



CHAPTER 5

ICHTNOLOGICAL DIAGNOSIS OF ANCIENT STORM-WASHOVER FANS, YELLOW BANKS BLUFF, ST. CATHERINES ISLAND

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Ichnology, the study of modern and fossil traces, has a long and venerated history as a science with diverse applications, such as in paleoecology (Cadée and Goldring, 2007; MacEachern et al., 2007a; Mángano and Buatois, 2007; Savrda, 2007), stratigraphy (MacEachern et al., 2007b), evolutionary biology (Walker, 2007; Wilson, 2007), petroleum production (Pemberton, 1992; Hubbard et al., 2002), and archaeology (Gautier, 1993; Johnson, 2002; Lim et al., 2007; West and Hasiotis, 2007; Roberts, 2009). With regard to the latter, ichnology has been used to interpret paleoenvironments of archaeological sites, as well as discern the effects of bioturbation on provenance of artifacts (Johnson, 2002; Canti, 2003). In a broader sense, though, ichnology can continue to assist in developing models for the geological history of a given place, such as the Pleistocene and Holocene of the Georgia barrier islands (e.g., Weimer and Hoyt, 1964; Hoyt and Hails, 1967; Hoyt, Henry, and Weimer, 1968; Farrell, Hoffman, and Henry, 1993; Gregory, Martin, and Campbell, 2004). In this respect, one of the advantages enjoyed by ichnologists on the Georgia coast is the ready availability of modern analogs of traces and tracemakers in a wide variety of environments, which lend easily to comparisons with fossil examples (Weimer and Hoyt, 1964; Frey and Howard, 1969; Howard and Reineck, 1972; Basan and Frey, 1977; Morris and Rollins, 1977; Howard and Scott, 1983; Pemberton and Frey, 1985; Bishop and Bishop, 1992; Farrell, Henry, and Cofer-Shabica, 1993; Gregory, Martin, and Campbell, 2004; Gregory et al., 2006; Martin and Rindsberg, 2007a, 2007b).

With such facility in mind, in this study we

will (1) look at storm-washover fans as environments that contribute to stratigraphic and ecological changes in coastal ecosystems; and (2) demonstrate how modern traces of these environments, when incorporated with other facies information, can provide models for interpreting ancient examples of storm-washover fans. With regard to the latter, we further explore a hypothesis proposed recently about the storm washover origin of enigmatic strata within Yellow Banks Bluff, the most extensive purported outcrop of the Pleistocene Silver Bluff Formation on St. Catherines Island (Martin and Rindsberg, 2008). We also hope to convey how trace fossils can be used to better discern paleoenvironmental changes that contribute to the geological history of the Georgia barrier islands, especially when such interpretations are informed by ichnological processes and tracemakers observed in the context of modern environments. Although the washover fans interpreted here predate human occupation of St. Catherines and other Georgia barrier islands (Vento and Stahlman, chap. 4), their interpretation will add to a more general understanding of the geological history of the island (Bishop et al., 2007; Linsley, Bishop, and Rollins, 2008).

PREVIOUS RESEARCH ON ICHNOLOGY OF STORM-WASHOVER FANS

OVERVIEW OF MODERN-ANCIENT STORM-WASHOVER FANS AND ICHNOLOGY

This study is one of a few to focus on the ichnology of washover fan deposits (Frey and Mayou, 1971; Hippensteel and Martin, 1999; Martin and Rindsberg, 2008). More studies are available

on the physical stratigraphy and geomorphology of washover fans (Andrews, 1970; Deery and Howard, 1977; Sedgewick and Davis, 2003; Morton, 2007), some of which include valuable ichnological data. In addition, several works on Georgia coastal ichnology contain information pertaining specifically to washover fans (Frey and Mayou, 1971; Deery and Howard, 1977; Frey and Pemberton, 1987; Linsley, Bishop, and Rollins, 2008; Martin and Rindsberg, 2008).

Washover fans, among the most readily accessible coastal environments, are generally glossed over in works on coastal ichnology, apparently because they are not as interesting as neighboring environments such as dunes, beaches, and marshes (Dörjes and Hertweck, 1975; Basan and Frey, 1977; Frey and Howard, 1986, 1988; Frey and Pemberton, 1987; Martin, 2006; Martin and Rindsberg, 2007a). Washover fans tend to have not only a low degree of bioturbation (with some exceptions, as noted later), but also a low diversity of tracemakers. Ancient washover fans are recognized largely by their stratigraphic position and physical sedimentary structures, especially planar lamination, proximal channels, and distal delta foresets, but also antidunes and trace fossils (Schwartz, 1975, 1982; Barwis and Hayes, 1985; Zonneveld, Gingras, and Pemberton, 2001; Donnelly and Sallenger, 2007). Washovers commonly contain a low diversity of molluscan shells, as well, especially robust forms in an abraded and broken condition, explained further on. Algal mats may develop on top surfaces of washover fans, particularly where they may wash over into intertidal or ponded areas (Sedgewick and Davis, 2003). Washover fans form at, or slightly above, high tide level along the backbeach (Deery and Howard, 1977), which constrains the elevation of high tide level in the past.

Plants that inhabit washover fans are of low diversity but may have large populations. The few species that can tolerate the difficult physical conditions prevailing on washovers may thrive here particularly, and can be valuable as indicator species where abundant. In general, however, plant cover is incomplete, leading to excellent preservation of original physical sedimentary structures with relatively little biogenic reworking (with some exceptions, noted later), as long as storm washovers continue to repeatedly drape the fan with sediment. Plants living on washover fans commonly include low-growing marsh plants, rather than trees or shrubs; among

these on the Georgia barrier islands are some halophytes, including *Spartina alterniflora*, *S. patens*, and *Salicornia virginica*. In instances where washovers spill into the edges of maritime forests, plants may also include red cedar (*Juniperus virginiana*), wax myrtle (*Myrica cerifera*), and other plants more adapted to freshwater, yet tolerant of some salinity. For example, in cores from St. Catherines Island, Linsley, Bishop, and Rollins (2008) described and interpreted modern washover fans overlying Pleistocene deposits. These bioturbated muddy deposits were interpreted as evidence of poststorm colonization by high marsh organisms, which are typically represented by halophytes (*Spartina*, *Salicornia*, and *Distichlis*), as well as ribbed mussels (*Geukensia demissa*), marsh periwinkles (*Littoraria irrorata*), and fiddler crabs (*Uca* spp.). Linsley, Bishop, and Rollins (2008) also point out, however, that such ecosystems may be short-lived as continued deposition of storm washovers soon places sedimentary surfaces well above the mean tidal range, resulting in a more depauperate halophyte assemblage or one more typical of eolian dunes.

Animals may live permanently in washover fans or enter briefly to forage. Permanent inhabitants must respond to extreme daily and seasonal changes in physical conditions, which may include high ranges of temperature, immersion, and exposure to sunlight, wind, and predators. As a result, elite residents tend to be animals that are active and can burrow rapidly, such as some arthropods (e.g., ocypodid decapods, talitrid amphipods), and the largest residents may burrow deeply to escape inclement conditions at the surface. Ocypodids include sand fiddlers (*Uca pugnator*), mud fiddlers (*U. pugnax*), and ghost crabs (*Ocypode quadrata*). Where washovers breach dunes and spill over into marshes, fiddlers tend to occupy the marshward (distal) areas, whereas ghost crabs prefer the shoreward margin (Frey and Mayou, 1971). Abundant snails (*Littoraria irrorata*) feed on microbiota, including algal films, on grass stems and the sediment surface, making characteristic trails (Basan and Frey, 1977). Terrestrial vertebrates, some of which are common tracemakers in supratidal environments of the Georgia coast (Frey and Pemberton, 1986), frequently affect surfaces and upper portions of fan deposits by walking across these open areas or digging into fans in search of sustenance. On the Georgia coast, common tracemakers include sandhill

cranes (*Grus canadensis*), great blue herons (*Ardea herodias*), raccoons (*Procyon lotor*), armadillos (*Dasypus novemcinctus*), deer (*Odocoileus virginianus*), and feral hogs (*Sus scrofa*). On the shoreward sides of washovers and closer to dunes and the upper beach, sea turtles (e.g., the loggerhead *Caretta caretta*) will nest in thick, sandy deposits they deem suitable for egg laying (Brannen and Bishop, 1993; Bishop et al., chap. 13).

Although washover fans might be less attractive than other coastal environments as objects for study, to an ichnologist they have certain advantages. For example, modern washover fans are prominent in beach and barrier geomorphology, especially in the study of storm effects. Such deposits and their geometry are easily identified from aerial photographs or satellite imagery. For example, with the Georgia barrier islands, including St. Catherines, fans can be detected by using the freeware Google Earth™, enabling better planning for ichnological investigations. Additionally, traces of washovers have a fairly high potential for preservation in the geological record, particularly if filled with contrasting sediments. The traces, moreover, should be easily distinguishable because of low overall bioturbation, especially where sandstone beds are bound by algal films on top surfaces or separated by films of clay (Sedgewick and Davis, 2003), which can provide for readily split surfaces. Contrasts in sediment color and texture among microbially bound layers, muddy sediments, and sandy sediments also should help in identifying trace fossils in ancient washover fan deposits, explained in detail later.

Criteria for recognition of ancient washover fan deposits are chiefly based on physical sedimentary structures, and secondarily on body fossils and biogenic sedimentary structures (Frey and Mayou, 1971; Deery and Howard, 1977; Anderson and McBride, 1996). Washover fan deposits are characteristically transported through a channel cut in previous beach and/or dune sediments, and spread laterally on the landward side of a barrier. This avulsion results in the fanlike geometry of modern washover fans, analogous to crevasse splays in fluvial systems. Sediments composing washover fans tend to consist of sand to gravel originating in beach and dune environments (Deery and Howard, 1977; Sedgewick and Davis, 2003; Morton, 2007). Sorting in general is poor, and organic matter may be lacking, al-

though driftwood may be incorporated with the sediment load along with suspended, fine-grained organic matter (Deery and Howard, 1977).

Additionally, Anderson and McBride (1996: table 3) summarized previous work on shell beds in washover fan deposits and showed that storms may carry large amounts of shell debris in washovers, creating single-event shell beds without biological reworking. Molluscan species in such deposits are typically shallow-marine, but may also include shells from exhumed estuarine deposits. Shells are commonly abraded and consist largely of robust species; individual shells are oriented convex-upward, convex-downward, or at random, and may be nested (Albertzart and Wilkinson, 1990; Sedgewick and Davis, 2003). Coarse and fine shell beds may alternate; individual beds are ungraded and commonly are cross-stratified. Similarly, foraminifera in washover fans may have low diversity but very high populations. For example, on the Atlantic shore of the Virginia part of the Delmarva Peninsula, Culver et al. (1996) found an average of about 42 specimens ml⁻¹ (especially of the indicator species *Quinqueloculina seminula*) in washover samples.

Biological signatures of former inhabitants of washover fans, represented by trace fossils, can be distinctive. As mentioned earlier, actual biodiversity is low but can be coupled with numerous individuals for each species living on or near fan deposits. The most abundant modern animals living on, within, and near Georgia washovers include ocypodids, especially fiddler crabs (e.g., *Uca pugnax* and *U. pugilator*; Frey and Mayou, 1971; Deery and Howard, 1977). Hence trace fossils matching known forms of modern ocypodid traces should be present in any Pleistocene interglacial deposits in the same area. Similarly, root traces of plants common to or ecologically succeeding washover fans should be present; such traces are especially valuable in falsifying interpretations of shallow marine paleoenvironments (Gregory, Martin, and Campbell, 2004). Where depositional rates become low, plant bioturbation may dominate the ichnoassemblage (Warme, 1971; Edwards and Frey, 1977). In general, the animal traces of the Georgia littoral environments are much better characterized than the plant traces. More work is needed to describe modern roots in these environments. Lastly, escape (equilibrium) traces may also be present in washover deposits where infauna attempted to burrow up

in reaction to a rapid influx of sand. Although such traces have not been documented in detail, bivalve escape traces have been noted in wash-over fans of St. Catherines Island (Harold Rollins, personal commun., 2009).

YELLOW BANKS BLUFF: DESCRIPTION AND INTERPRETATION

GEOLOGICAL SETTING, PREVIOUS INVESTIGATIONS OF ST. CATHERINES ISLAND

St. Catherines Island is one of several regressive barrier islands formed along the Atlantic coast of Georgia and South Carolina from Pleistocene times to the present (fig. 5.1). Bishop et al. (2007) and Linsley, Bishop, and Rollins (2008) outlined the stratigraphy of the island and provided interpretations of its geological history. Johnson et al. (1974), Hudson (1978), and Coile and Jones (1988) studied island vegetation, whereas Booth, Rich, and Bishop (1999), Booth et al. (1999), Booth and Rich (1999), and Rich and Booth (chap. 6, this volume) examined the palynology and other plant fossils of Pleistocene-Holocene deposits, including those at Yellow Banks Bluff. Morris and Rollins (1977), Fierstien and Rollins (1987), and Prezant et al. (2002) provided thorough reviews of the island's marine invertebrates. Ichnological studies have been limited mostly to neoichnology, the study of modern traces and their makers, such as intertidal and subtidal tracemakers (Morris and Rollins, 1977; Bishop and Bishop, 1992) and sea turtles in beach-dune environments (Brannen and Bishop, 1993). In contrast, Booth, Rich, and Bishop (1999), Bishop et al. (2007), Linsley, Bishop, and Rollins (2008), Vento and Stahlman (chap. 4, this volume) studied different geological aspects of the Silver Bluff Formation on St. Catherines Island, but did not focus on its ichnology. Our study is the first in-depth examination of trace fossils on St. Catherines, specifically in the Silver Bluff Formation as exposed on Yellow Banks Bluff.

STRATIGRAPHIC DESCRIPTION OF YELLOW BANKS BLUFF

Yellow Banks Bluff is a seacliff and the tallest exposure on the island, revealing about 5 m of vertical section, with the lowermost portion representing the Pleistocene Silver Bluff Formation (figs. 5.2, 5.3). Most of the bluff consists of poorly consolidated yellowish sand, with mi-

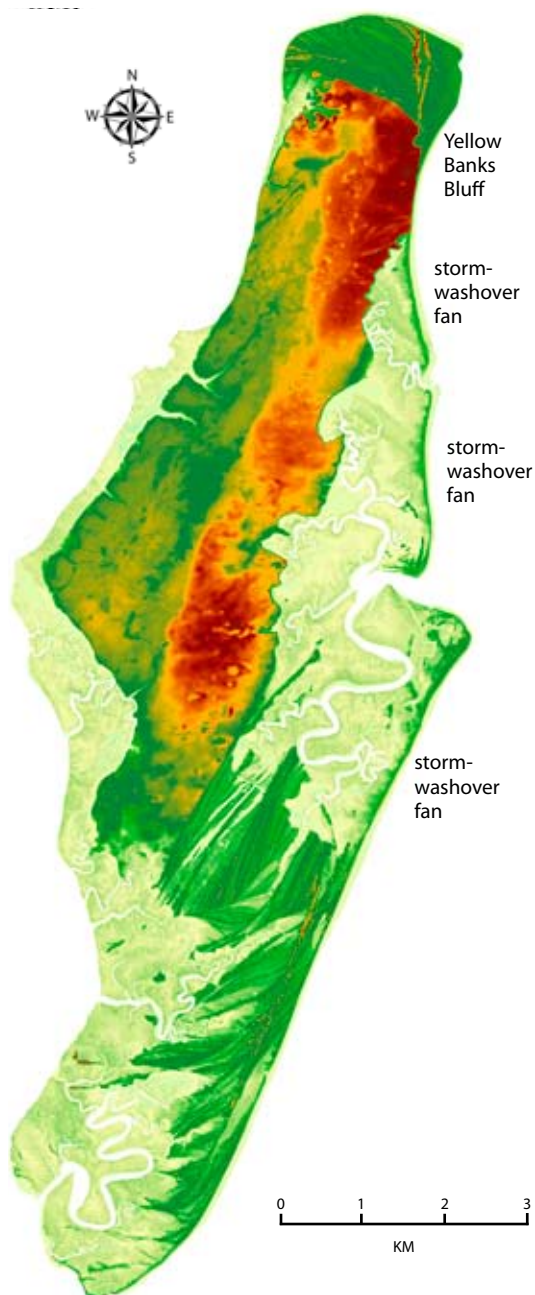


Fig. 5.1. Locality map of Yellow Banks Bluff and modern storm-washover fans, St. Catherines Island, Georgia. Map created by Brian K. Meyer.

nor clay in lenticular deposits. Dark-brown to black clay is also exposed at the northern and southern ends of the cliff, interpreted as relict Holocene marsh deposits, with the southern deposit explained in more detail later. Geographical coordinates of the Magnolia Bluff overlook toward the southern end of Yellow Banks Bluff are 31.67791°N, 81.13721°W.

The Silver Bluff shoreline complex was deposited during a sea level highstand of about 1.5 m (Bishop et al., 2007; Linsley, Bishop, and Rollins, 2008). Yellow Banks Bluff probably originated as a cut bank along an estuarine channel between St. Catherines Island and a hypothetical Guale Island eroded away during the Holocene, which is now represented by the submerged substrate lying off Yellow Banks Bluff (Bishop, 1990) and by sediment transported southward as Guale Island was eroded. Within historical time, the bluff has been rapidly eroded and refreshed when storms (hurricanes or nor'easters) coincide with high spring tides, and is now retreating at an average of about 1.8 m per year (Potter, chap. 7). The oak-pine-palm forest atop the bluff contributes fallen trees to the beach, forming a "tree bone yard," which complicates reconnaissance of the outcrop in places. Furthermore, the outcrop face is riddled with the roots of modern trees, particularly those of cabbage palms (*Sabal palmetto*) and saw palmettos (*Serenoa repens*),

which will be discussed later with regard to their impact on proper diagnosis of trace fossils in the Silver Bluff Formation.

Basal strata of the examined section (fig. 5.3) have planar to ripple laminae composed primarily of very fine quartz sand; some laminae are rich in dark heavy minerals, also present as very fine sand. These beds show some evidence of disruption by bioturbation, and although trace fossils are difficult to classify from vertical sections, they seem to include: 0.5–1.0 cm wide *Skolithos* isp. (simple vertical burrows); abundant 1–3 mm wide *Planolites* isp. (simple horizontal burrows with organic-enriched, structureless fill); and 0.5–2.5 cm wide *Psilonichnus up-silon* (vertical and oblique burrows) (fig. 5.4A, B). Sections scraped parallel to bedding planes revealed that *Psilonichnus* is indeed the most likely ichnogenus for the larger burrows, which are more common just above the zone containing *Planolites* and *Skolithos*. Accompanying this upward increase in *Psilonichnus* is a decrease in heavy minerals and ripple bedding, which is probably a direct result of increased bioturbation. This zone grades upward into sediments dominated by 0.5–1.0 cm wide *Taenidium* isp., evident as horizontal and oblique burrows with meniscate fill.

Overlying strata include two or more weakly consolidated (possibly with humate) dark brown-



Fig. 5.2. Outcrop view of Yellow Banks Bluff, indicating relative position of one thin, dark, ephemeral stratum examined in this study and interpreted as an ancient storm-washover fan; arrows point toward lateral extent of bed, which is about 29 m wide. Photograph is a digital composite of three successive, lateral shots (left to right) taken from same vantage point.

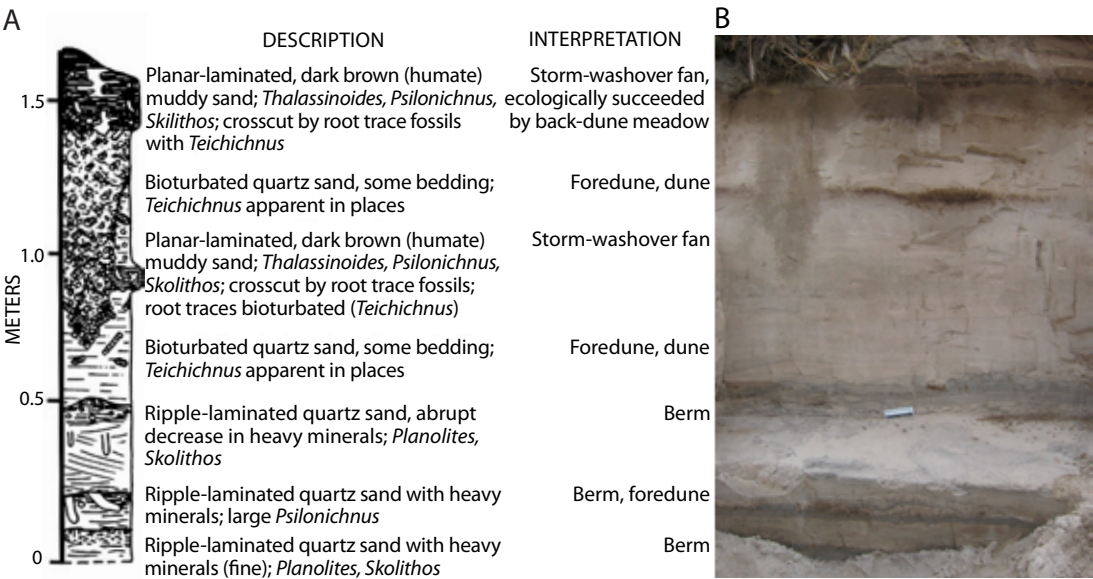


Fig. 5.3. Graphic log and photograph of studied 1.5 m thick interval in lower part of Yellow Banks Bluff, accompanied by verbal descriptions and paleoenvironmental interpretations: **A**, graphic log; **B**, photograph of excavated interval, with bedding-plane exposure at about 25 cm above modern berm level.

ish, bioturbated zones separated by a completely bioturbated quartz sand. These beds are thin (5–15 cm) and ephemeral, but can be as much as 30 m in lateral extent. The beds contain laminae discernible as dark brown and light brown alternations of sediment, and also are crosscut by *Thalassinoides* isp., small *Pylonichnus* isp., and *Skolithos* isp., which in turn are crosscut by *Taenidium* isp. (fig. 5.4C–E). These trace fossils have sharp boundaries with surrounding sediment, and most are contrasted from the host lithology by white quartz-sand fills. Bedding-plane views of burrows show circular to oval cross sections with discrete boundaries, ranging from 0.5 to 1.5 cm wide, but with most about 1.0 cm. Most burrows and strata are crosscut by large, conical-downward root traces in places, which are also crosscut by *Taenidium* isp. (fig. 5.5), obscuring outlines of former root traces that are now only detectable through original color differences (i.e., root traces are typically dark brown against a pale brown host sediment). Some root traces originate at the upper of the two brownish beds and extend vertically below for nearly a meter, whereas others do not have a

clear upper origin. Aside from sandy deposits, Yellow Banks Bluff includes a lenticle of peat, peaty clay, and very fine quartz sand exposed near the south end of the outcrop. Based on outcrop expressions and some excavation, this channellike deposit, which crosscuts older strata, is at least 1.5 m deep and 3–5 m wide, incised into sandy deposits below that are similar to the lowermost part of the stratigraphic section described previously. The peat contains terrestrial plant debris such as wood fragments, pinecones, and nuts, the latter possibly from hickory. This peat is also noteworthy for what it lacks, such as in situ remains of *Spartina alterniflora*, *Geukensia demissa*, and other species characteristic of exhumed relict salt marshes on St. Catherines and other Georgia barrier islands (Morris and Rollins, 1977; Frey and Basan, 1981; Pemberton and Frey, 1985). The contact between the peat and overlying fine-grained quartz sand is gradational because of extensive bioturbation, most of it attributable to *Taenidium* isp. We also noted that the lowermost part of the boundary between the dark clay and the underlying sand, corresponding to the base of a channel, is sharp and

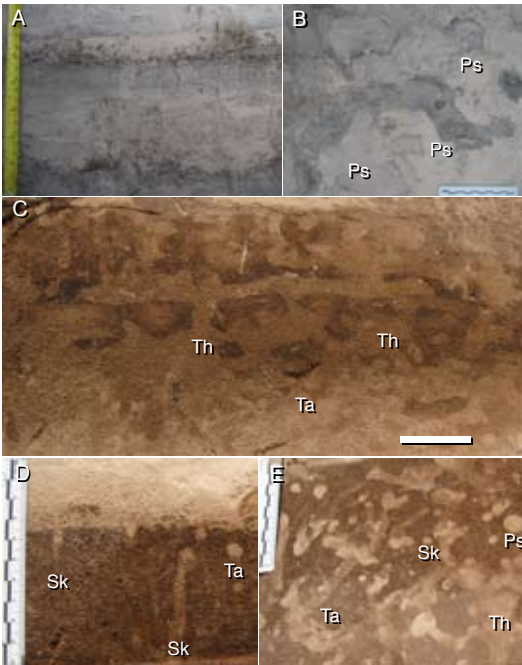


Fig. 5.4. Trace fossils within studied interval of Yellow Banks Bluff (see fig. 5.3 for stratigraphic positions): **A**, *Planolites* isp. (Pl), cross-sectional view, with organic fills contrasting with surrounding cross-bedded sand, at 10–20 cm in vertical section (see fig. 5.3A); scale in cm (left); **B**, larger *Pylonichnus* isp. (Ps), bedding plane view, showing partial collapse and fill of heavy minerals in burrows, at about 20 cm; scale = 10 cm; **C**, *Thalassinoides* isp. (Th), cross-sectional view, in upper dark-brown laminated bed, at about 135–150 cm in vertical section; scale bar = 5 cm; **D**, *Skolithos* isp. (Sk), and *Taenidium* isp. (Ta), cross-sectional view, in lower dark-brown laminated bed, at about 110 cm; scale in centimeters (left); **E**, *Taenidium* isp. and circular cross sections of smaller *Pylonichnus* isp. and *Skolithos* isp., bedding plane view, at about 150 cm; scale bar = 5 cm.

unbioturbated, but further up the original channel banks the higher portions of that same contact are blurred by bioturbation. Remarkably, a 9.1 m vibracore taken in relict marsh mud south of the bluff consisted entirely of marsh mud, whose unusual thickness is still anomalous, and used as evidence of an extensive marsh system between St. Catherines and Gualie islands (Bishop et al., 2007: 43, 50).

As mentioned earlier, modern roots from the

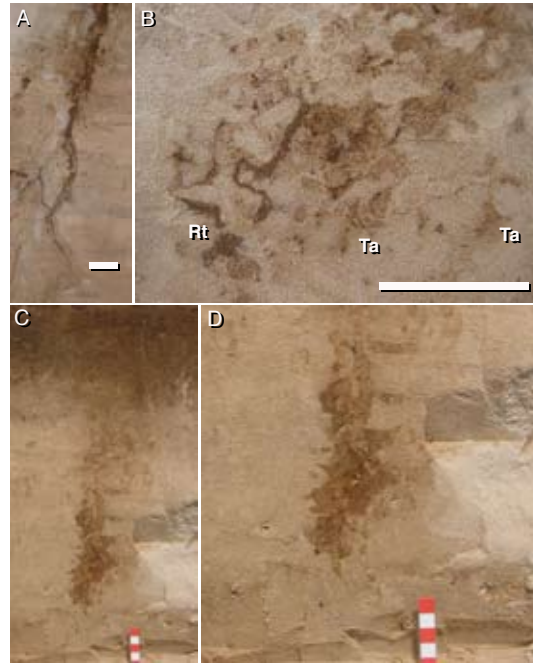


Fig. 5.5. Root trace fossil in Yellow Banks Bluff. **A**, root trace fossil in vertical view; scale bar = 10 cm. **B**, cross-sectional (bedding plane) view of same root trace fossil, showing dark halo, associated *Taenidium* isp., and other forms of bioturbation; scale bar = 5 cm. **C**, root trace originating from dark laminated zone and extending into bioturbated zone; scale in cm. **D**, close-up of distal end of root trace, showing direct association of *Taenidium* isp. in former site of root.

overlying oak-pine forest extend downward to as much as 5 m, or the total exposed thickness of the outcrop above the beach surface. These roots include those of live oak (*Quercus virginiana*), longleaf pine (*Pinus palustris*), cabbage palm (*Sabal palmetto*), and saw palmetto (*Serenoa repens*). Live oak-dominated forests are likely to have existed in prehistoric times (Coile and Jones, 1988), hence these modern root traces are potentially confused with fossil ones. In regard to abiogenic structures that might be mistaken for root traces (modern and fossil), Bishop et al. (2007: 50) also reported obscure, nearly vertical joints in the bluff sand. Some joints have been followed by roots or marked by clay deposition from soil eluviation. Mass wasting of undercut slopes follows joints in places.

ICHTHOLOGY OF YELLOW BANKS BLUFF

DIAGNOSIS OF YELLOW BANKS BLUFF: Because Yellow Banks Bluff is the only extensive outcrop of its age on the island, the two dark-brown laminated beds are key for determining a part of St. Catherines prehistory. Partly on the basis of the bioturbate textures of the beds, Bishop et al. (2007: 50) proposed two hypotheses regarding their origin: (1) the beds might be marine firmgrounds formed during Pleistocene highstands preceding the Silver Bluff highstand; or (2) they might represent marine erosional terraces on the Silver Bluff shoreline. During our initial visit to the island in March 2007, we discussed these possibilities with Bishop et al.; an in-depth investigation of the ichnology of the outcrop then took place during a follow-up visit in June 2007.

Aided by the newly described ichnological data related previously, we interpret the lowermost 1.5 m of the Silver Bluff Formation exposed at Yellow Banks Bluff as foredune facies succeeded vertically by backdune, storm-washover fans, and backdune meadow facies. These new interpretations overturn previous hypotheses of the Silver Bluff Formation as marine still-stand facies and the dark-brown strata as marine firmgrounds or terraces formed during a Silver Bluff sea level high (Bishop et al., 2007). Instead, we propose that facies were deposited well above the high-tide mark and adjacent to terrestrial environments, albeit affected occasionally by marine processes such as storm surges. Accordingly, facies must have been deposited while sea level was only slightly higher than the current level; moreover, the vertical succession of facies suggests a shallowing-upward sequence similar to that interpreted from the Raccoon Bluff Formation (Pleistocene) of Sapelo Island (Gregory, Martin, and Campbell, 2004).

Foredune facies are inferred from low-angle cross-bedding of very fine sand, heavy mineral concentrations in the basal part of the section, small-diameter burrows (*Skolithos*, *Planolites*) that are likely from insects or juvenile ghost crabs (*Ocypode quadrata*), and large-diameter sand-filled burrows consistent with those of *Psilonichnus* and attributable to ghost crabs. Backdune facies are diagnosed from a gradual decrease in heavy mineral abundance corresponding with an increase in pervasive, small-diameter backfilled burrows (*Taenidium*). This facies is punctuated by two thin dark-brown laminated beds (each separated vertically by about 30 cm), which are

from storm-washovers that breached coastal dunes. Their distinctive color was imparted by suspended organics mixed with very fine sand and mud deposited in low-amplitude, mostly continuous sheet deposits (fans), some of which later had their surfaces bound by algal mats.

Rapid poststorm colonization of fan surfaces was mainly facilitated by fiddler crabs (*U. pugnax* or *U. pugilator*), as evinced by crosscutting vertical, J-shaped, and horizontal burrows (*Skolithos*, *Psilonichnus*, and *Thalassinoides*); the abundance and numerous intersections of these burrows suggest multiple generations of burrowing, although some may also represent branching networks. These burrows were later passively filled with eolian sand, burrowed in places by insects and crosscut by root traces that were then burrowed by insects. Some root traces, which imparted darker hues to affected sediment, originate at this stratum and extend downward for 40–50 cm, further supporting poststorm colonization and the start of ecological succession. Eolian sand buried and filled open fiddler crab burrows, which provided for excellent visual contrast and definition of the trace fossils (fig. 5.6). Infaunal insects bioturbated these eolian sands, forming more pervasive zones of *Taenidium*, some of which are more easily discerned around root traces because of sediment contrast; some *Taenidium* crosscut the burrows of the washover fan, further demonstrating ecological succession. Different species and/or growth stages of infaunal insects are probable, based on significant size differences between some backfilled burrows. At least some of the root traces, however, are related to recent roots of extant trees on the top of Yellow Banks Bluff (fig. 5.6A); some of these even contain root tissues. This circumstance hints at the potential complexity of root-trace histories within the outcrop.

INVERTEBRATE TRACE FOSSILS: *Taenidium* (figs. 5.4C–E, 5.5D) is interpreted as an actively backfilled burrow made by either an insect larva or nymph; among the most commonly invoked tracemakers for *Taenidium* in terrestrial deposits are cicada nymphs (O'Geen and Busacca, 2001; Gregory, Martin, and Campbell, 2004; Smith and Hasiotis, 2008), but beetle larvae are also implicated as possible tracemakers (Ekdale, Bromley, and Loope, 2007). *Taenidium* has been previously identified in Pleistocene deposits of the Georgia barrier islands, specifically in the Raccoon Bluff

Formation of neighboring Sapelo Island (Gregory, Martin, and Campbell, 2004).

Larger-diameter *Psilonichnus* (fig. 5.4B) are interpreted as the burrows of *Ocypode quadrata*, a common infaunal component of foredune areas, particularly along the Georgia coast. These burrows consist of gently curved J-shaped burrows with subcircular cross section and distinct walls; the tracemaker generally added a branch in the same plane to form a Y-shaped burrow system (Fürsich, 1981; Frey, Curran, and Pemberton, 1984; Frey and Pemberton, 1987; Nesbitt and Campbell, 2006). Although not as clearly defined in vertical section, horizontal sections scraped from the lower portion of the section revealed large-diameter burrows marked by sediment contrasts provided by heavy minerals. One caveat is that the loose consolidation of the Silver Bluff Formation here allows for the possibility of modern ghost crabs burrowing into the formation, then having these burrows filled by water- or wind-borne sand to give a false appearance of being part of the original ichnocoenose. We reduced this possibility of mistaken interpretation by digging nearly 1 m horizontally into the out-

crop; moreover, the rapid rate of erosion of Yellow Banks Bluff makes it less likely that recently made burrows would have been filled and buried before our excavations.

Smaller *Psilonichnus* and *Thalassinoides* (figs. 5.4D, E) are interpreted as the burrows of fiddler crabs belonging to various species of *Uca*, although we think they are most likely attributable to the sand fiddler crab *Uca pugilator*. This is the only local fiddler crab whose mouthparts are modified to feed on sandy substrates (Miller, 1961), although *Uca pugnax* and *U. minax* also live in high marsh sandy substrates. Basan and Frey (1977: 59) described similar burrows from sandy high marshes on nearby Sapelo Island. The modern burrows of *Uca pugilator* are simple, L- to J-shaped, with the upper shaft steeply inclined or vertical and the lower gallery angled to a gentler slope, in many cases terminating with a flat-floored, horizontal chamber at a depth of 10–20 cm within the substrate. The burrows' cross sections are circular to sub-circular or somewhat irregular, ranging from 1 to 2 cm in diameter. The animals also construct shallow excavations that may represent tempo-

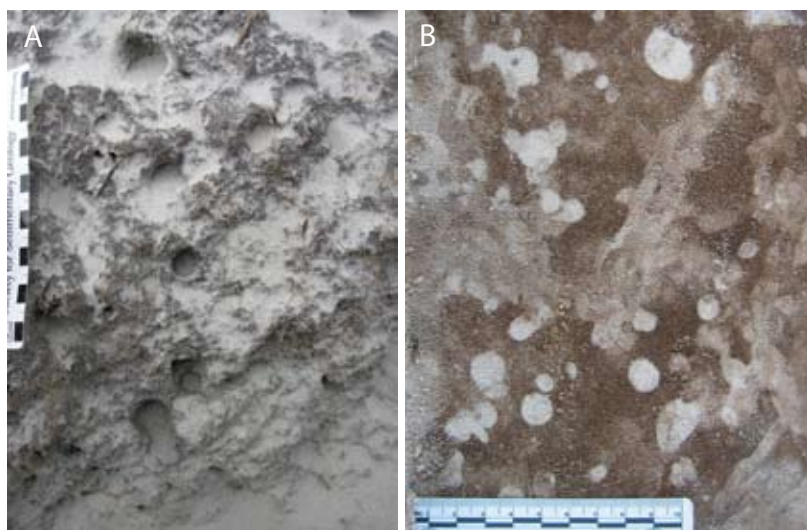


Fig. 5.6. Taphonomic comparison of bedding-plane views for burrows attributed to *Uca* spp. in relict marsh from Cabretta Beach (Sapelo) and Yellow Banks Bluff. **A**, probable *Uca* spp. burrows in relict marsh, showing eolian sand filling burrows with circular cross sections and causing sediment contrast between host sediment and fill. **B**, probable *Uca* spp. burrows, cross sections of *Thalassinoides* isp., *Skolithos* isp., and *Psilonichnus* isp., in interpreted washover fan, with similar sediment contrast between host lithology and fill.

rary hiding or resting burrows (Basan, 1975). Prezant et al. (2002) reported that *Uca pugilator* is also common in St. Catherines marsh flats and tidal creeks. The burrows of *Uca pugilator* are generally unconnected with one another.

A slight alternative to this hypothesis is that these burrows were made by the mud fiddler crab *Uca pugnax*, the only local fiddler known to excavate multibranched burrows, which occur where populations are especially dense. Basan and Frey (1977: 59) described burrows of *U. pugnax* on Sapelo Island as "unbranched, nearly straight or highly sinuous shafts, to simple or complex systems consisting of shafts and U-shaped components; all burrows unlined, mostly 1–2 cm in diameter, commonly intersecting burrows of other species." Many variations of these burrow forms exist, and they would thus account for the geometric complexity of the burrows. Interactions with plants are also important. *Uca pugnax* tends to dig more shallowly in densely rooted substrates than in root-free areas; moreover, roots commonly penetrate open burrows (Basan, 1975). Nonetheless, *Uca pugnax* and *U. pugilator* are restricted ecologically by grain size and probably represent amensalism (habitat displacement); various species of *Uca* represent divergence from a common ancestor influenced by behavioral and ecological selection pressures (Strumbauer, Levinton, and Christy, 1996; Rosenberg, 2001). At Yellow Banks Bluff, with numerous interconnected horizontal, oblique, and vertical burrow components, we interpret the complexity of the ichnofabric in the inferred washover fans as a result of intersecting individual burrows, rendering a false branching and "networks" that may be only apparent.

ROOT TRACE FOSSILS: The ichnological aspects of the root traces (fig. 5.5) at Yellow Banks Bluff are complex owing to the taphonomic mixing of modern and fossil root traces along with closely associated invertebrate traces and trace fossils, discussed in the following section. Nonetheless, root trace fossils are discernible within Yellow Banks Bluff, particularly where such traces originate at washover horizons; accordingly, these are interpreted as having formed shortly after deposition of washover sediments and representing poststorm ecological succession.

Criteria used for distinguishing root trace fossils from abiogenic structures (e.g., joint fills) or invertebrate trace fossils were those outlined by Gregory, Martin, and Campbell (2004): (1) inconsistent diameters within any given length,

which are especially notable if they taper; (2) secondary and tertiary branching that also shows distal tapering with each successive branch; (3) dichotomous, Y-shaped branching with junctions that are not noticeably enlarged; (4) downward, near-vertical to oblique orientations (with some exceptions based on responses of a plant to the originally affected substrate); (5) lack of evidence for active fill (or, conversely, evidence favoring passive fill from overlying layers); and (6) carbonized or otherwise preserved plant material in the structures (noting, however, that some invertebrate traces contain plant material placed in burrows). The most diagnostic traits of root traces include both distal tapering and dichotomous branching, unaccompanied by enlarged branch junctions.

The only one of these criteria not fulfilled by the suspected Yellow Banks Bluff root-trace fossils is the presence of carbonized material within traces, signifying former tissue. Of course, as is typical for trace fossils, body-fossil evidence of the tracemaker is not necessary for confirming identity, but the in situ nature of roots as trace-making parts of vascular plants makes such a combination more likely.

MODERN TRACES: As mentioned previously, Yellow Banks Bluff is eroding actively at a rapid rate (nearly 2 m per year), resulting in the foundering of mature trees from the maritime forest adjacent to the bluff (Potter, chap. 7). This erosion has also exposed the roots of trees still in place (however temporarily), which allows for viewing their root architecture and effects on the underlying Pleistocene sediments. In particular, examples of the root systems of the saw palmetto (*Serenoa repens*) and cabbage palm (*Sabal palmetto*) (fig. 5.7A) have their full subsurface architecture defined above and on the outcrop. In brief, these palms have 5–10 mm roots that radiate outward from a much thicker trunk (in the case of the cabbage palm) or rhizome (saw palmetto). The cabbage palm (Wade and Langdon, 1990) has a root system similar to that of the more fully described date palm (Zaid and de Wet, 2002). In contrast, the saw palmetto has a reclining, shallowly buried to emergent rhizome whose roots radiate from the rhizome's lower half (Fisher and Jayachandran, 1999). Accordingly, the two local palms are readily distinguished both from other plants and also from one another. The roots have a pervasive effect through their numerous downwardly oriented and radial penetrations of nearly

5 vertical m of strata in the outcrop.

Other considerations are of modern infauna mixing their traces with trace fossils in the outcrop, alluded to earlier with regard to modern *Ocypode quadrata* burrows. One of us (Martin) also noted that sphecids wasps (tentatively identified as *Stictia signata*) were actively burrowing into sandy slopes of eroded sand and vertical faces of the outcrop (fig. 5.7B), presumably constructing brooding chambers. We also wonder about the depth of bioturbation by modern infaunal insects toward the top of the stratigraphic section, and the amount of overprinting that may occur between modern meniscate burrows and fossil ones.

COMPARISON OF MODERN AND ANCIENT STORM-WASHOVER FANS

Keeping in mind Tobler's first law of geography, "Everything is related to everything else, but near things are more related than distant things" (Tobler, 1970), we examined some washover fans on St. Catherines Island (fig. 5.8), as well as some on Sapelo Island (fig. 5.8A). Some of the best-developed modern washover fans on St. Catherines are distributed along Seaside Spit, south of Yellow Banks Bluff (compare with fig. 5.1), behind a beach flanked with a narrow strip

of low dunes. Washovers consist of an apron of partly coalesced fans extending into Seaside Marsh; the apron makes up about 80% of Seaside Spit, which is 1.7 km long (Bishop et al., 2007: 51). These washovers are active during the same storms that erode Yellow Banks Bluff. The shoreline has retreated at rates ranging from 6.5 to 21 m a⁻¹ from 1979 to 2005, averaging 3.8 m a⁻¹ over the past 50 years (Goodfriend and Rollins, 1998; Prezant et al., 2002; Bishop et al., 2007). As sand is washed over protected intertidal marsh, relict marsh mud is exposed along the beach (Morris and Rollins, 1977). Bishop et al. (2007) reported that waves sort and deposit denser, dark heavy minerals over lighter quartz sand in the fans.

The surfaces of the washover fans are nearly smooth, gentle slopes that merge westward into sandy marsh and shallow sandy channels (fig. 5.9). These surfaces, particularly on their edges, are moist and are microbially bound, which subdues erosion by wind or water. The lower parts of the fans are the wettest, and these areas are inhabited by dense populations of fiddler crabs, either *Uca pugilator* or *Uca pugnax*, depending on whether the substrates are muddy or sandy, respectively (fig. 5.9B, C). The adjoining marsh is dominated by cordgrass (*Spartina alternifolia*) but higher sand flats are dominated by black rush (*Juncus roemerianus*). Washover fans support

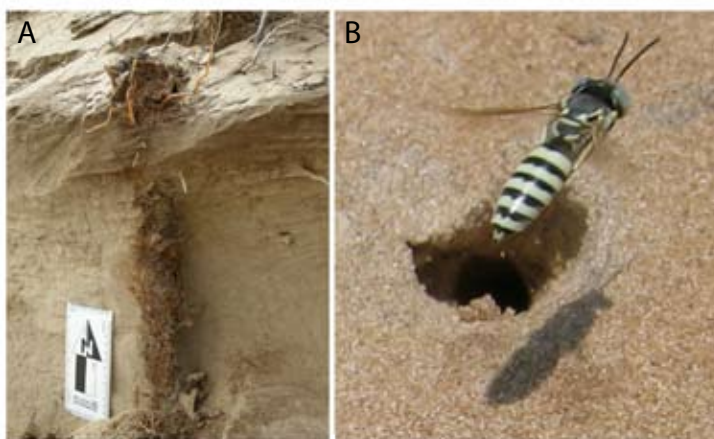


Fig. 5.7. Modern tracemakers associated with Yellow Banks Bluff. **A**, modern roots of cabbage palm (*Sabal palmetto*), imparting darker coloration around roots and staining nearby trace fossils; **B**, Vespoidean (tentatively identified as *Stictia signata*) burrowing into sand talus on eroded face of Yellow Banks Bluff.



Fig. 5.8. Aerial view of modern washover fans, St. Catherines Island, Georgia. **A**, overall view of northern third of St. Catherines, with Seaside Spit area (south of Yellow Banks Bluff) containing prominent washover fans; **B**, close-up of inset area showing fans (arrows) and characteristic fan morphology; note overlapping (coalescing) fans in places. Base maps from Google Earth™.

only a few species of plants and animals. The dominant organism is the sand fiddler crab, *Uca pugilator* (Prezant et al., 2002: 24). Accordingly, fiddler-crab tracks, scrape marks, feeding pellets, feces, and burrows are the most voluminous traces on fans. In addition, during our visit on June 1–6, 2007, we noted the presence of trackways of feral hogs (*Sus scrofa*), raccoons (*Procyon lotor*), great blue herons (*Ardea herodias*), sandhill cranes (*Grus canadensis*), and, closer to the shore, burrows of ghost crabs (*Ocypode quadrata*; fig. 5.9D–G). All of these animals can feed on fiddler crabs, which represent an abundant food source. Raccoons were responsible for numerous excavations of fiddler crab burrows; these ranged considerably in outline and depth, but represented significant disruptions of surface and subsurface sediments of the fan deposits, some as much as 20 cm deep and 30 cm wide (fig. 5.9E). Other potential vertebrate tracemakers on or adjacent to washover fans that are, or historically were, present on the Georgia coast include canids, felines,

otter, skunk, black bear, beaver, rabbit, opossum, bison, alligator, tortoise, terrapin, and rattlesnake, as well as numerous species of birds (Larsen, 1982: 164–165; Laerm et al., 1999). A newcomer to Sapelo Island is the armadillo, which may have come over to the island in the 1970s (fig. 5.9G). On the proximal side of fans (abutting coastal dunes), sea turtle nests might also be incorporated in the proximal portions of washovers.

Trackways are common on the surface of the fans. Vertebrate trackways are dominant on the distal part of the fan, and invertebrate trackways on the proximal part. Microbial binding of fan surfaces (fig. 5.9C) also may aid in preserving trackways, which can be identified to species for several days or weeks after their formation. As mentioned earlier, vertebrate trackways include those of great blue heron (*Ardea herodias*), raccoon (*Procyon lotor*), feral hog (*Sus scrofa*), and other birds and mammals. In marked contrast to their behavior in other environments, all the animals tend to forage in straight lines while on the

relatively featureless parts of the washover fans (fig. 5.9G). Raccoons and feral hogs typically follow established paths in the dunes and marsh edges, fanning out to forage nocturnally in more open areas of the marsh and washover fans. In contrast, herons are solitary and stalk their prey diurnally.

Raccoons (*Procyon lotor litoreus*) have been intensively studied on St. Catherines Island (Harman and Stains, 1979; Anderson and Hudson, 1980). These omnivores have extremely varied diets, but feed largely on fruits when available (Harman and Stains, 1979). In the winter and spring, as plant foods such as acorns and fruits become scarce, their diet shifts to small invertebrates, including marsh crustaceans. Sand fiddler crabs (*Uca pugnator*) are the raccoons' most important food item during these seasons (fig. 5.8E); other marsh crabs ("*Eurytium depressum*," *Panopeus herbstii*, *Sesarma reticulatum*, and probably *Uca minax*) are eaten as well, but mainly along marsh creeks and oyster beds. The brown squareback crab, *Sesarma cinereum*, is available in high marsh areas but is present (and eaten) only in low numbers. Harman and Stains (1979) observed groups of as many as six raccoons foraging in the marsh on relatively warm days in the coldest months (January and February); the fiddler crabs become active when their burrow temperatures reach 16°C (Teal and Teal, 1969), and this is when the raccoons prey upon them. Raccoons on St. Catherines tend to forage within ranges that may exceed 100 ha, but ranges shift seasonally with food availability (Harman and Stains, 1979; Anderson and Hudson, 1980). The animals are basically nocturnal but are sometimes active during the day as well.

In terms of invertebrate trackways, ghost crabs (*Ocypode quadrata*) dominate the upper (proximal) part of a fan, whereas the lower (distal) fan would primarily contain sand-fiddler crab tracks (*Uca pugnator*). We expect that other invertebrates may also leave tracks on washover surfaces, but we currently have no information on which taxa. Ghost crabs (*Ocypode quadrata*) are most common in back-beach and foredune facies on Georgia islands, but also live on washover fans within a short distance of the sea; these decapods require seawater for reproduction, respiration, and hydration (Martin, 2006). Furthermore, Duncan (1986) found that: (1) the more inland ghost crab burrows are particularly large; (2) burrows made on gently sloping surfaces, such as washovers, dip relatively steeply; and (3) burrow

apertures tend to point downslope. As mentioned earlier, the fossil burrow *Psilonichnus* is often ascribed to ghost crabs (Frey, Curran, and Pemberton, 1984; Frey and Pemberton, 1987), but also could have been formed by other ocypodids (such as fiddler crabs) and other decapods (Nesbitt and Campbell, 2006).

The tracemaking activities of the sand fiddler crab (*Uca pugnator*) have been documented on St. Catherines washover fans (Frey, Curran, and Pemberton, 1984: figs. 3a–c), and more extensively on Sapelo Island (Frey, Basan, and Scott, 1973: fig. 1a; Basan and Frey, 1977). These fiddlers walk and burrow sideways as well as grazing on the substrate as surface-deposit feeders, and all of these activities create distinctive traces with some potential for preservation in the geological record. As described above, these are simple, L- to J-shaped burrows having a circular to oblate cross section about 1–2 cm in diameter (Basan and Frey, 1977). Deery and Howard (1977) also point out how washover fans on Ossabaw Island had thin layers of eolian sands on their top surfaces, which we observed as well on St. Catherines and Sapelo Island fans. These windblown sands then can passively fill concavities, such as fiddler crab burrows, which one of us (Martin) documented on Sapelo Island (fig. 5.6).

Uca pugnax digs complex burrow systems, though they start out as simple burrows similar to those of *Uca pugnator* (Frey, Basan, and Scott, 1973: fig. 1d; Basan and Frey, 1977). Simple L- to J-shaped burrows may be indistinguishable from those of *Uca pugnator* in form and size, but (as described above) *Uca pugnax* can proceed to construct a U-shaped burrow, or even a complex system consisting of U-shaped components. The basal part of the burrow of *U. pugnax* tends to be curved, while that of *U. pugnator* tends to be more level (Frey and Basan, 1977). Burrows of both may be present in high marsh environments, and one or both are probably present at Yellow Banks Bluff.

Presumably, washover fans during Silver Bluff time and today share a common biota; sea level, forest vegetation, and hence climate may have been similar. The Pleistocene network burrows we interpret here are morphologically similar to modern fiddler crab burrows, and were probably made by *Uca pugnax*, perhaps accompanied by *Uca pugnator* in a mostly barren high marsh environment atop a washover fan. Pleistocene *Taenidium* resembles the burrows



of modern cicada nymphs (Gregory, Martin, and Campbell, 2004), and attests to the freshening of the high marsh. Evidently the washover fan surface was eventually buried and covered by a backdune meadow; today it is the site of a modern maritime forest. Pleistocene trackways, if present, would not be readily seen in vertical exposures of unconsolidated sand, but might be visible on bedding planes after consolidation to sandstone. Slight lithologic differences, for instance, in heavy mineral concentration or microbial consolidation, might result in bedding planes being more easily split in the distant future. The species list would have been markedly different before the Pleistocene mass extinction, which eliminated most of the larger animals. Pigs were introduced in historical times; they commonly forage along beaches and in marshes as well as in the forests. The only known Pleistocene hooved mammals (artiodactyls) that may have inhabited Georgia barrier islands, and thus made trackways analogous to those of hogs, would have been deer and bison (Kurtén and Anderson, 1980; Laerm et al., 1999). Other traces of hogs, particularly their extensive root-

ing and excavation of deep subterranean nests (e.g., those of sea-turtle eggs) have no known Pleistocene equivalent.

SUMMARY OF WASHOVER FAN ICHNOLOGY

In summary, we propose that ancient storm-washover fans, such as those interpreted here from the Silver Bluff Formation, may contain distinctive and diagnostic suites of plant, invertebrate, and vertebrate trace fossils that can be applied to interpreting similar ancient deposits on the Georgia barrier islands and elsewhere. Discerning such suites requires a thorough knowledge of the behavioral ecology of modern tracemakers and their traces in washover fans, the latter of which can then be reasonably compared to trace fossils in ancient deposits. As a result, the geological histories of these islands can be more accurately assessed; in some instances, the smallest macroscopic evidence (e.g., fiddler crab burrows) can be the most important in discerning large paleoenvironmental changes in the Georgia barrier islands.

Fig. 5.9 (left). Modern washover fans and their ichnology. **A**, washover fan immediately adjacent to (west of) Cabretta Beach, Sapelo Island; photograph is digital composite of three successive, lateral shots (left to right) from same vantage point; **B**, distal end of same washover fan showing transition between sandy substrates of fan and muddy marsh, including abundant burrows of *Uca pugnax* at transition; **C**, organic-rich muddy zone in transition of same washover fan with algal films (shiny area to the right), presenting a probable model for Yellow Banks washover-fan strata; **D**, typical vertebrate tracks of modern washover fans: tridactyl tracks of sandhill crane (*Grus canadensis*) and artiodactyl hoofprints of feral hog (*Sus scrofa*); note abundant burrows and feeding pellets of *Uca pugilator*, and how some of the pellets fill the tracks of both vertebrates: St. Catherines Island; scale = 10 cm. **E**, excavation trace of raccoon (*Procyon lotor*) predation on *Uca pugilator*, plus dead fiddler crab (left): St. Catherines Island; scale = 10 cm. **F**, raccoon trail in proximal part of washover fan: St. Catherines Island; **G**, raccoon and armadillo (*Dasypus novemcinctus*) trackways crossing edge of washover fan depicted in A, with *Spartina alterniflora* (tall grass) and groundcover of *Salicornia virginica* denoting marsh: Sapelo Island, Georgia.

