris.

FOLK, R. L. (1968): Petrology of Sedimentary Rocks. – Hemphill's, Austin.

MARTIN-KAYE, P. H. A. (1958): The Geology of Carriacou. – Bull. amer. Paleont. *38*/175, 395–404.

— (1969): A summary of the Geology of the Lesser Antilles. – Overseas Geol. miner. Resour. *10*/2, 172–206.

MAURY, R. C., & WESTERCAMP, D. (1985): Variations chronologiques et spatiales des basaltes néogènes des Petites Antilles. Implications sur l'évolution de l'arc. In: MASCLE, A. (Ed.): Géodynamique des Caraïbes (p. 77–89). – Technip, Paris.

MUTTI, E., PAREA, G. C., RICCI LUCCHI, F., SAGRI, M., ZANZUCCHI, G., GHIBAUDO, G., & IACCARINO, S. (1975): Examples of turbidite facies and facies associations from selected formations of the Northern Apennines. – Field trip A 11, IX Int. Congr. Sedimentol., Nice 1975.

MUTTI, E., & RICCI LUCCHI, F. (1972): Le torbiditi dell'Appeninno settentrionale: introduzione all'analisi di facies. – Mem. Soc. geol. ital. *9*, 161–199.

OSGOOD, R. G. (1970): Trace fossils of the Cincinnati area. – Palaeontographica amer. *6*/41, 277–444.

RAMSEY, A. T. S. (1974): The distribution of calcium carbonate in deep sea sediments. – Spec. Publ. Soc. econ. Paleont. Mineral. *20*, 58–76.

ROBINSON, E., & JUNG, P. (1972): Stratigraphy and age of marine rocks, Carriacou, West Indies. – Bull. amer. Assoc. Petroleum Geol. *56*/1, 114–127.

SANFILIPPO, A., & RIEDEL, W. (1976): Radiolarian occurrences in the Caribbean Region. – Trans. 7th Caribbean Geol. Conf., p. 145–168.

SAUNDERS, J. B., & CORDEY, W. G. (1968): The biostratigraphy of the Oceanic Formation in the Bath Cliff Section, Barbados. – Trans. 4th Caribbean Geol. Conf., p. 179–181.

SAUNDERS, J. B., BERNOULLI, D., MÜLLER-MERZ, E., OBERHÄNSLI, H., PERCH-NIELSEN, K., RIEDEL, W. R., SANFILIPPO, A., & TORRINI, R., Jr. (1984): Stratigraphy of the Late Middle Eocene to Early Oligocene in the Bath Cliff Section, Barbados, West Indies. – Micropaleontology *30*/4, 390–425.

SIMPSON, S. (1957): On the trace fossil *Chondrites*. – Quart. J. geol. Soc. London *112*, 475–499.

SPEED, R. C., WESTBROOK, G. K., MASCLE, A., BIJU-DUVAL, B., LADD, J. W., SAUNDERS, J. B., STEIN, S., SCHOONMAKER, J. E., & MOORE, J. C. (1984): Lesser Antilles arc and adjacent terranes. – Atlas 10, Ocean Margin Drill. Program, Reg. Atlas Ser. Marine Sci. Internat., Woods Hole.

SPEED, R. C., & LARUE, D. K. (1985): Tectonic evolution of Eocene turbidites of Grenada. In: MASCLE, A. (Ed.): Géodynamique des Caraïbes (p. 101–108). – Technip, Paris.

TOUMARKINE, M., & BOLLI, H. M. (1970): Evolution de *Globorotalia cerroazulensis* (Cole) dans l'Eocène moyen et supérieur de Possagno (Italie). – Rev. Micropaléont. *13*/3, 131–145.

WESTERCAMP, D., ANDREIEFF, P., BOUYSSE, PH., MASCLE, A., & BAUBRON, J. C. (1985): The Grenadines, Southern Lesser Antilles Part I. Stratigraphy and volcano-structural evolution. In: MASCLE, A. (Ed.): Géodynamique des Caraïbes (p. 109–118). – Technip, Paris.

Manuscript received 9 April 1985
Revision accepted 20 June 1985