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Strontium isotope dates for the Oligocene Antigua Formation, Antigua, W. I.

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ABSTRACT. Five new Sr isotope dates for the Antigua Formation of Antigua, West Indies, ranging from 26.3 Ma to 27.8 Ma provide independent confirmation of the late Oligocene, Chattian age for that formation, originally cited as the reference standard of the Oligocene of the Western Hemisphere. The dates also extend understanding of the early appearance of the miogypsinid larger foraminiferal group in the Caribbean region.

Keywords: Chattian, stratigraphy, miogypsinids, Caribbean

1. INTRODUCTION

Antigua lies within the northeastern part of the Lesser Antilles island arc at the eastern boundary of the Caribbean plate (**Bouysse et al., 1990**). Since the first account of its geology by **Nugent** (**1821**), work by a number of geologists established three primary stratigraphic units on the island (**Figure 1**), formalized by **Martin-Kaye** (**1959**) and modified slightly in terminology by **Weiss** (**1994**). **Weiss** (**1994**) summarized the stratigraphic succession on the island in some detail and reviewed previous work on the geology. More recently **Tomblin** (**2005**) and **Donovan et al.** (**2014**) published descriptions of the geology for use as field guides.

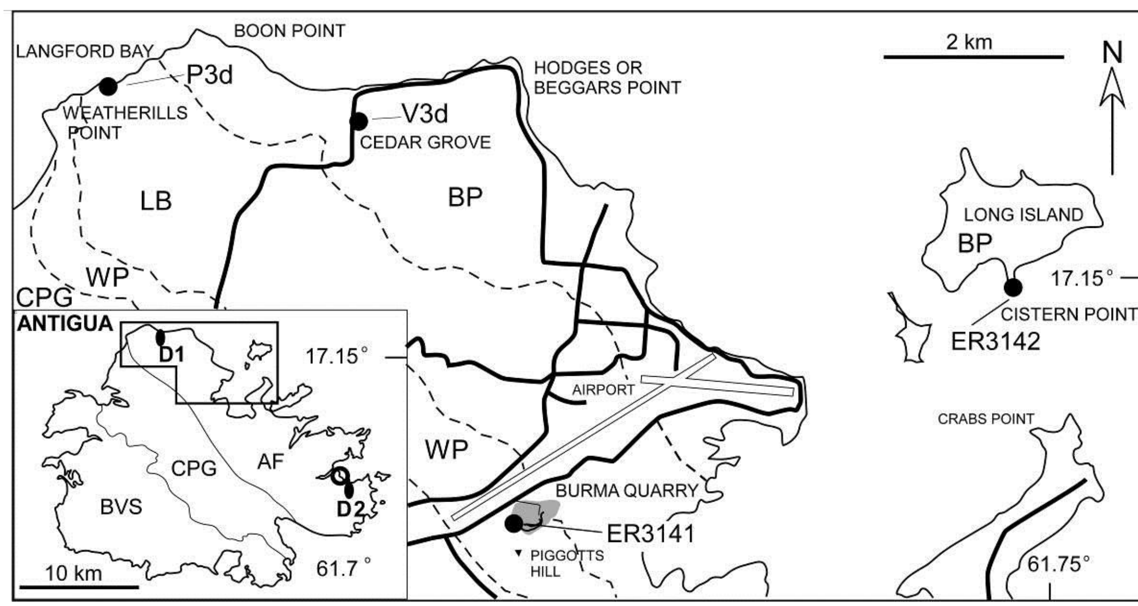

Figure 1. Map of part of northern Antigua, showing locations of samples used in this study (black dots), The members of the Antigua Formation (Persad, 1969) indicated on the main map are from base to top WP Weatherills Point; LB Langford Bay; BP Boon Point. Inset shows location of study area, and extent of the three main Antiguan lithostratigraphic units (positions of contacts after Frost and Weiss, 1979). BVS, Basal Volcanic Suite; CPG, Central Plain Group; AF, Antigua Formation. On the inset map, black ovals, D1 and D2, are the locations of reported post-Antigua Formation basalt intrusives; circle, calcareous nannofossil locality at Hughes Bay (Robinson and Persad, 1989, see text for explanation). Regional dip is towards the north-east.

The lowest Basal Volcanic Suite (BVS; Christman, 1972; Jackson, 2013) is a 2000 m series of intrusive and extrusive predominantly andesitic volcanic rocks with some basalts, including tuffs and pyroclastic material, accumulated within an island arc setting and exhibiting considerable metasomatism (**Jackson, 2013**; **Gunn and Roobol, 1976**). It contains several intercalations of limestone units, one of the most prominent being the Seaforth Limestone. This is succeeded by the Central Plain Group (CPG; **Martin-Kaye, 1959**; **Mascle and Westercamp, 1983**). The CPG Consists of up to 1500 m of a mixed series of sandstones, conglomerates, mudrocks, minor limestones and tuffs, the siliciclastic rocks being derived from the erosion of the BVS. Distinctive fossils include petrified wood and freshwater snails (**Donovan et al., 2014**) as well as ostracodes and charophytes indicative of lacustrine and terrestrial depositional environments. The sedimentary rocks have been extensively silicified locally forming chert (Corbison chert of **Martin-Kaye, 1969**).

These rocks are succeeded by the mainly carbonate Antigua Formation (AF; **Persad 1969**; **Frost and Weiss, 1979**, **Mascle and Westercamp, 1983**). These authors distinguished several sub-units within the Antigua Formation, including patch reefs and biostromes in the lower and western part of the sequence and deeper water slope deposits in the upper and eastern part of the formation (**Weiss, 1994**; **Donovan et al., 2015**). Minor interbedded volcaniclastics are also present. Undated late intrusive mafic dykes cut the Antigua Formation at two locations at Crosbies and at Pig Point, Nonsuch Bay (**Purves, 1885**; **Earle, 1923**; **A. Holmes** in **Trechmann, 1941**; **Martin-Kaye, 1959**; John Tomblin pers. com. to ER, 10th June 2013); D1 and D2 on **Figure 1** inset).

Estimates of the thickness of the AF have varied between 450 m and 550 m (**Weiss 1994**, p. 5). On **Figure 1** we have used the subdivisions erected by Persad for the estimated 300-m-thick succession in the northwest of the island (**Persad, 1969**; **Robinson and Persad, 1989**).

The Antigua Formation was originally cited, on palaeontological grounds, as the reference standard for the Oligocene of the Western Hemisphere (**Vaughan, 1919**; p. 203). Investigations since Vaughan increasingly suggest that the formation and, perhaps, the entire succession in Antigua, represent only the upper Oligocene. Here we present five strontium isotopic determinations from the AF that provide independent evidence for this ongoing discussion.

2. Previous Age-Related Work

Earlier estimates of the age of the Antigua Formation, and the underlying BVS and CPG, were largely based on the palaeontological studies of **Vaughan** (**1919**, corals) and **Cushman** (**1919**, foraminifers), reviewed by **Frost and Weiss** (**1979**). Work on the planktonic foraminifera was initiated by **Bolli** (**1957**), on ostracodes by **van den Bold** (**1966**) and on calcareous nannofossils by **Mascle and Westercamp** (**1983**) and **Jiang** (in **Robinson and Persad, 1989**).

Radioisotopic dating for the BVS (**Nagle et al., 1976**; **Briden et al., 1979**) yielded ages in the range 40 Ma to 36 Ma for the volcanics (**Weiss, 1994**; **Tomblin, 2005**), but these have been judged unreliable due to post-magmatic alteration of the rocks (**Jackson, 2013**). The limestones interbedded with the BVS contain fossil assemblages, dominated by corals and larger foraminifera, indistinguishable from those of the overlying CPG and AF (**Frost, 1974**; **Frost and Weiss, 1979**).

On the basis of planktonic foraminiferal assemblages the whole succession in Antigua was placed in the middle Oligocene G. opima opima and/or G. ciperoensis ciperoensis zones (of **Bolli, 1957**; approximately P21-P22 zones of **Blow, 1969**), or spanning the late middle and early late Oligocene of the previously recognised tripartite subdivision of the Oligocene (as used by **Bolli and Saunders, 1985**). **Bold** (**1966**) favoured correlation with the older G. opima opima and/or G. ampliapertura zones of **Bolli** (**1957**), approximately equivalent to the O5 to O2 zones of **Wade et al.** (**2011**; early late to early Oligocene of current terminology). In **Weiss**'s review (**1994**), the entire sedimentary succession, including the limestone lenses within the BVS as well as the AF, was correlated with the Globigerina ciperoensis ciperoensis zone (of **Bolli and Saunders, 1985**; P22 zone of **Berggren and Miller, 1988**; O6 zone of **Berggren and Pearson, 2005**; O6 and O7 zones, in part, of **Wade et al., 2011**) of late Oligocene (Chattian) age.

Mascle and Westercamp (**1983**) reported a nannoflora from the base of the Antigua Formation, belonging to the N24/N25 zones, and placed the formation in the upper Oligocene. Jiang has reviewed an earlier report on a nannofloral assemblage from Hughes Bay (in **Robinson and Persad, 1989**) and suggests an age for this sample of basal NP25 to NP24 (Jiang pers. comm. to ER, 18th August 2014; **Figure 1**, circle on inset map).

Frost and Weiss (**1979**) favoured an early Late Oligocene age for the Antigua Formation, but remarked on the apparent absence of miogypsinid

Table 1. $^{87}Sr/^{86}Sr$ determinations on the samples from Antigua and strontium stratigraphy ages based on the 2012 Geological time scale Lowess curve (McArthur et al. in Gradstein et al., 2012). For sample locations, see Figure 1.

Sample Number	Determination $^{87}Sr/^{86}Sr$	Interpreted Age (McArthur et al., 2012)	Sample material	Locality
ER3141	0.70809	26.2-26.9 Ma	*Kuphus* sp.	Burma Quarry
ER3141	0.70810	25.9-26.6 Ma	Matrix	Burma Quarry
ER3142	0.70807	26.8-27.5 Ma	*Eulepidina* sp.	Cistern Pt. Long Island
ER3142	0.70810	25.9-26.6 Ma	Matrix	Cistern Pt. Long Island
P3D	0.708046	27.63-28.05 Ma	Whole Rock	Langford Bay

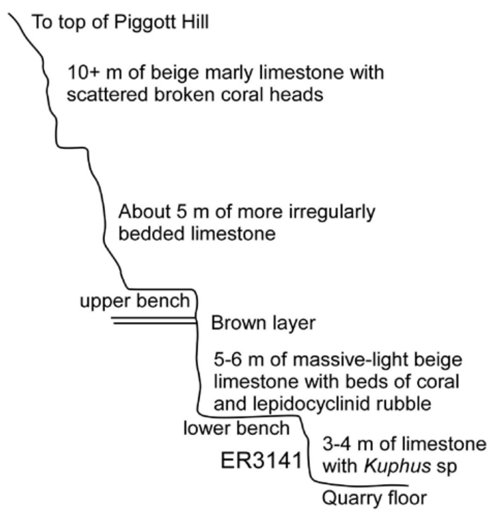

Figure 2. Sketch section of the limestones in Burma quarry, near the airport, Antigua, and stratigraphic horizon of sample ER3141. See Figure 1 for location.

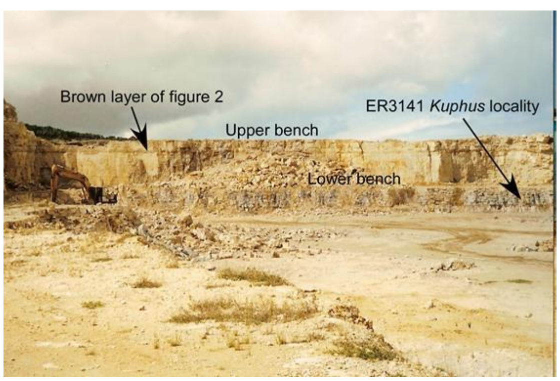

Figure 3. Burma quarry, showing locations described in Figure 2. Photograph taken November 28, 2001. The upper bench is about 10 m above the quarry floor.

larger foraminifera. However, **Persad** (**1969**) listed miogypsinids from the upper part of the formation (locality V3d of **Figure 1**) as well as *Pararotalia mexicana* throughout. **Robinson and Persad** (**1989**) described this occurrence, as *Miogypsinoides* cf. *M. bermudezi* (= *Miogypsinella* see **Robinson 2004**, **Boughdager-Fadel et al., 2000**), in more detail, correlating it with other Western Hemisphere occurrences in upper Oligocene strata. *Miogypsinella* (as *Miogypsinoides*) was also reported from the Antigua Formation by **Mascle and Westercamp** (**1983**; their fig 5, near to locality P3d of this paper, **Figure 1**).

The Antigua Formation itself was inferred by **Weiss** (**1994**, figure 4) to be 25 to 26 Ma, on the basis of the position of third order cycle sequence boundaries of **Haq et al.** (**1988**). In a more recent review of volcanic island evolution in the Lesser Antilles, **Jackson** (**2013**) suggested an age of between 24 Ma and 27 Ma for the deposition of the formation.

3. METHODS

Five samples, one of in situ *Kuphus* sp. (ER3141), one of the larger benthic foraminifer *Eulepidina undosa* (Cushman) (ER3142), one whole rock (sample P3d), and two matrix samples were selected for strontium isotope ratio determinations (**Table 1**). Sample ER3141, was collected from the Burma quarry (**Figures 2, 3**), near the airport and within the middle part of the formation (Langford Bay member of Persad). *Kuphus* is a crypt-dwelling bivalve in which the siphonal canal secretes a calcified tube. Such tubes have been used previously for strontium isotope determinations in Jamaica and Puerto Rico (**Robinson, 2004**; **Ramirez et al., 2006**; **Ortiz-Ariza, 2011**; **Ortega-Ariza et al., 2015**).

Sample ER3142 was collected from the upper part of the Antigua Formation (**Figure 1**). Larger foraminifers have also been used for Sr isotopic dating from Caribbean localities (**Robinson, 2004**; **Baumgartner-Mora et al., 2004, 2008**). The sample (**Figures 1, 4, 5**) came from a foraminiferal coquina at the approximate type localities of *Lepidocyclina undosa* Cushman 1919 (= *Eulepidina undosa*) and of *Heterostegina antillea* Cushman (1919), at Cistern Point on Long Island (USGS locality 6869; see **Cushman, 1920**, pl. 25, fig. 3 for illustration of the lithology). It contains abundant *E. undosa* with saddle-shaped tests up to 30 mm in

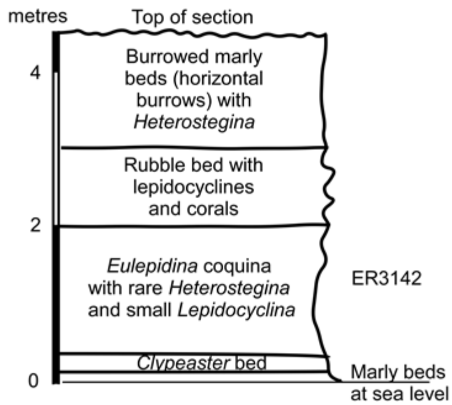

Figure 4. Sketch stratigraphic section of the Antigua Formation at Cistern Point, Long Island, Antigua. See Figure 1 for location.

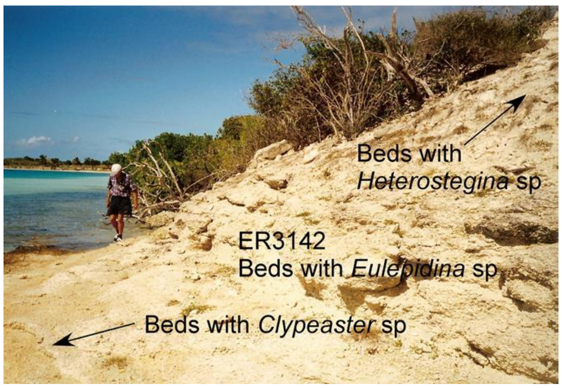

Figure 5. The *Eulepidina* coquina and sample ER3142 at Cistern Point on Long Island. For scale the person (John Tomblin) is approximately 1.7 m tall. Photograph taken November 28, 2001. See Figure 4 for section detail.

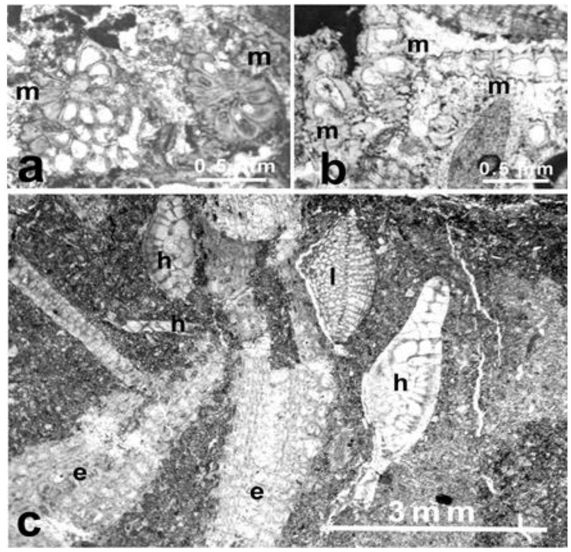

Figure 6. a, b, *Miogypsinella bermudezi* Akers & Drooger from locality V3d. a, two off-centred equatorial sections (m); b, three off-centred subaxial sections (m). A specimen of *Lepidocyclina* is seen in the upper right corner of b. c, Three species of larger foraminifera from locality ER3142, Cistern Point. e, partly abraded and broken selliform specimens of *Eulepidina undosa* (Cushman); h, three specimens of *Heterostegina antillea* Cushman, two fragmental; l, *Lepidocyclina* sp.

diameter, rare *H. antillea* and rare *Lepidocyclina* ?*parvula* Cushman (**Figure 6**). The stratigraphic horizon is in the upper part of the exposed Antigua Formation, at approximately the same horizon as the lower strata exposed at Hodges Point (**Figure 1**; Boon Point member of Persad) where rocks of similar lithology occur. Sample P3d collected by K. M. Persad from Langford Bay in 1967 (**Figure 1**), is from the same section from which Mascle and Westercamp (1983, fig. 5B) reported *Miogypsinoides*.

Thin sections were made of samples from ER3142 and P3d. Both consisted of bimodal larger foraminiferal wackestone. The large bioclasts are of the foraminifers *Eulepidina*, *Lepidocyclina* and *Heterostegina*. These float in much finer grained, but poorly sorted, micrite and bioclastic debris. The larger foraminifers are frequently broken and partly abraded. Accidental sections through the nuclei of *Lepidocyclina* were encountered in both samples. In P3d the nucleus was filled with blocky calcite crystals. In ER3142 the nucleus was partly filled with finely crystalline calcite. In many of the foraminifers the chambers and chamberlets were empty of sediment or post-depositional crystal growth. In others infilling with micrite or finely crystalline calcite was more or less complete. Minor unfilled fractures, probably resulting from sample preparation, were seen. The thin sections were stained with Alizarin Red S. No dolomite was seen.

The samples were prepared by scraping off the surface, pulverizing the surface-scraped specimen using a micro-drill and targeting fossils or matrix areas separately as much as possible. The powder was then cleaned 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, aluminum and iron were determined by HR-ICPMS (Thermo Element XR). 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

Table 2. Trace element to Ca ratios of the samples discussed in the text.

Sample	Sr/Ca mmol/mol	Mg/Ca mmol/mol	Al ppm	Mn ppm	Fe ppm	U ppm
P3d Bulk	0.556	0.640	0.0015	24	206	0.058
3142 Matrix	1.500	0.972	0.0038	3.6	178	0.250
3142 Shell	1.520	0.931	0.0015	2.4	187	0.130
3141 Matrix A	0.687	0.723	0.0003	3.9	82	0.101
3141 Matrix B	0.685	0.725	0.0003	3.9	81	0.100
3141 Matrix C	0.681	0.719	0.0003	3.9	81	0.100
3141 Shell	0.715	0.821	0.0001	1.8	45	0.043

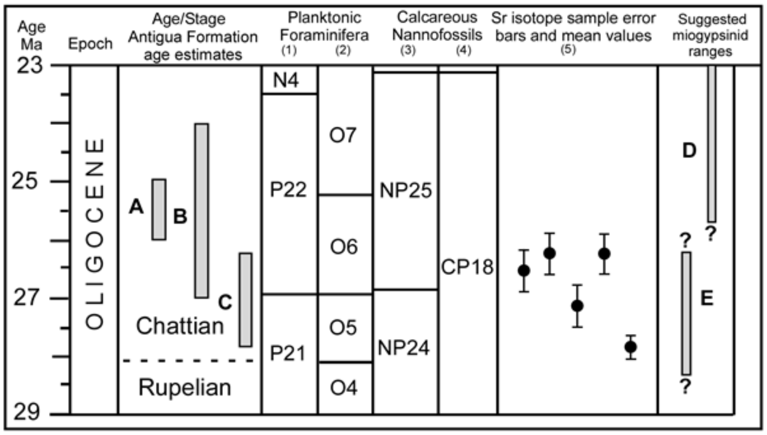

Figure 7. Antiguan strontium isotopic dates compared with current planktonic foraminiferal and calcareous nannofossil zonations for the upper Oligocene, Chattian Stage, redrawn and modified after Gradstein et al. (2012, p. 857). Planktonic foraminiferal zones from Berggren et al., 1995 (1); from Berggren and Pearson, 2005, as emended by Wade et al., 2011. (2). Calcareous nannofossil zones of Martini, 1971 (3) and Bukry, 1973, 1975 (4). Sr age deterinations (5) are in same order, left to right, as in Table 1. Vertical bar A, Weiss, 1994, estimated age range for the Antigua Formation. Vertical bar B, Jackson, 2013, estimated age range for the Antigua Formation. Vertical bar C age range indicated by this study. Bar D suggested partial range of *Miogypsina* s. l. spp. based on the literature (Baumgartner et al., 2004, 2008; Ramirez et al., 2006; Robinson, 2004; using Sr isotope interpreted ages of McArthur et al. (in Gradstein et al., 2012, p. 127-144). Bar E suggested range of *Miogypsinella* spp. in Antigua.

uncertainty in the data is 0.000009 based on repeat analyses of samples and standards. Strontium stratigraphy (ages) were assigned based on the 2012 Geological time scale Lowess curve (McArthur et al. in **Gradstein et al., 2012**, p. 127-144).

4. Results and Conclusions

Results of the Sr isotope ratio determinations for the samples are given in **Table 1**. Trace element to Ca ratios (Sr/Ca < 2 mmol mol^{-1} and Mg/Ca < 1 mmol mol^{-1}) of the samples are consistent with acceptable ratios for carbonate, and the low concentrations of Fe, Al and Mn suggest that other phases like silicates and iron or manganese coatings were not present (**Table 2**).

Assuming the fossils analyzed are pristine (supported by the low trace metal levels), our results suggest about a 600,000 year difference between the Long Island sample (*Eulepidina* sp., 27.15 Ma) and the sample from Burma quarry (*Kuphus* sp. 26.55 Ma). Estimated age maximum uncertainty including analytical and Sr age curve uncertainties (added not geometric mean) is 0.3 million years for the represented time interval. Thus, the observed difference likely indicates that the stratigraphic section between the middle and top of the Antigua Formation represents at least 0.3 million years of sedimentation in the Late Oligocene.

The matrix Sr isotope ratios at both sites are identical and indicate slightly younger ages (e.g., 26.25 Ma). While this age is consistent with the Lares ages (**Ramirez et al., 2006**), it is unlikely that the samples from the middle and top of the Antigua Formation are of the same age as this would imply unreasonably rapid sediment accumulation rates. It is indeed not surprising if lithification of the carbonate matrix occurred after deposition *in-situ* from pore fluids within the sedimentary environment (e.g., recording slightly younger ages). Although we did not perform detailed petrographic or geochemical tests to the matrix carbonate, it is conceivable that the lithification of the matrix cement took place in younger marine fluids which have more radiogenic Sr and thus record younger ages. Note that subareal diagenesis after uplift is likely to shift the Sr ratios to less radiogenic values since there are abundent volcanic rocks with Sr isotope ratios of <0.708 in the region (USGS open file report 97-470-K, **French and Schenk, 2004**).

Figure 7 compares the Sr isotopically-derived ages with zonations based on planktonic foraminifers and calcareous nannofossils. The isotopic ages are older than the ages estimated by **Weiss** (**1994**, fig. 4) based on biostratigraphical and sequence stratigraphical grounds, but support his conclusion that the Antigua Formation is of late Oligocene, Chattian age. Weiss recognized a deepening up trend in the AF, also noted by **Donovan et al.** (**2015**), while **Persad** (**1969**) attributed the deeper water limestones as probably reflecting paleogeographical variations between patch reefs and the flanking sediments.

On **Figure 7** the suggested biostratigraphical ranges of the miogypsinid larger benthic foraminiferal complex are based on the observed occurrence of *Miogypsinella* in the Antigua Formation (**Figure 6**), and the reported occurrence of *Miogypsina* s. s. in the slightly younger sedimentary rocks in Costa Rica and Carriacou (**Baumgartner et al., 2004, 2008**). A Sr isotope determination for a *Miogypsinella*-bearing sample from Jamaica of 26.8 Ma (Robinson et al., research in progress) is in agreement with the results of this paper. It should be emphasised that the occurrences in the Antigua Formation represent a local range as *Miogypsina* s. s. has not been seen and *Miogypsinella* has not been reported from the BVS and CPG. Miogypsinid ranges published by **Boudagher-Fadel and Price** (**2010a, 2013**) indicate that *Miogypsinella* and similar forms extend into the lower Oligocene (Rupelian). Any differences may be attributable to their being recorded from a different (South Atlantic) faunal province (**Boudagher-Fadel et al., 2010b**). Our dates are close to those obtained from the San Sebastian Formation of Puerto Rico (**Ortega-Ariza et al., 2015**, fig. 8) where one of us (ER) has collected *Miogypsinella* from the middle part of that unit. All these are generally older than the ranges of **Baumgartner et al.** (**2008**) for rocks containing *Miogypsina* s. s.

Coincident with plate reorganization in the Lesser Antilles arc, eastern Caribbean (http://www.odsn.de/odsn/index.html; **Bouysse et al., 1990**), major volcanic activity became dormant in Antigua during the late Oligocene and early Miocene as the zone of magma generation migrated during the next 10 million years to points further west (**McCann and Pennington, 1990**; **Bouysse and Westercamp, 1990**; **Jackson 2013**). The radioisotopic date of 20.8 Ma for the stock at Cherry Hill and Sugar Loaf mentioned by **Weiss** (**1994**, p. 9) may indicate the date of the last igneous activity in Antigua, and possibly the age of the undated dykes cutting the Antigua Formation. Although the deepening-up trend within the formation (**Weiss, 1994**; **Donovan et al., 2015**) invites correlation with the late Oligocene temperature/ice volume changes of **Zachos et al.** (**2008**) and **Gradstein et al.** (**2012**), our dates are earlier than Weiss's, and encompass the Oi2a and Oi2b cooling events (**Wade and Pälike, 2004**; in **Gradstein et al., 2012**, p. 886), so that changes in the depositional depth of the Antigua Formation may be a reflection of relatively short-lived eustatic sea-level variations near the base of the Chattian, such as are suggested by **Gradstein** (in **Gradstein et al., 2012**, p. 59), and/or a consequence of local tectonism.

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