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1996

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K. R. Ludwig
U.S. Geological Survey

D. R. Muhs
U.S. Geological Survey, dmuhs@usgs.gov

K. R. Simmons
U.S. Geological Survey, ksimmons@usgs.gov

R. B. Halley
U.S. Geological Survey

E. A. Shinn
U.S. Geological Survey

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K. R. Ludwig*
D. R. Muhs — U.S. Geological Survey, MS 963, Box 25046, Federal Center, Denver, Colorado 80225
K. R. Simmons
R. B. Halley — U.S. Geological Survey, Center for Coastal Geology, 600 4th Street South, St. Petersburg, Florida 33701
E. A. Shinn

ABSTRACT

Studies from tectonically active coasts on New Guinea and Barbados have suggested that sea level at ~80 ka was significantly lower than present, whereas data from the Atlantic and Pacific coasts of North America indicate an ~80 ka sea level close to that of the present. We determined ages of corals from a shallow submerged reef off the Florida Keys and an emergent marine deposit on Bermuda. Both localities are on tectonically stable platforms distant from plate boundaries. Uranium-series ages show that corals at both localities grew during the ~80 ka sea-level highstand, and geologic data show that sea level at that time was no lower than 7–9 m below present (Florida) and may have been 1–2 m above present (Bermuda). The ice-volume discrepancy of the 80 ka sea-level estimates is greater than the volume of the Greenland or West Antarctic ice sheets. Comparison of our ages with high-latitude insolation values indicates that the sea-level stand near the present at ~80 ka could have been orbitally forced.

INTRODUCTION

The last interglacial period in its broadest sense has been correlated with all of deep-sea oxygen isotope stage 5 (~130–80 ka). Three $\delta^{18}O$ minima during stage 5 are generally inferred as reflecting sea-level highstands at ~125 ka, ~105 ka, and ~80 ka, and are commonly correlated with emergent coral reefs of these ages found on tectonically rising coastlines. Though considerable attention has been given to the oldest, and apparently highest, sea-level stand (~125 ka), much less study has been made of the younger two. Assuming constant uplift rates, studies on tropical island coasts such as New Guinea calculated that sea level at ~80 ka could have been as high as −6.6 m (Bloom and Yonekura, 1985, 1990) or as low as −19 ± 5 m (Chappell and Shackleton, 1986, Table 1) relative to present sea level (Fig. 1). On the basis of data from tectonically rising Barbados, sea-level estimates for ~80 ka vary from −10 m to −18 m (Bender et al., 1979; Gallup et al., 1994). In the tectonically stable Bahamas, U-series dating of submerged speleothems suggests that at ~80 ka, sea level was below −15 m (Lundberg and Ford, 1994) or below −18 m (Richards et al., 1994). A recent study of deep-sea sediments, using Mg/Ca in ostracodes combined with oxygen isotopes in foraminifera, suggests that sea level at ~80 ka could even have been as low as −60 m to −70 m (Dwyer et al., 1995). However, data from the tectonically active Pacific coast of North America suggest that sea level at ~80 ka could have been closer to the present, perhaps around −1 m (Muhs et al., 1994). In addition, in tectonically stable Virginia and North Carolina, several corals from the Norfolk and Kempsville Formations (or their equivalents), at elevations of −4 to +5 m, give AS (alpha-spectrometric) ages ranging from 78 ± 10 ka to 66 ± 8 ka (all errors 2σ)

and average about 72 ka (Szabo, 1985). These formations may therefore correlate with the ~80 ka sea-level highstand and, if so, imply a sea level near the present level at that time. Thus there is not a consensus on the position of sea level at 80 ka even among the various coastal records, and the ostracode Mg/Ca study implies a vastly different (landbound) ice volume.

Summer insolation values at high latitudes are considered to be critical for the growth and decay of ice sheets according to the orbital forcing theory of climate change (Milankovitch, 1941). The rise toward the 11 ka insolation high is considered to have been the trigger for the decay of the late Wisconsin ice sheets at the close of the last glaciation (Mix, 1987; Ruddiman, 1987). At ~84 ka, June insolation at lat 60°N was actually higher than at 11 ka (Fig. 1). According to the orbital forcing theory, therefore, insolation at ~84 ka could have been sufficient to bring about ablation of glacial ice to the extent that sea level rose to the present level.
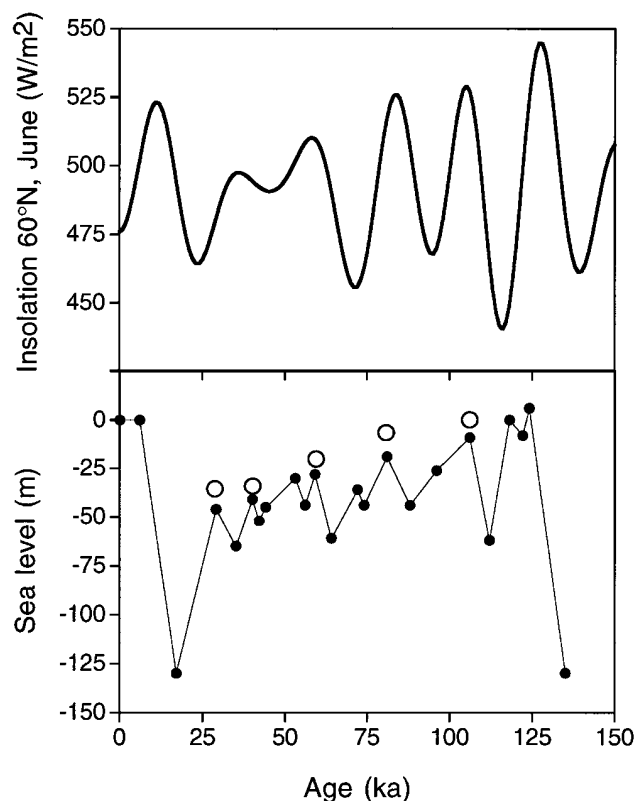

Figure 1. Comparison of insolation values for June at lat 60°N (data from Berger and Loutre, 1991) and sea-level record from coral reefs on tectonically rising New Guinea (solid circles from Chappell and Shackleton, 1986; open circles from Bloom and Yonekura, 1985, 1990).

*Present address: Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, California 94709.

Geology; March 1996; v. 24; no. 3; p. 211–214; 4 figures; 1 table.
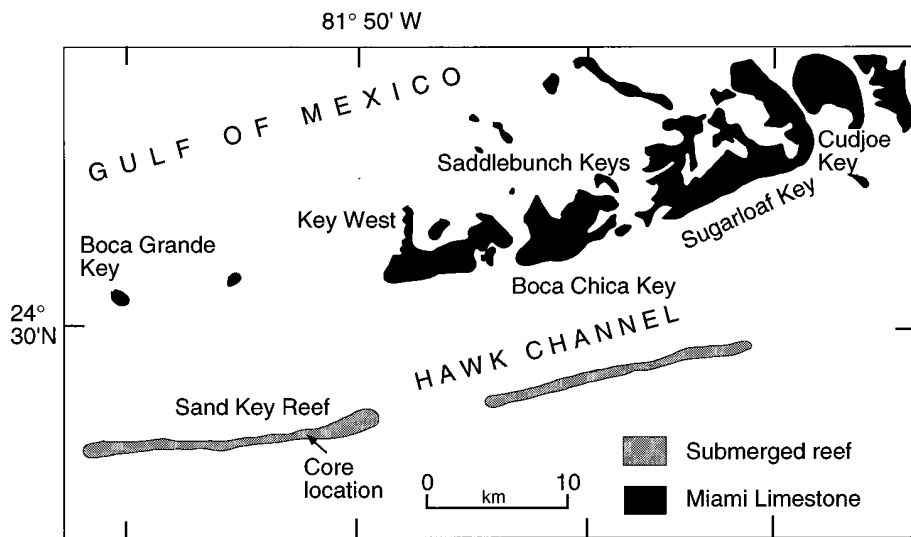
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Figure 2. Location of submerged offshore reef south of Florida Keys (black), and sample locality. Reef location data generalized from Lidz et al. (1991).

In order to investigate further the sea level at ~80 ka, we studied two localities on the tectonically stable Florida Keys and Bermuda (Figs. 2 and 3), where any sediments deposited at 80 ka, whether onshore or offshore, should be unaffected by uplift or subsidence. We report here new ^{230}Th/U ages of corals from these localities.

URANIUM-SERIES DATING

All coral samples analyzed are 95%–100% aragonite. Analyses were done by thermal ionization mass spectrometry, as described in Ludwig et al. (1992). All samples have low ^{232}Th contents, indicating negligible initial ^{230}Th (Table 1). Although Harmon et al. (1983) reported ^{234}U/^{238}U values in living corals from Bermuda that were significantly lower than values reported for modern sea water (e.g., Chen et al., 1986), analyses of two late Holocene corals (*Oculina* and *Siderastrea*) that were collected on the modern beach at Shelly Bay, Bermuda, and analyzed in duplicate (Table 1) yield initial ^{234}U/^{238}U values within 0.25% of our mean value for other young corals, and agree with modern sea water values. The same is true for a modern *Siderastrea* (FL-31) collected on the modern beach at Big Pine Key, Florida. With one exception noted below, all fossil corals we analyzed have calculated initial ^{234}U/^{238}U that are within 0.35% of values

measured for modern sea water and modern corals (Fig. 4).

FLORIDA KEYS STUDY AREA

High-resolution seismic-reflection profiles by Lidz et al. (1991) have demonstrated the presence of a submerged outlier-reef tract system extending discontinuously for ~57 km seaward of the emergent Florida Keys (Fig. 2), formed during the last interglacial. Near Sand Key Reef, ~12 km southwest of Key West, this feature has multiple, small, outlier reefs, but the main body of the reef has a topographic crest that is ~10–12 m below sea level. The reef is dominated by the colonial coral *Montastrea annularis*, although examination of a core from this reef revealed a thin overgrowth of the reef crest species *Acropora palmata*, which grows only within 5 m of sea level. Lidz et al. (1991) reported a radiocarbon age of >38 ka for a *Montastrea* sample collected from one of their cores. We determined ^{230}Th/U ages of samples of *Montastrea annularis* and *Acropora palmata* from two newly acquired cores.

Results from the submerged reef off the Florida Keys confirm the earlier >38 ka radiocarbon result of Lidz et al. (1991) and indicate that the *Montastrea* corals in this reef grew during the ~80 ka sea-level highstand (Table 1). A sample (FL-23) of this coral from a core depth of 1.2 m gives an age of 80.9 ± 1.7 ka, and a sample (FL-20) from a depth of 5.5 m in the same core gives a stratigraphically consistent age of 83.2 ± 0.9 ka. In an adjacent core, a sample of *Montastrea* (FL-33) from a core depth of 3.5 m gives an apparent age of ~87 ka, but its initial ^{234}U/^{238}U is much higher (1.1733) than modern sea water, indicating an open-system history. A sample (FL-32) of *Acropora palmata* from this latter core, taken from 0.1 m below the core top, gives an age of 8.2 ka, showing that this colony is a Holocene overgrowth on the ~80 ka coral.

BERMUDA STUDY AREA

The island of Bermuda (Fig. 3) has a core of pre-Quaternary volcanic rocks derived from the Mid-Atlantic Ridge, but its surficial deposits are Quaternary carbonates—mostly eolianite, but also consisting of isolated sublittoral marine and beach deposits and some emergent, fossil patch reefs (Vacher et al., 1989). Most of the marine facies have been mapped as belonging to the Belmont Formation (penultimate interglacial age) or the Devonshire marine member of the Rocky Bay Formation (last interglacial age); AS ^{230}Th/U ages of corals from these formations are about 200 ka and 125 ka, respectively (Harmon et al., 1983). Both formations have eolianite facies that overlie
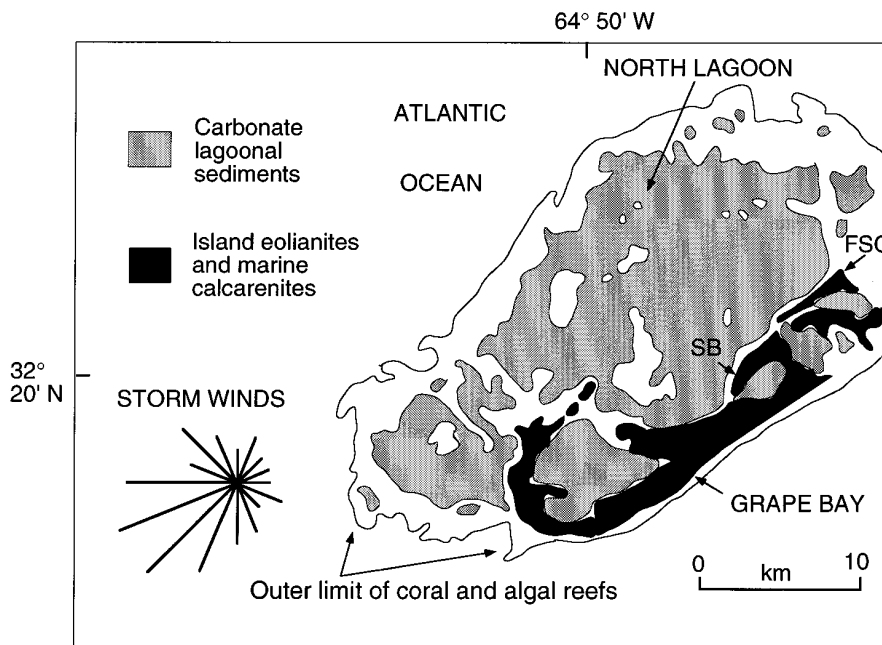

Figure 3. Study localities on island of Bermuda, and distribution of outer reef and lagoon on Bermuda platform (from Vacher et al., 1989). FSC = Fort St. Catherine, SB = Shelly Bay.

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the marine facies. An eolianite unit that is slightly younger than the Rocky Bay Formation, called the Southhampton Formation, can be differentiated from the Rocky Bay Formation on the basis of stratigraphic relations (Vacher and Hearty, 1989) and amino-acid racemization data (Hearty et al., 1992). At least three Southampton Formation localities on Bermuda have fossil-bearing marine facies 1–2 m above sea level, where mollusks yield amino-acid ratios that are lower (i.e., younger) than those found in shells from the marine facies of the slightly older Rocky Bay Formation (Vacher and Hearty, 1989). In addition, Harmon et al. (1983) reported a single AS ^{230}Th/U age of 85 ± 12 ka for an *Oculina* sp. coral collected from a Southampton marine facies near Fort St. Catherine, though the significance of this age has been disputed (Harmon et al., 1983; Vacher and Hearty, 1989).

We examined the locality at Fort St. Catherine, collected fossil *Oculina* corals for dating, and studied the marine facies of the older Rocky Bay Formation at Grape Bay for comparison. Our analyses of *Oculina* corals from the +1 m to +2 m marine deposit at Fort St. Catherine on Bermuda give ^{230}Th/U ages of 82.3 ± 3.6 ka, 82.4 ± 0.9 ka, 77.9 ± 0.4 ka, and 77.2 ± 2.5 ka. These ages agree with the single AS age reported by Harmon et al. (1983) for a coral from this deposit, and also show that the Bermuda corals grew during the same ~80 ka highstand as those from the Florida Keys.

A *Siderastrea* coral from the Devonshire member (the marine facies of the Rocky Bay Formation) at Grape Bay gave a ^{230}Th/U age of 116.1 ± 2.4 ka, has a calculated initial ^{234}U/^{238}U indistinguishable from that of modern sea water (Table 1), and agrees with AS ages of 124 ± 6 ka and 124 ± 12 ka for *Diploria strigosa* corals analyzed by Harmon et al. (1983) from the same locality. At this locality, thin marine deposits of the Devonshire member of the Rocky Bay Formation are overlain by an eolianite facies of this formation. The two members are separated by a weakly developed paleosol only in the back-beach area. The paleosol is so minimally developed that it implies only a very short hiatus in sedimentation between the marine and eolian facies in the back-beach area; elsewhere, the two members are conformable.

IMPLICATIONS FOR SEA LEVEL AT 80 KA

The new ^{230}Th/U data and geologic setting of our samples allow estimates of the position of sea level at ~80 ka from tectonically stable platforms. Off the Florida Keys, the reported depth of the topographic crest of the main reef body (Lidz et al., 1991) is

TABLE 1. ISOTOPIC AND AGE DATA FOR CORALS

Sample*	Genus†	Age§ (ka)	U (ppm)	Th (ppb)	^{234}U/^{238}U**	^{230}Th/^{238}U**	^{234}U/^{238}U** (initial)
Bermuda, modern:							
SB-1 #1	Oc	2.11 ± 1.10	3.05	0.79	1.1499 (20)	0.0221 (110)	1.1508 (20)
SB-1 #2	Oc	2.15 ± 0.26	3.14	0.34	1.1445 (26)	0.0224 (27)	1.1454 (27)
SB-2 #1	Si	1.82 ± 0.44	2.87	4.78	1.1460 (24)	0.0194 (45)	1.1468 (24)
SB-2 #2	Si	1.50 ± 0.12	2.86	4.44	1.1459 (16)	0.0161 (10)	1.1465 (16)
Bermuda, Southampton Formation:							
FSC-3	Oc	82.4 ± 0.9	2.47	0.62	1.1163 (19)	0.5996 (45)	1.1468 (24)
FSC-4	Oc	77.9 ± 0.4	2.98	0.44	1.1161 (16)	0.5772 (16)	1.1448 (20)
FSC-5	Oc	77.2 ± 2.5	2.98	1.48	1.1181 (28)	0.5744 (127)	1.1470 (36)
FSC-6	Oc	82.3 ± 3.6	2.77	3.27	1.1195 (29)	0.6016 (175)	1.1509 (40)
Bermuda, Rocky Bay Formation:							
GB-2	Si	116.1 ± 2.4	3.80	3.01	1.1072 (29)	0.7373 (83)	1.1489 (41)
Florida:							
FL-31	Si	<1.0	2.66	0.41	1.1441 (22)	<0.011	1.1441 (23)
FL-32	Ap	8.16 ± 0.10	3.31	0.24	1.1446 (10)	0.0829 (10)	1.1479 (11)
FL-33	Ma	86.6 ± 0.9	2.27	0.15	1.1356 (12)	0.6320 (43)	1.1733 (16)
FL-23	Ma	80.9 ± 1.7	2.71	0.21	1.1146 (20)	0.5912 (84)	1.1441 (27)
FL-20	Ma	83.2 ± 0.9	2.99	0.17	1.1192 (21)	0.6056 (42)	1.1509 (27)

*FSC = Fort St. Catherine, GB = Grape Bay, SB = Shelly Bay; sample size ~120 mg.

†Oc = *Oculina*, Si = *Siderastrea*, Ma = *Montastrea annularis*, Ap = *Acropora palmata*.

§Ages calculated using half-lives for ^{230}Th and ^{234}U of 75,380 and 244,600 yr, respectively, and include a neglible to very small correction for a secular-equilibrium detrital component with ^{232}Th/^{238}U = 3.8.

**Activity ratios, calculated from the atomic ratios by normalizing to a secular equilibrium standard, assuming the above half lives. Numbers in parantheses are 2σ errors of the least-significant digits.
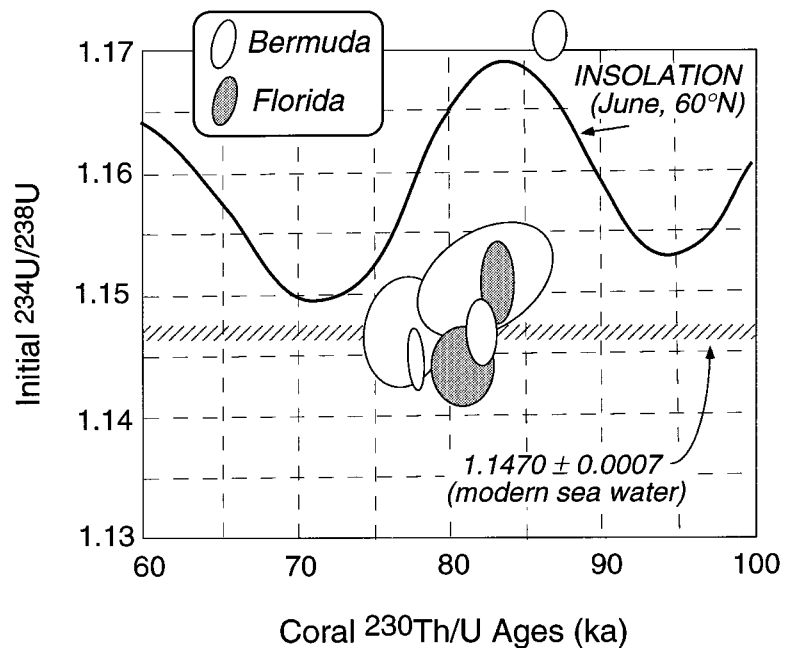

Figure 4. Calculated initial ^{234}U/^{238}U (activity) for ~80 ka corals from Florida and Bermuda, plotted against their ^{230}Th/U ages (shown by their 2σ error ellipses). Diagonal-rule band shows initial ^{234}U/^{238}U of modern sea water, taken as mean and 95% confidence limit for 27 Holocene corals analyzed in our laboratory. Curved line shows relative insolation values for 60–100 ka (Berger and Loutre, 1991).

10–12 m. *Montastrea* grows over a considerable depth range down to 80 m, but has optimum growth depths of 3–45 m (Shinn et al., 1989). If we assume conservatively that the *Montastrea* dated in the present study grew in water depths as shallow as 3 m, the 10–12 m depth of the submerged reef implies a sea level no lower than −7 to −9 m, relative to present, at ~80 ka. Sea level could have been much higher if the corals grew in water deeper than 3 m, which is likely.

The paleo-sea-level significance of the marine deposits at Fort St. Catherine has been controversial. Harmon et al. (1983) interpreted the sediments to be storm generated and concluded that despite their AS [230]Th/U age of 85 ± 12 ka for an *Oculina* coral, the sediments provided no constraints on sea level at ~80 ka. However, Vacher and Hearty (1989) noted that storm waves likely would have had to traverse an outer reef, followed by a 15–20 km passage through an 11–15-m-deep lagoon on the Bermuda Platform before reaching the vicinity of Fort St. Catherine. In addition, they reported amino-acid ratios for mollusks in marine facies of the Southampton Formation at two other localities on Bermuda that correlate these deposits with those at Fort St. Catherine. Vacher and Hearty (1989) observed that the marine deposits at Fort St. Catherine do not appear in any way different from those of older marine deposits such as the Rocky Bay Formation and the Belmont Formation. We also see no significant difference between the sequence of depositional events at Grape Bay during the 116–124 ka highstand and the sequence at Fort St. Catherine during the ~80 ka sea-level highstand. Thus, we agree with the conclusions of Vacher and Hearty (1989) that the marine facies at Fort St. Catherine and correlative sediments elsewhere on Bermuda imply a sea level close to, or above, that of the present at ~80 ka.

CONCLUSIONS

Our conclusions have important implications for the history of late Quaternary sea level. An 80 ka sea level close to the present, derived from tectonically stable platforms, conflicts with estimates of −10 to −20 m derived from tectonically rising New Guinea and Barbados (Chappell and Shackleton, 1986; Bender et al., 1979; Gallup et al., 1994). The results also conflict with speleothem records from the Bahamas, where sea level at ~80 ka is estimated to be lower than −15 to −18 m, based on what is interpreted to be continuous subaerial calcite growth during this period (Richards et al., 1994; Lundberg and Ford, 1994). Our studies provide no evidence for the drastic drop in sea level to −60 to −70 m implied by the Mg/Ca record in ostracodes (Dwyer et al., 1995). The difference in ice volume between most previous sea-level estimates and the present study is greater than the volume of the Greenland ice sheet (7 m sea-level equivalent) or West Antarctic ice sheet (5–10 m sea-level equivalent). However, our hypothesis of an ~80 ka sea level close to the present agrees with marine records from the tectonically stable Atlantic Coastal Plain of the United States (Szabo, 1985) and the slowly rising Pacific coast of North America (Muhs et al., 1994), and is close to an independently calculated estimate from New Guinea by Bloom and Yonekura (1985, 1990). Comparison of our ages with high-latitude insolation values indicates that the sea-level stand at ~80 ka could have been orbitally forced.

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