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NOTE

A late Miocene low-nutrient window for Caribbean reef formation?

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Abstract Miocene and Pliocene reef tracts of the Caribbean were less common and smaller than older Oligocene and younger Pleistocene to Recent reefs. In the present study, samples from the Arroyo Bellaco exposures in the Cibao Valley, northern Dominican Republic were analyzed for $^{87}Sr/^{86}Sr$ to refine the age for a rare, well-developed Mio-Pliocene reef sequence. A mean age of 6.2 million years old (Ma) was determined for the reef. This age places the reef in the latter part of the late Miocene Messinian stage. The reef originated in a low-nutrient window at the end of a global cooling event and sea level lowstand, coincident with a period of decreased upwelling intensity from 6.2 to 5.8 Ma. Reef demise is attributed to a latest Miocene transgression and an associated pulse of marine siliciclastic deposition.

Keywords Dominican Republic · Late Miocene · Coral reef · Strontium isotopes

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Introduction

Cenozoic records of Caribbean coral reef assemblages indicate increased reef formation during the late Oligocene, and Pleistocene to Recent time periods (Budd 2000). Well-developed late Oligocene reefs in Antigua, Jamaica, Mexico, Puerto Rico, and the Gulf Coast of the United States mark the height of Cenozoic Caribbean reef development, while increased reef buildups beginning in the Pleistocene are most evident by extensive late Pleistocene terraces (Geister 1980) and Holocene reef tracts (Spalding et al. 2001) throughout the Caribbean. Bracketed by these time periods, Miocene to Pliocene reefs were typically smaller with zooxanthellate coral communities more often living on carbonate platforms or in siliciclastic-dominated settings with poorly defined zonation (Vaughan 1919; Budd 2000).

This pattern of Cenozoic reef development is likely due to variation in the nutrient flux within the Caribbean region (Johnson and Pérez 2006). Evidence suggests regional planktonic productivity increased from late Oligocene to middle Miocene time (Edinger and Risk 1994, 1995), and later declined during the Plio-Pleistocene (Allmon et al. 1996; Collins et al. 1996a). The role of abundant nutrients as a limiting factor of reef growth is well documented (Schlager 1981; Hallock and Schlager 1986; Birkeland 1997; Glynn 2001). Hallock and Schlager (1986) summarized the potential mechanisms as: (1) a reduction in water clarity, (2) phosphate inhibition of calcium carbonate crystal formation, (3) biotic disruption, and (4) increased rates of bioerosion.

In the current study, strontium-isotope chronostratigraphy was used to obtain age constraints on an uncharacteristically well-developed late Miocene reef in the Cibao Valley, northern Dominican Republic. The Cibao Valley lies on the northern flank of the Cordillera Central that was uplifted by the middle Miocene. Further structural alteration of the basin did not occur until much later (~3 million years old [Ma]), during the uplift of the Cordillera Septentrional which bounds the northern margin of the basin. The reef lies within the Cercado Formation, exposed approximately 2.5 km upstream of the confluence of Arroyo Bellaco with the Rio Cana, approximately 80 m below the contact with the overlying Gurabo Formation (Fig. 1). The excellent exposures of the approximately 19 m thick reefal section reveal a well-developed coral framework with a mixed carbonate/siliciclastic matrix. A total of 46 coral species (78% extinct) have been identified from four distinguishable stratigraphic zones (Fig. 2). These zones include: (1) a fine-branching thicket zone, (2) a thick-branching *Stylophora/Pocillopora* zone, (3) a massive head coral zone, and (4) a mixed free-living/small head coral zone (Klaus and Budd 2003). Stratigraphically, the reef sequence shallows upward to very shallow water depths (<5 m). Overlying the reef sequence at Arroyo Bellaco is a package of marine siliciclastic sediments (>20 m). From the standpoint of accommodation space alone, this transition must represent a latest Miocene sea-level transgression and margin backstepping that could not be explained by changes in sedimentation or subsidence rate alone.

Previous chronostratigraphic studies of the region by Saunders et al. (1986) constrained the Cercado Formation to calcareous nannoplankton zone NN11 (8.6–5.5 Ma) of the late Miocene, with no additional constraints on the timing of the Arroyo Bellaco reef. Thus, poor age constraints for the reef have inhibited detailed correlation with regional paleoceanographic events.

The revised strontium isotope dates from Arroyo Bellaco were correlated to sea level records and regional paleoceanographic events to propose a model of reef formation during a late Miocene period of warming, transgression, and decreased upwelling intensity. These results provide insights into environmental constraints on Cenozoic to Recent Caribbean reef formation.

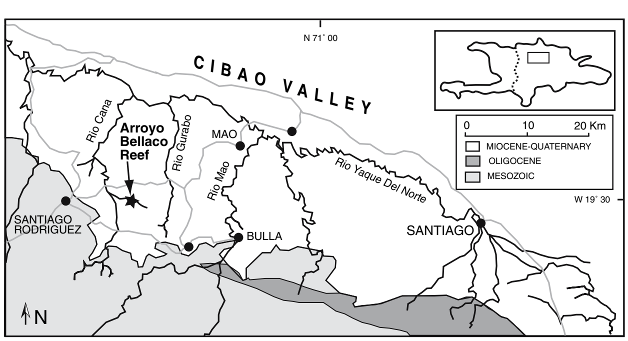

Fig. 1 Geologic map of the Cibao Valley, northern Dominican Republic, showing the location of the Arroyo Bellaco reef

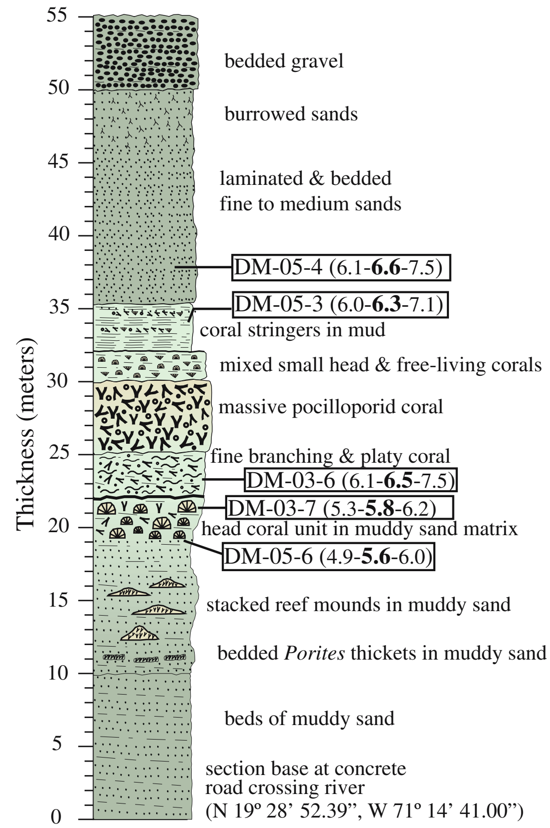

Fig. 2 Stratigraphic column for the Arroyo Bellaco study area. Locations of samples and facies descriptions are displayed next to the column. Ages based on five Sr isotope samples (DM-03-6 = 0.70896 ± 0.0012; DM-03-7 = 0.70900 ± 0.0015; DM-05-3 = 0.70897 ± 0.0011; DM-05-4 = 0.70896 ± 0.0011; DM-05-6 = 0.70901 ± 0.0012)

Materials and methods

Strontium-isotope ratios were used to determine the absolute age of the Arroyo Bellaco sequence. Seven bivalve shells were collected from exposed walls of the Arroyo Bellaco section in May 2005 (Fig. 2). Samples were cleaned using Ultra High Purity distilled water in an ultrasonic bath to remove any attached mud or sand, and powdered with a small microdrill to obtain 50 mg samples.

Strontium isotope ratios were determined for five low-magnesium calcite samples (four from the family Pectinidae, one from the family Ostreidae) showing no visible signs of meteoric diagenesis using petrographic and stereoscopic microscopy and stable isotopic ratios within the range of pristine molluscan material. Ranges of stable isotopic ratios of carbon and oxygen for these five samples were 0.03–2.86‰ and −1.69 to −1.22‰, respectively. Two visibly pristine samples with more negative values of $\delta^{13}C$ (−0.44, −1.80‰) were culled from the data set. Isotopic ratios of carbon and oxygen were determined on a Finnigan MAT 251 mass spectrometer in the Stable Isotope Laboratory at the University of Miami.

Strontium isotope ratios were determined at the University of Florida using a VG354 thermal ionization mass spectrometer in the triple collector dynamic mode with a 1.5–2.0 V (0.015–0.020 nA) ion beam. Strontium isotope ratios were normalized to the Standard Reference Material (now NIST)-987 = 0.710248 (rounded to 0.71025). Results are reported as $^{87}Sr/^{86}Sr$ ratios, calculated in delta notation, and converted to absolute ages. All age determinations were based on the McArthur et al. (2001) LOWESS strontium regression curve and the Berggren et al. (1995) revised time scale. Tables accompanying the third version of the McArthur curve report interpolated ages for $^{87}Sr/^{86}Sr$ in steps of 0.000001. The NIST-987 value was rounded to the nearest 0.00001 to correct the results to the standard of the McArthur et al. (2001) curve. Instrumentation error was determined to be $\pm$ 0.00002. The NIST-987 corrected strontium ratios and machine error for each sample were increased by 0.000005 to represent their median value on the strontium table. Stratigraphic ranges for these three values were found from the 95% confidence interval given in the table, and each maximum and minimum strontium ratio was converted to the nearest absolute age. A total of six age values were calculated for each sample. The minimum and maximum are given as the range of uncertainty, and the corrected strontium ratio from the sample is reported as the age. This conservative method incorporates both instrument and stratigraphic error in the age range of each sample.

Results and discussion

The mean age of the five strontium isotope samples was 6.2 Ma with a maximum and minimum age range of 6.6 to 5.6 Ma (Fig. 2). The ages values increase slightly upsection. This inversion likely reflects natural variability in the strontium-isotope ratio through time; we do not suspect redeposition of older shells. While additional chonostratigraphic methods may further constrain the ages, the strontium dates from this study definitively place the Arroyo Bellaco reef in the latter part of the late Miocene Messinian stage.

The refined age of the Arroyo Bellaco reef is of interest with respect to regional late Miocene paleoceanographic events. A model of reef development using the ~6.2 Ma age is presented in Fig. 3. This model proposes that reef deposition occurred near the end of a prolonged regression (~8.6–6.4 Ma), when sea level reversed during a short highstand (~6.4–5.7 Ma) (Miller et al. 2005). A pulse of marine siliciclastic sediment associated with this trangression likely contributed to reef demise. Globally, from the Miocene-Pliocene boundary upward into the early Pliocene, shallow water sedimentation is marked by a transgression and highstand sea level (McNeill et al. 2000). Based on siliciclastic sediments and analyses of planktic foraminifera (Saunders et al. 1986), the early Pliocene warming and highstand is represented by a deepening of water depth in the Cibao Valley sections overlying the Arroyo Bellaco reef (5.0–4.5 Ma).

Evidence also suggests that the Arroyo Bellaco reef formed during a period of decreased upwelling intensity between 6.2 and 5.8 Ma. This event was first recognized by Keigwin (1979) in the $\delta^{13}C$ record of deep-sea sediments of the Indo-Pacific region and later by Shackleton and Hall (1997) based on a 1‰ shift toward less positive values in $\delta^{13}C$ at Ocean Drilling Program (ODP) Site 926 on the Ceara Rise.

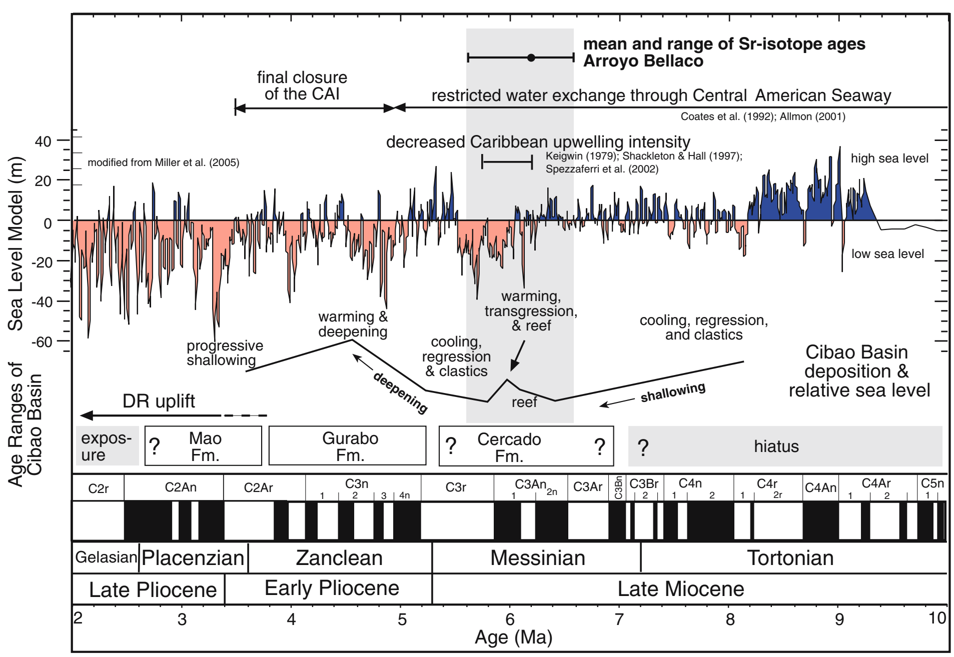

Fig. 3 Summary of regional and global paleoceanographic events that may have influenced Arroyo Bellaco reef formation. A late Messinian reef is coincident with a brief highstand during an overall drop in sea level and a reduction in regional upwelling. The early Pliocene transgression likely correlates to the abrupt deepening recorded in the massive siltstone of the Gurabo Formation. *CAI* Central American Isthmus, *DR* Dominican Republic

Results from drilling in the Bahamas during the Bahamas Drilling Project (BDP) and ODP Leg 166 further support reduced upwelling during this time period. In addition to a similar shift toward more positive values of δ^{13}C, Spezzaferri et al. (2002) found that at ~6 Ma upwelling indicators such as siliceous sponge spicules and radiolarians disappear from ODP Site 1006 off the western margin of the Great Bahama Bank.

Results from BDP core Unda, drilled on the platform margin, indicate that reefs initiated during this interval following a long period of fine-grained shelf sedimentation (McNeill et al. 2001). While less precisely dated, well-developed reefs of this time period are also known from Isla de Mona, Puerto Rico, just east of the Dominican Republic (Gonzalez et al. 1997).

Reduced upwelling during this late Miocene lowstand is thought to be a result of restriction of shallow and intermediate water flow from the Pacific into the Caribbean (Spezzaferi et al. 2002). Ocean circulation between the Atlantic and Pacific was likely diminished by the late Miocene (6–10 Ma), with final closure of the Central American Seaway (CAS) no later than 3 Ma (Coates et al. 1992; Collins et al. 1996b). Development of the Central American Isthmus, the decrease in eastward flow, and strengthening of the Atlantic western boundary flow is suspected to be the main control on this change in upwelling regime. Less upwelling likely resulted in reduced nutrient flux on the margins of the Caribbean islands and the carbonate platforms in the Bahamas.

The late Miocene episode of decreased upwelling intensity between 5.8 and 6.2 Ma is significantly older than the younger and more pronounced transition of western Atlantic waters to conditions of reduced upwelling commonly reported at about 3.0 Ma in association with final closure of the CAS (Allmon 2001). As a result of this younger transition, intermediate waters of the present day Pacific are older and relatively nutrient rich, while those of the western Atlantic are younger and relatively nutrient poor. The 3 Ma age of this transition to reduced nutrients correlates fairly well with the extinction of several Neogene invertebrate groups, most notably corals and mollusks (Jackson and Johnson 2000). However, records of benthic foraminifera and reef corals indicate a period of accelerated evolution and diversification beginning in the late Miocene (Collins et al. 1996a). Patterns of diversification in benthic foraminifera indicate increasing proportions of carbonate associated species originating during the late Miocene. These authors suggest the expansion of carbonate rich environments during this time may have been caused by decreased coastal upwelling (Collins et al. 1996a).

Records of Cenozoic reef corals indicate a prolonged period of species origination between 7 and 4 Ma, prior to the main extinction peak at approximately 2 Ma (Budd and Johnson 1999). This origination event is significant in that more than 60% of extant Caribbean corals originated during this period. In a generalized model of marine faunal turnover events of the late Pliocene, Allmon (2001) proposed that changes in nutrient flux associated with CAS closure would isolate populations either by a disruption and decrease in food supplies, or by instability in food and nutrient flux, either of which could have promoted an increase in rate of speciation. This late Miocene low nutrient window may mark the early stages of Caribbean nutrient instability and the protracted faunal turnover event of corals.

While further work is needed to substantiate the model of a late Miocene low nutrient window for Caribbean reef formation, the temporal correlation of the Arroyo Bellaco reef with reef initiation on the Great Bahama Bank and regional indicators of reduced upwelling and nutrient flux is intriguing, and highlights the importance of obtaining well-constrained age dates in paleoecological studies.

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