Catastrophic extinction of Caribbean rudist bivalves at the Cretaceous-Tertiary boundary

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ABSTRACT

Strontium isotope ratios ($^{87}Sr/^{86}Sr$) in pristine low-Mg calcite of shells of rudist bivalves from the *Titanosarcolites* limestones exposed in the Central, Maldon, and Marchmont inliers of Jamaica indicate that species-rich rudist-coral associations persisted into the latest Maastrichtian (66–65 Ma). This finding contradicts the currently accepted hypothesis of stepwise extinction of rudist bivalves in the middle Maastrichtian and argues for a catastrophic, impact-related demise of Caribbean Cretaceous reefal ecosystems at the Cretaceous-Tertiary boundary.

Keywords: Jamaica, Maastrichtian, chemostratigraphy, $^{87}Sr/^{86}Sr$, rudists, Cretaceous-Tertiary boundary.

Figure 1. Bedding-plane view of *Titanosarcolites* with both valves conjoined, Maldon inlier near Shaw Castle. Diameter of lens cap is 53 mm.

INTRODUCTION

The timing and pattern of biotic extinctions in the Late Cretaceous leading up to the Cretaceous-Tertiary (K-T) boundary in tropical carbonate platforms and reefal ecosystems is poorly defined globally owing to imprecise biostratigraphic control (Johnson and Kauffman, 1996; MacLeod et al., 1997; Philip, 1998). During the Late Cretaceous, extensive carbonate platforms were present in the Caribbean, and because of their proximity to the Yucatan site of impact of a large extraterrestrial body at the K-T boundary (Alvarez et al., 1980; Smit, 1999), they should have been severely affected by impact-related environmental perturbations. However, reefal ecosystem decline and the demise of rudist bivalves in the Caribbean have previously been attributed to stepwise extinction in the middle Maastrichtian, possibly caused by sea-level changes and climatic deterioration (Jiang and Robinson, 1987; Johnson and Kauffman, 1996, 2001; Johnson et al., 1996).

Upper Cretaceous carbonate sequences in the Caribbean are well developed on the island of Jamaica (Kauffman and Sohl, 1973), and these sections have been critical in determining the patterns of rudist bivalve extinction during the Maastrichtian (Jiang and Robinson, 1987; Johnson and Kauffman, 1996). The Cretaceous succession is exposed in several inliers, but is buried beneath Tertiary limestones elsewhere on the island. The inliers contain successions consisting of conglomerates, sandstones, shales, and limestones; the limestones contain the *Titanosarcolites* rudist fauna (Fig. 1), the youngest rudist assemblage in the Caribbean region (Chubb, 1971; Johnson and Kauffman, 1996; Gunter, 2002). Although the stratigraphy of individual inliers is well known (e.g., Coates, 1965; Jiang and Robinson, 1987; Mitchell, 1999; Mitchell and Blissett, 2001), detailed correlation between inliers, and with international stages, is difficult because of the endemic nature of much of the fauna.

To determine the age of the *Titanosarcolites* limestones in these inliers, we analyzed strontium isotope ratios in the diagenetically most stable form of biological carbonate, low-Mg calcite, in shells of rudist bivalves from localities in the Central, Maldon, Marchmont, and Jerusalem Mountain inliers of Jamaica (Fig. 2). Variation of this isotope ratio in seawater during the Late Cretaceous and Tertiary is known in detail (McArthur et al., 1998, 2000, 2001; MacLeod et al., 2001) and provides a precise tool for global stratigraphic correlation (Veizer et al., 1997). Owing to the long residence time of Sr in seawater, the $^{87}Sr/^{86}Sr$ values in waters of normal marine salinity are globally uniform, so the $^{87}Sr/^{86}Sr$ values of diagenetically unaltered carbonates can be used to derive precise numerical ages. This method avoids problems of conventional biostratigraphy, such as correlation between different faunal provinces or endemic associations (Hazel and Kamiya, 1993), and has been increasingly used as a tool for global stratigraphic correlation (McArthur, 1994; Steuber, 2001).

MATERIALS AND METHODS

Samples were drilled with tungsten instruments (0.6 mm diameter) from polished sections of well-preserved areas of the outer shell layer of valves of the rudist genera *Plagioptychus*, *Hippurites*, and *Chiapasella* and from oyster shells. Diagenetic calcite, either as void-filling precipitate or as replaced aragonite, was also sampled. We analyzed 58 samples from 27 specimens of rudists and oys-

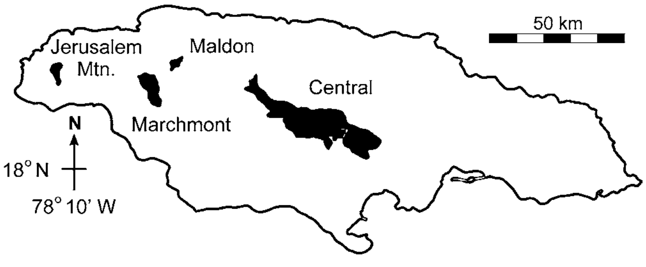

Figure 2. Locations of Cretaceous inliers in Jamaica from which samples were analyzed.

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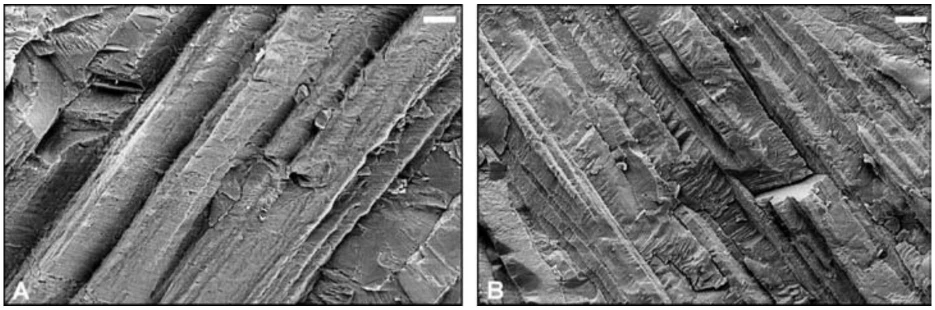

Figure 3. Scanning electron microscope images of fibrous prismatic ultrastructure in outer-shell layer of *Plagioptychus*. A: Sample C546, Central inlier, Rio Minho section, level F1; scale bar represents 10 μm. B: Sample C593, Maldon inlier, locality 13; scale bar represents 20 μm.

ters[1]. Element concentrations were measured with inductively coupled plasma–mass spectrometry (ICP-MS) on splits of samples submitted for Sr isotope analyses. Sr was separated by standard ion-exchange methods, and isotope ratios were analyzed on a Finnigan MAT 262 thermal-ionization mass spectrometer. Isotope ratios were normalized to an ^{86}Sr/^{88}Sr value of 0.1194. The long-term mean of ^{87}Sr/^{86}Sr of modern seawater (USGS EN-1) measured in 2000–2001 at the Bochum isotope laboratory is 0.709 146 ($n = 68$, 2 s.e. [standard error] $= 2 \times 10^{-6}$), and the mean of standards run together with samples analyzed for this study is 0.709 143 ($n = 8$, 2 s.e. $= 4 \times 10^{-6}$). The ^{87}Sr/^{86}Sr ratios of samples are adjusted by $+29 \times 10^{-6}$ to a value of 0.709 175 of USGS EN-1, to derive numerical ages from the look-up table of McArthur et al. (2001). Interlaboratory comparison of samples, including latest Cretaceous biological calcite, has proven the correctness of this approach, which is critical for the precise derivation of numerical ages (McArthur et al., 2001).

RESULTS

Preservation of Original Sr Isotope Ratios

The original seawater ^{87}Sr/^{86}Sr values of skeletal carbonate can be altered by diagenesis, and samples must be carefully screened for such effects. Scanning electron microscopy (SEM) shows that the low-Mg calcite outer shell layer of the rudists analyzed has well-preserved, fibrous, prismatic ultrastructure (Fig. 3). Because the state of preservation can vary significantly between different areas of a single shell, the elemental composition of splits of samples analyzed for Sr isotope ratios was used to select the best-preserved samples. Diagenesis of low-Mg calcite typically involves decreasing Sr and increasing Fe and Mn concentrations (Veizer, 1983). This pattern is clearly seen in the samples analyzed (Fig. 4). Below a threshold of 20 μg/g Mn and 200 μg/g Fe, ^{87}Sr/^{86}Sr values of samples from each locality are constant within the range of analytical error. This concordance of ^{87}Sr/^{86}Sr values of samples obtained from different parts of single shells and/or from several shells from each locality (Table 1) argues for a preservation of original seawater ^{87}Sr/^{86}Sr values, because alteration characteristically proceeds patchily (McArthur, 1994). Sr concentrations of these samples range from 1270 to 1643 μg/g, characteristic of Late Cretaceous rudist calcite (Steuber, 1999, 2002). Consequently, numerical ages were derived only from the ^{87}Sr/^{86}Sr values of samples that had Mn and Fe concentrations below 20 and 200 μg/g, respectively (Table 1). Although other samples with elevated Mn and Fe concentrations had ^{87}Sr/^{86}Sr values within the range of best-preserved calcite (Fig. 4), these have been excluded from the calculation of numerical ages. This approach may have eliminated samples in which the original Sr isotopic composition is still preserved, because Fe and Mn may derive from oxyhydroxide coatings within the shells instead of being structurally bound in the calcite (McArthur, 1994). Because ^{87}Sr/^{86}Sr values decrease only slightly with increasing Mn and Fe concentrations (Fig. 4), the chosen threshold appears to be justified, because minor diagenetic shifts of isotope ratios may have otherwise remained unnoticed. No sample from oyster shells matched the criteria just discussed, and there is considerable scatter in their ^{87}Sr/^{86}Sr values, although original shell structures are well preserved.

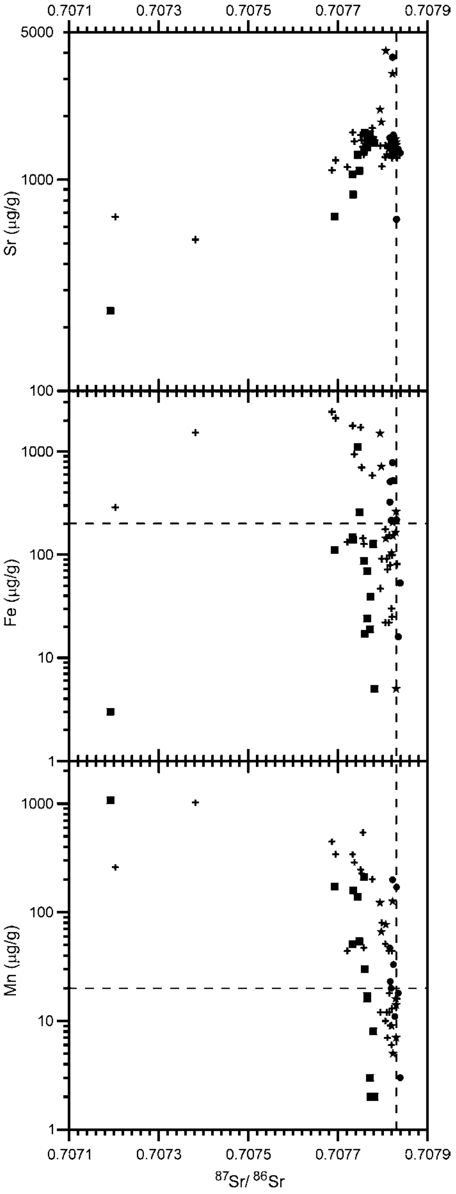

Figure 4. Sr, Fe, and Mn concentrations vs. ^{87}Sr/^{86}Sr values in samples analyzed from Central (crosses), Maldon (circles), Jerusalem Mountain (boxes), and Marchmont (stars) inliers (see text footnote 1). Three samples with lowest ^{87}Sr/^{86}Sr values are from diagenetic calcite. Vertical broken line indicates highest Late Cretaceous ^{87}Sr/^{86}Sr value of seawater that occurs near Cretaceous-Tertiary boundary (McArthur et al., 2001). Horizontal broken lines indicate thresholds of Mn and Fe concentrations on which selection of best-preserved samples was based.

Most samples with high Mn and Fe concentrations have lower ^{87}Sr/^{86}Sr values than best-preserved rudist shells. Diagenetic calcite, either as void-filling precipitate or as replaced aragonite of the inner shell layers of rudists, has the lowest ^{87}Sr/^{86}Sr values among the samples analyzed (Table 1). Such a trend is expected in a diagenetic environment where the Sr of pore fluids is derived predominantly from island-arc–type volcaniclastic sediments that are intercalated with rudist-coral limestones of Jamaica (Mitchell, 1999) and that typically have low, mantle-dominated ^{87}Sr/^{86}Sr values. Consequently, diagenesis would have shifted the original seawater composition of rudist shells to lower ^{87}Sr/^{86}Sr values that would result in higher numerical ages (Fig. 5).

Numerical Ages

Compared with the ^{87}Sr/^{86}Sr reference curve for Cretaceous seawater (McArthur et

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[1] GSA Data Repository item 2002118, Analytical results of low-Mg calcite of shells of rudist bivalves from Jamaica, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

TABLE 1. ANALYTICAL RESULTS OF LOW-Mg CALCITE OF RUDIST BIVALVES FROM JAMAICA AND DERIVED NUMERICAL AGES

Locality, sample no.*	^{87}Sr/^{86}Sr	±2 s.e. ($\times 10^{-6}$)	Sr (μg/g)	Mg (μg/g)	Fe (μg/g)	Mn (μg/g)	Age† (Ma)		
Central inlier									
Rio Minho section§ (N18°09′22″; W77°22′47″)									
Lower C									
C551	0.707 806	6	1454	1265	176	51			
C551/2	0.707 806	6	N.D.	N.D.	N.D.	N.D.			
mean	0.707 806	8					>66.21	66.68	<67.46
D1									
R1089/1	0.707 820	6	1432	1083	30	6			
R1089/2	0.707 795	5	1448	1144	47	12			
R1089/3	0.707 811	7	1419	1065	72	7			
mean	0.707 809	7					>66.13	66.55	<67.17
D25									
C598/1	0.707 815	7	1471	861	154	12			
C598/2	0.707 809	6	1321	1066	91	12			
C598/3	0.707 815	5	1428	950	98	18			
mean	0.707 813	7					>65.95	66.39	<66.91
F1									
C547/1	0.707 821	7	1302	594	99	13			
C547/2	0.707 832	6	1270	599	81	16			
mean#	0.707 827	8						65.78	<66.31
Logie Green (N18°09′34″; W77°25′44″)									
R1081/1	0.707 806	6	1279	1055	22	10			
R1081/2	0.707 817	7	1309	1285	79	9			
mean	0.707 812	8					>65.95	66.43	<67.03
Jerusalem Mountain inlier									
Loc. 17 (N18°19′34″; W78°13′48″)									
C562/2	0.707 765	7	1544	924	24	17			
C564/2	0.707 782	6	1489	689	5	2			
C564/3	0.707 772	7	1643	842	19	3			
mean	0.707 773	7					>68.30	69.05	<69.70
Loc. 18 (N18°19′29″; W78°13′49″)									
C561	0.707 773	6	1506	891	39	2			
C561/2	0.707 779	6	1547	1057	127	8			
C561/3	0.707 765	7	1422	1310	69	16			
mean	0.707 772	7					>68.37	69.12	<69.76
Maldon inlier									
Loc. 13 (N18°19′58″; W77°48′41″)									
C578	0.707 827	6	1360	2284	0	11			
C578/3	0.707 839	6	1341	1021	53	3			
C593	0.707 835	7	1389	801	16	18			
C593/2	0.707 838	7	N.D.	N.D.	N.D.	N.D.			
mean#	0.707 835	5							<65.83
Marchmont inlier									
Loc. 20 (N18°17′56″; W77°54′49″)									
C581#	0.707 823	12	1341	1035	151	5		65.99	<66.63
Loc. 23 (N18°15′40″; W77°52′56″)									
C582	0.707 830	6	1460	712	5	7			
C582/2	0.707 829	7	1564	1322	164	16			
C582/3	0.707 820	6	1396	1154	104	9			
mean	0.707 826	7					>65.06	65.84	<66.31

[*] Extensions of sample numbers following slashes indicate samples taken from different parts of the same shell.

[†] Numerical ages derived from McArthur et al. (2001), following the method of McArthur et al. (2000). Upper and lower age limits were obtained by adding two standard errors (s.e.) of the mean value of isotopic results from each locality to the statistical uncertainty of the seawater curve (Fig. 5). For most localities, fewer than four values were available, and uncertainty was considered to be twice the standard error of the mean value of USGS EN-1 run together with samples (±0.000 012, ±0.000 008, or ±0.000 007, for $n = 1$, 2, and 3, respectively).

[§] Sample levels of the Rio Minho section are rhythms or divisions (Mitchell, 1999).

[#] No mean value or lower age limit is obtained from the look-up table for ^{87}Sr/^{86}Sr values close to the maximum Late Cretaceous ratio near the Cretaceous-Tertiary boundary.

al., 2001), all analyses of rudist shells from the *Titanosarcolites* limestones of Jamaica indicate a latest Maastrichtian age, with the exception of rudist formations of the Jerusalem Mountain inlier that were deposited close to the lower Maastrichtian–upper Maastrichtian boundary (Fig. 5). The age of rudist-coral associations from the Jerusalem Mountain inlier corresponds with previous biostratigraphic data obtained from nannofossils (Jiang and Robinson, 1987). No reliable numerical age was obtained from the Sr isotope composition of shells from the Oyster Limestone, which was thought to overlie the Jerusalem Mountain rudist limestones and was interpreted to reflect the middle Maastrichtian extinction event (Johnson and Kauffman, 1996). The most continuous section of Maastrichtian limestones (Guinea Corn Formation) is exposed in the bed of Rio Minho (Mitchell, 1999). The increase of mean ^{87}Sr/^{86}Sr values of samples from four successive levels of the section supports our assumption that the original seawater ^{87}Sr/^{86}Sr signature is well preserved in those samples that have been selected to derive numerical ages, although data on elemental composition from samples of the lowest level are not decisive. The highest sample is from a level 36 m below the top of the Guinea Corn Formation and yielded an age of 65.8 Ma. Logie Green is the type locality of several rudist species, among them the type species of genera that have numerous records elsewhere in the New World such as *Titanosarcolites* and *Chiapasella*. According to Sr isotope stratigraphy, this locality can be correlated with the middle part of the Rio Minho section (Fig. 5). The youngest age was obtained from the *Titanosarcolites* limestone of the Vaughansfield Formation exposed in the Maldon inlier (Fig. 5; Table 1). Samples from there have a mean ^{87}Sr/^{86}Sr value of 0.707 835 ± 5 $\times 10^{-6}$, which is within analytical uncertainty of the values of 0.707 828 ± 3 $\times 10^{-6}$ and 0.707 832 ± 7 $\times 10^{-6}$ given for the K-T boundary in Europe and Antarctica, respectively, by McArthur et al. (1998).

DISCUSSION

The data presented here provide, for the first time, precise ages for the *Titanosarcolites* limestones and indicate that species-rich associations of rudist bivalves—as well as numerous groups of associated benthos that thrived in the shallow-water, tropical marine environments of the Caribbean—persisted into the latest Maastrichtian. This finding provokes the scenario of a catastrophic extinction related to the impact of a large extraterrestrial object at the K-T boundary. However, supporting sedimentological evidence does not yet exist in Jamaica. The critical intervals are either unrecognized within thick volcaniclastic successions that buried the carbonate platforms, or hidden beneath Tertiary limestone cover. In the Mediterranean and Middle Eastern Tethys deposits, a reduction in diversity and abundance of rudists is noted as early as the Campanian, and this decline was probably related to a loss of habitat, although precise stratigraphic control is available only for a few occurrences (Philip, 1998). Consequently, a clear pattern of extinction has not yet emerged. Our data show that the history of Late Cretaceous carbonate platforms can be traced with considerable precision by Sr isotope stratigraphy and that the global pattern of timing as well as the causes of the demise of the distinctive ecosystems of late Mesozoic tropical shallow-water environments must be reevaluated.

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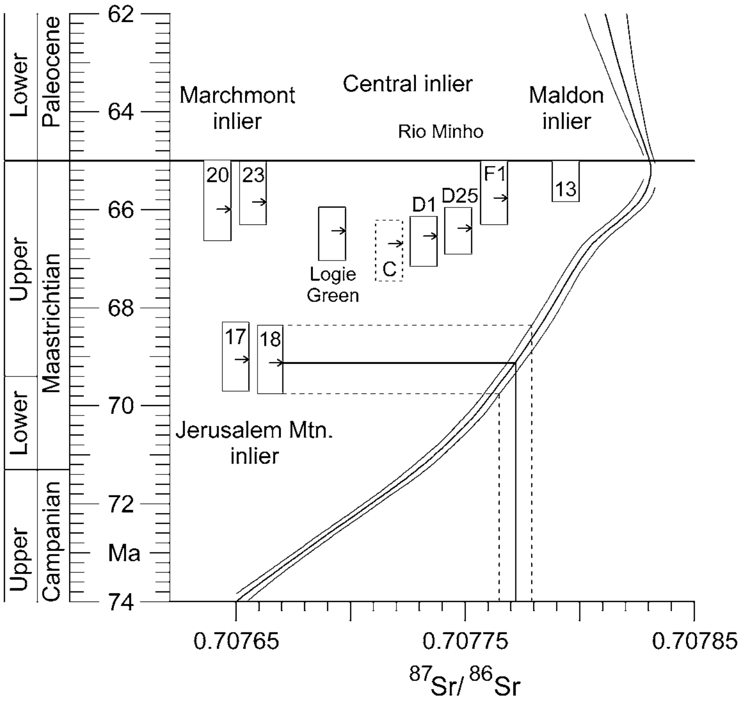

Figure 5. Variation of ^{87}Sr/^{86}Sr values in Cretaceous seawater (bold curve; thin curves are 95% confidence limits [Howarth and McArthur, 1997; McArthur et al., 2001]), and numerical ages (arrows) derived from Sr isotope stratigraphy of low-Mg calcite of rudist shells from localities of *Titanosarcolites* limestones of Jamaica (Table 1). Vertical bars indicate age ranges due to limits of analytical precision and statistical uncertainty of seawater curve, as shown by broken lines for data of locality 18. Only upper age limit is indicated for locality 13; mean ^{87}Sr/^{86}Sr value of samples from this locality is above value currently accepted for latest Maastrichtian seawater. Time scales of Cande and Kent (1995) and Obradovich (1993) for 62–70 and 70–74 Ma, respectively.

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