Robinson, E., Paytan, A., Chien, C.-T. and Broach, K. 2018. Dating the White Limestone of Jamaica using Sr isotope stratigraphy: a progress report. *Caribbean Journal of Earth Science*, **49**, 11-21. © Geological Society of Jamaica. Available online 18th December 2018.

Dating the White Limestone of Jamaica using Sr isotope stratigraphy: a progress report

EDWARD ROBINSON[1], ADINA PAYTAN[2], CHIA-TE CHIEN[2] AND KYLE BROACH[2]

[1]*Department of Geography & Geology, University of the West Indies Mona, Kingston 7, Jamaica*

[2]*University of California Santa Cruz, Earth and Planetary Science, 1156 High Street, Santa Cruz, CA95064, USA*

ABSTRACT. Twenty six carbonate samples from localities covering several formations of the White Limestone Group of Jamaica were analysed for the $^{87}Sr/^{86}Sr$ isotopic ratios. The assemblages of larger foraminifera from these samples and three additional samples, for which Sr isotopes were previously recorded, were also examined. The results provide a preliminary framework for dating both the foraminiferal assemblages and the lithostratigraphic units from which the samples were obtained. Sr isotopic ages range from 38 Ma (Ipswich Formation, late middle Eocene) to 19.7 Ma (Newport Formation, early Miocene). They suggest that at least part of the Somerset Formation is of early Oligocene age, and that the Browns Town and Walderston Formations are coeval stratigraphic units, of Oligocene (Rupelian to early Chattian) age, older than the Newport Formation, at least in their type areas. Alternative ages for the type localities of the Claremont and Ipswich formations, based on the Sr isotope curve, may be greater than 40 Ma but are constrained by the age of the first appearance of Lepidocyclina ss at about 41 Ma. Although the biostratigraphic age ranges of the associated larger foraminifera are still poorly defined, the results confirm an early Oligocene age for at least the upper part of the range of *Fabularia verseyi* and a highest occurrence of *Fallotella* spp. at about the top of the Rupelian.

Keywords: Jamaica, larger foraminiferal stratigraphy, Sr isotope dating, White Limestone Group.

1. INTRODUCTION

The measured radiogenic isotopic ratio of Strontium (Sr) dissolved in seawater, $^{87}Sr/^{86}Sr$, is homogenous throughout the ocean but has varied over time and has been used as a stratigraphic tool (**McArthur et al., 2012**). In particular, seawater $^{87}Sr/^{86}Sr$ has varied considerably over the past 40 million years and can be used to date marine sedimentary rocks, especially limestones, to a high degree of accuracy (**McArthur et al., 2012**; **Baumgartner-Mora et al., 2008**; **Ortega-Ariza et al., 2015**). This approach is particularly useful for well-lithified limestones deposited in shallow water palaeo-environments in which planktonic foraminifera and calcareous nannofossils are scarce or absent, preventing good biostratigraphic control, as is the case with much of the mid-Tertiary White Limestone Group of Jamaica.

Geologically the Jamaican White Limestone carbonates are distributed across a series of structural blocks, dominated by shallow-marine deposits, and belts containing mainly pelagic limestones, locally including resedimented material from the blocks (**Hose and Versey, 1957**; **Robinson and Mitchell, 1999**; **Mitchell, 2013**). The largest block, the Clarendon Block, which encompasses most of the formational type localities, is the region of interest for the present paper (**Figure 1**).

The Geological Survey Department embarked on a systematic survey of the mid-Tertiary White Limestone of Jamaica in 1951, initially in response to requests for augmenting supplies of groundwater (**Geological Survey Department, 1951**). The larger benthic foraminiferal zonation developed by **C. A. Matley** (**1925**) was used by **Hose** (**1950**) and in a modified form by Versey (in **Geological Survey Department, 1951**). Over the next four years a modified approach to the study of the White Limestone, using microfacies analysis, led to the subdivision of that unit into a number of named sub-units (**Figure 2**). The Troy and Somerset limestones were assigned an Eocene age, and the Walderston and Newport limestones were placed in the Oligocene to early Miocene. These units were named in 1953, based largely on borehole information from the Mandeville region (**Geological Survey Department, 1955**). To these were added the Browns Town limestone in 1954 (**Geological Survey Department, 1956**) based on the 1951 surveys, and the Ipswich limestone in 1955 (**Geological Survey Department, 1957**). **Hose and Versey** (**1957**) and **Versey** (**1957a, b**) described the new units in detail, with the addition of the Gibraltar Limestone. The name Claremont Limestone was added in an updated account by Versey (in **Zans et al., 1963**). Current usage accepts these traditional units as formations within

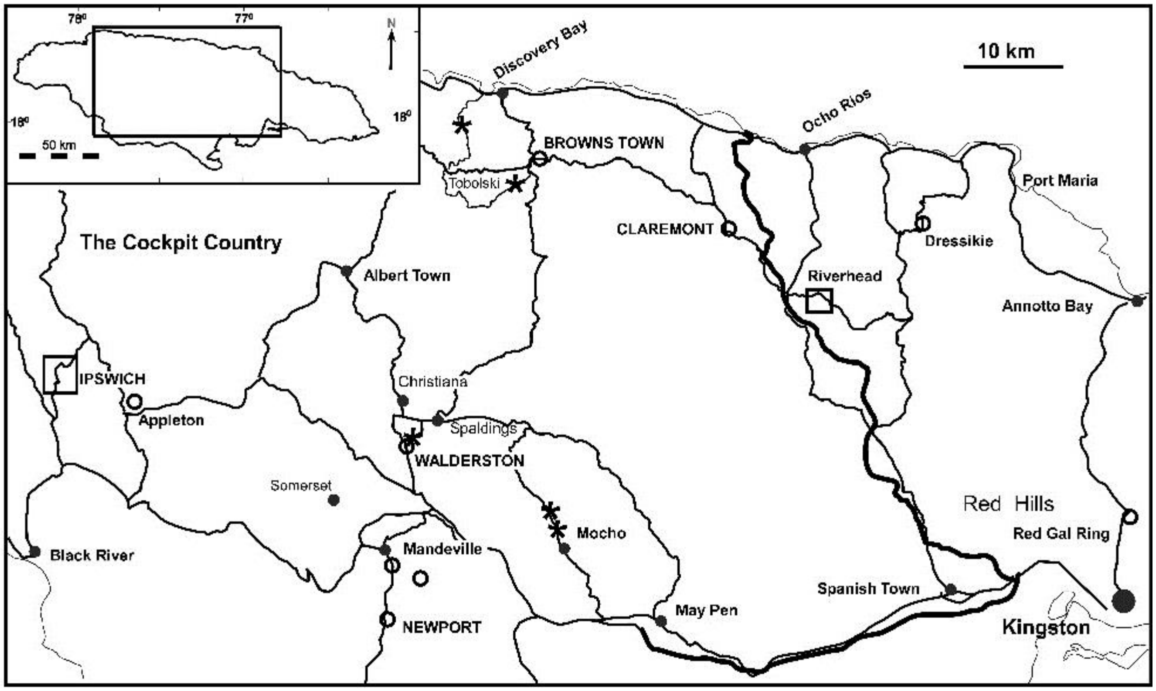

Figure 1. Location map of samples used in the present study. Circles, sample locations, stars, locations of samples analysed by Land (1991) and P. Mueller (in Robinson and Mitchell, 1999). Boxes, locations of Figures 3 and 4. Names of locations are capitalised for four of the five type localities of formations included in sampling for this study. The Somerset Formation was not sampled at its type locality but the unit was sampled at Riverhead (Figure 3).

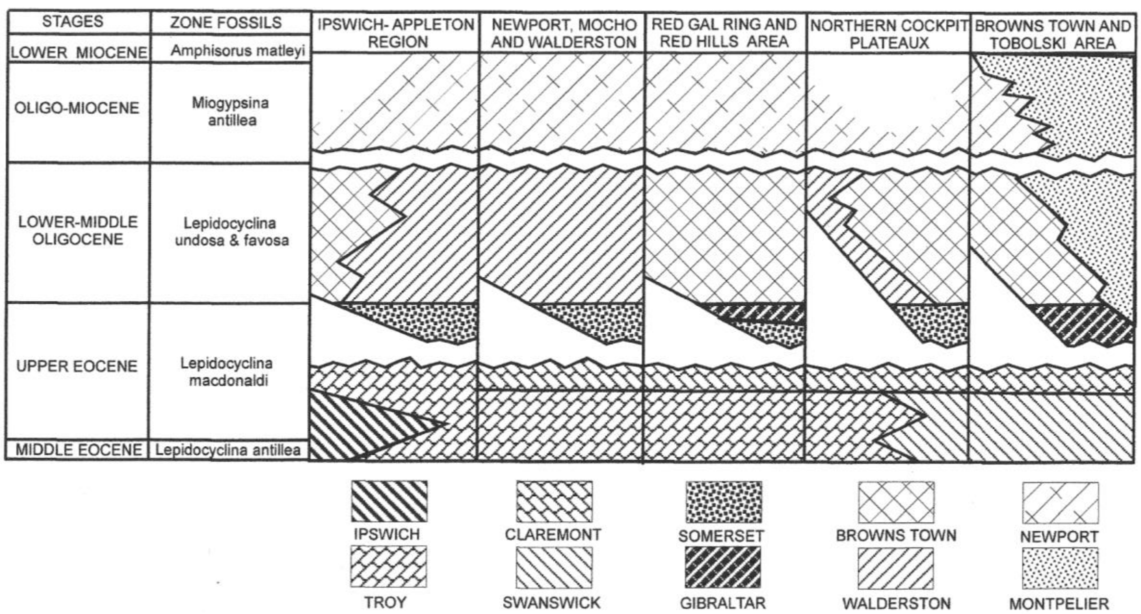

Figure 2. Stratigraphy of the White Limestone Group as recognised in 1963 based on mapping by the Geological Survey; modified from Versey (in Zans, 1963, pages 31, 32). Regional headings modified to reflect geographical information of Figure 1.

the White Limestone Group, although the name Gibraltar has fallen into disuse and the Troy and Claremont limestones have frequently been combined for mapping purposes. Combining of most of these into one Moneague Formation has also been suggested (**Robinson and Mitchell, 1999**; **Mitchell, 2004**; see **Hill, 1899** for the origination of the name). **Figure 2** shows the stratigraphic distribution of the various units for the different areas of **Figure 1** as understood by Versey (in **Zans et al., 1963**).

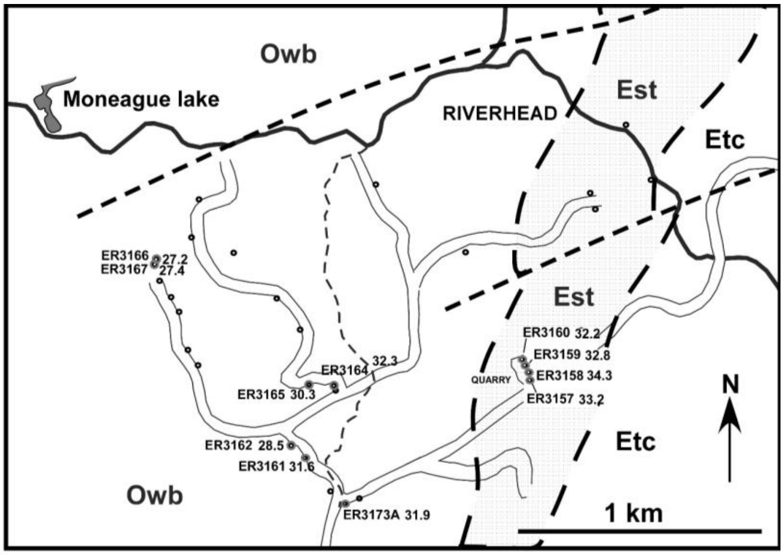

Figure 3. Location map for samples collected in the Riverhead district (Figure 1). Sample numbers followed by Sr ages in Ma. Geology adapted from 1:50,000 scale Geological Sheet 18, Ocho Rios (1978 Edition; geological contacts must be regarded as approximate), with bauxite mine access roads added. Etc, Eocene Troy/ Claremont Formation; Est, Somerset Formation; Owb, Oligocene Walderston/Browns Town Formation.

Hose and Versey (**1957**) applied the microfacies concept, mainly using larger foraminiferal assemblages, to evaluate the ages and depositional environments of the various units of the White Limestone. To a large degree this led to lithological units being defined by their fossil content, rather than their lithostratigraphic features. Descriptions of some of the larger benthic foraminifera involved have been published by **Vaughan** (**1928a, b, 1929**), **Cole** (**1956**), **Robinson** (**1993**) and **Robinson and Wright** (**1993**). More recently **Mitchell** (**2013, 2015**) remapped and redefined parts of the White Limestone Group using lithostratigraphic and sequence stratigraphic criteria.

To better constrain and refine the stratigraphy of the White Limestone Group we have generated $^{87}Sr/^{86}Sr$ isotopic ratios to provide an independent evaluation of the ages at some of the localities typifying the traditional formational names erected for units of the Group in the 1950s. Although several Sr dates have been generated for previous studies (**Land, 1991**; **Robinson and Mitchell, 1999**; **Robinson, 2004**), for the present review twenty six samples were collected from shallow marine facies of the White Limestone on the Clarendon Block (**Figure 1**).

2. Localities

The lithostratigraphic and biostratigraphic associations of the samples examined for their Sr isotopic ratios are briefly described below. For each locality references to past investigations are given. Samples prefixed by the letters ER were collected by the first author of this paper at various times dating back to the early 1960s.

2.1 Dressikie (Figure 1)

Sample ER176 was collected from a turbidite unit in the Montpelier Formation in June 1962 during a study of the geology of the Benbow Inlier (**Burke et al., 1969**). Calcareous nannofossil data indicate an NP21 zone for the enclosing planktonic foraminiferal micrites (M. Jiang, pers. comm.) Larger Foraminifera from this locality have been illustrated previously (**Robinson, 2004**, figure 16).

2.2 Riverhead (Figure 3)

Eleven samples for Sr isotope determinations were collected on January 3, 1999 and July 10, 2003 from four short sections exposed on a network of mine access roads cut by Alcan Jamaica Ltd. south of Riverhead (**Figure 3**). The sampled sections extend from the top of the Claremont limestone through the Somerset and Walderston/Browns Town limestones (**Figure 2**; see also **Robinson and Mitchell, 1999**).

2.3 Claremont (Figure 1)

Sample ER1539A was collected on August 16, 1971 with P. Jung, from the old Claremont quarry, at one end of the type section for the Claremont limestone, described by Versey (in **Zans et al., 1963**, p. 34) as extending between Claremont and Claremont school. At the time of collection the quarry had recently been reopened. The Claremont limestone of the surrounding area is noted for its molluscan fauna, forming the Phacoides band of **Hose and Versey** (**1957**), based on the large bivalve *Phacoides megameris* Dall (now *Superlucina megameris* fide **Mitchell, 2013**, p. 114).

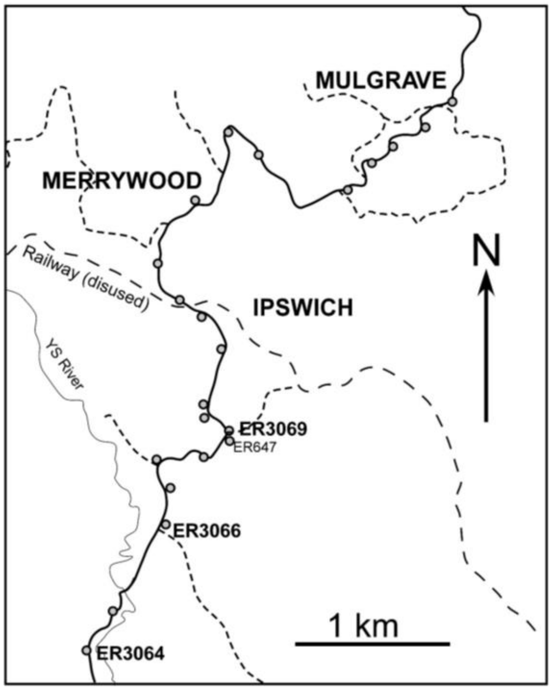

Figure 4. Location of samples in the Ipswich section (Figure 1). ER3069 from the higher part of the Ipswich limestone of Versey (1957a) is regarded as typical. Overlying strata contain the upper Eocene marker *Heterostegina ocalana*.

2.4 Browns Town (Figure 1)

Sample ER2614 was collected on October 21, 1994 with H. L. Dixon from Lee's Marl crushing plant and quarry, just northeast of Browns Town on the road to Claremont and adjacent to an old quarry now partly submerged beneath housing. The old quarry is probably the one originally designated by **Hose and Versey** (**1957**) as the type locality for their Browns Town limestone (**Figure 1**; see also **Geological Survey Department, 1955**, p. 5; **Dixon and Donovan, 1999**; **Mitchell, 2013**). Additional material from the site, containing larger foraminifera, was donated by Hal Dixon.

2.5 Walderston (Figure 1)

The name Walderston limestone first appeared in the Geological Survey's report for 1953-54 (**Geological Survey Department, 1955**, p. 4) and a type section was identified by **Hose and Versey** (**1957**). Versey (in **Zans et al., 1963**, 26-43) defined it as extending "from Walderston one mile along the road to Christiana, Manchester". One of us (ER) visited the section on October 26, 1968 with P. Jung, and again in January 2001 (samples ER3128, ER3133). An adjacent section from Walderston along the road to Spaldings was sampled on March 11, 1994 with H. L. Dixon (ER2563, ER2566). The larger foraminiferal assemblages from the adjacent section were published by **Robinson** (**1995**, figure 2) and republished with the addition of one Sr isotope ratio determined by P.A. Mueller, University of Florida at Gainsville (**Robinson and Mitchell, 1999**, figure 7).

2.6 Newport-Mandeville (Figure 1)

The type section of the Newport formation was stated to be along the road from Newport to Mandeville (**Figure 1**). Since the definition was published (**Hose and Versey, 1957**; Versey in **Zans et al., 1963**) mining activities of the bauxite industry have extensively altered the landscape and road alignments in the area. In **Versey**'s (**1963**) description of the formation he mentioned that the lower part of the unit, not represented in the type section, contained a sparse foraminiferal assemblage including *Heterostegina* and miogypsinids. We chose two localities, at each end of the type section, to examine samples for Sr isotopic ratio analysis. DAR1 (*Kuphus* sp.) and DAR2 were collected by D.-A. Rowe and G. Nunes from the southern end of the section in a disused quarry just north of Newport. ER3185, collected at the northern end of the type section, from the road below the Northern Caribbean University, is the same locality as ER2511 from which an archaiasinid fauna was illustrated in **Robinson** (**2004**, figures 12 and 13). A sample from locality TSN3.1 east of the road, from the lower part of the formation, was isotopically dated by us previously (**Table 1**; **Robinson, 2004**, p. 57).

2.7 Ipswich (Figure 4)

The Ipswich limestone was named for outcrops of variably impure limestone on the south-western edge of the Clarendon Block which, while lithologically similar to the Yellow Limestone, contained foraminiferal assemblages similar to parts of the White Limestone (**Versey, 1957**; Versey in **Zans et al., 1963**, p. 34). The type section (**Figure 4**) was visited by one of us (ER) on February 4, 1966 with R. M. Wright and again on June 9, 1999. Three samples were examined for their Sr isotopic ratios (**Figure 4**). ER 3069/ER647 (fig. 4 and **Table 1**) were collected from what was regarded as the upper and typical Ipswich limestone (H. R. Versey, pers. comm. 1966).

2.8 Appleton (Figure 1)

During a survey of the now disused Western Cement Company's property near Appleton in 1997 (**Figure 1**) a number of samples were collected for larger foraminiferal analysis. One of these, ER2756, was later submitted for Sr isotope analysis (**Table 1**).

Table 1. Occurrences of larger foraminifera plotted against Sr dates generated for this study and for previously generated Sr data as follows: a, Land 1991; b, Paytan in Robinson 2004; c, Mueller in Robinson and Mitchell, 1999; d, samples from the Gibraltar limestone as described in Versey 1963, p. 35 at Red Gal Ring (Figure 2), demonstrated by Howard Versey during a field trip attended by the senior auther (in Chubb and Versey, 1958). Formation names suggested for each sample. Grid references generated from Jamaica 200 Series, scale 1:12,500 topographic maps (units in feet). *The possible range of Sr based ages are given using the Sr stratigraphy LOWESS table in the Geological Time Scale 2012 (McArthur et al., 2012). Samples marked "not used for Sr" are neighbouring samples chosen to supplement foraminiferal data for the Sr dated sample immediately above it in the table. Samples used for the geochemical analyses were taken either from *Kuphus* tubes, as indicated in the first column of the species list, or from foraminifera contained in the samples and bulk samples.

JAMAICAN STRONTIUM ISOTOPE DATED SAMPLES AND ASSOCIATED LARGER FORAMINIFERA

SAMPLE	LOCATION	Imperial Grid (ft)	$^{87}Sr/^{86}Sr$	*Sr AGE (Ma)	REF	SUGGESTED STRAT UNIT	Kuphus sp used for Sr dating	Archaiasinids	Heterostegina antillea CUSHMAN	Lepidocyclina canellei LEMOINE & R DOUVILLE	Nummulites sp s.l.	Miogypsina spp	Eulepidina undosa (CUSHMAN)	Nephrolepidina vaughani (CUSHMAN)	Miogypsinella complanata SCHLUMBERGER	Amphistegina sp	Borelis sp	Peneroplids	Planorbulina?	New gen new sp?	Neorotalia mexicana (NUTTALL)	Fallotella cookei (MOBERG)	Fallotella floridana (COLE)	Praerhapidionina delicata HENSON	Lepidocyclina parvula CUSHMAN	Eulepidina chaperi (LEMOINE & R. DOUVILLE)	Lepidocyclina pustulosa H. DOUVILLE	Fabularia verseyi COLE	Coskinolina floridana (COLE)	Pseudochrysalidina floridana COLE	Nummulites stiatoreticulatus L. RUTTEN	Heterostegina ocalana CUSHMAN	Asterocyclina spp	Pellatispirella matleyi (VAUGHAN)	Cushmania americana (CUSHMAN)	Cyclorbiculinoides jamaicensis ROBINSON	Lepidocyclina gubernacula COLE	Fabiania cubensis (CUSHMAN & BERMUDEZ)	Nummulites floridensis HEILPRIN	Lepidocyclina proteiformis VAUGHAN	Rotalia sp A	Nephrolepidina n. sp.	Pliolepidina tobleri H. DOUVILLE flat var.	Lepidocyclina macdonaldi CUSHMAN	Pliolepidina cf P. tobleri, irregular var.	Amphistegina parvula (CUSHMAN)	Yaberinella panamensis ROBINSON	Lepidocyclina ariana COLE & PONTON	Fabularia vaughani COLE & PONTON	Pseudofabularia matleyi ROBINSON	Yaberinella jamaicensis VAUGHAN
DAR-2/ER3183	**Old Newport quarry**	**37353877**	**0.708440**	**19.55-19.80**		**type Newport Formation**		X																																													
DAR-1/ER3182	**Old Newport quarry**	**37353877**	**0.70834**	**21.45-21.65**		**type Newport Formation**	X																																														
Land 1991	in situ Tobolski reef	41855344	0.70833	21.50-21.80	a	Newport Formation?																					AQUITANIAN STAGE																							
YD-5	Tobolski reef	41545336	not used for Sr			Newport Formation?			X	cf	X																																								
Land 1991	reef block in chalk	39855550	0.70831	21.85-22.15	a	Debris in Montpelier Fm																					LOWER MIOCENE																							
	Neighbouring Samples	several	not used for Sr			Debris in Montpelier Fm			X	X	X	X	X	?																			23.0 Ma																		
TSN 3.1/ER3174	May Day district,	38644012	0.70823	23.35-23.70	b	Newport Formation	X																																												
ER3186	**N. Caribbean U.**	**37614051**	**0.708207**	**23.80-24.10**		**type Newport Formation**		X																																											
ER3151	May Day district, Manchester	38004011	not used for Sr			Newport Formation			X	X		X																																							
ER3147	May Day district, Manchester	38374049	not used for Sr			Newport Formation		X	X																																										
ER408	Red Gal Ring section	62304250	0.708082	26.50-27.05		Newport Formation?			X	X					X	X												CHATTIAN STAGE																						
ER2585	Mocho section	43154189	0.70807	26.90-27.40	c	Walderston ls		X								X	X?	X	X	X																														
ER3166	Riverhead section 4	51574958	0.70807	26.90-27.40		Browns Town facies					X		X								X							UPPER OLIGOCENE																						
ER3167	Riverhead section 4	51574957	0.708062	27.15-27.60		Browns Town facies							X																																						
ER3128/2563	Walderston-Cobblers rd	38124472	0.70805	27.50-27.95	b	Walderston ls	X								X			X	X		X?	X											28.1 Ma																		
ER3162	Riverhead section 2	51754932	0.708024	28.20-28.70		Walderston ls																sp	sp																												
ER3133	**Walderston-Christiana rd**	**37934488**	**0.708005**	**28.75-29.30**		**type Walderston ls**											X	X						X																											
ER2614	**Browns Town quarry**	**42445429**	**0.70800**	**28.90-29.45**	**b**	**type Browns Town ls**					X		X	X							X				X																										
ER3165	Riverhead section 3	51774940	0.707967	30.00-30.60		not determined																																													
ER399	Red Gal Ring section	62304250	0.707954	30.40-31.05		Browns Town ls							X								X			X																											
ER3161	Riverhead section 2	51764931	0.707932	31.25-31.80		Walderston ls																sp																													
ER3173A	Riverhead section 2	51824923	0.707913	31.85-32.35		"Gibraltar"/Browns Town ls?													RUPELIAN STAGE							cf																									
ER3160	Riverhead section 1	52054943	0.707911	31.90-32.40		Somerset/"Gibraltar" ls?																				X	X																								
ER3164	Riverhead section 3	51804939	0.707905	32.10-32.55		Walderston ls	X												LOWER OLIGOCENE																																
ER3163	Riverhead section 2 m below 3164	51804939	not used for Sr			Walderston ls																X				sp	X																								
ER2566	Rd Walderston-Cobblers	38064464	0.70790	32.20-32.65	c	Walderston ls												X				X	X																												
ER337	Red Gal Ring section	62304250	0.707891	**32.45-32.85**	d	"Gibraltar ls" of Versey 1963, p.35																X						X																							
ER3159	Riverhead section 1	52054943	0.707887	32.55-32.90		Somerset ls																						X																							
ER329	Red Gal Ring	62304250	0.707874	**32.85-33.15**		Upper Claremont of Robinson 1974																X						X		X				X	X	X															
ER176	St Mary	55495200	0.707871	**32.90-33.20**		Montpelier Formation																				X					X	X	X						X												
ER3157	Riverhead section 1	52054942	0.707866	33.00-33.30		Somerset/Gibraltar?																				X																									
ER2572	Mocho section	42944238	0.707850	33.30-33.60	c	Somerset ls																X						X	X?	X																					
ER366	Red Gal Ring section	62304250	0.707840	33.45-33.80	d	"Gibraltar ls" of Versey 1963, p.35																				X		X																							
ER363	approx 9 m below ER366	62304250	not used for Sr		d	"Gibraltar ls" of Versey 1963, p.35						33.9 Ma														X		X			X	X	X	X																	
ER3064	Ipswich section	26104644	0.707824	33.80-34.11		Ipswich section																					X					X	X				X	X	X												
ER3158	Riverhead section 1	52054942	0.707806	34.15-34.50		gastropods below F. verseyi													PRIABONIAN STAGE																																
ER3066	Ipswich section	26184667	0.707794	34.40-34.80		Ipswich section																									X									?	X	X	X	?	X	X	X				
ER2756	old lime quarry near Appleton	28854614	0.707776	34.90-35.70**		Appleton limestone																					X								X		X						X	X		X					
ER1539A	**Claremont quarry**	**48925193**	**0.707773**	**35.05-35.95****		**type Claremont Formation**																													X													X			
ER285	Red Gal Ring section	62304250	0.707757	35.95-37.25**		Claremont Formation						37.8 Ma							UPPER EOCENE											X					X													X		
ER3069/ER647	**Ipswich section**	**26344687**	**0.707741**	**37.25-38.80****		**type Ipswich Formation**																																X	X	X	X	X		?		X	X		X	X	?
																			BARTONIAN STAGE																																
		** Sample age could also be >40Ma see text for discussion																																																
																			UPPER MIDDLE EOCENE																																

[A larger version of this Table is available for download Here]

ER3103 collected from about 3 metres below ER2756 on June 9, 1999, yielded rare nannofossils, including *Chiasmolithus grandis* and small *Cribrocentrum reticulatum*, indicative of an upper NP16 to NP17 zone age (M. Jiang pers. comm. August 29, 1999).

2.9 Red Gal Ring (Figure 1)

The lower part of the section at Red Gal Ring (**Figure 1**) was published by **Robinson** (**1974**, textfigs 1, 2). The foraminiferal succession in the upper part appeared in **Robinson** (**1995**, figure 4). Six samples were examined for Sr isotope ratio data: ER285, ER329, ER337, ER366, ER399, ER408 (**Table 1**).

2.10 Previous Sr Determinations (stars on Figure 1)

Land (**1990**) published a number of Sr isotope ratios from the vicinity of Browns Town and Discovery Bay (**Figure 1**). Two of these are relevant to the present discussion (**Figure 1**, **Table 1**). Three earlier results provided by P. A. Mueller for the sections at Walderston and Mocho (in **Robinson and Mitchell, 1999**, p.12; **Table 1**) are also included.

3. METHODS

Samples were prepared by scraping off the surface, pulverizing the surface-scraped specimen, cleaning the powder by repeat rinses with ethanol and sonication, followed by dissolving in 0.75N HCl. The soluble fraction was collected and concentrations of strontium, calcium, magnesium, manganese, iron and uranium, were determined by HR-ICPMS (Thermo Element XR) (**Table 2**). Strontium was separated using conventional ion chromatographic procedures. Samples were loaded on Ta filaments and analyzed by thermal ionization mass spectrometry (Finnigan 261). Values have been normalized to $^{86}Sr/^{88}Sr$ of 0.1194. We measured the SRM987 standard along with each batch of samples and adjusted the $^{87}Sr/^{86}Sr$ of the samples to SRM987 = 0.71024, which is the average value measured in the laboratory along with the samples. The uncertainty in the data is 0.000009 based on repeat analyses of samples and standards. Strontium stratigraphy (ages) were assigned based

Table 2. Trace element analyses of bulk carbonate of some samples appearing in Table 1. Approximately 5 mg of sample were dissolved in 3.5 mL of 2% nitric acid (Optima grade) for ICPMS analysis. Trace element concentration was determined on a Thermo Finnegan Element XR using a house-prepared rendition of the NIST 1D standard reference material (argillaceous limestone). Sr/Ca and Mg/Ca are reported as ratios of these elements in the sample, and Al, Fe, Mn, and U are reported as mass fractions of the original bulk carbonate sample. Values in italics (sample ER 3069) suggest the inclusion of some additional mineral phases in the sample possibly manganese-oxide.

Sample	Sr/Ca mmol/mol	Mg/Ca mmol/mol	Al ppm	Fe ppm	Mn ppm	U ppm
ER3182	6.51	3.12	298	971	11	1.7
ER 3064A	3.88	3.39	891	1247	16	1.8
ER 3064A	3.65	3.22	1394	1209	15	1.7
ER 2756	3.17	4.13	2962	1768	62	1.0
ER 1539A	4.82	3.82	502	1373	13	2.6
ER 285	2.07	2.32	7822	10002	72	1.5
ER 3069	4.90	8.17	3874	17462	*616*	2.0
ER 3183	3.45	3.87	628	1955	18	6.8
ER 3186	3.16	3.04	498	1240	13	3.7
ER 408	5.90	3.74	1161	4986	169	3.9
ER 3133	3.98	3.00	662	1778	14	6.9
ER 399	6.68	2.76	15409	5580	145	2.9
ER 337	2.17	2.37	2294	2116	20	2.4
ER 329	1.69	2.80	2493	9346	123	3.7
ER 363	4.93	1.68	7772	4243	44	0.6
Precision (±%)	0.59	0.97	0.14	0.16	0.71	3.3

on the 2012 Geological time scale Lowess curve (**McArthur et al., 2012**).

Larger benthic foraminiferal identifications were mostly based on inspection of randomly oriented foraminiferal remains in petrographic thin sections, prepared from samples collected at various times extending back to 1961. Additional SEM images and oriented thin sections were prepared from free specimens.

4. Results

Table 1 contains the detailed results of all Sr isotope ratios collected to date and the occurrences of the identified larger foraminifera. Grid references based on the Jamaica 200 Series 1:12,500 topographic maps published in the 1970s, are included for all the samples. Sr dates for the type localities of five of the formations of Versey (in **Zans et al., 1963**) are emphasised. The Sr isotopic ages determined in this study, plus several previously published results, range from 38 Ma (Ipswich Formation) latest Bartonian, middle Eocene, to 19.7 Ma (Newport Formation, early Miocene). **Table 2** includes the elemental ratios (Sr/Ca and Mg/Ca) and select trace metal concentration (Fe, Mn and U) in the samples. On **Figure 5** the Sr determinations for each identified stratigraphic unit are plotted against the chronostratigraphic scale used in the Geological Time Scale 2012 (**Gradstein et al., 2012**).

5. Discussion

The Sr determinations made for this paper and previously on type sections/localities include three from the Newport, three from the Walderston, one from the Browns Town, one from the Claremont and one from the Ipswich. The Ipswich limestone of Versey is divisble into two units based on larger foraminiferal associations, but only the upper and classical part is discussed here. Other units named by Versey (**Figure 2**) including the Troy largely unfossiliferous and recrystallised limestone, the Swanswick and Gibraltar limestones and the Somerset limestone have not been examined at their type localities. Lithic units assigned with confidence to the Somerset and Gibraltar limestones occur at Red Gal Ring (Versey in **Zans et al., 1963**; **Robinson, 1974**). The remaining Sr determinations mainly cover limestones assigned to the Walderston, Browns Town and Newport formations (**Table 1**).

At both Ipswich and Appleton the upper Ipswich limestone of Versey is overlain by limestones containing upper Eocene foraminifera, including flat forms of *Pliolepidina tobleri*. Of four samples determined from Ipswich and Appleton, only one, ER3069, is from the type upper Ipswich

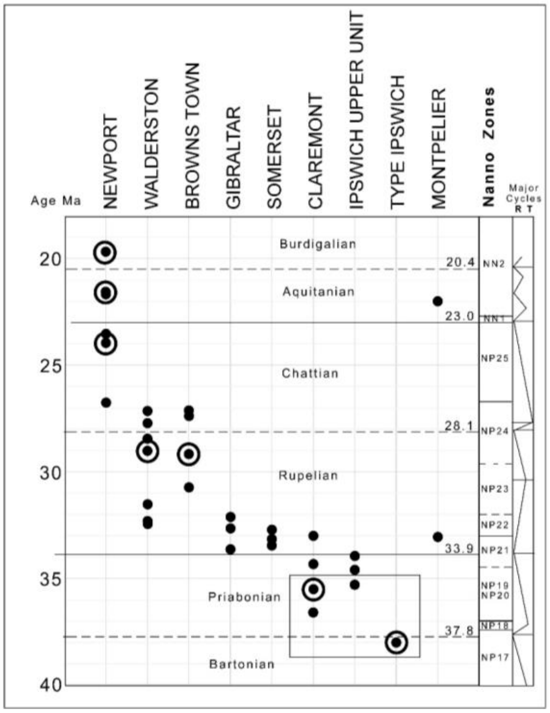

Figure 5. Summary ages of Sr dated samples and the formation names originally assigned to them. Ringed spots are Sr determinations from type localities. Spots inside the box are Sr determinations that generate alternative ages greater than 40 Ma (see text for discussion). Chronostratigraphy, nannofossil zones and major cycles based on data in GTS 2012 (pp. 857, 936).

as defined by **Versey** (**1957a**; and see Figure 4). Its Sr age of 38 Ma is compatible with the only date determined by calcareous nannofossils (upper NP16-NP17) for a horizon near Appleton assigned to the Ipswich Formation. Samples overlying the nannofossil-dated horizon at Appleton including ER2756 (**Table 1**) contain the *Pliolepidina tobleri* assemblage similar to ER3066, which overlies the typical Ipswich at Ipswich (**Table 1**, **Figure 4**). These samples have Sr ages of 35.3 and 34.6 Ma respectively, significantly younger than that determined for the type Ipswich (**Table 1**). The ages are similar to those from Claremont and Red Gal Ring for samples assigned to the Claremont Formation. It is suggested that the Appleton strata overlying the nannofossil horizon and similar strata overlying the typical Ipswich Limestone belong to a lithological unit coeval with the Claremont Formation. It should be noted that *Pliolepidina tobleri* is traditionally a marker for the upper Eocene (e.g., **Vaughan and Cole, 1941**; **Caudri, 1996**).

The Sr age determinations for the four samples discussed above have alternative age assignments available, greater than 40 Ma (**Figure 5** box and **Table 1**; **McArthur et al., 2012**). Of these only the ones associated with the Sr isotope curve flexure younger than 45 Ma need to be considered. Alternative age assignments older than this pre-date the first appearance of the lepidocyclinids at about the boundary between the N16 and N17 calcareous nannofossil zones (**Robinson and Jiang, 1995**; **Robinson, 1996**) at about 40 Ma (**Gradstein et al., 2012**). Sample ER1539A, type Claremont formation contains *Lepidocyclina ariana*. ER3069, type Ipswich formation, contains *Lepidocyclina proteiformis*. Both these species are among the earliest true lepidocyclinids to appear and are the immediate successors of the *Polylepidina* group. The earlier alternative date for ER1539A (43.5 Ma) is too old. It is also likely that the alternative for ER3069 (41.8 Ma) is too old hence we accept the Sr ages of 35.3 and 34.6 Ma for these samples.

Isotopic ages of 21.7 and 22 Ma were recorded as being from the Browns Town limestone at Tobolski and from a sample of reworked material in the Montpelier formation by **Land** (**1991**). No faunal determinations were given by him. The assignment of these dates by Land to the Browns Town was accepted by **Mitchell** (**2013**). Versey and Zans (in **Geological Survey Department 1954**, p. 2) first described this part of the succession, recognising two lower and upper Oligocene crystalline units, including one characterised by miogypsinid foraminifera. Versey later (in **Zans et al., 1963**, p. 38) mentioned the existence of outliers of the Newport limestone at Tobolski and elsewhere on the northern part of the Clarendon Block. Our assigned ages for the Newport Formation in its type section (20.9 and 21.65 Ma) support our suggestion that Land's samples probably came from a Newport Formation outlier at Tobolski and not from the underlying Browns Town Formation. The presence of *Heterostegina antillea* in limestone from Tobolski (**Table 1**, **Figure 6**) and its apparent absence at the Browns Town type locality lends support to this suggestion (**Robinson, 2004**, p. 54).

Other biostratigraphic changes indicated on **Table 1** are the disappearance of the genus Fallotella at about the end of the Rupelian, and the common occurrence of *Fabularia verseyi* in the early part of the Rupelian. In Florida *Fallotella* had been considered, somewhat controversially, as an Eocene guide fossil (**Cole, 1941**, and arguments therein) but has been recorded from the lower Oligocene (**Beckmann, 1958**; **Robinson and Wright, 1993**). *Fabularia verseyi* had always been regarded as an upper Eocene index until Sr dating suggested that at least some occurrences are lower Oligocene (**Robinson and Mitchell, 1999**, p.12, 14 and this paper).

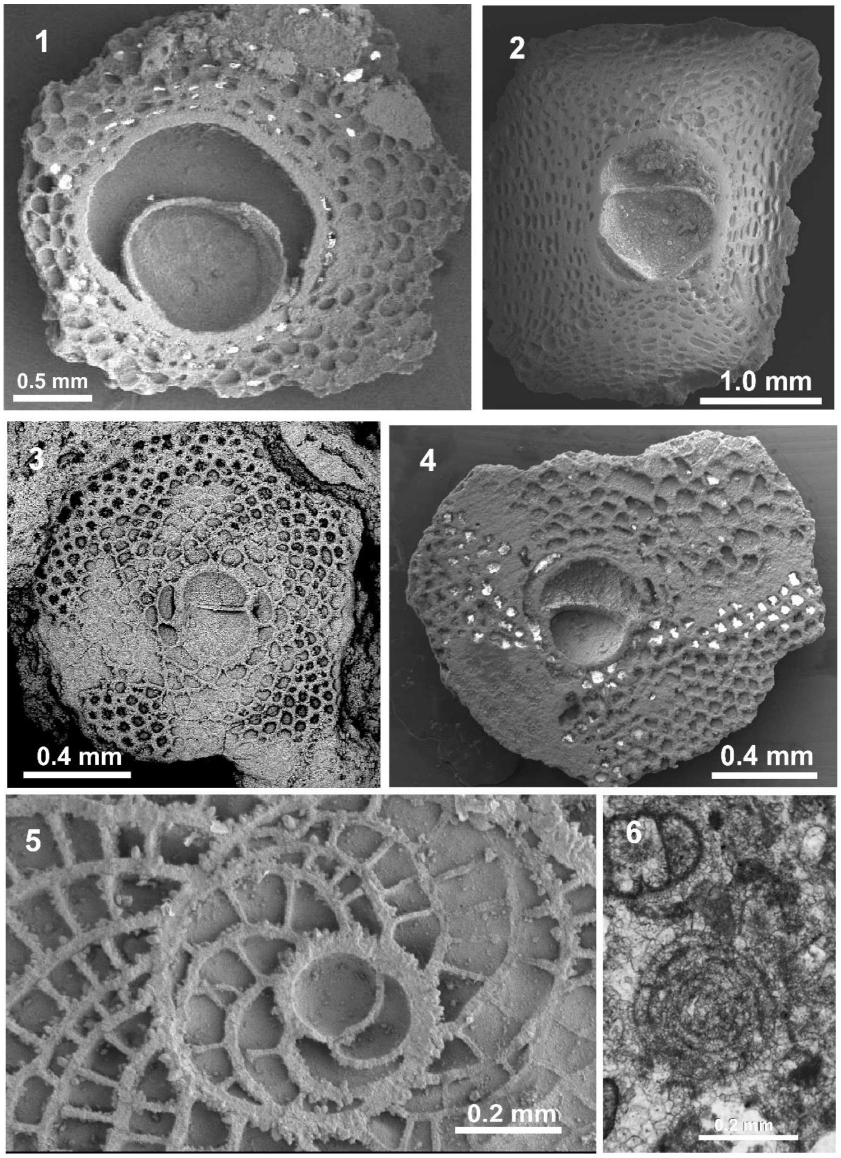

Figure 6.

1, *Eulepidina undosa* (Cushman);

2, E. undosa, selliform specimen;

3, *Lepidocyclina parvula* Cushman;

4, *Nephrolepidina vaughani* (Cushman);

5, *Heterostegina antillea* Cushman;

6, *Borelis* sp.

1-4 from Lee's marl crushing plant, Browns Town;

5, from YD-5, Tobolski,

6 from ER 3133, Walderston.

While we accept the early Oligocene age for shallow-water carbonate assemblages containing *Fabularia verseyi*, there are two samples that include regionally well-established Eocene foraminiferal markers. ER176 from the Montpelier formation at Dressikie contains well-preserved examples of *Heterostegina ocalana*, *Asterocyclina minima* and other species of late Eocene age (e.g., **Cole, 1952**; **Robinson, 2004**). Mark Jiang determined a calcareous nannofossil assemblage referable to the NP21 zone. This zone straddles the Eocene-Oligocene boundary and its upper contact with NP22 is at about 33 Ma. The Sr age of 32.9-33.2 Ma for ER176 (**Table 1**) and the sedimentology would suggest downslope reworking of the shelf-edge larger foraminiferal assemblage, but it is possible that they also transgress the currently accepted Eocene-Oligocene boundary (**Gradstein et al., 2012**). Similarly the presence of *Cushmania americana* and *Pellatispirella matleyi* in sample ER329 at Red Gal Ring (Sr age 32.85-33.15 Ma) could be attributed to reworking, although this would seem less likely in a more inner shelf environment, and calcareous nannofossils and planktic foraminifera are absent from this sample. Alternatively, it is also possible that the use of dilute hydrochloric acid to dissolve the bulk carbonate sample prior to isotope analysis may have released Sr from clays or other minor terrestrial mineral phases resulting in slightly more radiogenic Sr isotope ratios and an age estimate that is younger (lower Oligocene) than the fossil based ages (Eocene-Oligocene boundary). More work has to be done to verify this, however an assessment of elemental ratios (Sr/Ca, Mg/Ca) and trace elements (Fe, Mn and U) in the sample show values similar to other samples analyzed (**Table 2**) and do not indicate a substantial contribution from clays. Specifically, ancient calcite is considered 'unaltered' if Sr/Ca ratios are >0.9 mmol/mol in the Holocene (**Regenberg et al., 2007**) or >1.2 mmol/mol in samples as old as the Cretaceous (**Bralower et al., 1997**) and Fe, Mn and U concentrations are typical for carbonates.

The age distribution of Sr dated samples in **Figure 5** seems to indicate that either sampling has not yet been comprehensive enough to cover the entire mid-Tertiary time spectrum (most likely reason) or sedimentation/ sediment thicknesses/ hiatuses may have varied considerably over time. So far sampling has been limited to a few discrete areas (**Figure 1**). Noticeable on figure 5 are information gaps in Sr data between 22 and 23.3 Ma, 24 and 26.8 Ma, and 36.5 and 38 Ma. That at 24 and 25.6 Ma is compatible with the unconformable base of the Newport Formation as understood by **Hose and Versey** (**1957**, figure 2). It is also possible that there is a discontinuity between the typical and lower part of the classical Newport Formation at about the Chattian-Aquitanian boundary. That between 36.5 and 38 Ma may correspond to the end-Bartonian regressive termination.

6. Conclusions

Twenty six samples from the White Limestone group of Jamaica were analysed for their Sr isotope ages. Of the eleven or more formations within the Group, five, the Newport Walderston, Browns Town, Claremont and Ipswich, were dated at their type localities. Two more, the Somerset and Gibraltar limestones, were dated from exposures other than the type localities. Although the Somerset Formation was thought to be Eocene during work carried out by the then Geological Survey Department of Jamaica in the early 1950s mapping, our results strongly suggest an early Oligocene age for this unit, and for the Gibraltar limestone. The relationships and ages of the Browns Town, Walderston and Newport limestones, also named and mapped in the 1950s by the Geological Survey, appear to be confirmed by our dating. The occurrences of the associated larger foraminiferal assemblages are generally compatible with the Sr dated samples. Exceptions include *Fabularia verseyi* long considered to be an Upper Eocene marker but found by us to be in samples of early Oligocene age. The extension of the range of *Fallotella cookei* through the Rupelian is confirmed. Regionally reliable markers for the upper Eocene are thought to be reworked into the earliest Oligocene in the two samples in which they occur but an upwards extension of their range is not ruled out. Further work is planned to extend dating to the type localities of the remaining classical units erected by the Geological Survey of Jamaica.

7. Taxonomic Note

Superfamily ASTERIGERINOIDEA d'Orbigny, 1839
Family LEPIDOCYCLINIDAE Scheffen, 1932
Sub-Family HELICOLEPIDININAE Tan, 1936
Genus *Nephrolepidina* H. douville, 1911

***Nephrolepidina*? n. sp. Figures 7.5, 7.7, 7.8.**

?1942, *Lepidocyclina (Pliolepidina) cedarkeysensis* Cole, p.43-45, pl. 3, figs 1, 2; pl. 8, fig 11; pl. 11, figs 6, 7; pl.12, figs 1-7.

?1928, *Lepidocyclina sherwoodensis* Vaughan, p. 287, pl.48, figs 4-8.

In samples ER3069 and ER647 there occurs a lepidocyclinid, evidently related to the *Nephrolepidina pustulosa* group in which, in equatorial section, the equatorial and principal auxiliary chambers are partially obscured by structures that, overall, generate a decidedly concentric appearance to the chambers of the equatorial layer. It is associated with other lepidocyclinids assigned to *L. proteiformis* Vaughan (**Figures 7.9, 7.10**).

In axial section this new pecies resembles the axial sections of the type figures of *Lepidocyclina sherwoodensis* Vaughan and *L. (Pliolepidina) cedarkeysensis* Cole. It differs from L. cedarkeysensis in posessing a much larger nucleus, about the size of that of *L. sherwoodensis*, but resembles *L. cedarkeysensis* in posessing what Cole described (p. 45) as "small wedge-shaped projections into the chamber cavities from the pillars or vertical walls between adjacent chambers". This feature is well shown only on **Cole**'s (**1942**) plate 11, figure 6, but appears on most of the specimens randomly sectioned from ER647 for the present paper (e.g. **Figure 7.7, 7.8**). The new species differs from both the above species in posessing a nephrolepidine nucleus, the protoconch about 0.4 mm wide and the deuteroconch about 0.45 to 0.5 mm wide. In equatorial section, the nucleus is distinctly compressed in a direction normal to the wall separating the protoconch from the deuteroconch so that the protoconch as well as the deuteroconch is irregularly ovoid in shape (**Figures 7.7, 7.8**). Because of the wedge-shaped projections the principal auxiliary chambers are obscured. The species is left in open nomenclature pending the preparation of oriented sections of free specimens, but it is mentioned here as being a likely important biostratigraphic marker, perhaps a form ancestral to the *Pliolepidina tobleri* group.

Acknowledgements. *We thank Deborah-Ann Rowe and Garth Nunes for collecting samples (DAR-1 and 2) from the old Newport quarry, and Tom Stemann for the sample TSN3.1 from S.E. of Mandeville. Yolanda Drakopoulos donated the sample YD-5 from the mining area at Tobolski. Mark Jiang provided determinations on the calcareous nannofossils from the Appleton area and from Dressikie.*

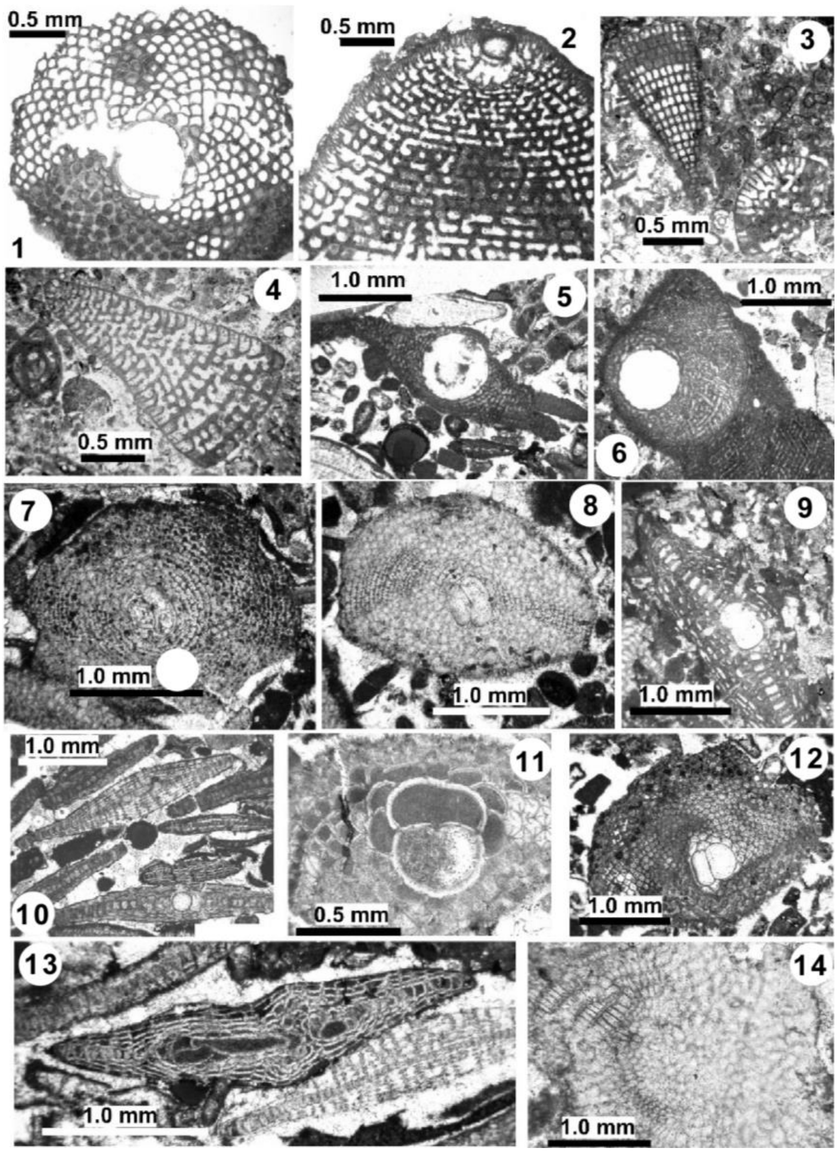

Figure 7

1, *Lepidocyclina ariana* Cole & Ponton;

2, *Cushmania americana* (Cushman);

3, 4, *Fallotella cookei* (Moberg);

5, 6, *Yaberinella panamensis* Robinson;

7, 8, *Nephrolepidina*? n. sp.;

9, *Lepidocyclina macdonaldi* Cushman;

10, axial sections of a, *Nephrolepidina*? n. sp. and b, *L. proteiformis* Vaughan;

11, 12, *Lepidocyclina proteiformis* Vaughan;

13, *Pliolepidina*? aberrant specimen with two nuclei;

14, Orthophragminid.

1, 2, ER1539A, Claremont;

3, ER2566, Walderston;

4, ER3128, Walderston;

5-8, ER647/ER3069, Ipswich;

9, ER2756, old Western Cement property, Appleton;

10-14, ER647/ER3069, Ipswich.

REFERENCES

Baumgartner-Mora, C., Baumgartner, P.O. and Tschudin, P. 2008. Late Oligocene Larger Foraminifera from Nosara, (Nicoya Peninsula, Costa Rica) and Windward (Carriacou, Lesser Antilles), calibrated by ^{87}Sr/^{86}Sr isotope stratigraphy. *Revista Geológica de América Central*, **38**, 33-52.

Beckmann, J.P. 1954. Correlation of pelagic and reefal faunas from the Eocene and Paleocene of Cuba. *Eclogae geologicae Helvetiae*, **51**, 416-422.

Bralower, T.J., Fullagar, P.D., Paull, C.K., Dwyer, G.S. and Leckie, R.M. 1997. Mid-Cretaceous strontium-isotope stratigraphy of deep-sea sections. *Bulletin of the Geological Society of America*, **109**(11), 1421-1442.

Burke, K., Coates, A.G. and Robinson, E. 1969. Geology of the Benbow Inlier and surrounding areas. *Transactions of the Fourth Caribbean Geological Conference, Port of Spain, Trinidad, 1965*, 299-307.

Caudri, C.M.B. 1996. The larger foraminifera of Trinidad (West Indies). *Eclogae geologicae Helvetiae*, **89**, 1137-1309.

Chubb, L.J. and Versey, H.R. 1958. Field meeting on Stony Hill and the Junction road, Jamaica. *Proceedings of the Geologists' Association*, **69**(1), 35-37.

Cole, W.S. 1941. Stratigraphic and Paleontologic studies of wells in Florida. *Florida Geological Survey Geological Bulletin*, **19**, 1-91.

Cole, W.S. 1942. Stratigraphic and Paleontologic studies of wells in Florida-No.2. *Florida Geological Survey Geological Bulletin*, **20**, 1-89.

Cole, W.S. 1952. Eocene and Oligocene larger Foraminifera from the Panama Canal Zone and vicinity. U.S. *Geological Survey Professional Paper* **244**, 1-41.

Cole, W.S. 1956. Jamaican larger foraminifera. *Bulletin of American Paleontology*, **36**, 205-233.

Dixon, H.L. and Donovan, S.K. 1999. Report of a field meeting to the area around Browns Town, parish of St. Ann, north-central Jamaica, 21st February, 1998. *Journal of the Geological Society of Jamaica,* **33**, 24-30.

Geological Survey Department 1951. *Annual Report of the Geological Survey Department for the Financial Year 1950-51*. Government Printer, Kingston, 10 pages.

Geological Survey Department 1954. *Annual Report of the Geological Survey Department for the Financial Year 1952-53*. Government Printer, Kingston, 6 pages.

Geological Survey Department 1955. *Annual Report of the Geological Survey Department for the Financial Year 1953-54*. Government Printer, Kingston, 21 pages.

Hose, H. R. and Versey, H. R. 1957 (dated 1956). Palaeontological and lithological divisions of the Lower Tertiary. limestones of Jamaica. *Colonial Geology and Mineral Resources*, **6**, 19-39.

Land, L.S. 1991. Some aspects of the late Cenozoic evolution of north Jamaica as revealed by strontium isotope stratigraphy. *Journal of the Geological Society of Jamaica*, **28**, 45-48.

Matley, C.A. 1925. Recent Geological Work in Jamaica. *Report to the British Association, Toronto, 1924*, 391-392.

Martini, E. 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation, In: **Farinacci, A. (Ed.)**, *Proceedings of the Second Planktonic Conference, Roma, 1970*, Technoscienza, 739-785.

McArthur, J.M., Howarth, R.J. and Shields, G.A.. 2012. Strontium Isotope Stratigraphy, In: **Gradstein, F.M., Ogg, J,G., Schmitz, M.D. and Ogg, G. (Eds.)**, The Geologic Time Scale 2012, , Elsevier, 127–144, ISBN: 978-0-444-59425-9

Mitchell, S.F. 2004. Lithostratigraphy and palaeogeography of the White Limestone Group. In **S.K. Donovan (Ed.)**, *The mid-Cainozoic White Limestone Group of Jamaica. Cainozoic Research*, **3**, 5-29.

Mitchell, S.F. 2013. Stratigraphy of the White Limestone of Jamaica. *Bulletin Société géologique de France*, **184**, 1-2, 111-118.

Mitchell, S.F. 2015. *Geology of the parish of St Catherine (1:50,000 scale).* Geological Map. Department of Geography and Geology, The University of the West Indies, Mona, Kingston 7, Jamaica.

Ortega-Ariza, D., Franseen, E.K., Santos-Mercado, H., Ramírez-Martínez, W.R. and Core-Suárez, E.E. 2015. Strontium Isotope Stratigraphy for Oligocene-Miocene Carbonate Systems in Puerto Rico and the Dominican Republic: Implications for Caribbean Processes Affecting Depositional History. *Journal of Geology*, **123**(6), 539-560.

Regenberg, M., Nümberg, D., Schönfeld, J. and Reichart, G.-J. 2007. Early diagenetic overprint in Caribbean sediment cores and its effect on the geochemical composition of planktonic foraminifera. *Biogeosciences*, **4**(6), 957-973.

Robinson, E. 1974. Some larger foraminifera from the Eocene limestones at Red Gal Ring, Jamaica: *Verhandlungen der Naturforschenden Gesellschaft in Basel*, **84**(1), 281-292.

Robinson, E. 1993. Some imperforate larger foraminifera from the Paleogene of Jamaica and the Nicaragua Rise. *Journal of Foraminiferal Research*, **23**(1), 47-65.

Robinson, E. 1995. Larger foraminiferal assemblages from Oligocene platform carbonates, Jamaica: Tethyan or Caribbean? In **Langer, M.R. (Ed.)**, *Forams '94, Marine Micropaleontology*, **26**, 313-318.

Robinson, E. 2004. Zoning the White Limestone Group of Jamaica using larger foraminiferal genera: a review and proposal. In **Donovan, S.K. (Ed.)**, *The mid-Cainozoic White Limestone Group of Jamaica. Cainozoic Geology*, **3**(1-2), 39-75.

Robinson, E. and Mitchell, S.F. 1999. Middle Eocene to Oligocene stratigraphy and palaeogeography in Jamaica: a window on the Nicaragua Rise (UNESCO/IUGS IGCP 393). *Contributions to Geology UWI Mona*, **4**, 45 p.

Robinson, E. and Wright, R.M. 1993. Jamaican Paleogene larger foraminifera. In **Wright, R.M. and Robinson, E. (Eds.)**, *Biostratigraphy of Jamaica, Geol.ogical Society of America Memoir* **182**, 283-345.

Vaughan, T.W. 1928a. Species of large arenaceous and orbitoidal foraminifera from the Tertiary deposits of Jamaica. *Journal of Paleontology*, **1**(4), 277-298.

Vaughan, T.W. 1928b. *Yaberinella jamaicensis*, a new genus and species of arenaceous foraminifera. *Journal of Paleontology*, **2**, 7-12, pls. 4-5.

Vaughan, T.W. 1929. Additional new Species of Tertiary Larger Foraminifera from Jamaica. *Journal of Paleontology*, **3**(4), 373.

Vaughan, T.W. and Cole, W.S. 1941. Preliminary report on the Cretaceous and Tertiary larger foraminifera of Trinidad British West Indies. *Geological Society of America Special Paper* **30**, 1-137.

Versey, H.R. 1957a. The Ipswich Limestone of Jamaica and its structural significance. *Report of the 20th International Geological Congress, Mexico, 1956*, Section **V** (Segundo Tomo), 519-524.

Versey, H.R. 1957b. *The White Limestone of Jamaica and the palaeogeography governing its deposition.* M.Sc. Thesis, University of Leeds, 56pp.

Zans, V.A., Chubb, L.J., Versey, H.R., Williams, J.B. Robinson, E. and Cooke, D.L. 1963. *Synopsis of the Geology of Jamaica*. Bulletin **4**, Geological Survey Department, Kingston, 72 pp.

Editorial Responsiblity: Dr S. James-Williamson. Type setting: Prof. S. F. Mitchell

Accepted 8th March 2018