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Uranium-series coral ages from the US Atlantic Coastal Plain–the "80 ka problem" revisited

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Abstract

Uranium series coral ages for emergent units from the passive continental margin US Atlantic Coastal Plain (ACP) suggest sea level above present levels at the end of marine oxygen isotope stage (MIS) 5, contradicting age-elevation relations based on marine isotopic or coral reef models of ice equivalent sea level. We have reexamined this problem by obtaining high precision $^{230}Th/^{238}U$ and $^{231}Pa/^{235}U$ thermal ionization mass spectrometric ages for recently collected and carefully cleaned ACP corals, many in situ. We recognize samples that show no evidence for diagenesis on the basis of uranium isotopic composition and age concordance. Combining new and earlier data, among those ages close to or within the age range of MIS 5, over 85% cluster between 65 and 85 ka BP. Of the corals that we have analyzed, those that show the least evidence for diagenesis on the basis of uranium isotopic composition and age concordance have ages between 80 and 85 ka BP, consistent with a MIS 5a correlation. The units from which these samples have been collected are all emergent and have elevations within ~3–5 m of those few units where early stage 5 (~125,000 ka BP) coral ages have been obtained. The ACP appears to record an unusual history of relative sea level throughout MIS 5, a history that is also apparent in the dated coral record for Bermuda. We speculate that this history is related to the regional (near-to intermediate-field) effects of ancestral Laurentide Ice sheets on last interglacial shorelines of the western North Atlantic.

1. Introduction

The geochronology of Pleistocene coral terraces, combined with marine isotopic records, elucidates the timing and magnitude of changes in global ice volume on a variety of time scales. The interval between ca. 140 and 70 ka BP, well dated by classical (alpha-spectrometry) and modern thermal ionization mass spectrometric (TIMS) uranium-series techniques, is understood to include a series of ice-volume minima (sea-level maxima) that can be broadly defined as the "last interglacial." This interval (marine isotope stage (MIS) 5) includes a period of smaller-than-present ice volume (eustatic sea level higher than present) around 125 ka BP (substage 5e), with subsequent ice-volume minima at roughly 105 ka BP (substage 5c) and 80 ka BP (substage 5a). Sea levels during substages 5c and 5a have been interpreted to have been between 10 and 25 m lower than present, compared with roughly 120–135 m below present for full-glacial ice volume (Lambeck and Chappell, 2001; Yokoyama et al., 2001; Cutler et al., 2003 and references therein).

The sea levels derived from tropical coral terraces and the marine isotopic record are references against which other dated coastal records can be compared. These comparisons can yield estimates of local tectonic deformation rates, or they can provide age estimates for a sequence of coastal units when there is little independent geochronologic information. In some cases, reliable geochronologic data for selected coastal units in mid-latitude regions are inconsistent with eustatic records based on tropical coral reef chronologies (Muhs et al., 2002a, b).

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There is a long history of U-series dating of sites from the US Atlantic Coastal Plain (ACP) (Fig. 1), beginning with Oaks et al. (1974) and continuing with work by Szabo and colleagues at the US Geological Survey (Cronin et al., 1981; McCartan et al., 1982; Szabo, 1985). The vast majority of these results, all obtained by alpha-spectrometry on ahermatypic corals collected from units that are presently emergent (elevations up to +8 m), fall in the interval between 65 and 85 ka BP. These U-series ages have been questioned because of: (1) their inconsistency with what has been assumed to be a global eustatic record (e.g., Bloom et al., 1974; Shackleton, 1987), given the assumed tectonic stability of the passive margin ACP; (2) some isotopic evidence for open system behavior, and (3) problematic implications of associated amino acid racemization results (Wehmiller and Belknap, 1982; Szabo, 1985; Wehmiller et al., 1992). Additionally, the striking paucity of ACP U-series coral ages in the 125 ka BP range (the age most frequently observed for emergent units on other low-uplift-rate continental margins and islands—e.g., Chen et al., 1991; Stirling et al., 1998; Muhs et al., 2002a) suggests that the coastal evolution of the dated portions of the ACP may be unique.

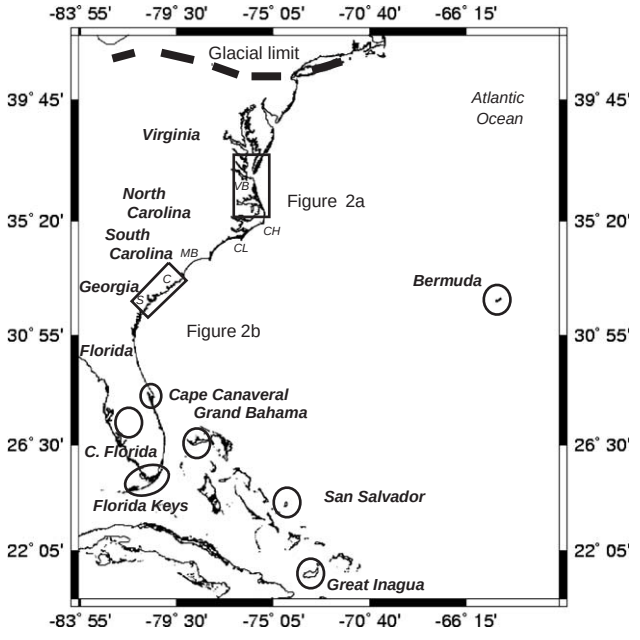

Fig. 1. Coastlines of the western North Atlantic, including the Atlantic coastal plain (New Jersey to Florida), Bermuda and the Bahamas, showing sites dated by U-series methods Open boxes: enlarged as Fig. 2a and b; S = Savannah, Georgia; C = Charleston, South Carolina; MB = Myrtle Beach, South Carolina; VB = Virginia Beach, Virginia; CL = Cape Lookout, North Carolina; CH = Cape Hatteras, North Carolina Circles: Bermuda: Muhs et al. (2002b); San Salvador and Great Inagua: Chen et al. (1991); Grand Bahama, Lundberg and Ford (1994); Central Florida: (Muhs et al., 1992, 2004); Florida Keys: Osmond et al. (1965); Broecker and Thurber (1965); Toscano and Lundberg (1999); Fruijtier et al. (2000); Muhs et al. (1992, 2004); Cape Canaveral: Osmond et al. (1970).

In this paper we review existing ACP U-series data and present 26 new U-series coral ages, the first ACP dates obtained with TIMS and inductively coupled plasma mass spectrometric (ICP-MS) methods (Edwards et al., 1987; Shen et al., 2002). The samples are from one site in southeastern Virginia, one in northeastern North Carolina, two in central South Carolina, and one in Georgia. These samples were collected with mollusks that are part of ongoing studies of amino acid racemization geochemistry/geochronology at these and other related localities (Wehmiller et al., 1988, 1992; Mirecki et al., 1995). In no case have new collections been made at the precise location of previous analyses, although in at least two cases the new collections very closely duplicate collections made in the late 1970's and early 1980's (McCartan et al., 1982; Szabo, 1985). The TIMS and ICP-MS results presented here refine and reinforce the previous conclusions based on alpha-spectrometric ages.

2. Localities and samples

Information about the sample collection sites is summarized in Table 1. Fig. 2 shows the locations of these collection sites, along with some nearby sites for which relevant alpha-spectrometric U-series data are available (Szabo, 1985). In most cases, the exposures at these sites have been created by commercial excavation, so outcrops change rapidly or disappear after several years. An exception is the excavation at Gomez Pit, Virginia Beach, Virginia (G), which has been accessible for over 15 years. Corals from various sites within this large ($\sim$1 km^2) excavation were collected between 1985 and 1999. The Moyock, North Carolina (M), site was originally sampled in the late 1970's (Cronin et al., 1981) but only samples collected in 1992 were included in the present study; the Rifle Range (RR) and Berkeley Pit (BP) South Carolina exposures were created in 1990 and were collected in 1991 and 1992. The Jones site (J) Georgia (Hulbert and Pratt, 1998), created in 1995, is a private excavation that it is now flooded. Images of most of these sites and analyzed coral specimens can be found at http://www.geology.udel.edu/wehmiller/CoralGeochronology/CoralMap.html.

The deposits from which the corals were collected generally consist of shelly sands (G, M, RR) or fine sands and muds, representing back-barrier or inlet depositional environments (typical water depths $\sim$1–6 m). In most cases, these deposits are less than 4 m thick, overlying either earlier Pleistocene or Tertiary units. At G, at least one earlier Pleistocene unit is found below the coral-bearing unit (Mirecki et al., 1995). At the BP and RR pits, a wide range of racemization ratios suggests that multiple ages of mollusks are present, although diagenetic effects are also apparent (Wehmiller

Table 1
Sample localities, with information on elevation, collection history, and other references describing the sites

Site	N. Latitude	W. Longitude	Outcrop elevation range (m)	Max. elevation of coral-bearing unit (m)	Collection date	Previous alpha-spec data?	Associated racemization data	Reference
Gomez Pit, Va	36.7823	76.1966	−2 to +8	~7.5	Jul-89	Yes[a]	Yes	Cronin et al. (1981), Szabo (1985),
Gomez Pit, Va	36.7807	76.1943	−2 to +8	~7.5	Jun-99	Yes[a]	Yes	Mirecki et al. (1995)
Moyock, NC	36.508	76.153	0 to +4	~5	Jan-92	Yes	Yes	Cronin et al. (1981), Szabo (1985)
Berkeley Pit, SC	32.8586	79.7803	−1 to +6	~5	Jun-91	Yes[b]	Yes	Cronin et al. (1981), McCartan et al. (1982)
					Jun-92			Wehmiller and Belknap (1982), and Szabo (1985) for nearby sites
Rifle Range Pit, SC	32.8152	79.8324	−1 to +6	~5	Jun-91	Yes[b]	Yes	Cronin et al. (1981), McCartan et al. (1982), Wehmiller and Belknap (1982) and Szabo (1985) for nearby sites
Jones Site, GA	31.916	81.071	−1 to +4	~3	Jul-95	No	Yes	Hulbert and Pratt (1998)

For additional information on most of these sites, see: http://www.geology.udel.edu/wehmiller/CoralGeochronology/CoralMap.html.
[a] On nearby exposures: Cronin et al. (1981) and Szabo (1985).
[b] On nearby sites: Cronin et al. (1981); McCartan et al. (1982) and Szabo (1985); early results in ~95 kyr range (Cronin et al., 1981) later recalculated to ~86 ka (Szabo, 1985).

et al., 1993). Because superposed aminozones (clusters of distinct D/L values—see Wehmiller and Miller, 2000) are found at other sites in the Charleston, South Carolina, area (Corrado et al., 1986; York et al., 1999; Harris, 2000), there is often the possibility of multiple sample ages being found in any of these exposures, but this issue is not a factor in the present discussion of the coral results. Corals (genera *Astrangia* and *Septastrea*) are relatively common at all sites, often attached to mollusk shells or other clasts. Articulated bivalves (mostly *Mercenaria*) in life position are found at all these sites, suggesting that there has not been extensive transport of fossil material. At BP the coral samples are abundant in a fine-grained deposit, mostly attached to in situ oysters (*Crassostrea*), also implying that the corals have not been transported. The J site contains a mixture of *Crassostrea* and *Mercenaria*, with corals attached to shells of both genera. The M corals used in this study were collected from sorted spoil material at the site; they were selected for preliminary testing of sample preparation procedures because of the unusual abundance of coral material from this site. Additional descriptions of most of these sites can be found in Kaufman et al. (1996), who studied the U-series geochemistry of Pleistocene mollusks from the region.

3. Analytical methods

Because previous alpha-spectrometric results required relatively large (usually greater than 3 gm) coral samples, many of the early analyses were conducted on whole-coral samples that were not cleaned extensively by mechanical or chemical methods prior to analysis (Szabo, 1985; Szabo, personal communication, 1992). These methods raised the potential for contamination by detrital minerals, and wide age ranges and/or relatively low $^{230}Th/^{232}Th$ activity ratios (a measure of detrital contamination) were apparent in many of the analyses (Cronin et al., 1981; Mixon et al., 1982; Szabo, 1985). In the present study, available TIMS and ICP-MS technology permits analysis of much smaller samples, usually less than 400 mg. Consequently, one of the major efforts in sample preparation involved reduction of the coral sample to only the most robust and visibly "clean" polyp walls. This reduction was accomplished with the use of carbide or diamond-tipped dental burrs (<1 mm diameter). Coral fragments were viewed under a binocular microscope and all discolored, chalky or porous carbonate material was removed by slow abrasion while keeping the coral fragments immersed in distilled water. At the end of this process,

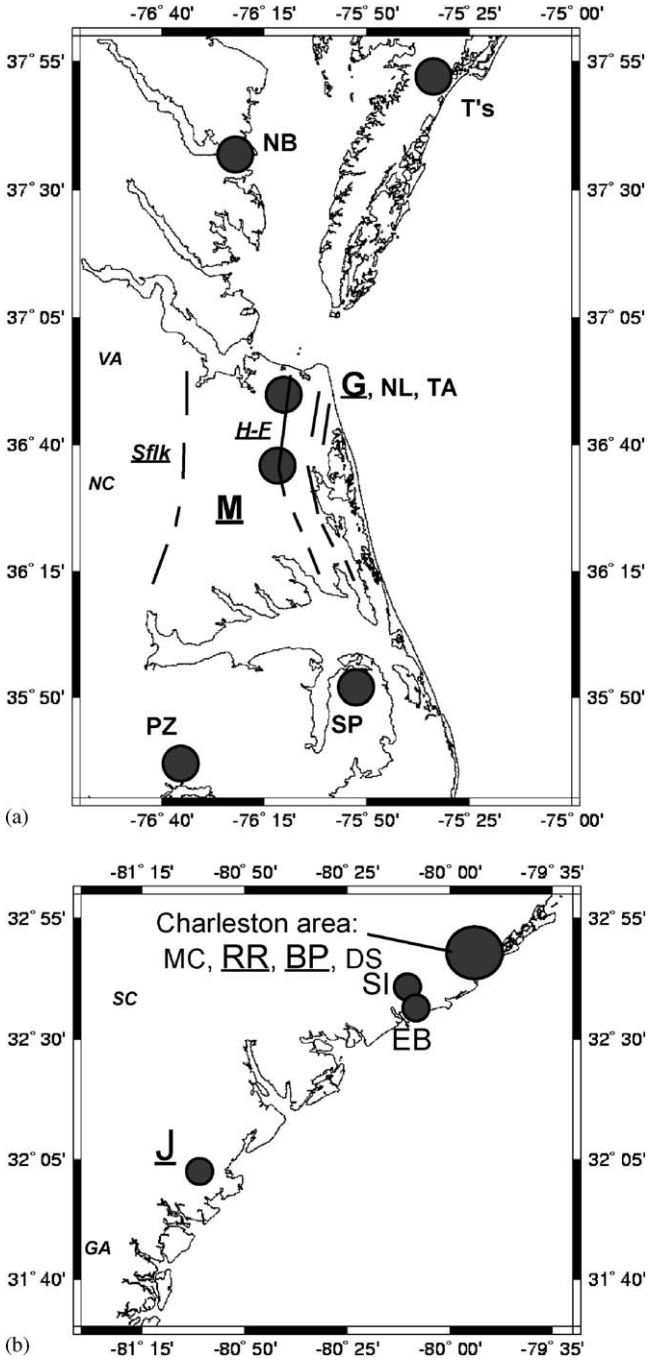

Fig. 2. (a) Details of southeastern Virginia; see Cronin et al. (1981), Mixon et al. (1982), Szabo (1985), and Wehmiller et al. (1988). Approximate positions of shoreline features (scarps) as mapped by Oaks et al. (1974): H–F = Hickory–Fentress scarp; Sflk = Suffolk Scarp. Site abbreviations: T's = T's corner, Virginia; NB = Norris Bridge, Virginia; G, NL, TA = Gomez Pit, New Light, and Toy Avenue, Virginia Beach, Virginia; M = Moyock, North Carolina; SP = Stetson Pit, North Carolina; PZ = Ponzer, North Carolina. Underlined symbols (G, M) identify sites from which samples analyzed here have been collected. (b) Details of South Carolina and Georgia locations; see Cronin et al. (1981), Szabo (1985), Wehmiller et al. (1988), Hulbert and Pratt (1998) and York et al. (2001). Site abbreviations: EB = Edisto Beach; MC = Mark Clark; RR = Rifle Range; BP = Berkeley Pit; DS = Detyens Shipyard; SI = Scanawah Island; J = Jones Pit, Skidaway Island. Underlined symbols (BP, RR, J) identify sites from which samples analyzed here have been collected.

several dozen fragments of coral polyp wall (most weighing <25 mg) were produced, each with no visible porosity, discoloration, or adhering detritus. Each sample required a minimum of 3 h of processing in order to obtain enough material for TIMS analysis. In a few cases, corals selected for processing failed to yield enough suitable material. Calcite-aragonite determinations were made on selected grains of each coral prepared in this manner. In all cases, calcite above detection limit (approximately 1.5%) was not observed. In the initial phases of this work, the $^{230}Th/^{238}U$ TIMS analyses were performed at the US Geological Survey in Denver, Colorado using samples collected between 1989 and 1995 and analytical methods described by Ludwig et al. (1992). Later in the course of this study, with the advent of techniques for TIMS $^{231}Pa/^{238}U$ geochronology (Edwards et al., 1997), a second sample from the J site was analyzed by TIMS techniques at the University of Minnesota lab for both $^{230}Th/^{238}U$ and $^{231}Pa/^{238}U$. TIMS $^{230}Th/^{238}U$ techniques at both laboratories are modifications of those of Edwards et al. (1987), with specifics of the US Geological Survey methods given in Ludwig et al. (1992) and specifics of the University of Minnesota methods given in Cheng et al. (2000). The TIMS $^{231}Pa/^{238}U$ techniques are given in Edwards et al. (1997) and Shen et al. (2003).

Additional G samples (JW99-59 in Table 2), collected in June 1999 from a freshly excavated exposure, were used to examine intra-sample variability using a less aggressive cleaning procedure than the mechanical disaggregation described above. Samples JW99-59-J-1 (1, 2, 3) and JW99-59-J-2 (1, 2, 3) (Group Ga in Table 2) were subsampled on the outer portions of the coral, after removing the fine septa and encrusting detritus within the coral polyps. Cleaned samples were immersed in distilled water and subjected to ultrasonic cleaning for 20 min, after which the densest (least chalky) fragments were selected for analysis. Samples 99-59-J-1 (11, 12) and 99-59-J-2 (11, 12), along with samples 99-59-J-3 (11, 12) (Group Gb in Table 2) were taken from deeper within the coral polyps and sonicated for 30 min prior to selection of fragments for analysis. These samples were analyzed for $^{230}Th/^{238}U$ using ICP-MS techniques (Shen et al., 2002).

4. Results

The results of the TIMS and ICP-MS analyses from both laboratories are presented in Table 2. Ages have been calculated using the half lives reported in Cheng et al. (2000). Information is given for uranium content, ^{232}Th (as an indicator of initial ^{230}Th and ^{231}Pa), $^{230}Th/^{238}U$ and/or $^{231}Pa/^{235}U$ ages, and initial $^{234}U/^{238}U$ (derived from the measured $^{234}U/^{238}U$ and the $^{230}Th/^{238}U$ age). Corrected ages are calculated by

subtracting a component of the sample's ^{230}Th calculated from the measured ^{232}Th content of the sample. The uranium in this component is calculated assuming a $^{232}Th/^{238}U$ ratio equivalent to the bulk earth value of 3.8. The ^{234}U, ^{230}Th, and ^{231}Pa contents of this component are calculated assuming that these nuclides are in secular equilibrium with their uranium parents. The calculated $^{230}Th/^{232}Th$ atomic ratio of this component is $4.4 \pm 2.2 \times 10^{-6}$ and the calculated $^{231}Pa/^{232}Th$ atomic ratio is $8.88 \pm 4.44 \times 10^{-8}$. Errors on these ratios are arbitrarily assumed to be 50%. Corrections using this component are insignificant for all samples except for 95-61c1 and 95-61c2, both from the J. These are the samples upon which $^{231}Pa/^{235}U$ analyses were performed. As larger samples sizes were required for the Pa analyses, contaminant levels were somewhat higher (see ^{232}Th concentrations for these samples as compared with the others in Table 2). However, even for the J samples, with the highest ^{232}Th levels of any in this study, the corrections only amount to about 1.5 ka for the ^{231}Pa ages and 3 ka for the ^{230}Th ages. Thus, these corrections are small, on the order of analytical error, and much smaller than the difference in age between marine oxygen isotope sub-stages.

The $^{230}Th/^{238}U$, $^{231}Pa/^{235}U$, and $^{231}Pa/^{230}Th$ ages of the J samples are all concordant within errors, with ages ranging between 82 and 92 ka BP (Table 2, 82–87 ka BP range if the ^{231}Pa age with the largest error is ignored). These observations, along with the observation that the J samples all have marine uranium isotopic composition (discussed below) suggest that the ages of these samples are accurate and are consistent with an MIS 5a correlation.

5. Discussion

5.1. Ages and isotopic systematics

Following earlier discussions of the ACP U-series geochronology, we will show that the mass spectrometric coral ages presented here are quite likely "late stage 5" (~80 ka BP) in age, confirming the original alpha-spectrometric late stage 5 age assignments for sites in the region (Szabo, 1985). The relatively large range (up to 12 kyr) of $^{230}Th/^{238}U$ ages seen in some of the analyses from the RR and BP sites may be the result of instrumental problems that resulted in relatively high errors. These problems were eliminated during the latter stages of the analyses. There is internal consistency between the two laboratories, and the range of mass spectrometric results (from 64 ka to 87 ka BP) matches the range seen in earlier studies (Szabo, 1985). However, this range is too large to be consistent with the general range of "late stage 5" (~76–84 ka BP: Gallup et al., 1994; Shackleton, 2000; Cutler et al., 2003) unless diagenetic factors are invoked.

Some insight into a possible diagenetic overprint on the results is gained from Fig. 3, which shows that initial $^{234}U/^{238}U$ values are lower for those samples with the younger apparent ages, and that many of these initial $^{234}U/^{238}U$ activity ratios are too low to be consistent with modern seawater analyses (modern corals give a modern marine $^{234}U/^{238}U$ activity ratio of 1.1458 ± 0.0019: Cheng et al., 2000). The samples with the lowest $^{234}U/^{238}U$ activity ratio are generally those from G that were subjected to the least aggressive mechanical cleaning (the Ga sample series, Table 2). This positive correlation between initial $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ age has been observed in reef-building corals at a number of localities worldwide and has been most extensively studied in Barbados (Bender et al., 1979; Gallup et al., 1994; Thompson et al., 2003). It is likely that this broad relationship is due to mobility of both ^{230}Th and ^{234}U coupled with dissolution/reprecipitation of coralline aragonite (Gallup et al., 1994), with the proportions of these nuclides influenced by recoil phenomena (Thompson et al., 2003). Of interest in this regard is the slope of our $^{234}U/^{238}U$–$^{230}Th/^{238}U$ age trend, which is four times lower than the slope for comparable-age reef-building corals from Barbados. Much of the Barbados trend can be explained by recoil phenomena (Thompson et al., 2003). The difference in slope indicates that the ACP trend must involve additional processes beyond recoil-related phenomena. Kaufman et al. (1996), in their study of [U] and $^{234}U/^{238}U$ of mollusks from several of these sites, noted $^{234}U/^{238}U$ values (even in the same mollusk) that were both greater and less than modern seawater values, suggesting a variety of possible paths for either uranium gain or loss. Without specific knowledge of the processes responsible for the trend, we follow earlier workers and consider those samples with initial $^{234}U/^{238}U$ values closest to the marine value to be the ones that are least altered. Inspection of the trend and the individual data points in Fig. 3 shows that the ages of the samples that record marine uranium isotopic composition lie broadly in the range of 80–85 ka BP. Included among the samples that record marine uranium isotopic compositions are the J samples, which also record concordant $^{230}Th/^{238}U$, $^{231}Pa/^{235}U$, and $^{231}Pa/^{230}Th$ ages (see above), supporting the accuracy of this age assignment.

5.2. The elevation of ~80 ka BP deposits on the US ACP

The U-series coral ages presented here reinforce a continuing conflict between the ACP Quaternary record and eustatic sea levels derived from either marine isotopic data, uplifted tropical coral reef sequences, or carbonate island submerged speleothem records (Bloom et al., 1974; Shackleton, 1987; Bard et al.,

Table 2
ACP corals: U and Th concentrations, isotopic activity ratios, and U-series ages

Locality and sample name	Genus	U ppm (+/−)	^{232}Th ppb (+/−)	^{234}U/^{238} U AR corr(+/−)	^{230Th}/^{238}U AR corr (+/−)	^{230}Th/^{232}Th atomic $\times 10^{-6}$	^{230}Th/^{238}U Age (ka) (+/−)	^{234}U/^{238}U init AR (+/−)	^{231}Pa/^{238}U Age (ka) (+/−)
Gomez Pit VA Gu[a]									
JW 89-118	*Astrangia*	2.139 (0.002)	8.4 (0.1)	1.1155 (0.0021)	0.5544 (0.0041)	2300	73.9 (0.80)	1.1424 (0.0026)	nd
JW 89-117	*Septastrea*	2.315 (0.003)	21.1 (0.3)	1.1165 (0.0021)	0.5476 (0.0067)	982	72.6 (1.30)	1.143 (0.0026)	nd
JW 89-124B	*Septastrea*	1.935 (0.003)	14 (0.9)	1.1139 (0.0028)	0.562 (0.0356)	1262	75.6 (6.80)	1.141 (0.0043)	nd
Ga[a]									
JW99-59 J-1-1	*Astrangia*	2.953 (0.005)	25.2 (0.1)	1.1072 (0.0024)	0.4958 (0.0032)	844	63.9 (0.70)	1.1287 (0.0045)	nd
JW99-59 J-1-2	*Astrangia*	2.505 (0.005)	23.1 (0.1)	1.1098 (0.0026)	0.5067 (0.0039)	902	65.6 (0.80)	1.1325 (0.0050)	nd
JW99-59 J-1-3	*Astrangia*	2.66 (0.005)	23.6 (0.1)	1.1096 (0.0028)	0.5146 (0.0033)	950	67 (0.70)	1.1328 (0.0051)	nd
JW99-59 J-2-1	*Astrangia*	2.634 (0.005)	23.9 (0.1)	1.1134 (0.0023)	0.5288 (0.0032)	964	69.2 (0.70)	1.1382 (0.0046)	nd
JW99-59 J-2-2	*Astrangia*	2.634 (0.007)	51.8 (0.5)	1.1097 (0.0030)	0.5437 (0.0071)	456	72 (1.50)	1.1352 (0.0061)	nd
JW99-59 J-2-3	*Astrangia*	2.614 (0.006)	24.4 (0.1	1.108 (0.0036)	0.5282 (0.0036)	933	69.6 (0.90)	1.1318 (0.0063)	nd
Gb[a]									
JW99-59 J-1-11	*Astrangia*	2.632 (0.008)	19.3 (0.2)	1.1157 (0.0044)	0.5487 (0.0058)	1232	72.7 (1.30)	1.1424 (0.0080)	nd
JW99-59 J-1-12	*Astrangia*	2.818 (0.01)	21.7 (0.2)	1.1121 (0.0042)	0.552 (0.0051)	1186	73.6 (1.20)	1.1383 (0.0084)	nd
JW99-59 J-2-11	*Astrangia*	2.881 (0.008)	27.2 (0.3)	1.1125 (0.0037)	0.5608 (0.0061)	981	75.2 (1.30)	1.1395 (0.0070)	nd
JW99-59 J-2-12	*Astrangia*	2.784 (0.008)	28.9 (0.2)	1.111 (0.0040)	0.5559 (0.0047)	886	74.4 (1.10)	1.1374 (0.0075)	nd
JW99-59 J-3-11	*Astrangia*	2.9 (0.01)	115.5 (0.4)	1.1135 (0.0030)	0.4956 (0.0036)	205	62.5 (1.20)	1.1369 (0.0059)	nd
JW99-59 J-3-12	*Astrangia*	3.064 (0.009)	100.8 (0.5)	1.1099 (0.0037)	0.5003 (0.0046)	251	63.8 (1.20)	1.1328 (0.0070)	nd
Moyock NC Mu[a]									
JW92-48b	*Septastrea*	2.483 (0.003)	44.6 (0.3)	1.1203 (0.0020)	0.5775 (0.0040)	526	77.8 (0.8)	1.1499 (0.0024)	nd
Berkeley Pit SC Bpu[a]									
JW 91-175	*Septastrea*	3.468 (0.004)	41.4 (4)	1.1102 (0.0024)	0.5986 (0.0588)	821	83.2 (12.1)	1.1394 (0.0056)	nd
JW 91-187	*Septastrea*	2.329 (0.003)	7.6 (0.5)	1.1135 (0.0019)	0.5982 (0.0409)	2981	82.7 (8.3)	1.1434 (0.0041)	nd
JW 91-186	*Septastrea*	2.715 (0.003)	23 (0.3)	1.1098 (0.0019)	0.5833 (0.0078)	1122	80.2 (1.6)	1.1377 (0.0024)	nd
Rifle Range Pit SC RRu[a]									
JW91-52	*Astrangia*	2.128 (0.002)	18.1 (1.6)	1.1101 (0.0035)	0.5594 (0.0509)	1074	75.5 (9.8)	1.1363 (0.0056)	nd
JW91-54	*Astrangia*	2.179 (0.003)	104.6 (8.6)	1.1129 (0.0026)	0.6126 (0.0514)	209	85.8 (10.8)	1.1439 (0.0054)	nd

Table 2 (*continued*)

Locality and sample name	Genus	U ppm (+/−)	^{232}Th ppb (+/−)	^{234}U/^{238} U AR corr(+/−)	^{230Th}/^{238}U AR corr (+/−)	^{230}Th/^{232}Th atomic $\times 10^{-6}$	^{230}Th/^{238}U Age (ka) (+/−)	^{234}U/^{238}U init AR (+/−)	^{231}Pa/^{238}U Age (ka) (+/−)
Jones Pit GA									
Ju[a]									
96-061-bu	*Septastrea*	2.211 (0.003)	15 (0.2)	1.119 (0.0017)	0.6112 (0.0033)	1439	84.7 (0.70)	1.1512 (0.0021)	nd
96-061-a	*Septastrea*	2.55 (0.003)	21 (0.1)	1.1152 (0.0019)	0.5986 (0.0052)	1193	82.6 (1.10)	1.1455 (0.0024)	nd
Jm[a]									
95-61c1(I)	*Septastrea*	2.983 (0.006)	426.9 (8.6)	1.1169 (0.0045)	0.6229 (0.0051)	725	83.8 (4.3)	1.1541 (0.0077)	86.2 (6.7)
95-61c1(II)	*Septastrea*	2.964 (0.003)	334 (8.3)	1.1157 (0.002)	0.6178 (0.0029)	918	83.7 (3.3)	1.1512 (0.0054)	84.3 (5.4)
95-61c2	*Septastrea*	3.149 (0.003)	516.9 (6.5)	1.1166 (0.0012)	0.617 (0.0039)	628	82.1 (4.7)	1.1538 (0.0033)	92 (11.0)

AR = activity ratio; initial AR calculated from ^{230}Th/U age.

The Gomez Pit Ga group represents two separate corals, each split into three subsamples (J-1-1, J-1-2, etc.) from the outer portion of the coral. The Gomez Pit Gb group represents three corals (including the two in Ga), each subsampled twice in the deeper portions of the coral. See text for further discussion.

[a] Abbreviations are those used for data plotted in Fig. 3; all those ending with "u" were analyzed at USGS Denver, others analyzed at University of Minnesota.

1990; Lundberg and Ford, 1994; Gallup et al., 1994; Chappell et al., 1996; Ludwig et al., 1996; Toscano and Lundberg, 1999; Lambeck and Chappell, 2001; Cutler et al., 2003). However, similar late stage 5 ages have been obtained for corals presently above sea level in Bermuda, an oceanic island that is interpreted to have had little or no vertical motion during the late Quaternary (Harmon et al., 1983; Ludwig et al., 1996; Muhs et al., 2002b). Only by invoking uplift of at least 10–15 m can the nearly uniform (0–~ +6 m) elevation of these ~80 ka BP units in Virginia, South Carolina, and Georgia be reconciled with the record inferred from uplifted coral terraces. This conflict requires continuing discussion of the geochemistry, stratigraphy, geomorphology and tectonics of the region. It is clear that the US ACP preserves an unusual record of late Pleistocene sea levels, although both the Bermuda record and that of the southern Australian margin Murray-Wallace (2002) raises similar questions about the elevation of late stage 5 shorelines, as do dated records from clastic terraces on the Pacific coast of the US (Muhs et al., 1994, 2002a) and even some interpretations of the New Guinea terrace sequence (Bloom and Yonekura, 1985).

One approach to the question of the present elevation of the units discussed here is to compare these ages with any ~125 ka BP (early stage 5 or substage 5e) coral ages that are available. Presently no TIMS ages in the substage 5e range have been obtained from sites on the US ACP, but Szabo (1985) presented two such alpha-spectrometric ages for sites near Charleston, South Carolina (sites DS and MC, Fig. 2b). Assuming that these alpha-spectrometric ages are correct, we note that the elevations of the early stage 5 units are within 3 m of the late stage 5 units in the Charleston region. Therefore, any monotonic uplift mechanism invoked as an explanation for the elevation of the late stage 5 units would be expected to resolve the 5e and 5a records geomorphically much more than presently observed. It appears that early and late stage 5 units are preserved at very similar elevations, at least in South Carolina (no early stage 5 coral U-series ages are available from the North Carolina or Virginia sites). Additional coral ages between 80 and 130 ka BP for localities near Myrtle Beach, South Carolina (Fig. 1) are problematic because of sample quality and/or stratigraphic ambiguity, but nevertheless reinforce the conclusion that early and late stage 5 coral ages are observed at comparable elevations (Szabo, 1985; Hollin and Hearty, 1990). Similarly, all the other reliable[3] alpha spectrometry ages (two ~200 ka BP ages from North Carolina, one from South Carolina) (Szabo, 1985) also occur within units that are no more than 8 m above present sea level. The low elevation of these <250 ka BP Pleistocene units is

[3] A single ~130 kyr alpha-spectrometric coral age from the Intracoastal Waterway in Myrtle Beach SC was rejected by Szabo (1985); a ~200 ka alpha-spectrometric coral age from Norris Bridge VA is also considered inaccurate (B.J. Szabo, personal communication, 1992).

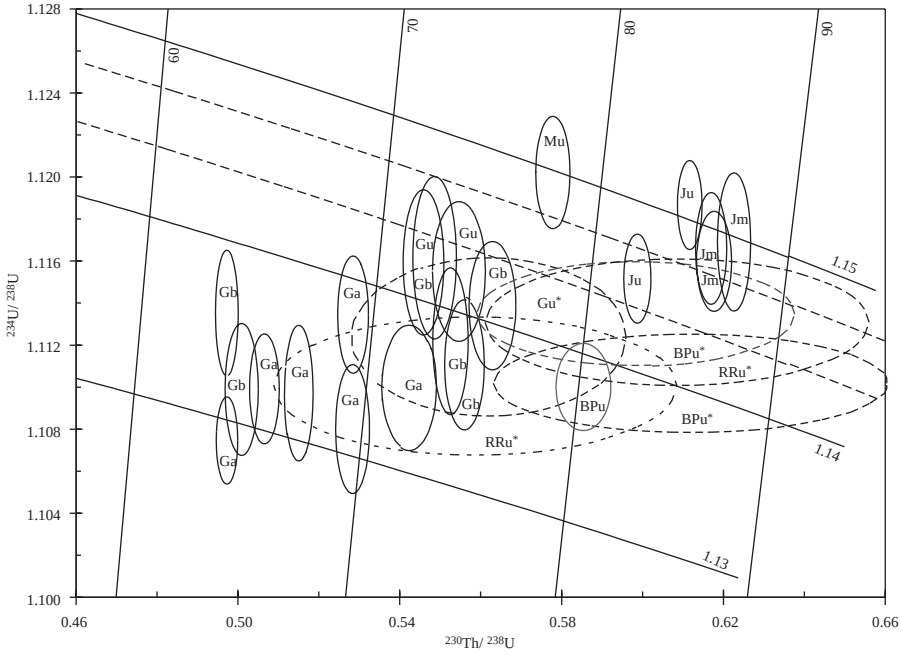

Fig. 3. $^{234}U/^{238}U$ vs. $^{230}Th/^{238}U$ values (corrected for initial Th) and ^{230}Th age for all analyses reported in Table 2. Isotope ratio evolution curves for initial $^{234}U/^{238}U$ values of 1.13, 1.14, and 1.15 are shown, as well as an envelope (dashed lines) representing the analysis of modern seawater (1.1458 ± 0.0019: Cheng et al., 2000). Plotted uncertainties are the 2 sigma ranges as reported in Table 2. Abbreviations as in Fig. 2, modified as follows: Gu = Gomez Pit USGS analyses; Ga and Gb = Gomez Pit Minnesota analyses with differing sample cleaning steps (grouped in Table 2 and discussed in text)); Mu = Moyock, BPu = Berkeley Pit and RRu = Rifle Range Pit, all USGS analyses; Ju = Jones Pit, USGS analyses; Jm = Jones Pit, Minnesota analyses. Analyses marked with asterisk (*) and portrayed with dashed ellipses have large uncertainties—most represent analyses done early in the course of this work when instrumental difficulties had not yet been minimized.

difficult to explain if uplift has affected the younger units that yield the ~80 ka BP TIMS ages.

Muhs et al. (2002b) reported numerous U-series TIMS coral ages for sites in Bermuda (Fig. 1), including the controversial site (ca. +1 m) at Fort St. Catherine, at the eastern end of Bermuda. These new results for the Fort St. Catherine site cluster tightly around 80 ka BP, while at Grape Bay (Bermuda), samples at +1 to +4 m date to ~120 ka BP. Consequently, it appears that the Bermuda record is comparable to that of the ACP in that both have deposits ranging from ~125 ka to ~80 ka BP (early to late stage 5) at very similar elevations, slightly above present sea level. Because of contrasting responses to possible hydroisostatic deformation between the oceanic island (Bermuda) and the broad continental shelf (ACP), the similarity in elevations of stage 5 records in Bermuda and the ACP must represent a large-scale regional signal rather than being a local record. Only at more southerly latitudes, near the southern end of the Florida peninsula and in the Bahamas (Fig. 1) do the substage 5e and 5a records appear to have significantly different elevations (10 m or more), based on a combination of data from emerged coral reefs and either submerged reefs or speleothems (Chen et al., 1991; Lundberg and Ford, 1994; Richards et al., 1994; Ludwig et al., 1996; Toscano and Lundberg, 1999).

The apparent trend of increasing separation of elevations of the early and late stage 5 (125 ka to 80 ka BP) shoreline records from north to south (specifically, Virginia to Florida—see Fig. 1) appears to be a unique feature of the western North Atlantic region. We interpret this record to be an as yet unexplained "near-to intermediate-field" effect of the Laurentide Ice Sheet (Fig. 1), which would have produced forebulge growth and collapse during stages 6 and 5, just as during stages 2 and 1 as recorded in Holocene sea level rise rates for the ACP (e.g., Peltier, 1999). It is beyond the scope of this paper to propose any model for the complex isostatic adjustment history of the ACP through multiple glacial–interglacial cycles, but attempts are underway to understand this phenomenon (Potter et al., 2002; Potter and Lambeck, 2004), which has most likely been modulated by hydroisostatic effects on the broad continental shelf of eastern North America (e.g., Cronin et al., 1981). Various studies of coastal units (with less precise age control) between 38°N and 40°N (Toscano and York, 1992; Toscano, 1992; Sheridan et al., 2000; O'Neal and McGeary, 2002; O'Neal and Dunn, 2003) also support the conclusion that the age/elevation relation for western North Atlantic late Quaternary shorelines is not the same as that seen in stable or uplifted records in far-field regions such as New Guinea or Barbados.

5.3. Stratigraphic implications—the nature of the stage 5 coastal record on the ACP

The stratigraphic record of Quaternary coastal deposits preserved on the US ACP is complex, with a variety of erosional and depositional features produced through multiple glacial sea-level cycles on a passive continental margin with a limited sediment supply. The emergent portion of the ACP Quaternary marine record is mostly below 30 m elevation, and deposits of the upper middle and upper Pleistocene are generally below ~15 m and typically less than 10 m thick (see reviews by Colquhoun et al., 1991; Muhs et al., 2004). In many cases, only the final regressive phase of a transgressive cycle is reasonably well preserved, as earlier highstand deposits were overtopped or eroded. Removal of pre-existing units is particularly common across the Cape Fear Arch south of the Albemarle Embayment in North Carolina, as evidenced by condensed stratigraphic sections (Pilkey et al., 1981; Riggs and Belknap, 1988; Riggs et al., 1992, 1995) and the presence of reworked Pleistocene mollusks on modern beaches (Wehmiller et al., 1995). Consequently, because of incomplete preservation on the ACP, landforms and associated stratigraphic units representing Pleistocene highstands may be difficult to correlate with specific ice-volume minima.

From the distribution of U-series ages, it appears that the stratigraphic record of isotope stage 5 sea levels is dominated by those units representing the last of the three transgressive phases (substage 5a), rather than the earliest phase (substage 5e) that would be predicted based on elevation alone. For example, in southeastern Virginia, the shoreline and barrier-island complex associated with the G and M sites, the Hickory–Fentress ridge of Oaks et al. (1974), is the most prominent shoreline feature of the outer Coastal Plain (Fig. 2a). In part because of the +7.5 m elevation of the top of the barrier deposits (an indicator of contemporaneous sea level), this allostratigraphic unit has been considered the most likely candidate for the substage 5e highstand. This interpretation is supported by the existence of three additional pre-Holocene shoreline ridge complexes that lie seaward of the Hickory–Fentress ridge (Oaks et al., 1974). However, if the Hickory–Fentress shoreline is indeed ~80 ka BP or slightly younger, as required by the U-series data, these younger shoreline features must represent deposition over ~5 kyr during post-80 ka BP regression before a rapid drop in relative sea level (Cutler et al., 2003). Older upper Pleistocene units are recognized in southeastern Virginia and the Virginia Eastern Shore based on geomorphic, stratigraphic, and racemization data (Mixon, 1985; Mixon et al., 1989), but none has been identified as ~125 ka BP based on U-series analysis.

South of Charleston, South Carolina (Fig. 2b), a series of five to seven upper Pleistocene shorelines can be arranged into groups of barriers (oldest to youngest) with elevations of 7.3–6.1 m, 4.9–3.6 m, and 4.5–3.0 m and 3.0–0.0 m (Winker and Howard, 1977; Colquhoun et al., 1991; Harris, 2000). Geomorphic, allostratigraphic, and aminostratigraphic evaluation of these shoreline features suggests that the units at BP and RR pit, north of Charleston Harbor, are correlative with all but the oldest of these barriers, although the record north of Charleston Harbor is condensed and individual highstand events are less well resolved (Weems and Lemon, 1993). Additional racemization results for a site near Edisto Beach, South Carolina (Fig. 2b) (York et al., 2001), compared with paired racemization and U-series data for Scanawah Island, South Carolina (Fig. 2b) further imply that shoreline features younger than 80 ka BP are preserved above present sea level, just as in southeastern Virginia.

The pattern of preservation for these representative sections of the ACP is that the surficial units for much of the outer Coastal Plain, with elevations from +7.5 down to 0 m, comprise a series of regressive shorelines deposited during substage 5a. Substage 5e highstand deposits have minimal preservation as erosional remnants at +7 to +8 m, except where sediment supply was sufficient to create a barrier island or spit and shoal complex. Substage 5c deposits, if preserved, have subtle surface and subsurface records. The apparent occurrence of early and late stage 5 units and/or landforms at nearly identical emergent elevations, with coral ages from substage 5a being far more abundant than those from substage 5e, requires some mechanism (such as hydroisostatic subsidence) by which the ~45 kyr of flooding of the continental margin during stage 5, coupled with forebulge collapse following MIS 6 glaciation, generated this unusual record of coastal evolution. If this model of sea-level history for the region is correct, then the relative frequency of ~80 ka BP U-series ages compared with ~125 ka BP ages should not be surprising. We note also that some paleoenvironmental interpretations of sites in the region (Cronin et al., 1981; York et al., 1989) have implications for this model. In contrast to several Pacific coast records, where faunal records of warm and cool water correspond with early and late stage 5 age estimates, respectively (Muhs et al., 2002a), records from central South Carolina are interpreted as "subtropical" (warmer than present) throughout the interval dated between ~125 ka and ~75 ka BP (Cronin et al., 1981). Although this record could be explained by a stable Gulf Stream influence on the region throughout MIS 5, mixing of early stage 5 (warm) fossils into the later stage 5 units could also result in a similar paleoclimatic interpretation.

6. Summary and conclusions

The TIMS and ICP-MS coral ages presented here confirm the original alpha-spectrometric ~80 ka BP coral ages obtained by Cronin et al. (1981), Mixon et al. (1982), and Szabo (1985), although there is evidence for open system alteration of at least some of the newly analyzed corals. Nevertheless, concordant $^{230}Th/^{238}U$, $^{231}Pa/^{235}U$, and $^{231}Pa/^{230}Th$ ages and marine initial $^{234}U/^{238}U$ values for a number of samples support the general conclusion that these ~80 ka BP ages are indeed accurate, in spite of years of speculation about their consistency with eustatic sea level records. Although most of the ~80 ka BP corals were not attached to any substrate when collected, a few of these corals were very definitely in place, hence their current position or elevation cannot be explained as the result of storm transport.

The vast majority of the "stage 5" U-series dates for emergent units of the ACP, either previous or new, fall in the ~80 ka BP range, rather than in the ~125 ka BP range that would be expected based on the elevation of the deposits and comparisons with eustatic sea level models derived from the Barbados and New Guinea coral terrace records. The similarity in elevation of units containing ~80 ka BP and ~125 ka BP corals suggests that the most recent transgression could have removed some or all of the record of early stage 5 (or older units) in selected areas.

Emergent ~80 ka BP deposits are also found in Bermuda, at elevations virtually identical to those for ~125 ka BP deposits (Muhs et al., 2002b). The similarity of the Bermuda and ACP records (those north of Florida) suggests a large-scale regional effect on these sea level records, explained by the multiple cycles of submergence, emergence, and forebulge growth and collapse over the past ~150 ka or more. If this hypothesis is correct, then it is not necessary for the sea level records of Bermuda or the ACP to have the same age-elevation relation as seen in other stage 5 deposits from far-field regions.

Amino acid racemization data from the ACP, particularly from sites near Charleston, South Carolina, have been cited as evidence against the accuracy of the original alpha-spectrometric ~80 ka BP coral ages (Wehmiller and Belknap, 1982; Wehmiller et al., 1988). The new mass spectrometric coral ages clearly support the accuracy of the original analyses, requiring reevaluation of the models used to interpolate racemization data between widely separated calibration sites (e.g., Wehmiller, 1997; Muhs et al., 2004). That ongoing evaluation will offer a combination of diagenetic and stratigraphic factors to explain some of the inconsistencies between racemization models and U-series results.

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