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Boulder Deposits from Large Waves during the Last Interglaciation on North Eleuthera Island, Bahamas

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Seven boulders measuring 100 to 1000 m^3 are scattered along the coastal ridge of north Eleuthera. Some are situated on ridge crests up to 20 m above present sea level. The boulders were probably deposited during oxygen-isotope substage 5e or 5d, as shown by their stratigraphic setting and by amino acid racemization ratios. D-alloisoleucine/L-isoleucine ratios were determined for land snails, and oolite of both marine and eolian origin was associated with the boulders. Like the boulders, the probable source rocks exposed in the adjacent cliffs are composed of marine and eolian limestone of oolitic and peloidal composition. The source beds are correlated with stage 9 or 11. The largest boulder is about 10 times the size of the largest Holocene ones moved by waves in the area. Tsunamis are a reasonable possibility as a transporting mechanism of the Pleistocene boulders. However, if deposited instead by storms during the last interglaciation, the storms were of much greater intensity than those occurring in the region during the late Holocene. © 1997 University of Washington.

INTRODUCTION

Several large boulders are scattered along the coastal ridge of north Eleuthera, Bahamas. The stratigraphy associated with some of the boulders indicates that they were deposited during the Pleistocene. The boulders are of much greater size than Holocene counterparts and point to the occurrence of very large waves.

Large boulders on exposed coastlines of the tropical oceans have generally been attributed to a giant wave mechanism, generally tsunamis (seismic sea waves). Deposits of large boulders have been reported on the tectonic coastlines of the Caribbean, but this is the first time they have been recognized in the Bahamas. Jones and Hunter (1992) indicated that 40-ton boulders along the coast of Grand Cayman Island were deposited by ''giant waves,'' generated by either hurricane or seismic waves in the Caribbean. Corals encrusted on the boulders have ^{14}C ages of about 330 years. Taggart *et al.* (1993) described very large Holocene reef-rock boulders (maximum size 9.5 × 6 × 4 m) deposited on the southwestern shore of Isla de Mona, west of Puerto Rico, and attributed their deposition to a large wave event sometime after 4200 yr B.P. Similarly, Bourrouilh and Talandier (1985) described ''cyclopean blocks'' (15 × 10 × 5 m) in Polynesia that were deposited by ''tidal waves'' during the Holocene.

Moore and Moore (1984) attributed Pleistocene rubble deposits up to 326 m above present sea level from Lanai (Hawaiian Archipelago) to enormous waves that occurred during the last-interglaciation. Lipman *et al.* (1988) tied the Lanai deposits to the Alika submarine landslide to the east on the island of Hawaii. Young and Bryant (1992) associated sedimentary disruption of stage 5e deposits above 15 m in New South Wales, Australia (14,000 km away) to the Lanai wave event about 105,000 yr ago. Jones (1992), however, disputed the Hawaiian source of the tsunami, citing problems with wave attenuation and evidence of uplift of the Hawaiian Islands to explain the Lanai deposits. In reply, Young and Bryant (1992) appropriately noted that, despite some debate on the source of the large waves, the disruption of last-interglacial sand barriers over 500 km of Australian coastline is in itself an impressive geomorphic product of large waves in the Pacific Ocean. In a later paper, Jones and Mader (1996) modeled the potential wave effect of the Alika slide and concluded that it could not have been the source of the destruction of the last-interglacial barrier in Australia. Jones and Mader (1996) then proposed that waves generated by an asteroid impact were more appropriate to explain these geomorphic features in Australia.

This paper (1) presents a detailed description of the boulders of north Eleuthera, (2) demonstrates that they were deposited by waves during the Pleistocene, (3) describes the time and stratigraphy related to boulder emplacement, and (4) evaluates tsunamis, slumping of the bank margin, and storms as potential wave-generating mechanisms.

METHODS

This study examines the boulders and their setting in the context of previous stratigraphic investigations in north Eleuthera (Kindler and Hearty, 1995, 1996; Hearty, 1998). Amino acid racemization (AAR) analyses of whole-rock and land snail samples provide a means of correlating the boulders with their probable source beds, as well as constraining

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the time of boulder deposition on the basis of the age of the underlying rocks and encrusting soils.

The AAR method is based on the racemization of amino acids preserved in fossilized biominerals (Hare and Mitterer, 1967), in this case those contained in organic-rich, whole-rock limestone and *Cerion* land snails (Pulmonata). Mitterer (1968) showed that ooids and aragonite muds contain concentrations of amino acids similar to those in mollusks and bioclastic limestones. Through time, L-amino acids racemize (or, more specifically in the case of the amino acid isoleucine, epimerize) to their D-isomer form. The ratio of D-alloisoleucine/L-isoleucine (or A/I) amino acids measures the extent of epimerization. In the A/I epimerization reaction, the ratio is initially zero and increases to an equilibrium ratio of about A/I of 1.30 with time after death of an organism and removal of biological constraints. Like other chemical reactions, the rate of racemization/epimerization depends on the ambient temperature of the reaction medium and the sample taxon. Fundamentals of the AAR method and a variety of applications are discussed by Miller and Brigham-Grette (1989) and Wehmiller (1993).

In a comparison of various sample materials from Bermuda (Hearty *et al.*, 1992), it was demonstrated that A/I ratios on marine shells (*Glycymeris* sp.), pulmonate gastropods (*Poecilozonites* sp.), and whole-rock bioclastic limestones generated parallel kinetic trends and superposition in 97% of 257 stratigraphically oriented samples. The whole-rock method (Hearty *et al.*, 1992) depends on the averaging of A/I ratios from several hundred or thousand individual skeletal and/or oolitic grains contained in the limestone sample.

Kindler and Hearty (1996) showed that equivalent stratigraphic units in the Bahamas have similar petrographic composition. Given these petrographic similarities, the potential variation of A/I ratios from whole-rock samples between coeval stratigraphic units across the region is minimized. In north Eleuthera, this similar petrography of the samples and negligible variation in temperature history among the sites further increases the precision of the method. A large number of empirical tests from Bermuda and the Bahamas confirm that the whole-rock method is an effective tool for local and regional correlations. Table 1 demonstrates this precision of A/I ratios from oolite among last-interglacial (substage 5e) sites across Eleuthera. In a small percentage of cases ($<10\%$), samples situated 1 or 2 m below paleosol horizons may experience some minor effects of chemical leaching, which tend to lower ratios (e.g., Two Pines, Table 1). Also, because of a variety of diagenetic effects (leaching, heating, and lower concentrations of amino acids), older middle Pleistocene samples generally show greater statistical variance in A/I ratios, but nonetheless remain effective for correlation across the region. Calibration of A/I ratios (Hearty and Kindler, 1993, 1997) is provided by uranium-series ages from coeval deposits on other islands (Muhs *et al.*, 1990; Chen *et al.*, 1991).

Soils are important for interpretation of the relative age of the depositional sequence of the boulders. Two soil types are considered. The first is an entisol (Soil Survey Staff, 1975), in which ''pedogenic processes have left only a faint imprint'' (Birkeland, 1974). Since the sandy, yellowish-brown entisols are observed within substage sequences, the time required for their formation is constrained to a few hundred to a few thousand years. Vacher and Hearty (1989) informally described these immature soils as ''protosols'' and discussed the environmental conditions surrounding their formation. Aluminous lateritic soil (or Hapluxtox of Soil Survey Staff, 1975) (see Foos, 1991 for more descriptive notes) caps limestone sequences, and thus in a stratigraphic sense, postdates the interglaciations during which the carbonate rocks were deposited. Muhs *et al.* (1990) determined that the parent material of most Bahamian reddish paleosols originates as atmospheric dust from the Sahara. This parent material is concentrated on exposed limestone surfaces during periods of low carbonate imput, mainly during intervals of glacially lowered sea level (Bricker and Mackenzie, 1970). Thus, formation of these soils encompass lowstand intervals from 50,000 to 100,000 yr duration. In distal areas beyond the coastal depocenter, the parent material of soils from atmospheric sources may accumulate over hundreds of thousands of years. Bowles (1975) established from eastern equatorial North Atlantic deep sea cores that the most rapid rates of accumulation of atmospheric dust from a Saharan source are tied to glacial periods when prevailing easterly winds are most intense, confirming their association with lowstands of sea level.

SETTING

The tectonically quiescence Bahama Islands are situated on the passive margin of the North American plate. Carew and Mylroie (1995) showed that the equivalent elevation of contemporaneous shoreline features across the 900-km-long platform area is a demonstration of tectonic stability. There is no record of earthquake activity during historical times in the Bahamas. Eleuthera is situated on the eastern margin of Great Bahama Bank (Fig. 1) some thousands of kilometers from the nearest plate boundaries and from potential sources of tsunamis in the Caribbean and along the Mid-Atlantic Ridge.

The north Eleuthera study area is asymmetrical in cross section, with highest elevations of about 30 m along the cliffs. The narrow isthmus ranges from a few tens of meters to nearly a kilometer wide. High seas regularly wash through and over the island in the area around Glass Window bridge. The bank side of the study area is shallow with maximum depths of about 6 m extending for more than 50 km southwest of the study area (Fig. 2). The shelf on the Atlantic margin lacks a barrier reef and plunges to 100 m water depth within a kilometer of the shore. On the Atlantic margin, a

TABLE 1
Mean A/I Ratios from Substage 5e Oolite in Eleuthera

Eleuthera locality	Sample #	Field #	A/I ratio ± 1σ	Sedimentary facies
Whale Point	1567A	EWP2i	0.395 ± 0.002	beach
Cotton Hole	1564A	ECH2i	0.372 ± 0.010	beach/washover
Boiling Hole	1563A	EBH1d	0.407 ± 0.003	beach
Sub-Boulder 4	1812A	EMB4e	0.385 ± 0.004	beach
Sub-Boulder 2	1814A	EMB2o	0.400 ± 0.003	eolian
Hatchet Bay	1275A	EHA1a	0.406 ± 0.007	beach
	1275B	EHA1a	0.388 ± 0.008	beach
Two Pines	1094B/1104C	ETP1c	0.363 ± 0.010	eolian
	1104B/1094A	ETP1a	0.320 ± 0.026[a]	eolian
Savannah Sound	1094D	ESV1c	0.345 ± 0.005	eolian
	1094C	ESV1a	0.403 ± 0.004	eolian
Rainbow Cay	1467A	ERC2a	0.369 ± 0.006	eolian

[a] Sample was collected within 1 m of overlying soil. Eleuthera mean: 0.379 ± 0.027 (n = 12)

1.5-km-wide spur, with water depths as shallow as 20 to 30 m, extends about 6 km to the northeast. All the largest boulders found in north Eleuthera are located within 3 km of each other (Fig. 2) at the apex of this horseshoe-shaped embayment.

Earlier studies of the stratigraphy and surficial geology of Bahama Islands were presented by Garrett and Gould (1984), Carew and Mylroie (1987), and Hearty and Kindler (1993, 1997), while a collection of papers relevant to carbonate island geology and this study was published more recently (Curran and White, 1995). In Eleuthera, up to six interglacial parasequences (stages 1–13) are represented in the cliff and

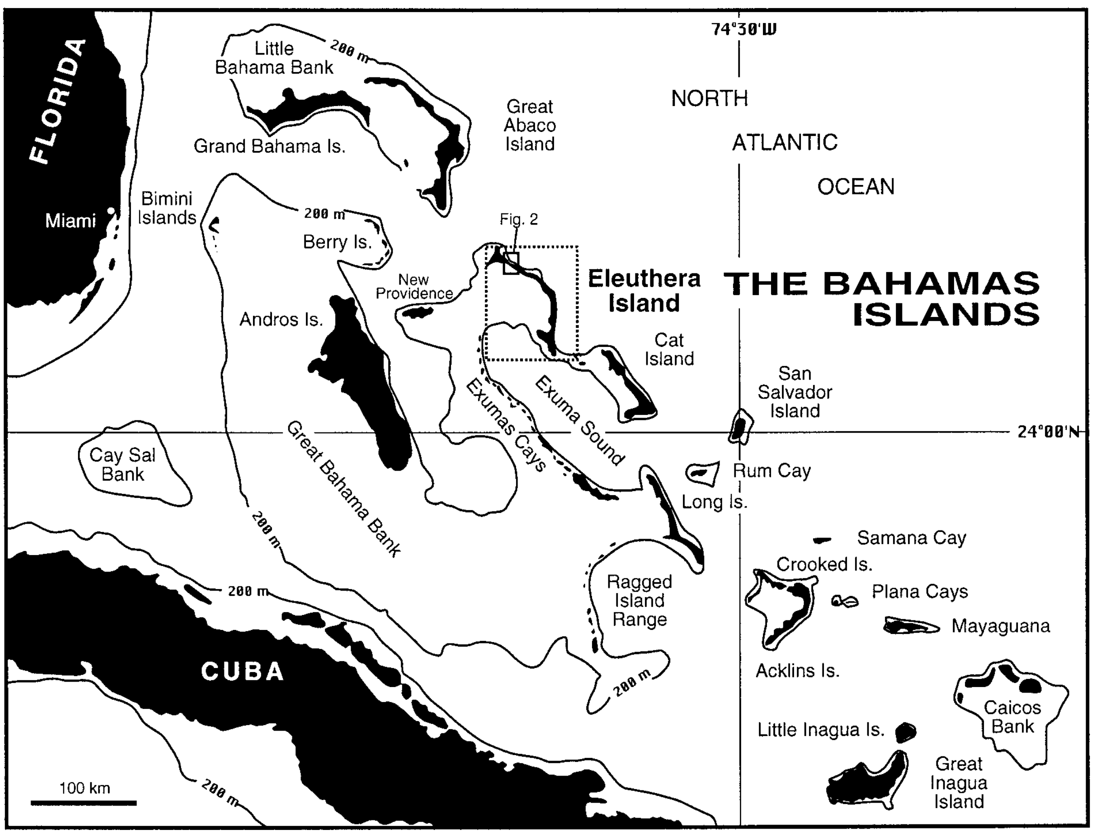

FIG. 1. Map of the Bahamas showing the location of north Eleuthera on the northeastern margin of the Great Bahama Bank.

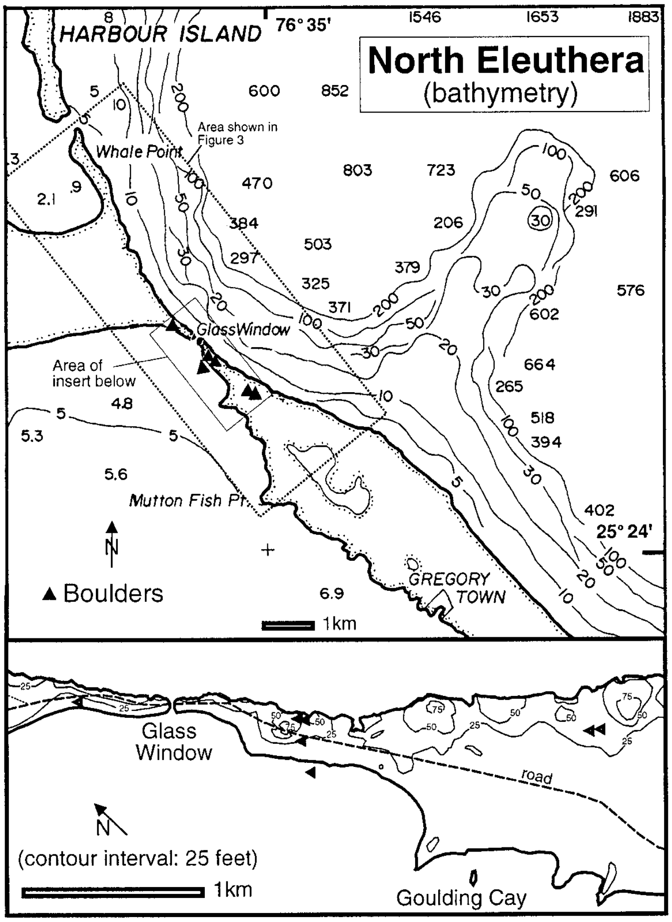

FIG. 2. Hydrographic chart (depths in m; from Defense Mapping Agency 1:100,000 Hydrographic Chart #26307) of the north Eleuthera showing the bathymetry surrounding the study area and submerged spur extending about 6 km to the northeast. The largest boulders in the area are found at the apex of this horseshoe-shaped structure. A topographic map of the land area is shown in the inset.

roadcut sections (Kindler and Hearty, 1996; Hearty, 1998). The cliffs are cut into an undulatory complex of numerous middle Pleistocene coastal ridges, including those correlated with stages 7–13 or older (Hearty, 1998). Substage 5e deposits, represented by facies of oolitic subtidal, intertidal, and beach environments, fill swales on the middle Pleistocene landscape. Substage 5e eolian deposits form large dune ridges and blanket much of the study area. Holocene deposits of coarse, angular skeletal composition are washed through narrow gaps between older ridges and accumulate in basins behind the coastal cliffs.

It is apparent from the well-developed coastal beach and dune complexes that a broad, shallow shelf area, required to generate and supply sediments to the coastline, must have been present at least through the last interglaciation. Today the coastal profile drops off to more than 100 m depth within a kilometer of the cliffs (Fig. 2), greatly inhibiting the formation and landward transport of sediments. The lack of an obvious sediment source required to supply the Pleistocene shorelines suggests that there has been significant coastal retreat since the last interglaciation.

DESCRIPTION OF BOULDERS

Seven large boulders were identified and examined in the study area. The size, setting, stratigraphy, association with paleosols, and relative ages of the boulders, probable source beds, and underlying strata were investigated. Photographs and sketches provide additional information about some of the boulders and the stratigraphy beneath them. The aim of this detailed field study is to assess their age and confirm that they were deposited by waves.

Geographic and Topographic Distribution of the Boulders

The study area is characterized by undulating surface topography reflecting the eolian origin of the landforms. There are no land areas other than the cliffs that expose jointed bedrock, naturally quarried areas, pits, or ''plucking scars'' (Young *et al.*, 1996) that would account for the boulders falling, rolling, or being transported from the bank or by longshore waves.

The seven boulders show a nonrandom distribution along the coastal ridge of the north Eleuthera (Fig. 3). Boulders 1 and 2 are situated at about 15 to 20 m elevation at the cliff tops, near the crest of the island ridge (Fig. 4). Boulder 3 is located nearby, midway on the 150-m-wide asymmetrical isthmus at about 10 m elevation. Boulder 5 is located on the same axis about 150 m offshore, partially submerged in 1 to 2 m of calm water of the western Eleuthera banks. Farther north, Boulder 4 came to rest near the bankward shore at about 3 m elevation (Fig. 5). Boulders 6 and 7 lie within a washover basin at about 6 to 8 m elevation at the southern end of the study area. The base of these boulders are partially buried by Holocene sands. Amino acid ratios, identified in boxes in the figures, are discussed below.

Physical Characteristics of the Boulders

The boulders are generally blocky, subrectangular, and steep sided. Some rest on ''pedestals'' of limestone, generally between 0.5 and 2 m higher than the surrounding rocks (Figs. 6A–6D). Vegetation and thin soils occur in small karstic pits at the tops of some boulders.

The boulders were measured at the average distance along *a*, *b*, and *c* axes (longest to shortest dimensions) (Table 2). Since the boulders often have irregular surfaces, the measurements of volume and weight are estimates. The *average* individual volume of the seven boulders is approximately 500 m^3, while the greatest volume is nearly 1000 m^3 (13 $\times$ 11.5 $\times$ 6.5 m). The greatest weight (from an estimated density of 2.4 g/cm^3) is about 2300 tons for Boulder 1.

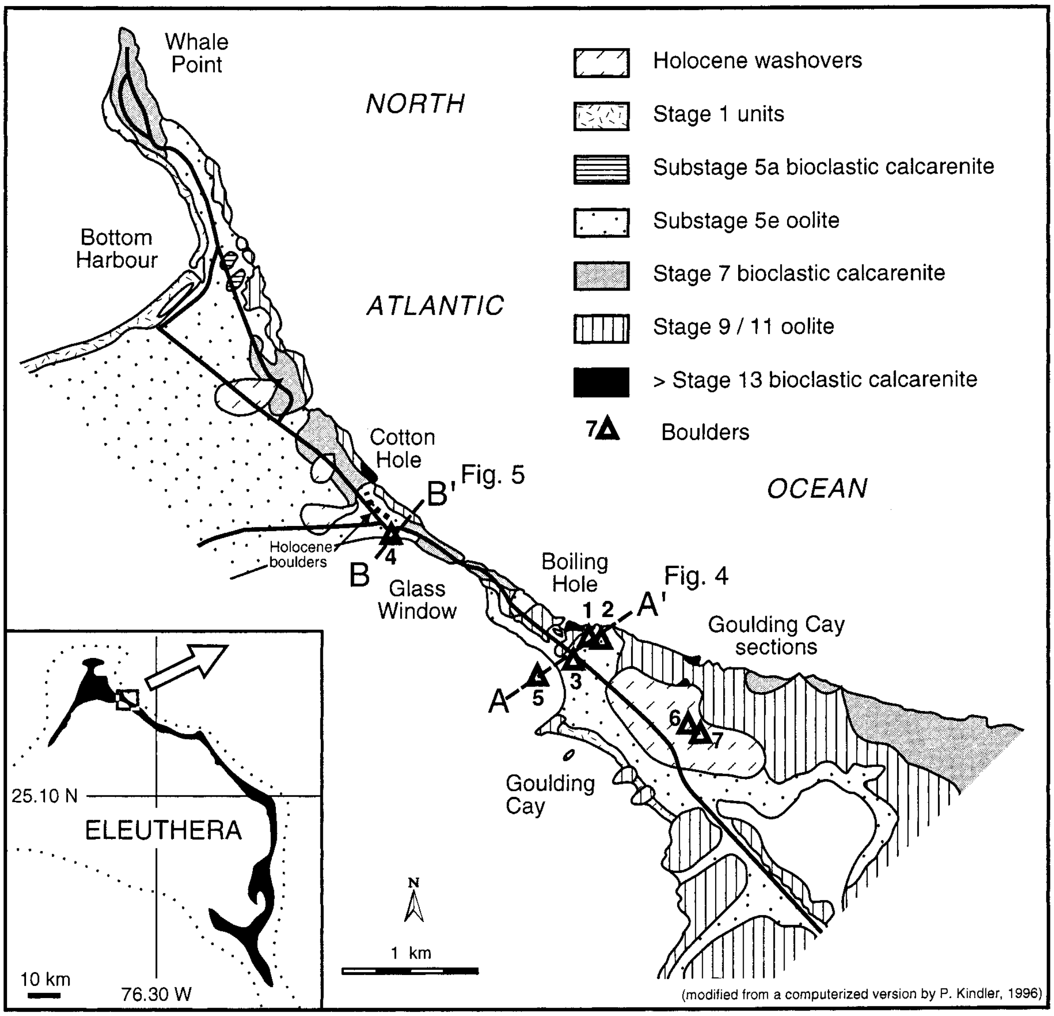

FIG. 3. Geologic map of the study area in north Eleuthera. Boulders are identified by numbered triangles. The Holocene boulder limit is indicated by broken line near Cotton Hole.

Disorientation of Bedding Planes

In most cases, the bedding orientation far exceeds the highest angles of naturally deposited sediments, i.e., eolian foresets. The angle of repose of spherical ooids deposited by wind is about 30°–33° (Ball, 1967). The probable source beds reveal both low-angle, seaward-oriented beach bedding (0°–10°) and occasional eolian and washover cross beds with angles dipping between 20° and 30° from horizontal.

Dips of bedding planes in boulders range between 30° and 75° and are oriented in random compass directions. Fenestral porosity, as associated with beach facies (generally dipping 5°–10° seaward), is observed in samples from Boulder 5, indicating minimum rotation of the boulder by 40° from its primary *in situ* orientation.

Composition of Boulders

Thin-section analysis and hand-lens petrography indicates that the boulders are generally oolitic/peloidal in composition (Table 2), similar to middle Pleistocene strata along the base of adjacent coastal cliffs (Kindler and Hearty, 1995, 1996). Like the *in situ* middle Pleistocene units, the boulders are dense (porosity ~12%), firmly cemented, and largely recrystallized. With the exception of the exposed cliff faces (probable source of the boulders), most of the study area is mantled by at least two sequences of younger rocks (Figs. 4 and 5) that are less diagenetically altered than the boulders. The younger units, correlated with isotope stages 7 and 5e, mantle the older middle Pleistocene strata on the lee slope of the ridge where most boulders are situated.

SUB-BOULDER STRATIGRAPHY

Physical Stratigraphy

Similarities of the sub-boulder stratigraphy among three boulders (Figs. 7A–7C) reveal the timing and depositional

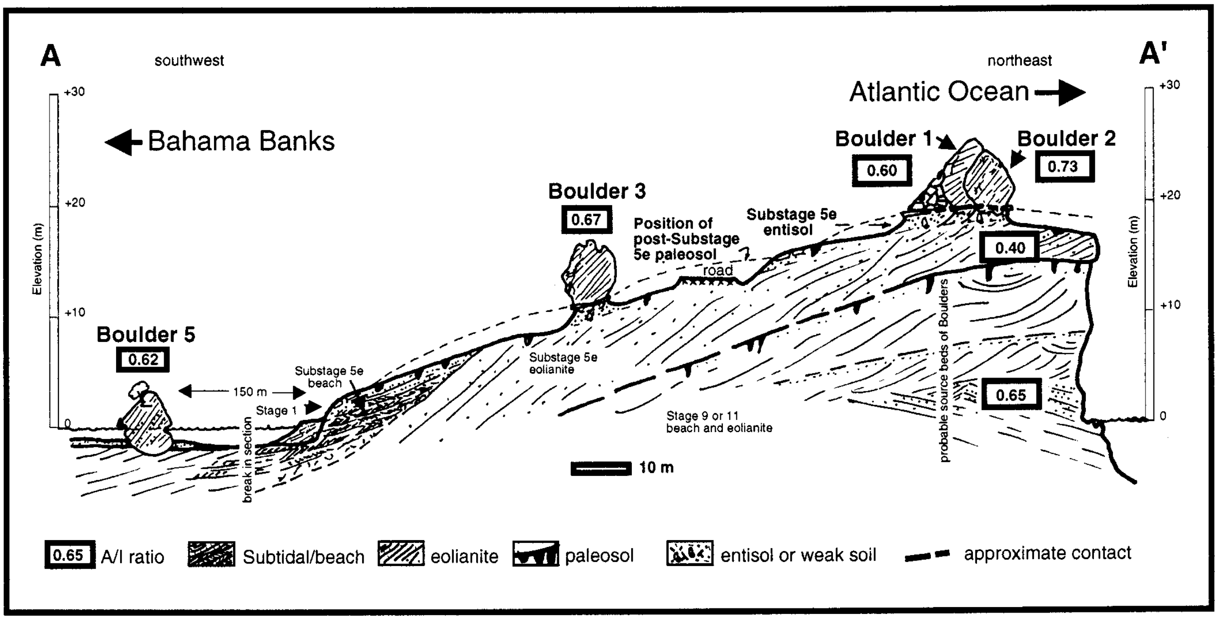

FIG. 4. Measured geologic cross section (A–A′) near Boiling Hole showing the distribution of boulders on crest (Boulders 1 and 2), midway on the landward slope (Boulder 3), and partially submerged in the quiet waters (Boulder 5) of the Bahama Banks of north Eleuthera. In the cross sections, surveys and measurements were made in the field at the cliff face, while topography and horizontal distances were determined from 1:25:000-scale topographic maps. Whole-rock A/I ratios (in boxes) show the stratigraphic inversion of older boulders on younger bedrock. Legend applies to this figure and Figures 5 and 7.

sequence associated with the boulders. In observable cases (i.e., those boulders not submerged or partially buried), the boulders rest directly upon weakly developed oolitic entisols. The entisols beneath the boulders are fortuitously exposed as a result of erosion around the boulders over the past 100,000 yr. According to Gould (1988), the land snail *Cerion*

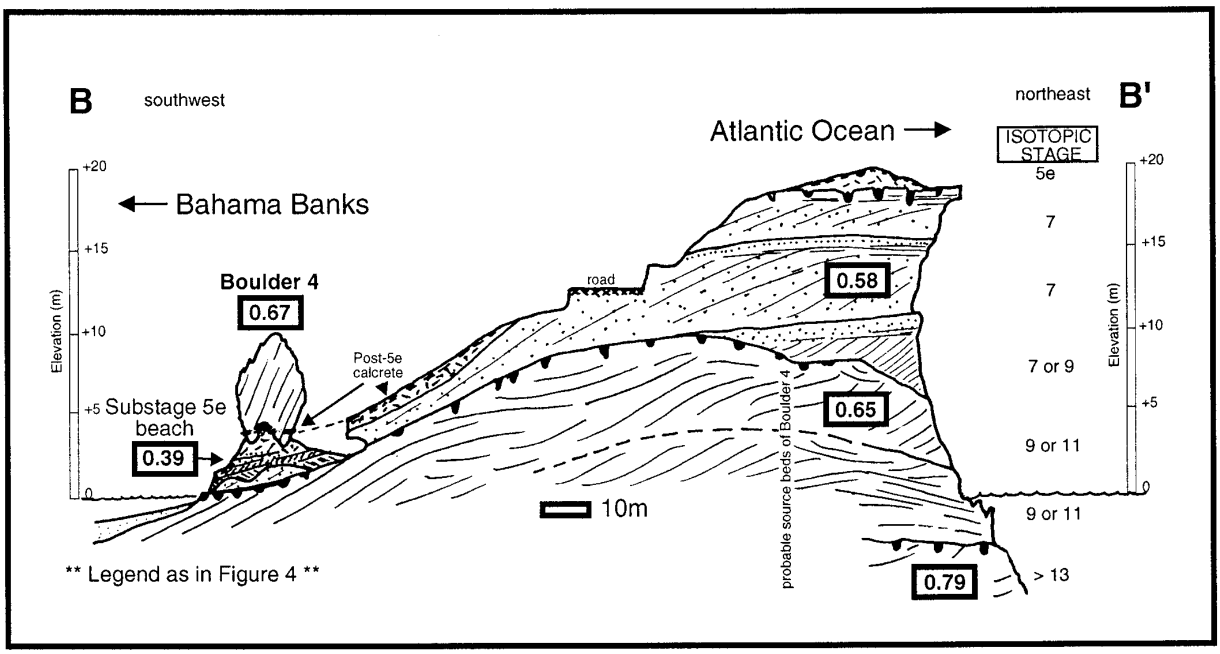

FIG. 5. Measured geologic cross section (B–B′) of north Eleuthera between Glass Window and Cotton Hole. A/I ratios are indicated in boxes.

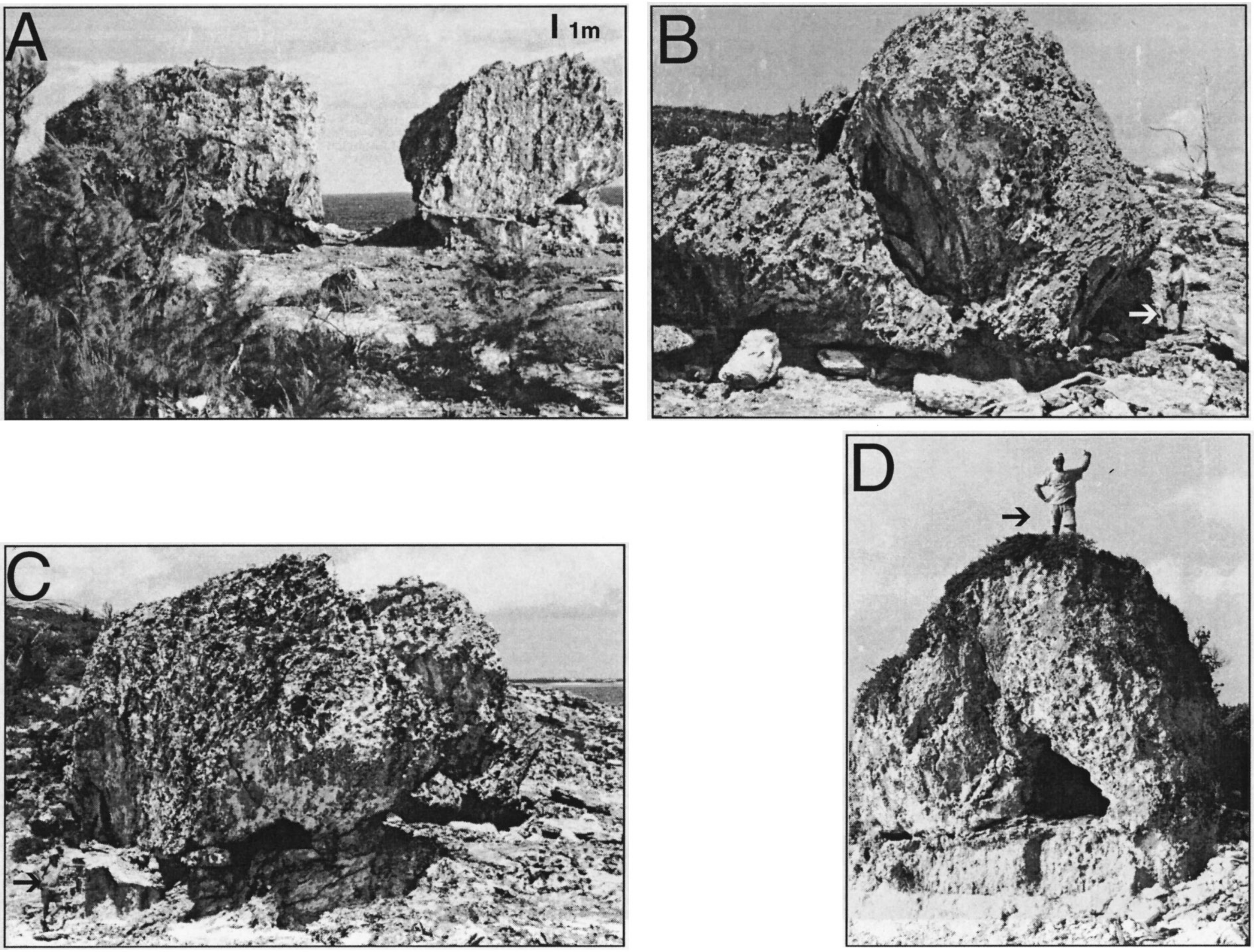

FIG. 6. Photographs of boulders: (A) Boulders 1 and 2 are situated at the top of the +20 m coastal ridge; (B) Boulder 1 with a person (1.8 m) on the right of the boulder; (C) Boulder 2 showing calcrete and paleosol at left hand of a person (1.9 m) in the lower left of the photo; (D) Boulder 4 rests on an entisol, and is flanked by calcrete. The author, on top of the boulder, is 1.85 m tall.

agassizi, found in the entisols, is typical of the last interglaciation. He further observed that *C. agassizi* is present in Holocene deposits on Eleuthera and Cat islands, but not in significant numbers. The eolianite and beach deposits upon which the boulders rest (Figs. 7A and 7B) are also correlated with substage 5e on the basis of their oolitic composition, unrecrystallized aragonitic mineralogy, and higher-than-present sea-level indicators (Kindler and Hearty, 1995, 1996; Neumann and Hearty, 1996).

Because the entisols occur at the end of a complex interglacial sequence, after deposition of a regressive beach deposit of substage 5e, the time of formation of the entisols with *Cerion* is restricted to a fairly short interval. Induration of Bahamian carbonates occurs quickly with cessation of sediment deposition as sea level falls, and the deposits are exposed subaerially. Thus, the time during which land snails and vegetation would thrive during this regressive phase is limited to a few hundred years.

The boulders are flanked by pedogenic calcrete (Wright, 1994) and associated aluminous lateritic paleosol (Fig. 7), generally equated with glacial sea-level lowstands (Bricker and Mackenzie, 1970; Bowles, 1975). The pedogenic calcrete encircles the base of the boulders, marking the previous level of the land surface, and is not developed on the strata beneath them (Fig. 7C). At Boulder 1, a red aluminous lateritic paleosol is developed on rubble that onlaps the boulder on its landward side (Fig. 7A). Lateritic soils are not generally observed on the boulders themselves, which may be a function of high erosion and dissolution rates on the exposed surfaces. The presence of pedogenic features directly in contact with boulders indicates that the boulders were deposited before a prolonged period of low sediment input, presumably

TABLE 2
Physical Characteristics of Seven Boulders from North Eleuthera

Boulder ID	*a* axis (m)	*b* axis (m)	*c* axis (m)	Est. vol. (m^3)	Est. weight (tons)	Min. dist. trav. (m)	Dip and orientation	AAR whole-rock A/I	Elevation (m)
Boulder 1	13.0	11.5	6.5	970	2330	30	37° S W	0.604 ± 0.008	20
Boulder 2	8.1	5.5	5.7	254	610	25	50° N W	0.734 ± 0.019	20
Boulder 3	14.0	7.3	6.7	684	1640	150	40° S W	0.667 ± 0.016	13
Boulder 4	6.4	4.5	5.2	150	360	125	75° E	0.737 ± 0.025	3
	9.3	6.0	4.0				50° SSW		−1.5
Boulder 5	5.8	5.1	5.0	370	890	300		0.619 ± 0.013	
Boulder 6	7.2	5.7	5.0	205	490	500	56° E	no data	7
Boulder 7	6.2	5.0	3.7	115	280	500	46° E	no data	7

Note. Boulder 5 consists of two adjacent, aligned blocks that appear to have formerly been united. The longer northern block has slumped and rotated on its long axis about 25° toward the east. Boulder 6 and Boulder 7 are partially buried in Holocene washover sand making the vertical measurement an estimate only. Utah State University Amino Acid Laboratory numbers for Boulders 1–5 are AAL-1815, 1809, 1811, 1810, and 1813, respectively.

the last-glacial sea-level lowstand. Coastal sediments of Holocene age are never associated with either calcrete or *terra rossa* paleosols, precluding the possibility that the boulders were deposited during the present interglaciation.

The stratigraphic setting of the boulders constrains their deposition between substage 5e (resting on the entisols which are the youngest 5e unit represented in the area) and the last glaciation (before the development of encrusting calcrete and paleosol on the boulder). On the basis of the unweathered contact between the boulder and the underlying entisols, it appears that the duration of exposure of the surface between the time of development of the entisol and the deposition of the boulder is rather short. The best record of this close timing of events is revealed in the stratigraphy of Boulder 4 (Fig. 7C). The stratigraphic evidence at Boulder 4 indicates that the boulders were emplaced after the deposition of a regressive substage 5e beach at +2.5 m and the entisol (indicating further regression), but before any significant aluminous lateritic soil could develop on these deposits. A renewed rise of sea level after boulder deposition is not evident from the local stratigraphy or notching of the boulders, and thus it appears that sea level continued to fall below the present datum to substage 5d (?) or glacial stages 4–2 lowstand levels.

Boulder, Sub-boulder, and Local Aminostratigraphy (AAR)

Aminostratigraphy is used to confirm lithostratigraphic correlations and to determine relative ages of the stratigraphic units and boulders. A regional aminostratigraphy for both *Cerion* and whole-rock samples has previously been established for several Bahamian islands (Hearty and Kindler, 1993, 1997) including Eleuthera (Hearty, 1998), providing a framework for comparison of results obtained in this study.

A/I ratios from *Cerion* land snails in entisols beneath the boulders average 0.720 ± 0.029. These ratios are concordant with the mean values of substage 5e samples from Eleuthera and New Providence Island (Table 3) and establish a maximum age for the emplacement of the boulders. Oolitic marine facies beneath Boulder 4 (Fig. 7C, Unit 3) and eolian facies beneath Boulder 2 (Fig. 7B, Unit 1) have ratios of 0.385 and 0.400, respectively, which agree with the regional substage 5e whole-rock ratio of 0.379 ± 0.027 ($N = 12$) for Eleuthera (Tables 1 and 3).

Whole-rock A/I ratios from Boulder 1 through Boulder 5 yield ratios of 0.604, 0.734, 0.667, 0.737, and 0.619, respectively (Table 2). These ratios represent significantly greater ages of the boulders than of the underlying oolite. The mean boulder ratio (0.671 ± 0.063) compares favorably with *in situ* middle Pleistocene strata in the seaward cliffs whose ratios range from 0.559 to 0.789, and specifically correlates with the stage 9 or 11 oolitic/peloidal unit in the cliffs that averages 0.651 ± 0.030 (Table 2). Measured profiles in Figures 4 and 5 illustrate the stratigraphic and aminostratigraphic setting of the boulders relative to probable source beds.

DEPOSITION BY HUGE WAVES

Arguments Favoring Wave Transport of Boulders

In addition to the evidence provided above, there are deductive elements that support emplacement of the boulders by large waves.

The boulders could only have been transported to their current position by waves for the following reasons: (1) except for downward movement by gravity, they are too large to be transported by any medium other than waves that originated from the Atlantic Ocean; (2) blockfall or downslope movement by gravity can be excluded because two of the larger boulders are situated at the crest of the island ridge, with no lithologically appropriate source areas higher than the boulders; (3) other boulders situated on the

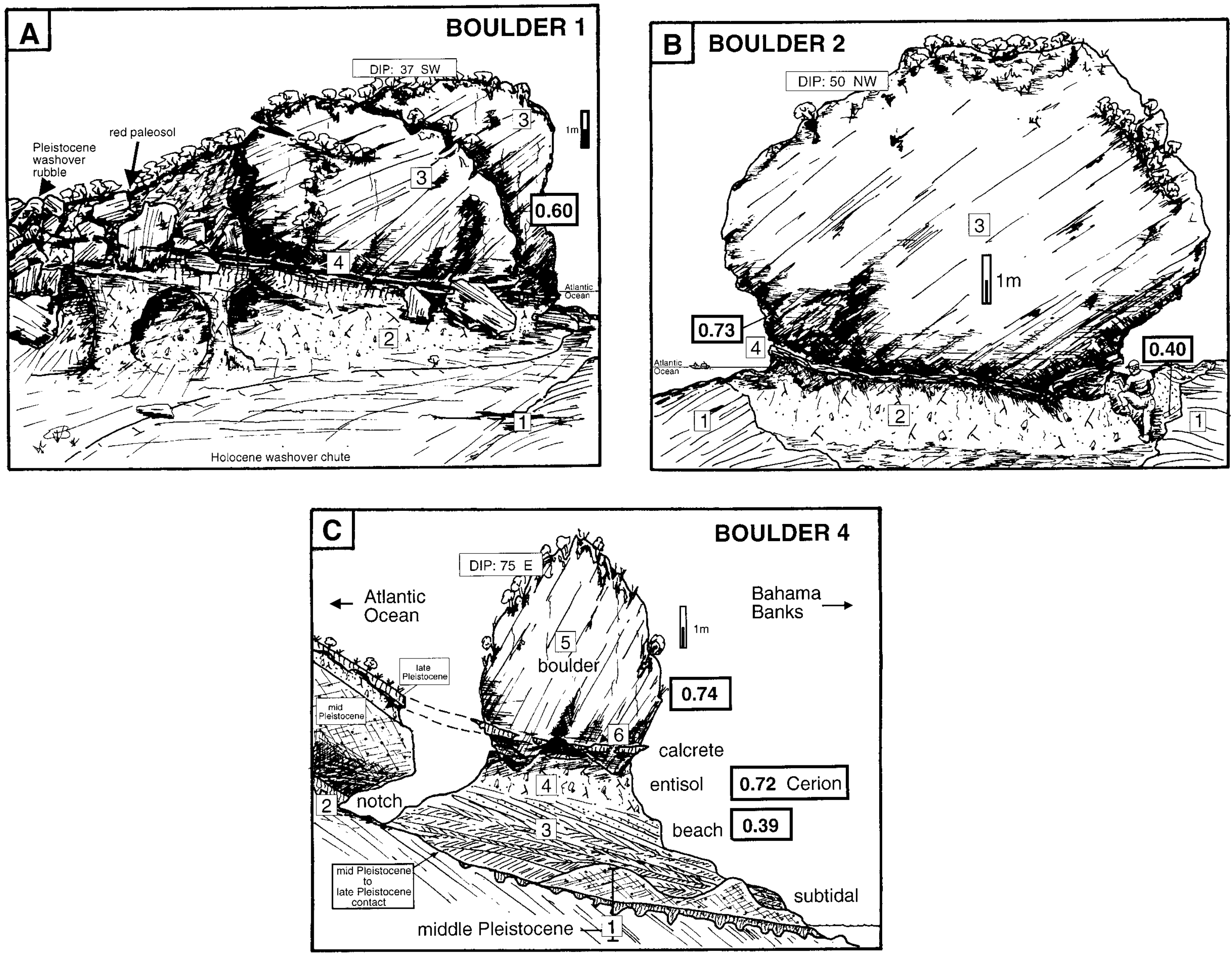

FIG. 7. Stratigraphy and depositional sequence related to three boulders. (A and B, Boulders 1 and 2): (1) oolitic eolianite of substage 5e age; (2) substage 5e entisol (weak soil) with *Cerion* land snails; (3) boulder emplacement; (4) formation of calcrete and paleosol during sea-level regression. Red paleosols also occur within the washover rubble on the landward margin and lapping onto the boulder. (C, Boulder 4): (1) middle Pleistocene limestone; (2) notch formation; (3) regressive subtidal and beach deposits; (4) entisol with *Cerion* land snails; (5) displaced boulder; and (6) calcrete and paleosol. A/I ratios are indicated in boxes. Note surface lowering in the unprotected areas surrounding the boulders. Legend as in Figure 4.

landward slope of the island rest on a mantle of substage 5e oolite, with no exposed source beds or plucking scars other than from the cliffs on the Atlantic margin of the island; (4) longshore rolling of the boulders is untenable over an undulating topography with 10 to 20 m of relief. In a longshore direction, there are no more-likely source beds than in a cross-island direction; and (5) in addition to lacking an obvious boulder source area, the wave energy on the bankward side of Eleuthera is far too low to account for their transport upslope. In contrast, the deep and unprotected margin on the Atlantic coast of Eleuthera not only provides a source of the boulders in the exposed cliffs, but also the required wave energy from the open ocean.

Relative Sea Level and Timing of Boulder Deposition

Petrographic composition and A/I ratios of the boulders are the same as *in situ* middle Pleistocene, recrystallized, stage 9 or 11 oolitic-peloidal limestone (Hearty, 1998) exposed at the base of the eastern cliff faces of north Eleuthera (Figs. 4 and 5). The highly recrystallized boulders rest in an inverted stratigraphic position on aragonitic substage 5e oolitic eolianite and entisol.

The maximum age of boulder deposition of ca. 120,000 to 115,000 yr is established from the entisols, eolianite, and regressive beach deposits underlying the boulders. The +2.5 m beach deposits indicate that sea level was falling from the

TABLE 3
Amino Acid Ratios (A/I) from *Cerion* Land Snails and Whole-Rock Samples

Stratigraphic unit	A/I *Cerion* Eleuthera Island	A/I *Cerion* New Providence Island	Whole-rock A/I New Providence Island	Whole-rock A/I ratio Eleuthera Island	New Providence Island uranium-series ages[a] (yr)
Boulders (Table 2)				0.671 ± 0.063 (5)	
Sub-boulder entisol	0.720 ± 0.029 (4)				
Late-5e entisol		0.741 ± 0.023 (13)			
Sub-boulder 5e oolite				0.393 ± 0.011 (2)	
Late-5e oolite			0.352 ± 0.030 (3)	0.345 ± 0.005	117,000 ± 3,000
Mid-5e entisol	0.785 ± 0.014 (7)	0.806 ± 0.047 (7)			
Early-5e oolite			0.384 (1)	0.403 ± 0.004	115,000 ± 3,000 124,000 ± 4,000 128,000 ± 4,000 131,000 ± 4,000
Stage 7 skeletal eolianite			0.559 ± 0.024 (3)	0.579 ± 0.004 (2)	
Stage 9/11 oolite			0.672 ± 0.005 (2)	0.651 ± 0.030 (9)	>300,000
Stage 13? skeletal eolianite			NA	0.789 ± 0.036	

Note. The data are presented in stratigraphic order. Whole-rock values from Eleuthera identify the stratigraphic reversal associated with the middle Pleistocene boulders on younger 5e oolites. Further, boulder whole-rock ratios compare favorably with their probable Stage 9 or 11 oolitic/peloidal source beds in the adjacent cliffs.

[a] Whole-rock U-series ages from Muhs *et al.* (1990) from New Providence Island. The combined Substage 5e mean whole-rock A/I for Eleuthera and New Providence Islands is 0.372 ± 0.033 ($N = 16$).

substage 5e highstand level and did not return to a level above the modern datum. The aluminous lateritic paleosol and calcrete attached to the base of the boulders and onlapping Boulder 1 indicates the passage of a glacial lowstand *after* boulder deposition and thus establishes a minimum age (pre-last glaciation or ca. 75,000 yr) for boulder emplacement. Deposition of the boulders must have taken place when sea level was still relatively high (i.e., an interglacial highstand); otherwise even larger waves would have been required to lift the boulders over the cliff and ridge. Because there is no evidence of soil development between the boulder and underlying beds and because maximum sea level during later substages of stage 5 were significantly lower than that of 5e, these younger events are not considered likely intervals of boulder deposition. Therefore, I conclude that the early regression from the substage 5e highstand is the most probable time of boulder deposition.

Estimates of Size and Velocity of the Waves

The field setting indicates that 10 m boulders were transported landward over a coastal ridge or cliff that was at least 15–20 m high based on the evidence of substage 5e sea level lower than +2.5 m. Simplistically, this would imply that waves entraining the boulders would have to be as high as the sum of the ancient ridge height plus the minimum boulder dimension, or approximately 20 to 30 m.

Lacking sufficiently accurate models for particle transport by waves along irregular coastlines, it is necessary to adopt unidirectional flow parameters from fluvial models in order to estimate apparent flow velocity. Unidirectional flow models would apply to tsunami runup on the coastline, but not to oscillatory, breaking waves such as those created by storms. Costa (1983) established that the mean unidirectional velocity required to sustain boulder transport approximated 0.18 $d_I^{0.487}$, where d_I is the average intermediate axis of the five largest boulders. Young and Bryant (1992) estimated breaking wave velocities of 18 m/s from their studies of tsunami-generated landforms in Australia. Young *et al.* (1996) subsequently estimated flow velocities of over 10 m/s to transport 4 m boulders to a coastal ramp in New South Wales. In the case of the north Eleuthera boulders, an 8 m d_I yields an estimated velocity of about 16 m/s. The largest boulder has a d_I of 11 m, requiring a velocity of 19 m/s to sustain transport, where slope is not considered. However, not only is the velocity required to initiate movement greater than that required to sustain transport, but also the boulders were transported upslope, making these absolute minimum estimates of velocity.

Considering that the Eleuthera boulders are larger than any described in the above examples, it is reasonable to assume that flow velocity easily must have exceeded 20 m/s. Although numerous other variables and conditions are involved in the calculation of critical velocity and competence of seawater to move large rocks, this exercise provides a first-order estimate of the flow required to entrain the boulders.

The bathymetry to the east of the study area reveals a large horseshoe-shaped embayment, a submerged limb of which extends 6 km northeastward from the boulder locations (Fig. 2). The orientation of this embayment suggests that waves originating from the northeast would most likely be increased in size by the funneling effect of the submerged ridge. Conversely, the size of waves originating from the east or south would probably be diminished upon encountering the submerged ridge.

TABLE 4

Dimensions of the Ten Largest Boulders Observed along the Recent Washing Limit Near Cotton Hole, Eleuthera, in the Northern Part of the Study Area (Fig. 3)

Boulder sample #	*a* axis (m)	*b* axis (m)	*c* axis (m)	Estimated volume (m^3)	Estimated weight (tons)
1	4.9	4.5	1.2	26.5	58
2	7.8	4.7	2.5	91.7	202
3	6.4	2.7	0.5	8.6	19
4	3.8	2.5	2.0	19.0	42
5	4.3	3.6	0.8	12.4	27
6	3.8	3.2	1.5	18.2	40
7	3.0	2.7	1.3	10.5	23
8	4.3	3.0	1.2	15.5	34
9	3.7	2.1	1.0	7.8	17
10	4.3	1.7	1.5	11.0	24
Average	4.6	3.1	1.3	22.1	48

Note. The boulder limit is approximately 10 m above sea level. Most of the boulders are composed of oolitic marine and eolian facies of late Pleistocene age.

WAVE-FORMING MECHANISMS

I infer that the boulders were entrained and deposited by huge waves, probably from a tsunami, but perhaps from local bank-margin slumping or giant storms in the Atlantic Ocean.

Tsunamis

Tsunamis can be generated by submarine earthquakes, landslides, or meteorite impact. Since the cliffs of north Eleuthera face eastward toward the deep, open Atlantic Ocean and are unprotected by barrier reefs or islands, waves could strike the cliffs with unimpeded strength. However, the physical barrier created by the northeast-trending 6 km ridge offshore from the study area (Fig. 2) may restrict the effective wave penetration to the northeasterly quadrant. Indeed, the largest boulders in the region are situated at the apex of this structure. Given that, we might consider an earthquake- or landslide-induced tsunami originating along plate margins of the mid-Atlantic Ridge, or the Azores.

Although large boulder deposits have been described on islands along Caribbean plate boundaries (Jones and Hunter, 1992; Taggart *et al.*, 1993) that could be attributed to seismic sea waves, the probability of a Caribbean Plate source appears to be less likely and difficult to explain given the northeast exposure of north Eleuthera and its bathymetric setting. Meteorite impact in the Atlantic might also be considered as a potential source of a tsunami, but no information is available to support this hypothesis.

Slumping along the Bahama Platform Margin

The absence of any apparent sediment source (i.e., broad shelf) to form the large coastal ridges along the present deep-shelf margin of northern Eleuthera suggests that this margin has retreated a significant distance during the late Quaternary. Freeman-Lynde and Ryan (1985) and Mullins and Hine (1989) proposed that the steep and scalloped margin of the Bahama Banks could be explained by spalling of large blocks from the margin. Zones of fractures are present within the study area similar to those described in the Exuma Cays by Aby (1994). Detachment and sliding of large bank-marginal blocks, and the subsequent backwash could trigger locally massive surges that are potentially capable of having moved the boulders to their present positions.

Storm Waves

Holocene boulder deposits in the study area (Fig. 3) provide an indication of the force of hurricanes and storms originating in the Atlantic during the past few thousand years. The average size of the ten largest rocks is 22 m^3, with the largest measuring 92 m^3 (Table 4). A majority of these slabby, rectangular blocks appear to have been ripped up from the supratidal zone and transported about 200 m landward to about 10 m above present sea level. Abraded tracks on the bedrock indicate that many of the smaller boulders have been shifted, apparently by sliding, during recent storms, including the October 30, 1991 ''northeaster'' (originating from a deep low pressure off the New England coast) and Hurricane Andrew (August 1992). A reinforced concrete bridge spanning the 20 m gap at Glass Window was also shifted several meters off its abutments during both of these storms. The bridge is situated about 12 m above sea level and weighs several hundred tons.

If storm waves transported the Pleistocene boulders, they must have been of considerably greater magnitude than storms during the Holocene. Perhaps massive, slow-moving hurricanes or intense storms could result from the combination of warmer tropical seas of substage 5e and the compression of atmospheric cells during the rapid expansion of ice at the onset of substage 5d (Andrews and Mahaffy, 1976). Neumann and Hearty (1996) considered the transition from warmer-than-present ''greenhouse'' conditions during substage 5e to mid-glacial ''icehouse'' conditions of 5d to be a climatic ''madhouse'' in the Bahamas on the basis of geologic evidence of rapid sea-level changes, dune building, and intense storms at that time.

CONCLUSIONS

Boulders were transported over 20 m coastal cliffs of northern Eleuthera by waves after substage 5e sea level fell below +2.5 m at the end of the highstand cycle. The maximum 120,000 yr age of the giant wave event is constrained by A/I ratios of *Cerion* land snails and of whole-rock samples underlying the boulders. A minimum age of 75,000 yr is inferred from the aluminous lateritic soils attached to the boulders, which indicate a prolonged glacial lowstand after the boulders were deposited. The oolitic/peloidal composition and A/I ratios of the boulders point to their probable source among *in situ* middle Pleistocene strata exposed in cliffs along the Atlantic Ocean margin.

The waves that transported the boulders may have been initiated by tsunamis, local slumping of the bank margin, or massive storms. The unidirectional flow generated by a tsunami is capable of transporting very large blocks, but if massive storms were responsible, they must have been much larger than those occurring during the Holocene. These findings may have important implications related to global warming during the present interglaciation.

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