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Middle Eocene Storm Deposition in the Northwestern Gulf of Mexico, Burleson County, Texas, U.S.A.

James E. Flis[1], Thomas E. Yancey[2], and Christopher J. Flis[3]

[1]*3304 Attaway Cove, Corinth, Texas 76208, U.S.A.*

[2]*Department of Geology and Geophysics, Texas A&M University, MS 3115, College Station, Texas 77843, U.S.A.*

[3]*Whiteside Museum of Natural History, 310 N. Washington St., Seymour, Texas 76380, U.S.A.*

ABSTRACT

Many storm beds deposited during the beginning of the MECO (Middle Eocene Climate Optimum) climate event are exposed at Stone City Bluff on the Brazos River. Hummocky sands preserved in inner-mid shelf deposits of a transgressive systems tract record many storms affecting this part of the Gulf of Mexico during the Eocene. Hummocks have width of 0.14–5.3 m and height up to 0.6 m in a continuum that includes multi-meter width hummocks. Small-width hummocks occur as isolates and within large-width hummocks. The storm sands have a primary grain size mode of 85–95 µm and secondary mode of 180–200 µm for peloids and bioclasts. Gutter fills are present, containing coarse clasts derived from winnowed seafloor sediment, including high-density clasts that exceed the capacity of combined flow currents to transport sediment. They are interpreted to originate as the basal part of a bipartite mass flow that developed concurrent with combined flow currents. Comparison of Stone City Bluff storm beds to historic Gulf of Mexico storm deposits suggests that storms as strong as Hurricane Carla, a Category 5 hurricane that hit the Central Texas shoreline, occurred during the Eocene.

INTRODUCTION

This study examines the sedimentary record of storm events preserved in a large exposure of Eocene mid-inner shelf strata exposed at Stone City Bluff in Central Texas (Fig. 1A) obtained over a 5 yr period as flooding produced serial-sectioning of exposures. Continuous lateral exposure reveals storm beds containing a great variation in bedforms and a variety of storm deposits. Stone City Bluff exposes a thick transgressive systems tract (Loutit et al., 1988; Cattaneo and Steel, 2003) present in the late middle Eocene Stone City Member of the Crockett Formation, deposited on a low gradient inner-mid shelf surface on a coastline dominated by river input of sediment (Galloway et al., 2011). Large amounts of sediment input created conditions favorable for preserving storm deposits of small and great energy level storms during a warm climate event. Morton (1988) pointed to the microtidal, muddy shelf region of the northwest Gulf of Mexico as an important study area for documenting the effects of major storms. The strata of Eocene age were deposited on an area of the shelf with substantial river input supplying fine siliciclastic sediment to the coast. Although deposited during transgression, changes in storm deposits along a depth gradient are similar to those described by Duke et al. (1991), Harms et al. (1975), and Cheel and Leckie (2009) for prograding, regressive deposits. High rates of sediment accumulation combined with moderate rates of bioturbation resulted in preservation of original bedform and depositional fabric in stratal thicknesses of millimeter and decimeter scale. Strata at Stone City Bluff were deposited during the early phase of the MECO (Middle Eocene Climate Optimum), a short-lived (~600,000 yr) warming event that started about 42.0 Ma (Bohaty and Zachos, 2003; Zachos et al., 2008).

Strata at Stone City Bluff have previously received attention for the excellent exposure of varied lithologies (Stenzel, 1936; Nelms, 1979; Thornton, 1994; Yancey, 1995), great abundance and diversity of marine fossils (Palmer, 1937; Thomas, 1941; Balderas, 1953; Stenzel et al., 1957; Nelson, 1975; Knight et al., 1977; Stanton and Nelson, 1980; Zuschin and Stanton, 2002), presence of peloid-rich sands (Huggett et al., 2010; Harding et al., 2014), submarine firmground (Thornton and Stanton, 1994), and the presence of concretions formed around pathways of methane migration through sediment (Hendricks et al., 2012). This section is conspicuous in a region where few units contain easily recognizable indicators of normal salinity marine origin. The documentation of marine planktic microfossils in the upper part of the Stone City Bluff Member (Yancey and Davidoff, 1991; Hodgkinson et al., 1992) points to deposition in an offshore inner-mid shelf marine environment.

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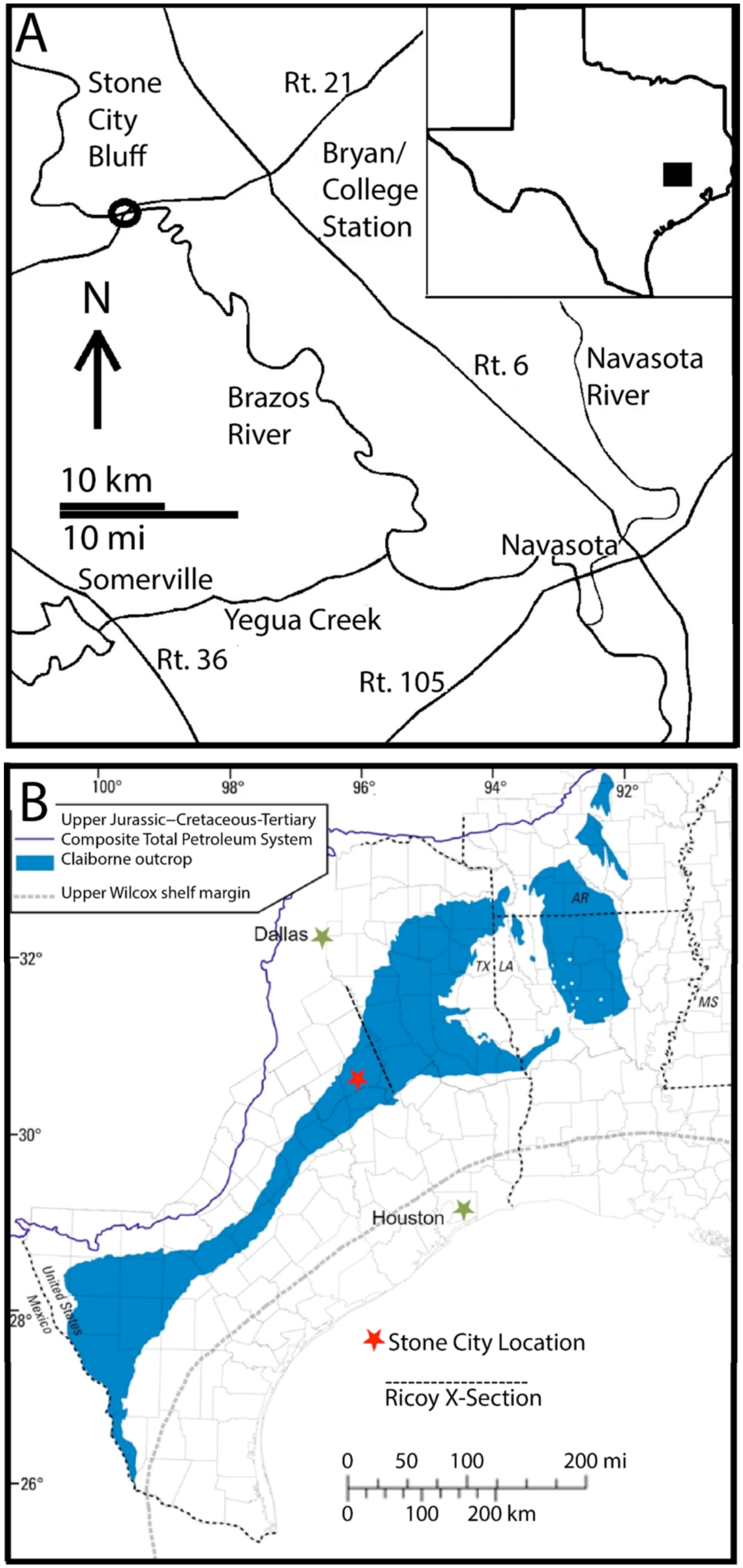


Figure 1. (A) Location map of Stone City Bluff study area. (B) outcrop area of Claiborne Group strata in the northern Gulf region compared to updip limit of basin deposits and shelf margin. Stone City study location marked with star. Map modified after Hackley and Ewing (2010), with dashed line added to show location of schematic cross section of Claiborne units depicted by Ricoy (1976).

Stone City Bluff is located on the west bank of the Brazos River at the river crossing of Texas Route 21, a site 18 km west of Bryan, Texas, approximately 150 km northwest of Houston (Fig. 1A). This is a classic middle Eocene (Claiborne Group) marine fossil locality (Fig. 1B) and a frequently visited geology study site.

GEOLOGIC SETTING

The sedimentary deposits exposed at Stone City Bluff were deposited on the inner-mid reaches of a continental shelf extending from a wide coastal plain (Galloway et al., 2011) along the northwest margin of the Gulf of Mexico (Fig. 2A). Sediment was transported by rivers across low-gradient coastal plains and deposited in fluvial channels, strandplain systems, including barrier island-bound strandplains, delta complexes, large bays/lakes, and open-ocean bottoms (Fisher and McGowan, 1967). Sediment deposited on these surfaces consists primarily of fine-grained siliciclastic mudstone and sandstone, with minor amounts of lignite on the coastal plains and shell/peloid-rich concentrates on the marine shelf.

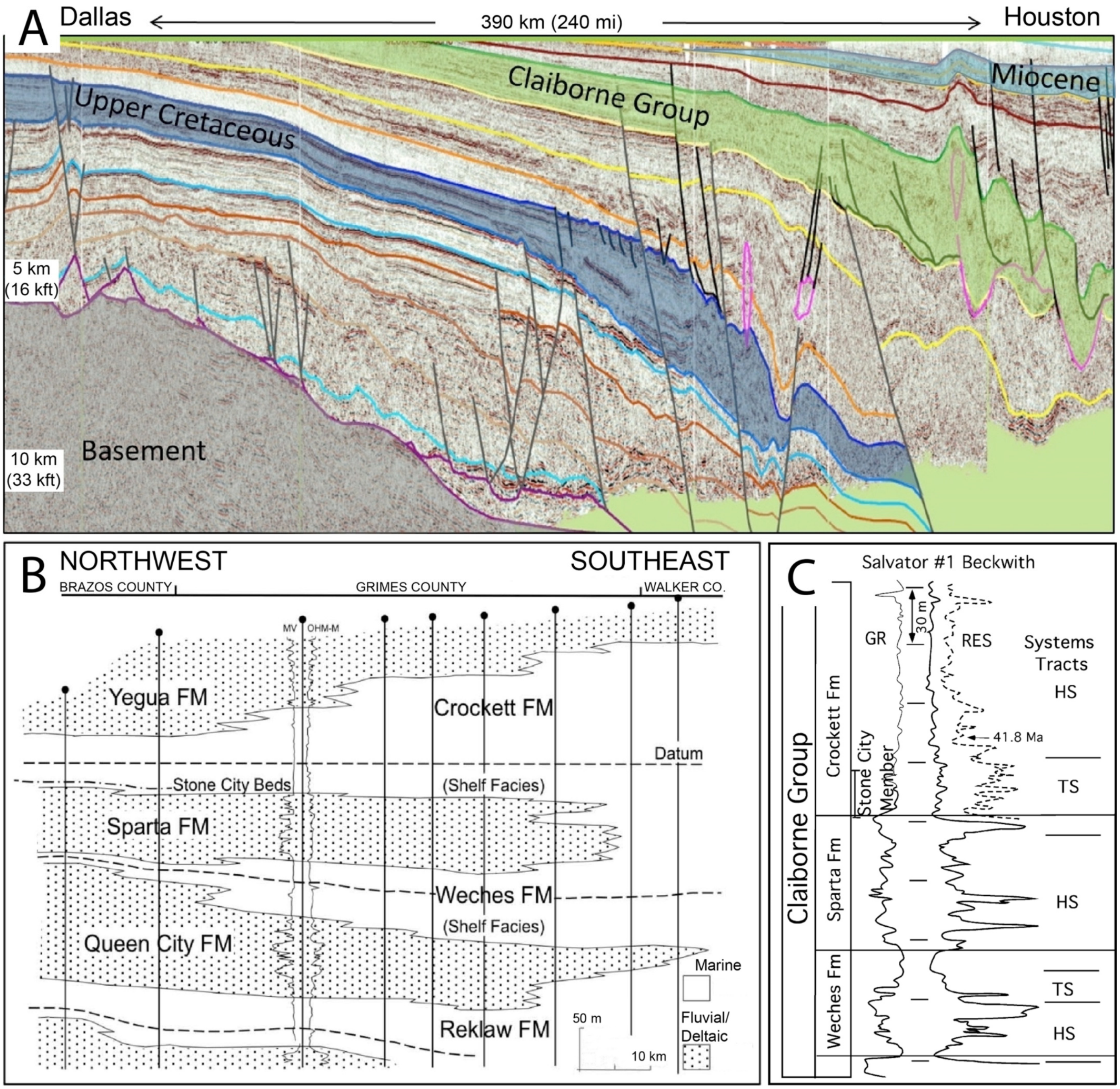


Figure 2. (A) Seismic section showing subsurface extent of sedimentary units in the Houston Embayment of East Texas; boundaries marked with pink show salt diapirs; location of seismic line shown by thin dashed line crossing Claiborne outcrop trend and extending on a line between Dallas and Houston; GulfSPAN data courtesy of ION/GXT, data supplied by GPI and SEI. (B) Schematic cross-section showing regional interfingering of open marine formations (no shading) and unfossiliferous sandstone or sand-mud formations in the Houston Embayment, East Texas (Ricoy, 1976); updip to left; basinward to right. (C) Well log for interval of Weches to Crockett formations of the upper Claiborne Group in southern Brazos County, Brazos River Valley (modified after Davidoff and Yancey, 1993); GR, gamma ray, and RES, resistivity.

With little change in river systems and drainage basins since Laramide uplift of sediment sources in the Rocky Mountains (Galloway et al., 2011), depositional systems along the northern Gulf of Mexico margin are expected to have remained the same during the Eocene, with limited change in the position of depocenters. Eocene river systems delivering sediment to the northern Gulf are projected to have flowed on a coastal plain similar to that of the lower coastal plain of southeastern Texas where small changes in sea level can produce long distance migration of shorelines and cycles of marine inundation (Fig. 3A) with alternating transgressive deposits and regressive deposits (Loutit et al., 1988; Mancini and Tew, 1991, 1993). Basinward tilting of strata at Stone City Bluff has produced a 1° dip to the southeast (16 m/km) (Parker, 1979), contrasting with a gradient of 0.6 m/km on the lower coastal plain of Texas.

The storm sand-bearing Stone City Member (Fig. 4) is 18 m thick (Stenzel et al., 1957; Kersey and Stanton, 1979; Yancey, 1995) and outcrop exposures have been correlated to the subsurface using well logs (Davidoff and Yancey, 1993; Ewing, 1994). The Crockett-Sparta contact has been mapped as a stratigraphic datum in regional lithostratigraphic studies of the Sparta Formation (Figs. 2B and 2C) (Ricoy, 1976) and in Paleogene sequence stratigraphic correlations in the Brazos River Valley (Davidoff and Yancey, 1993).

AGE OF STRATA

The age of strata exposed at Stone City Bluff is established using biostratigraphy and radiometric dating of volcanic ash beds in the overlying Wheelock Member of the Crockett Formation (Heintz et al., 2015). Calcareous nannoplankton indicates an age of biochronozone NP16 (Yancey and Davidoff, 1991, p. 80) and planktic foraminifers indicate deposition during the *Morozovella lehneri* (P12) or *Orbulinoides beckmanni* (P13) zones (Gaskell, 1989). A 25 cm thick volcanic ash bed present in overlying strata of the Crockett Formation, about 15 m above the Moseley bed (Kersey and Stanton, 1979), has an $^{40}Ar/^{39}Ar$ radiometric date of 41.841 ± 0.016 Ma (Heintz et al., 2015). The ash-bearing strata are further corroborated as upper part of biochronozone NP16 by Marie-Pierre Aubry (2002, unpublished report) and the upper part of biochronozone P12 (= E10–E11 biochronozones) by W. A. Berggren (2004, unpublished report), based on an overlap of *Acarinina bullbrooki* and *Turborotalia pomeroli*. Copies of the Aubry and Berggren reports are available upon request to T. E. Yancey at Texas A&M University, College Station. The dated volcanic ash layer is known to extend from the Little Brazos River in Brazos County to Hurricane Bayou in Houston County (Gimbrede, 1951; Heintz et al., 2015). The volcanic ash occurs within the *Turritella cortezi–Crassatella texalta* Zone of Stenzel (1940), an interval characterized by a *Plicatula filimentosa*–rich horizon and laterally persistent siderite ironstone beds. This age places the deposition of the marine Stone City beds during the early part of the MECO. In the Brazos River Valley this event is marked by abundance peaks of foraminiferans (Greenfield, 1957; Gaskell, 1991), molluscan diversity (Dockery and Lozouet, 2003), and marine vertebrates (Westgate, 1989).

METHODS OF STUDY

Bedforms, lithology, and stratigraphy of storm sand deposits at Stone City Bluff were documented along a 200 m transect on the west bank of the Brazos River. The outcrop was flagged and digitally photographed every 6 m. Photos were spliced into a photo-panorama and spot photos taken over a 5 yr period to reveal bed forms and sediment texture. During this time erosion by the Brazos River created serial cuts through portions of the storms deposits, greatly improving the quality of data recorded. The baseline station 0.0 m is at the upstream (west) side of the railroad bridge abutment beside the Route 21 crossing of the Brazos River. The transect extends to the upstream limit of exposure of the Stone City section.

Several locations were measured vertically, sampled, and photographed and representative examples of lithologies taken for analysis and tabulation of recording lithology, grain size, sorting, consolidation, clay content, estimated visual porosity, and cements. Sediment mineralogy was determined by powder X–ray diffraction (XRD) and rock samples were photographed with a Zeiss Axiocam MRc5 digital camera at the Chevron U.S.A. Briarpark Lab Complex, Houston, Texas. Storm sand grain size was measured with the use of a Retsch Camsizer at Texas A&M University, College Station, on samples taken from base to top of selected storm deposits. Sediment was disaggregated and secondary cemented masses (tiny concretions; cemented laminae) and clayey burrow fills were removed by visual inspection.

Dimensions of storm sand hummocks are measured from pinchout to pinchout (defined as width) and from basal boundary over lag deposit or mudstone to top boundary below mud in the suspension fall-out zone (defined as height). On hummocks underlain with a lag deposit, the base is set at the boundary where coarse particles are lacking and the sand becomes finer grained and better sorted. An upward increase in clay and silt content marks the change from hummocky sand to settling-out sediment.

SEDIMENTS AND DEPOSITIONAL SETTING OF THE CROCKETT FORMATION IN STONE CITY BLUFF

Strata exposed at Stone City Bluff (Fig. 3A) were deposited in a range of coastal to mid shelf environments subject to episodic storm events (Yancey, 1995). This contrasts with Stenzel's (1936) interpretation of lower strata being dominantly nonmarine, based on the presence of scattered plant fragments and inferred absence of marine fossils. The presence of marine fossils preserved within concretions and wood with borings made by marine bivalves reveals that the sediments were deposited in ocean waters and corrects that misidentification. The presence of peloid grains ("glauconite") with an odinite mineral composition indicates formation in a verdine clay mineral facies (Harding et al., 2014). The verdine clay mineral facies develops in warm-climate marine waters between 5 and 60 m depth (Odin, 1988; Harding et al., 2014) where odinite can form rapidly in nearshore bottom waters with an influx of iron from terrigenous sources (Ku and Walter, 2003). This is an environment very similar to that inferred from other characters of the sediments at Stone City Bluff. Microfossils (Thomas, 1941; Balderas, 1953; Greenfield, 1957; Yancey and Davidoff, 1991; Hodgkinson et al., 1992) indicate an inner to middle neritic (<20–100 m water depth) and open marine environment for upper Stone City Bluff strata. Planktic foraminiferans occur in fossil-rich beds and show an upsection increase in the planktic to benthic (P:B) ratio (Fear et al., 2010).

Stone City Bluff strata (12 m is exposed now) are divisible into two intervals of generally similar depositional character (Fig. 4), with storm sands prevalent in the upper half. The lowest exposure interval (Stenzel unit I–K on Figure 4) contains sands with dune morphology and planar crossbedding. Crossbed laminae have a gray cap with higher clay content indicative of tidal movement of water. Tidalite sands and dune morphology point to a nearshore depositional setting outside the breaker zone of waves (Yancey, 1995).

The cross-bedded sands at the base of exposure are overlain by a 3.6 m interval of silty mudstone and siltstones (Stenzel units M–O) with thin subordinate layers of coarse silt and very fine sand (Fig. 3B). The mudstones consist of laterally persistent thin layers (Fig. 3C) stacked up to the base of the storm sand-bearing half of the section. This interval contains scattered carbonate and pyrite concretions and a cluster of large elongate carbonate concretions oriented with long dimension perpendicular to bedding

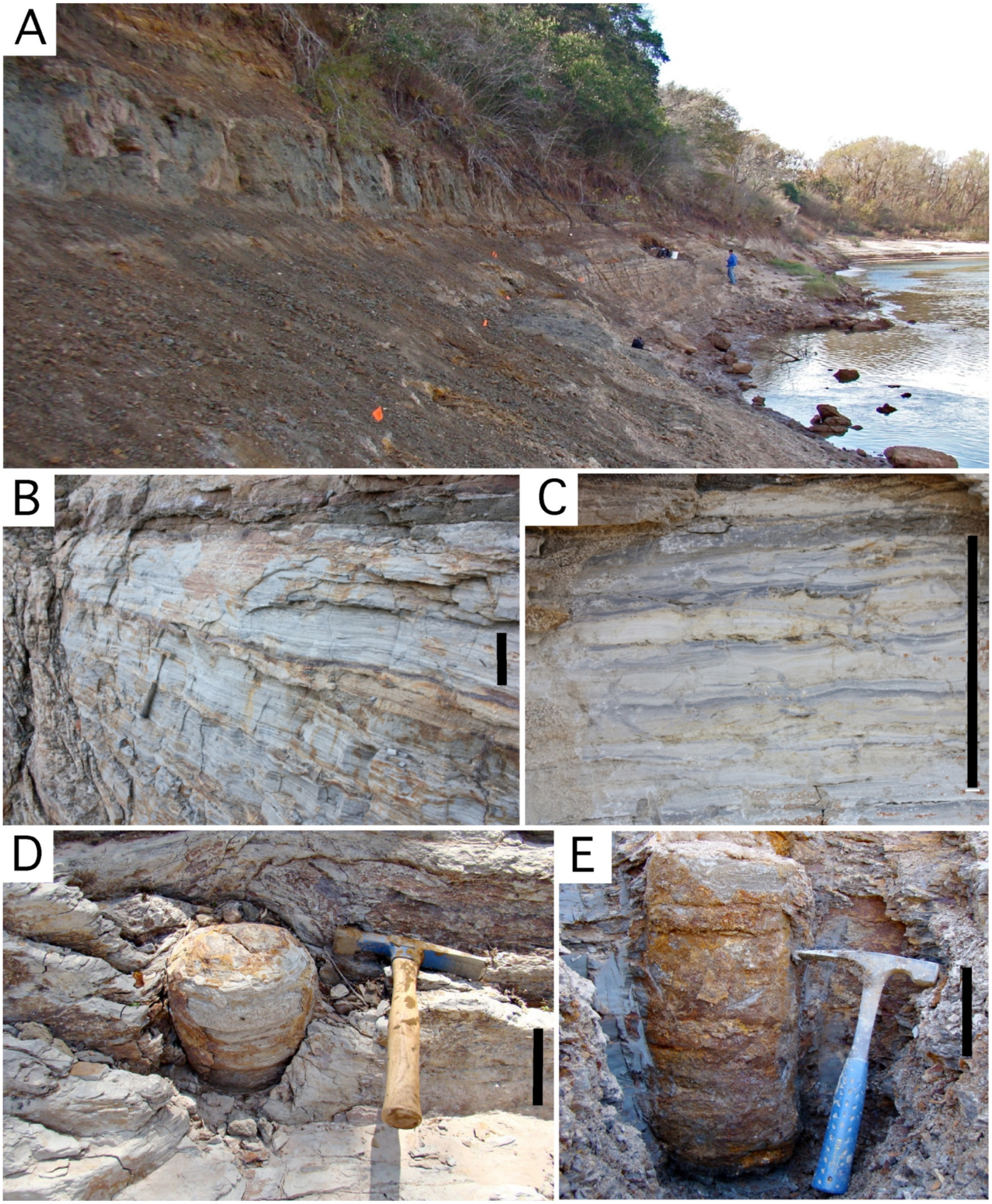
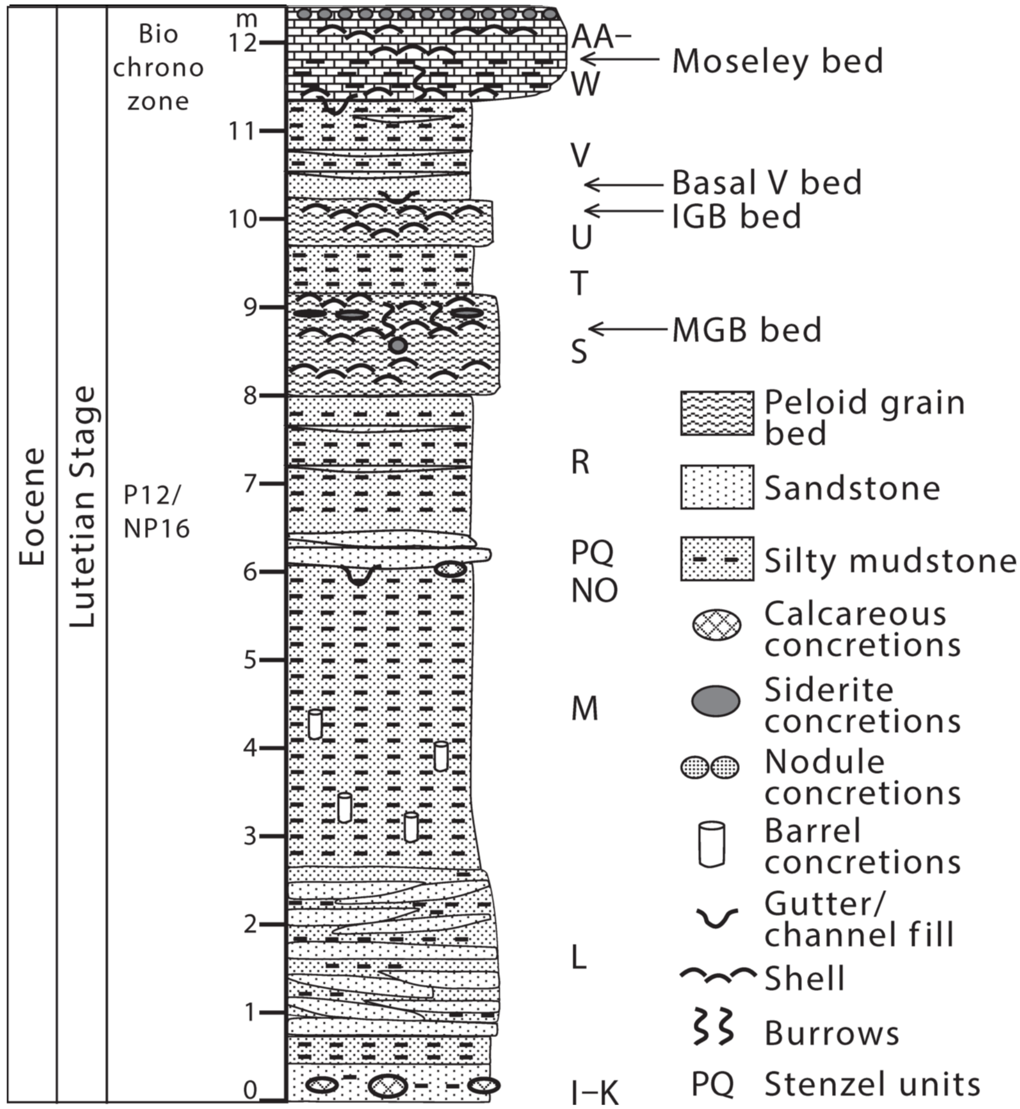


Figure 3. (A) Stone City Bluff section on the Brazos River at Highway 21 bridge, Burleson County, Texas, with Main Glauconite Bed (MGB) forming the vertical gray exposures in upper part of photo and PQ storm sand bed occurs at the level of flags and the pit excavation (above standing person). (B) Laminated silty mudstone and siltstone layers with rhythmic alternation of fine and coarser layers at two scales in unit M, overlain by sand of the PQ sandstone, exposed on joint surface; brown staining marks silt-rich and sand layers; site at 84 m on outcrop transect; scale bar, 10 cm. (C) Cyclic layers of siltstone and mudstone; light gray layers are silt-rich and dark gray layer are clay-rich; site at 84 m on outcrop transect; scale bar, 10 cm. (D) Top of large "discovery" concretion that revealed the presence of methane seep concretions oriented perpendicular to bedding in lower part of Stone City Bluff section, Stenzel unit L; site at 137 m; scale bar, 10 cm. (E) parallel sides (barrel shape) of typical methane seep concretion at Stone City Bluff; site at 137 m on outcrop transect; scale bar, 10 cm.

Figure 4. Stratigraphic section exposed at Stone City Bluff. Letters refer to unit designations of Stenzel et al. (1957); condensed beds are named; MGB = Main Glauconite Bed; IGB = Intermediate Glauconite Bed.



(Figs. 3D and 3E). These barrel concretions formed around pyrite-lined micropipes that precipitated around pathways of methane seepage (Hendricks et al., 2012).

Outcrops of strata underlying the storm sands are exposed on smooth, clean surfaces revealing fine-grained sediments with a record of background sedimentation below fair-weather wave base. This consists of layers of laterally continuous, laminated, silt or muddy silt with sharp lower and upper contacts, minor variation in bed thickness, and little burrowing disturbance (Figs. 3B and 3C). Laminae and very thin layers can be traced laterally for m, giving the unit a pin-striped appearance that contrasts with mudstones in overlying intervals that have thicker and more irregular bedding. These lower mudstone beds contain rhythmic laminae at two scales: an alternation of light and dark laminae and sets of laminae up to 20 cm thick. Some layers of fine sand with small, low amplitude hummocky bedding are also present (Fig. 3B) but there is little indication of scour. These characteristics point to fair-weather deposition by wave-generated bottom flow just offshore of a zone of regular wave agitation (Bentley et al., 2003). Although river flood-generated hyperpycnal plumes or slumping-generated density flows (Bhattacharya and MacEachern, 2009) could produce somewhat similar deposits, the bedding is most consistent with a type of wave-generated bottom flow like the wave-enhanced sediment-gravity-flow (WESGF) deposits illustrated by Lazar et al. (2015). The scale of depositional periodicity in these silt beds indicates high frequency deposition moderated with longer duration events. The lamination is consistent with daily tidal variation and the 10–20 cm groups of laminae could be associated with monthly or yearly time scales. A combination of tidal, wind, and seasonal change would produce periodicity like that present in this unit.

The middle of the section contains the 0.6 m PQ sandstone (Stenzel units P and Q on Figure 4), a complex of storm sands extending across Stone City Bluff as a laterally semi-continuous sandstone body. The PQ sandstone contains two or more amalgamated or overlapping event deposits containing hummocky cross-stratified bedding. Some of the lensing bedforms contain basal gravels that are frequently excavated for vertebrate fossil remains (Fig. 5D). Upward from this horizon the strata contain many lens-shaped beds of storm sand with varied width and thickness. The 1.7 m interval of mudstone and sand above the PQ sandstone contains several sandstone beds of limited lateral extent (Fig. 5A).

The upper part of the section contains two resistant beds that support the river bluff upstream from the highway and train bridges: the Main Glauconite Bed (MGB) and Moseley bed of Stenzel et al. (1957). The 1.2 m Main Glauconite Bed is the primary source of fossils at Stone City Bluff (Fig. 4). Above the MGB is a 2.0 m interval (units T–V on Figure 4) of mixed lithology: mudstones, shell-rich condensed beds with mud matrix, and quartzose sandstones, including a thinner condensed bed (the Intermediate Glauconite Bed: IGB) between the MGB and the Moseley bed. The section is capped by the 0.9 m Moseley bed (Fig. 4), a bed containing winnowed, cross-bedded, well-

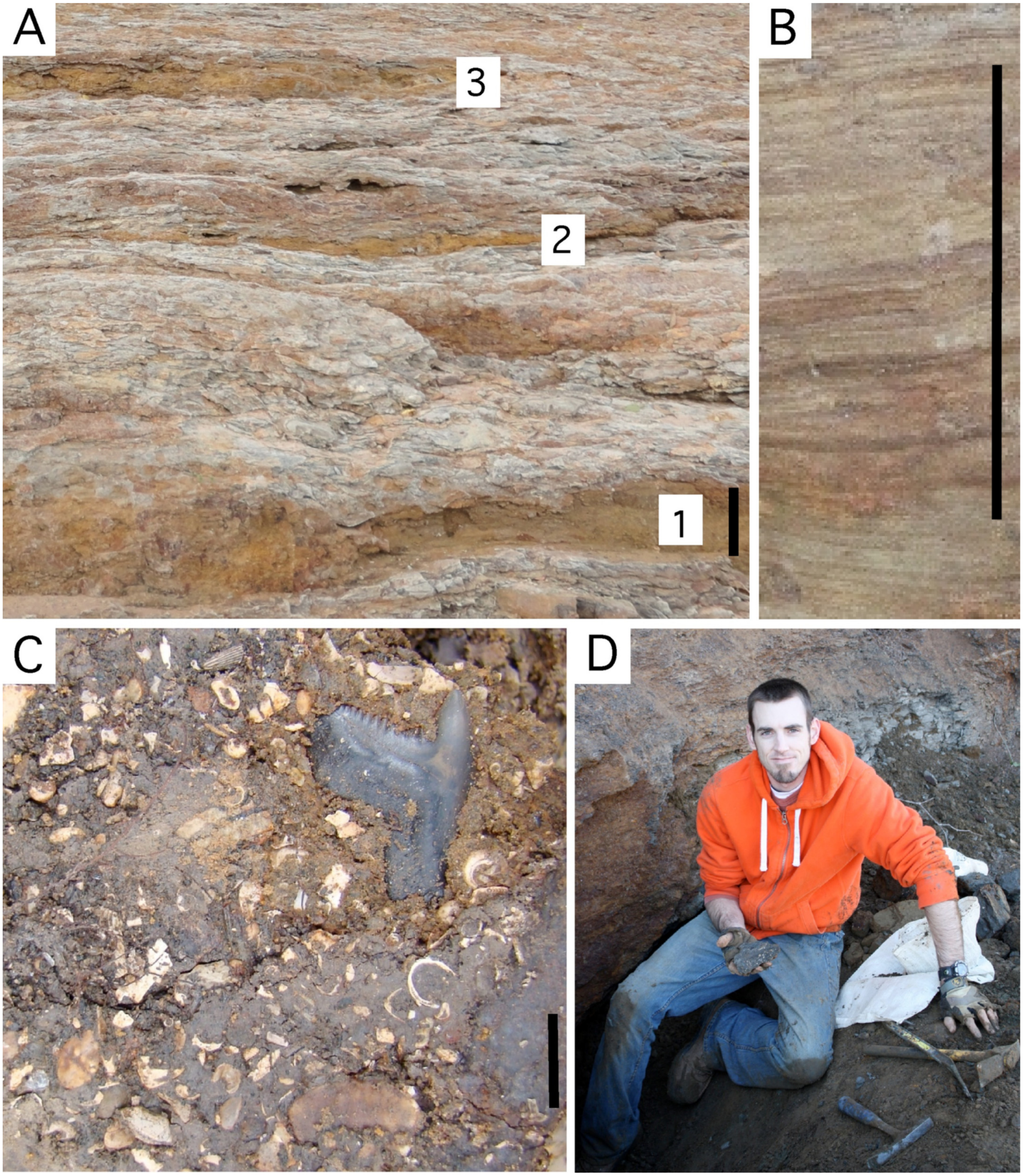


Figure 5. (A) Stacked storm sandstone layers; thick sand #1 near base of photo is part of the PQ sandstone; numbers #2 and #3 sands are smaller lenses in mudstone unit between PQ sandstone and Main Glauconite Bed; at site 123 m on outcrop transect; scale bar, 10 cm. (B) Cyclic variation of laminae within storm sand of PQ sandstone; darker laminae correlate with increased content of peloids and mud clasts in sand; sparse clay-filled burrows throughout; site at 128 m on outcrop transect; scale bar, 10 cm. (C) vertebrate and invertebrates fossils in basal gravels of PQ storm sands: shark tooth (upper right) and otoliths (bottom left and right) in block of sediment; scale bar, 1 cm. (D) collecting vertebrate fossils at site 130 m on the outcrop transect.

cemented peloid-rich sand that produced a submarine firmground (Thornton and Stanton, 1994) with colonial corals and bryozoa growing on it (Stenzel, 1936). Storm-induced scour eroded the top of the MGB down to a zone of cemented burrows and eroded the top of the Moseley bed down to the top of cemented peloid grainstone. This indicates early cementation of sediments close to the seafloor in the upper half of the section.

STORM DEPOSITS

Sands with sedimentary profiles and structures characteristic of the HCS (BPHFXM) model of storm deposits (Dott and Bourgeois, 1982; Walker et al., 1983) occur throughout the upper half of the Stone City Bluff section. These occur within mudstones and in shell/peloid-rich condensed beds. The thinner storm sand beds occur as a series of discontinuous lenses with tapering edges and are aligned on discrete horizons within the section. The largest sand lenses are in the PQ sandstone bed, whereas the most laterally continuous storm sand is the Basal V sandstone (Fig. 4) near the top of the section. Although this is a prominent unit in present exposures at Stone City Bluff, the bed was not given unit status by Stenzel et al. (1957).

The PQ sandstone contains the lowest occurrence of substantial storm event sands and the largest dimension storm bedforms, as shown in outcrop photomosaic (Fig. 6). Lenses of laminated sand in this unit have sharp, scoured basal contacts and are capped with an upward-fining layer of fine-grained sediment (Figs. 5A, 7, and 8). At several places a basal deposit of coarser-grained sand with pebble/cobble clasts and high-density particles is present. The PQ sandstone contains multiple layers of storm deposit; commonly having two thick sandstone layers separated by a mudstone layer, subunits designated by Stenzel et al. (1957) as units P and Q, although in some places only one sand layer is preserved. Where two sandstones are present the lower sandstone tends to contain greater amounts of peloid grains of fecal pellet origin in contrast to the upper sandstone composed mostly of quartz sand with few peloids (Stenzel et al., 1957).

The storm sand lenses have the geometry and internal bedding of hummocks (Figs. 7 and 8) and large-width storm sand lenses are comparable in size to megaripples that form on the tops of sand sheets in modern storm-disturbed areas of seafloor (Swift et al., 1983; Swift, 1985; Passchier and Kleinhans, 2005). Scouring to 20 cm depth (Fig. 9A) is present at several locations and one site shows scour to 25 cm where a layer of more consolidated mud was partially undercut (Fig. 9B). At other locations scour was less pronounced and produced a grooved fluted surface (Fig. 9C) or a more irregular surface, limited by the presence of resistant objects in the seafloor sediments.

The Basal V sand bed is a laterally extensive storm sand deposit (Figs. 4 and 10A) composed of very fine sand with very few pellet grains and indistinct laminated bedding. It is developed as sheet sand in contrast to the discontinuous lenses of the PQ sandstone and thinner storm sands present in the section. It also contains some hummocky crossbedding. The Basal V sand bed (Fig. 10A) rests on a 10–15 cm layer of siltstone or mudstone in most areas, with grooves and gutters limited to 5 cm depth. Only in one area is the underlying siltstone/mudstone scoured deep enough for Basal V sands to be deposited on top of the IGB condensed bed and have a coarse-grained basal lag layer (Fig. 10C).

Other storm deposits are thin, laterally variable sands interlayered with mudstone (Figs. 11A and 11B) or occur within peloid-rich condensed beds (Zuschin and Stanton, 2002) (Fig. 11C). Storm sands within condensed beds are bioturbated, whereas storm sands at the base of condensed beds have sharp, scoured bases and tops that grade upward into bioturbated bioclast- and peloid-rich mud sediment. Mudstone-bound sands consist of semi-isolated lenses connected by millimeter-thick sheets of sand or not connected at all. Also present in the mudstones are gutter casts, filled with sand and shell bioclasts (Fig. 10B). Gutters are a depositional structure associated with storm events (Myrow, 1992; Hadley and Elliott, 1993; Cheel and Leckie, 2009). Storm sands throughout the Stone City Bluff section have alternating light and dark laminae and an upward-fining grain size trend (Fig. 5B).

Lens-shaped hummock sand bodies have cross-section dimensions ranging from 0.14 by 0.04 m width to height (W:H) up to 5.3 by 0.6 m W:H. Dimensions and characters of measured storm sand lenses in the PQ sandstone and Unit V are presented in Table 1. Height and width measurements are taken with the assumption that the sand body has a standard lens shape and an ovoid-round outline in plan view, similar to hummock shape. If a sand body has an elongate plan outline, length is assumed to match average dimension made on an oblique cut. Craft and Bridge (1987) compiled dimensions for 12 worldwide hummock occurrences that are shown with those from Stone City Bluff (Fig. 12). This comparison shows that the Stone City bedforms plot within the dimensions of hummocks tabulated in a worldwide compilation. Three sites provide indication of current direction, with two (Figs. 9C and 10B) revealing sediment scour perpendicular to outcrop trend (a southward direction on water movement) and one is aligned at low angle to the outcrop (an ESE direction of water movement).

Sands of the PQ sandstone are composed mostly of very fine to fine grained (80–125 µm) sand with small amounts of mud matrix between grains. Unfilled pore space between sand grains can be as much as 20%. The sand is quartzose in composition and well sorted, but portions of the lower sand layer can contain up to 60% peloid grains, irregular shell bioclasts, and carbonized wood. A powder XRD analysis of sand from a site 18 cm thick reveals a computed composition of quartz (75%), K–feldspar (10%), plagioclase feldspar (3%), Di 2:1 clay (illite-smectite) (8%), kaolinite clay (4%), and calcite (0.7%). Calcite in this sample consists of shell bioclast grains. In addition, other parts of the sand body contain variable amounts of rock fragment grains, peloids, mud clasts and some mica flakes. In comparison to the sand, XRD analysis of under- and overlying mudstones show increased amounts of clays and calcite, less quartz, and the presence of pyrite.

Storm sands in the PQ and V units have medium sorting and a size range of 60–250 µm, with a dominant grain size mode in the 85–95 µm size range for quartz grains and a secondary mode in the 180–200 µm size range for peloids (Fig. 13; Table 2). Some samples contain bioclasts of larger size, mostly 300 µm or larger, but bioclasts occur mostly in basal lags and in coarse basal deposits. There is a small upward decrease in grain size in a hummock, sometimes exaggerated by a concentration of bioclasts at the base of the sand. Apart from bed thickness and sedimentary structures, storm sand has similar grain characteristics throughout the section.

Gravel-bearing coarse sediment is present at the base of some larger storm sands (Figs. 5C, 9A, 10B, and 10C) and contains bioclasts and cemented concretion nodules of local origin winnowed from seafloor sediments (Figs. 5C and 10B). Bioclasts have a wide size range and are suspended within a massive sand matrix. Many occur as unbroken shells, including both fragile and robust shells. The lack of lamination in sand and poor sorting of bioclasts imply a different mode of sediment transport for the coarse sediment than for the main mass of storm sand.

Fossil bioclasts are the dominant coarse particles and include complete and fragmented shell, octocoral stems, shark teeth, and teeth and bone of fish in a mixed assemblage of open marine, marginal marine and estuarine vertebrate remains (Fig. 5C). Many of the largest clasts are reworked concretions, including calcite and siderite nodules, concretions formed in shell-rich sands, and cemented burrow fills (Fig. 14B). Some concretions present in the gravel have holdfasts of corals or bryozoans on their surface, indicating previous exposure time and multicyclic

Figure 6. Photomosaic of storm sand beds in the PQ sandstone within the interval 83 m (east) to 136 m (west) on transect of the study area; where distinct, two layers are shown, otherwise the shaded bands indicate the limits of groups of hummocky bedforms; location of key bedforms described in text are shown in boxed areas.

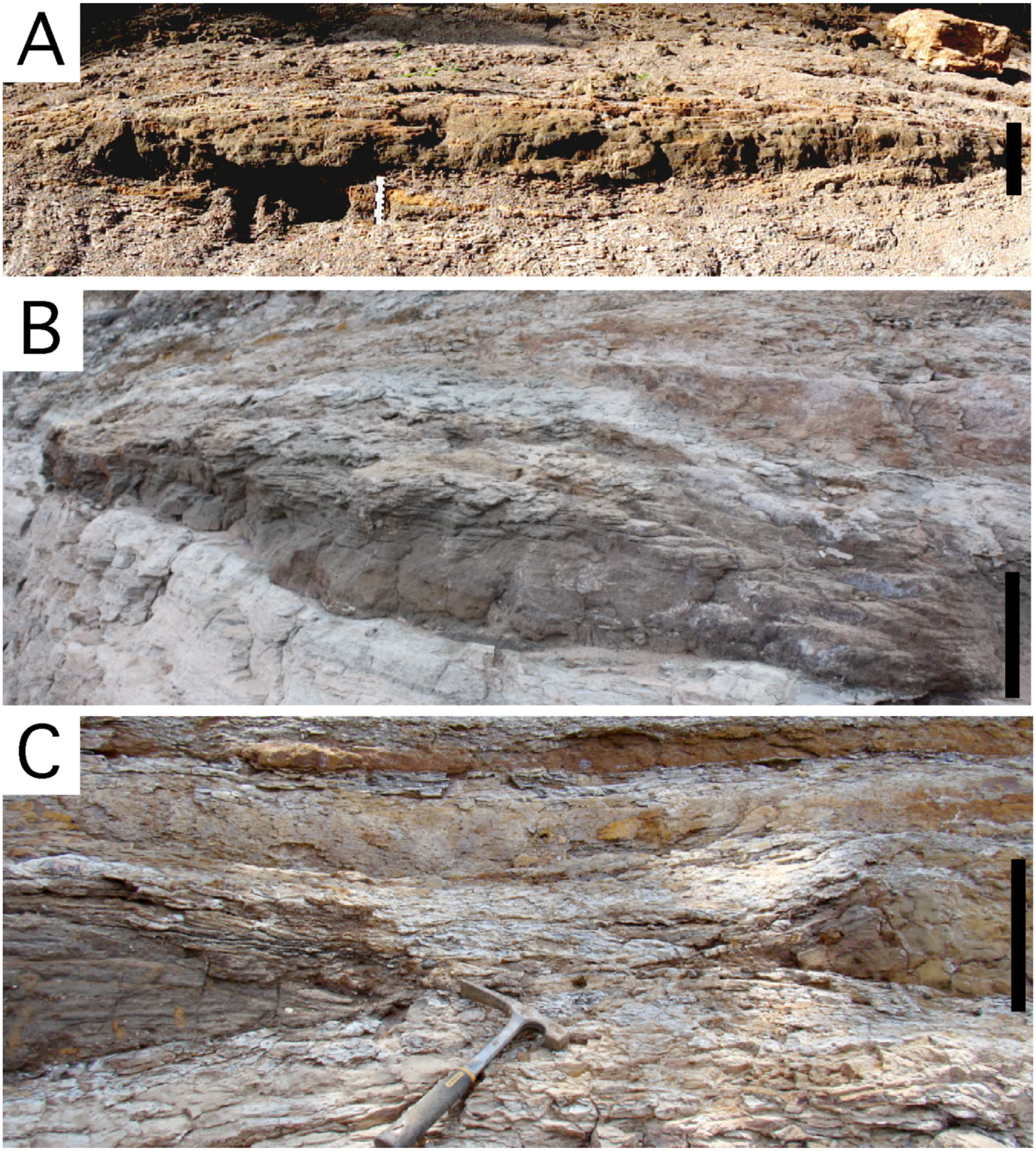


Figure 7. Outcrop photos of Stone City Bluff hummock bed forms. (A) Isolated 5.3 m lens of storm sand in PQ sandstone with main mass of laminated sand; site at 116–122 m on outcrop transect; scale bar, 20 cm. (B) Lens-shaped geometry of sand hummock; darker color of sand due to high moisture content and abundance of peloid grains; site at 103–107 m on outcrop transect; scale bar, 20 cm. (C) Lensing bedforms of storm sand in PQ sandstone; the base of lens on right (brown) can be traced to rise above lens on the left (gray), evidence that the peloid-rich storm sand (left) was deposited before the quartzose sandstone to the right (light brown); thin storm sand bed (stained red brown) present in upper part of photo; site at 122 m on outcrop transect; scale bar, 20 cm.

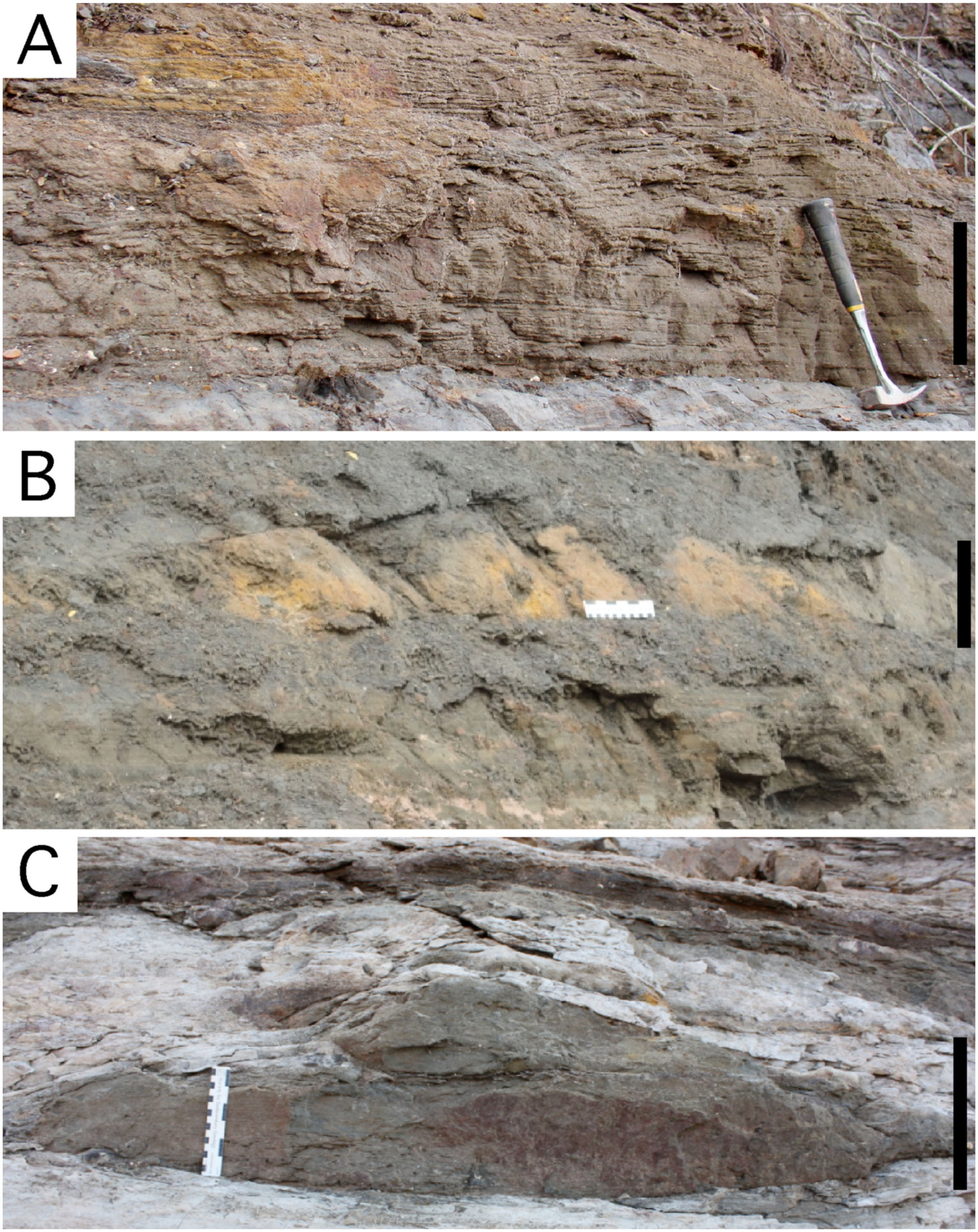


Figure 8. Outcrop photos of Stone City Bluff hummock bed forms. (A) Large hummock in PQ sandstone with short-width hummocky crossbedding (above hammer) in upper part; site at 105 m on outcrop transect; scale bar, 20 cm. (B) Large symmetric hummock in PQ sandstone with sharp basal and top boundaries; site at 90 m on the outcrop transect; scale bar, 20 cm. (C) Isolated hummock at base of PQ sandstone; fine mudstone and siltstone of unit M below the ruler; site at 137 m on the outcrop transect; scale bar, 20 cm.

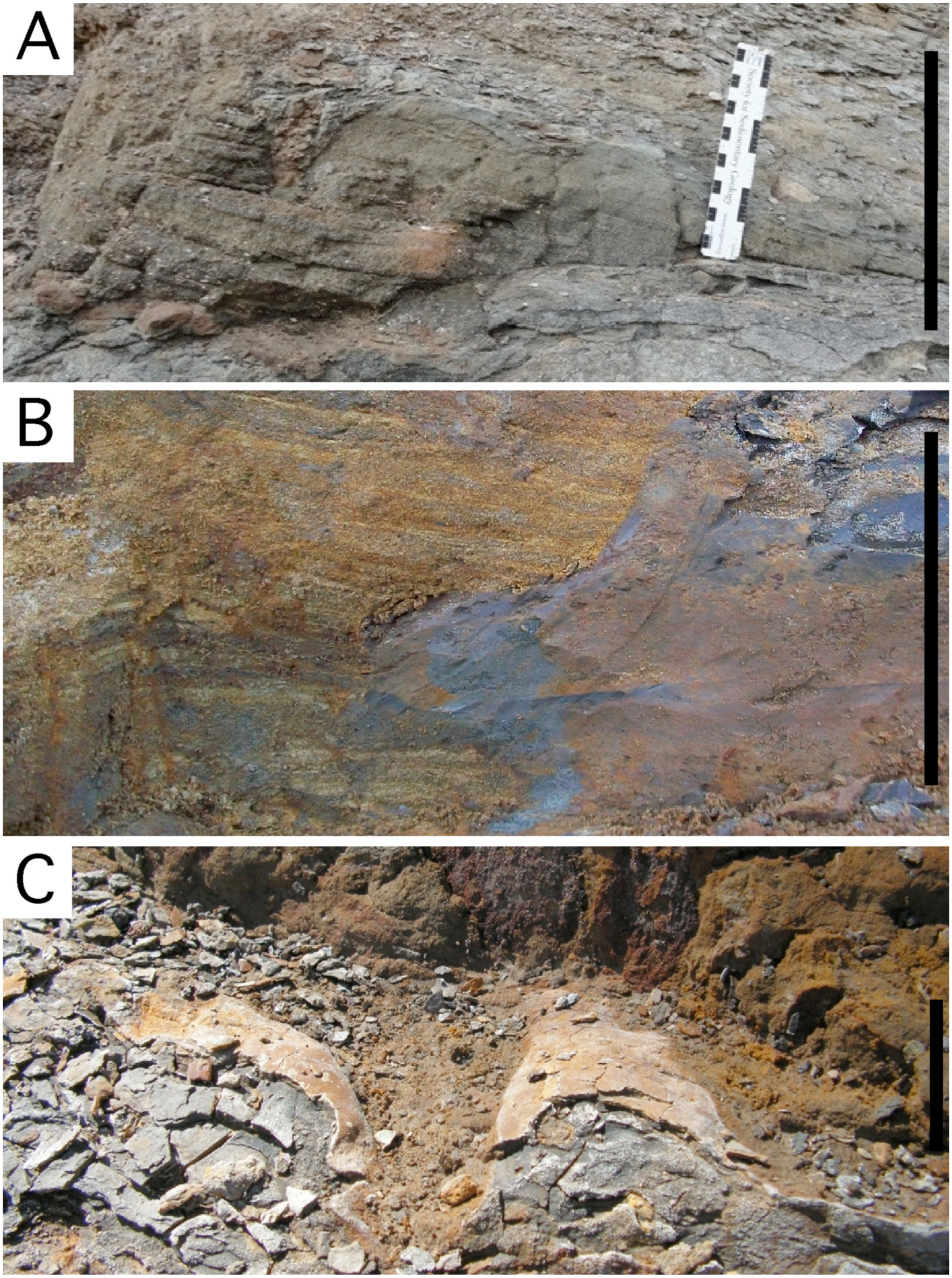


Figure 9. **Examples of scour of the PQ storm sandstone. (A) Channel fill at the base of a PQ sandstone sand lens, showing 15–20 cm of scour and filling with coarse, peloid-rich sand with fossils; site at 59 m on outcrop transect; scale bar, 20 cm. (B) Erosional margin of PQ sandstone with undercutting of mudstone bed; some mud-filled burrows in sand; site at 107 m on outcrop transect; scale bar, 20 cm. (C) Fluting at the base of PQ sand showing grooves cut into stiff mud, shown by presence of thin veneer of cement on top of mud at scour surface; site at 123 m on outcrop transect; scale bar, 5 cm.**

Figure 10. (A) Basal V storm sand (BV), overlying Intermediate Glauconite Bed (IGB); site at 148 m on outcrop transect; scale bar, 20 cm. (B) Gutter cast in mudstones; site at 10 m on outcrop transect; ruler scale in cm. (C) Scoured base of Basal V bed with coarse-grained lag layer where the storm sand lays directly on top of Intermediate Glauconite Bed, site 10 m on the outcrop transect; scale bar, 10 cm.

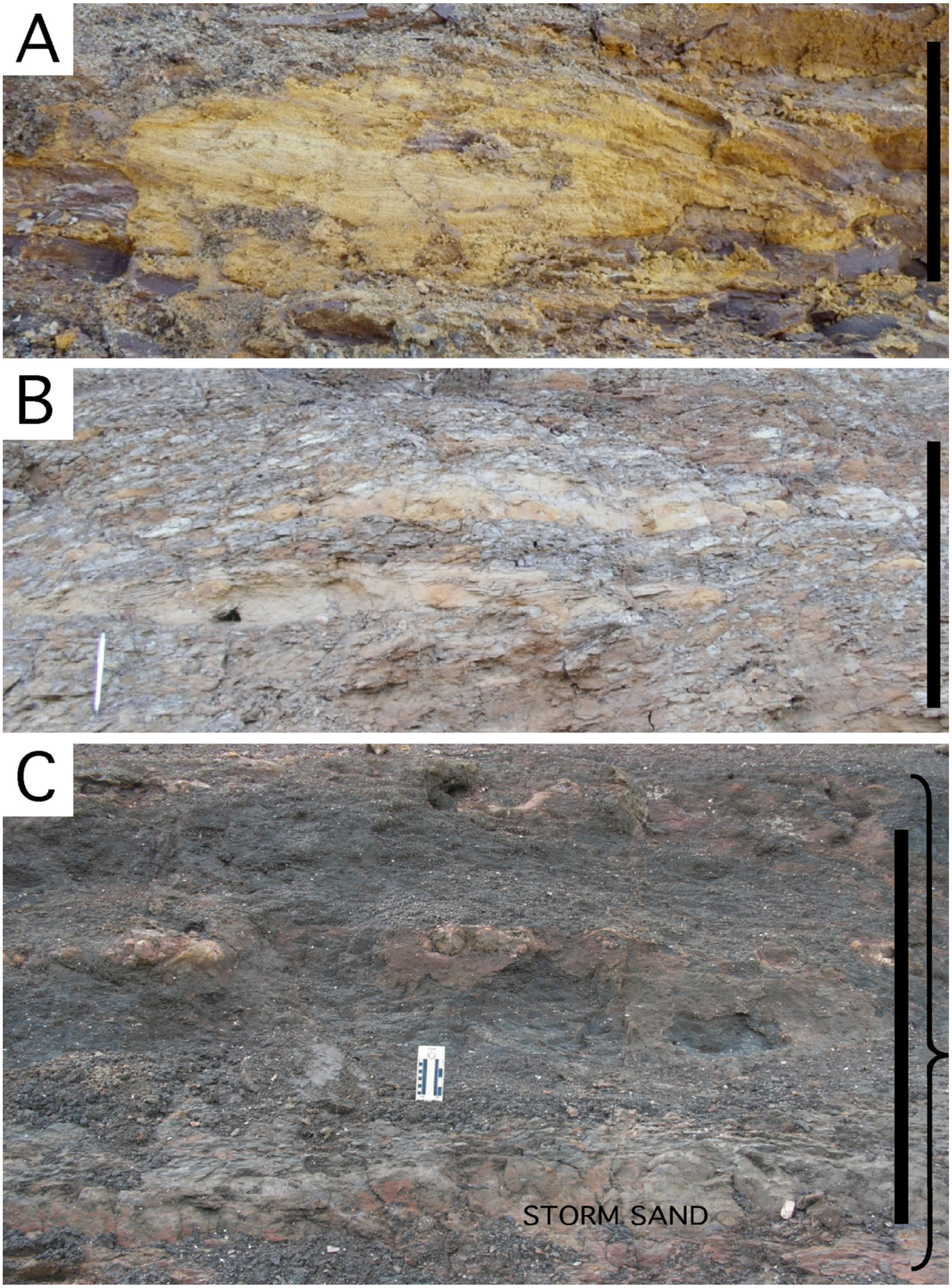


Figure 11. (A) Closeup of unit V storm sand lens; gray areas of mud within sand are mud-filled burrows; site at 10 m on outcrop transect; scale bar, 5 cm. (B) Isolated storm sand lenses in unit V; resistant layer at top is part of Moseley Bed; site at 15 m on outcrop transect; marker pen at lower left, 12 cm; scale bar, 40 cm. (C) Storm sand (below ruler scale) at base of Main Glauconite Bed (upper and lower boundaries of MGB unit shown by parenthesis) condensed unit where storm sand grades upward to bioturbated shell-rich, peloidal mudstone; a thin storm sand is also present at top of MGB; site at 30 m on outcrop transect; ruler scale, 1 m.

Table 1. Bedform characters of sandstone lenses in PQ sandstone and unit V sandstones, arranged in order of increasing width.

Width (m)	Height (m)	Unit	Station site (m)	Upper contact	Lower contact
0.14	0.04	V	5	sharp	scoured
0.50	0.10	V	10	sharp	scoured
0.60	0.15	V	139	upward-fining	gradation
0.80	0.10	V	12	sharp	scoured
0.80	0.12	V	10	upward-fining	sharp
1.0	0.10	V	16	sharp	scoured
1.1	0.10	V	15	sharp	scoured
1.4	0.15	V	8	sharp	scoured
1.8	0.25	PQ	98–100	sharp	sharp
3.0	0.17	PQ	122–125	upward-fining	scoured
3.7	0.60	PQ	128–132	bioturbated	scoured
4.2	0.40	PQ	87–91	bioturbated	scoured
4.9	0.50	PQ	103–108	upward-fining	scoured
5.3	0.45	PQ	116–122	upward-fining	scoured

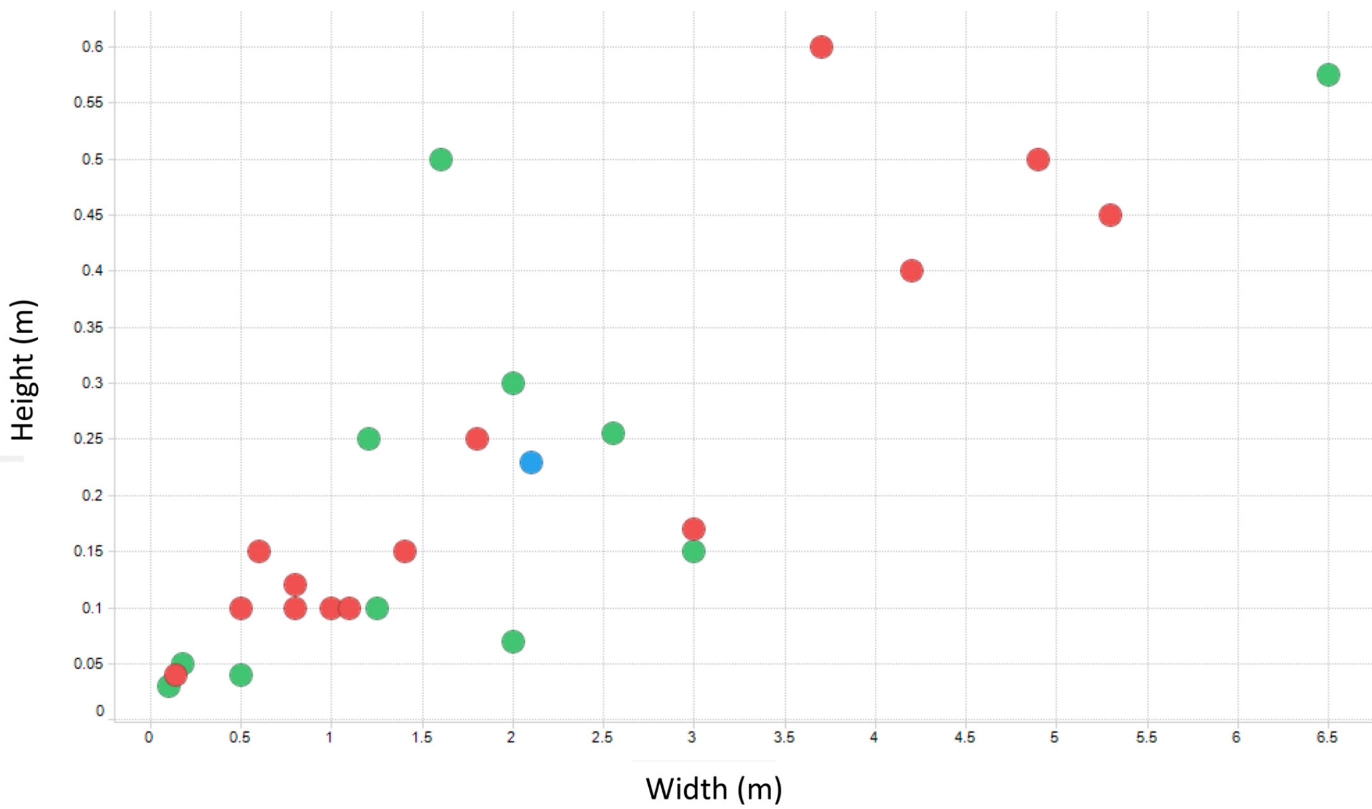


Figure 12. Crossplot of average height versus width of measured hummocks at Stone City Bluff with comparison to world averages from Craft and Bridge (1987). Green dots, average dimensions of hummocky bed forms from Craft and Bridge (1987); red dots, average dimensions of Stone City hummocks; and blue dot, average dimension of all Stone City hummocks.

movement on the seafloor as a gravel clast before final deposition. Cemented and excavated *Ophiomorpha* and *Thalassinoides* burrows are infrequent, but can reach 25 cm in length. Carbonate-cemented pieces of wood, often densely bored by teredid bivalves, and some carbonized pieces of wood are present. Tabulation for lithology and diameter of spherical to sub-rounded gravel clasts counted 590 clasts ranging from 0.42 to 4.4 cm (Fig. 14A), with a median diameter of 1.3 cm. Calcite and siderite concretions have the largest average diameter and coarse-grained sandstone concretions have the smallest average diameter.

DISCUSSION

Stone City Bluff has laterally extensive exposures of proximal and distal portions of storm beds deposited on an open marine shelf during times of transgression with high sedimentation

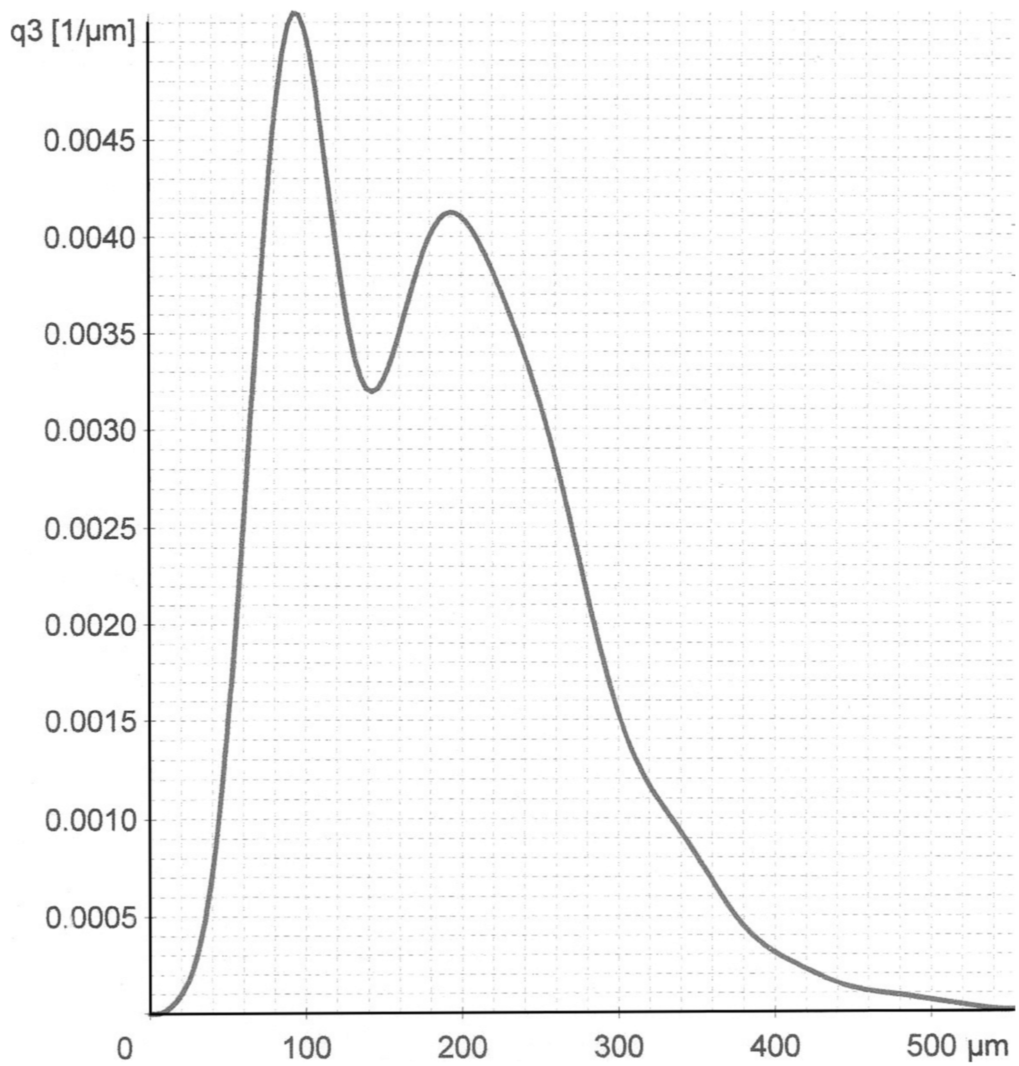


Figure 13. Grain size distribution of peloid-rich sand 11 cm above base of hummock in lower PQ sandstone; the mode at 92 µm is quartz sand grains; the mode at 195 µm is verdine peloids; coarser grains consist of bioclasts; grain size measurement on Camsizer instrument; sample from site 122 m on outcrop transect.

Table 2. Median and 90 percentile grain size of sand in PQ sandstone and unit V sandstones.

Sample	50 percentile (µm)	90 percentile (µm)
Unit V 50–53 cm level	64	175
Unit V 40–42 cm level	83	187
Basal V sand (upper)	73	172
PQ A	96	217
PQ 10B	97	188
PQ 14C	89	206
PQ 17A	176	375

rate (Yancey and Davidoff, 1991). A few beds of amalgamated origin occur in condensed shell/peloid-rich sediment beds (MGB, IGB, and Moseley on Figure 4) and are not considered in the following discussion. The distinctive feature of Stone City Bluff storm sands is their dominant occurrence as separated lenses of sand instead of being continuous sheet sands. This is consistent with conditions of sand carried by storms onto a mud bottom as storm waves shape it into hummock bedforms.

The margins of storm sand bodies embedded within mudstone are defined by the sand-mud boundary and the cross section of lens-shaped bedforms can be accurately measured. Their origin as primary components of single storm events is shown by the orientation of sand laminae concordant to lateral and upper boundaries of the bedform, paralleling the sloping sides of the lens. This is characteristic of hummocky cross-bedding. It points to an origin from combined flow currents that carry sediment and deposit it from short-term suspension over all of the upper surface of the bedform, in contrast to traction migration of sand by unidirectional currents (Swift et al., 1983). Small sand lenses tend to be aligned along bedding planes and are connected by thin sand laminae. Two horizons with discontinuous sand lenses occur at 40 and 52 cm above the Basal V sandstone at the east end of the bluff exposure (Figs. 11A and 11B). These reveal discontinuous deposition of sand on the seafloor and the influence of strong wave control on combined flow currents carrying sand. Discontinuous deposition points to small amounts of sus-

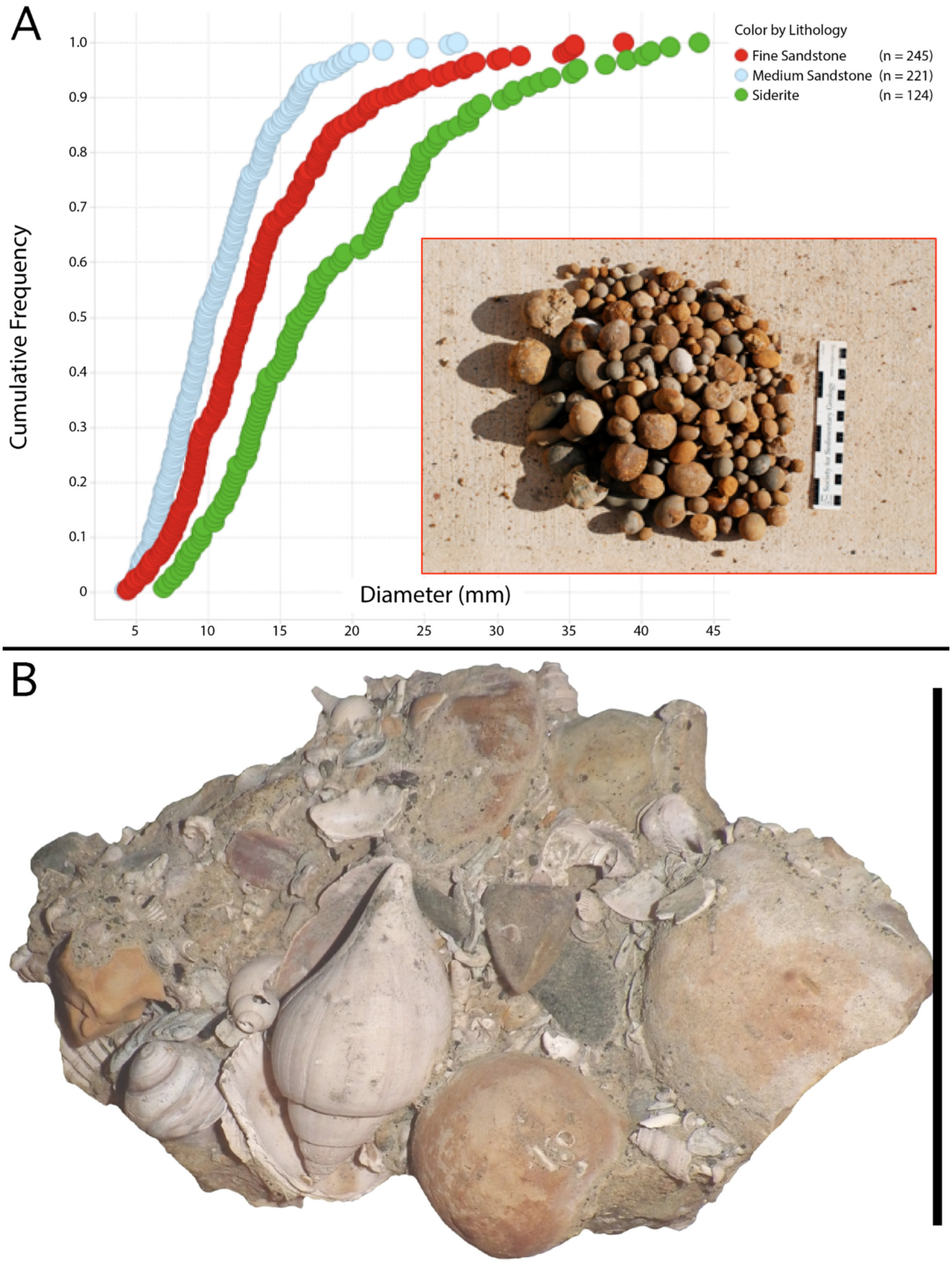


Figure 14. (A) Size range of coarse clasts from sample of gravel layer at base of storm lens in PQ sandstone; clasts are a composite from basal lag of storm sands at 111 m, 130 m, and 154 m on outcrop transect. (B) Basal gravel with mixture of undamaged and heavily eroded shell, fish otoliths (lower center and left), round siderite concretions, and fragments of septarian concretion; site at 130 m on the outcrop transect; scale bar, 10 cm.

pended sand being carried by these storm-generated currents or to a distal to marginal location within the area of storm disturbance. The patchy distribution of storm sand is consistent with the distribution of sand bedforms produced by modern storm events on the Gulf Coast (Swift et al., 1983; Swift, 1985; Snedden and Nummedal, 1989; Keen and Glenn, 1999; Keen et al., 2012).

Multi-meter hummocks (Figs. 7 and 8) are present in the lower part of the storm sand interval, along with some small-width ones, consistent with a proximal origin in a transgressive systems tract. Stone City storm sands differ from reported ancient storm deposits in having few laterally extensive sand sheets and containing hummocks with a wide range of lateral dimensions (Table 1; Fig. 12). Multi-meter hummocks are similar to sediment megaripples documented by Swift et al. (1983), Swift (1985), and Passchier and Kleinhans (2005). Most sand beds change upward to mudstone without a small-width hummock zone or ripple layer at the top. A ripple zone developed in silts would be obliterated by bioturbation in post-storm mud. Bentley et al. (2002) reported that 5–7 cm of bioturbation occurs in muds preserving deposits of modern Gulf Coast storms.

Well-preserved storm beds reveal that small-width hummocks develop on the top of large-width hummocks, although they are sparse. This indicates that large-width hummocks developed during peak energy condition of storm deposition and small-width hummocks (HCS bedding) developed during the waning phase of a storm event under conditions of continuing sand deposition. Passchier and Kleinhans (2005) determined that megaripples formed during storms at flow velocities >0.4 m/sec in combined flow currents and that HCS bedding (small-width hummocks) formed at lower velocities. The threshold velocity for deposition of these bedforms is probably different for Gulf Coast sediments because sediment along the Gulf Coast has a smaller median grain size (grain size 85–95 µm). Despite the different sediment grain size, the concept that a difference in flow velocity of combined flow currents is responsible for producing large-width versus small-width hummocks is supported by Stone City Bluff occurrences.

Hummocky bedding is documented from experimental and field studies to be a product of long period complex oscillatory flows and wave-dominated combined flows (Harms et al., 1975; Duke et al., 1991; Southard et al., 1990; Arnott and Southard, 1990; Dumas et al., 2005; Perillo et al., 2014). Using varying oscillatory and undirectional currents in wave-tunnel experiments, Dumas et al. (2005) identified a variety of bedforms historically attributed to deposition under storm-generated combined flow currents. Hummocky bedforms were generated under either purely oscillatory flow (Uo, ~50–90 cm/sec) or oscillatory-dominant combined flow (Uu, ~12 cm/sec). Experimental runs using oscillatory wave periods of 9.2–10.8 sec and sand grain sizes of 110–140 µm shows that the transition from ripple to hummock to plane bed correlates with increasing oscillatory currents and the effect of increasing unidirectional currents is to narrow the range of oscillatory current in which hummocky bedforms develop. This points to oscillatory water motion as a stirrer of sea floor sediment and combined flow currents as a mover of sediment, as noted by others (e.g., Grant and Madsen, 1979).

In addition to deposition from combined flow currents, basal portions of some storm sand beds are produced by high-density mass flows. Bioclasts and high verdine peloid content is consistent with winnowing of seafloor sediment, but coarse sands with 4 cm clasts and 8 cm concretion fragments (produced by fragmenting septarian concretions having large shrinkage cracks) are derived from sediment located below the seafloor-mixing zone. These are available for transport only under conditions of substantial erosion of the seafloor and are too large to be moved by combined flow currents.

The occurrence of mass flow deposits as a basal component of storm sands suggests they are co-genetic with overlying combined flow deposits. A density flow (Gani, 2004) or slurry flow (Lowe and Guy, 2000) would be capable of eroding channels in underlying sediment and producing scours and fluting, then filling the channel as flow ebbs. A density/slurry flow with partly laminar and partly turbulent movement would produce the irregular distribution of coarse particles present in the Stone City Bluff storm deposits. Localized high-density flows are probably generated by offshore-directed surging water masses during brief intervals of very high-energy waves (Snedden and Nummedal, 1991) and while combined flow currents are present.

The broad, extensive exposure of storm deposits at Stone City Bluff makes possible a comparison with marine shelf deposits of modern, historic storms. Stone City Bluff storms occurred during the MECO, a time of higher global temperatures than modern climates when storm events could be of greater intensity than modern storms (Knutson et al., 2010). To attempt a determination of the intensity of storms producing the Stone City Bluff storm beds, a comparison has to be made to historic storms with good documentation of marine shelf deposits. The Gulf of Mexico storm with the best documentation of marine shelf deposits along a sand-dominated shoreline is Hurricane Carla, a 1961 storm that came ashore in the coastal bend region of Texas. In addition to being extensively documented over a large area of shelf, Hurricane Carla impacted a sand-dominated shoreline with a large sand supply available for transport; a condition that is comparable to the shorelines of the middle and late Eocene. The transgressive systems tract at Stone City Bluff extends down into a thick interval of sand in the underlying sandstone formation. At most times of the Eocene, Texas shorelines are reconstructed as having curvilinear form with minimal irregularity (Galloway et al. (2011) and Eocene Texas shorezone deposits are thick (up to 5 m thickness) sand sheets (Yancey and Davidoff, 1991; Yancey et al., 2010; McBride et al., 2012), consistent with presence of a sand sheet extending out to fair-weather wave base at ~10 m water depth. Historic hurricanes striking other parts of the Gulf of Mexico are not known to produce extensive deposits of shelf sands over a range of water depths. Most recent studies of historic hurricanes have focused on documenting marginal marine sediment deposited by landward transport of sediment from the shoreline, as summarized by Hippensteel (2010) and Muller et al. (2017). Sand deposited by Hurricane Carla is known to occur out to 50 m depth (Niedoroda et al., 1989) and to be preserved as recognizable sand deposits from 20–50 m depth (Snedden and Nummedal, 1989) in the northwestern Gulf of Mexico. Microfossils present in the enclosing Stone City Member mudstones place the storm deposits within water depths of 20–50 m. No other historic hurricane striking the Texas Gulf Coast has as much documentation of its shelf-deposited sediments.

Hurricane Carla deposited quartzose sand (modal size of 68 µm) in lobes 10–18 cm thick out to 30 m water depth and covering a minimum area of 200 by 40 km near the storm track (Snedden et al., 1988; Niedoroda et al., 1989; Snedden and Nummedal, 1991). Nearly continuous storm beds were recognized to water depths of 20 m, with discontinuous deposition in deeper waters and a lack of identifiable storm sand at depths greater than 40 m. Current meters indicated that the threshold for sand transport did not extend to 74 m depth (Snedden and Nummedal, 1989). The range in velocity of currents in the Gulf of Mexico is shown in a compilation of bottom and near bottom current data for historic named hurricanes, extra-tropical events (Ext), and fair-weather coastal currents (Fw) (Fig. 15A; Appendix). Fair-weather current flows along the coast are in the range of 12–60 cm/sec in contrast to 68–200 cm/sec for hurricanes. Current meters at 84 m water depth and directly in the path of Hurricane Ivan recorded flows up to 131 cm/sec and consequent scouring of 32 cm around seabed moorings (Teague et al., 2006, 2007).

The discontinuous character of Eocene PQ storm sands in hummocks is consistent with deposition in 20–50 m water depth. Hummocks in the PQ sandstone are comparable (mean: 23 cm;

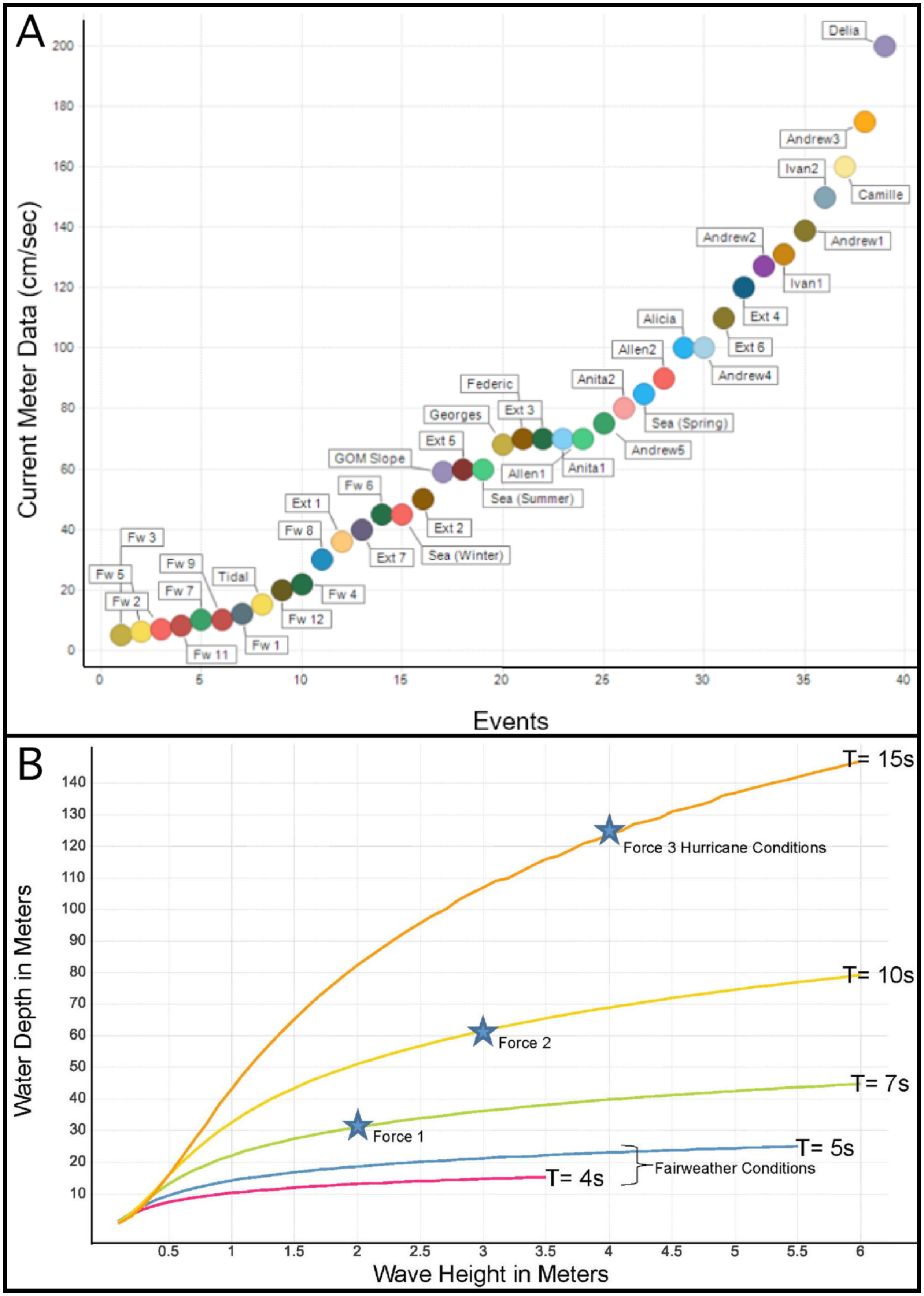


Figure 15. (A) Compilation of measured ocean bottom current data generated by varied events in the Gulf of Mexico. Compiled from multiple sources (see Appendix). (B) Threshold wave heights and wave periods needed to move 0.1 mm sand during typical conditions of Force 1 to Force 3 hurricane winds (modified after Komar and Miller, 1975, and Pentland and Boyd, 1985).

maximum: 60 cm) to sediment patches of Hurricane Carla. By reference to measurements of current flow (Fig. 15A) and threshold wave heights and wave periods (Fig. 15B) in the Gulf of Mexico, Eocene storms producing the PQ sands are estimated to have produced wave conditions comparable to those of Hurricane Carla. An improved estimate of Eocene storm intensity is dependent on developing better methods of determining storm wave conditions from storm deposits.

CONCLUSIONS

Storm sands are a prominent component of a transgressive systems tract of sediment exposed at Stone City Bluff. They occur in an interval of inner-middle shelf mudstones and condensed shell beds that overlie an interval of tide and fair-weather wave-dominated sediment deposits. Documentation is presented to show that the upward trend of deposits corresponds with increasing water depth and probable increase in distance from shore. The trend corresponds with an upward decrease in thickness and volume of storm deposits. The upward trend of storm deposits in Stone City Bluff from large-width hummocks to gutter casts and small lenses fits well with studies of depth-related changes in modern storm deposits (Swift, 1985; Swift and Niedoroda, 1985; Amos et al., 1996; Snedden and Nummedal, 1989; Passchier and Kleinhans, 2005) and ancient storm deposits (Duke et al., 1991; Cheel and Leckie, 2009). Strata containing thick, multi-meter scale sand lenses are overlain by strata containing thin, small lens-shaped sand bodies and gutter casts.

Bedforms in multiple storm sand beds can be examined at scales ranging from multi-meter to centimeter scale and their morphology, bedding, and boundaries examined laterally and partly in three dimensions as floods carve river-bank exposures. Large-width hummocks occur to 5.3 m width and sparse small-width hummocks populate the tops of large-width hummocks at the same site. Small-width hummocks can occur in isolation from other hummocky bedforms or connected to adjacent bedforms by a lamination of sand. Some large-width hummocks have coarse-grained gravel sediment at their base that is distinct from the finer-grained sand of the main mass of the hummock but was deposited during the same storm event. These gravel-rich deposits are interpreted to be the product of co-occurring high-density mass flow beneath combined flow currents, generated from the occurrence of extra-high wind and current-induced development during peak storm conditions. Large-width hummocks are related to megaripple bedforms that are produced by modern storm events and subsequently populated by small width hummocks (Swift et al., 1983; Swift, 1985; Passchier and Kleinhans, 2005).

Stone City Bluff storm sands are compared to storm sands deposited by the very large 1961 Hurricane Carla that came ashore in the northwest corner of the Gulf of Mexico. The larger Eocene storm events are comparable to Hurricane Carla and their deposits are the product of high intensity storms (Fig. 16).

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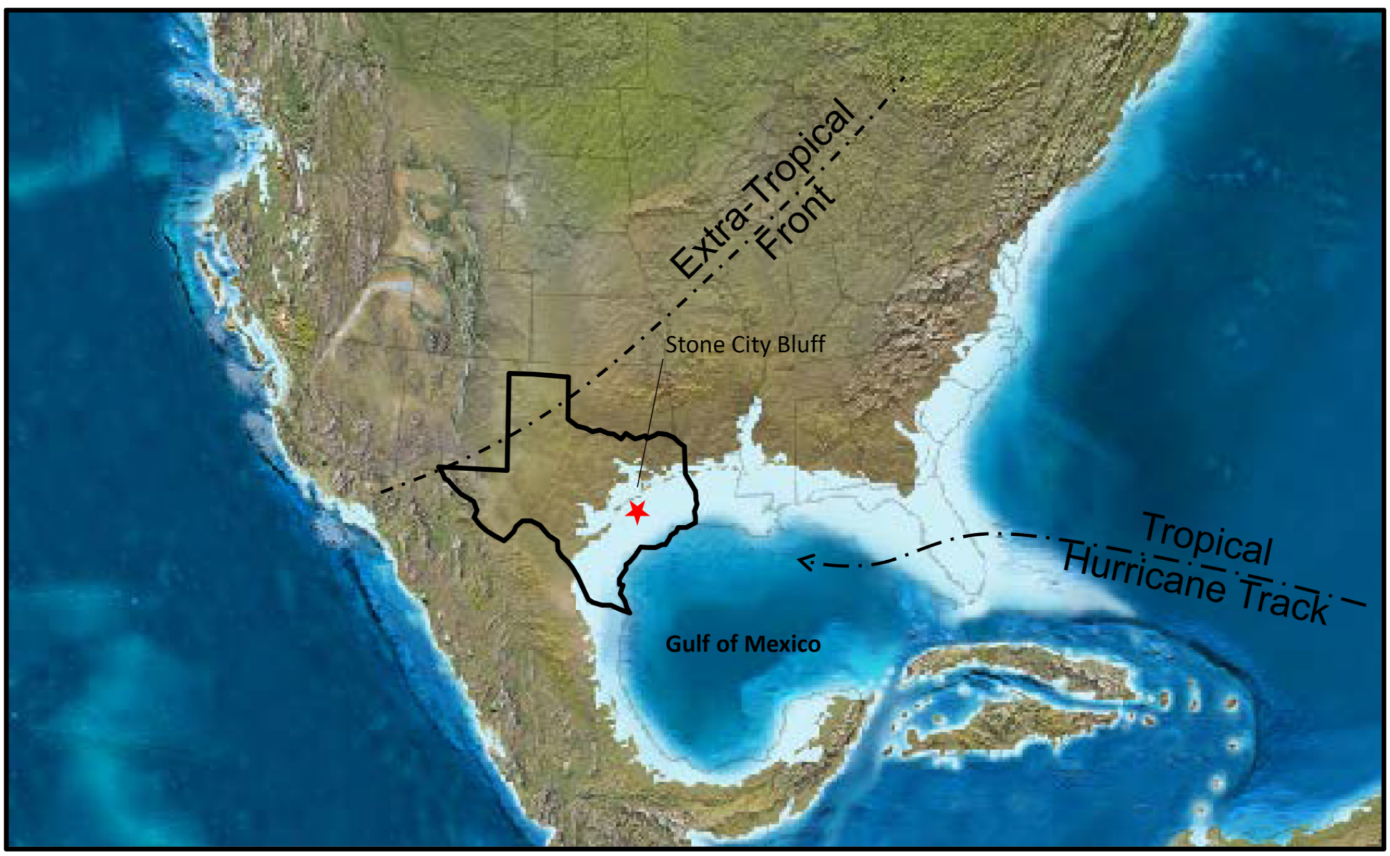

Figure 16. Paleogeographic map of Eocene highlighting the location of the Stone City Bluff; storm bedforms at site record the sedimentary impact of hurricanes and extra-tropical storms along the Gulf Coast during the Eocene. Map modified after http://www2.nau.edu/rcb7/nam.html and courtesy of Dr. Ron Blakey, Northern Arizona University, Flagstaff, Arizona.

Science. Comments from reviewers have stimulated development of concepts presented here.

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APPENDIX

Table A1. Compilation of measured ocean bottom current data generated by varied meteorological events in the Gulf of Mexico. Compiled from multiple sources, data for recent named hurricanes, extra-tropical events (Ext), tides (Tidal), and fair-weather coastal currents (Fw).

Event	Cmwd (m)	Current (cm/sec)	Reference	Comments
Andrew1	40	139	Cardone et al. (2004)	Latex Mooring #14
Andrew2	190	127	Cardone et al. (2004)	Latex Mooring #13
Federic	92	70	Gordon (1991)	WD 99 m
Fw 1	20	12	Wright et al. (2001)	Offshore Timbalier Bay, their Table 3, 1993
Fw 2	20	7	Wright et al. (2001)	Offshore Timbalier Bay, their Table 3, 1993
Fw 3	28	5	Trefry et al. (1991)	Southwest Pass Miss. Delta Anchor Sta. #1
Ext 1	28	36	Trefry et al. (1991)	Southwest Pass Miss. Delta Anchor Sta. #1
Ext 2	12	50	Walker and Hammack (2000)	WD 22 m, mouth of Atchafalaya Bay, Sta. #18
Ext 3	2.5	70	Walker et al. (2002)	Atchafalaya Bay
Fw 4	2.5	22	Walker et al. (2002)	Atchafalaya Bay
Fw 5	11	6	Jarosz and Murray (2005)	WD 17.7 m, 49 km offshore TX and LA Coast
Ext 4	10	120	Nowlin et al. (2005)	South Texas Coast
Ext 5	13.5	60	Murray (1970)	WD 15.6 m
Tidal	10.5	15	Murray (1970)	WD 15.6 m
Alicia	20	100	Morton (1988)	Unidirectional alongshore.
Camille	4.9	160	Murray (1970)	WD 6.3 m, 100 km east of eye
Delia	18	200	Forristall et al. (1977)	WD 20 m, 40 km offshore, 1973
Fw 11	9.8	8	Smith (1978)	Port Aransas, 1975
GOM Slope	315	59	Hamilton and Badan (2009)	Near bottom jets
Georges	300	68	Burden (2000)	150 km from eye
Ivan1	84	131	Teague et al. (2007)	Slope in 90 m WD
Ivan2	900	150	Mitchell et al. (2005)	Slope in 1000 m WD
Fw 6	14	45	Hall (1976)	Offshore Galveston Island
Fw 7	14	10	Hall (1976)	Offshore Galveston Island
Fw 8	2.5	30	Wells and Kemp (1981)	Station #1, WD 5 m
Sea (Winter)	8	45	Crout and Hamiter (1981)	WD 9 m, 11 km off LA Coast
Sea (Spring)	8	85	Crout and Hamiter (1981)	WD 9 m, 11 km off LA Coast
Sea (Summer)	8	60	Crout and Hamiter (1981)	WD 9 m, 11 km off LA Coast
Anita1	15	70	Smith (1978)	WD 17 m, 21 km off Texas Coast
Anita2	7	80	Smith (1978)	WD 17 m, 21 km off Texas Coast
Andrew3	12	175	Keen and Glenn (1999)	Latex Mooring #13, WD 200 m
Andrew4	100	100	Keen and Glenn (1999)	Latex Mooring #13, WD 200 m
Andrew5	190	75	Keen and Glenn (1999)	Latex Mooring #13, WD 200 m
Ext 6	5.4	110	Freeman (2010)	Tripod #1, his Figure 5.8 and Table 4
Fw 12	12	20	Snedden et al. (1988)	Current meter A, T = 6 sec, WH = 1 m
Fw 9	140	10	Snedden et al. (1988)	Current meter A, T = 6 sec, WH = 1 m
Ext 7	34	40	Snedden et al. (1988)	Current meter C, T = 9 sec, WH = 2 m
Allen1	12	70	Snedden et al. (1988)	Current meter A, T = 11 sec, WH = 7 m
Allen2	70	90	Snedden et al. (1988)	Current meter D, T = 11 sec, WH = 7 m

Event Key: Ext = Extratropical Storm, Fw = Fairweather Event, Cmwd = Current meter water depth, Sea = Season, and WD = Water depth (bathymetry).

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