Supplementary material for

Effects of 2010 Hurricane Earl amidst geologic evidence for greater overwash at Anegada, British Virgin Islands

Figure S1. Overview maps.
S1-1, Regional and local index maps. Airphoto mosaic in D courtesy of British Virgin Islands Department of Disaster Management.
S1-2, Geologic sketch maps adapted from Atwater et al. (2012b).

Figure S2. Uranium-series dating of Pleistocene coral.

Figure S3. Limits of storm surge and storm waves of Hurricane Earl.
S3-1, Windlass Bight.
S3-2 West of The Settlement.
S3-3, Within The Settlement.
S3-4, East of The Settlement.

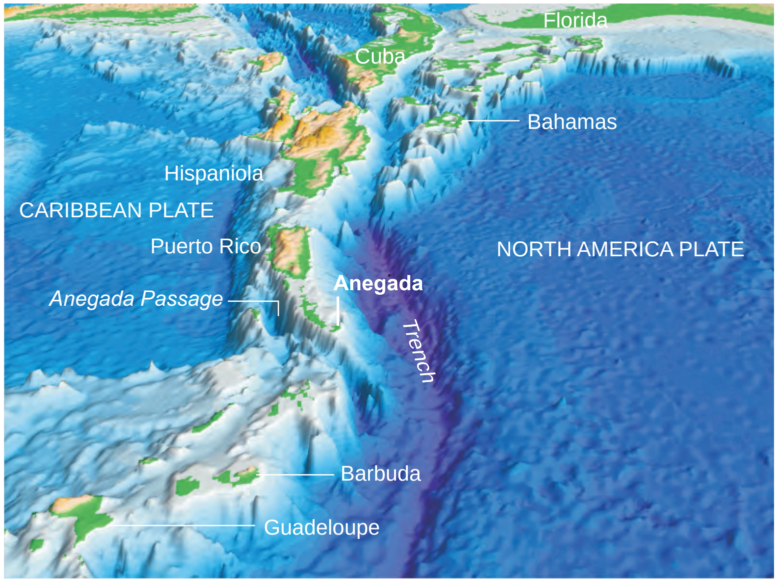
Figure S4. Spillover landforms on south shore.
S4-1, Near inlet to western salt ponds.
S4-2, West of The Settlement.

Figure S5. Spillover stratigraphy on south shore.
S5-1, Overview.
S5-2, Deposits of western fan.
S5-3, Deposits of eastern fan. Radiocarbon ages expressed as an activity ratio were converted to sidereal years with the calibration data of Hua and Barbetti (2004) and the calibration program of Reimer and Reimer (2012). The earliest age from the eastern fan (NOSAMS-89526) was calibrated with the Intcal09 data of Reimer et al. (2009).

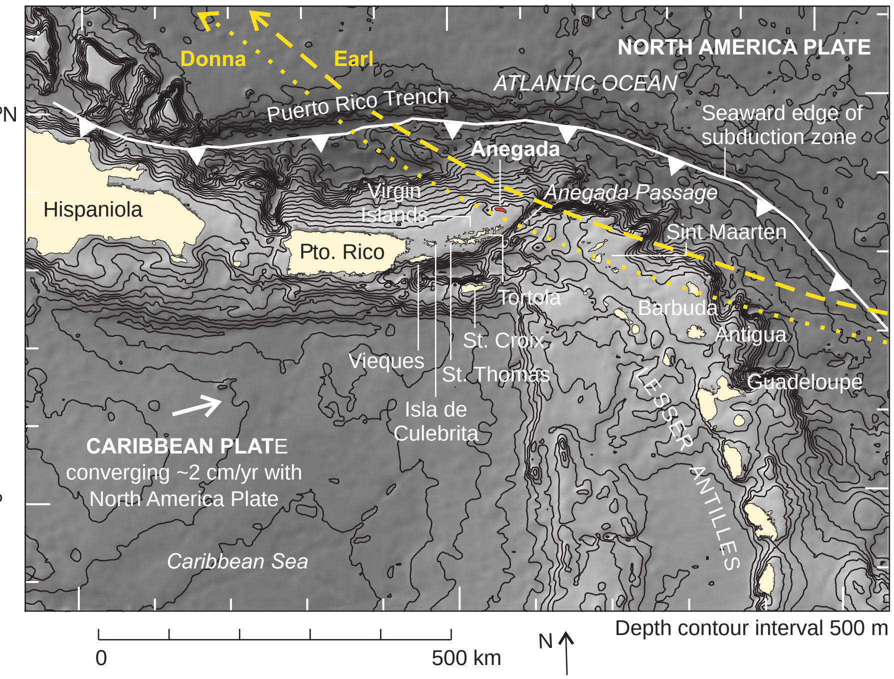
Figure S6. Comparisons between microbial detritus of Hurricane Earl and evidence for catastrophic overwash in 1650-1800 or earlier.
S6-1, Geologic setting after Atwater et al. (2012b).
S6-2, Breach north of Bumber Well Pond.
S6-3, Boulder in breach north of Red Pond.
S6-4, Cobble field in northeast Red Pond.
S6-5, Brain-coral head on playa west of Red Pond. Coral ages computed with marine-reservoir correction ΔR of 0 14C yr BP (Kilbourne et al., 2007) to -200 14C yr BP (http://calib.qub.ac.uk/marine/), Marine09 calibration data of Reimer et al. (2009), and version 6.1 of the calibration software introduced by Stuiver and Reimer (1986).

Figure S1-1 Index maps [page 1 of 2]

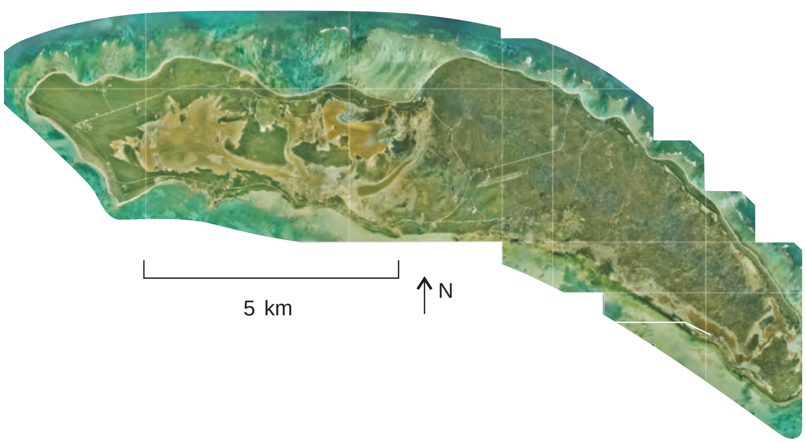
A **Perspective diagram** looking eastward



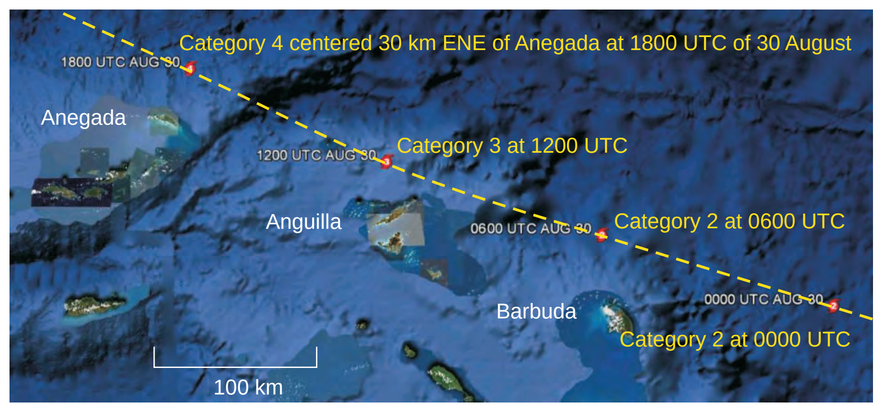
B **Tracks of hurricanes Donna and Earl**



D **Mosaic of rectified airphotos** of Anegada taken 2002



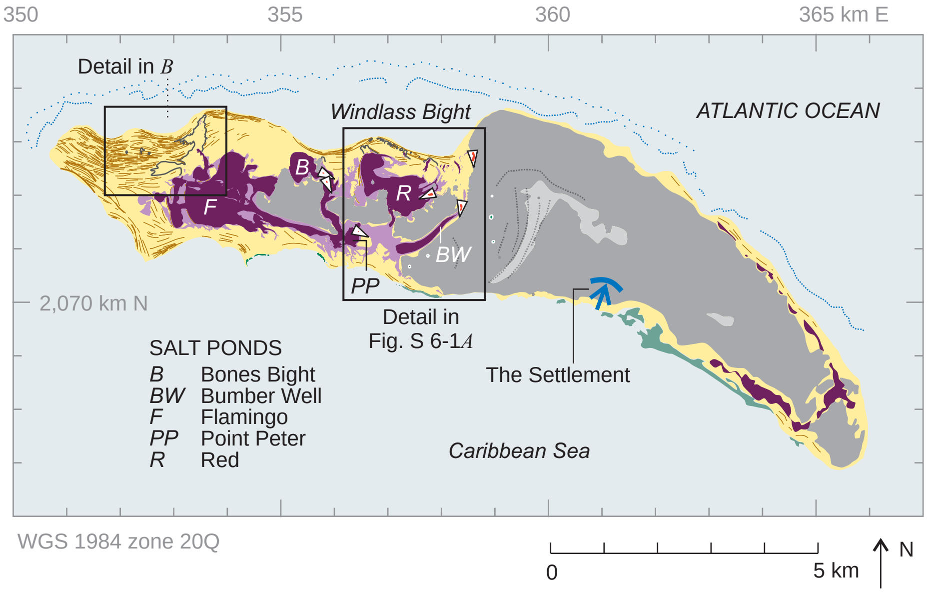
C **Track of Hurricane Earl** as it approached and passed Anegada



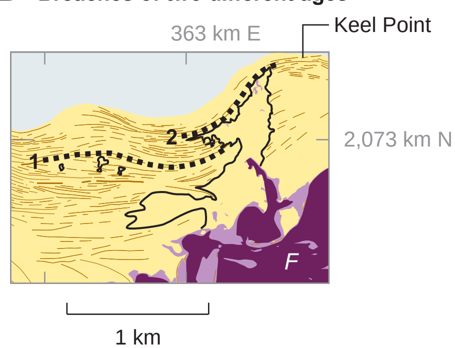
National Hurricane Center kmz file al072010

Figure S1-2 Geologic sketch maps [page 2 of 2]

A **Anegada**



B **Breaches of two different ages**



MAP UNITS

Mangrove (modern)—Swamps on leeward (south) shore

Unconsolidated deposits (Holocene)

Sand—Above seasonal high water of salt ponds. Deposited mainly on prograding beaches and their back-beach dunes

Muddy sand—Bioturbated by fiddler crabs. Mud derived from seasonal flooding by salt ponds. Upper limit mapped at lowest widespread shrubs or trees

Microbial mats and evaporite crusts—Deposited on perennial floors of salt ponds.

Boulders and cobbles—Mapped only in western half of island. Fields appended to limestone outcrops. Red symbol shows extent. White triangle shows approximate flow direction inferred from the field's elongation and probable source.

Limestone (late Pleistocene)—Surficial caliche 1-2 m thick underlain by unconsolidated bioclastic sand (Fig. S 2-1*B*) and in situ remains of corals. 121,000±166 years old where dated by U/Th methods (Fig. S 2-1).

OTHER SYMBOLS

Storm surge of Hurricane Donna (1960)—Reportedly entered from the south after passage of the hurricane's eye. Blue symbol shows generalized limit in The Settlement inferred from eyewitness accounts (Fig. S 3-3*A*).

Fringing coral reef (modern)—Sketched from airphotos taken in 2002

Seaward limit—Northern edge of spur-and-groove bathymetry

Crest—Marked by breaking waves

Beach ridge crest (Holocene)—Line dashed where ridge is indistinct or approximately located on airphotos from 2002. Line thick where ridge cuts across trend of several earlier ridges.

Margin of breach—Mapped where cuts across beach ridge or ridges. In many cases, partly encloses a small salt pond or salt flat. Margin may be depositional on windward (north) side tangent to a beach ridge.

Inferred shoreline at time of breach—Shown only in *B*. 1, older; 2, younger

Landforms in Pleistocene deposits

Sinkhole—Confirmed in field.

Lineament—Roughly north-south lines may represent bedding or sedimentary facies. Roughly east-west line to their north coincides with a topographic step that may represent a Pleistocene shoreline.

Highest parts of island—About 7-8 m above modern sea level. Data from Shuttle Radar Topographic Mission, 90-m horizontal resolution

C and **D** after Fig. S 2 of Atwater and others

Figure S2-1 Pleistocene corals sampled from sand pit and dated to 121,000 years ago [continued on next page]

A **Setting** of sand pit in mosaic of rectified airphotos taken 2002

B **Northwest wall** of pit

C **Index map** of Anegada

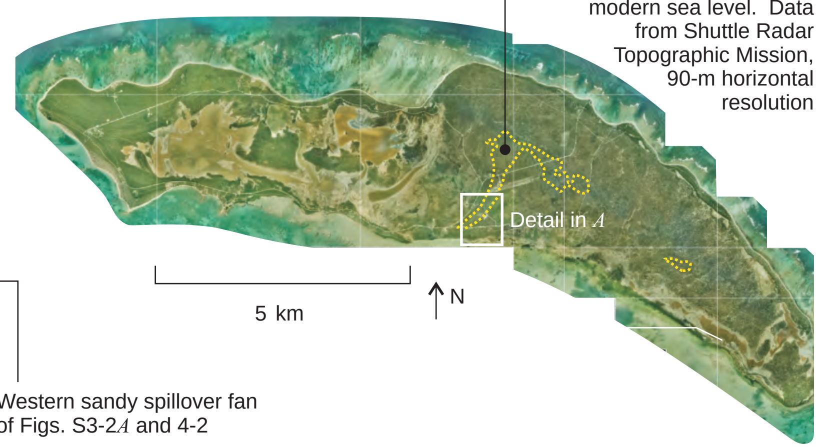


Figure S2-1 **Pleistocene corals** sampled from sand pit and dated to 121,000 years ago [continued from previous page]

D **Beach rock** slabs

Scale 20 cm (upper 6 cm partly hidden)

E ***Porites furcata*** collected for U/Th dating

Homotrema rubra Squares 1 cm

F **Results** reported by William G. Thompson, Woods Hole Oceanographic Institution

$^{234}U/^{238}U$	1.1044 ± 0.0002	Measured activity ratios[1]
$^{230}Th/^{238}U$	0.7509 ± 0.0001	
Corrected age (yr)	121,110 ± 166	Computed from activity ratios[2]
Conventional age (yr)	121,096 ± 57	
Initial $^{234}U/^{238}U$ (δ, ppt)	147.0 ± 0.3	Tests of closed system[3]
U (ppm)	2.4942 ± 0.0004	
^{232}Th (ppb)	0.9513 ± 0.0002	

Decay series

^{238}U
^{234}Pa
^{234}Th
^{234}U
^{230}Th

All uncertainties at two standard deviations

[1] For half lives of 245,290 ± 490 yr (^{234}U) and 75,690 ± 230 (^{230}Th) (Cheng and others, 2000)

[2] As in Supplementary Table 2 of Thompson and others (2011). In the conventional age, a closed system is assumed. In the corrected age, exchange of U and Th with the environment is allowed, as measured by tests above.

[3] Tests for exchange of U and Th with the environment. The initial $^{234}U/^{238}U$, computed from the age and the measured $^{234}U/^{238}U$ ratio, is within the interglacial oceanic range of Holocene data compiled by Thompson and others (2011, Supplementary Figure 1). The measured U concentration is within the 1.9-3.6 ppm range of ^{238}U in living corals, while the ^{232}Th concentration is higher than the quality-control threshold of 0.4 ppb of Thompson and others (2011, Supplementary Table 1).

Figure S3-1 **Storm-water limits** near Windlass Bight [page 1 of 2]

Figure S3-1 **Storm-water limits** near Windlass Bight [continued from previous page]

C-E **Topographic profiles** from shore to vicinity of highest wrack of Hurricane Earl

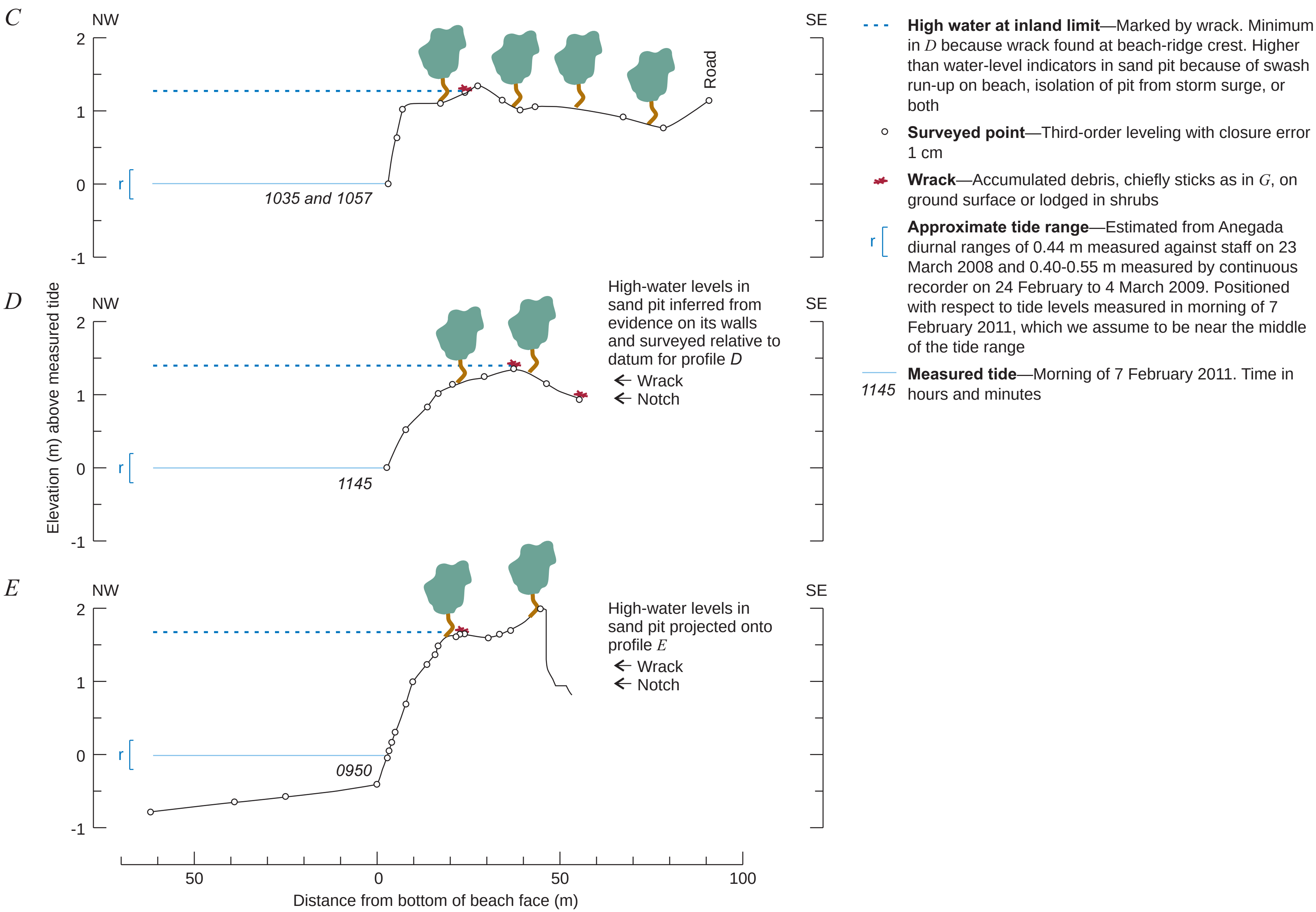
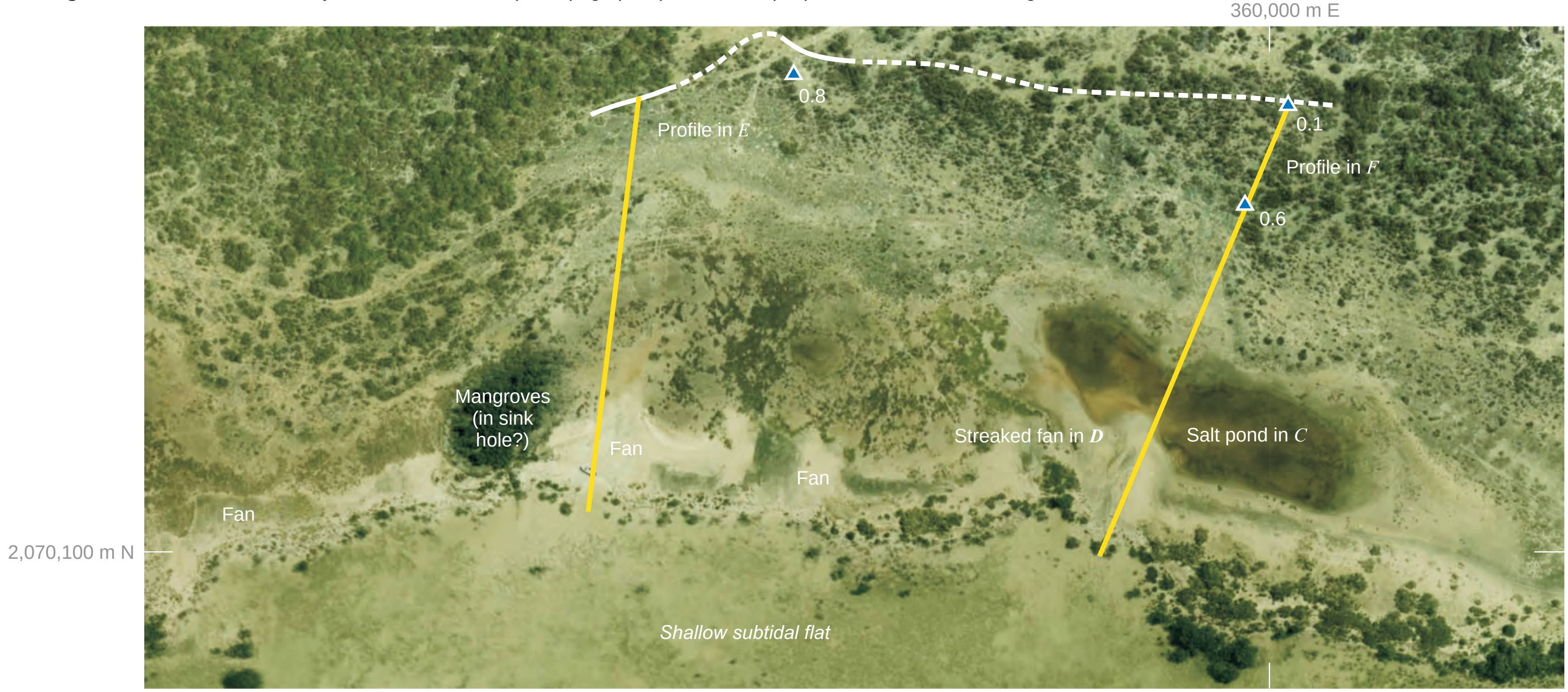


Figure S3-2 **Surge and wave limits** west of The Settlement [page 1 of 2]

A **Surge and wave limits** marked by wrack, and index map to topographic profiles. Oblique post-Hurricane views in Fig. S4-2 *A-C*



B **Index map** of Anegada

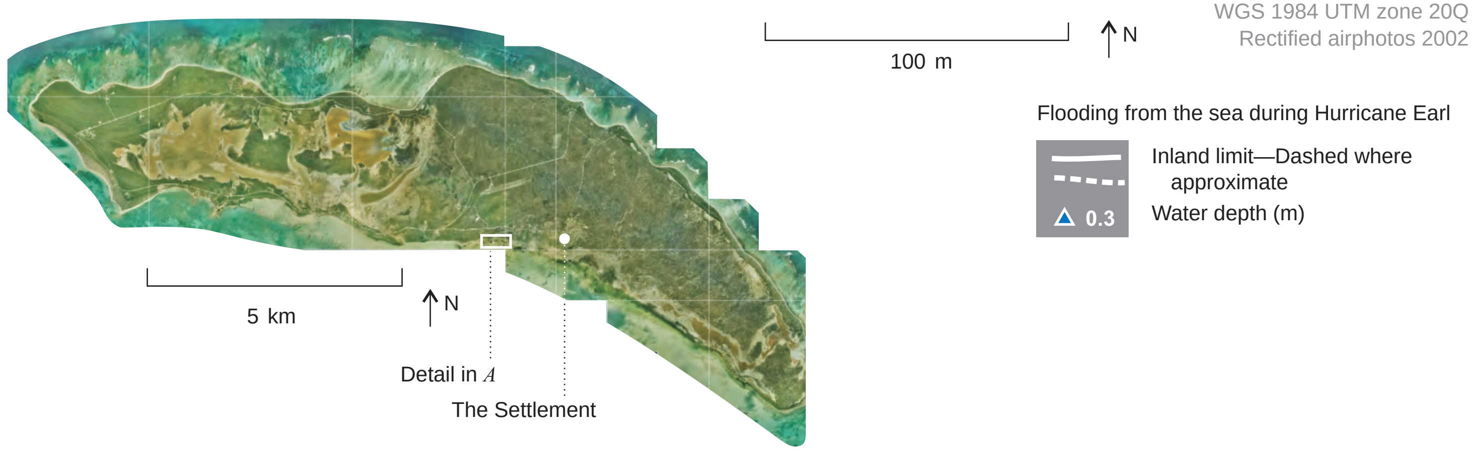
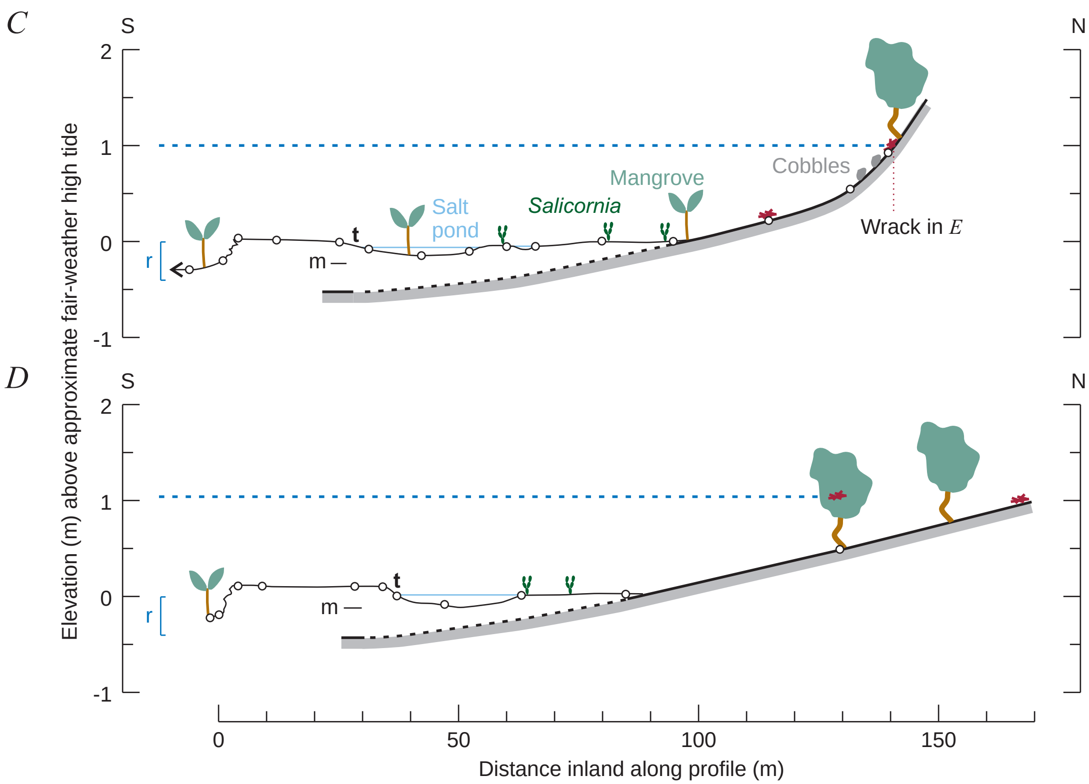


Figure S3-2 **Surge and wave limits** west of The Settlement [page 2 of 2]

C,D **Topographic profiles** from shore to vicinity of highest wrack of Hurricane Earl



- - - **High water at inland limit**—Marked by wrack
- ○ **Surveyed point**—Third-order leveling with closure error 1 cm
- t **Toe of Earl fan**—Landward limit of sandy spillover fan probably deposited during Hurricane Earl
- m— **Lowest buried mat**—Remains of microbial mat that rests on mud, which in turn extends downward to limestone (Figs. S5-1, S5-2*A,D*, and S5-3*B,F*)
- **Top of limestone**—Black line marks upper surface of caliche from weathering of Pleistocene carbonate deposits. Dashed where extensively buried and not observed
- **Wrack**—Accumulated debris, chiefly sticks as in G, on ground surface or lodged in shrubs
- r [**Approximate tide range**—Estimated from water levels and wrack lines observed February 5 and 7, 2011; and from diurnal ranges of 0.44 m measured against staff on 23 March 2008 and 0.40-0.55 m measured by continuous recorder on 24 February to 4 March 2009.
- ← **Seaward continuation**—Profile in *C* was extended 150 m southward across shallow subtidal flat. Water depths 0.2-0.5 m deep at ~mid-tide level. Bottom sandy, mounded by ejecta of crab(?) burrows.

E **Wrack**, chiefly sticks, interpreted as marking limit of surge and waves of Hurricane Earl along profile in *C*. Stripes 0.1 m long

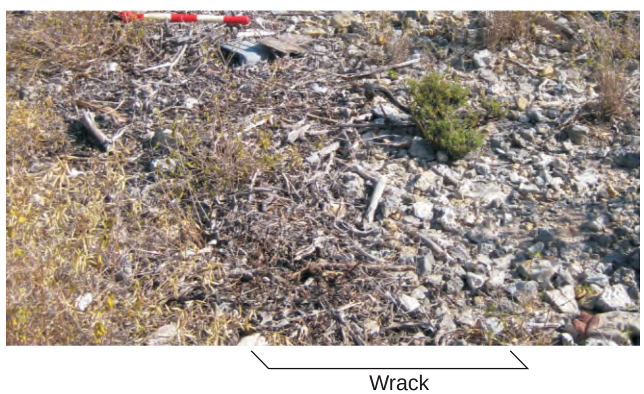
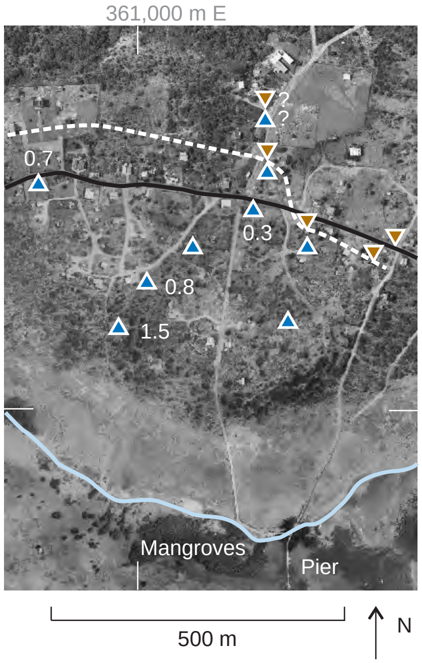
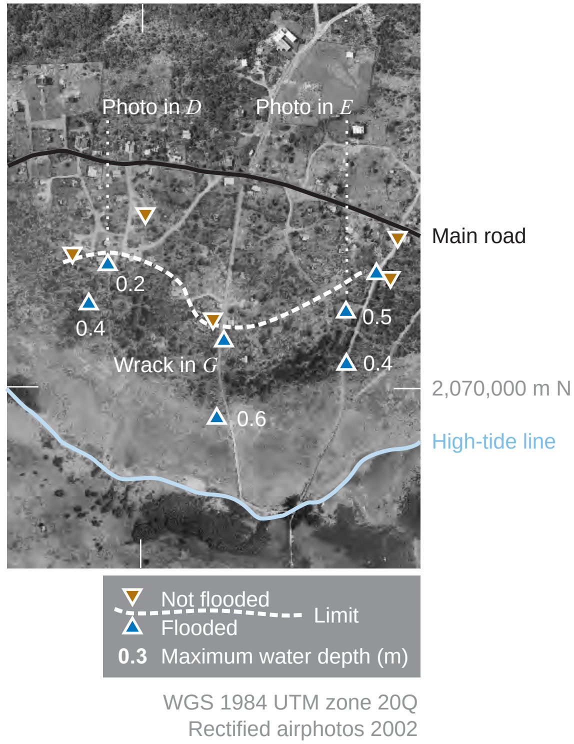


Figure S3-3 Storm-surge limits in The Settlement [page 1 of 2]

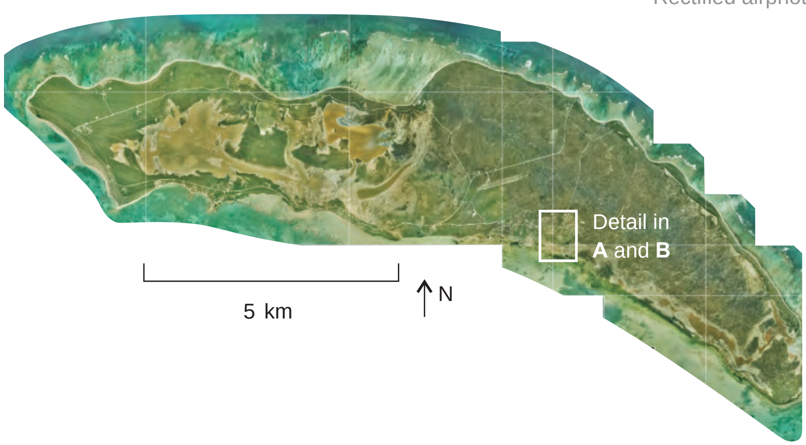
A **1960 Hurricane Donna**



B **2010 Hurricane Earl**



C **Index map** of Anegada



D **Earl and Donna limits** reported by Julian Vanterpool

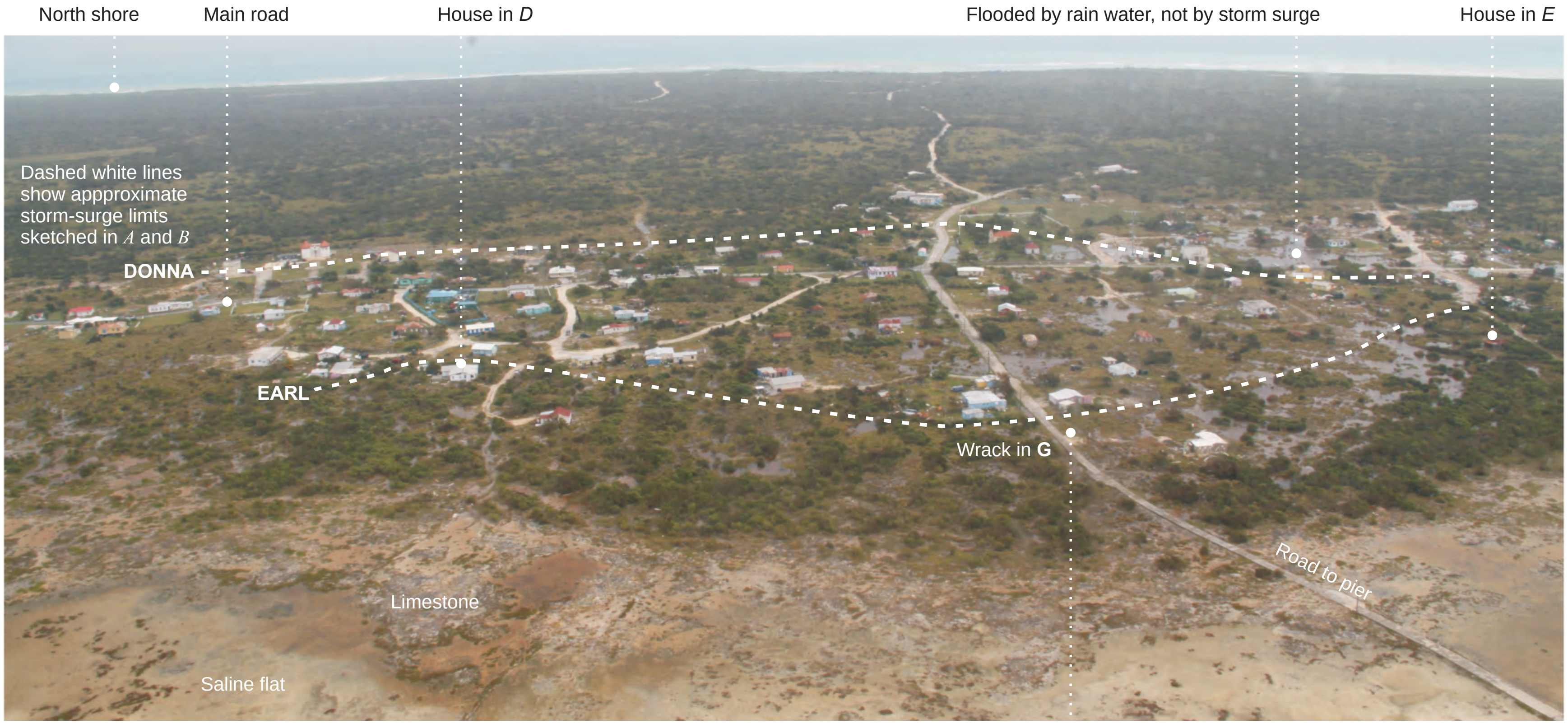
Mr. Vanterpool stated that Earl rose to the top of this step (depth labeled 0.2 in *B*), and that Donna was one foot deep at his former home (0.3 in *A*).

E **Earl limit** reported by Allen Goeff

Mr. Goeff, also known as Spouge, stated that he was in this house during the hurricane, and that the water rose about two feet against it without flooding the floor. The ruler, marked in 0.1-m stripes, shows that the underlying foundation, rises 0.7 m above the ground.

Figure S3-3 **Storm-surge limits** in The Settlement [page 2 of 2]

F **Oblique aerial view** northward, morning of 31 August 2010 (about 20 hours after Earl's closest approach)

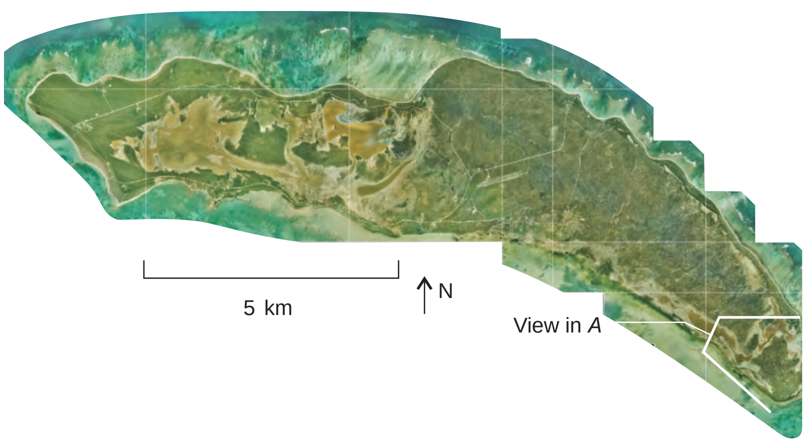


G **Most-inland of the Earl wrack** spotted along road to pier

Figure S3-4 **Storm-surge limits** east of The Settlement

A **Oblique aerial view** southeastward, morning of 31 August 2010 (about 20 hours after Earl's closest approach)

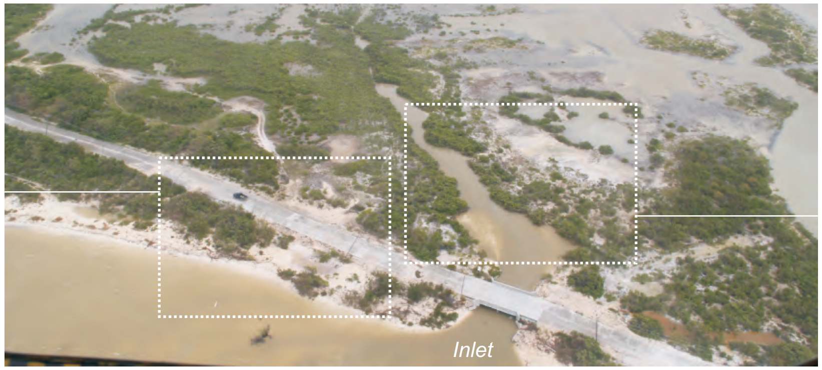
B **Index map** of Anegada



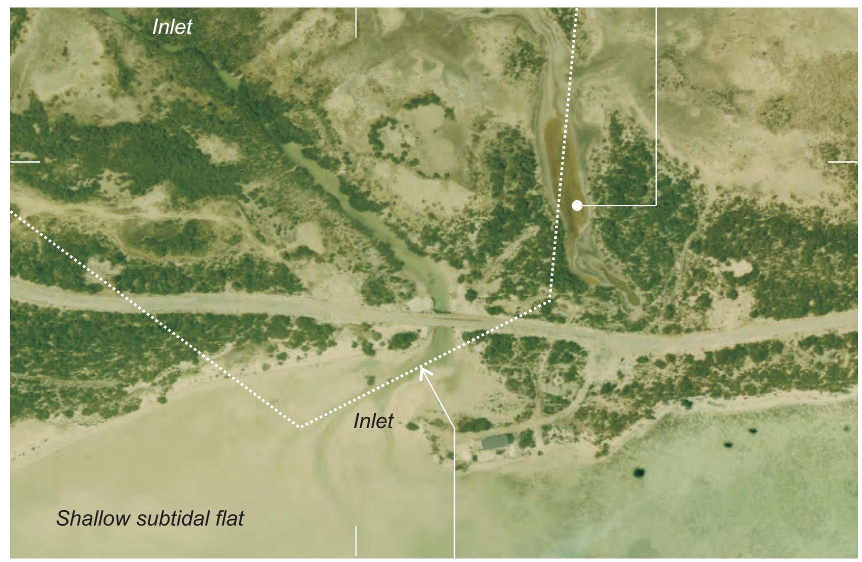
C **Wrack** of Hurricane Earl near White Bay. Shovel handle 0.5 m long

Figure S4-1 **Spillover fans** near inlet to western salt ponds [page 1 of 3]

A **Oblique airphoto** taken morning of 31 August 2010 (about 20 hours after Earl's closest approach)



B **Setting** viewed vertically in 2002



C **Index map** of Anegada

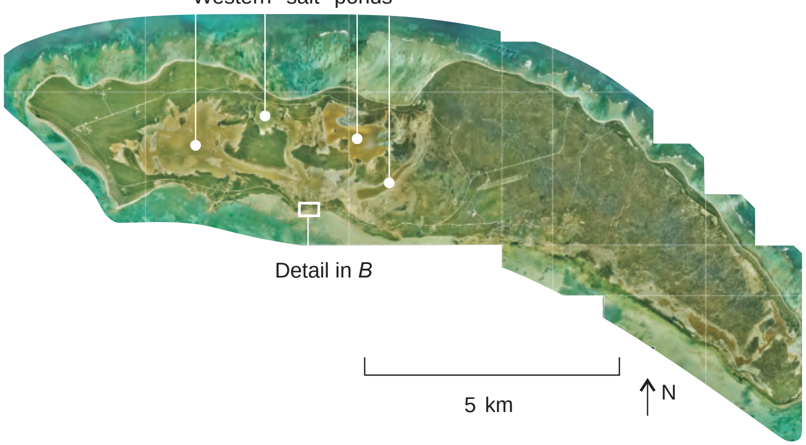
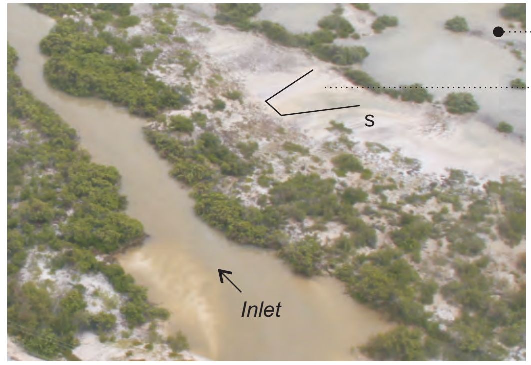


Figure S4-1 **Spillover fans** near the inlet to the western salt ponds [page 2 of 2]

D,E **Oblique airphotos** taken morning of 31 August 2010 (about 20 hours after Earl's closest approach). Location in *A*

D **Sand** west of bridge

E **Sand streaks** on bank of inlet



Still flooded the day after Earl but usually dry, as in *B*

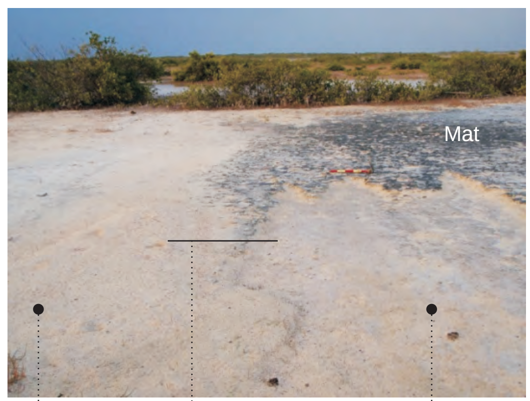
View in *F*

The sand streaks suggest that storm surge from Hurricane Earl overflowed the inlet's right bank.

s, sand that appears freshly deposited

F,G **Ground views** of sand on bank of inlet, March 2011. Shovel handle 0.5 m

F **Overview** looking away from inlet. Location in **E**

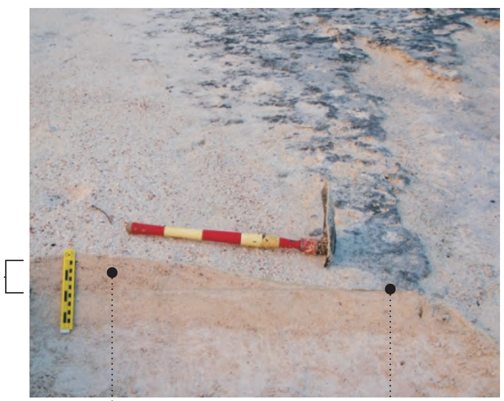


Fan of recently deposited sand and brown cerithid gastropod shells

Line of section in *G*

Microbial mat absent, apparently eroded before or during Hurricane Earl. Mat edge near shovel is scalloped inland as in scabland of Fig. S4-2*D*.

G **Cross section** through tapering fan deposits



Fan deposits

Beds dip toward fan edge

Pre-Earl mat extends horizontally to left beneath fan deposits

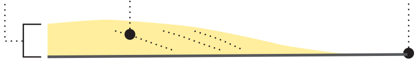


Figure S4-2 **Spillover fans** west of The Settlement [page 1 of 2]

A-C **Oblique aerial views,** southeastward (*A*) and northward (*B,C*), morning of 31 August 2010 (about 20 hours after Earl's closest approach)

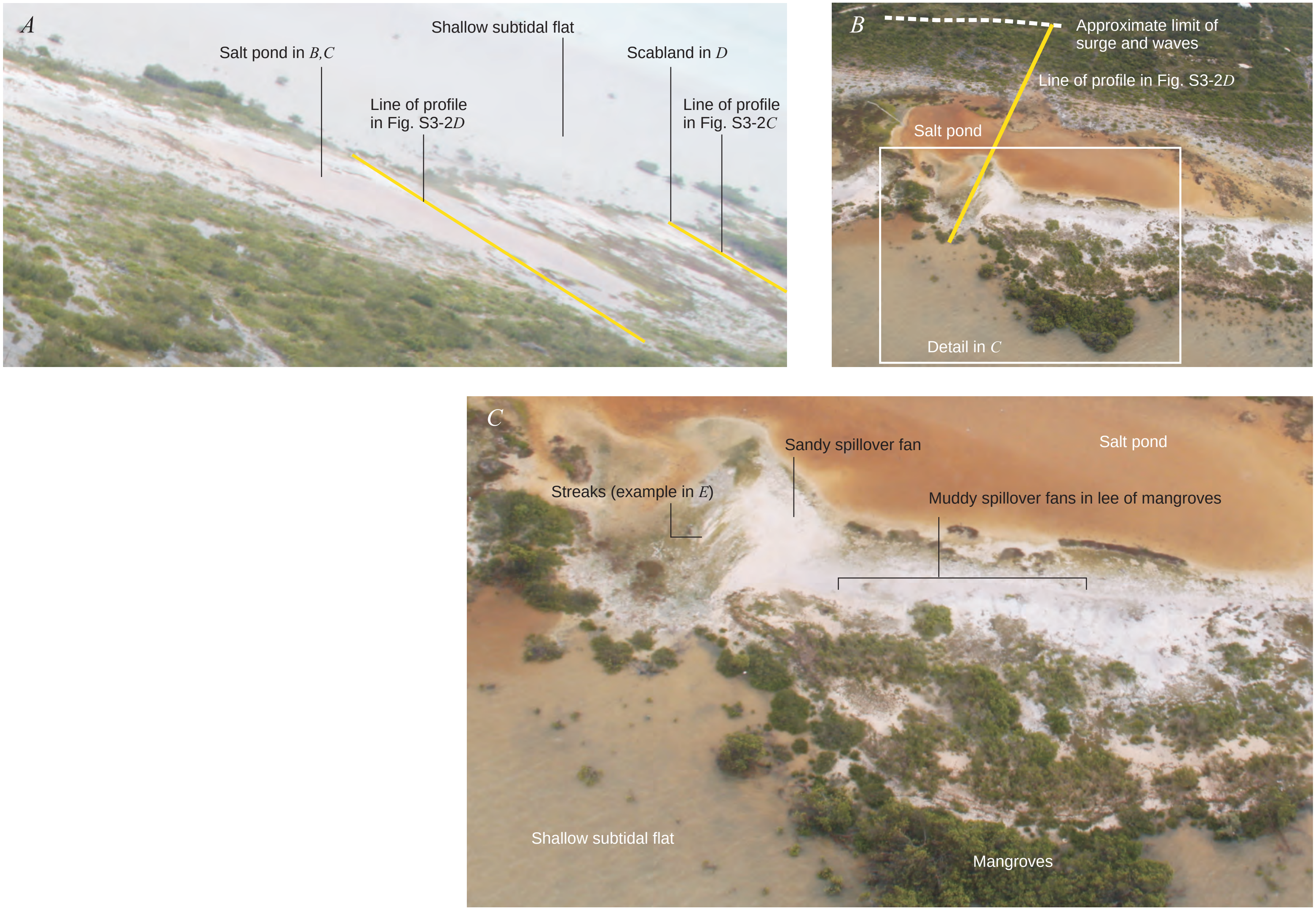


Figure S4-2 **Spillover fans** west of The Settlement [page 2 of 2]

D,E **Erosional landforms near shore,** photographed 5 months after Hurricane Earl

D **Scabland** seaward of fan, near south end of profile in Figure S3-2*C*. Patchy erosion of microbial mat has exposed the sandy mud that underlies it. Most of the mat has a thin, pale coating of lime mud. Foot for scale

E **Streak** in gray microbial mat on sandy spillover fan. The streak is made of sand, and the sand occupies a gap in the mat. Elsewhere on the fan this mat is mantled by sand that was probably deposited during Hurricane Earl. Shovel handle 0.5 m long

Figure S5-1 Overview of sandy fan stratigraphy west of The Settlement

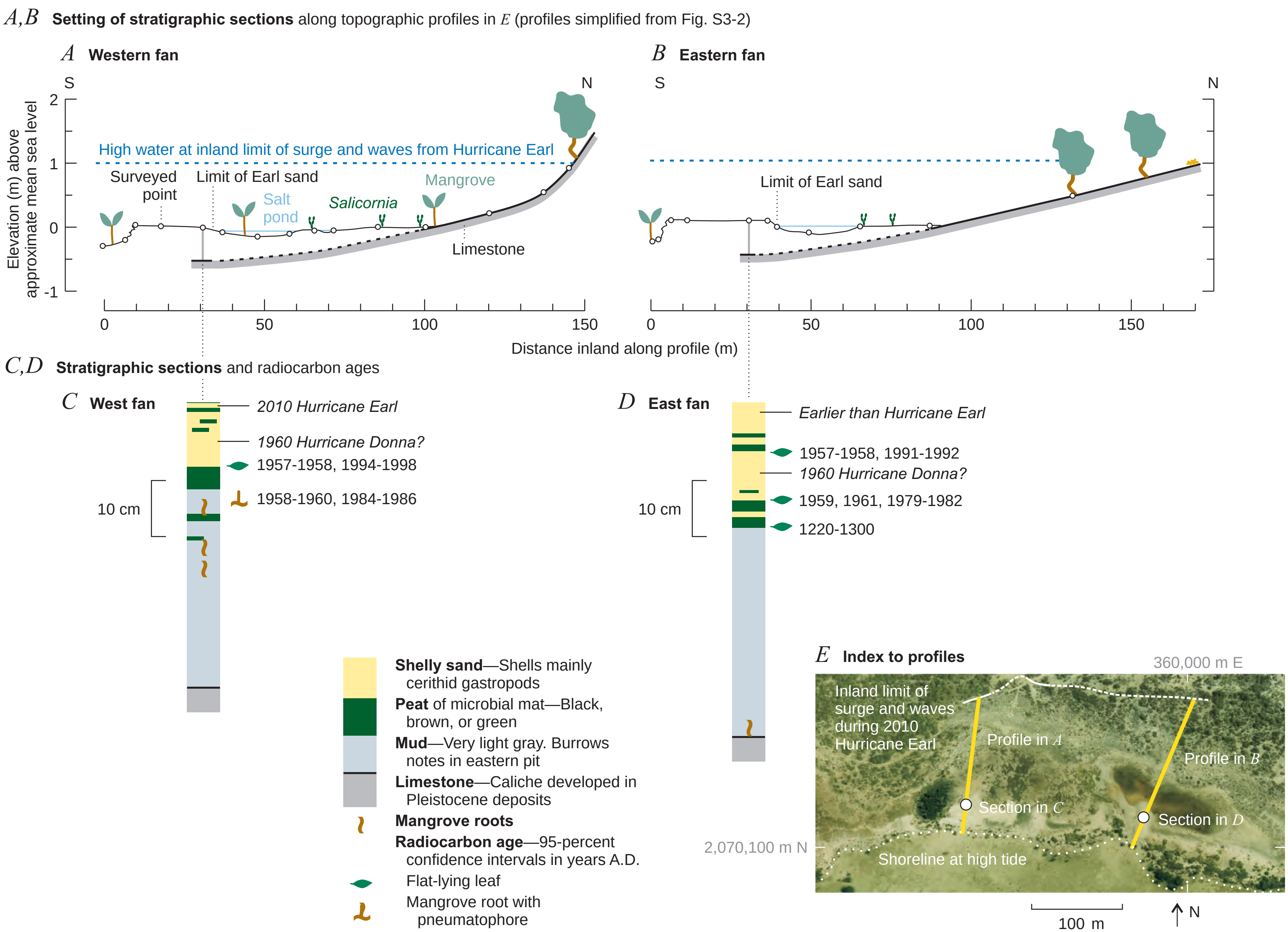
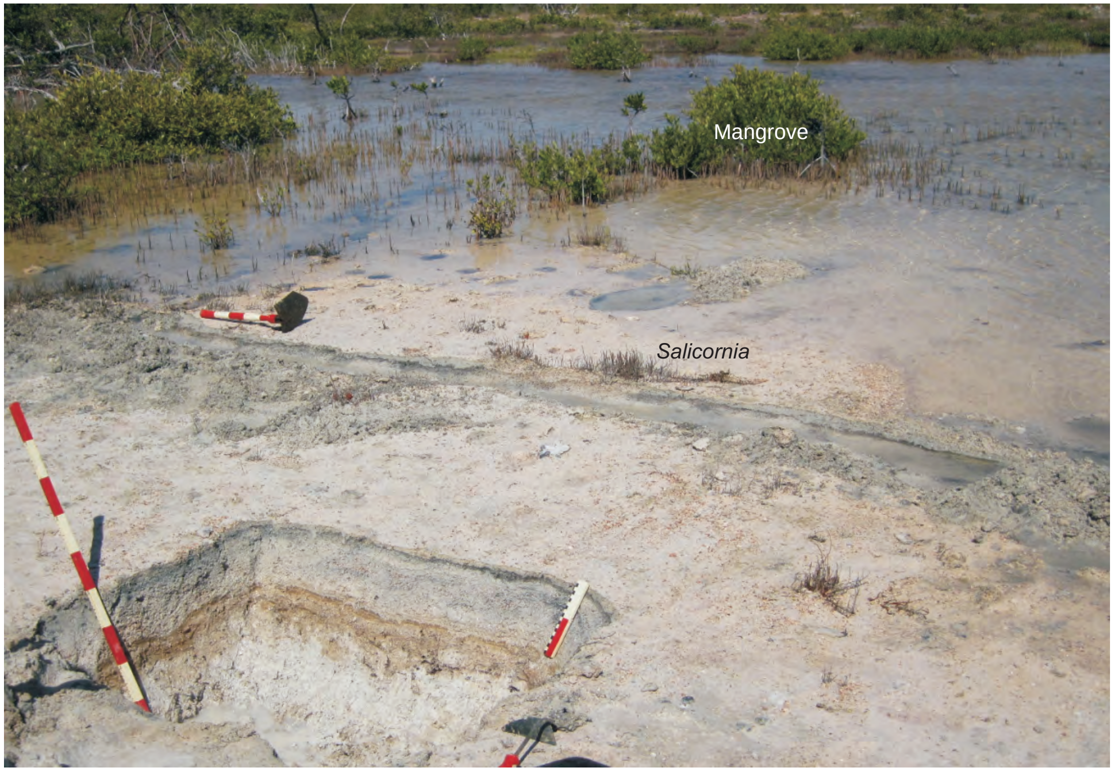


Figure S5-2 Deposits of western fan [page 1 of 3]

A **View northwestward** across trench and pit on profile in Figs. S3-2*A,C* and S4-2*A*



Approximate landward limit of sand deposited by Hurricane Earl

Trench in *B,C*

Stripes on shovel and rulers 0.1 m long

Pit in *D-F*, 20 m inland from shore

Inland, and approximately northward, along profile

Figure S5-2 **Deposits of western fan** [page 2 of 3]

B **Trench** in *A*

C **Detail of sand ascribed to Hurricane Earl**

Figure S5-2 Deposits of western fan [page 3 of 3]

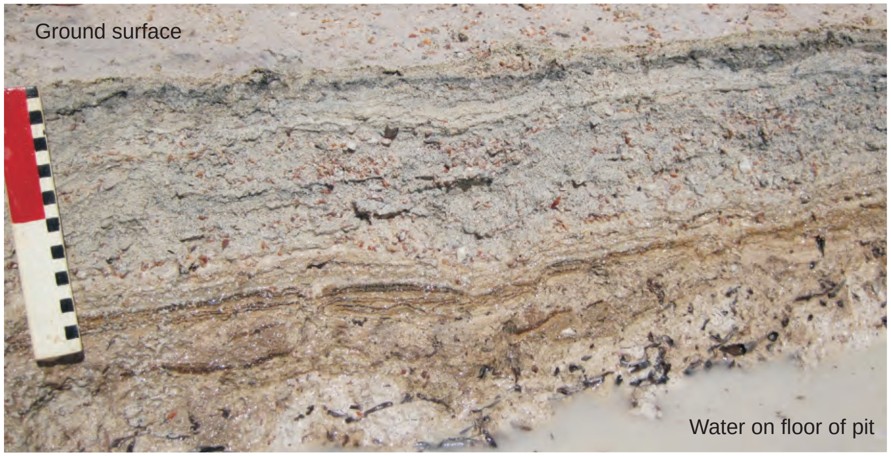
D-F Stratigraphy and chronology of pit in A

_D_ North wall

Squares 1 cm
Ruler inclined

Stratigraphic ranges below *E* *F*

Microbial mats



Sand ascribed to 2010 Hurricane Earl

Sand perhaps deposited by 1960 Hurricane Donna

1957-1958, 1994-1998 (detail in *E*)

1958-1960, 1984-1986 (detail in *F*)

10 cm true thickness

Shelly sand—Shells mainly cerithid gastropods

Microbial mat—Black, brown, or green

Mud—Very light gray. Burrows notes in eastern pit

Limestone—Caliche developed in Pleistocene deposits

Mangrove roots

Radiocarbon age

1957-1958, 1994-1998 — **Calibrated ranges** at two standard deviations in yr A.D.

Materials dated

Flat-lying leaf

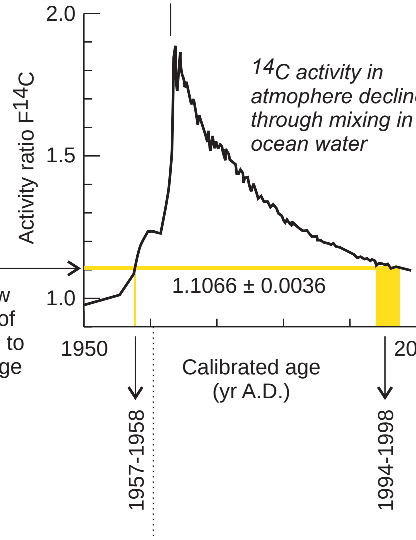
Mangrove root with pneumatophore

1.1066 ± 0.0036 — **Activity ratio** $F^{14}C$—Ratio of sample to oxalic-acid standard

NOSAMS-87308 — **Lab number**

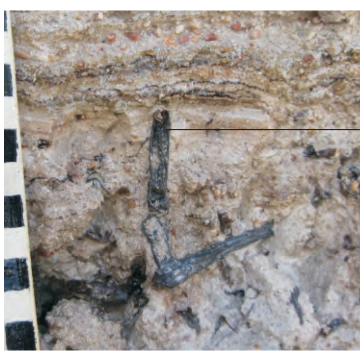
_E_ Dated leaf above black mats

1.1066 ± 0.0036
NOSAMS-87308



Arrows show conversion of activity ratio to calibrated age ranges

_F_ Dated root below black mats



Pneumatophore apparently capped by microbial mats

1.2076 ± 0.0037
NOSAMS-87307

Calibrated ranges computed from activity ratio as in *E*. Ratios exceed 1.0 because atmospheric testing of nuclear weapons in the 1950s and early 1960s enriched the atmosphere in radiocarbon.

Calibration data is zonal average compiled by Hua and Barbetti (2004) for the northern hemisphere between latitude 40º and the mean summer intertropical convergence zone (NH_zone2.14c dataset). The average uses measurements of the atmosphere and organic material, including tree rings. Local and seasonal values may deviate from the zonal average.

Calibration program CALIBomb of P.J. Reimer and R. Reimer (http://calib.qub.ac.uk/CALIBomb/frameset.html)

Activity ratio $F^{14}C$ defined by Reimer and others (2004)

Figure S5-3 **Deposits of eastern fan** [page 1 of 3]

A,B **Overviews** looking northward

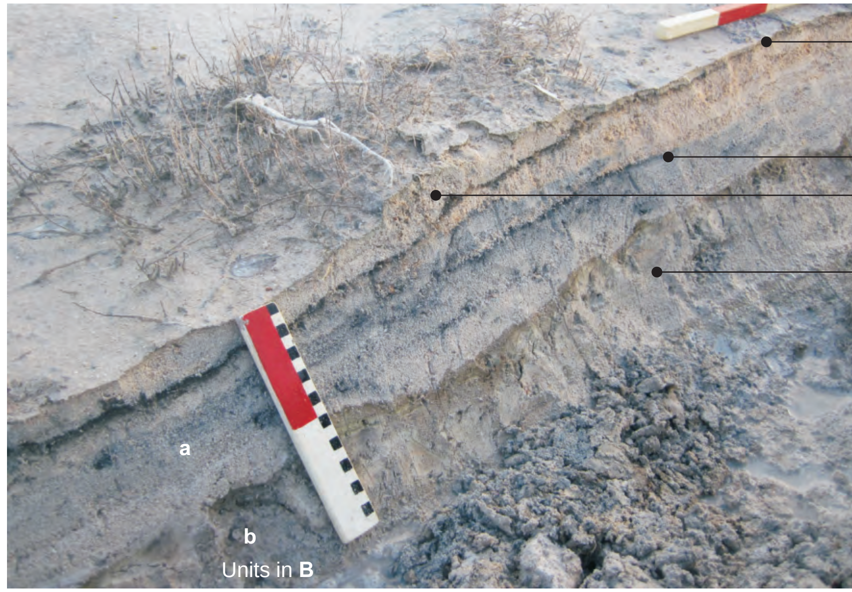
A **Fan** of Fig. S4-2*C,E*

B **Toe of fan** with trench (detail in *C-E*) and pit (detail in *F,G*)

Figure S5-3 **Deposits of eastern fan** [page 2 of 3]

C **Trench** in *B* viewed northward

D,E **East wall of trench** viewed southeastward

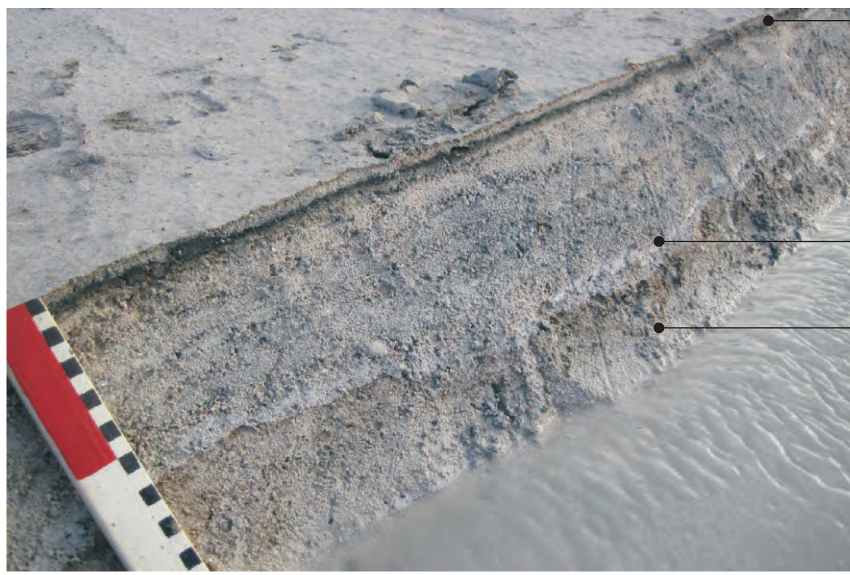


Mat veneered with sand ascribed to Hurricane Earl

Erosional remnant of earlier mat

Sand veneer thickens in and near *Salicornia* clump

Sandy unit **b** in *B*, underlain by mat along southern part of trench



Mat veneered with sand ascribed to Hurricane Earl

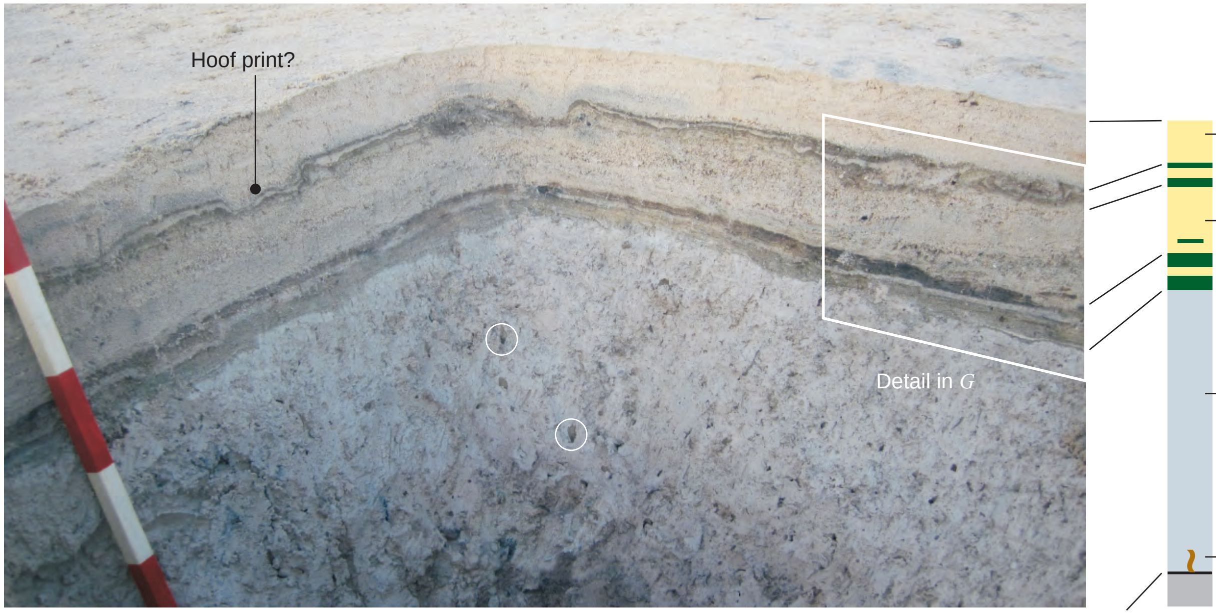
Lime mud low in shelly sand

Sandy unit **b** in *B*, underlain by mat along southern part of trench

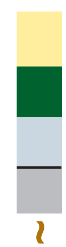
Stripes on shovel handle and ruler are 10 cm long

Figure S5-3 Deposits of eastern fan [page 3 of 3]

F **Pit** in *B* viewed northward



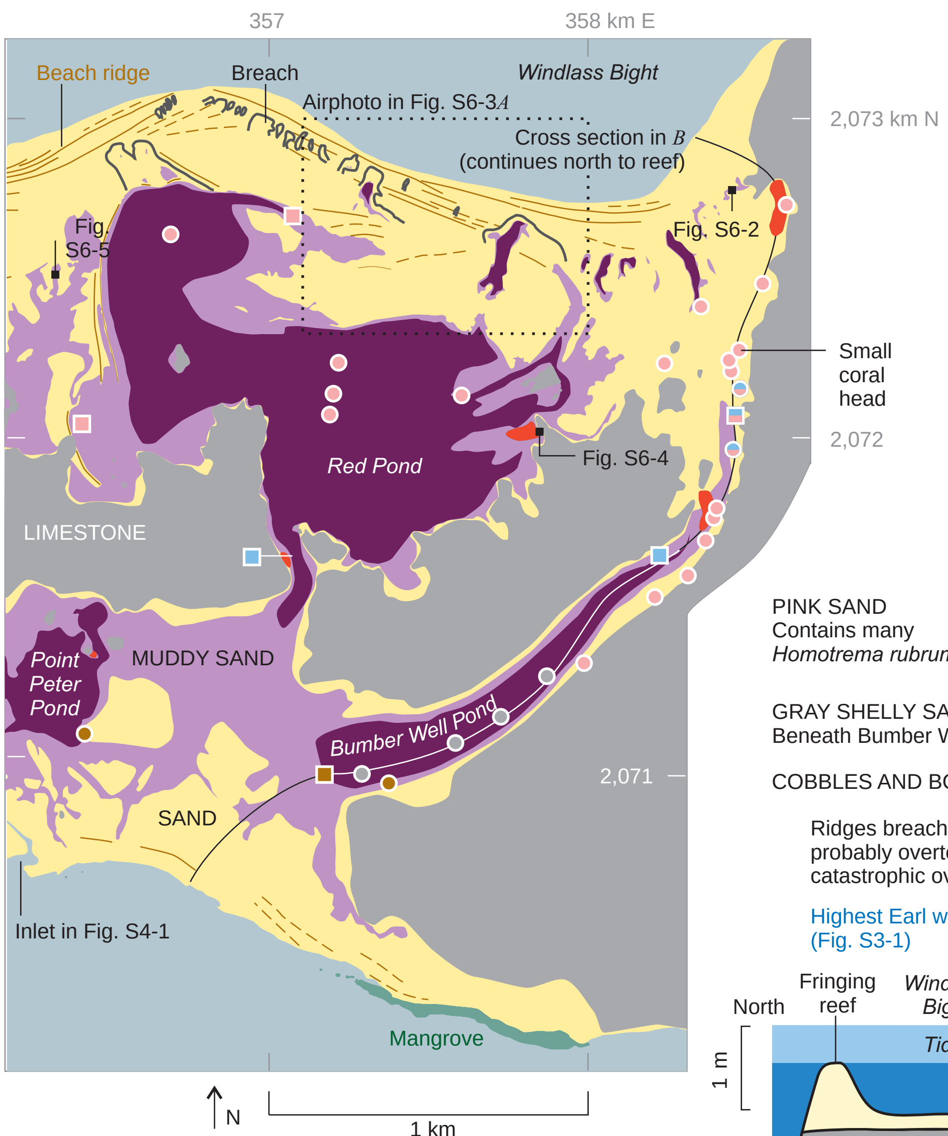
G **Landward-dipping beds** between mat pairs



Calibration of bomb carbon illustrated in Figure S5-2*D*-*F*

Figure S6-1 **Comparisons** between evidence for castrophic overwash and effects of 2010 Hurricane Earl

A **Geologic setting** (broader context in Fig. S1-2*A*)



B **Cross section** through evidence for catastrophic overwash

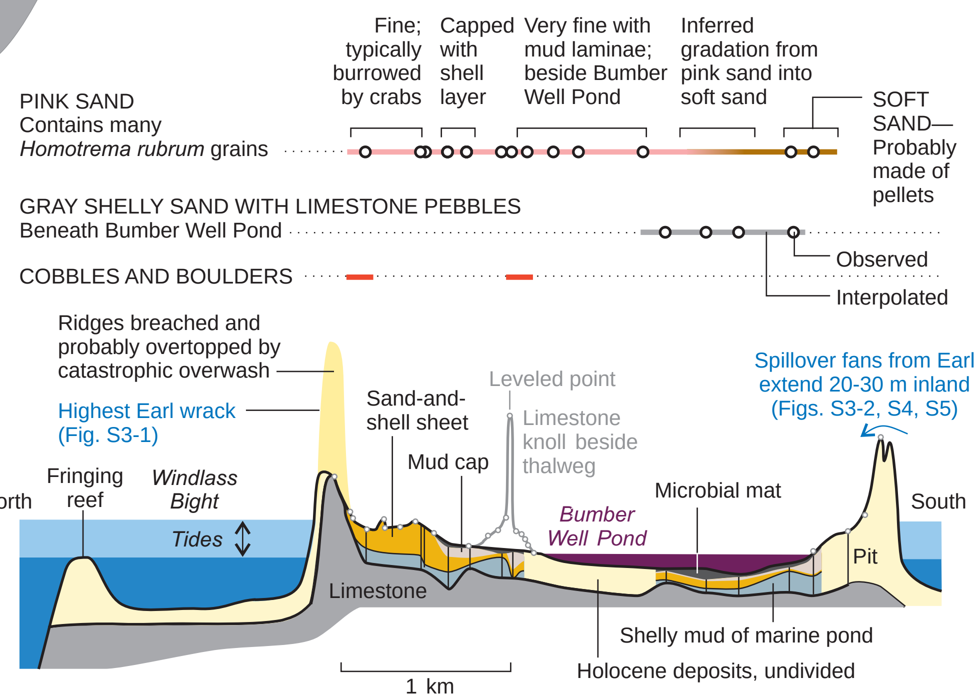
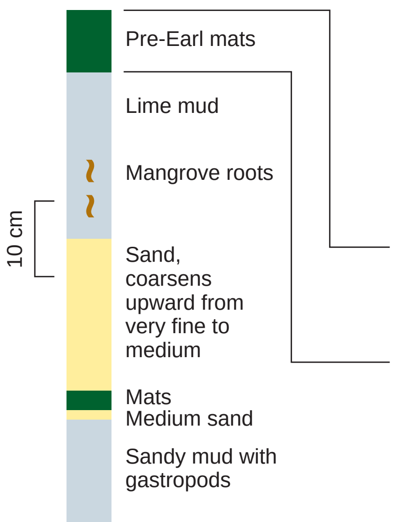


Figure S6-2 Microbial detritus in breach north of Bumber Well Pond

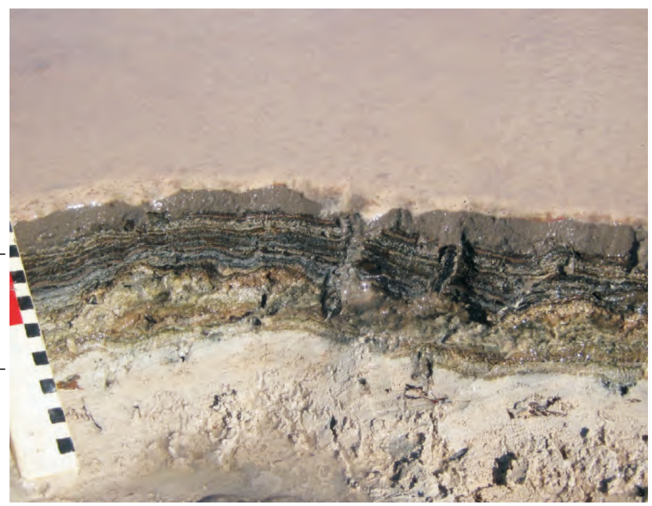
A **Microbial detritus**, with *in situ* microbial coating, ranging from soft and continuous at wet center of pond to firm and chunky on desiccated fringe

B **Dried microbial detritus** shrunken into chunks on pond fringe

C **Stratigraphy** logged in 2009



D **Soft gray microbial detritus above pre-Earl mats** of pond center



Scale oblique, squares 1 cm

E **Detail** of deposits in *D*

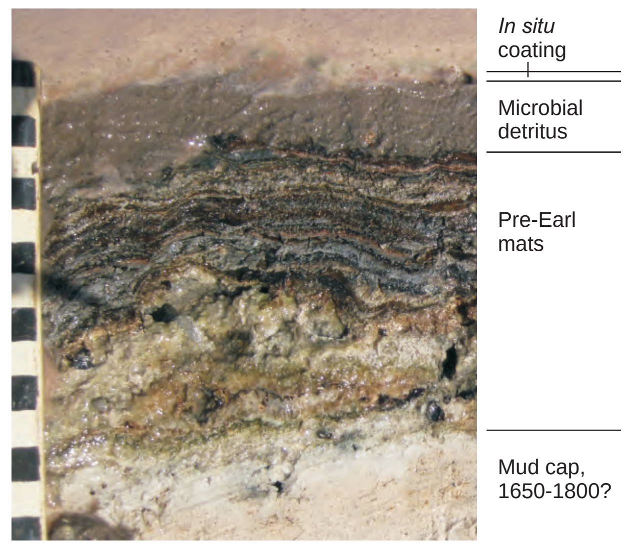


Figure S6-3 **Microbial detritus and boulder** juxtaposed in breach north of Red Pond [page 1 of 4]

A **Overview** of breaches in beach ridges

Figure S6-3 Microbial detritus and boulder juxtaposed in breach north of Red Pond [page 2 of 4]

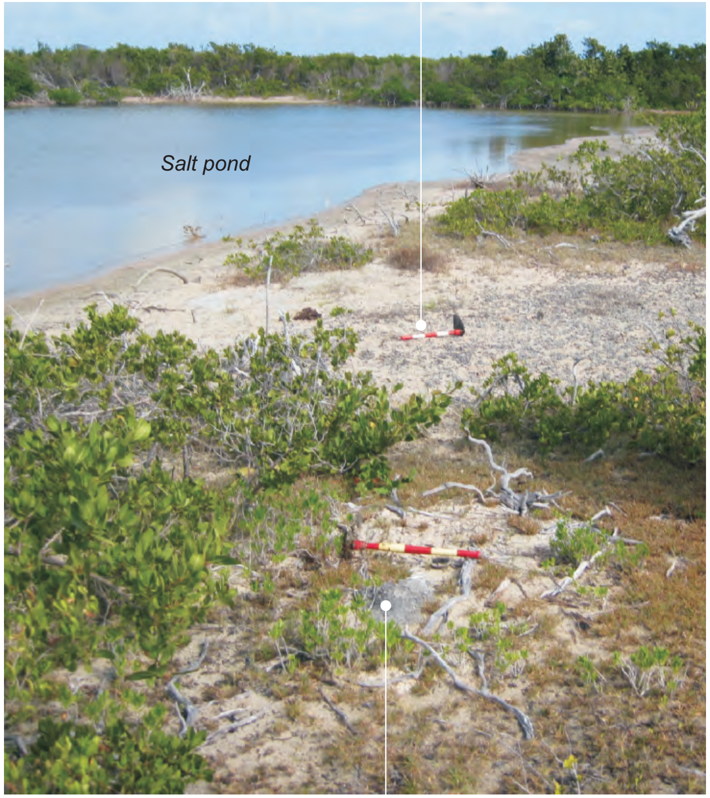
B **Microbial detritus** deposited by Hurricane Earl, variously desiccated

C **Green and red microbial mats** beneath the Earl deposits. Stripes on handle 0.1 m long

D **Leaves exhumed** by shrinkage of Earl deposits that had covered them. Divisions on ruler 1 cm long.

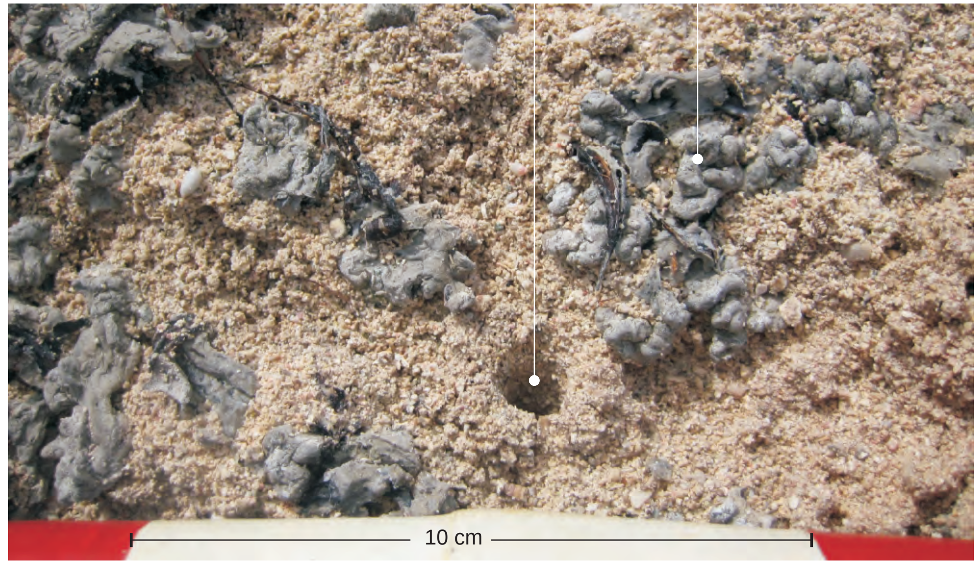
Figure S6-3 Microbial detritus and boulder juxtaposed in breach north of Red Pond [page 3 of 4]

E **Overview** to north



Stripes on shovel handles 0.1 m long

F **Desiccated microbial detritus**



G **Boulder** embedded in sand above Earl high-water line. Additional details in *H-J*.

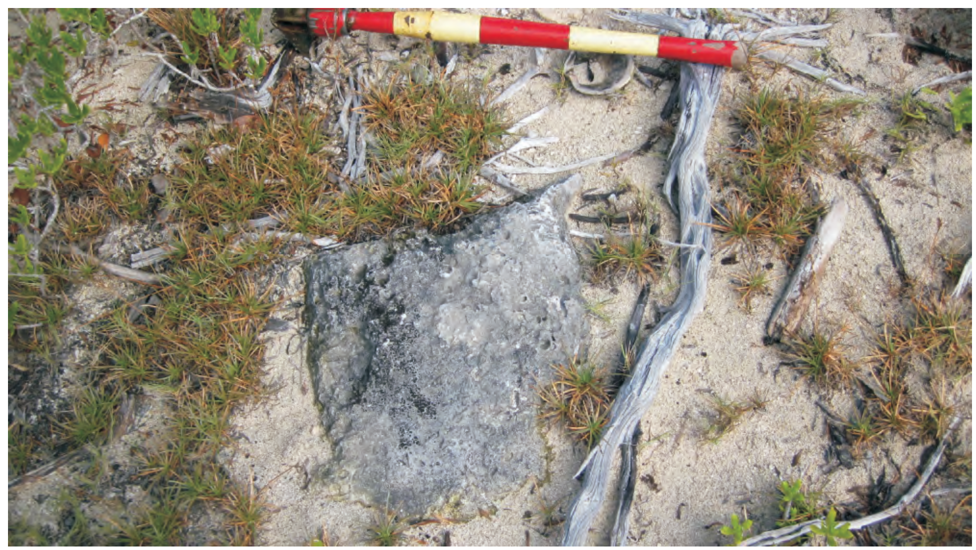


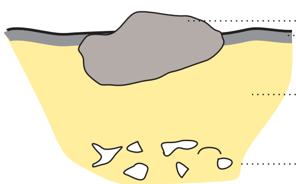
Figure S6-3 **Microbial detritus and boulder** juxtaposed in breach north of Red Pond [page 4 of 4]

H **Overview** to north after excavation of boulder (compare with *E*)

Pit sketched in *I*

Boulder removed from pit, used as display rack in *J*

I **Stratigraphic sketch** of pit in *H*



Boulder in position as in *E*

Organic sand

Fine sand with *Homotrema* grains

Cobble-size clasts displayed in *J*

J **Clasts found beneath boulder**. All derived from reef or from subtidal flat landward of reef.

Finger pointing to *Strombus* (conch)

Acropora cervicornus (staghorn coral)

Acropora palmata (elkhorn coral)

Codakia

Pink from encrusting *Homotrema*

The boulder is made of caliche that resulted from weathering of Pleistocene deposits, as in Fig. S2-1*B*. The boulder was likely derived from caliche that underlies the adjoining breach; it was probably transported by flows that created or reoccupied this

Figure S6-4 **Microbial detritus mantling cobble field** of northeast Red Pond

A **Notch 27 months before Earl** (March 2008)

Pleistocene brain coral

Shoreline notch probably occupied by marine pond before overwash of 1650-1800

B **Notch 6 months after Earl** (February 2011)

Coral head obscured by dried microbial detritus

C **Cobbles 6 months after Earl** (February 2011)

Cobbles and boulders scattered southward by catastrophic overwash into Red Pond in 1650-1800 or earlier

Cobbles surrounded by microbial detritusl

Limestone partly coated by microbial detritus

Figure S6-5 Large head of the brain coral *Diploria* on seasonally flooded play west of Red Pond

A **18 months before Earl** (February 2009)

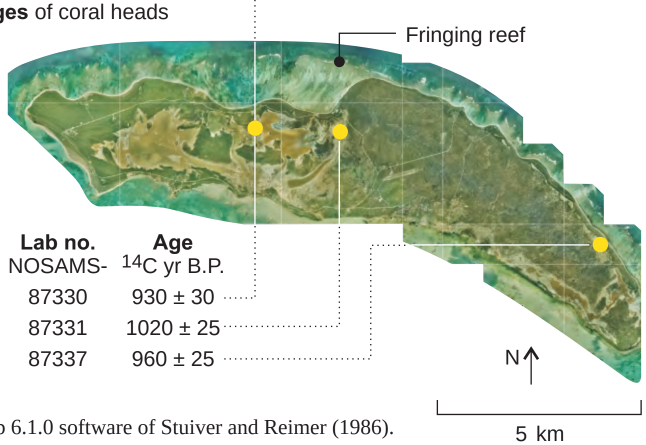
View to southeast

B,C **6 months after Earl** (February 2011)

B **Dried microbial detritus** litters ground. Spalled coral fragment in foreground displaced little if any by Hurricane Earl despite the fragment's low density.

D **Radiocarbon ages** of coral heads

Ages measured on outer growth bands of coral heads that retain growth shape as above. Western heads moved 1.5 km if from fringing reef. All ages are in the range A.D. 1200-1450, if the area's marine-reservoir adjustment ΔR is between 0 and -200 ^{14}C yr, with Marine09 calibration data of Reimer and others (2009) and Calib 6.1.0 software of Stuiver and Reimer (1986).



Lab no. NOSAMS-	Age ^{14}C yr B.P.
87330	930 ± 30
87331	1020 ± 25
87337	960 ± 25

C **Stratigraphy** 3 m east of coral head