Strontium Isotope Stratigraphy for Oligocene-Miocene Carbonate Systems in Puerto Rico and the Dominican Republic: Implications for Caribbean Processes Affecting Depositional History

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ABSTRACT

87Sr/86Sr-derived mean ages from low-Mg calcite Kuphus incrassatus and Ostrea haitensis bivalves provide an updated and refined chronostratigraphy for selected Oligocene-Miocene carbonate and siliciclastic units in Puerto Rico and the Dominican Republic. Results indicate ages of middle to late Oligocene for the San Sebastian Formation (ca. 29.78–26.51 Ma), the Lares Limestone (ca. 26.51–24.73 Ma), and the Montebello Member (ca. 27.30–24.10 Ma); middle Miocene to the early part of the late Miocene for the Cibao Formation (ca. 12.17 Ma), the Aguada (Los Puertos) Limestone (ca. 14.67–11.14 Ma), and the Aymamón Limestone (ca. 10.98 Ma) in northern Puerto Rico as well as for the Ponce Limestone (ca. 14.97–9.84 Ma) in southern Puerto Rico and the Yanigua–Los Haitises Formations (ca. 15.75–12.58 Ma) in northeastern Dominican Republic; and late Miocene for the Cercado Formation (ca. 6.31–5.88 Ma) in northwestern Dominican Republic. These results show some significant modifications to previous chronostratigraphic studies. The San Sebastian Formation marks the last major input of siliciclastics in Puerto Rico. The Lares Limestone is characterized by a diverse warm- and cool-water coral assemblage, whereas the Montebello Member is characterized by large benthic foraminifera and mollusks, which likely indicates differences in depth of deposition or environments that were differentially influenced by upwelling. The ultimate disappearance of warm-water corals in the late Oligocene coincides with the end of global warming and coral extinction events. The Cibao Formation, the Aguada (Los Puertos) Limestone, the Aymamón Limestone, the Ponce Limestone, and the Yanigua–Los Haitises Formations are predominantly composed of shallow marine deposits consisting of red algae, mollusks, small benthic foraminifera, and cool-water corals in the upper parts. These characteristics are consistent with an upwelling control, which has been documented as a regionally important process in the Caribbean during that time. The reappearance of corals indicates an environmental change that coincides with closure of the Central American Seaway. The closure resulted in circulation changes, warm temperatures, and low nutrients in the Caribbean, which created suitable conditions for diverse coral reef development, as exemplified by the Cercado Formation.

Online enhancement: supplemental table.

Introduction

The Oligocene-Miocene was a time of significant global, regional, local tectonic, oceanographic, climatic, and sea level changes in the Caribbean region |e.g., Duque-Caro 1990; Coates et al. 1992; Edinger and Risk 1994; Hafalr and Mutti 2005; Miller et al. 2005|. Shallow marine systems in Puerto Rico and the Dominican Republic were deposited in this time interval, and it is important to understand the timing of deposition and how the various processes affecting the Caribbean influenced their deposition. Stratigraphic and biostratigraphic studies are numerous in Puerto Rico and the Dominican Republic, with the original work dating back to Gabb (1873) in the Dominican Republic and to Berkey (1915) in Puerto Rico. However, determining absolute age dates for these sedimentary deposits, es-
especially at a high resolution, has been problematic, which directly limits our ability to correlate with processes that were affecting the Caribbean during deposition of the sedimentary systems. The current understanding of ages is mostly based on foraminiferal and nannoplankton assemblages (Moussa and Seiglie 1970, 1975; Vokes 1979; Monroe 1980; Seiglie and Moussa 1984; Saunders et al. 1986; Moussa et al. 1987; Banerjee et al. 2000). More recent studies have refined and further constrained some of the biostratigraphic ages in Puerto Rico and the Dominican Republic using paleomagnetic, strontium isotope, and U/Pb data [Ramírez et al. 2006; Maier et al. 2007; Dennison et al. 2008; McNeill et al. 2012; Ruidiaz-Santiago 2013]. However, several poorly constrained or conflicting ages still remain in both Puerto Rico and the Dominican Republic.

Strontium isotope dating especially holds promise for better age constraints because the gradient of the seawater $^{87}$Sr/$^{86}$Sr curve during the Oligocene-Miocene is mostly steep, which decreases the dating error (McArthur et al. 2001). Several studies have successfully used this technique in Oligocene-Miocene shallow-water deposits in the Caribbean from phosphorite [Mallinson et al. 1994], bivalve [Robinson et al. 2004; Ramírez et al. 2006; Maier et al. 2007; McNeill et al. 2012; Ruidiaz-Santiago 2013], and chalk (Land 1991) samples.

This study uses strontium isotope data from low-Mg calcite Kuphus incrassatus and Ostrea hatensis bivalves to update the chronostratigraphy of Oligocene-Miocene shallow-water deposits in Puerto Rico and the Dominican Republic. The new Puerto Rico and Dominican Republic $^{87}$Sr/$^{86}$Sr-derived ages provide additional temporal constraints to better understand the global, regional, and local factors that influenced deposition of the Oligocene-Miocene shallow-water marine systems.

**Geological Settings**

Puerto Rico and Hispaniola (Haiti and the Dominican Republic), part of the Greater Antilles arc system, are located in the northern margin of the Caribbean plate (fig. 1). Currently, the northern margin of the Caribbean plate is in left lateral strike-slip contact with the North American plate. The strike-slip movement, beginning in the Eocene, resulted from collision of the Caribbean plate with the Bahamas. This coincided with termination of island-arc volcanism along that collisional margin, which had been active during the Cretaceous (Pindell and Barrett 1990; Pindell and Kennan 2009). The end of volcanism was a diachronous event, occurring in the middle Eocene on Hispaniola (Mann et al. 1991) and in the late Eocene in Puerto Rico (Dolan et al. 1991). During the Oligocene-Miocene, shallow-water carbonate and siliciclastic rocks in Puerto Rico and the Dominican Republic, the focus of this study, were deposited unconformably on top of Cretaceous-Eocene volcanic-arc basement within a relatively stable tectonic setting unaffected by nearby plate boundaries (Meyerhoff et al. 1983; Mann et al. 1991; Van Gestel et al. 1998, 1999). Some authors have proposed subsidence during this time, in Puerto Rico related to sediment loading and thermal contraction (Birch 1986) and in the Dominican Republic related to different stages of uplift along the Cordillera Septentrional (Erikson et al. 1998). Since the late Miocene–early Pliocene, northern Hispaniola has been in oblique collision with the southeastern edge of the Bahamas carbonate platform (Calais et al. 2002; Mann et al. 2002, 2005). That collision has caused uplift of the Cordillera Septentrional and increased convergence (thrusting) in the Dominican Republic [Erikson et al. 1998] as well as extension and counterclockwise rotation of Puerto Rico (Reid et al. 1991; Mann et al. 2005). By 10 Ma, the Caribbean region had nearly assumed its modern configuration [Pindell and Barrett 1990; Pindell and Kennan 2009; fig. 1].

**Puerto Rico (Northern and Southern).** Oligocene time is characterized by initial deposition of nearshore marine siliciclastics in both northern and southern Puerto Rico, represented by the San Sebastian Formation and the Juana Diaz Formation (middle-late Oligocene). Late Oligocene to late Miocene–Pliocene deposits are characterized by shallow marine carbonates of the Lares Limestone, the Cibao Formation, the Montebello Member of the Cibao Formation, the Aguada Limestone, the Cercado Formation (late Miocene), and the Ponce Limestone in southern Puerto Rico as well as the Ponce Limestone in southern Puerto Rico (Monroe 1980; Frost et al. 1983; figs. 2, 3).

**Dominican Republic (Northwestern and Northeastern).** The shallow-water mixed carbonate and siliciclastic Cercado Formation is exposed in Arroyo Bellaco, an affluent of the Cana River in the northwestern portion of the Cibao Valley (fig. 2). The Cercado Formation (late Miocene) overlies the Oligocene-Miocene Baitoa and Tabera Formations and is overlain by the late Miocene–Pliocene Gurabo and Mao Formations (Saunders et al. 1986; McNeill et al. 2012; fig. 3). The organic-rich sandstone and shale facies of the nearshore Yanigua Formation (early-middle Miocene) are overlain conformably by the shallow-water carbonate Los Haitises Formation (middle-late Miocene) exposed along highway DR7, in the vicinity of the Parque Nacional Los Haitises, northeastern Dominican
Republic (Iturralde-Vinent 2001; fig. 2). In this study, we combined the Yanigua and Los Haitises Formations because the boundary between the two formations is not clearly defined at our sampling locations.

Material and Methods

*Kuphus incrassatus* (Puerto Rico and the Dominican Republic) and *Ostrea haitensis* (Puerto Rico) bivalve shells from Oligocene-Miocene outcrops and cores in Puerto Rico and the Dominican Republic were analyzed for strontium isotope ratios (*\(^{87}\)Sr/\(^{86}\)Sr; figs. 1, 4). These shells, composed of low-Mg calcite, are known for being relatively resistant to diagenetic alteration and thus are ideal candidates for *\(^{87}\)Sr/\(^{86}\)Sr* analyses (e.g., McArthur 1994; Veizer et al. 1999, p. 70–72, 652–656). However, since low-Mg calcite can also suffer diagenetic alteration, we used cold cathodoluminescence petrography (CL), transmitted light microscope petrography, *\(^{13}\)C* and *\(^{18}\)O* stable isotopes, and elemental concentrations (Sr, Fe, and Mn) to gauge possible diagenetic alteration and to select the best samples. CL was of limited use in this study. This technique (50 mTorr, 10 kV, 0.5 mA) can aid in identifying nonluminescent calcite (absence of Mn\(^{2+}\)), which is consistent with pristine mineralogy (Dickson 1990). Most of our shell samples were completely nonluminescent, and no samples were discarded after evaluation using CL. Skeleton integrity and microsampling location was guided by transmitted light microscope petrography. Samples were collected from layers or rims within the *Ostrea* and *Kuphus* bivalves that appear to preserve the original internal shell texture (fig. 4). Powder from unaltered areas was collected from ~2-mm-thick sections using a microscope-mounted dental drill with tungsten carbide burs: ~100–400 mg for stable isotopes, ~100–200 mg for elemental concentrations, and ~1 mg for strontium isotope analyses.

Stable isotope data were analyzed using a Thermo-Finnigan MAT 253 isotope ratio mass spectrometer. The stable isotopic ratios obtained were compared with measured values from modern mollusks (Lloyd 1964; Tucker 1990; Patterson and Walter 1994) to further evaluate possible diagenetic alteration. Sr, Fe, and Mn elemental concentrations were determined with an inductively coupled plasma atomic
Figure 2. Generalized stratigraphic sections and maps showing locations for northwestern Dominican Republic (composite section modified from Saunders et al. 1986 and McNeill et al. 2008), northeastern Dominican Republic (modified from Iturralde-Vinent 2001), and northern and southern Puerto Rico (modified from Frost et al. 1983).
Figure 3. Currently accepted nomenclature for the Dominican Republic and Puerto Rico, with Sr-derived mean ages generated from this study. Composite stratigraphic framework for northwestern Dominican Republic is modified from Saunders et al. (1986) and McNeill et al. (2012). The numbers along the gray and black bars denote the Sr-derived mean ages from each unit (bold numbers in tables 1, 2). The lines along both extremes of the bars represent the minimum and maximum ages from each unit (tables 1, 2). Sampling captures the full extent, from lower to upper boundaries, of the San Sebastian Formation and the Lares Limestone. Partial age ranges are shown for the other units. DR = Dominican Republic; Fm = Formation; Fms = Formations; LP = Los Puertos; Ls = Limestone; Mbr = Member; PR = Puerto Rico.
emission spectrocope [PerkinElmer Optima 5300DV]. Trace element concentrations versus \(^{87}\text{Sr}/^{86}\text{Sr}\) values were also used to evaluate diagenetic alteration.

\(^{87}\text{Sr}/^{86}\text{Sr}\) ratios from powdered samples (tables 1, 2) were determined using a VG Sector 54 [run at signal strength of Sr88 = 4 V] thermal ionization mass spectrometer operating in dynamic mode. Samples were dissolved in 3.5 N HNO₃, and the strontium was eluted through ion-exchange columns filled with strontium-spec resin. The raw strontium isotope ratio and instrumental precision (± 0.000015) for each sample was corrected to the NIST-987 value of 0.710248 to use the McArthur et al. (2001) LOWESS lookup curve. These three values were converted to ages from the McArthur et al. (2001) curve, each including a maximum and minimum age (stratigraphic uncertainty). Thus, a total of nine age values were calculated for each sample. The corrected \(^{87}\text{Sr}/^{86}\text{Sr}\) value is reported as the mean age, and the minimum and maximum values (of the nine) determine the range of uncertainty. This conservative method incorporates both the instrument and the stratigraphic error of the McArthur et al. (2001) curve. Estimated age resolution, calculated by subtracting the minimum age and the maximum age from the mean age, varies within formations from \(~0.3\) to \(1.3\) m.yr. (tables 1, 2).

**Results**

\(\delta^{18}\text{O}\) and \(\delta^{13}\text{C}\) Stable Isotopes. Of a total of 117 samples analyzed for \(\delta^{18}\text{O}\) and \(\delta^{13}\text{C}\), 41 yielded values that ranged between \(~3.56\)‰ and \(~0.02\)‰ and between \(~1.75\)‰ and \(2.74\)‰, respectively. These values fall within the expected range for unaltered shallow-water marine bivalve shell material [approximately \(~4.0\)% and \(~1.5\)% for \(\delta^{18}\text{O}\), approximately \(~2.0\)% and \(3.0\)% for \(\delta^{13}\text{C}\); Tucker 1990]. An additional 24 samples had \(\delta^{18}\text{O}\) values that fell within...
Table 1. Analytical Results of Low-Mg Calcite *Kuphus Incrassatus* Bivalves and Derived Numerical Ages from Puerto Rico (PR) and the Dominican Republic (DR)

<table>
<thead>
<tr>
<th>Lithologic unit, locality/sample ID</th>
<th>Raw value</th>
<th>Corrected value</th>
<th>δ¹³C (PDB)</th>
<th>δ¹⁸O (PDB)</th>
<th>Sr (ppm)</th>
<th>Mg (ppm)</th>
<th>Fe (ppm)</th>
<th>Mn (ppm)</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
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<td>Ponce Limestone, Guayanilla, PR/8 5.5</td>
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<td>455</td>
<td>2956</td>
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<td>4</td>
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<td>Ponce Limestone, PQ, Ponce, PR/A6 CEM1 U16</td>
<td>0.70885 0.70883</td>
<td>-3.32 -1.77</td>
<td>496</td>
<td>3222</td>
<td>115 17</td>
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<tr>
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<td>2708</td>
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<td>4478</td>
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<td>515</td>
<td>2146</td>
<td>120</td>
<td>4</td>
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<td>120</td>
<td>4</td>
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Note. Raw Sr data are corrected to NIST-987 value of 0.710248 to use the McArthur et al. [2001] lookup curve. Error results are from 2 SEs of mean Sr isotope value and confidence limits of the seawater Sr isotope curve. Estimated age resolution: Ponce Limestone, ∼0.7–1.3 m.y.; Lares Limestone, ∼0.6–0.8 m.y.; San Sebastian Formation, ∼0.6 m.y.; Cercado Formation, ∼0.3 m.y.; Yanigua-Los Haitises Formations, ∼0.3–1.3 m.y. Bold analytical data indicate samples outside the accepted ranges (see “Material and Methods” and “Results”). AB = Arroyo Bellaco, PDB = Pee Dee belemnite, PQ = Ponce Quarry.

* Sample collected from *Ostrea haitensis* bivalve.
Table 2. \(\delta^{13}C\) and \(\delta^{18}O\) Results of Low-Mg Calcite *Kuphus Incrassatus* Bivalves and Derived Numerical Ages from Puerto Rico (PR)

<table>
<thead>
<tr>
<th>Lithologic unit, locality/sample ID</th>
<th>Raw value</th>
<th>Corrected value</th>
<th>(\delta^{13}C) (PDB)</th>
<th>(\delta^{18}O) (PDB)</th>
<th>Minimum</th>
<th>Mean</th>
<th>Maximum</th>
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<td>.708856</td>
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<td>.708852</td>
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<td>.708849</td>
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Note. Raw Sr data are corrected to NIST-987 value of 0.710248 to use the McArthur et al. (2001) lookup curve. Error results are from 2 SEs of mean Sr isotope value and confidence limits of the seawater Sr isotope curve. Estimated age resolution: Aymamón Limestone, ∼0.9 m.yr; Aguada (LP) Limestone and Cibao Formation, ∼1 m.yr; Montebello Member, ∼0.5–0.8 m.yr; Lares Limestone, ∼0.6–0.8 m.yr; and Ponce Limestone, ∼0.7–1.3 m.yr. Bold \(\delta^{13}C\) data indicate samples outside the accepted ranges (see "Material and Methods" and "Results"). LP = Los Puertos; NC = North Coast; PDB = Pee Dee belemnite; PP = Ponce Playa.

* Sample collected from *Ostrea haitensis* bivalve.
the expected range for shallow-water marine bivalve shell material but were depleted in δ13C (−2.02‰ to −6.90‰), which may indicate shallow, restricted conditions rather than postmeteoric diagenesis (Lloyd 1964; Patterson and Walter 1994; fig. 5; tables 1, 2).

Although meteoric diagenesis can cause δ13C depletion (e.g., Tucker 1990; Moore 2001), Lloyd (1964) and Patterson and Walter (1994) showed that depleted δ13C in modern carbonate platforms (Bahamas Banks and Florida Bay) can be related to several factors: environmental restriction, freshwater runoff, and the lack of exchange with open-ocean water. Thus, carbonates precipitated in lagoonal environments could have been associated with modified seawater (Patterson and Walter 1994) and may yield depleted δ13C values. The Puerto Rico and Dominican Republic samples that show depleted δ13C values are from the San Sebastian Formation, the Montebello Member, the Ponce Limestone, the Cercado Formation, and the Yanigua–Los Haitises Formations (tables 1, 2). These lithologic units represent fluvial, coastal lagoon, and nearshore to inner shelf environments (Monroe 1980; Seiglie and Moussa 1984; Iturralde-Vinent 2001; Maier et al. 2007; McNeill et al. 2012; Braga et al. 2012; fig. 2). It is reasonable to suggest that these environments may have been affected by restriction, freshwater input, and mangrove organic-rich sediment settings that caused depleted δ13C values. The samples with depleted δ13C values that were analyzed for elemental concentrations (table 1) indicate that the depleted δ13C values were not caused by diagenetic alteration.

Trace Element Concentrations. The elements Sr, Fe, and Mn are commonly used to evaluate the degree of diagenetic alteration (Veizer 1983; Veizer et al. 1992). Diagenetically altered low-Mg calcite shells usually contain high Fe and Mn (e.g., >100 ppm; McArthur et al. 1994) and low Sr (e.g., <900 ppm; Bonilla-Rodriguez et al. 2014) concentrations (Veizer 1983; Dickson 1990; Flügel 2004, p. 70–72, 652–656). However, lower Fe and Mn concentrations alone do not prove good preservation (McArthur 1994). In addition, average Sr concentrations may vary between taxa so that different values can be indicative of pristine shells (e.g., >1000 ppm in Cretaceous rudists; Steuber et al. 2002). One method to determine appropriate values for evaluating diagenetic alteration is to plot the Sr, Mn, and Fe concentrations against 87Sr/86Sr values (Steuber and Schlüter 2012). This crossplot shows grouping of the values within analytical uncertainty in well-preserved samples. These groupings are then used to select threshold levels considered to represent diagenetically unaltered low-Mg calcite for each lithologic unit. In this study, the groupings indicate thresholds of >400 ppm for Sr, <30 ppm for Mn, and <250 ppm for Fe (fig. 6). In

Figure 5. δ18O versus δ13C stable isotopes for Puerto Rico and Dominican Republic Kuphus incrassatus and Ostrea haitensis samples. The dark gray box shows samples with δ13C and δ18O ratios that fall within the expected range for unaltered shallow-water marine bivalves (Tucker & Wright 1990). The light gray box shows samples with depleted δ13C. See tables 1 and 2 for more details. Fm = Formation; Fms = Formations; LP = Los Puertos; Ls = Limestone; Mbr = Member; PDB = Pee Dee belemnite.
addition, a plot comparing Sr and Mn concentrations helps highlight diagenetically altered outliers and trends of analyzed samples (Steuber and Schlüter 2012; Bonilla-Rodriguez et al. 2014; fig. 7).

Twenty-six samples (of 45) show high Sr (>400 ppm), low Mn (<30 ppm), and low Fe (<250 ppm) concentrations (modified from Steuber 2001; Steuber et al. 2002; Steuber and Schlüter 2012; fig. 6; table 1). Sr concentrations above the 400-ppm threshold occur for most of the study samples (fig. 6), and samples from the same formations are grouped in clusters of similar Sr concentrations (fig. 7). There is one outlier from the Yanigua–Los Haitises Formations that plots below the 400-ppm threshold (231 Sr ppm, Km87-15). This outlier, however, has Fe and Mn concentrations that conform to the concentration thresholds and shows a similar mean age (ca. 15 Ma) as another sample from the same location (Km87-A26; table 1). In addition, both samples have depleted δ¹³C that we interpret to result from deposition in a shallow, restricted coastal lagoon setting, as explained previously. Also, a mean age of 15 Ma agrees with previous work (see, e.g., Iturralde-Vinent 2001 and “Ages for Stratigraphic Units”).

**Figure 6.** $^{87}$Sr/$^{86}$Sr values versus Sr, Mn, and Fe concentrations in samples analyzed from Puerto Rico and the Dominican Republic. See table 1 for details. Horizontal dashed lines indicate thresholds of Sr, Mn, and Fe concentrations on which selection of the best-preserved samples was based. Vertical dashed lines indicate accepted $^{87}$Sr/$^{86}$Sr mean values for each lithologic unit. The gray box in the Sr graph shows a Sr outlier sample below 400 ppm. Fm = Formation, Ls = Limestone, Y-LH Fms = Yanigua–Los Haitises Formations.
Mn concentrations for most samples plot below the 30-ppm threshold (fig. 6). As with Sr concentrations, samples from the same formation show similar Mn concentrations (fig. 7). One sample from the Yanigua–Los Haitises Formations plots above 30 ppm (272 Mn ppm, Km124), and two samples from the San Sebastian Formation show Mn concentrations of 167 and 1019 ppm. Both formations are interpreted as representing fluvially influenced coastal lagoons, which can explain elevated Mn concentrations and depleted δ13C. In addition, q10 Sr ratio–derived mean ages for the San Sebastian Formation samples of ca. 29–26 Ma (Oligocene) agree with previous work (see, e.g., Monroe 1980 and "Ages for Stratigraphic Units").

Most samples yield Fe concentrations below the 250-ppm threshold (fig. 6). Higher Fe concentrations (>250 ppm) were obtained from one sample from the San Sebastian Formation, from two samples from the Lares Limestone, from one sample from the Yanigua–Los Haitises Formations, and from one sample from the Ponce Limestone. The sample from the San Sebastian Formation and base of the Lares Limestone, immediately overlying the San Sebastian Formation (fig. 3), were deposited in shallow, restricted coastal lagoons, which can explain the high Fe concentrations. Similar environmental controls can explain the results from the Yanigua–Los Haitises Formations. The Sr-derived mean age from the basal Lares Limestone of ~26 Ma agrees with Ramirez-Martinez et al. (2006).

Two microsamples from an Ostrea haitensis oyster in the Ponce Limestone were analyzed and resulted in different Fe concentrations (table 1). Petrographic study of this oyster sample shows unaltered low-Mg layers as well as other layers that were composed of recrystallized neomorphic calcite. A reasonable explanation for the different Fe concentration is that one sample came from a low-Mg calcite-stable nonaltered mineralogy layer and the other included material from a recrystallized Fe-rich layer. The recrystallization, however, did not affect Mn or Sr concentrations or δ13C and δ18O values. In addition, both samples yielded Sr-derived mean ages of ca. 13 Ma (table 1).

In summary, 65 Sr-derived mean ages were produced from Kuphus incrassatus and O. haitensis bivalves on the basis of a combination of analytical techniques. Thirty-seven samples are within the established ranges of δ13C and δ18O stable isotopes and elemental concentrations for unaltered extant bivalve material. Twenty-eight samples show either depleted δ13C and/or low Sr, high Fe, or high Mn concentrations. However, the mean ages obtained from these samples correlate well with the mean ages obtained from unaltered samples from the same lithologic unit (tables 1, 2).

Ages for Stratigraphic Units. Numerous stratigraphic frameworks have been proposed through the years, starting with Gabb (1873) and Berkey (1915). The stratigraphic boundaries of formal units show significant differences in absolute ages due to the large error associated with the biostratigraphic data (on the order of 10 m.yr.). Strontium isotopes provide higher-resolution absolute age dates with errors of ~0.5–1 m.yr. We compare our Sr age-date results with those frameworks that currently are the most commonly used in the study areas (fig. 3). For a historical perspective on the evolution of stratigraphy in Puerto Rico, see Monroe (1980),
Renken [2002], and Ward et al. [2002]; for the Dominican Republic, see McNeill et al. [2008, 2012]. We point out that our sampling captures the full extent, from lower to upper boundaries, of the San Sebastian Formation and the Lares Limestone, thereby providing full age ranges for the two units. Shell material for sampling was not available throughout the other units, so our data indicate partial age ranges for those units.

Below, we discuss ages for each of the studied units, incorporating our strontium isotope data, starting with those in Puerto Rico [oldest to youngest] followed by those in the Dominican Republic. We follow the use of the formal lithostratigraphic designations for ease of comparison with the previous studies. However, in contrast to the previous studies, our data in northwest Puerto Rico show that portions of lithostratigraphic units indicate chronostratigraphic equivalence, which we address in “Discussion.”

San Sebastian Formation (Northern Puerto Rico; Oligocene, Late Rupelian–Chattian). Monroe [1980], Seiglie and Moussa [1984], and Ward et al. [2002] placed the San Sebastian Formation in the middle-late Oligocene, but they did not agree on the exact age of the upper and lower boundaries. Our data indicate a mean age range of 29.78–26.51 Ma for the San Sebastian Formation on the basis of samples from the basal part of the San Sebastian Formation at the Guatemala River location, which yield mean ages of 29.78–29.17 Ma [early Oligocene, late Rupelian–Chattian], and samples from the top of the formation [at the contact with the overlying Lares Limestone] at PR111, which give a mean age of 26.51 Ma [late Oligocene, Chattian; figs. 1, 3; table 1]. The upper boundary [26.51 Ma] agrees with a reported age of 26.85 ± 0.74 Ma by Ramírez et al. [2006] from the same PR111 location sampled in this study.

Lares Limestone (Northern Puerto Rico; Late Oligocene, Chattian). The placement of the upper and lower Lares Limestone boundaries differs among previous studies. Our data indicate an age range of 26.51–24.73 Ma [late Oligocene, Chattian] for the Lares Limestone on the basis of samples from the basal Lares Limestone at the contact with the underlying San Sebastian Formation at PR111 (one sample from PR448), which yield a mean age of 26.51 Ma [late Oligocene, Chattian], and samples from the same PR111 location, which indicate a mean age of 24.73 Ma [late Oligocene, Chattian] for the top of the formation at the contact with the overlying Montebello Member (figs. 1, 3; tables 1, 2). The age range from our study agrees with that of Monroe [1980] and Seiglie and Moussa [1984] but differs from that of Ward et al. [2002], who extended the formation into the early Miocene. A late Oligocene age for the entire formation is also supported by the Sr-derived mean ages from the overlying Montebello Member unit, which are late Oligocene ages (see “Discussion”).

Montebello Member of the Cibao Formation (Northern Puerto Rico; Late Oligocene, Chattian). Seiglie and Moussa [1984] and Ward et al. [2002] show the Montebello Member as an early Miocene unit. Our data suggest a significantly different age range of 27.30–24.10 Ma [late Oligocene, Chattian] for the Montebello Member on the basis of mean ages of 27.30–26.51 Ma for the basal part [contact with the underlying Lares Limestone] at PR10, mean ages of 25.82–24.10 Ma for the middle part at PR10, and mean ages of 25.29–24.64 Ma for the basal part [contact with the underlying Lares Limestone] at PR111 (figs. 1, 4; table 2). Our data indicate that the Montebello Member and the Lares Limestone overlap in age. An early Miocene age cannot be ruled out for the upper part of the Montebello Member, as we did not collect samples from that portion of the unit.

Cibao Formation (Northern Puerto Rico; Middle Miocene, Serravallian). Seiglie and Moussa [1984] and Ward et al. [2002] show the Cibao Formation as the late part of the early Miocene in age. Our data differ with those authors and indicate a mean age of 12.17 Ma [middle Miocene, Serravallian] from one sample collected from the NC11 core at the top of the Cibao Formation [figs. 1, 3; table 2]. Sampling was based on the lithologic description and stratigraphic location as defined by Hartley [1989]. Local replacive dolomitization is present in that interval of the core. However, petrographic examination confirms that there was no dolomite in the sample we used for age dating.

Aguada (Los Puertos) Limestone (Northern Puerto Rico; Middle-Late Miocene, Langhian–Tortonian). The Aguada [Los Puertos] Limestone has been placed in different stratigraphic positions in previous studies: early Miocene by Monroe [1980], middle Miocene by Seiglie and Moussa [1984], and early-middle Miocene by Ward et al. [2002]. Our data are in partial agreement with the previous studies and indicate a mean age range of 14.67–11.14 Ma [middle Miocene, Langhian–early Tortonian] on the basis of one sample from the NC6 core [mean age, 14.67 Ma] and four samples from the basal contact of the Aguada [Los Puertos] Limestone with the underlying Cibao Formation in the NC11 core [mean ages, 11.74–11.14 Ma; figs. 1, 3; table 2]. In contrast to previous studies, our results extend the age of the Aguada [Los Puertos] Limestone into the late Miocene. Local dolomitization was described in the NC11
core from which some of our samples (three of four) were obtained [Hartley 1989]. However, petrographic analysis indicated that there was no dolomite in the bivalve shells or matrix of the four samples. In addition, the δ13C and δ18O values from all four samples are consistent with the expected range for unaltered marine fossils [Tucker 1990]. On the basis of this evidence and the similar ages given by all four samples, we believe it is unlikely that the data show the timing of dolomitization.

Ayamón Limestone (Northern Puerto Rico; Late Miocene, Tortonian). Due to the lack of index fossils, Seiglie and Moussa (1984) suggested a middle or late Miocene age for the Ayamón Limestone based solely on stratigraphic position. Our data from one sample collected from the NC13 core at the base of the Ayamón Limestone is consistent with Seiglie and Moussa (1984) and indicates a mean age of 10.98 Ma [late Miocene, Tortonian], with the lower uncertainty error extending into the middle Miocene [Serravallian; figs. 1, 3; table 2]. Sampling was based on lithologic description and stratigraphic location as defined by Scharlach (1990).

Ponce Limestone (Southern Puerto Rico; Middle-Late Miocene, Langhian-Tortonian). Most previous work agrees on the timing of deposition for the Ponce Limestone as middle-late Miocene (Moussa and Seiglie 1975; Monroe 1980; Frost et al. 1983; Barnejee et al. 2000). Moussa and Seiglie (1975) designated the lower part of the Ponce Limestone as early-middle Miocene on the basis of stratigraphic position and planktonic foraminifera present in the underlying unit (termed the New Formation by Frost et al. 1983). Frost et al. (1983) corroborated this age using coral faunal assemblages. Van den Bold (1969) used ostracods to assign a late Miocene–early Pliocene age for the upper part of the Ponce Limestone. Our data are in partial agreement with the previous studies and indicate that mean ages for the Ponce Limestone range from 14.97 to 9.84 Ma [middle-late Miocene, Langhian-Tortonian] on the basis of samples from Peñuelas (14.97–14.38 Ma), Guayanilla (12.93–9.84 Ma), Tuque (11.14–10.84 Ma), Ponce Playa (10.57 Ma), and Ponce Quarry (14.87–10.09 Ma; figs. 1, 3; tables 1, 2).

Our mean ages are consistent with previous work that assigned a middle-late Miocene age but differ with the latest Miocene–earliest Pliocene age for the upper part of the unit, as suggested by Van den Bold (1969). Our results are also supported by Sr ages of 11.56–9.92 Ma by Ramirez et al. (2006) from Guayanilla [same location as this study] and by Ruidiaz-Santiago (2013), who reported Sr ages of 13.66 ± 0.16 Ma and 13.79 ± 0.19 Ma at the base of Ponce Limestone at Jaboncillo Beach, Guanica, just above an angular unconformity separating early Miocene from middle Miocene strata [Frost et al. 1983].


Our Sr data indicate a middle Miocene age for the sampled sites. Two samples from highway DR7 [Km87] yielded mean ages of 15.75 and 15.25 Ma [middle Miocene, Langhian], and one sample from highway DR7 [Km124] yielded a mean age of 12.58 Ma [middle Miocene, Serravallian] for the Yanigua–Los Haitises Formations (figs. 1, 3; table 1).

Our data are consistent with the earlier work by Brouwer and Brouwer (1982), Iturralde-Vinent and MacPhee (1996), Iturralde-Vinent (2001), and Van den Bold (1988). Additional detailed study is needed to resolve the discrepancy in assigned ages and determine the full age range of the Yanigua–Los Haitises Formations, which could be wider than previously thought.

Cercado Formation (Northwestern Dominican Republic; Late Miocene, Messinian). Previous studies assigned a late Miocene [Messinian] age for the Cercado Formation on the basis of calcareous nanoplankton [zone NN11, 8.6–5.5 Ma; Saunders et al. 1986] and planktonic foraminifera from the base of the formation [zones N17 and N18, ~7.0–5.9 Ma; Lutz et al. 2008]. Recently, the age was refined by Maier et al. (2007), who reported a *87Sr/86Sr mean age of 6.2 Ma [at Arroyo Bellaco, which is the same location that we sampled], and McNeill et al. (2012),...
who used strontium isotopes and paleomagnetic data to assign an age of 6.6–6.0 Ma. Our data are consistent with the former studies and indicate mean ages of 6.31–5.88 Ma on the basis of four samples from Arroyo Bellaco (figs. I, 3; table 1).

Discussion

A major goal in determining absolute ages for sedimentary systems is to evaluate local, regional, and global processes that could have affected their deposition. In this study, the sedimentary units focused on are dominantly carbonate systems, which are particularly sensitive to environmental controls. Our new age data provide an opportunity to build on previous studies and to revisit the sedimentary units in terms of time-equivalent events and processes that occurred during their deposition (fig. 8).

Figure 8 shows the chronostratigraphy of the rocks studied in Puerto Rico and the Dominican Republic relative to global, regional, and local Caribbean processes and events. Although an exhaustive treatment is beyond the scope of this article, a discussion of some major events in relation to the timing and nature of the sedimentary units follows. Note that this discussion focuses on units and time periods for which samples were collected.

Middle-Late Oligocene (ca. 29.78–24.10 Ma). Northern Puerto Rico exposes middle-late Oligocene outcrops of the San Sebastian Formation (ca. 29.78–26.51 Ma), which is a unit composed of mostly siliciclastics; the Lares Limestone (ca. 26.51–24.73 Ma); and the Montebello Member (ca. 27.30–24.10 Ma), also a limestone unit. During most of this time, Puerto Rico was experiencing tectonic quiescence [Meyerhoff et al. 1983; Van Gestel et al. 1998, 1999] and slow subsidence related to thermal contraction and sediment loading [Birch 1986]. However, there was active development of two arches (northwest-trending Guajataca along the west, and northeast-trending San Juan along the east) during this time, which is evidenced by thinning of the San Sebastian Formation, the Lares Limestone, and the Montebello Member toward the axes of the two arches [Larue et al. 1998; Van Gestel et al. 1998, 1999].

The San Sebastian Formation immediately overlies an angular unconformity and represents the last major input of siliciclastics in Puerto Rico, which were eroded from the Cordillera Central [Monroe 1980; Van Gestel et al. 1999]. The basal part of the San Sebastian Formation consists of terrestrial siliciclastic deposits likely reflecting uplift [Monroe 1980; Van Gestel et al. 1999; Mann et al. 2005] as well as low global sea level [Haq et al. 1987; Miller et al. 2005]. The basal deposits grade upward into nearshore marine siliciclastics and then marine limestones at the top [Lares Limestone and Montebello Member; Ortega-Ariza 2009; Ortega-Ariza et al. 2010, 2013]. This upward trend reflects marine flooding during the late Oligocene, likely tied to global sea level rise [Miller et al. 2005] and tectonic quiescence and subsidence [Meyerhoff et al. 1983; Birch 1986; Van Gestel et al. 1998, 1999].

Our data indicate some overlap in the timing of deposition of the San Sebastian Formation, the Lares Limestone, and the Montebello Member in the late Oligocene, suggesting that those parts of the units reflect lateral facies changes. The Lares Limestone is noted for its high diversity of shallow-water corals consisting of corals tolerant of cool, turbid water [e.g., Montastraea, Porites, and Siderastrea genera] and, importantly, corals that indicate warm, clear, shallow water [e.g., Actinacis and Antiguastra genera; Frost et al. 1983; Edinger and Risk 1994].

Our age dates sampled the lower and upper boundaries of the Lores Limestone. Those dates show that the entire extent of the Lores Limestone coincides with the range of late Oligocene warming reported by Zachos et al. [2001], which likely contributed to conditions suitable for development of the diverse coral assemblage seen in the Lores Limestone (fig. 8). The Montebello Member has some similarities with the Lores Limestone, but it also has some significant differences. It is characterized by large benthic foraminifers and mollusks [Monroe 1980; Seigle and Moussa 1984; Ramirez-Martinez 2000] as well as corals. Part of the Montebello Member coincides with the late Oligocene warming; however, in contrast to the Lores Limestone, the Montebello Member contains a less diverse coral assemblage and consists only of corals tolerant of cool, turbid water [e.g., Montastraea and Porites genera; Edinger and Risk 1994; Ramirez-Martinez 2000; Ward et al. 2002]. The lack of diversity and the absence of warm- and clear-water corals suggest the presence of environmental factors different from those for the Lores Limestone. Upwelling in the Caribbean started in the late Oligocene and continued through the Miocene [Maurrasse 1993; Edinger and Risk 1994; Mallinson et al. 1994; Hafar and Mutti 2005; fig. 8]. This timing agrees with the upper age date for the Lores Limestone from our study. In terms of the facies differences between the Lores Limestone and the Montebello Member, the Lores Limestone could represent a shallower, warmer-water environment, and the Montebello Member could represent a cooler, deeper-water environment. Alternatively, the Lores Limestone could represent areas protected from upwelling, and the Montebello Member could reflect areas that were influenced
Figure 8. Comparison of Dominican Republic and Puerto Rico Sr-derived mean ages from this study with time-equivalent global, regional, and local events and processes affecting the Caribbean. The numbers along the gray and black bars denote the Sr-derived mean ages from each unit (bold numbers in tables 1, 2). The lines along both extremes of the bars represent the minimum and maximum ages from each unit (Tables 1, 2). Sampling captures the full extent, from lower to upper boundaries, of the San Sebastian Formation and the Lazes Limestone. Partial age ranges are shown for the other units. BCP = Bahamas Carbonate Platform; CAS = Central American Seaway; CCW = counterclockwise; Fm = Formation; Fms = Formations; LP = Los Puertos; Ls = Limestone; Mbr = Member; NCP = North Coast Platform; PR = Puerto Rico; PRVI = Puerto Rico–Virgin Islands; SCP = South Coast Platform.
by upwelling. The disappearance of the diverse, shallow, warm-water coral facies [Lares Limestone] and zooxanthellate benthic foraminifera [Montebello Member] coincides with the end of deposition of the facies associated with the Lares Limestone as well as with the end of the Oligocene warming event and the beginning of a documented global coral extinction episode (~24–16 Ma; Vaughan 1919; Frost 1977; Edinger and Risk 1994; Budd 2000). In contrast, nearly all coral genera tolerant of cold water and turbidity survived and are present in the middle-late Miocene units [Edinger and Risk 1994]. Whereas our data indicate that deposition of facies attributed to the Lares Limestone ended ca. 24.7 Ma, facies attributed to the Montebello Member continued to be deposited, although the entire age range is unknown because of the lack of sampling of the upper part of the Montebello Member.

**Middle Miocene to Early Part of the Late Miocene** *(ca. 14.97–9.84 Ma in Puerto Rico; ca. 15.75–12.58 Ma in the Dominican Republic).* Strata from the middle Miocene to the early part of the late Miocene include the Cibao Formation (12.17 Ma), the Aguada (Los Puertos) Limestone (14.67–11.14 Ma), and the Aymamón Limestone (10.98 Ma) in northern Puerto Rico; the Ponce Limestone (14.97–9.84 Ma) in southern Puerto Rico; and the Yanigua–Los Haitises Formations (15.75–12.58 Ma) in northeastern Dominican Republic. All of these units have been interpreted as shallow marine environments, including coastal lagoons and inner and outer platforms with local patch reefs [Monroe 1980; Frost et al. 1983; Seiglie and Moussa 1984; Iturralde-Vinent 2001; Braga et al. 2012; fig. 2]. Our data indicate significant overlap in the timing of deposition of the units. During the middle Miocene and the early part of the late Miocene, Puerto Rico and northeastern Dominican Republic experienced tectonic stability [e.g., Van Gestel et al. 1999], and Puerto Rico was undergoing slow subsidence [Birch 1986; fig. 8]. Oblique collision occurring between north and south Hispaniola started in the early Miocene and caused uplift and erosion on most of Hispaniola, but northeastern Dominican Republic was unaffected [Mann et al. 1991].

Our data indicate that portions of the Cibao Formation, the Aguada [Los Puertos] Limestone, and the Aymamón Limestone are time-equivalent deposits in northwest Puerto Rico. The Cibao Formation consists of facies varying from siliciclastics (sand- and pebble-sized grains) to limestone [Monroe 1980], which have been interpreted to represent terrestrial to shallow marine coastal environments [Seiglie and Moussa 1984]. The siliciclastics were shed from a topographic high in the west that may be reflected in volcanic sandstones, conglomerates, and shales facies of the Guajataca Member interpreted as a fan-delta system [Monroe 1980]. The presence of siliciclastics in the Aguada [Los Puertos] Limestone and its absence in the Aymamón Limestone suggest that the Aguada [Los Puertos] Limestone was more proximal to the source of the siliciclastics and that the Aymamón Limestone was more distal. Apart from the siliciclastic components, the time-equivalent parts of the Cibao Formation, the Aguada [Los Puertos] Limestone, and the Aymamón Limestone have similar facies characteristics [see below] that are interpreted as representing shallow marine environments. These characteristics—and the lack of thinning of the units toward the Guajataca and San Juan arches—suggest that much of the previous paleotopography had been subdued and that deposition occurred over a broad, relatively flat substrate [Ortega-Ariza et al. 2010, 2013].

All units studied in this time interval are characterized by abundant red alage, benthic foraminifera [e.g., miliolid and soritid foraminifera], mollusks, echinoids, and bryozoans, especially in basal and middle portions of the units. Significantly, the lower to middle parts of the units lack abundant photosynthetic biota, including warm-water corals [Monroe 1980; Seiglie and Moussa 1984; Braga et al. 2012]. During the Burdigalian–early Serravallian, there was a global increase in productivity based on a long-term shift toward higher δ13C values [Vincent and Berger 1985], and upwelling continued to be a major process affecting the Caribbean [Maurrasse 1993; Edinger and Risk 1994; Mallinson et al. 1994; Halfar and Mutti 2005; fig. 8]. Halfar and Mutti (2005) recognized a global increase in coraline algae during this time, including in the Caribbean, which they interpreted to result from increased nutrients due in large part to enhanced upwelling conditions. The facies characteristics and their widespread distribution are supportive of regional upwelling in the Caribbean being a major control on the carbonate systems.

Upper portions of the Aguada [Los Puertos] Limestone, the Aymamón Limestone, and the Ponce Limestone in Puerto Rico and the middle to upper portions of the Yanigua–Los Haitises Formations show the reappearance of photosynthetic corals that are tolerant of cool, turbid water conditions [e.g., Goniopora, Porites, Agaricia, and Montastraea genera; Edinger and Risk 1994; Ward et al. 2002; Ortega-Ariza and Franseen 2011; Braga et al. 2012]. These corals are interpreted to have formed as reef flats, fringing reefs, and small patch reefs [Monroe 1980; Braga et al. 2012]. Timing of the coral development appears to be generally coeval in the studied units in Puerto Rico [ca. 13–10 Ma]. Estimated timing is
based on the presence of corals in NC6, NC11, and NC13 core descriptions [Hartley 1989; Scharlach 1990] and outcrops of the Ponce Limestone [Ortega-Ariza and Franseen 2011]. The timing of coral development in the Dominican Republic (ca. 15–12 Ma) is less certain; it could have been earlier than that in Puerto Rico on the basis of our data [approximately coinciding with the end of the coral extinction period, as shown by Edinger and Risk [1994]], although considering the range in error associated with age dates, that coral development overlapped with its development in Puerto Rico cannot be ruled out (fig. 8). Independent of precise timing, the reappearance of corals suggests a regional control. The coral species [tolerant of cool, turbid water conditions], dominance of heterozoan components [Edinger and Risk 1994], and phosphorite deposits [Riggs and Sheldon 1990; Mallinson et al. 1994] indicate that upwelling conditions were still important. The reappearance of the corals could indicate decreasing upwelling intensity as well as changing paleoceanography and climate conditions associated with the initial closing of the Central American Seaway (Duque-Cano 1990; Coates et al. 1992; Collins 1996).

At approximately 11–10 Ma there was a major fall in global sea level [Haq et al. 1987]. Ortega-Ariza and Franseen (2011) recognized a major unconformity evidencing subaerial exposure in the Ponce Limestone (ca. 12–11 Ma). Similarly, a major unconformity is recorded in the Aymamón Limestone [Monroe 1980; Seiglie and Moussa 1984, figs. 3, 8]. Our age data indicate that these unconformities match closely in time with the global drop in sea level. Other studies have recognized a major unconformity in Haiti, Cuba, the Dominican Republic, and the Windward Passage, the age of which was determined through biostratigraphy [Calais and Mercier de Lépinay 1995]. The somewhat older age that these studies assign to the unconformity could be an indication of the duration of the sea level drop, of a lack of resolution given by the biostratigraphy, or that it is a different unconformity.

**Late Miocene (ca. 6.31–5.88 Ma).** Late Miocene (Messinian) strata sampled in this study come from the Cercado Formation in the Cibao Basin in northwestern Dominican Republic. The Cercado Formation is composed of shallow-water mixed carbonate-siliciclastic facies with a diverse warm-water coral assemblage (e.g., *Stylophora*, *Pocillopora*, and *Dicracoenax* genera) that formed 15–20-m-thick laterally discontinuous reef interpreted as patch reefs [Maier et al. 2007; McNeill et al. 2012]. The Messinian was a time of ice-house conditions characterized by high-frequency, high-magnitude sea level fluctuations [Miller et al. 2005] superimposed on lower-frequency sea level fluctuations [Haq et al. 1987; fig. 8]. As previously postulated by McNeill et al. [2012] and Maier et al. [2007], a relative sea level rise [Miller et al. 2005], decreased upwelling intensity [Spezzaferri et al. 2002; Maier et al. 2007], and warm ocean surface temperatures [Emiliani et al. 1972] during the Messinian created favorable conditions for reef development in the Cercado Formation. Closure of the Central American Seaway and restriction of water exchange between the Caribbean and Pacific Oceans began approximately in the middle Miocene (Serravallian) and culminated in complete closure and isolation of the Caribbean waters from the Pacific Ocean in the Pliocene (~3.5 Ma; Coates et al. 1992; Collins 1996; fig. 8). The Central American Seaway tectonic event resulted in significant changes in circulation patterns and perhaps contributed to creating suitable conditions for reef deposition, including warm temperatures and decreased upwelling.

Cercado patch reefs are capped by a thick succession of shallow marine siliciclastics that mark the culmination of carbonate deposition within the Cercado Formation [Maier et al. 2007; Ortega-Ariza and Franseen 2012]. A hiatal unconformity (ca. 6 Ma) separates the Cercado Formation from overlying Gurabo Formation (ca. 5.8–4.0 Ma; McNeill et al. 2012). This contact locally evidences subaerial exposure reflecting a relative fall in sea level [Ortega-Ariza and Franseen 2012], which appears to correlate with a global sea level fall of Miller et al. (2005), as shown by McNeill et al. (2012) and Haq et al. (1987).

**Conclusion**

*Ostrea haitiensis* and *Kuphus incrassatus* molusk was sampled for strontium isotope dating from units described as Oligocene through Miocene shallow marine sedimentary systems in Puerto Rico and the Dominican Republic (e.g., Monroe 1980; Saunders et al. 1986). This study provides an updated and refined chronostratigraphic framework to better understand the relationship to time-equivalent regional and local factors that may have influenced deposition.

The Sr isotope data obtained indicate the following: (1) a middle to late Oligocene age (ca. 29.78–26.51 Ma) for the San Sebastian Formation, which is consistent with previous studies but provides an additional age for the upper extent of the unit; (2) a late Oligocene age (ca. 26.51–24.73 Ma) for the entire Lares Limestone, which is different from previous studies that indicated late Oligocene–early
These characteristics suggest a warmer, 

Miocene ages; [3] a late Oligocene age [ca. 27.30–24.10 Ma] for the part of the Montebello Member of the Cibao Formation that was sampled, which disagrees with previous studies that assigned an early Miocene age; [4] a middle Miocene age [ca. 12.17 Ma] for the Cibao Formation, which differs from previous studies indicating an early Miocene age; [5] a middle to late Miocene age [ca. 14.67–11.14 Ma] for the Aguada [Los Puertos] Limestone, which partially differs from other studies that indicate an early to middle Miocene age; [6] a late Miocene age [ca. 10.98 Ma] for the Aymamón Limestone, which is consistent with previous studies; [7] a middle to late Miocene age [ca. 14.97–9.84 Ma] for the Ponce Limestone, which is consistent with previous studies; [8] a middle Miocene age [ca. 15.75–12.58 Ma] for the Yanigua–Los Haitises Formations, which agrees with all previous work except one recent study that suggests a Pliocene to early Pleistocene age; and [9] a late Miocene age [ca. 6.31–5.88 Ma] for the Cercado Formation, which is consistent with previous studies.

During the middle-late Oligocene, Puerto Rico was experiencing tectonic quiescence (Meyerhoff et al. 1983; Van Gestel et al. 1998, 1999) and slow subsidence related to thermal contraction and sediment loading (Birch 1986). However, there was active development of two arches [northwest-trending Guajataca along the west, and northeast-trending San Juan along the east]. San Sebastian Formation siliciclastics were eroded from the uplifted areas, representing terrestrial to shallow marine environments. The time-equivalent Lares Limestone consists of a diverse assemblage of warm-water corals and cool- and turbid-water corals, whereas the Montebello Limestone is characterized by large benthic foraminifers, mollusks, and a less diverse coral assemblage consisting only of corals tolerant of cool, turbid water. These characteristics suggest a warmer, shallower environment [or an environment protected from upwelling currents] for the Lares Limestone and a cooler, deeper-water environment [or an environment influenced by upwelling] for the Montebello Member. The end of deposition of the facies associated with the Lares Limestone coincides with the end of the Oligocene warming event (Zachos et al. 2001) and the beginning of a documented global coral extinction episode [e.g., Edinger and Risk 1994] where only corals tolerant of cool, turbid water survived, as reflected by continued deposition of Montebello Member facies.

From the middle Miocene to the early part of the late Miocene, Puerto Rico and northeastern Dominican Republic experienced tectonic stability, and Puerto Rico was undergoing slow subsidence [Birch 1986; Van Gestel et al. 1999]. Oblique collision occurring between north and south Hispaniola started in the early Miocene and caused uplift and erosion on most of Hispaniola, but northeastern Dominican Republic was unaffected. In Puerto Rico, the Cibao Formation consists of facies varying from siliciclastics to carbonates, which have been interpreted to represent terrestrial to shallow marine coastal environments [Monroe 1980]. The presence of siliciclastics in the time-equivalent Aguada [Los Puertos] Limestone and its absence in the Aymamón Limestone suggests that the Aguada [Los Puertos] Limestone was more proximal to the source of the siliciclastics and that the Aymamón Limestone was more distal. All of the units during this time interval in Puerto Rico and the Yanigua-Los Haitises Formations in the Dominican Republic are similarly characterized by abundant red algae, benthic foraminifiers [e.g., miliolid and soritid foraminifera], mollusks, echinoids, and bryozoans, especially in basal and middle portions of the units, indicating that upwelling continued to be a major process affecting the Caribbean. Upper portions of the units show the reappearance of photosynthetic corals, which are dominated by those that are tolerant of cool, turbid water, possibly reflecting decreasing upwelling intensity as well as changing paleoceanography and climate conditions associated with the initial closing of the Central American Seaway [e.g., Coates et al. 1992]. The late Miocene Cercado Formation in the Dominican Republic is composed of shallow-water mixed carbonate-siliciclastic facies with a diverse warm-water coral assemblage. The final stages of the Central American Seaway tectonic event resulted in significant changes in circulation patterns and perhaps contributed to creating suitable conditions for reef deposition, including warm ocean surface water temperatures and decreased upwelling.

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\frac{\text{Sr}}{\text{Sr}} \text{stratigraphy from the } \text{Coelocithum-Capsimamia} \text{ rudist assemblage in the Greater Antilles (Puerto Rico, Dominican Republic and Jamaica). Cret. Res. 35:90–109.}
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Appendix from D. Ortega-Ariza et al., “Strontium Isotope Stratigraphy for Oligocene-Miocene Carbonate Systems in Puerto Rico and the Dominican Republic: Implications for Caribbean Processes Affecting Depositional History” (J. Geol., vol. 123, no. 6, p. 000)
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<tr>
<td>DR7/14-124</td>
<td>18°50.75′N, 69°44.06′W</td>
</tr>
<tr>
<td>DR7/26-87</td>
<td>19°06.59′N, 69°50.03′W</td>
</tr>
<tr>
<td>DR7/15-87</td>
<td>19°06.59′N, 69°50.03′W</td>
</tr>
</tbody>
</table>

Note.—LP = Los Puertos; m abo = meters above base of outcrop; PQ = Ponce Quarry.
* Sample collected from *Ostrea haitensis* bivalve.