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Superstorms: Comments on Bahamian Fenestrae and Boulder Evidence from the Last Interglacial

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ABSTRACT

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Sea level during the last interglacial (Marine Isotope Substage 5e [MIS 5e]) was ~6 m above present, interpreted to represent a warmer climate, with increased storm intensity and storm frequency. Two hypotheses have been advanced to demonstrate an increase in storm intensity during MIS 5e. The first considers fenestrae in eolian calcarenites at elevations up to 43 m in the Bahama Archipelago to be evidence of superstorm washover. Additional observations include rip-up clasts and loss of bedform and root structures as a result of wave scour. Such an event should produce a tempestite with a wide-ranging footprint, but none exists above 10 m. This paper argues that the fenestrae are rainfall slurries, rip-up clasts are weathering products of calcarenite protosol development, and bed-form and root structure absence or presence reflects transgressive-phase *vs*. regressive-phase eolian formation, respectively. In the second case, a 2-km section of the coast of Eleuthera Island contains boulders proposed to have been tossed upward onto the land by superstorm waves, creating an age inversion of older boulders lying on younger rock. These boulders are now karrentisch and rest on pedestals produced by denudation. To emplace them would require extreme energies, but other interpretations such as fossil tower karst and boulders rolling downslope remain viable alternatives. The proposed chronology of boulder emplacement at the end of MIS 5e conflicts with the field evidence of a terra rossa paleosol separating the pedestals and the boulders. A recent paper has argued that normal hurricane activity could have emplaced the boulders. Both of these interpretations fail to explain the lack of similar-sized boulders elsewhere in the Bahama Archipelago. The failure to account for past coastline configuration, cave development in the boulders, and post-MIS 5e boulder denudation makes both boulder analyses incorrect, as discussed herein.

ADDITIONAL INDEX WORDS: *Eleuthera, karst denudation, wave energy, coastline configuration.*

INTRODUCTION

Future "superstorms" have been a topic of conversation within the debate centered on climate change. The major thesis is that increased thermal loading of the atmosphere and sea surface will lead to either an increase in the number of subtropical cyclones (tropical depressions, tropical storms, and hurricanes) on the coasts of North America and elsewhere, an increase in the intensity or strength of subtropical cyclones, or both; a decrease in storm frequency may also occur (*e.g.*, Bender *et al.,* 2010; Elsner, Kossin, and Jagger, 2008; Knutson and Tuleya, 2004). To anticipate the future of superstorms, it is useful to examine the rock record to determine if such storms had occurred in earlier, warmer times on Earth. The nearest proxy in time is the Last Interglacial, or Marine Isotope Substage 5e (MIS 5e), 124–115 ka (Thompson *et al*., 2011). During MIS 5e time sea level is believed to have been at least ~6 m higher than at present, as a result of the planet being slightly warmer (1.1–1.3°C warmer during MIS 5e; Hoffman *et al*., 2017). Did this warming lead to superstorms?

Recently, several papers and field trips involving the coastal geological community have focused attention on an area on northern Eleuthera Island, Bahamas, at an area called the Cow and Bull (Figure 1), where it has been suggested that a superstorm that occurred during MIS 5e deposited giant boulders on the landscape (Hearty and Tormey, 2017 and references therein). In addition, fenestral porosity found in Pleistocene eolianites across the Bahamas, specifically Eleuthera, San Salvador, and West Caicos islands, have been proposed to be the result of large storm-wave washover, up to elevations as high as 43 m (Hearty and Tormey, 2017). Doubts about both of these hypotheses have been presented by this author (Mylroie, 2008, 2016, 2017) and about the boulders by Rovere *et al*. (2017). These Bahamian observations have been given international publicity, with articles appearing twice in the *Washington Post*, first in November of 2015 under the title *Another danger of climate change: Giant flying boulders?* (Mooney, 2015) and then again in October 2017 under the title *Why climate scientists are so obsessed with two mysterious boulders in the Bahamas* (Mooney, 2017). The Bahama geology

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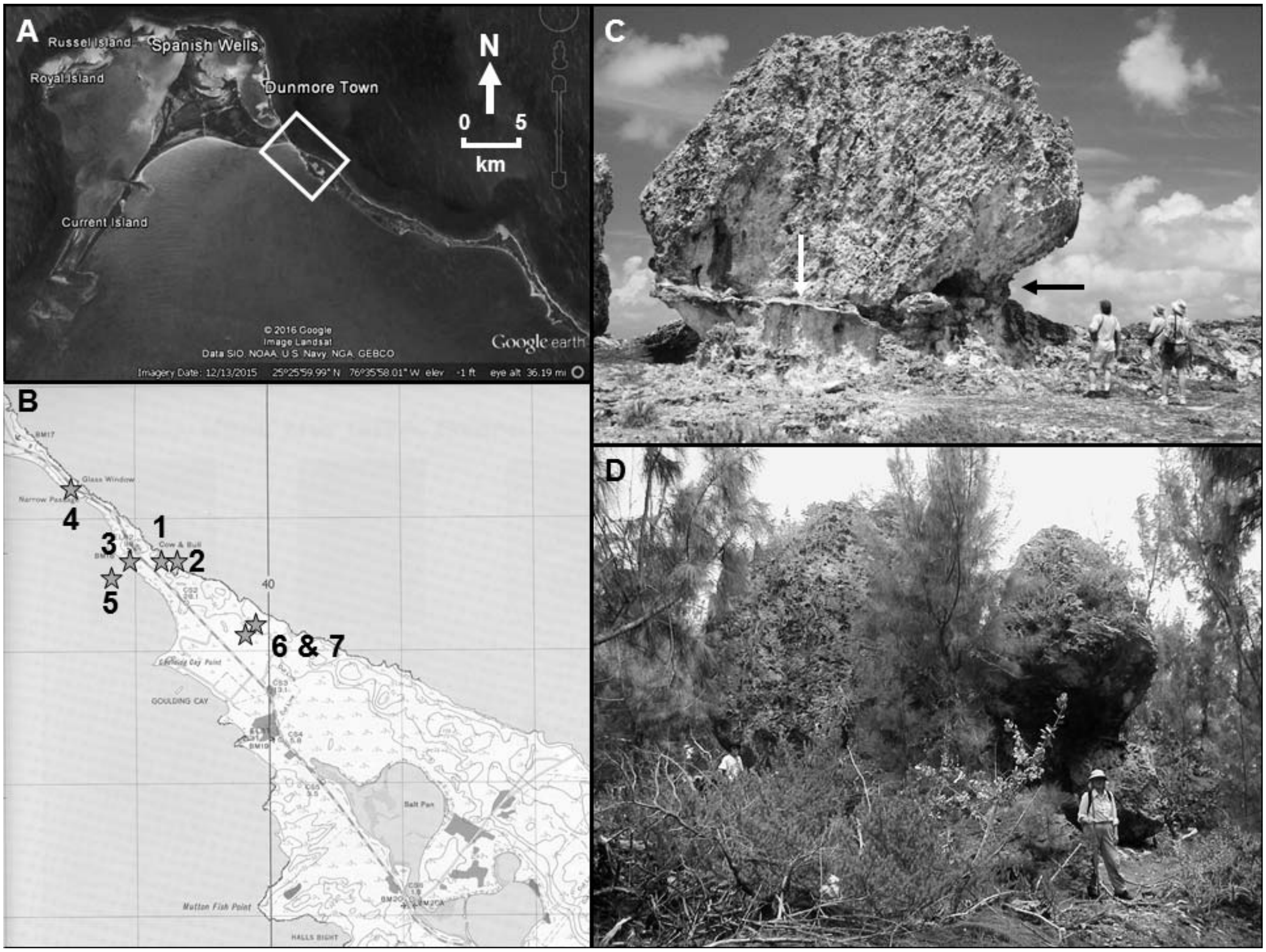

Figure 1. (A) Google Earth image of northern Eleuthera; box shows the location of the boulders. (B) Segment of the British Lands and Surveys topographic map of Eleuthera from 1970; grid is 1 km. The Cow (1) and Bull (2) are named; five other large boulders (3 through 7) are shown in approximate position. (C) The Bull or boulder 2; note that the boulder rests on a pedestal separated from the boulder by a terra rossa paleosol (vertical white arrow). A cave entrance is visible (left of the horizontal black arrow); this cave leads through the boulder to two additional entrances (see also Figure 5A). The Cow is barely visible on the left margin. (D) Boulder 3; this boulder has split and one or more of its components has rotated. A cave, with a chamber over 2 m high, exists within this boulder (Figure 5B).

discussed in this paper is based on Carew and Mylroie (1995a, 1997) and Kindler *et al*. (2010).

There is a political debate between the scientific community and people who deny climate change exists, or if it exists, that it is entirely natural and not human induced. Given that the Last Interglacial (MIS 5e) was a natural climatic warming event, sorting out climate-change drivers as natural or human induced is important. The public climate-change debate has been intense. It is important that evidence used in the scientific debate be well vetted. If at a later time such evidence is found to be incorrect, then that topic can become the focus of controversy. The purpose of this paper is not to address directly the question of superstorms, climate change, or global warming; it is solely to examine the arguments concerning the Cow and Bull and the fenestral porosity of the Bahama Archipelago purported to be rock record evidence of superstorm activity during MIS 5e. The author firmly believes that climate change is occurring, and that the change is human induced; this paper was not written to support denial of climate change.

FENESTRAE IN BAHAMIAN EOLIANITES

Fenestrae are millimeter-sized pore spaces commonly found in beaches and subsequent beach rock. These spaces formed as air bubbles are trapped in the beach sediment during the swash and backwash of waves, when the water sinks into the beach sands and the air in the pore space is expelled. They are usually round or flattened ovoid spaces, are considered diagnostic of the beach environment, and are called fenestral porosity. When infilled by cements, they are termed birdseye structures (Shinn, 1968). Bain (1985) pointed out the occurrence of fenestral porosity in late Pleistocene eolianites on San Salvador Island, Bahamas (French Bay Member of the Grotto Beach

Formation, Carew and Mylroie, 1995a) at elevations above 20 m. He attributed the development of these fenestrae not to beach process, but to rainfall slurries, an idea earlier suggested by Stieglitz and Inden (1969). Kindler (1991) independently observed similar fenestrae in Bahamian eolianites on other islands, and collaborated with Bain to publish a paper that also supported the rainfall slurry interpretation (Bain and Kindler, 1994).

In a series of abstracts, (Donovon and Tormey, 2015; Tormey and Donovon, 2015; Tormey, Donovan, and Hearty, 2016), it was proposed that the fenestrae found in Bahamian eolianites well above 6 m elevation (including the Turks and Caicos) were not formed by rainfall slurries, but by wave run-up and washover, and were therefore indicators of superstorms in the Pleistocene. This argument was subsequently combined with other data (Hearty and Tormey, 2017, see Cow and Bull section) to provide a comprehensive model of superstorms during MIS 5e.

In support of this argument, the above-mentioned authors interpreted isolated clasts at high elevations in eolianite facies as rip-up clasts and breccias caused by wave washover, which also removed root structures (rhizoliths) and bedding by wave scour. Such breccia deposits are common in the Bahamas at elevations within 8 m of modern sea level, consistent with attack of back-beach dunes by wave processes during the +6-m MIS 5e sea-level highstand (Carew and Mylroie, 1985; their Figure 4); however, interpreting such blocks higher in the eolianite section as storm-wave clasts is controversial. The authors may be conflating multiple processes to the same cause. Disarticulation of eolianite material in a calcarenite protosol horizon (Figure 2) also produces breccia (Carew and Mylroie, 1995a, 1997), as does subsidence and collapse features produced by adjacent karst processes (Florea, Mylroie, and Carew, 2001). The presence or absence of root trace fossils and bedding may be tied to the origin of the dune, transgressive-phase (few roots) *vs*. regressive phase (many roots), as described by Carew and Mylroie (1995a, 1997); see also Mylroie, Birmingham, and Mylroie (in press).

Although Hearty and Tormey (2017) state that fenestral porosity is found only on the seaward sides of Pleistocene eolianites, their figures 10A and 10B show both seaward and landward sides of eolianites with abundant fenestral porosity horizons; each horizon would require a separate washover event. As the eolianites are both Grotto Beach Formation deposits from MIS 5e, and Owl's Hole Formation deposits from MIS 9, 11, and 13, the superstorm hypothesis, under the model of Hearty and Tormey (2017), would have occurred during each glacioeustatic sea-level highstand of the mid- to late Pleistocene. There is no convincing evidence presented by Hearty and Tormey (2017) to disprove the rainfall slurry model of Bain and Kindler (1994).

The wave run-up and washover model fails to explain the absence of marine shells and related material in the eolianites. A run-up to 43 m, as proposed, with the power to remove root sections and to create breccias, should have enough power to transport marine shells and leave such a record. The only shell material found in many of these clast horizons are land snails (Figure 2C), supporting a pedogenic origin (occasional marine gastropod shells, transported by hermit crabs and also dropped by birds, can be found in Bahamian eolianites, but are not solely associated with fenestrae horizons).

Essentially, Hearty and Tormey (2017) are describing a tempestite, the type of deposit produced by catastrophic storms. Such deposits are not common in the Bahama Archipelago, but can be found in the SW side of Providenciales, Turks and Caicos (Figure 3). A tempestite should show evidence of nonselective transport, *i.e*. many sizes and shapes of clasts and particles should be present. The deposit should also have large areal footprint indicative of a large storm event, as opposed to a small footprint caused by focusing of wave energy by coastal and lagoonal configuration. As seen in Figure 3, the clasts are of a variety of sizes; the large clasts, including coral fragments, have been rounded, and shell material is ubiquitous. The coastal outcrop extends for more than a kilometer. Such features are not found in the eolianites described by Hearty and Tormey (2017). Although wave energy should dissipate with height, and clast size thus decrease with altitude, if a run-up of 43 m is hypothesized, then significant tempestite deposits would be expected at least at the 10- to 15-m elevation position, which would have experienced higher wave energies. To form fenestrae in the eolianites, by whatever mechanisms (slurry *vs*. washover), those fenestrae had to occur while the eolianite was still an uncemented sand. As the fenestrae occur repeatedly within the same dunes, dune growth was also occurring at the time of fenestrae formation. Tempestites, if present, would have been preserved within the dunes at the same time but none are found in the Bahama Archipelago above 10 m.

COW AND BULL AREA, ELEUTHERA

The Cow and Bull (Figure 1) are two of seven very large boulders first described in detail by Hearty (1997) as having been emplaced by large waves; the origin of the waves was interpreted as either from a local bank margin collapse, a tsunami, or perhaps from a giant storm (later to be called a "superstorm"). The bank margin failure and tsunami interpretations have been discarded in favor of a storm mechanism following the superstorm hypothesis (Hearty and Tormey, 2017 and references therein). The seven boulders are found along a 2-km section of Eleuthera (Figure 1B). Hearty (1997) identified the boulders by numbers, the Cow and Bull being boulders 1 and 2; boulder 3 is west across the road from the Cow and Bull, boulder 5 is close to shore in the shallow lagoon west of the Cow and Bull, and boulder 4 is west of the road just north of the Glass Window Bridge. The two easternmost boulders, 6 and 7, are SE of the Cow and Bull, and NE of the highway; they are noticeably smaller in size than the other five, and will not be discussed further. Hearty (1997) and Hearty and Tormey (2017) have hypothesized that the boulders were flung up and over a MIS 5e sea cliff by a superstorm (as the energies involved would be necessarily high), placing rock from low in the cliff, and therefore older than the rock on top of the cliff, into their present position on top of the cliff. Hearty and Tormey (2017) listed numerous global examples of large boulder movement caused by storm action. It is important to note that none of the large boulder examples discussed was presented to have been emplaced by carrying those boulders up and over a large cliff as is the argument for the Eleuthera boulders. Rovere *et al*. (2017)

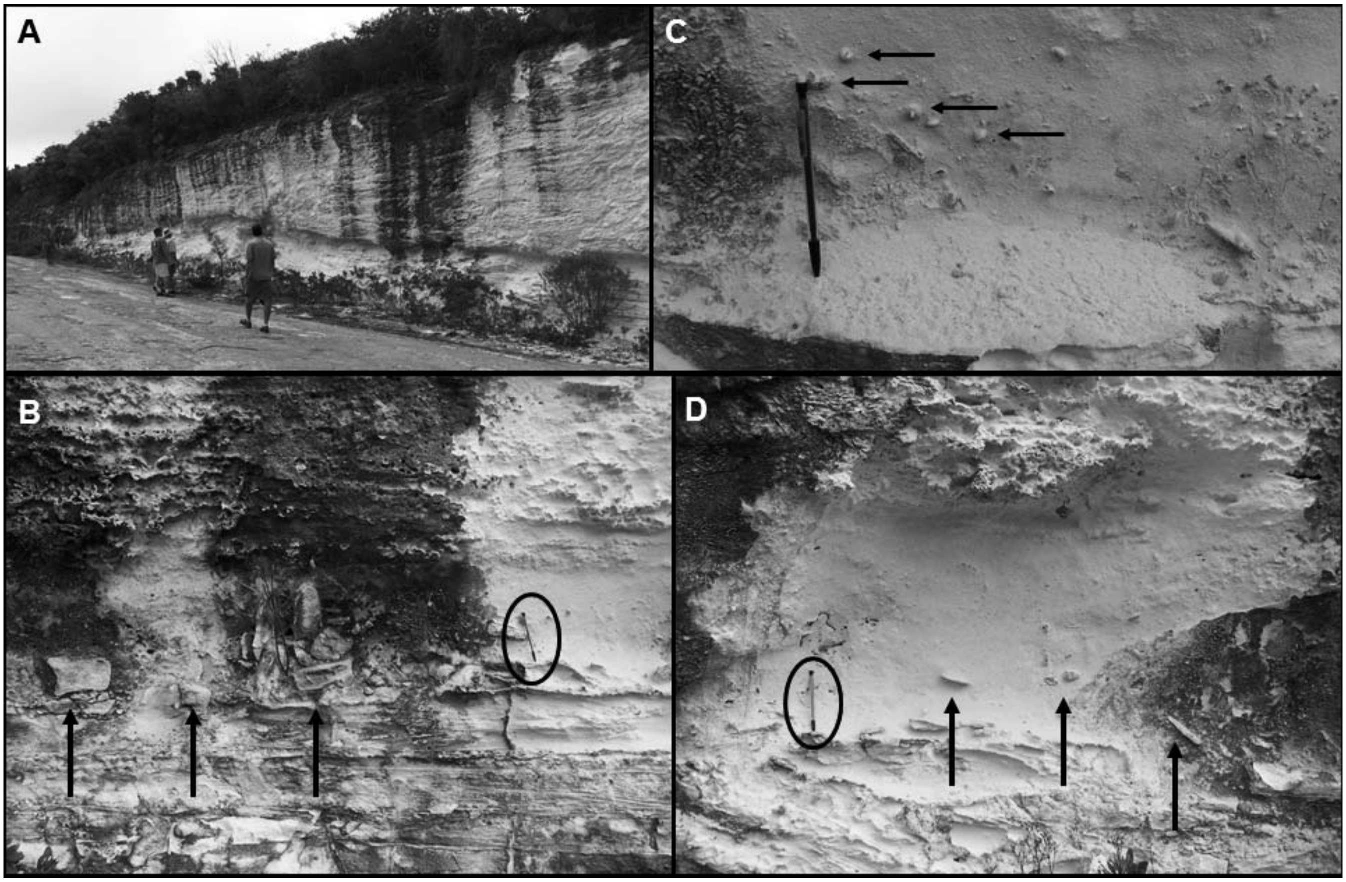

Figure 2. Twin Pines road cut, central Eleuthera (see Kindler *et al*. [2010] for a full description). (A) Road cut showing a calcarenite protosol within a Pleistocene dune. (B) Breccia blocks (arrows) within the calcarenite protosol produced by pedogenic processes; pen in circle and in C and D is 15 cm long. (C) Land snails present in the calcarenite protosol (arrows); no marine fossils are present. (D) Small blocks within the calcarenite protosol (arrows); note the unstructured nature of the protosol as a result of early pedogenesis before burial and entombment by the overlying dune, not the result of washover scour.

also point out this problem when considering modern analogues.

The focus of the inquiry of Hearty and Tormey (2017) was on boulders 1, 2, and 4, all of which are visible from the road and easy to find and examine. Boulder 3, somewhat obscured by vegetation (Figure 1D), also contains important information, as will be presented later. These four boulders all rest on pedestals 1 to 2 m high, indicating that denudation since boulder emplacement has been significant. Boulder 5 is in the nearshore shallow lagoon; if a pedestal exists it is buried in lagoon sands. Boulders six and seven rest in a sandy area, and if pedestals exist they are not observable, as the underlying outcrop is sand covered. Between each of the four boulders on observable pedestals is a terra rossa paleosol (Figure 1C). The boulders have acted as karrentisch (literally German for "karst tables"; Ford and Williams, 2007), where the boulder body protects the underlying carbonate rock from meteoric dissolution. Karrentisch are common in regions of carbonate rock where glaciation has left erratic blocks on the rock surface (Figure 4 A,B), but they also have been reported from tropical locations (Figure 4 C–D) where carbonate boulders have been placed on carbonate outcrops (Mylroie and Mylroie, 2017). Denudation can also cause topographic inversion that results in pinnacle development in eolianites, as seen in Rottnest Island, Australia (Mylroie and Mylroie, 2010), Rodrigues Island in the western Indian Ocean (Mylroie, Mylroie, and Middleton, 2016), and throughout the Bahama Archipelago (Carew and Mylroie, 1995a, 1997). The dissolutional denudation of young, or eogenetic, carbonates is rapid as their inherited depositional porosity can be as much as 30%, reducing the amount of rock to be removed to gain the same linear measurement of land surface lowering compared with older, telogenetic carbonates. Compare Figure 4 A,B, dense telogenetic carbonates, with Figure 4 C,E, porous eogenetic carbonates (Mylroie and Mylroie, 2017; the time span for this comparison is significantly different for the two examples). Very young eolianites (Holocene to late Pleistocene) will also be primarily aragonitic, and will dissolve a bit faster than older calcitic material (Figure 4 C,E; see Mylroie and Mylroie, 2017, their figure 4). Karst denudation is rarely recognized by workers on carbonate islands, and the assumption that exposed fossil reefs represent the depositional elevation of the living reef is not correct. Depending on local climate, the elevation loss for an exposed MIS 5e fossil reef can be 1 to 5 m (Mylroie

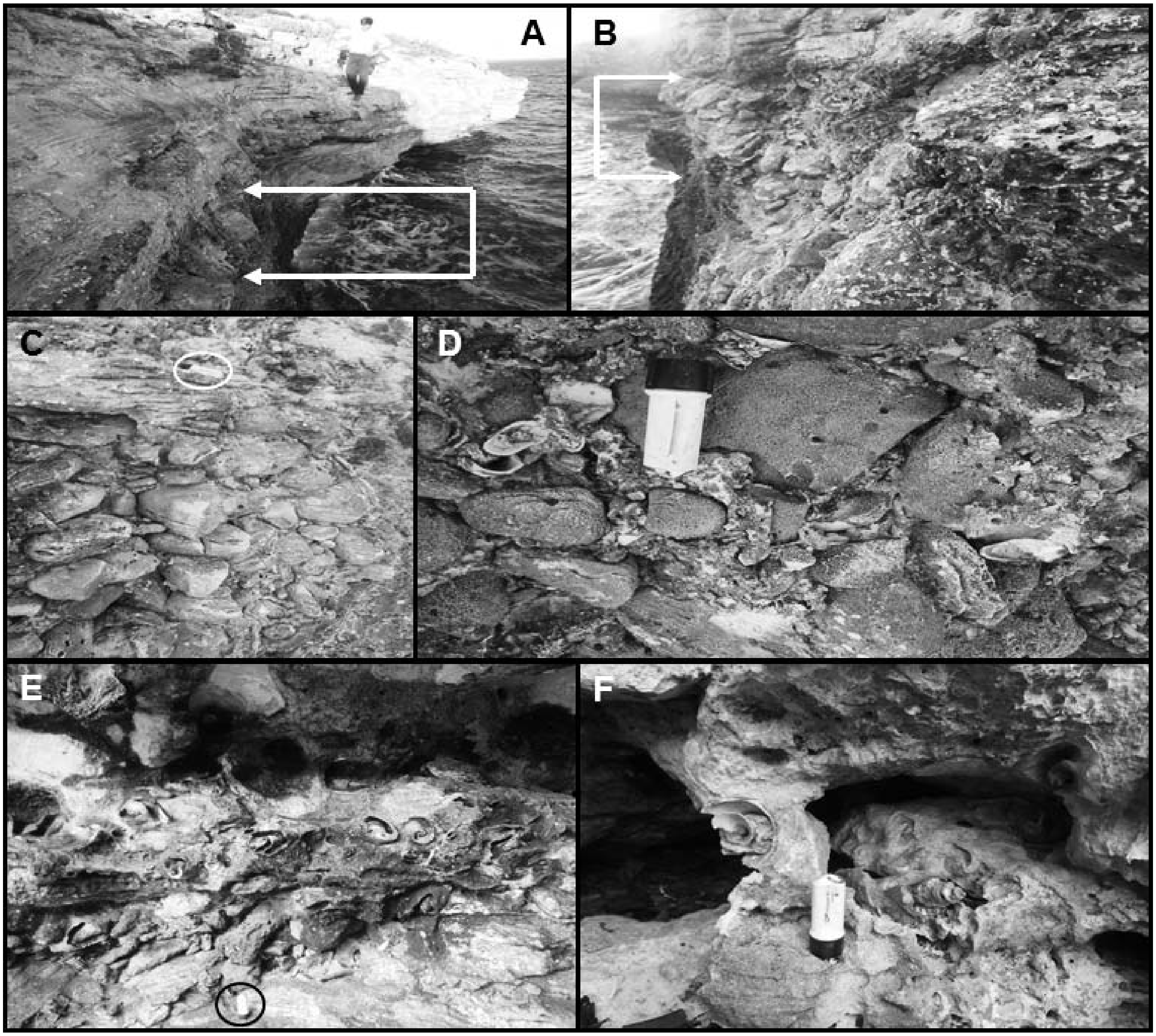

Figure 3. Tempestite outcrop from southwestern Providenciales, Turks and Caicos. (A, B) Tempestite (white arrows) in the modern coastal outcrop; an overlying terra rossa paleosol indicates a Pleistocene age. (C, D) Close-up of the outcrop in (A) and (B); small flashlight here and in (E) (circle) and (F) is 6 cm long. Note clasts are of all sizes, well rounded and contain coral and mollusk material. (E, F) One km to the west of the outcrop shown in (A) and (B) in a breached flank margin cave in Pirates Cove, where a tempestite displays its large footprint. This deposit contains abundant queen conch shells (*Strombus gigas*). Initially thought to be a cave infill, the cave was developed through the deposit, as shown in (F), indicating a pre-existing tempestite.

and Mylroie, 2017). In addition, the Bahama Archipelago is thought to be subsiding 1 to 2 m per 100 ka (Carew and Mylroie, 1995b and references therein), further lowering fossil reefs from their initial depositional position. The karst and subsidence lowering of the Bahamian land surface applies to all features, including the boulders. Given several meters of karst denudation that has occurred in the boulder area, smaller-sized boulders, rocks, cobbles, and sediment that might have been present because of possible wave transport (the bank margin failure, tsunami, or superstorm trio of Hearty [1997]) have probably been removed.

The four boulders all have phreatic dissolutional passages developed in them at their base, on top of the terra rossa paleosol that caps their pedestals (Figure 5). These caves are significant features but are unexplained by Hearty and Tormey (2017), although U/Th dating of speleothem material from these caves was utilized by them. Dense, well-laminated calcite speleothems such as the ones sampled cannot form in open-air conditions; they require the high humidity and lack of

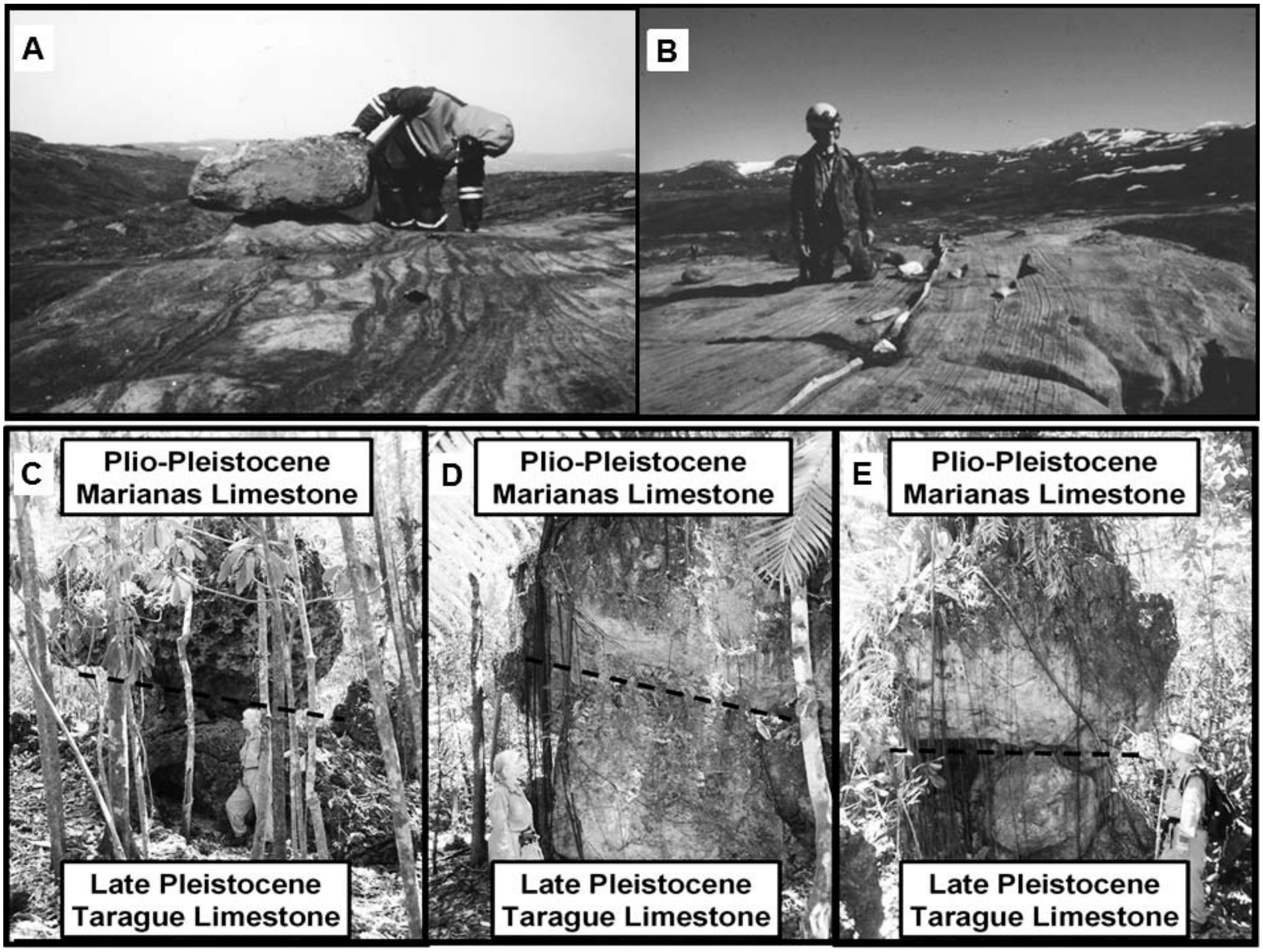

Figure 4. Karrentisch. (A) Granite boulder resting on Cambro-Ordovician marbles, northern Norway. Glaciers left this region ~8 ka, and the pedestal on which the granite boulder rests has been formed by meteoric dissolution of the marble over that time span, creating a karrentisch. (B) Setting only a few kilometers from (A), where Cambro-Ordovician marble was planed smooth by glaciation ~8 ka, and meteoric dissolution since that time has exposed an insoluble quartz vein to a maximum height equivalent to the pedestal height in (A), an independent measure. (C–E) Karrentisch formed at Ritidian Point, northern Guam, caused by calcitic boulders of the Plio-Pleistocene Marianas Formation falling from an adjacent 170-m-high cliff onto a flat MIS 5e Taraque Limestone bench, which is aragonitic. Pedestal height represents a minimum denudation measure since MIS 5e time (as the boulders could have fallen anywhere in the time span from then until the present). Adapted from Mylroie and Mylroie (2017).

evaporation found in relatively sealed cave environments (Taboroši, Mylroie, and Kirakawa, 2006). The diffusion of CO_2 from cave drip water to the cave atmosphere drives calcite precipitation for classic speleothems such as stalactites, stalagmites, and flowstone, best done without evaporative competition. Under the current open conditions of the caves in the boulders, a more tuffaceous speleothem typical of evaporative conditions develops (Taboroši, Mylroie, and Kirakawa, 2006); these tuffaceous speleothems commonly have open system problems, making them unsuitable for U/Th dating. The caves in the boulders must have been more enclosed than today when the speleothems formed, as the speleoethems are dense and well laminated, so boulder denudation has been substantial to breach the caves containing those speleothems. Any model of boulder development must take into account both denudation and how the formation of cave passages does or does not support that model.

The interpretation of these boulders as being transported upward from low on the seaward cliff by bank margin failure, tsunami, or superstorm activity, as proposed by Hearty (1997) and subsequently by Hearty and Tormey (2017), has been debated (Mylroie 2008), with two alternative explanations being offered. One explanation is that the boulders are remnant tower karst (figure 13 of Mylroie, 2008). That interpretation requires explaining the age inversion of amino acid racemization (AAR) data reported by Hearty and Tormey (2017), where the boulders have AAR ages older than the pedestals on which they rest; however, despite attributions that AAR data are accurate to a single sea-level highstand (see their figure 3), the AAR data for the boulders

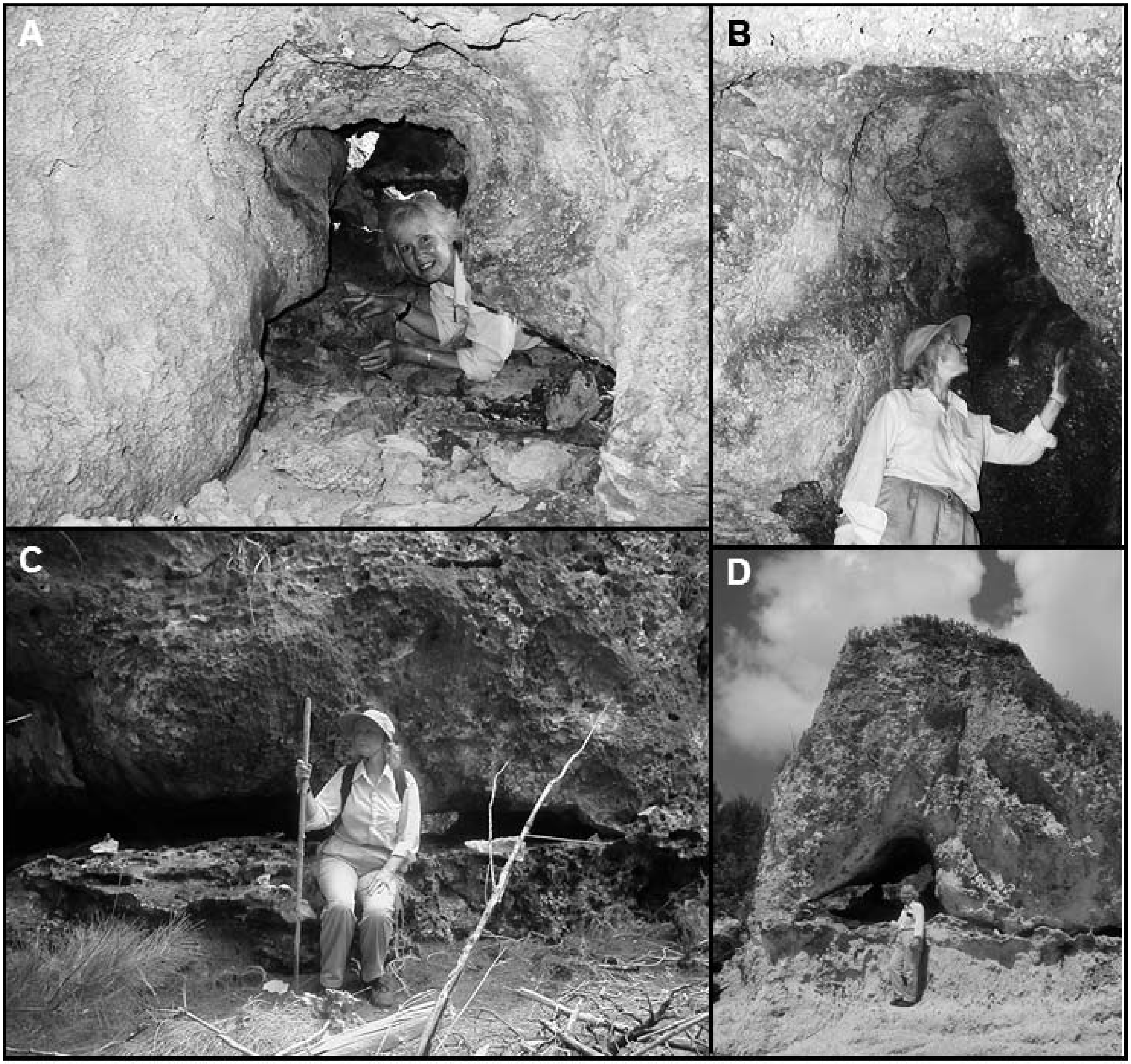

Figure 5. Cave passages in the Eleuthera boulders. (A) Cave passage in the Bull (boulder 2), displaying phreatic sculpture; the cave has three entrances around the boulder perimeter. (B) Cave chamber more than 2 m high inside boulder 3. (C) Entrances to the cave in boulder 3; subject is sitting on the terra rossa paleosol of the boulder's pedestal. Note that cave entrances are much smaller than chamber inside, and that cave runs completely through the boulder (daylight visible past the subject). (D) Boulder 4 displays a cave passage that runs completely through the boulder and rests on a pedestal capped by a terra rossa paleosol.

are ratios of 0.58 to 0.71, which, on the basis of their figure 3, yield an imprecise boulder age somewhere within MIS 7, 9, or 11. Hearty and Tormey (2017, p. 8) state that the boulders are "...MIS 9 or 11 age (300–400 kyr...")", a lack of precision that suggests that the assigned AAR age for the boulders may be problematic. Age determinations by AAR assume certain conditions about the rock unit being sampled. These boulders stick up into the environment, and are subject to solar heating from all sides, a thermal loading factor not true for flat-lying outcrops. As racemization is both a time- and temperature-controlled action, amino acids in the upstanding boulders may have racemized faster than anticipated by a simple age model, explaining the variable age data, and thusly the apparent AAR age inversion, where none actually exists. The pedestals have an AAR age from MIS 5e, which, as will be seen later, is itself problematic.

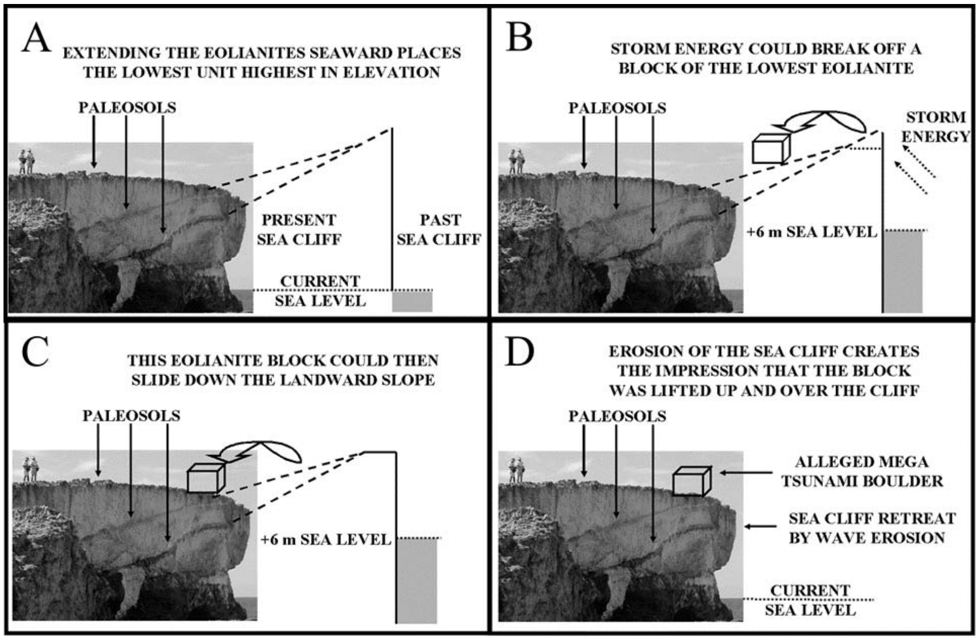

Figure 6. Cliff retreat model of Mylroie (2008), his figure 11.

The boulders are also reported to display dips of their eolian beds of 30° to 70°, the higher-magnitude dips being greater than those found in depositional settings; therefore the boulders had to be transported from elsewhere (Hearty and Tormey, 2017). This interpretation assumes that the boulders have not moved while on their pedestals. Boulder 3 demonstrates obvious rotation as it has split in two and separated (Figure 1D). Given that significant denudation has occurred to produce the pedestals on which the boulders rest, similar denudation has occurred to the boulders themselves. This denudation has altered their center of mass and their stability, so *in situ* movement such as to place low depositional dips (and other geopetal indicators such as pendulous cements) at nondepositional angles is feasible.

The tower karst model was presented as a possible alternative to a bank margin collapse, tsunami, or storm origin for the boulders. That model has many problems, for which explanations have been offered as noted above, but the tower karst model has not been disproved. The issue of cave formation is most easily explained by the tower karst model, as it proposes dissolution by phreatic water as part of a local water table perched on the underlying terra rossa paleosol acting as an aquiclude or aquitard. The caves of the Cow and Bull are located more than 6 m above sea level, so they were not formed in an island-wide freshwater lens during MIS 5e time (see Mylroie and Mylroie [2007] and Mylroie [2013] for a review of carbonate island karst processes). The caves are humanly passable (Figure 5) and show obvious phreatic speleogens. Furthermore, these caves are not sea caves or tafoni, which have different diagnostic attributes (Waterstrat *et al*., 2010). The failure of Hearty and Tormey (2017) to discuss these caves, from which they took U/Th samples, is a major omission.

A second alternative explanation (Mylroie, 2008) is that the boulders were not flung up from low on the sea cliff as proposed by Hearty and Tormey (2017), but merely rolled down from a higher elevation (Figure 6). The sea cliffs in this region of Eleuthera (and throughout the Bahamas) show evidence of significant retreat due to coastal erosion. The morphology of the stacked eolianites demonstrates that the underlying, and therefore older, eolianites rise seaward and that younger eolianites lap onto them (Figure 6). Wave energy need not be enough to lift blocks up and over a sea cliff, but only enough to fracture the cliff edge such that the boulders roll or slide downslope landward onto the younger, on-lapping eolianites to create both the age inversion and dip of beds reported by Hearty and Tormey (2017). Rovere *et al*. (2017) state essentially the same thing, that the boulders more likely rolled or slid across the bench on which they are currently found, and were not uplifted over a 15-m-high cliff (at MIS 5e time). This roll- or slide-down model explains all the observed features of the boulders with a simpler and more likely model (Figure 6). This discussion also demonstrates that Hearty and Tormey (2017) did not take into account the coastal configuration at the time of MIS 5e; they took the current coastal setting as a starting point, which leads to incorrect conclusions. Figure 7 shows examples of the scale and magnitude of coastline retreat on Bahamian eolianites and in older, more resistant rocks in New Zealand. The coastal retreat in the Bahama Archipelago during the later stages of MIS 5e (postboulder emplacement) and in the last 5000 years has been significant and use of the present coastline as the basis for interpretation is not appropriate.

This second interpretation by Mylroie (2008) fails to explain the cave development found in the boulders. If, as proposed

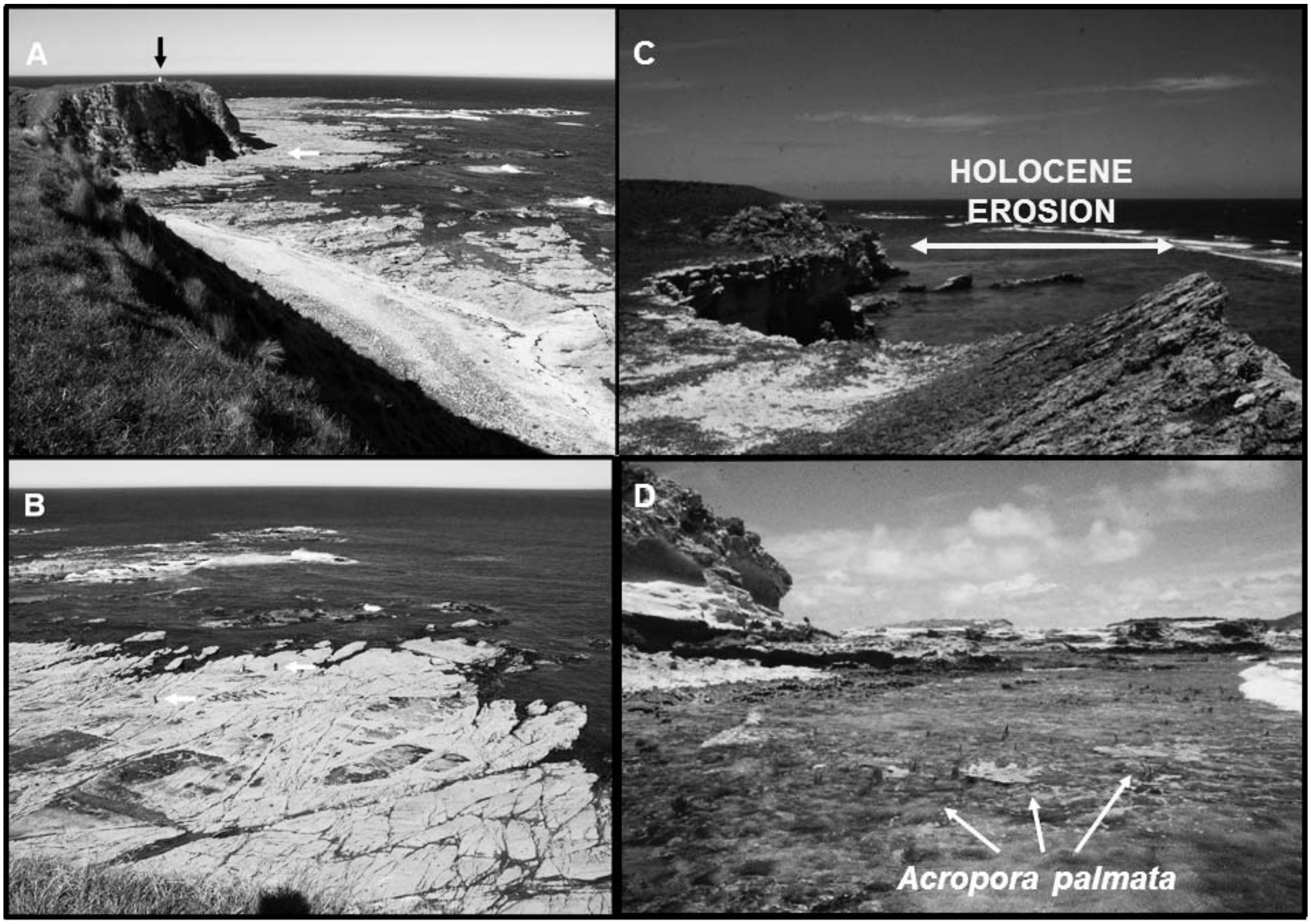

Figure 7. Coastal retreat during the Holocene. (A) Sea cliff in the Paleocene Amuri Limestone on the Kaikoura Peninsula, South Island, New Zealand. Vertical black arrow points to a building 3 m high for scale; the horizontal white arrow points to people on the wave-cut bench (too small to see at this scale). (B) Expansion of the image in (A); white arrows point to people just visible. This bench has been cut by Holocene wave action, after sea level reached modern levels about 3 ka. (C) Sea cliff developed in ~5000-year-old North Point Member eolianites on San Salvador Island, Bahamas at High Cay, demonstrates how the dune has been eroded backward to produce a wave-cut platform. Note how the eolian beds are truncated to the right; the dune obviously once extended much farther seaward. (D) Spring low tide on the wave-cut bench of (C), with living *Acropora palmata* corals exposed. The truncated North Point Member dunes form sea cliffs to the left. Dunes here were deposited ~5 ka, then truncated within the 3-ka time window since sea level stabilized at current elevations, a cautionary story for interpretation of sea coast configuration anywhere in the Bahamas during MIS 5e time.

earlier, the caves formed in a local freshwater body perched on the underlying terra rossa paleosol, the boulders would have to have been larger than they are now, as the caves today are open and dissected by denudational retreat of the boulder walls. The degree of opening of the caves suggests that the boulders were significantly larger, by meters of lateral dimension at a minimum, and the calcite speleothems indicate that the caves were once isolated from the surface evaporative environment. The tops of the boulders also have been denuded, by at least the 1 to 2 m indicated by the height of the pedestals on which the boulders rest. Some of the caves in the boulders (Figure 5B) are large enough for a human to stand up in, at least ~ 2 m high. That cave height requires that the freshwater body that created the caves be at least 2 m thick. The boulders, as currently situated and configured, cannot support a 2-m-thick freshwater body. They must have been larger, and perhaps embedded in a deposit that has since been denuded. The boulders could be the erosional remnant of larger bodies that contained the perched water body. The seven U/Th ages considered reliable by Hearty and Tormey (2017), go back to ~109 ka, indicating that these caves had to have formed after MIS 5e boulder emplacement. Hearty and Tormey (2017) argue that boulder emplacement had to have occurred near the end of MIS 5e, ~115 ka, but before ~109 ka when calcite speleothems began to form, a tight time window of only ~6 ka. Such rapid cave development has been proposed for flank margin cave genesis in the Bahamas (Mylroie and Mylroie, 2007; Mylroie, 2013), but the Cow and Bull boulders are too high in elevation to have been in a late MIS 5e seawater/freshwater mixing environment. Boulders 3 and 4, at lower elevations, could have had a MIS 5e freshwater lens. Such an environment would have been lost as sea level fell at the end of MIS 5e, so the ~6-ka time window for cave formation by the mixing method would have been even shorter in duration if the boulders were emplaced at the end of MIS 5e.

The boulders rest on a pedestal with a terra rossa paleosol between the boulders and pedestal. Terra rossa paleosols take tens of thousands of years to form. They represent surface denudation and pedogenesis over the long exposure times that separate each interglacial (Carew and Mylroie, 1995a, 1997). The red color in these paleosols comes from iron oxide, which, accompanied by other resistate minerals (*e.g.*, aluminum and titanium oxides), derived from Saharan dust blown west on the easterlies (Muhs *et al.*, 1990). Holocene eolianites do not have a red soil as their age is too young (6 ka to current) to have accumulated sufficient Saharan dust to create a terra rossa soil. They have instead a calcarenite protosol, or immature soil, appropriate for their young age. The point is, if the underlying rock of the pedestal is MIS 5e, as stated by the AAR work (ratio of 0.40) of Hearty and Tormey (2017), then why does it have a terra rossa paleosol between it and the overlying boulder, which is alleged to have been deposited at the end of MIS 5e? The pedestal deposit would have to be a transgressive-phase eolianite, formed as the MIS 5e transgression reached the top of the Bahamian platform, and lagoonal carbonate sediment production commenced. The time between that event, ~124 ka, and boulder emplacement sometime before 115 ka, is far too short to generate the mature terra rossa paleosol found between the boulders and the supporting pedestals. The AAR age data for the pedestal as MIS 5e cannot be correct. Rather, the pedestal is from an earlier interglacial, developed a terra rossa paleosol before MIS 5e, and then the boulders were emplaced on that paleosol. If the MIS 5e AAR age is correct for the pedestal, then the boulders had to be emplaced after the paleosol was formed, which would make them Holocene in origin. The pedestal denudation, cave, and speleothem data from the boulders indicate that a Holocene age is not possible. Thus, the model of Hearty and Tormey (2017) for boulder emplacement does not work. The two alternative models presented by Mylroie (2008) are not subject to the same time constraints as those of Hearty and Tormey (2017), as a sea-level highstand earlier than MIS 5e would suffice and remain workable for those models from a chronological viewpoint.

The loss of sea-level information from the carbonate island rock record as a result of denudation has been recently characterized (Mylroie and Mylroie, 2017). The failure to recognize the degree of boulder size reduction caused by denudation since boulder emplacement means that all the mathematical calculations regarding the energy needed to transport the boulders are incorrect; the investigators have assumed that the boulders today are the same size as when they were emplaced (by whatever mechanism). Because volume goes up by the cube of the linear dimension, even a few meters' larger size for the boulders means an exponential increase in boulder mass and a concurrent increase in the traction forces needed to move the boulders. The superstorm hypothesis therefore needs even greater energy than has been proposed by Hearty and Tormey (2017). These higher energy requirements therefore make either of the two models proposed by Mylroie (2008) more likely, especially the model calling for rolling or sliding of boulders downslope from a paleo sea-cliff peak (Figure 6).

Another problem with the superstorm hypothesis is the extremely small footprint represented by the boulders (Figure 1 A,B). It is only 2 km long. Why are boulders of this size and character found only here, and not elsewhere in the 1000+-km extent of the Bahama Archipelago from Grand Bahama to the Turks and Caicos? Recent storms (Figure 8), such as Katrina and Sandy, had huge footprints; Hurricane Joaquin in 2015 was a category 4, the largest to strike the Bahamas since 1866 (Berg, 2016). Superstorms by definition should have a large footprint. Was there only one superstorm that grazed only one small area of the Bahama Archipelago? If there were many superstorms, and they were big, then the Bahamas should have Cow and Bull boulders in many locations. The coastal condition and bathymetry of the Cow and Bull area as described by Hearty and Tormey (2017) is not unique in the Bahama Archipelago (*e.g.*, the coastal conditions at The Gulf on southern San Salvador Island). The fact that such examples do not exist argues against the superstorm hypothesis being correct. Hearty and Tormey (2017) call for storm-wave wash-over up to an elevation of 43 m, citing multiple fenestrae examples from Eleuthera to West Caicos, data that would indicate many superstorms, operating over multiple interglacials, with a broad footprint, and multiple storms affecting each dune reported (their figure 10 shows multiple fenestrae horizons). However, there is only one Cow and Bull local area. The Cow and Bull, and the fenestral porosity at high dune elevations, would appear to be mutually exclusive, a single event *vs*. multiple events, respectively, as opposed to mutually supportive. Only the bank margin failure scenario proposed by Hearty (1997) and supported later by Hasler, Simpson, and Kindler (2010) and Kindler *et al.* (2010) explains the single-site uniqueness of the boulders in northern Eleuthera, a scenario now rejected by Hearty and Tormey (2017).

In late 2017 Rovere *et al.* (2017) suggested that a typical hurricane storm event could have emplaced the Cow and Bull. They displayed detailed surface and nearshore bathymetric mapping of the area, and sophisticated mathematical analysis of the forces necessary to emplace the boulders. However, the work of Rovere *et al.* (2017) has four main flaws in it basic assumptions. First, as with Hearty and Tormey (2017), the authors have used the current coastline position for their calculations and analysis. In MIS 5e time, the coast was farther away, and the cliff likely higher, than they have assumed (*e.g.*, Figures 6 and 7). Their calculations originate from the wrong spatial starting point. Second, they state that the 6-m-higher sea level of MIS 5e reduced the energy necessary for boulder emplacement at this location in MIS 5e time. If that is true, then every cliff in the Bahamas that is 6 m lower than the cliff at the Cow and Bull today should have boulders emplaced during modern hurricane events such as Joaquin. This statement leads directly to the third problem, which is, where are all the other boulder sites of similar magnitude in the Bahamas from MIS 5e or from today? There are none. Finally, the boulders were far bigger when they were emplaced, and have been downsized by meters of dimension during at least 115 ka of denudation, so the starting point for the various boulder mass calculations are significantly incorrect. The

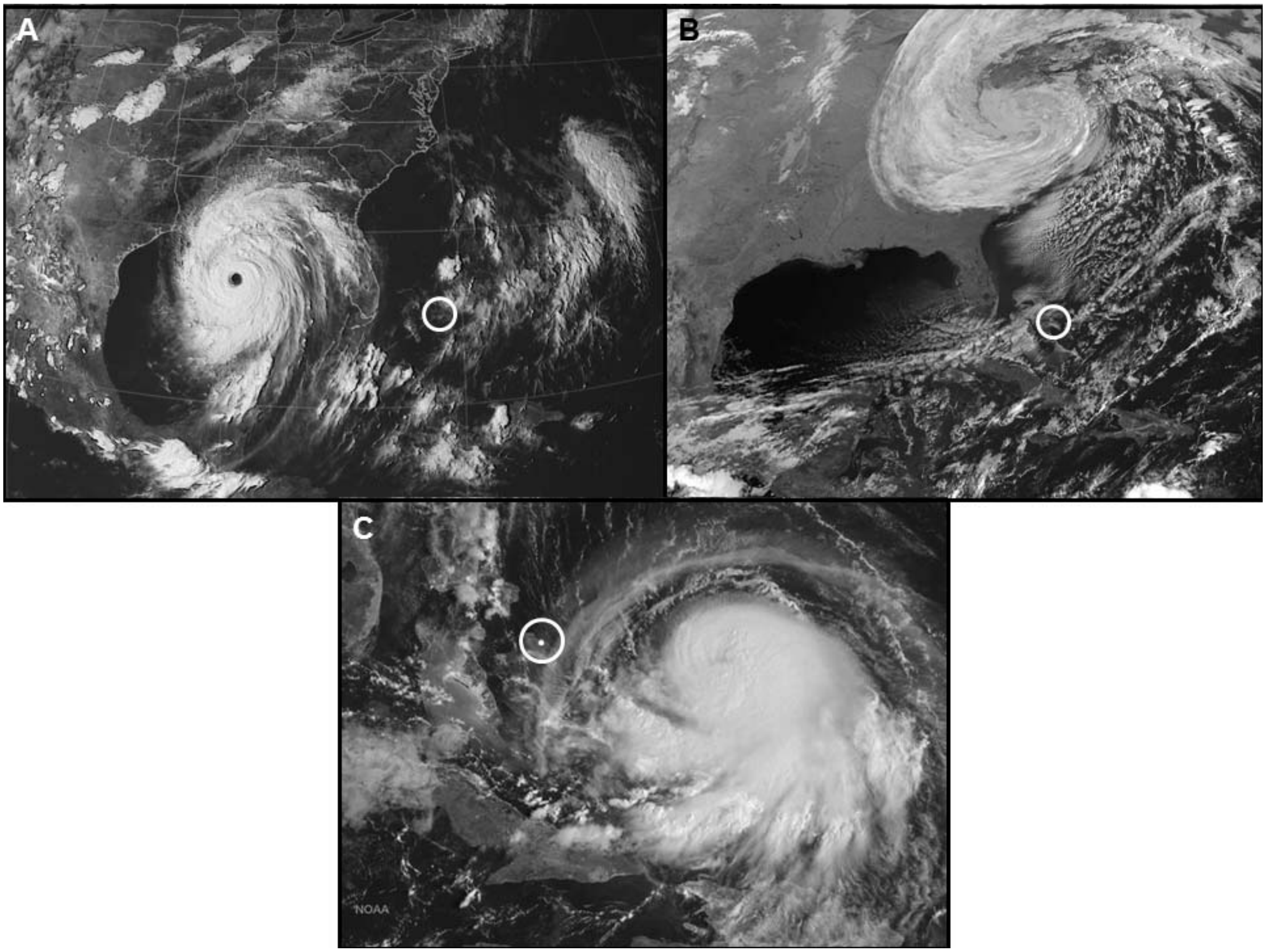

Figure 8. Recent large storms. (A) Hurricane Katrina in 2005; the white circle encompasses all of Eleuthera. (B) Superstorm Sandy in 2012; the white circle encompasses all of Eleuthera. (C) Hurricane Joaquin in 2015; the white circle and dot are the locations of the Cow and Bull. Images courtesy of the National Oceanic and Atmospheric Administration.

paper of Rovere *et al*. (2017) does not explain the caves within the boulders and demonstrates a failure to view the effects of time and space as a result of focusing solely on the immediate present-day local setting.

CONCLUSIONS

The evidence for superstorms in the rock record of Bahama Archipelago from MIS 5e events has not been demonstrated. Fenestrae at elevations up to 43 m in Bahamian eolianites are not the result of storm-wave washover but are rainfall slurries. The Cow and Bull of northern Eleuthera, and the nearby boulders, are spectacular features. Their emplacement has been a source of controversy, with papers being published in 2017 that on one hand support a superstorm hypothesis (Hearty and Tormey, 2017), and on the other hand suggest that superstorms are unnecessary (Rovere *et al*., 2017). Both papers have serious flaws as demonstrated above. The failure to account for coastal configuration present during MIS 5e time, and the subsequent denudation (including cave formation) that followed, is a major flaw of both studies. Another critical aspect of the argument is, where are all the other boulders? Superstorm emplacement (Hearty and Tormey, 2017) or routine storm emplacement (Rovere *et al*., 2017)? Why only in northern Eleuthera and nowhere else? This author has offered alternative explanations (Mylroie, 2008) for the boulders, but those explanations also fail to explain the absence of boulders elsewhere; on the other hand, those models have no need to do so. The bank margin failure hypothesis of Hearty (1997) would create a unique condition for this portion of northern Eleuthera that could have emplaced the boulders, utilizing either the model of cliff rollback proposed by Mylroie (2008), or with much larger forces than those associated with the superstorm model of Hearty and Tormey (2017) (as the boulders were larger then than they are now). That hypothesis has been previously discussed as the best option (Hasler, Simpson, and Kindler, 2010; Kindler *et al*., 2010). Because this controversy has gained the attention of the international press, it has brought this unique area into the spotlight. Strong and well-substantiated arguments need to be put forward that can be validated by all of the evidence. Multiple dating techniques, petrography, bathymetry, and mathematical modeling have all been applied to the problem. However, too many of the fundamental assumptions were flawed, leading to faulty conclusions. Future work should examine the offshore bank margin in this area of Eleuthera for megabreccias and other deposits associated with bank margin failure (*e.g.*, Mullins and Hine, 1989).

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