The biostratigraphic record of Early Cretaceous to Paleogene relative sea-level change in Jamaica

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ABSTRACT

The island of Jamaica forms the northern extent of the Nicaragua Rise, an elongate linear tectonic feature stretching as far as Honduras and Nicaragua to the south. Uplift and subaerial exposure of Jamaica during the Neogene has made the island rare within the Caribbean region, as it is the only area where rocks of the Nicaragua Rise are exposed on land. Biostratigraphic dating and palaeoenvironmental interpretations using larger benthic foraminifera, supplemented by planktonic foraminifera, nannopalaeontology and palynology of outcrop, well and corehole samples has enabled the creation of a regional relative sea-level curve with the identification of several depositional sequences. This study recognises ten unconformity-bounded transgressive-regressive sequences which record a complete cycle of relative sea level rise and fall. Sequences are recognised in the Early to 'middle' Cretaceous (EKTR1), Coniacian-Santonian (STR1), Campanian (CTR1), Maastrichtian (MTR1-2), Paleocene-Early Eocene (PETR1), Eocene (YTR1-3) and Late Eocene-Oligocene (WTR1). These transgressive-regressive cycles represent second to fourth order sequences, although most tie to globally recognised third order sequences. Comparisons of the Jamaican relative sea-level curve with other published global mean sea-level curves show that local tectonics exerts a strong control on the deposition of sedimentary sequences in Jamaica. The effects of these tectonic events are exaggerated by contemporaneous global eustatic trends. The relatively low rates of relative sea-level rise calculated from the regional relative sea-level curve indicate that carbonate production rates were able to keep pace with the rate of relative sea-level rise accounting for the thick successions of Maastrichtian carbonates and those of the Yellow and White Limestone Groups. Carbonate platform drowning within the White Limestone Group during the Oligocene to Miocene is attributed to environmental deterioration given the low rates of relative sea-level rise.

Keywords: Carbonates, biostratigraphy, foraminifera, relative sea-level, tectonics

1. Introduction

Jamaica is the third largest island in the Caribbean, behind Cuba and Hispaniola. It is situated in the western portion of the Caribbean Sea and to the west of the Greater Antilles arc. The island of Jamaica forms the northern extent of the Nicaragua Rise, an elongate linear feature stretching as far as Honduras and Nicaragua to the southwest. The Nicaragua Rise is bounded on its northern side by the Cayman Trough and is separated from the Cuban arc by the Yucatán Basin (Arden Jr., 1977). The present day configuration of Nicaragua Rise comprises a shallow water carbonate platform up to 250 km in width, dropping steeply in to the Cayman Trough on its northern margin with a gentler incline into the Colombian Basin on its southern side (Arden Jr., 1977). The island of Jamaica is rare within the Caribbean region, as it is the only area where rocks of the Nicaragua Rise are exposed on land.

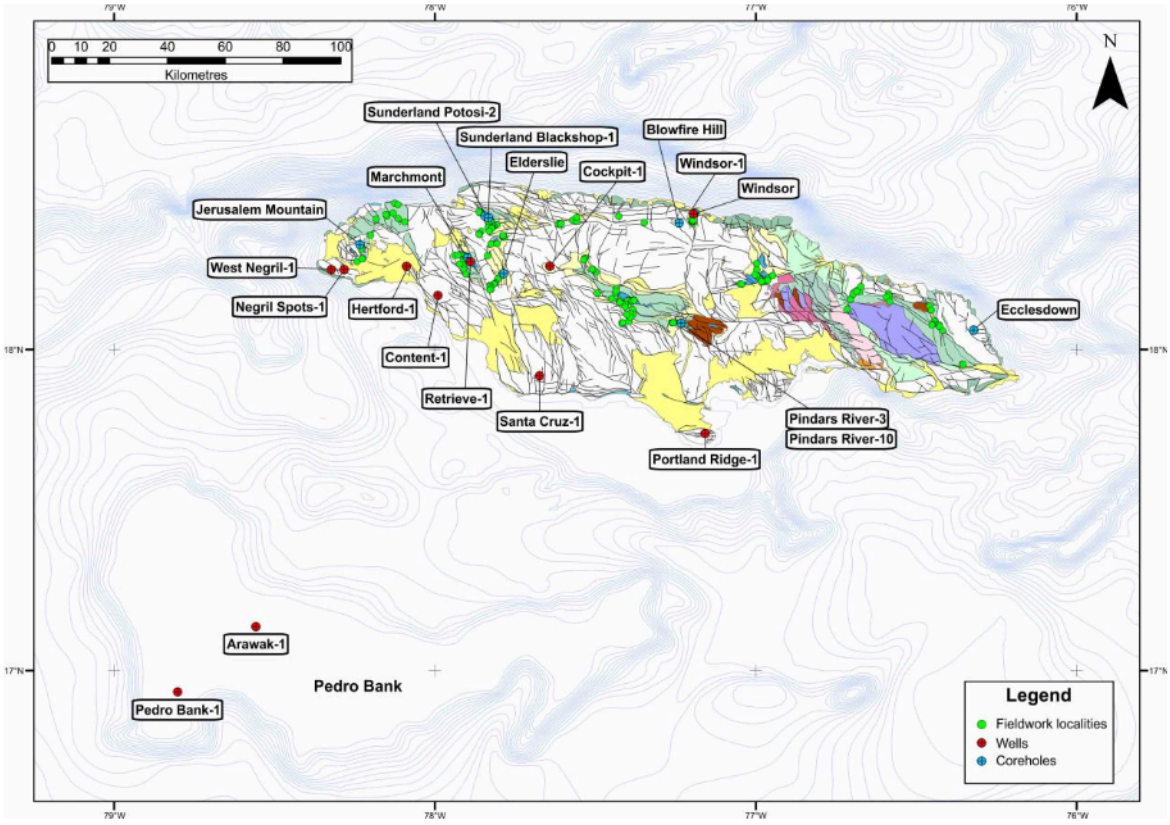


Fig. 1 – Geological map of Jamaica displaying locations of wells, coreholes and fieldwork localities.

Jamaica and its offshore sedimentary basins are sparsely explored, with only 2 wells drilled in the offshore section and 9 wells onshore along with several shallow coreholes (Fig. 1). No wells have been drilled since the mid-1980s. There have been oil or gas shows in 10 of the 11 wells drilled in the

onshore and offshore to date. The two wells drilled offshore Jamaica are Arawak-1 and Pedro Bank-1. The following nine wells are onshore: Cockpit-1, Content A/Content-1, Hertford-1, Negril Spots-1 (formerly known as Jamaica-1), Portland Ridge-1, Retrieve-1, Santa Cruz-1, West Negril-1 and Windsor-1. The distribution of all 11 wells across on- and offshore Jamaica is depicted in Figure 1.

The objective of this study is to describe new data from Jamaica which comprises new analyses of over 800 outcrop and well/corehole samples. In addition, these new biostratigraphic and sedimentological analyses revise and update the sequence-stratigraphic framework of Jamaica and tie depositional cycles to third-order sequences of Hardenbol *et al.* (1998) recalibrated to the 2012 Geologic time scale (Gradstein *et al.*, 2012).

2. Geological history

Formation of Caribbean oceanic plateau or large igneous province (CLIP) which forms the interior of the Caribbean Plate occurred during the early Jurassic (Burke *et al*., 1978; Burke, 1988). During the Early Cretaceous the crustal fragments that later assembled to form Jamaica and the Nicaragua Rise were in a period of relative tectonic quiescence depositing the shallow marine limestones of the Benbow Inlier, and similar rocks known from Puerto Rico and Trinidad, in vast epeiric seas close to a volcanic arc (Kauffman and Sohl, 1974). Strata of the Benbow Inlier are the oldest exposed in Jamaica, where there are no sediments older than Valanginian age (Brown and Mitchell, 2010). Early to 'middle' Cretaceous volcanics in the Central Inlier and the succession of the Benbow Inlier are interpreted to represent a volcanic island arc and/or ophiolite suite either as part of the CLIP, or a back/fore-arc spreading centre (Wadge *et al*., 1982; Jackson, 1987; Kerr *et al*., 2004; Mitchell, 2006). The Turonian-Coniacian unconformity is interpreted to have formed during the assembly of CLIP fragments and subduction of normal ocean floor at convergent margins on the northern and southern peripheries of the unusually buoyant CLIP ocean floor (Burke *et al*., 1978; Burke, 1988; Mitchell, 2006).

Following the formation of the Turonian-Coniacian unconformity deep water sedimentation was prevalent over Jamaica during the Coniacian and Santonian. This deep water setting is responsible for the deposition of the Windsor, Clamstead, Middlesex and Dias Formations. The transition to deep-water siliciclastics of these units suggests rapid subsidence associated with continued intra-arc rifting. A jump in the position of the magmatic arc during the latest Santonian, possibly related to the jarring of buoyant CLIP arriving at the trench of the volcanic arc (Burke *et al*., 1978), is responsible for the formation of the early Campanian unconformity at the base of the Crofts Synthem (Mitchell, 2003).

Mitchell (2003; 2006) attributed the late Campanian to early Maastrichtian unconformity to the collision between Caribbean Plate crustal fragments that make up the northern Nicaragua Rise and the Maya/Yucatàn Block of the North American Plate. This event thrust island arc material over

underlying rocks of the CLIP. The late Campanian to early Maastrichtian unconformity is associated with E-W trending thrust faults that form southward-verging imbricate thrust sheets onshore Jamaica which potentially extend as far south as the lower Nicaragua Rise (Mitchell, 2003). The remnant thrust sheets are now expressed as a series of E-W trending faults, which are the oldest structural features found on Jamaica. This event is recognised by tectonic models of Burke (1988), Pindell and Barrett (1990), Pindell (1994), Pindell and Kennan (2001; 2009), Kerr *et al*. (2004), Pindell *et al*. (2005) and Mitchell (2006).

The late Maastrichtian 'Kellits Synthem' of Mitchell (2003) is reported to represent a single major transgressive-regressive cycle (Mitchell and Blissett, 2001; Mitchell, 2003; 2006). This study recognises two T-R cycles within the Maastrichtian. In the east of Jamaica, a suture is recorded in the John Crow Mountain area between the characteristic island arc material that comprises the basement of the majority of Jamaica with crust similar to that of Haiti (Lewis *et al*., 2011). The suturing to the east of Jamaica is attributed to south-westward subduction of CLIP crust beneath northeast Jamaica initiating during the Maastrichtian (Arden Jr, 1977) and culminating in the formation of the Cretaceous-Tertiary unconformity. Continued subduction and melting of the CLIP beneath northeast Jamaica during the early Paleogene is responsible for the formation of the proto-Blue Mountains and extrusion of exotic volcanics, such as adakites, within the Halberstadt Volcanics during the Early Eocene (Hastie *et al*., 2010a, 2010b, 2011) which may be responsible for the formation of an unconformity recorded in eastern Jamaica at this time.

The unconformity between the Kellits Synthem and Middle Eocene strata of the Yellow Limestone Group over much of western Jamaica (Clarendon and Hanover Blocks) is interpreted to have formed during late Paleocene to Early Eocene northeast-southwest directed extension (Mitchell, 2003). This extension is related to sinistral strike-slip movement between the North American Plate and the northern margin of the Caribbean Plate (Pindell, 1994; Mitchell, 2003). Extension occurred over much of the Nicaragua Rise resulting in the formation of northwest-southeast trending horst and graben sturctures such as the onshore Montpelier-Newmarket and Wagwater Troughs, and the offshore Walton Basin and Pedro Bank horst. These grabens were filled with sediments shed from adjacent highs, most notably Paleocene strata of the Wagwater Trough in the east of the island (Arden Jr., 1969). Reactivation of NW-SE striking extensional faults to reverse faults during the Late Eocene resulted in the denudation of the tops of sedimentary sections and may be responsible for the unconformity between the White and Yellow Limestone units.

During the Neogene sinistral strike-slip motion along the boundary between the Jamaica plate and Cayman Trough was transferred to the southern boundary of the Gonave Plate by fault displacement through the Wagwater Trough (Mann *et al*., 1985; 1995; DeMets and Wiggins-Grandison, 2007; Abbott Jr. *et al*., 2013). The collision and locking of the South Hispaniola, Gonave, and lower Nicaragua Rise plates is believed to have caused this switch (DeMets and Wiggins-

Grandison, 2007). As a result, sinistral displacement passes through a restraining bend in the area of the Blue Mountains, resulting in major transpression and causing significant uplift. The interaction of Caribbean plates with Hispaniola also causes the regional uplift of Jamaica, with Campanian E-W thrusts reactivated as strike-slip faults to further accommodate sinistral displacement.

The youngest tectonic event began in the Late Miocene, approximately 8-9 Ma, and is continuing to the present day (Wright, 1971; Steineck, 1974; 1981; Katz and Miller, 1993). Convergence of the North American Plate along the NW-SE oriented northern margins of Cuba and Hispaniola resulted in a stress regime which is expressed by the Neogene uplift of Jamaica. This final stage of tectonic deformation causes Plio-Pleistocene age carbonate terraces to be uplifted at a rate of $1.5 mkyr^{-1}$ (Steineck, 1974; Katz and Miller, 1993; Cochran *et al*., 2017) and regional NW directed extension forming a large-scale structural trend that is broadly NE-SW. Within this stress regime the E-W oriented former thrust sheets are reactivated as sinistral strike-slip faults and spectacular NE verging folds within the Oligo-Miocene age Montpelier Formation are observed across the island.

3. Material and methods

This research forms part of a wider study evaluating the petroleum potential of Jamaica. During this study, fieldwork was conducted in 2016 on the island of Jamaica (Fig. 1). During the fieldwork 60 formations were described and/or sampled, with over 200 samples collected from over 200 localities. An additional 600 samples were collected from 10 Jamaican wells (Arawak-1, Cockpit-1, Content A/Content-1, Hertford-1, Negril Spots-1 (formerly known as Jamaica-1), Portland Ridge-1, Retrieve-1, Santa Cruz-1, West Negril-1 and Windsor-1) and 11 shallow coreholes (Blowfire Hill, Ecclesdown, Elderslie, Jerusalem Mountain, Marchmont, Pindars River-3, Pindars River-10, Sunderland Blackshop-1, Sunderland Potosi-2 and Windsor) provided by the Petroleum Corporation of Jamaica. In addition, data from 11 DSDP and ODP wells (DSDP 151, 152, 153, 154/A, ODP 999A/B, 1000A/B, 1001A/B) were reviewed.

Samples were analysed for biostratigraphic dating using planktonic and larger benthic foraminifera, palynomorphs and nannofossils. Ages have been established, wherever possible, from the published ranges of regionally or globally recognised marker fossils. Important global references for planktonic foraminifera include Sliter (1989) and Premoli Silva and Verga (2004) for the Cretaceous, Olsson *et al*. (1999) for the Paleocene, and Pearson *et al*. (2006) for the Eocene. The ranges of larger benthic foraminifera are taken from BouDagher-Fadel (2008), local references (Hanzawa, 1962; Jiang and Robinson, 1987; Robinson and Wright, 1993; Krijnen *et al.*, 1993; Robinson, 2004) and new interpretations of this study (Fig. 2). The planktonic foraminiferal zones used in the Paleogene are those of Berggren *et al*. (1995) and Berggren and Pearson (2005), recalibrated as sub-tropical foraminiferal Zones for the Cenozoic by Wade *et al*. (2011). Within the

Cretaceous, the zones are mainly a compilation by Gradstein *et al*. (2012) based on Robaszynski (in Hardenbol *et al*., 1998). The nannofossil zonations used in the Tertiary section are the NP Zones of Martini (1971), with the global zonations of Sissingh (1977) and Perch-Nielsen (1979, 1985a, 1985b) being applied in the Cretaceous. The time scale utilised is primarily taken from TSCreator (version 6.1.2, www.tscreator.org) using the 2012 Time scale (Gradstein *et al*., 2012).

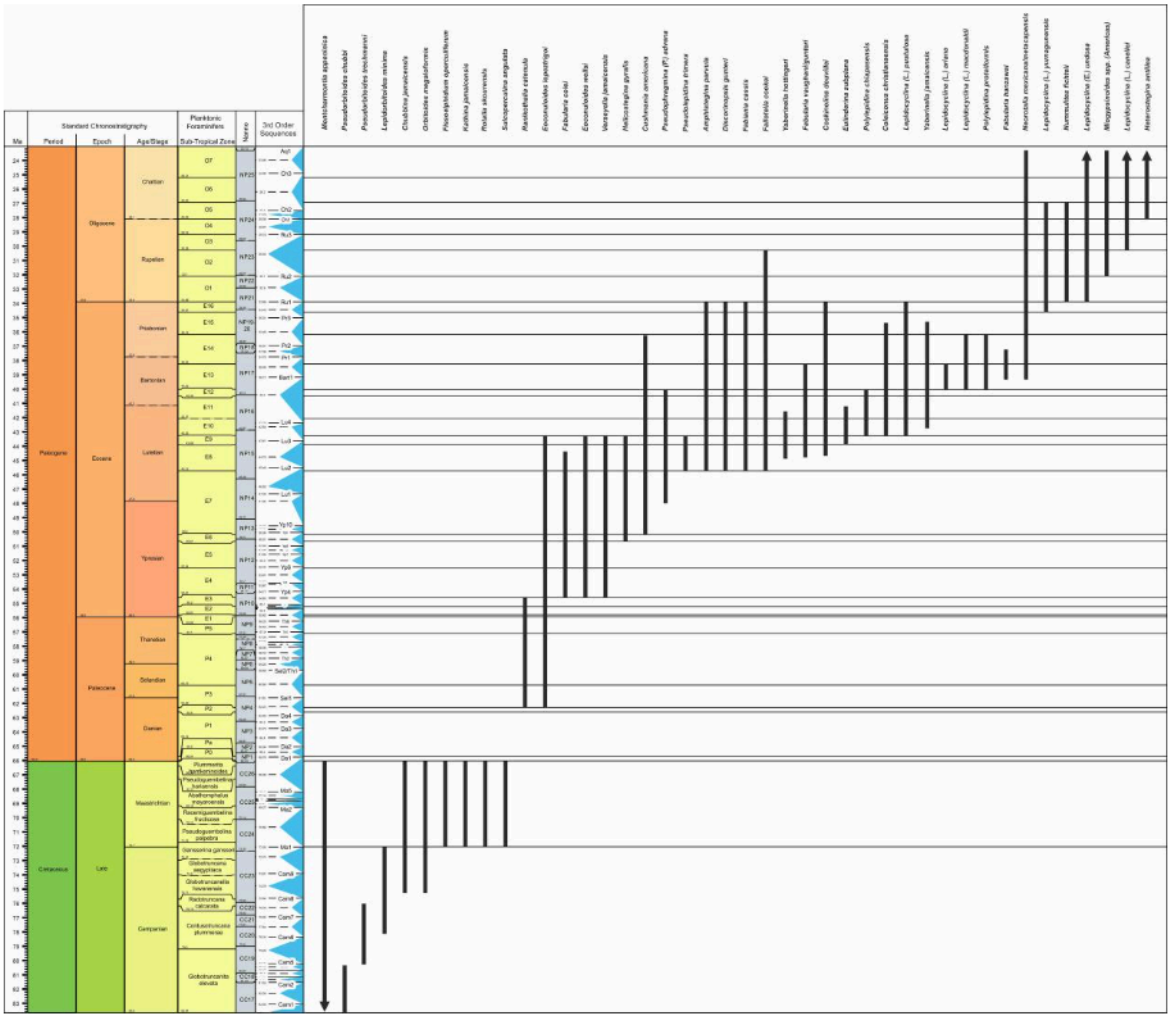


Fig. 2 – Ranges of key larger benthic foraminifera observed in this study. Ranges taken from references mentioned in the text and observations by this study. Stratigraphic column created using Timescale Creator (version 6.1.2, www.tscreator.org) following the timescale of Gradstein *et al*. (2012).

Palaeoenvironmental interpretations based on foraminiferal assemblages consider the environmental preferences of the organisms they contain; this includes, but is not limited to, water depth, nutrient availability and energy levels. Environmental preferences of foraminiferal assemblages are taken from Steineck (1974), Eva (1976), Bé (1977), Hallock and Glenn (1986), Murray (1991),

Beavington-Penney and Racey (2004), Robinson (2004), Hohenegger (2005), Murray (2006), BouDagher-Fadel (2008), Baker *et al.* (2009) and Mitchell (2013).

The island of Jamaica and the region of the northern Nicaragua Rise are described to have been part of a continuous carbonate 'megabank' during the Paleogene (Droxler, 1991; 1993; Sigurdsson *et al*., 1997; Mutti *et al*., 2005) therefore depositional settings are described using carbonate ramp terminology, defined by Burchette and Wright (1992). Seven depositional settings were defined for the purposes of this study including: terrestrial, paralic, proximal inner ramp, distal inner ramp, middle ramp, outer ramp and basinal. Each depositional setting was assigned a water depth, and each sample analysed was assigned to a depositional setting. Through biostratigraphic analyses the samples were also assigned an age in Ma, based on the biozones they were allocated. Average water depths per Ma were plotted as a graph to create a relative sea-level (RSL) curve. Standard error bars for each data point on the sea-level curve incorporate the full range of environments interpreted for that period of time by calculating the maximum, minimum and average bathymetry of all biostratigraphic control points. In total 266 samples were assigned a depositional setting, bathymetry and biostratigraphic age and were used to create the sea-level curve. This regional RSL curve was then compared to global sea-level curves to assess potential timing of tectonic events.

4. Depositional sequences

Environmental preferences of organisms identified during biostratigraphic analyses permit the construction of a RSL curve for the island of Jamaica (Figs. 3-6). The highest resolution of data points occur during the Maastrichtian, Middle to Late Eocene and Oligocene. The RSL curve reveals ten unconformity-bounded transgressive-regressive (T-R) depositional cycles which record a complete cycle of relative sea level rise and fall in the stratigraphy of Jamaica. Commonly, only the transgressive deposits are preserved, as strata deposited in the regressive phase of the previous sequence are eroded during transgressive reworking and production of transgressive ravinement surfaces. Maximum transgressive and regressive inflections in the RSL curve are associated with third-order sequences. However, the deposition of each sequence may be controlled by interplay between regional tectonic activity and global eustatic trends.

Single T-R cycles are identified within the Early Cretaceous (EKTR1), Santonian (STR1) and Campanian (CTR1), two T-R cycles are identified in the Maastrichtian (MTR1, MTR2), a further single T-R cycle within the Paleocene-Early Eocene (PETR1), three T-R cycles within the Middle Eocene age Yellow Limestone Group (YTR1, YTR2, YTR3) and a single transgressive sequence within the Late Eocene to Miocene age White Limestone Group (WTR1). Transgressions and regressions that are recorded within the Yellow Limestone Group represent changes in RSL of only several tens of metres. The White Limestone Group sequence WTR1 indicates a longer term,

lower-order, transgressive sequence than the shorter time-span Yellow Limestone Group sequences. This implies a longer term tectonic control on the deposition of these units, interpreted to be associated with the opening of the Cayman Trough.

4.1. Early Cretaceous (EKTR1)

The Early Cretaceous T-R cycle (EKTR1) is identified through biostratigraphic and sedimentological analyses to reach average water depths of approximately 80m at the maximum transgressive inflection of the RSL curve, interpreted to coincide with the Al8 (103.94 Ma) maximum flooding surface (MFS) of Hardenbol *et al.* (1998). The regressive phase of the RSL curve from the late Albian to late Turonian attains average water depths of less than 10m coinciding with the Tu4 (90.25 Ma) sequence boundary (SB) of Hardenbol *et al.* (1998). The EKTR1 sequence is represented by the Rio Nuevo Formation and Seafield Limestone. The EKTR sequence is observed within the Retrieve-1 and Windsor-1 wells.

The Rio Nuevo Formation contains a basal shale unit containing carinate planktonic foraminifera, including *Thalmanninella appenninca* spp. (Fig. 3), and globular morphologies. In addition, radiolaria and calcareous nannofossils are also abundant. This fossil assemblage and fine-grained laminated nature of the groundmass suggests deposition within a distal, low energy setting such as an outer ramp or basinal environment. A certain degree of terrigenous input is interpreted based on the occurrence of land-derived and water-transported fern spores in the palynological assemblages, such as *Deltoidospora* spp. and *Echinatisporis* spp.

Interbedded shallow water carbonates and organic-rich mudstones of the Seafield Limestone are observed in outcrop towards the top of the Rio Nuevo Formation suggesting periodic shallowing sequences associated with minor oscillations within the RSL trend. Similar interbedded limestones and organic-rich shales are observed in Albian to Cenomanian age strata in the Windsor-1 and Retrieve-1 wells and are interpreted to be coeval with Rio Nuevo and Seafield Limestone. Limestone interbeds contain an assemblage of shallow water rudist bivalves (Fig. 3) and predominantly agglutinated foraminifera indicating deposition within an oligotrophic, inner ramp setting. The interbedded organic-rich black shales are interpreted to correlate to highly restricted, anoxic, estuarine or lagoonal sediments. The occurrence of superabundant amorphous organic matter within the black shales suggests oxygen-deficient bottom conditions.

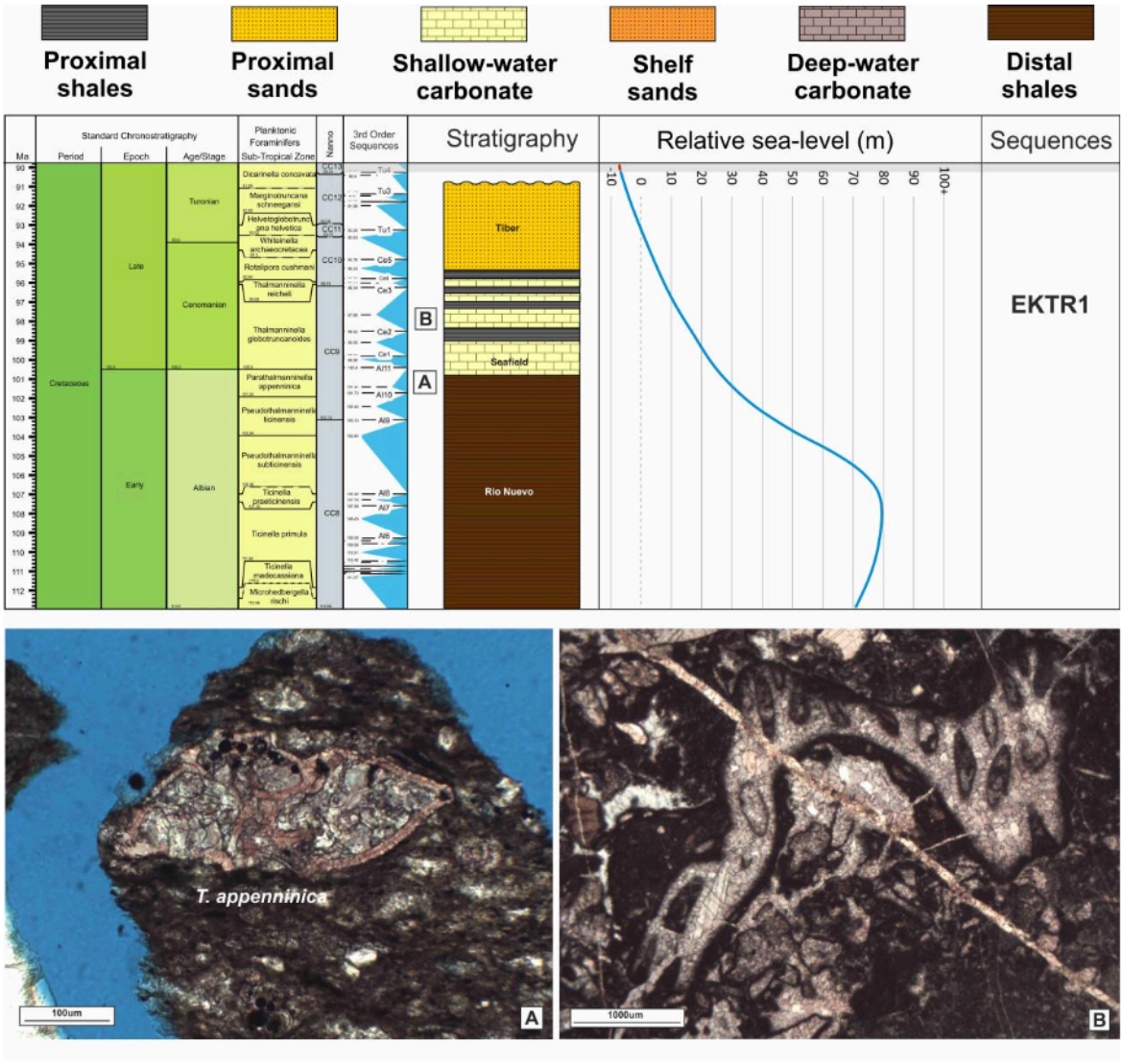


Fig. 3 – Jamaican RSL curve of the Early to 'middle' Cretaceous (EKTR1 sequence). The highest sea-level is associated with the Al8 MFS with the regressive phase culminating with the formation of the Tu4 SB. A) The planktonic foraminifera *Thalmanninella appenninica* are observed within the top of the Rio Nuevo Formation in the Retrieve-1 well, B) Caprinid rudists and dasycladacean green algae occur within the Seafield Limestone of the Windsor-1 well.

The overall shallowing upwards sequence of outer ramp shales, replaced by the inner ramp Seafield Limestone interbedded with marginal marine organic-rich shales throughout the entire Rio Nuevo Formation is correlated to the regressive phase of the EKTR1 sequence (Fig. 3). An unconformity separating Benbow Inlier strata from strata of the St. Ann's Great River and Lucea Inliers (Grippi, 1978; Mitchell *et al.*, 2011) is identified from the Turonian and Coniacian. This unconformity lasts a duration of 2.39 Ma and occurs between the Tu4 to Co1 sequence boundaries (90.25 to 87.86 Ma) where part of the *Dicarinella concavata* micropalaeontological Zone is missing.

4.2. *Santonian (STR1)*

The Late Cretaceous, Santonian T-R cycle (STR1) initiates at the Co1 SB of Hardenbol *et al.* (1998), reaching average water depths of approximately 80m at the maximum transgressive inflection of the RSL curve correlated to the Co1 MFS (86.92 Ma). The regressive phase of the STR1 sequence culminates with the Sa3 SB (84.08 Ma) where subaerial exposure of Jamaica resulted in the formation of the early Campanian unconformity. The STR1 sequence is represented by the Windsor and Clamstead Formations of the St. Ann's Great River Inlier and the Middlesex and Dias Formations of the Lucea Inlier, Retrieve-1 and Windsor-1 wells, and Sunderland Blackshop-1 and Windsor coreholes.

Interbedded sandstone/conglomerate and shale units within the Windsor Formation are interpreted as fining and deepening upwards sequences. Thick sandstone and conglomerate beds at the base of the Windsor sequence are interpreted to originate as shelf sands, with possible submarine volcanic material transported as sediment gravity flows causing emplacement of mudstone rip-up clasts (Mitchell *et al.*, 2011). The homogeneous nature of thick fine-grained sediments of the overlying Clamstead Formation suggests continued deposition under persistent low energy conditions. The abundance of carinate foraminifera including *Contusotruncana fornicata*, *C. morozovae*, *Dicarinella asymetrica*, *D. concavata*, *Marginotruncana marginata*, *M. pseudolinneiana*, *M. renzi*, *M. schneegansi*, *M. sigali, M. sinuosa*, *M. tarfayaensis*, *M. undulata, Whiteinella aumalensis* and *Whiteinella baltica* observed within fine-grained units of the Windsor and Clamstead Formations suggest deposition occurred in a distal marine, outer ramp to basinal setting associated with the Co1 MFS (Fig. 4).

Sedimentary structures such as groove and flute casts, and repetitive fining upwards Bouma sequences, within the Dias and Middlesex Formations suggest these units were deposited as deep-water turbidites. This interpretation supports that of Grippi (1978). The deposition of these deep-water turbidites is interpreted to be coeval with sediment gravity flows within the Windsor Formation and is also interpreted to correspond to the Co1 MFS within the STR1 sequence (Fig. 4). The early Campanian unconformity (Sa3 to Cam2, ca. 84.08 to 81.53 Ma) which lasted a duration of at least 2.55 Ma where nannofossil zone CC17 is missing occurs between sediments of the STR1 and CTR1 sequence.

4.3. *Campanian (CTR1)*

The Campanian T-R cycle (CTR1) initiates at the Cam2 SB (81.53 Ma), reaching average water depths of 35m at the maximum transgressive inflection of the RSL curve correlated to the Cam5 MFS (79.28 Ma). The regressive phase of the CTR1 sequence culminates with the Cam9 SB (73.91 Ma),

298 reaching average water depths of 15m before further subaerial exposure of Jamaica resulted in the
299 formation of the Maastrichtian-Campanian unconformity (Fig. 4). The CTR1 sequence is represented
300 by the Campanian age successions of the St. Ann's Great River, Sunderland and Marchmont Inliers,
301 Retrieve-1, West Negril-1 and Windsor-1 wells, and Marchmont, Sunderland Blackshop-1, Sunderland
302 Potosi-2 and Windsor coreholes
303 The T-R cycle of the CTR1 sequence is best displayed within the Sunderland and Marchmont
304 Inliers. Here, the base of the John's Hall Formation comprises a basal conglomerate that contains large
305 clasts and foraminiferal assemblage which suggests a proximal, marginal marine depositional
306 environment. The conglomerate contains occasional *Pseudorbitoides chubbi* which restricts the age of
307 this unit to the early Campanian (Jiang and Robinson, 1987; Krijnen *et al.*, 1993) and may represent a
308 basal conglomerate lag at the beginning of the CTR1 transgressive sequence which passes upwards to
309 deep-water shales within the Johns Hall Formation.
310 The deposition of the Sunderland Formation continues the deepening upwards trend from the
311 proximal Johns Hall Formation. The presence of *Planolites* ichnotaxa observed within the Sunderland
312 Formation suggests deposition within the mid to distal continental shelf (Benton and Harper, 1997).
313 Globular planktonic foraminifera including *Heterohelix* spp. and *Muricohedbergella* spp. and lack of
314 carinate morphologies within this unit also indicate moderate water depths of the middle to outer shelf
315 (e.g. Bé, 1977). This formation represents maximum transgressive point within the CTR1 sequence,
316 corresponding to the Cam5 MFS, and is interpreted to be contemporaneous with the Drax Hall
317 Formation of the St. Ann's Great River Inlier (Fig. 4). Planktonic foraminifera, such as *Globotruncana*
318 spp. (Fig. 4), and spherical radiolaria are common within the Drax Hall Formation. The presence of
319 *Globotruncana neotricarinata* in the Drax Hall Formation (Fig. 4) constrains the formation to a
320 Campanian age, ranging from the *Globotruncanita elevata* Zone to either the *Radotruncana calcarata*
321 or *Gansserina gansseri* Zones in stratigraphic sections from the Exmouth Plateau and Italy,
322 respectively (Petrizzo *et al*., 2011).
323 In the Sunderland and Marchmont Inliers, the Sunderland Formation is overlain by the
324 Newman's Hall Formation. The Newman's Hall Formation is described as comprising transitional
325 shelfal sands deposited between the deep water shales of the underlying Sunderland Formation and
326 overlying shallow water Stapleton Limestone (Krijnen *et al.*, 1993). This formation is interpreted to
327 mark the start of the regressive phase of the CTR1 sequence. Based on the Newman Hall Formation's
328 stratigraphic position above the Sunderland Formation, it is interpreted to be middle Campanian age.

The Stapleton Formation overlies the Newmans Hall Formation to the south of the Sunderland Inlier. This formation comprises fossiliferous limestone which contains a diverse assemblage of large rudist bivalves including radiolitids, caprinids, plagioptychids and hippuritids, particularly specimens of *Barrettia* spp., echinoids and larger benthic foraminifera. Limestones of the Stapleton Formation contain occasional specimens of *Pseudorbitoides trechmanni* (Fig. 4). The presence of this taxon restricts the age of the Stapleton Formation to the middle Campanian (Jiang and Robinson, 1987; Krijnen *et al.*, 1993). The microfossil assemblage suggests deposition within a shallow marine setting. The fragmented nature of the bioclasts indicates a moderate degree of hydrodynamic energy. Therefore, it is interpreted that the Stapleton Formation was deposited in a distal inner ramp setting approaching fair-weather wave base.

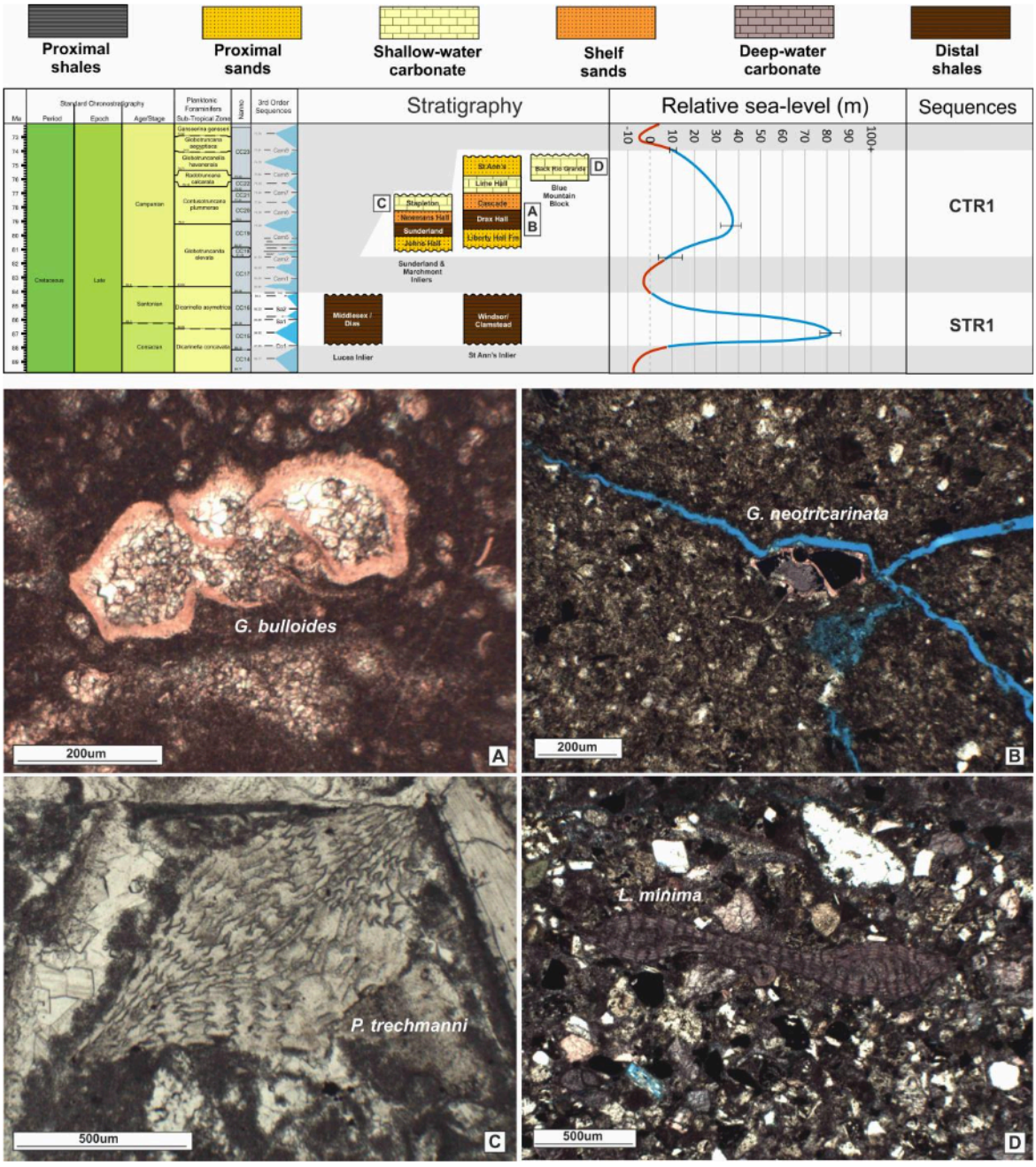


Fig. 4 – Jamaican RSL curve of the Coniacian to Campanian (STR1 and CTR1 sequences). High sea-level correlates with the Co1 MFS in the STR1 sequence and Cam5 MFS in the CTR1 sequence. The planktonic foraminifera *Globotruncana bulloides* (A) and *Globotruncana neotricarinata* (B) occur within the Drax Hall Formation. The larger benthic foraminifera *Pseudorbitoides trechmanni* (C) and *Lepidorbitoides minima* (D) within the Stapleton Limestone and Back Rio Grande Formation are characteristic of the middle to late Campanian.

The Stapleton Formation is interpreted to be a diachronous equivalent of the Lime Hall Formation of the St. Ann's Great River Inlier. The Lime Hall Formation contains a similar fossil

assemblage including rudist bivalves such as *Barrettia* spp. and common larger benthic foraminifera. The presence of *Pseudorbitoides* spp. observed within the Lime Hall Formation indicates it is no younger than late Campanian age (Mitchell and Ramsook, 2009). However, Mitchell *et al.* (2011) note an absence of *Pseudorbitoides* within the Lime Hall Formation which is interpreted here to be due to sampling, rather than stratigraphic, reasons as this taxon is observed in this study. Nevertheless, a late Campanian age for the age of the Lime Hall Formation is consistent with Mitchell *et al.* (2011). The Stapleton and Lime Hall Formations are interpreted to be diachronous equivalents of the Back Rio Grande Formation of the Blue Mountain Block (Fig. 4). Samples within the Back Rio Grande Formation contain *Orbitoides megaloformis* and *Lepidorbitoides minima* (Fig. 4), the latter reported as an index fossil for the Campanian found associated with late Campanian planktonic foraminifera in Europe (Aguilar *et al.*, 2002). Therefore, the Back Rio Grande Formation is interpreted to be late Campanian age. This is consistent with the age of the formation assigned by Mitchell and Ramsook (2009).

The Stapleton, Lime Hall and Back Rio Grande Formations represent a shallow water facies at the top of the St. Ann's Great River, Sunderland and Marchmont Inliers' regressive phase of the CTR1 sequence. This sequence shallows upwards from the deep water Sunderland and Drax Hall Formations, whose deposition is associated with the Cam5 MFS. The late Campanian to early Maastrichtian unconformity is interpreted to occur between sequence boundaries Cam9 and Ma1 (73.91 to 72.05 Ma), lasting a duration of at least 1.86 Ma, where parts of the *Globotruncana aegyptiaca* to *Gansserina gansseri* micropalaeontological zones are absent.

4.4. Maastrichtian 1 (MTR1)

The first Maastrichtian T-R cycle (MTR1) initiates at the Ma1 SB (72.05 Ma), reaching average water depths of 85m at the maximum transgressive inflection of the RSL curve correlated to the Ma1 MFS (70.66 Ma). The regressive phase of the MTR1 sequence culminates with the Ma2 SB (69.27 Ma) reaching average water depths of 5m before the transgression of the second Maastrichtian T-R cycle (Fig. 5). The MTR1 sequence is represented by the early to mid Maastrichtian age successions of the Jerusalem Mountain, Sunderland, Marchmont, Carlton Hill and Maldon Inliers, Blue Mountain Block, Cockpit-1, Content-1/A, Hertford-1, Negril Spots-1, Retrieve-1 and West Negril wells, and Jerusalem Mountain corehole.

In the Sunderland and Marchmont Inliers the MTR1 sequence commences with the deposition of the Shepherds Hall Formation. The Shepherds Hall Formation comprises a polymict, matrix-supported conglomerate consisting of medium-grained sandstone supporting centimetre scale subangular clasts. The Shepherds Hall Formation fines upwards towards a fine-grained, well sorted sandstone with internal millimetre scale ripple cross laminations. Based on the presence of

conglomerates and ripple laminations, this formation is interpreted to have been deposited in a fluvio-deltaic setting where conglomerates represent a basal conglomerate lag at the base of the transgressive phase of the MTR1 sequence. The Shepherds Hall Formation may also be a direct equivalent of the marginal marine Mint Formation of the Jerusalem Mountain Inlier (Mitchell and Edwards, 2016).

Limestones of the Thicket River Formation and Kensington Limestone overlie the Mint and Shepherds Hall Formations in the Jerusalem Mountain and Sunderland/Marchmont Inliers, respectively. These limestones contain a diverse fossil assemblage including rudist bivalves, particularly *Trechmannites rudissimus*, dasycladacean algae, miliolid foraminifera and gastropods which indicate photic, oligotrophic conditions with normal marine salinities. The highly fragmented nature of the bioclasts indicates high levels of hydrodynamic energy. Therefore, it is interpreted that the Thicket River Formation and Kensington Limestone was deposited in a distal, inner ramp setting approaching fair-weather wave base, marking a marginal deepening upwards trend from the underlying Mint and Shepherds Hall Formations. In the Blue Mountain Block the limestones of the Thicket River Formation and Kensington Limestone are coeval with the Rio Grande Formation which contains a benthic foraminiferal assemblage that includes *Orbitoides megaloformis* (Fig. 5), *Fissoelphidium operculiferum*, *Rotalia skourensis* and *Montcharmontia appenninica*, indicative of a Maastrichtian age.

The transgressive phase of the MTR1 sequence culminates with the deposition of relatively deeper water, middle to outer ramp, deposits of the Belleisle Formation in the Jerusalem Mountain Inlier. The Belleisle Formation may be a lateral equivalent to planktonic foraminifera-rich Bath Limestone of the Blue Mountain Block. The Bath Limestone contains abundant globotruncanid planktonic foraminifera including *Abathomphalus intermedius*, *Contusotruncana contusa* and *Globotruncana bulloides*. This assemblage is restricted to the *Abathomphalus mayaroensis – Pseudoguembelina palpebra* micropalaeontological zones, confirming the absence of the *Gansserina gansseri* zone at the Campanian-Maastrichtian unconformity and the upper zones of the Maastrichtian absent at the Cretaceous-Tertiary unconformity. Both the Belleisle Formation and Bath Limestone mark the maximum transgressive inflection of the MTR1 sequence, interpreted to correspond to the Ma1 MFS (Fig. 5).

The Belleisle Formation is overlain by the Jerusalem Formation (Mitchell and Edwards, 2016), which marks the start of the shallowing upwards, regressive phase of the MTR1 sequence. The Jerusalem Formation contains rudist bivalves, gastropods, oysters, algal material and larger benthic foraminifera commonly *Kathina jamaicensis* and *Sulcoperculina angulata* (Fig. 5) which are typical of Maastrichtian age strata in Jamaica (e.g. Brown and Bronnimann, 1957). The regressive phase of the MTR1 sequence is interpreted to follow the Ma1 MFS and terminate at the Ma2 sequence boundary (Fig. 5).

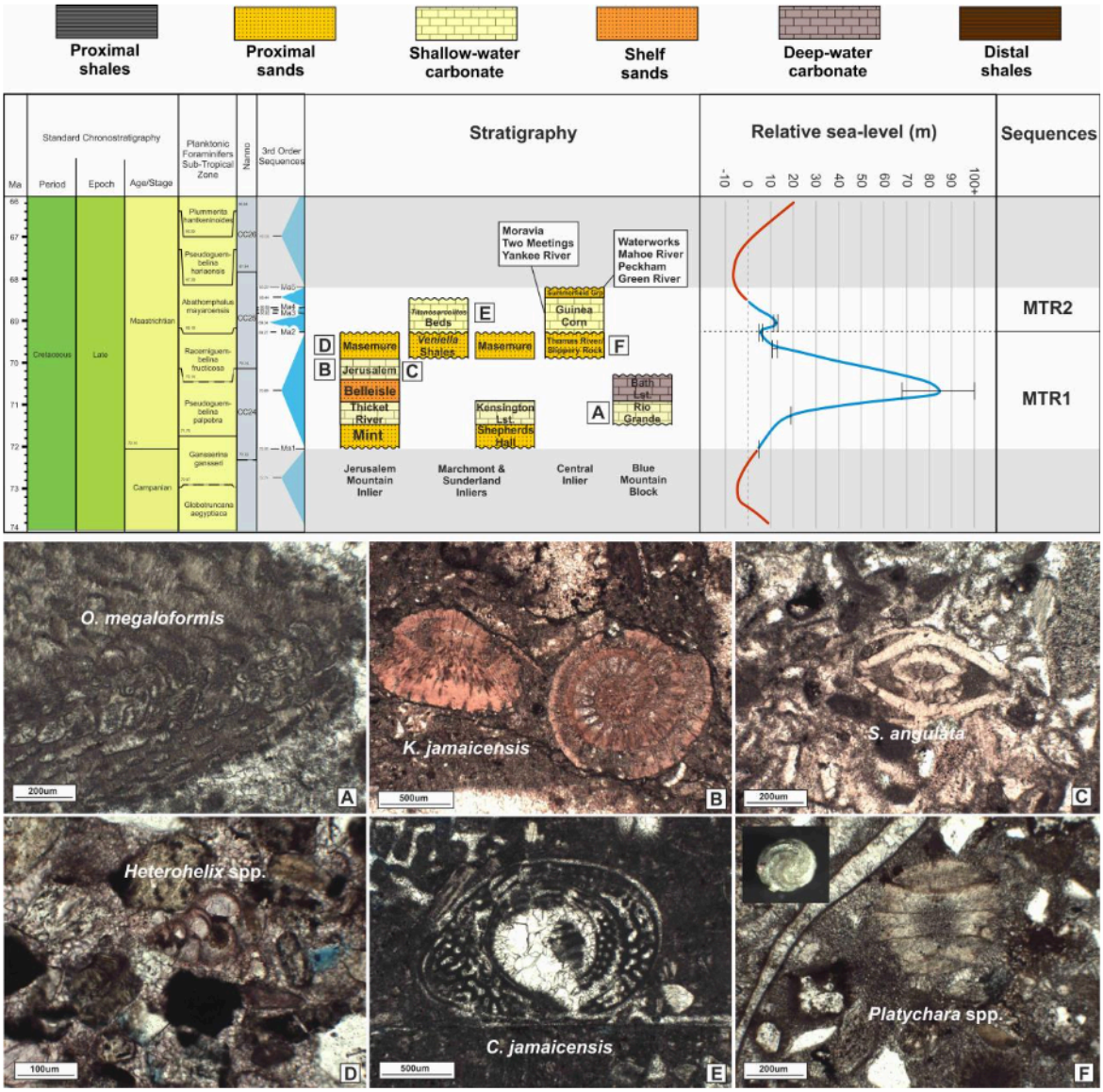


Fig. 5 – Jamaican RSL curve of the Maastrichtian (MTR1-2 sequences). High sea-level of the MTR1 sequence correlates with the Ma1 MFS. Two transgressive-regressive cycles occur within the Maastrichtian. The larger benthic foraminifera *Orbitoides megaloformis* (A), *Kathina jamaicensis* (B) and *Sulcoperculina angulata* (C) are common in Maastrichtian strata from Jamaica. Immature calcite cemented sandstones of the Masemure Formation contain rare planktonic foraminifera including *Heterohelix* spp. (D). The miliolid foraminifer *Chubbina jamaicensis* (E) is an index fossil for the late Maastrichtian observed within the *Titanosarcolites* beds. Freshwater charophytes including *Platychara* spp. (F) occur within the Slippery Rock Formation indicating terrestrially influenced deposition.

4.5. *Maastrichtian 2 (MTR2)*

The second Maastrichtian T-R cycle (MTR2) initiates at the Ma2 SB (69.27 Ma), reaching average water depths of 12m at the maximum transgressive inflection of the RSL curve correlated to the Ma2 MFS (69.04 Ma). The regressive phase of the MTR2 sequence culminates with the Ma5 SB (68.20 Ma) where terrestrially influenced strata top the sequence (Fig. 5). The MTR2 sequence is best represented by mid to late Maastrichtian age successions of the Sunderland, Marchmont and Central Inliers, Cockpit-1, Content-1/A, Hertford-1, Negril Spots-1, Retrieve-1 and West Negril wells.

The MTR2 sequence commences with deposition of the Masemure, Slippery Rock and Thomas River Formations, and the *Veniella* Shales. The Masemure Formation comprises well-sorted, fine-grained sandstone to siltstone. Grains are sub angular with moderate sphericity comprising quartz, plagioclase feldspar and clay minerals including chlorite within calcite cement. Masemure Formation sediments are therefore classified as texturally and mineralogically immature sandstones. Mitchell and Edwards (2016) report that the Masemure Formation does not yield fossils, yet samples from this formation analysed by this study recorded *Rotalia skourensis* and *Heterohelix* spp. (Fig. 5), indicative of a Maastrichtian age. This unit shares lithological characteristics to the *Veniella* shales which contain large bivalves including *Veniella*/*Roudairia* spp. The bivalves *Veniella*/*Roudairia* are reported from shallow marine deposits in California (Kirby and Saul, 1995). The immaturity of the microfaunal assemblage of the Masemure Formation suggests deposition within a marginal, paralic, marine environment. The Masemure Formation is also correlated to the Thomas River Formation (Mitchell and Edwards, 2016) and Slippery Rock Formation. Asymmetrical ripples on bedding surfaces observed at the Slippery Rock Formation type section indicate deposition under a unidirectional current presently directed to the north. It is interpreted that this is a fluvial deposit, which is further supported by the presence of freshwater charophytes (Fig. 5), particularly *Platychara* spp. and *Azolla* spp. spores (Peck and Forester, 1979; Kumar and Grambast-Fessard, 1984; Kumar and Oliver, 1984). It is interpreted that the Masemure, Slippery Rock and Thomas River Formations, and the *Veniella* Shales were deposited at the maximum regressive inflection of the Jamaican RSL curve between the MTR1 and MTR2 sequences, associated with the Ma2 SB.

The Slippery Rock and Thomas River Formations, and the *Veniella* Shales, are overlain by rudist limestones of the Guinea Corn Formation and *Titanosarcolites* Beds in the Sunderland, Marchmont and Central Inliers. The *Titanosarcolites* Beds contain a fossil assemblage characterised by rudist bivalves *Titanosarcolites*, *Thyrastylon*, *Trechmannites* and *Oligosarcolites*, which are often preserved in life position, dasycladacean green algae and common miliolid foraminifera, including *Kathina jamaicensis* and *Chubbina jamaicensis* (Fig. 5), indicating deposition in a shallow, photic and oligotrophic marine setting. Mitchell (2005) suggests *Chubbina* is an index fossil for the late

Maastrichtian. It is interpreted that the *Titanosarcolites* Beds were deposited in a proximal inner ramp setting.

The Guinea Corn Formation is also dominated by a rudist bivalve assemblage including *Chiapasella radiolitiformis* and *Titanosarcolites* spp. Larger benthic foraminifera including *Orbitoides megaloformis* and *Lepidorbitoides* spp. are also observed. The foraminifer *Orbitoides megaloformis* is reported from *Titanosarcolites* bearing strata in Jamaica ranging into the late Maastrichtian (Gunter *et al*., 2002). Consequently, the Guinea Corn Formation and *Titanosarcolites* Beds are considered correlative and assigned a late Maastrichtian age based on the presence of *Chubbina jamaicensis.* The occurrence of *Orbitoides megaloformis* and *Lepidorbitoides* spp. in the Yankee River and Moravia Members of the Guinea Corn Formation suggest moderate water depths and hydrodynamic energy, therefore these two members are interpreted to represent the distal inner ramp close to fair-weather wave base. The interbedded Two Meetings Member may represent a slight oscillation of RSL into shallower water and represent paralic sediments before transgressing back into the deeper waters of the Moravia Member rudist reef. Rare planktonic foraminifera including *Globotruncanella pschadae*, *Globotruncana ventricosa* and *Rugoglobigerina rugosa* in samples from the Two Meetings Member indicate an age no younger than the *Abathomphalus mayaroensis* Zone, which is consistent with the interpretation of the Cretaceous-Tertiary unconformity, where the *Plummerita hantkeninoides-Pseudoguembelina hariaensis* Zones are absent.

The *Titanosarcolites* beds and Guinea Corn Formation are both interpreted to have been deposited in an inner ramp setting during a transgressive episode following the deposition of marginal marine strata of the *Veniella* shales, Masemure, Slippery Rock and Thomas River Formations, associated with the Ma2 SB. Consequently, the *Titanosarcolites* beds and Guinea Corn Formation represent the transgressive phase of the MTR2 sequence culminating with the Ma2 MFS.

The Guinea Corn Formation is overlain by the Summerfield Group in the Central Inlier. The Summerfield Group comprises a massive sandstone polymict conglomerates. These conglomerates occur in repetitive parallel bedded fining upwards sequences between 30 and 60 cm thick. Each of them is floored by conglomerates that fine upwards from cobble to pebble sized polymict clasts that include andesites, mudstones and quartz within a sandstone matrix. The conglomerate fines into coarse and then medium grained sandstones. These conglomerates represent the Mahoe River Formation within the Summerfield Group. Fining upwards successions from basal conglomerate units within the Mahoe River Formation are interpreted to represent fluvial deposits of a braid delta system (Mitchell, 2000). This represents a shallowing upwards sequence following deposition of the inner ramp Guinea Corn Formation Limestones. The terrestrially influenced sediments of the Mahoe River Formation represents the culmination of the regressive phase of the MTR2 sequence deposited during a period of RSL lowstand and are interpreted to be associated with the Ma5 SB.

The MTR2 sequence is topped by the Cretaceous-Tertiary unconformity (Ma5 to Da1, ca. 68.20 to 65.76 Ma), lasting a time span of at least 2.44 Ma. Biostratigraphic analyses indicate that there are no Maastrichtian age sediments younger than the *Abathomphalus mayaroensis* Zone, where the *Plummerita hantkeninoides-Pseudoguembelina hariaensis* zones are absent at the Cretaceous-Tertiary unconformity (Fig. 5).

4.6. Paleocene – Early Eocene (PETR1)

The Paleocene to Early Eocene T-R cycle (PETR1) initiates at the Da1 SB (65.76 Ma), reaching average water depths in excess of 100m at the maximum transgressive inflection of the RSL curve correlated to the Da4 MFS (62.23 Ma). The regressive phase of the PETR1 sequence culminates with the Yp9 SB (50.04 Ma) interpreted to correspond to subaerial exposure resulting in the formation of the Early Eocene unconformity (Fig. 6). The PETR1 sequence is represented by Paleocene-Early Eocene age successions of the Blue Mountain Block and Wagwater Trough in the east of Jamaica, and Ecclesdown corehole.

The PETR1 sequence initiates with the deposition of the Moore Town Formation which comprises well bedded, dark grey interbedded shales and siltstones in repetitive fining upwards sequences. At the base of each fining upwards package, siltstone beds exhibit bed-parallel cylindrical trace fossils and unidirectional groove structures oriented 030. The siltstones grade normally to parallel and planar shale beds which exhibit internal laminations. The fining upwards siltstone and mudstone packages that exhibit sole structures are interpreted to represent bathyal turbidite deposits. Outer ramp to bathyal water depths are interpreted to have occurred during a period of high RSL, tentatively correlated to the Da4 MFS. The Moore Town Formation is reported to be Danian to Selandian age by Fluegeman (1998). Fluegeman (1998) assigned the Moore Town Formation to micropalaeontological Zones P1c-P3a, and to nannofossil Zones NP4-NP5.

The Wagwater Formation stratigraphically overlies the Moore Town Shales. It comprises various lithologies including polymict conglomerates and sandstones with limestone lenses. Limestones contain a fossil assemblage including bivalves, echinoids, ostracods and calcareous, agglutinated and miliolid benthic foraminifera. The foraminifer *Ranikothalia catenula* is observed (Fig. 6). This taxon is described from the Wagwater Formation and is reported to represent a late Paleocene, Thanetian, age (Ramsook and Robinson, 2009). Based on the *Ranikothalia* limestone observed along the Swift River, the Wagwater Formation is assigned an age within the range of micropalaeontological Zones P4b-P5. The Wagwater Formation represents a shallowing upwards, regressive phase of the PETR1 sequence following the deposition of the deep-water turbidites of the Moore Town Formation.

The Wagwater Formation is succeeded by the Richmond Formation in the Blue Mountain Block. The Richmond Formation comprises parallel and horizontally bedded fining upwards sequences of medium- to fine-grained sandstones, siltstones and shales. The Richmond Formation contains age-diagnostic palynomorphs including *Diphyes colligerum, Homotryblium tenuispinosum, and Cyclopsiella* '*reticulata*' indicating an age within the range of Middle Eocene, Lutetian to Early Eocene, intra-Ypresian. Consequently, the age of the Richmond Formation is interpreted to be Ypresian. The presence of pyrite and glauconite and iron-rich clay within siliciclastics, suggests deposition in agitated, reducing environments between 50-200m water depth. It is interpreted that the alternating sandstone and shale beds of the Richmond Formation were deposited as fan-delta to submarine-fan deposits as coarse sediments were shed from the highlands of the Blue Mountain Block into prograding deltas encroaching a steep submarine slope (Wescott and Ethridge, 1983).

The PETR1 sequence is topped by the Early Eocene unconformity to the east of Jamaica (Yp9 to Yp10, ca. 50.04 to 49.58 Ma), lasting a duration of at least 0.46 Ma (Fig. 6).

4.7. Yellow Limestone Group 1, Ypresian-Lutetian (YTR1)

The Yellow Limestone Group of Jamaica is divided into three T-R cycles (YTR1-3). The basal YTR1 cycle initiates at the Yp10 SB (49.58 Ma), reaching average water depths of 15m at the maximum transgressive inflection of the RSL curve correlated to the Lu1 MFS (46.82 Ma). The regressive phase of the YTR1 sequence culminates with the Lu3SB (43.61 Ma). The YTR1 sequence is represented by Early to Middle Eocene age successions (Fig. 6) of predominantly the Clarendon Block of central Jamaica, Content-1/A, Hertford-1 and Pedro Bank-1 wells, and Blowfire Hill corehole.

The New Ground Formation is here included as a basal unit of the lower Yellow Limestone Group T-R cycle (YTR1). This formation marks the most proximal depositional setting before the transgression of later marine influenced sediments. The New Ground Formation comprises matrix-supported, polymict conglomerates that contain moderately sorted, subangular, low sphericity grains that attain a maximum diameter of 6mm. The matrix consists of a medium grained, texturally and mineralogically immature sandstone. The conglomerate fines upwards to fine-grained sandstone and siltstones that are very well sorted and texturally and mineralogically mature. The fining upwards cycles within the New Ground Formation were lain down in episodes of initial high energy, depositing conglomeratic units and subsequent finer grains as the initial energy was waning. This is interpreted to have been deposited within a fluvial system. The age of this formation is given as Early Eocene by Mitchell *et al.* (2011).

The organic-rich Litchfield Formation (Section 4.8) was previously termed the 'Guy's Hill Formation', but subsequently renamed after sediments at the Guy's Hill type locality were found to be

569 Early Eocene in age (Mitchell, 2016). The 'true' Guy's Hill Formation described here refers to
570 sediments similar in appearance to the Litchfield Formation (Section 4.8), but are older and exposed
571 only in a small area close to the town of Guy's Hill, west of the Benbow Inlier, to the east of the
572 Clarendon Block. The Guy's Hill Formation comprises well bedded, arkosic sandstones that are coarse
573 to medium-grained, containing well-rounded and well-sorted grains, and occasional lignitic laminae.
574 The sandstones display planar cross bedding, with low angle foresets dipping towards the north. The
575 planar bedded sandstones are overlain by a trough cross-bedded sands that contain climbing foresets
576 which grade upwards into nodular impure limestone. Within this limestone, the presence of the benthic
577 foraminifera *Eoconuloides wellsi* and *Fabularia colei* and the rare occurrence of the planktonic
578 foraminifer *Globanomalina chapmani* constrain the age of the Guy's Hill Formation to
579 micropalaeontological Zone E4, Ypresian. This is supported by the nannofossil *Discoaster kuepperi*
580 which is assigned to Zones NP14a-NP11, within the Ypresian. The textural immaturity of the
581 siliciclastic components and highly fragmentary nature of the bioclasts within the Guy's Hill
582 Formation suggests deposition in a proximal, high energy, marine setting. The presence of planar
583 cross-beds may indicate foreshore deposits with seaward inclined laminae directed towards the north.
584 These are overlain by trough cross-bedded, upper shoreface deposits. This suggests a transgressive
585 sequence that deepens upwards towards shallow marine limestones of the overlying Freeman's Hall
586 and Stettin Formation. The transition from the Guy's Hill to Freeman's Hall and Stettin Formations
587 represents the transgressive phase of YTR1 following the Yp10 sequence boundary.
588 The Freeman's Hall and Stettin Formations consist of irregularly bedded, flaggy limestones
589 that contain a mix of wackestones, packstones and grainstones. These units yield an abundant and
590 diverse fossil assemblage that includes corals, molluscs (including large lucinid bivalves) and large
591 benthic foraminifera. The diverse microfossil assemblage within these limestones (Fig. 6) include the
592 larger benthic foraminifera *Discorinopsis gunteri*, *Fallotella cookei*, *Fabiania cassis*, *Fabularia colei,*
593 *Coskinolina douvillei*, *Fabiania cassis*, *Amphistegina parvula, Eoconuloides wellsi*, *Verseyella*
594 *jamaicensis* and *Helicostegina gyralis*, and the planktonic foraminifera *Morozovella crater* which
595 restrict the age of these units to micropalaeontological Zones E8-E9. The assemblage, including
596 common miliolid and agglutinated foraminifera plus significant micrite within packstones and
597 wackestones, indicates deposition within low energy, oligotrophic waters of the proximal inner ramp.
598 The Freeman's Hall and Stettin Formations are overlain by grainstones dominated by the benthic
599 foraminifera *Helicostegina gyralis*. These *Helicostegina* Beds are constrained to micropaleontological
600 Zone E9 based on the presence *Eoconuloides lopeztrigoi*, *Helicostegina gyralis* and *Pseudolepidina*
601 *trimera* (Fig. 6). The grainstones which contain large amounts of spar, robust lepidocyclinid
602 foraminifera, highly fragmented bioclasts and encrusting coralline red algae indicate high energy
603 depositional setting and may represent a foraminiferal shoal at fair-weather wave base at the distal
604 inner ramp. It is interpreted that the Freemans Hall and Stettin Formations, and *Helicostegina* Beds,

were deposited during the transgressive phase of the YTR1 sequence, which culminates with the Lu2 MFS. In the Maldon Inlier, the Stettin Formation is unconformably overlain by Litchfield Formation along an unconformity that is interpreted to correspond to the Lu3 SB (Fig. 6).

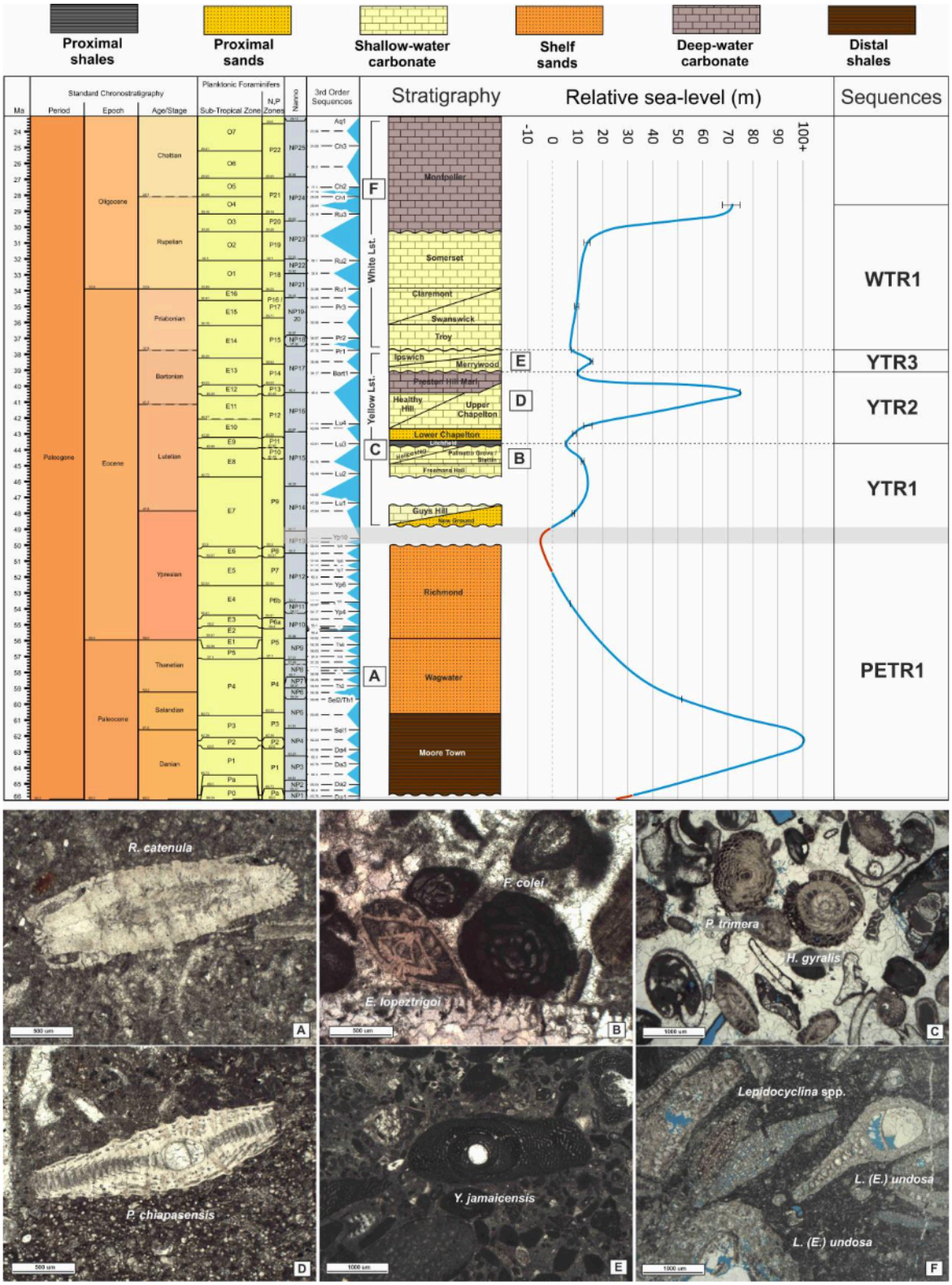


Fig. 6 – Jamaican RSL curve of the Paleogene (PETR1, YTR1-3 and WTR1 sequences). Paleocene limestones of the Wagwater Formation contain rare *Ranikothalia catenula* (A). Grainstones within the YTR1 sequence contain common *Eoconuloides lopeztrigoi* (B), *Fabularia*

***colei* (B), *Pseudolepidina trimera* (C) and *Helicostegina gyralis* (C). The disappearance of the foraminifer *Polylepidina chiapasensis* (D) is characteristic for the top of the Chapelton Formation and YTR2 sequence. The YTR3 sequence is characterised by larger forms of *Yaberinella jamaicensis* (E). Lepidocyclinids increase in abundance and diversity through the upper part of the Yellow Limestone and into the White Limestone Group. Large *Lepidocyclina* (*Eulepidina*) *undosa* (F) characterise the Brown's Town Formation which is often resedimented in calciturbidites of the Montpelier Formation.**

4.8. Yellow Limestone Group 2, Lutetian-Bartonian (YTR2)

The second Yellow Limestone Group T-R cycle (YTR2) initiates at the Lu3 SB (43.61 Ma), reaching average water depths of 75m at the maximum transgressive inflection of the RSL curve correlated to the Lu4 MFS (40.40 Ma). The regressive phase of the YTR2 sequence culminates with the Bart1 SB (39.17 Ma). The YTR2 sequence is represented by Middle Eocene age successions (Fig. 6) of the Clarendon and Hanover Blocks of western and central Jamaica, Arawak-1, Content-1/A, Negril Spots-1, Pedro Bank-1, Portland Ridge-1 and Santa Cruz-1 wells, and Elderslie and Pindars River-3 coreholes.

The Litchfield Formation is found within the Maldon, Marchmont and Central Inliers in the Clarendon Block of Jamaica. This formation contains dark, organic-rich shales and was previously termed the 'Guy's Hill Formation', but subsequently renamed after sediments at the Guy's Hill type locality were found to be Early Eocene in age (Mitchell, 2016). The Litchfield Formation is observed to comprise weakly cemented, porous sandstones and lignite-rich dark mudstones in fining-upwards sequences. In the Maldon Inlier, the Litchfield Formation rests unconformably on top of the Stettin Limestone, where occasionally it slumps into sinkholes developed in the karstic boundary between the two units. The Litchfield Formation is characterised by the presence of high numbers of *Lanagiopollis crassa*, which have been documented from the Middle Eocene Avon Park Formation in west central Florida (Jarzen and Dilcher, 2006). A Middle Eocene age is supported by the occurrence of *Margocolporites vanwijhei* and *Monoporites annulatus*, both indicating an age no older than Middle Eocene in the Caribbean region, and *Spinizonocolpites echinatus*, which indicates an age no younger than Eocene (Germeraad *et al*., 1968). Additionally, the co-occurrence of other taxa such as *Spirosyncolpites spiralis*, *Psilatricolporites caribbiensis*, *Retitricolporites irregularis*, *Spinizonocolpites baculatus*, *Polysphaeridium subtile*, *Homotryblium* spp. and *Operculodinium* spp. is fully consistent with this age assignment (González-Guzmán, 1967; Jaramillo *et al*., 2011). The high abundances of the miospore *Lanagiopollis crassa* reflect input from significant developments of mangrove-like vegetation along the adjacent coastline. In tropical areas of West Africa (Gulf of Guinea) and SE Asia (South China Sea), it has been shown that this kind of ecosystems spread during

periods of increasing sea level and deposition of lowstand system tracts (Poumot, 1989; Morley, 1991). Consequently, it is interpreted that the Litchfield Formation was deposited within a marginal marine, paralic, setting. This supports Robinson and Mitchell's (1999) interpretation that this formation was deposited within a tide-dominated estuarine complex. The Litchfield Formation is interpreted to correspond to a lowstand system tract that deposited during a period of low RSL associated with the Lu3 depositional SB at the base of the YTR2 sequence. The transgressive phase of the YTR2 sequence initiates with paralic and terrestrially-influenced deposits of the Litchfield Formation, transitioning to more marine sediments of the Chapelton Formation.

The Chapelton Formation overlies the Litchfield Formation within the Yellow Limestone Group. The Chapelton Formation comprises flaggy limestone containing a diverse fossil assemblage including large bivalves such as *Crassostrea* spp. and *Carolia cantraine* (Trechmann, 1923), gastropods such as *Campanile* spp. and other small molluscan fragments, algae, coral including *Stylophora* spp., and foraminifera. Lepidocyclinid foraminifera are absent from the lower part of the Chapelton Formation but increase in abundance and morphological complexity throughout the Chapelton Limestone succession. The lower part of the Chapelton Formation is constrained to micropalaeontological Zones E9-E10 and contains *Fabularia vaughani*/*gunteri*, *Verseyella jamaicensis* and *Yaberinella hottingeri*. The upper part of the Chapelton Formation is constrained to micropalaeontological Zones E10-E12. This is based on the presence of *Pseudophragmina advena, Lepidocyclina* (*Lepidocyclina*) *macdonaldi*, *Coleiconus christianaensis*, *Yaberinella jamaicensis* and *Polylepidina chiapasensis* (Fig. 6). The foraminifer *Polylepidina chiapasensis* is diagnostic of the upper Chapelton Formation and its disappearance marks the top of the Chapelton Formation.

The Healthy Hill Formation overlies the Chapelton Formation. It comprises a tight, pink-coloured foraminiferal grainstone. The Healthy Hill Formation contains and large miliolids including *Yaberinella jamaicensis* and is dominated by large lepidocyclinid foraminifers including *Eulinderina* spp. and *Polylepidina chiapasensis*. The foraminifer *Polylepidina chiapasensis* is restricted to micropalaeontological Zones E10-E12 therefore the Healthy Hill Formation is assigned a late Lutetian to early Bartonian age. The depositional setting and microfaunal assemblage of the Healthy Hill Formation is similar to the upper Chapelton Formation. It is interpreted that the Healthy Hill Formation represents distal inner ramp deposits that transgress diachronously across the top of the upper Chapelton Formation. This represents the transgressive phase of the YTR2 sequence.

The Preston Hill Marl Member of the Font Hill Formation represents a deep water lateral facies transition from the relatively shallower water Chapelton and Healthy Hill Formations. In places, the Preston Hill Marl is observed to transgress across the top of the Chapelton and Healthy Hill Formations. This unit is classified as a planktonic foraminiferal carbonate mudstone and comprises beige-coloured marl, consisting of abundant planktonic foraminifera and echinoid spines visible in hand specimen. The Preston Hill planktonic foraminiferal marl contains abundant carinate planktonic

foraminifera including *Morozovelloides* spp. and thick-walled taxa including *Globigerinatheka* spp. These morphologies are indicative of outer ramp to upper bathyal deposits (Bé, 1977). The Preston Hill Marl also contains the planktonic foraminifer *Orbulinoides beckmanni* which is restricted to micropalaeontological Zone E12 and is often found in maximum flooding surface deposits associated with the Lu4 MFS. Consequently, the deposition of the Preston Hill Marl is interpreted to mark the maximum transgressive inflection of the YTR2 sequence corresponding with the Lu4 MFS (Fig. 6). Regression following deposition of the Preston Hill Marl culminated with the formation of the Bart1 sequence boundary.

4.9. Yellow Limestone Group 3, Bartonian-Priabonian (YTR3)

The final Yellow Limestone Group T-R cycle (YTR3) initiates at the Bart1 SB (39.17 Ma), reaching average water depths of 15m at the maximum transgressive inflection of the RSL curve correlated to the Bart1 MFS (38.46 Ma). The regressive phase of the YTR3 sequence culminates with the Pr1 SB (37.75 Ma) which separates the Yellow and White Limestone Groups (Fig. 6). The YTR3 sequence is represented by latest Middle Eocene age successions of the Clarendon and Hanover Blocks of western and central Jamaica, Arawak-1, Content-1/A, Negril Spots-1, Portland Ridge-1 and Santa Cruz-1 wells.

The basal unit of the YTR3 sequence is represented by the Merrywood Formation, an informal name for a lithostratigraphic unit that unconformably overlies the Preston Hill Marl, Healthy Hill and Chapelton Formations. The Merrywood Formation comprises a pale orange to beige-coloured foraminiferal packstone containing a large amount of micrite. This formation contains abundant miliolids including large specimens of *Yaberinella jamaicensis* and *Fabularia hanzawai*. The Merrywood Formation is constrained to micropalaeontological Zones E13-E14, based on the highest occurrences of *Fabularia vaughani/gunteri* and *Cushmania americana* and the presence of *Fabularia hanzawai* which is restricted to these two biozones. The large number of miliolids and agglutinated foraminifera, together with a large amount of micrite matrix, indicates this unit was deposited in the low energy, oligotrophic waters of the proximal inner ramp. Continued transgression resulted in the deposition of the overlying distal inner ramp deposits of the Ipswich Formation within the YTR3 sequence.

The Ipswich Formation is the uppermost unit of the Yellow Limestone Group and is unconformably overlain by the White Limestone Group. The Ipswich Formation is observed to comprise a grey coloured foraminiferal mud-lean packstone to grainstone. This unit is dominated by an abundant and diverse lepidocyclinid assemblage including *Lepidocyclina* (*Lepidocyclina*) *macdonaldi*, *L.* (*L.*) *pustulosa* and *L.* (*L.*) *ariana*, although it also contains echinoid plates and rare specimens of large *Yaberinella jamaicensis*. The presence of *Fabularia hanzawai, Polylepidina*

proteiformis and *Lepidocyclina* (*Lepidocyclina*) *macdonaldi* restrict the age of the Ipswich Formation to micropalaeontological Zones E13-E14. The presence of *Lepidocyclina* (*Lepidocyclina*) *ariana* in some samples is restricted to Zone E13. The dominance of lepidocyclinids and large amount of calcite spar within these grainstones indicate it was deposited in an energetic environment such as a foraminiferal shoal and/or at fair weather wave base at the distal inner ramp. This represents a minor deepening trend following on from the proximal inner ramp deposits of the Merrywood Formation. This deepening trend marks the transgressive phase of the YTR3 sequence, culminating with the Bart1 MFS. Subsequent regression terminates at the Pr1 depositional SB and base of the overlying White Limestone Group (Fig. 6).

4.10. White Limestone Group, Priabonian-Rupelian (WTR1)

The White Limestone Group T-R cycle (WTR1) initiates at the Pr1 SB (37.75 Ma), reaching average water depths of approximately 75m at the maximum transgressive inflection of the RSL curve correlated to the Ru3 MFS (28.64 Ma). The WTR1 sequence is represented by Late Eocene-Oligocene age successions (Fig. 6) of Jamaica, Arawak-1, Negril Spots-1, Pedro Bank-1, Portland Ridge-1 and Santa Cruz-1 wells, and Ecclesdown corehole.

The Troy Formation unconformably overlies the Yellow Limestone Group and is the basal unit of the White Limestone. It comprises a dolomitic limestone that is black in colour on its weathered surface and pale orange/beige in colour on its fresh surface. Samples from the Troy Formation display pervasive dolomitisation with loss of original fabric; however rare exceptions retain 'ghosts' of larger benthonic foraminifera. Consequently, samples analysed for biostratigraphy yielded poor results due to the presence of pervasive dolomitisation. However, due to the Troy Formation's stratigraphic position between two well constrained units (the Ipswich and Swanswick Formations) it is assigned to micropalaeontological Zone E14. 'Ghosts' of conical dictyoconids and presumed abundance of fine-grained micrite prior to dolomitisation suggest the Troy Formation was deposited within very shallow, low energy, oligotrophic waters of the proximal inner ramp during a period of low RSL associated with the Pr1 depositional SB.

The Swanswick and Claremont Formations overlie the Troy Formation within the White Limestone Group succession. These units are observed to comprise massive, white coloured bioclastic grainstone. They contain an abundant and diverse foraminiferal assemblage dominated by the small rotaliid *Neorotalia mexicana* and large morphologically advanced lepidocyclinids. The presence of *Lepidocyclina* (*Nephrolepidina*) *yurnagunensis* within the Swanswick Formation indicates an age no older the Zone E16. Consequently, the Swanswick Formation is assigned a Late Eocene, late Priabonian, age and continues the deepening upwards, transgressive trend of the WTR1 sequence transitioning from the proximal inner ramp deposits of the Troy Formation. The presence of large platy

lepidocyclinids, encrusting red algae and grainstone facies suggest that the Swanswick and Claremont Formations were deposited in a distal inner ramp setting at fair-weather wave base where high hydrodynamic energy favours the precipitation of coarse calcite spar.

The Swanswick and Claremont Formations are overlain by the Montpelier Formation, an extremely thick and widespread unit found across most of Jamaica. The Montpelier Formation comprises interbedded chalk and chert, interpreted to represent deep-water calciturbidites deposited above the Calcite Compensation Depth (CCD). However, these turbidites must have been deposited a short distance from the shelf such as to receive transported (allochthonous) shallow water taxa including *Lepidocyclina* (*Lepidocyclina*) *canellei*, *Lepidocyclina* (*Eulepidina*) *undosa*, *Heterostegina antillea* and *Miogypsinoides* spp., sourced from the contemporaneous Brown's Town Formation that was deposited upslope of the Montpelier Formation. The presence of *Lepidocyclina* (*Lepidocyclina*) *cannellei*, *Lepidocyclina* (*Nephrolepidina*) *yurnagunensis*, *Heterostegina antillea* and *Nummulites fichteli* in samples from the Montpelier Formation constrain this unit to Zones O3-O5. These biozones represent the 'late' Rupelian and 'early' Chattian stages of the Oligocene. The presence of the foraminifera *Lepidocyclina* (*Nephrolepidina*) *yurnagunensis*, *Heterostegina antillea*, *Nummulites fichteli*, *Lepidocyclina* (*Lepidocyclina*) *canellei*, *Lepidocyclina* (*Eulepidina*) *undosa* (Fig. 6) within the Brown's Town Formation are also restricted to the Oligocene, micropalaeontological Zone O5. This corroborates the age of the transported units within the calciturbidites observed within the Monteplier Formation. The deposition of the Montpelier Formation is associated with the Ru3 MFS and marks the culmination of the WTR1 transgressive sequence that initiated at the Pr1 sequence boundary with the deposition of the Troy Formation (Fig. 6).

5. Discussion

5.1. The Jamaican relative sea-level curve

Transgressive-regressive cycles identified within the Jamaican sea-level curve represent second (10^7 years) to fourth (10^5 years) order sequences, although most tie to globally recognised third order (10^6 years) sequences of Hardenbol et al., (1998). The EKTR1 and PETR1 sequences are regarded as second order sequences, lasting a duration of approximately 23 Ma and 16 Ma, respectively. The duration of these sequences is consistent with long term regional tectonic events including the assembly of CLIP fragments and back/fore-arc spreading in the 'middle' Cretaceous and Late Cretaceous to Paleogene rifting across the Nicaragua Rise (see Section 2). The STR1 (ca. 4 Ma), CTR1 (ca. 7.5 Ma), MTR1 (ca. 3 Ma), YTR1 (ca. 5.5 Ma), YTR2 (ca. 4.5 Ma) and WTR1 (ca. 9.25 Ma) depositional cycles represent third order sequences and are regarded to be controlled by global eustatic trends (see Section 5.2). The MTR2 (ca. 1 Ma) and YTR3 (ca. 1.25 Ma) may represent fourth order sequences where local tectonism dictates shifts in facies.

In carbonate dominated sequences of the Maastrichtian, and Paleogene Yellow and White Limestone groups the average rates of RSL rise are calculated as approximately 26.6 m/Ma for MTR1, 10 m/Ma for MTR2, 3.6 m/Ma for YTR1, 15.5 m/Ma for YTR2, 4 m/Ma for YTR3 and 7 m/Ma for WTR1. Given the lowest accumulation rates of prograding carbonates is regarded as 30 m/Ma (Schlager, 1981; Handford and Loucks, 1993; Wissler *et al*., 2003), production rates of Maastrichtian and Paleogene carbonates could sufficiently keep pace with the low rates of RSL rise calculated for these sequences. This accounts for the several kilometres thick carbonate successions of Maastrichtian and Paleogene age units observed in Jamaica. However, the sharp change in gradient in the WTR1 sequence in the late Rupelian is calculated to require an increase in the rate of RSL rise to 27.5 m/Ma. Although optimal carbonate accumulation rates should keep pace with this rate of RSL rise, Jamaican carbonate platforms nevertheless succumbed to drowning during the Oligo-Miocene evident by thick sequences of the deep-water Montpelier Formation overlying shallow platform carbonates across the island. It is therefore interpreted that environmental factors (e.g. Mutti *et al*., 2005) exerted a greater control than global eustacy later on during the WTR1 sequence.

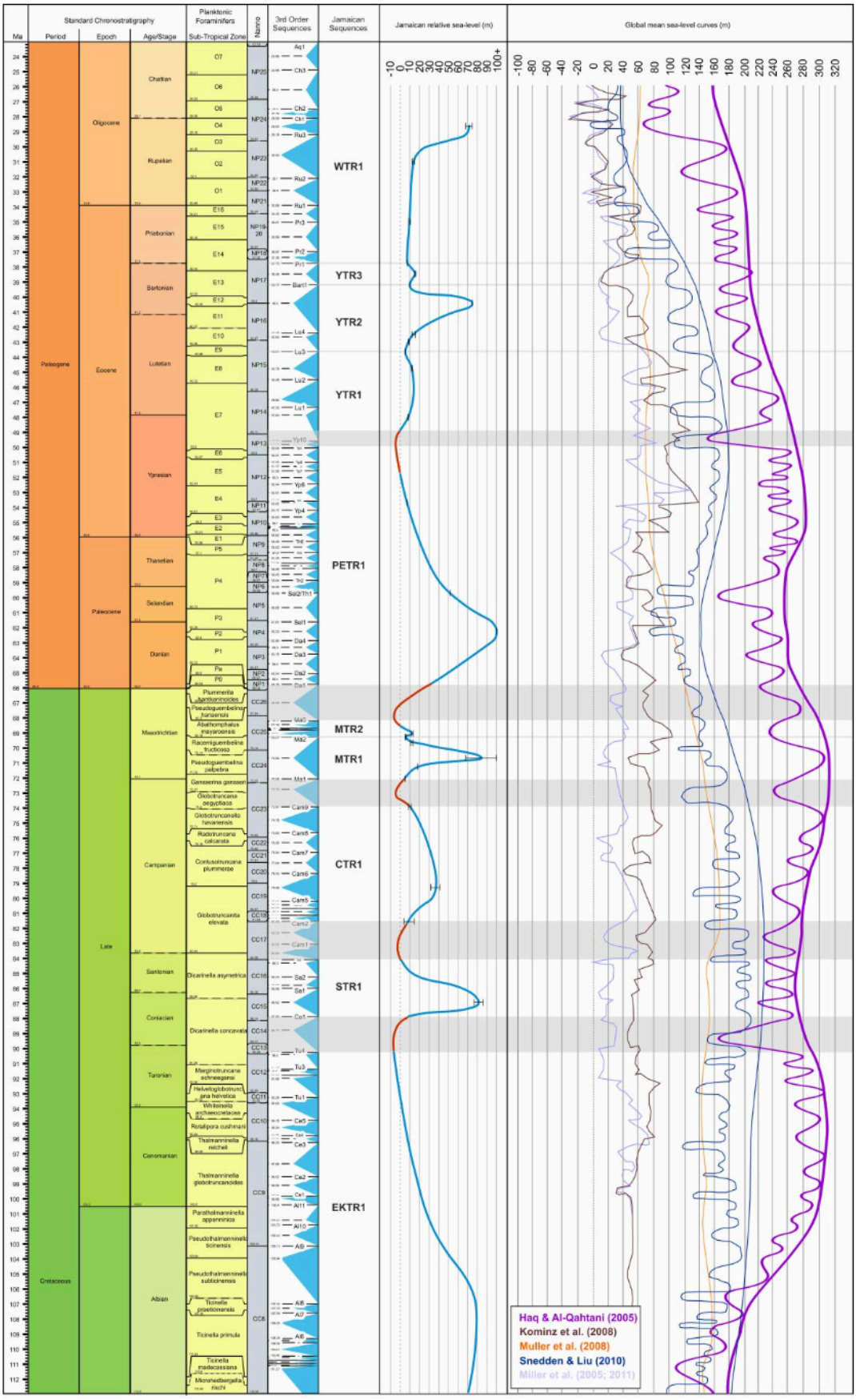
The curve presented here constitutes a simplified first attempt at reconstructing RSL change in Jamaica. This curve may be refined in the future by higher resolution field sampling, well analyses and numerical forward modelling. This will enable the identification of further fourth and even fifth order depositional cycles and better determine the, potentially multiple, controls on deposition of these sequences.

5.2. Comparisons with global sea-level curves

Maximum transgressive and regressive inflections of the Jamaican RSL curve correlate with similar trends in global sea-level curves of Haq and Al-Qahtani (2005), Kominz *et al*. (2008), Snedden and Liu (2010) and Miller *et al*. (2005; 2011), however they do not resemble those of Müller *et al*. (2008). Major unconformities in Jamaica are particularly well correlated to significant events of global sea-level fall (Fig. 7). However, this coincidence is unsurprising as many of the unconformities are interpreted to have formed subaerially, during periods of collisional uplift which, if occurring at the same time as global eustatic sea-level fall, will result in the formation of substantial unconformities lasting a time span of several million years. Many of the T-R cycles initiate during a period of low RSL, attributed to tectonic uplift, and are followed by transgressive episodes influenced by global eustacy or regional subsidence.

The Turonian-Coniacian unconformity between the EKTR1 and STR1 sequences coincides with a sharp decrease in the short-term trend of mean global sea-level recognised by Haq and Al-Qahtani (2005) and Snedden and Liu (2010) who record a drop in sea-level with a magnitude of approximately 50m and 110m, respectively (Fig. 7). Both Haq and Al-Qahtani (2005) and Snedden and Liu (2010)

824 also record a sharp increase in sea-level shortly after; with maximum transgressive inflections of the
825 short-term mean sea-level trend coinciding with that of the STR1 sequence (Fig. 7).
826


Standard Chronostratigraphy
Ma
Period
Epoch
Age/Stage
Planktonic Foraminifers
Sub-Tropical Zone
Nannofossil Zone
3rd Order Sequences
Jamaican Sequences
Jamaican relative sea-level (m)
Global mean sea-level curves (m)
Paleogene
Cretaceous
Oligocene
Eocene
Paleocene
Late
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
WTR1
YTR3
YTR2
YTR1
PETR1
MTR2
MTR1
CTR1
STR1
EKTR1
Haq & Al-Qahtani (2005)
Kominz et al. (2008)
Muller et al. (2008)
Snedden & Liu (2010)
Miller et al. (2005; 2011)

827

Fig. 7 – The Jamaican RSL curve compared to global mean sea-level curves of Haq and Al-Qahtani (2005), Kominz *et al*. (2008) Muller *et al*. (2008), Snedden and Liu (2010) and Miller (2005; 2011). Major Jamaican unconformities correlate with periods of significant global mean sea-level fall, the duration of the unconformities are approximately equal to the wave-length of sea-level fall.

The early Campanian unconformity between the STR1 and CTR1 sequences also coincides with a decrease in global mean sea-level recorded by Haq and Al-Qahtani (2005), Kominz *et al*. (2008), Snedden and Liu (2010) and Miller *et al*. (2005; 2011) of a magnitude between approximately 20m and 60m (Fig. 7). The Campanian-Maastrichtian unconformity between the CTR1 and MTR1 sequences correlates with a drop in mean global sea-level of approximately 60m recorded by Haq and Al-Qahtani (2005) and Snedden and Liu (2010). The maximum transgressive inflection of the MTR1 sequence correlates to a period of high mean global sea-level recorded as 285m above present day by Haq and Al-Qahtani (2005).

The Cretaceous-Tertiary unconformity between the MTR2 and PETR1 sequences coincides with a decrease in global mean sea-level recorded by Haq and Al-Qahtani (2005), Kominz *et al*. (2008), Snedden and Liu (2010) and Miller *et al*. (2005; 2011) of a magnitude between approximately 20m and 40m (Fig. 7). Following the Cretaceous-Tertiary unconformity, the PETR1 sequence does not fit global mean sea level trends of RSL fall due to the Late Cretaceous to Paleogene rifting event which occurred across the Nicaragua Rise (Mitchell, 2003) resulting in tectonic subsidence and localised RSL rise in Jamaica. The Early Eocene unconformity between the PETR1 and YTR1 sequences also coincides with a significant drop in the short-term mean global sea-level trend of between 60m and 110m recorded by Haq and Al-Qahtani (2005) and Snedden and Liu (2010). Minor oscillations in the Jamaican RSL curve within the Yellow Limestone Group correlate with minor oscillations in the short-term sea-level trend of Haq and Al-Qahtani (2005). The maximum transgressive inflections of the YTR2 and WTR1 sequences coincide with significant maximum transgressive inflections of the short-term mean global sea-level curves of Haq and Al-Qahtani (2005), Kominz et al. (2008) and Snedden and Liu (2010), although environmental deterioration may play a greater role towards the end of the latter sequence (e.g. Mutti *et al*., 2005).

The duration of the major Jamaican unconformities are approximately equal to the wavelength of periods of mean global sea-level fall (Fig. 7). The Turonian-Coniacian unconformity is calculated by this study to last 2.39 Ma, while the wavelength of sea-level fall at this time in the Haq and Al-Qahtani (2005) curve lasts approximately 2.7 Ma. The early Campanian unconformity lasts 2.55 Ma in this study, the wavelength in the Miller *et al*. (2005; 2011) curves lasts approximately 2.6 Ma. The Campanian-Maastrichtian unconformity lasts 1.86 Ma in this study where the wavelength of the Snedden and Liu (2010) curve lasts 2.6 Ma. The Cretaceous-Tertiary unconformity lasts 2.44 Ma and

the wavelength of the Kominz et al. (2008) curve lasts 2.9 Ma. Finally, the Early Eocene unconformity is calculated as 0.46 Ma by this study, whereas wavelengths of the Snedden and Liu (2010) and Haq and Al-Qahtani (2005) curves last 1.6 Ma and 2.2 Ma, respectively.

6. Conclusions

The ten Jamaican T-R sequences identified by this study each correspond to one complete cycle of RSL rise and fall. Comparisons of the Jamaican RSL curve with global trends show that local tectonism exerts a significant control on the deposition of sedimentary sequences in Jamaica. This is most evident where several unconformities attributed to major tectonic episodes also coincide with significant falls in mean global sea-level. The duration of the unconformities in Jamaica is comparable to the wavelength in oscillations of the short-term global trends of Haq and Al-Qahtani (2005) and Snedden and Liu (2010). Following major tectonic episodes, the Jamaican RSL curve follows global eustatic trends. The amplitudes of mean global sea-level rise and fall also match the amplitude of transgressive and regressive phases identified in Jamaica, in the order of several tens of metres. The relatively low rates of RSL rise and fall calculated in Jamaica and thick successions of carbonate sequences suggest that carbonate production rates were able to respond adequately to gradual changes in RSL during the Cretaceous to Paleogene until succumbing to drowning during a sharp increase in the rate of RSL rise and environmental deterioration in the Oligo-Miocene.

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