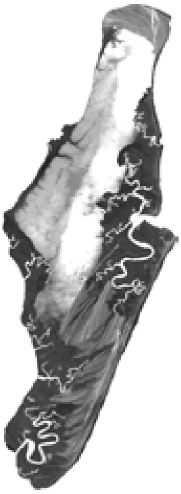

CHAPTER 13

THE FOUNDATION FOR SEA TURTLE GEOARCHAEOLOGY AND ZOOARCHAEOLOGY: MORPHOLOGY OF RECENT AND ANCIENT SEA TURTLE NESTS, ST. CATHERINES ISLAND, GEORGIA, AND CRETACEOUS FOX HILLS SANDSTONE, ELBERT COUNTY, COLORADO

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"Modern sea turtles ... spend virtually their entire life in the sea, except for the laying and development of eggs into hatchlings" (Bjorndal, 1979).[1] Sea turtles reproduce by laying eggs in nests excavated into the backbeach or sand dunes behind sandy beaches (Mast, 1911; Caldwell, Carr, and Ogren, 1959; Bustard, Greenham, and Limpus, 1975; Hopkins et al., 1982; Van Meter, 1992) where the eggs incubate and hatch. Sea turtle nesting is thus capable of leaving distinctive sedimentological imprints in the nearshore sedimentary record including nesting crawlways, nest excavations that disrupt "normal" backshore sedimentary structures, and hatchling crawlways made as the hatchlings make their way to the sea.

The goal of this chapter is to describe structures produced by nesting loggerhead sea turtles (*Caretta caretta* [Linnaeus, 1758]) on St. Catherines Island, document their use for the following two chapters on sea level fluctuation (chap. 14), and their potential[1] use by ancient Native Americans for locating sea turtle food resources (chap. 15), and also to summarize the only known fossilized sea turtle nesting suite (Bishop et al., 1997; Bishop, Marsh, and Pirkle, 2000; Bishop and Pirkle, 2008), from the Cretaceous of Colorado, providing a model for description of sea turtle traces and trace fossils from other species and other times.

Hasiotis and Martin (1999) described reptilian nesting structures in the Triassic Chinle Formation that they attributed to turtlelike reptiles and Hasiotis et al. (2006) summarized nesting structures from the fossil record. Sea turtles are known to have existed for at least the last 105 million years (Weems, 1988; Hirayama, 1998; Kear and Lee, 2006), from the Early Cretaceous to Holocene. The paleontological record of sea turtles is represented by more or less fragmentary body fossils comprised of skeletal body elements, and by one described trace fossil suite consisting of two egg chambers, a body pit, and a crawlway (Bishop et al., 1997; Bishop, Marsh, and Pirkle, 2000; Bishop and Pirkle, 2008). Marine turtles are significantly modified by adaptation to living an active nektonic life in the open ocean, including an increase in body size, reduction of carapace and plastron armoring, development of salt glands, and modification of appendages into oarlike flippers. While graceful in their marine habitat, sea turtles are poorly adapted for terrestrial activities because of their size and highly modified body plan and laterally oriented swimming appendages; they are clumsy moving across land.

Modern sea turtles utilize sandy beaches in the tropical, subtropical, and subtemperate regions for their nesting (Spotila, 2004). Evidence indicates that while individual sea turtles do not nest every year, when they do nest, they commonly deposit multiple clutches of eggs during a single season. Specific sequential events of nesting behavior, exemplified by the loggerhead nesting ethogram of Hailman and Elowson (1992), vary from species to species, but result in similar sedimentary structures in all extant sea turtles (providing a global suite of nesting structures used by indigenous peoples around the world to exploit these resources). Most sea turtles are solitary night nesters, but some extant species, such as the Kemp's Ridley (*Lepidochelys kempi*), have evolved communal daytime nesting behaviors (Lutz and Musick, 1997), emerging as groups called *arribadas*. The annual nesting of sea turtles on sandy beaches for an interval of over 105 million years (Hirayama, 1998) provides ample opportunity for the preservation of nesting crawlways (Witherington, 1992), turtle nests (Brannen and Bishop, 1993; Bishop et. al., 1997, 2000), and hatchling crawlways to be incorporated into the fossil record whenever back-beach and/or backshore sediments are preserved in the fossil record. Evidence of fossil traces made by nesting sea turtles is only known from recent observations and one described fossilized nesting suite (Bishop et. al., 1997, 2000; Bishop and Pirkle, 2008).

Loggerhead sea turtles commonly nest on the Georgia Golden Isles, a string of 12 barrier islands fringing the Georgia coast (Hoyt, 1967; Frey and Howard, 1988), including on St. Catherines Island (Brannen and Bishop, 1993), a barrier island 16 km long and 2–6 km wide, situated midway on the Georgia coast between Savannah and Brunswick (chap. 1: fig. 1.1).

SEA TURTLE NESTING HABITAT ON ST. CATHERINES ISLAND

The literature on Georgia coastal processes, barrier island formation, and coastal ecology is so robust that no comprehensive review of it is attempted in this limited space. However, several pertinent publications stand out as unusually important. These include Hoyt, 1967; Dörjes, 1972; Morris and Rollins, 1977; Frey, Howard, and Pryor, 1978; Howard and Scott, 1983; and Howard and Frey, 1985.

St. Catherines Island consists of two distinctive depositional fabrics (chap. 3: fig. 3.2), a high-standing, rather featureless area to the west and northwest and a low-standing, highly textured area to the east and southeast (Bishop, 1990; Linsley, 1993; Bishop, Marsh, and Pirkle, 2000; Linsley, Bishop, and Rollins, 2008). The high-standing portion of the island, the core, is attributed to the Silver Bluff Pleistocene and the low-standing area is Holocene in age (see Bishop et al., this volume, chap. 3), consisting of marsh and beach ridge complexes. The Silver Bluff core is attenuated by the low-standing Holocene sediments at both ends of the island and along the oceanic eastern margin. The eastern margin is characterized by broad marsh meadows developed behind long sand spits at Seaside Inlet, Middle Beach, and McQueen Inlet. The south end of South Beach presents a sequence of beach ridge systems that accumulated from north to south and become progressively younger seaward and southeasterly and that possess discrete dichotomous boundaries. These packages of sediment represent rapid periods of accretionary activity during the late Pleistocene and/or Holocene, interspersed with periods of erosional and depositional activity giving rise to "sedimentary accretionary terrains." The pattern of these accretionary terrains attests to the dynamic depositional history of the Holocene part of this barrier island both by their presence and their distribution and provides a powerful tool to decipher the Holocene history of St. Catherines Island and the record of sea level fluctuation in the recent past. These terrains provide ample evidence that St. Catherines has been a dynamic, rapidly changing barrier island upon whose changing coast sea turtles have been nesting for at least the last 6000 years (chap. 3, this volume).

The east side of St. Catherines Island fronting on the Atlantic Ocean is divided into three major beaches by two inlets. To the north is North Beach, separated from Middle Beach by Seaside Inlet and to the south is South Beach separated from Middle Beach by McQueen Inlet. South Beach is, in turn, separated into three beaches by two small channels, Flag Inlet and Beach Creek. These beaches and the sandy margins of St. Catherines Sound to the north and Sapelo Sound to the south provide ~20.1 km of dynamic nesting habitat (fig. 13.3) for loggerhead sea turtles. Its rapid erosion has placed stresses on nesting loggerhead sea turtles as indicated by annual habitat assessments done on St. Catherines Island (Bishop and Marsh, 1999b) and Georgia Department of Natural Resources (Dodd and MacKinnion, 2002), indicating a progressive deterioration of nesting habitat from 1999 to present, with approximately 15% of the present (2007) beach considered adequate for sea turtle nesting (see Bishop and Meyer, this volume, chap. 14).

GEORGIA BEACHES

Beaches on Georgia's barrier islands are dynamic systems dominated by tides, waves, winds, and organisms. Tidal energy generated by semi-

Fig. 13.1. Aerial view looking N23°E along the north end of South Beach, northward toward McQueen Inlet at low tide, showing diverse nesting habitats of loggerhead sea turtles on St. Catherines Island, including the McQueen Dune Field with its dunes, abundant washover fans, scarped dune ridges, and eroding hammocks with skeletal trees on beach. Relict marsh mud can be seen on the beach in the foreground. The remains of Beach Hammock lie just beyond the first washover fan, and the area we call “the big washover” lies north of the hammock in the middle of this image.

diurnal tides that average ~2–3 m (6.7–9.8 ft) during two high tides and low tides each lunar day and two spring tides and two neap tides per lunar month leads to daily variation in the level of the high and low tide lines across the beach. The Georgia coast is characterized by low wave energy (normal summer wave heights ~1.0 m) dissipated on barrier island beaches. Sand transfer by wind is a dominant process due to wide beaches and extensive ebb deltas exposed during low tides. Major beach modifications are made during short but intense storms, particularly hurricanes and nor’easters (Davis and Dolan, 1993). Nor’easters rapidly rework the sediment of the beach, dropping the elevation of the beach, eroding a prominent scarp at the back of the beach, and removing or modifying the physical and biological sedimentary structures generated during intervals between storms. These processes give rise to broad, compact beaches, typically 100–150 m wide having a 1°–2° seaward slope separated from the island by the shoreline marked by the latest storm high tide line, and separated into the backshore lying above normal high tide line, and the foreshore, lying below the normal high tide line (fig. 13.1).

The Backbeach

Active beach sediments deposited during the most recent storm event overlie eroded inactive sediment underlying the beach and truncate against the backbeach scarp on high areas or merge with washover fans in low areas resulting in a surface layer of horizontally interlaminated quartz sand and heavy mineral sands approximately 50 cm thick. Heavy-mineral sand deposits are often found within the active beach sediment at the back of the beach forming a 10–15 m wide band along the base of scarps or bluffs deposited as a basal bed of the active beach or interbedded with quartz sands (figs. 13.3D, 13.6) as records of smaller tidal and/or storm events (Bishop and Marsh, 1998a). Washover or washin fans form in areas backed by marshes as high-energy storms wash sediment over the backbeach berm (fig. 13.1) onto the surface of the marsh meadow or into the fringing forest.

Between storms or high spring tides, the backbeach is modified by wind-dominated processes resulting in secondary dunes and wind ripples accentuated by sorting of quartz sand from the heavy-mineral suite. Sedimentary structures produced include horizontal lamination, festoon cross-bedding (fig. 13.6), and small-scale ripple cross laminations. Storms produce heavy rains that form rills resulting in minor scour and fill structures and occasional blowouts through the upper beach. These processes lead to Georgia beaches that are comprised of sand that is very compact and very firm in contrast to soft, loamy Florida backbeaches.

The Forebeach

Forebeach sediment redeposited by storm events is sorted daily by waves on flood and ebb tides resulting in quartz sand interlaminated with diffuse laminae ("ghostly lamination") of heavy minerals dipping seaward at 1°–2°, on the lower foreshore; the upper foreshore is steeper (sloping at about 2°) and becomes gentler on the lower foreshore (sloping at about 1°), becoming more level and often rippled. Sand "waves" advance onto the foreshore from the seaward side, giving rise to beach ridge and runnel systems producing seaward, gently dipping laminated sands and shoreward-facing, steep cross-bed sets. Repeated migration of ridges onto the shoreface may result in formation of backbeach terraces, berms, and eventually erosional scarps (as the terraces are subsequently eroded). Runnels, characterized by ripple marks, are usually connected to the ocean by shallow channels crossing seaward ridges. Where beach obstructions are present and in the troughs of runnels, complex chaotic scour and fill systems form. Sounds, tidal inlets between the barrier islands, have steeper forebeaches and complex ripple-marked tidal flats with megaripples forming at midtide level at the shoulders of the island on ebb deltas.

Exposures of ancient marsh on the beaches of St. Catherines form relict mud deposits providing powerful evidence of landward barrier island migration. The erosion of beach exposures of relict marsh mud and entrained marsh body fossils and deposition onto the surrounding beach and shoreface provides evidence of dynamic intermixing of ancient and modern shells of all types and the processes of ecological mixing and stratigraphic leaking of fossils from one age to another.

The Beach to Island Transition

Behind the beach are accretional dune ridge systems and forested high-standing Pleistocene deposits, forested ridge and swale systems, and/or marsh meadows. Bluffs or scarps develop along elevated sections of shore, spits or berms along low areas. Washover fans are deposited in low areas by storms carrying sediment over the berm onto the flat surface of marsh meadows, low-lying forests, or interdune swales. Erosive forested areas develop prominent areas of skeletal trees on the beach, locally called "boneyards."

This transitional zone marking the backbeach-island transition (i.e., the spring high-tide line) is the preferred site of deposition of loggerhead sea turtle nests (see chap. 14: fig. 14.1) studied on St. Catherines Island and the preferred site of sea turtle nesting worldwide.

SEA TURTLE NESTING TRACES

Nesting by sea turtles has been described as a behavioral sequence of events (Caldwell, Carr, and Ogren, 1959) that includes, but may not be confined to: (1) locating a nesting site, (2) construction of a body pit by digging, (3) digging an egg chamber and depositing a clutch of eggs, (4) covering the nest, and (5) returning to the sea. One additional event, (6) hatching and emergence of the hatchlings, should be added to complete this sequence.

The sequence and duration of behavioral nesting phases (a nesting *ethogram*) was documented by Hailman and Elowson (1992: 3) for loggerhead sea turtles nesting on Jupiter Island, Florida. Hailman and Elowson's nesting ethogram is summarized by a sequenced list of discrete nesting events that will be tied to potential and documented trace fossils in this chapter: (1) approach to the beach, (2) ascent of the beach, (3) wandering to find a nesting site, (4) construction of a body pit, (5) excavation of an egg chamber, (6) deposition of the eggs, (7) backfilling of the egg chamber, (8) covering of the body pit and egg chamber, (9) return to the ocean. Total nesting time on Jupiter Island, Florida, for loggerhead sea turtles was reported to average 63 minutes by Hailman and Elowson (1992: 3). However, time for phase 3, wandering, was not reported because this behavior is unusual on the soft, hospitable Florida beaches, but often seen on the firmly packed erosional shores of Georgia.

Traces produced by these activities that are observed from modern sea turtle nests (fig. 13.2) consist of three general types (Brannen and Bishop, 1993): (1) trackways made as the female or hatchlings cross the beach, (2) disruption of backbeach or dune stratigraphy by digging and backfilling of the nest, and (3) structures made by predators attacking the eggs. Described traces of sea turtle nesting have been lacking in the literature, because of the low preservation potential of the beach environment. However, the long geological history of sea turtles (105 million years), and the intensity of annual nesting (some Florida beaches have ~1700 nests per km), suggests that these activities do result in preservable traces in the fossil record. This was demonstrated by the description of the world's first documented sea turtle nesting structures (Bishop et al., 1997).

The typical nesting sequence predicted by the nesting ethogram involves selection of a nesting site, egress of the turtle from the sea onto the beach, selection of a suitable nest site located at the backbeach, the digging of an egg chamber, covering of the nest, and reentry into the ocean (Hailman and Elowson, 1992); these behaviors produce a predictable suite of nesting structures (figs. 13.2 and 13.3). Crawling across the beach produces distinctive *crawlways* (figs. 13.3C, 13.5A–C) with species-specific morphologies. The nest (when used in a general context, *nest*

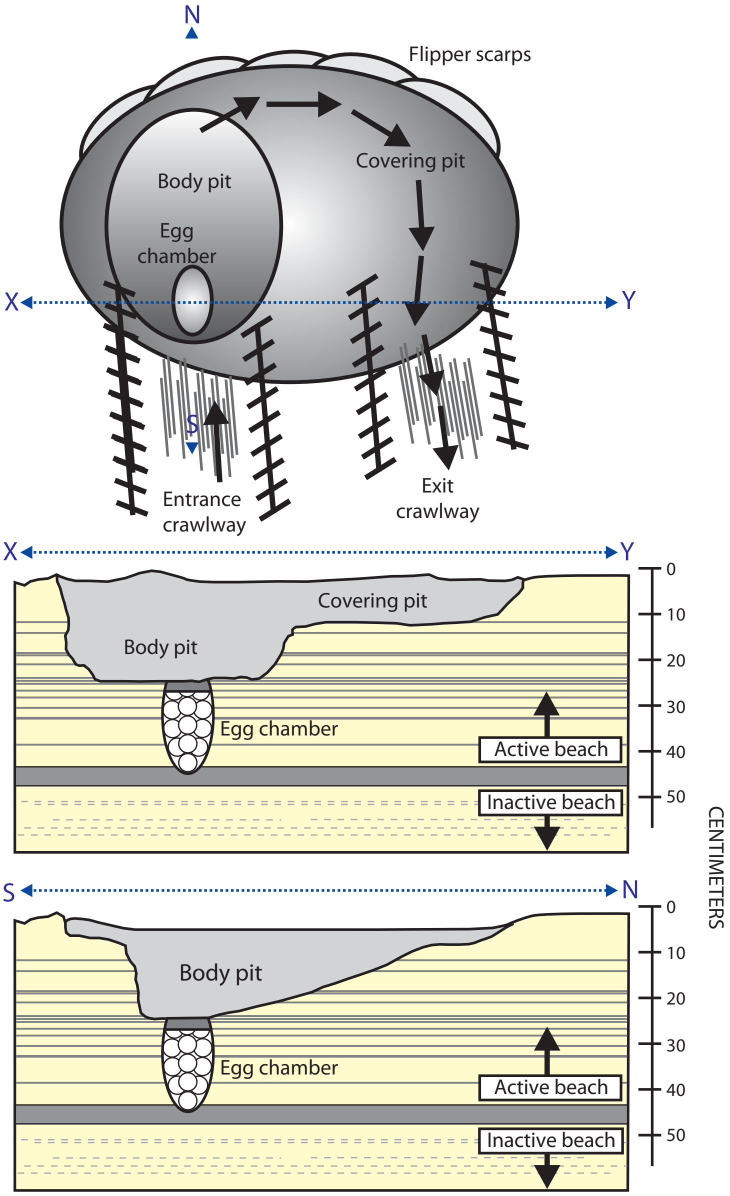


Fig. 13.2. Diagrammatic morphology of loggerhead sea turtle nest in horizontal (map) and two vertical (cross sectional) views to show bioturbated sand of egg chamber neck, body pit, and covering pit in contact with laminated backbeach sediment of the active beach, overlying the inactive beach.

will include mainly the area immediately surrounding the covering pit) is constructed by excavation of a depression about the size of the turtle (the *body pit;* also called the primary body pit by Witherington, 1992) into the loose surface sand (fig. 13.3A), which allows the turtle to then dig an *egg chamber* (figs. 13.3B, 13.6A–C) with its rear flippers into the underlying damp, cohesive sand to a proper depth to insure incubation. The total depth of the egg chamber is controlled by the length of the reach of the turtle's rear paddles; therefore, the nest depth is controlled by the stretched length of rear paddles added to the body pit depth (Carr, 1967). Once a clutch of eggs is deposited, the egg chamber is backfilled with the rear paddles and tamped (fig. 13.3D), and then the turtle goes into a covering behavior, which not only covers the body pit and its egg chamber, but significantly enlarges the nest area as the turtle scoots forward and rotates (fig. 13.5C–F). Many workers consider this to be part of the body pit, but it might be more precisely thought of as the *covering pit,* also known as the secondary body pit of Witherington (1992). The egg chamber, body pit, and covering pit constitute the nest.

Nesting loggerhead sea turtles approach the beach by swimming in from the sea. As they reach shallow water they stop swimming and begin crawling up the shoreface until they reach the backbeach. Nesting by loggerheads is initiated by temperature cues sensed from the sand. Stoneburner and Richardson (1981) reported that when a crawling loggerhead encounters a temperature gradient of 2.1°–3.6°C at a distance 0.5 m across the beach, nesting behavior is triggered. This normally corresponds to crossing the boundary from sand cooled by seawater on the last high tide(s) onto sands not cooled by tidal inundation, but rather sand warmed by receiving a full day's complement of solar heat.

Frey and Pemberton (1987) briefly described and figured a sea turtle crawlway made during its nesting on a Georgia beach (Frey and Pemberton, 1987: fig. 17). Nesting loggerhead sea turtles emerge primarily at night, apparently to escape desiccation and predation. They somehow select a nesting beach, often exhibiting great fidelity to a given location, then crawl across the exposed beach to a nesting site that is typically on the extreme backbeach or on the seaward slope of the first dune ridge (see chap. 14: fig. 14.1). The crawlway is typically a linear path of medial drag marks made by the turtle's plastron and intermittently prostrate neck bordered by lateral tracks made by the flippers pushing backward against the beach surface. Nesting sea turtles often crawl onto the beach without completing a nest, producing a trace (fig. 13.5) called a *nonnesting crawlway*. Nonnesting crawling activity may indicate an aborted nesting attempt or could be an evolutionary behavior to distract predators by laying lines of misinformation onto the beach. Nesting crawlways often indicate an extended search by the female for an adequate nesting site as she crawls about on the back part of the beach, forming a wandering crawlway. The turtle produces a crawlway called *entrance crawlway* as she crawls to find a nesting area. A second crawlway (the *exit crawlway*) is made after nesting is completed as the turtle returns to the sea. Similar, but much smaller and much more abundant, exit crawlways are made by emergent loggerhead sea turtle hatchlings (fig. 13.3F) as they scamper en masse from the emergence crater nest site toward the sea. The length of these crawlways is dictated by the width of the beach, which in turn is controlled by the height and stage of the tide at any given point. Nesting and hatchling crawlways are extremely ephemeral traces, being easily obliterated by subsequent high tides, windblown sand, or heavy rainfalls. Hatchling crawlways are similar to nesting crawlways, differing from them by being much smaller, by being very abundant, often so abundant that they cannot be differentiated one from another, by originating and fanning from a depression (the *emergence crater*) at the neck of the egg chamber, and, hence, by being much more ephemeral.

SEA TURTLE NESTS ON ST. CATHERINES ISLAND

Monitoring behavior of the loggerhead sea turtles nesting on the beaches of St. Catherines Island between 1990 and 2008 has allowed the observation of approximately 2195 nests and ~6000 nonnesting crawlways made by loggerhead sea turtles involved in nesting activity. Documentation of these traces presents a database of Recent sea turtle nesting traces that eventually led to the recognition of fossil traces of nesting sea turtles. Approximately 400 nests have been photographed, sketched, measured, and documented in field notebooks and approximately 150 nests have been trenched to expose vertical relationships within the entraining beach sediment. It

Fig. 13.3. Sedimentary structures of loggerhead sea turtle nests on St. Catherines Island. **A,** Body pit with outline of loggerhead sea turtle unsuccessfully attempting to nest on South Beach; **B,** open egg chamber (arrow) in first of four body pits made by a loggerhead sea turtle nesting on South Beach in 1906; **C,** covering pit of a simple, unobstructed, washover-fan nest [Nest 1906]; **D,** brecciated backfilling of egg chamber discontinuity surrounded by laminated backbeach sediment of a backbeach nest [Nest 1906]; **E,** depredation crater made by a feral hog depredating a simple, unobstructed loggerhead sea turtle nest (note hog tracks and shell fragments); **F,** emergence crater and hatchling crawlways of a loggerhead nest [93-033] on the morning after its emergence. Scales in C and D = 1.0 m or 10 cm.

must be emphasized that these observations are limited to nests deposited by two species on one barrier island, and ought to be interpreted with some caution and not overextended in application to the nesting by all sea turtles, fossil or living.

The nests on St. Catherines Island are protected from predation by raccoons and feral pigs by placing a 91.4 × 121.9 cm (3 × 4 ft) wire or plastic (since 2006) mesh screen centered above each nest's egg chamber. In order to do this, the egg chamber and clutch are located, validating that a given crawlway is indeed a nesting crawlway and allowing the precise center of the screen to be located directly above the egg chamber. To do this the nest must be "read," i.e., the suite of nesting traces of the turtle depositing the nest is deduced from crawlways, nest size, shape, and topography. These data are then integrated with our nest search model (fig. 13.2) and tested by excavating the covering pit to locate the egg chamber in the underlying body pit that was obscured by the covering activity.

The first step in reading a nest is to ascertain the probability that the turtle actually nested. Evidence of nesting is indicated by the presence of a covering pit, often with a swirled appearance, flipper scarping along the covering pit margins, thrown sand surrounding the covering pit, and (on ebb tides) significant differences in lengths of short entrance and longer exit crawlways. The turtles' direction of crawling into the nest is determined by crawlway clues, including Vs (produced by the dragging ends of flippers) opening in the direction of the crawling, push marks (asymmetric steep faces on backside of push marks) facing the direction of crawling, crosscutting relationships of the crawlways (exit crawlway crossing entrance crawlway), and crawlway drags across the covering pit (exit crawlway forming a smoothed exit ramp from the nest; see chap. 15, this volume). This information is recorded in the field notebook in the form of a description and sketch, photographs, and/or videotape, before validation by digging begins. This preserves as much information as possible before evidence presented on the surface is destroyed by excavation of the nest. The sketch and a verbal description of the turtle's nesting activity also allows us to develop major and alternative hypotheses as to the most probable position of the egg chamber before the surface evidence is compromised.

Data taken on covering pit size, orientation, and morphology are integrated with crawlway data to ascertain the direction from which the turtle entered the nest area. This usually suggests the relative position of the egg chamber (about half-turtle length [40–50 cm] on the midline of the entrance crawlway into the nest), because most turtles will pit and nest once they enter a suitable area. The probable position of the egg chamber can then be validated by excavation using a small entrenching shovel, trowel, or stem of a palm frond (see chap. 15, this volume). The soft sand of the covering pit and body pit will be bioturbated and churned up by the nesting activity. On St. Catherines Island this mottled, bioturbated sand usually stands in stark contrast to the highly laminated, firmly packed quartz and heavy mineral sands of the backbeach that underlie the covering pit. This stratigraphic relationship allows the position of the egg chamber to be determined by carefully excavating to expose undisturbed laminations of the backbeach sediment beneath the bottom of the body or covering pit, then carefully digging laterally, scraping the bottom of the body pit until the neck of the egg chamber is encountered as a circular *egg chamber discontinuity* (fig. 13.3D; see also figs. 15.2–15.4) cutting through the laminated sands beneath the body pit. The bioturbated filling of the egg chamber neck often appears marbled or brecciated and usually stands in remarkable contrast to the contourlike patterns of the surrounding, nearly horizontal interlaminated quartz and heavy mineral sands of the backbeach. Less contrast is evident in nests deposited in the more homogeneous sands of the dunes. The geometry of the body pit, usually deepest posteriorly, often assists in locating the egg chamber as one follows the bottom of the body pit downward toward the egg chamber discontinuity. Nests deposited in heavy mineral sands are often masked beneath the heavy mineral deposit, which often obscures the egg chamber discontinuity.

Subsequent to hatching, approximately 15% of the loggerhead nests on St. Catherines Island have been excavated by trenching to investigate their stratigraphic relationships. A flat sand shovel and trowel are used to excavate a trench in front of nests, the back face is leveled into a vertical wall, and the back face is shaved back until the egg chamber is encountered. The wall is then shaved back to approximately the center of the nest's egg chamber on both sides and carefully carried into the egg mass in an attempt to define the nest boundaries and enclosing stratigraphy.

Trenches usually expose (fig. 13.9D, F, H) approximately 50–80 cm of active beach overlying older, inactive beach sediments.

Information on loggerhead egg chamber morphology has been gathered since 2007 using casting techniques of Billes and Fretley (1992) and Raymond Carthy (personal commun. from http://www.flmnh.ufl.edu/natsci/herpetology/Uf-herp.htm). Open egg chambers (i.e., those dug but not filled by eggs [figs. 13.3B, 13.4A] or backfilled by sea turtles in aborted nesting attempts), or egg chambers left open after relocation of clutches of eggs are filled with expandable Polyurethane foam (Great Stuff™ Gap and Crack Filler by Dow Chemical Corp.) to produce an impression of the interior of the egg chamber (actually a mold of that interior surface). Because we relocate a substantial proportion of our at-risk or doomed nests on St. Catherines Island, those emptied egg chambers are often replicated by casting (fig. 13.4B–D). Upon extraction by excavation, the mold surface retains grains of the entraining sediment and forms a three-dimensional sedimentary peel, providing evidence of beach microstratigraphy. The size and geometry of egg chambers can thus be rapidly preserved and, after study, are used as manipulatives in K–12 classrooms of our teacher-interns (fig. 13.4C, D).

Hatchling loggerhead sea turtles emerging from nests on the backbeach or seaward-facing dune slopes emerge forming *emergence craters*, rapidly orient toward the sea, and form narrow *scamper ramps* toward the ocean, which take the form of triangular aprons (fig. 13.3F) with diverging sides as the hatchlings approach the surf zone.

Nests that are depredated may retain some of the physical evidence of nesting, but usually are strongly modified by digging activities of the egg predator. Small predators disrupt them less, such as ghost crabs that burrow into them and raccoons (*Procyon lotor*) that commonly dig one or more exploratory holes until they locate the egg mass (Anderson, 1981). Large predators, such as feral hogs (*Sus scrofa*) (Hayes, Marsh, and Bishop, 1995), root the entire nest area (fig. 13.3E) into a cone-shaped depression, destroying much of the evidence of nesting activity.

Beach Characteristics Affecting Nest Morphology

The characteristics of beaches on the Georgia coast are very different than those of beaches on the eastern coast of Florida. Georgia beaches are comprised of finer-grained sand, have less shell entrained as particles, and contain significant amounts of heavy minerals. The beaches of Georgia have a much higher tidal range, ~2–3 m (6.7 ft–9.8 ft) vs. 0.61 m (2 ft) than those at Juniper Beach, Hutchinson Island, a somewhat higher wind regime (waves average ~1.0 m at St. Catherines Island), and are far less urbanized than Florida beaches. As a result, Florida beach profiles tend to be narrower, steeper, and softer with a soft loamy sand substrate backed by continuous linear dune ridges. Georgia beaches tend to be wide, gently inclined and backed by numerous transitional environments and are largely erosional. They have a very compact, firm surface from the low tide line to the dune line or storm scarp. These differences account for nest variation that reflects differing beach conditions.

GEORGIA LOGGERHEAD SEA TURTLE NESTING STRUCTURES

Loggerhead Sea Turtle Crawlways

Crawlways of nesting loggerhead sea turtles (Frey and Pemberton, 1987: 342, fig. 17) consist of large, linear plastron drags paralleled by rows of alternating paddle prints made by the sea turtle's flippers as they push and pull the large animal across the beach toward backbeach nesting habitat (fig. 13.5A–C). These traces are the size of mature loggerhead turtles, approximately 60–110 cm in width, extending from water's edge at the time of ocean emergence onto the backbeach. Trails of turtles entering the beach (entrance crawlways) can be distinguished from trails made moving off the beach (exit crawlways) by evidence provided by the direction of V-like patterns front flippers make in the sand (Vs open in direction of crawling), by rear flipper push marks (steep faces of imprint face the direction of crawling), differing length of the traces (shortest crawlway is entrance crawlway on ebb tides), and by crosscutting relationships (exit crawlway often crossing over entrance crawlway). Each species of extant sea turtle produces a slightly different crawlway morphology (Witherington, 1992). Crawlways are extremely ephemeral traces, especially those lying below the high tide lines that are immediately obliterated by the subsequent high tide.

Crawlways of hatchlings (fig. 13.3F) mirror the morphology of those of nesting females, dif-

Fig. 13.4. Open egg chambers are often replicated by filling with expandable polyurethane foam to produce a mold of the size and geometry of the interior of the egg chamber and produce a three-dimensional peel of beach microstratigraphy. **A,** Natural open egg chamber of aborted loggerhead nesting attempt on South Beach (emergence 06-132); **B,** polyurethane foam impression of open egg chamber, shown in A (emergence 06-132); **C,** polyurethane foam impression being produced by K–12 teacher-interns in St. Catherines Island Sea Turtle Program for research and for use as a classroom manipulative [08-117w]; **D,** teacher-intern Cindy Hatala carrying *her* manipulative (foam egg chamber cast) back to her classroom to teach her students about sea turtle nesting ecology.

fering from them by being much smaller, by generally being unidirectional, by occurring in large groups rather than as individual crawlways, and by originating from emergence craters and fanning out toward the sea. The crawlways are linear trails or drags made by the plastron paralleled by two pairs of paddle prints on either side of the plastron drag. The patterns made by the hatchlings in their scamper for the sea are subparallel, but often have a braided, anastomosing pattern made as the hatchlings cross one another's trails. The pattern of individual crawlways becomes obliterated by interweaving as the number of hatchlings approaches 20 or 30 crawls.

VARIATION OF GEORGIA LOGGERHEAD NEST MORPHOLOGY

Loggerhead nesting trace assemblages (figs. 13.2, 13.3, 13.4A, 13.5, 13.6C, D, and 13.9B, D, F, and H) typically consist of the entrance and exit crawlways that lead to and from the nest, which consists of an elliptical area of several square meters. The nest consists of the circular or elliptical area of disturbed or bioturbated sand with a swirled appearance on the surface of the nest caused when the turtle generally moves forward and rotates clockwise or counterclockwise before exiting the nest, usually passing over the covered egg chamber during covering activity. The nest thus consists of the body pit and its subjacent egg chamber as well as the covering pit, resulting in a surface layer of disturbed sand about 20 cm thick. The egg chamber extends from the bottom of the body pit to a depth of approximately 34 cm. Once egg deposition is completed, the egg chamber is backfilled with bioturbated sand. The surface of the covering pit is typically swirled and of variable relief, which is rapidly modified by wind and rain until its presence is virtually undetectable on the beach surface, usually within hours or days.

The nesting area is increased significantly by a covering activity, clearly an evolutionary adaptation to protect the egg chamber from depredation by increasing the area of search while spreading scent clues over a much wider area. Data taken during 1994 on 70 nests (table 13.1) indicates that the average size of the egg chamber neck was 318.2 cm^2 and the average size of the nest was 3.72 m^2, yielding a target of cross-sectional area for predation of 1.01%.

Because the level of high tide varies on a monthly cycle, the thermal gradient across the beach varies in its position; thus the stimulus for nesting varies in position with tidal cycles. During neap tides the high tide on St. Catherines is approximately 0.67 m lower than on spring tide. Therefore, turtles depositing nests during neap tides may receive proper stimuli for nesting, but they nest significantly further out on the beach, resulting in a nest situated some distance in front of the back boundary of the beach. This position will place them in jeopardy of tidal inundation or erosion on subsequent high tides, producing a doomed nest (fig. 13.6C).

Classification of Loggerhead Nests

Loggerhead sea turtle nests can be classified by their complexity, position on the beach, and surface conditions overcome during nesting. Classification allows one to define commonalities in nest morphology and begin to understand their differences. In the SCISTP (the island sea turtle program) we have classified nests for many years according to this scheme. Two levels of complexity are recognized**.**

Complexity of Nests

Simple Nests: Nests in which the turtle crawls onto the beach, excavates her body pit in loamy sand facing shoreward, deposits her eggs, and exits as she covers by rotating 180° either over her egg chamber or by making a loop shoreward of the nest, forming an elliptical covering pit with entrance and exit crawlways at opposite ends of the nest (fig. 13.5C, E, F).

Complex Nests: Nests in which the turtle crawls onto the beach, often multiple times, wanders about, excavates her body pit in firm sand facing virtually any direction, deposits her eggs, and exits as she covers by rotating around over her egg chamber, forming an elliptical covering pit with entrance and exit crawlways on the ocean side of the nest (fig. 13.5B).

Positions of Nests Relative to the Beach

In addition to simple and complex nest configurations, sea turtle nests may be classified by four positions relative to the beach, nests deposited on the dunes, the backbeach, washover fans, and forebeach.

Dune Nests: Dune nests are formed when turtles nest on the front, top, or behind the first sand dunes on the beach; body pits are deep due to dry surface sand; subtle stratigraphic layering masks the position of the egg chamber (figs.

Fig. 13.5. Types of loggerhead nests deposited on St. Catherines Island. **A,** Nonnesting crawlway indicating loggerhead turtle turned around without nesting; **B,** complex, obstructed, backbeach nest [06-086] with complex wandering crawlway made by loggerhead searching for a nesting site, Yellow Banks Bluff; **C,** simple, unobstructed backbeach nest [94-038] with elliptical covering pit showing entrance and exit crawlways, margin of St. Catherines Sound; **D,** simple, unobstructed, loggerhead nest on top of sand dune, north end of South Beach (McQueen Inlet in background); **E,** simple, unobstructed, loggerhead nest in low, ephemeral dunes (a "Florida nest") at northern end of South Beach; **F,** simple, unobstructed, washover loggerhead nest on a washover at Seaside Spit, North Beach. Scale = 10 cm.

13.3C, 13.5D).

Loggerheads often cross the backbeach boundary onto sand dune fields (if they are present). Nests deposited in this habitat, herein called dune nests (fig. 13.5D) are primarily controlled by topography, as the orientation of the nesting turtle is easily changed by small variations in slope. Because dune sand is finer grained, drier, and softer than sands of the backbeach, body pits in this substrate tend to be randomly oriented and much deeper, often with egg chambers dug deeply beneath the surface. The orientation of the body pit tends to be extremely random. Egg chamber discontinuities are difficult to observe because the

TABLE 13.1

Loggerhead Sea Turtle Nest Dimensions

Nest bearing	Length, m	Width, m	Area, m^2	Egg chamber bearing	Egg chamber length, cm	Egg chamber width, cm	Egg chamber area, cm^2	Depth top egg	Target %
—	3.20	2.40	6.032	N 49 W	20.0	17.0	267.036	20.5	0.44%
—	1.44	1.53	1.730	N 68 W	19.0	19.0	283.529	29.0	1.64%
—	3.12	2.80	6.861	N 40 W	21.5	19.5	329.279	14.0	0.48%
—	2.48	2.35	4.577	S 88 W	23.0	17.0	307.091	40.0	0.67%
—	2.64	1.68	3.483	S 2 W	24.0	15.2	286.514	21.5	0.82%
—	1.64	1.43	1.842	N 8 E	19.8	15.5	241.039	22.8	1.31%
—	1.30	1.30	1.327	—	29.1	18.6	425.106	18.1	3.20%
—	2.94	1.80	4.156	—	23.0	17.6	317.930	26.5	0.76%
—	2.10	3.15	5.195	—	24.5	15.4	296.331	21.1	0.57%
—	2.26	1.87	3.319	—	24.0	16.5	311.018	23.8	0.94%
—	1.40	2.10	2.309	—	24.0	20.0	376.992	39.0	1.63%
—	2.55	1.54	3.084	—	21.5	21.0	354.608	18.6	1.15%
—	2.38	2.12	3.963	—	20.4	14.2	227.515	33.0	0.57%
—	4.24	1.77	5.894	—	25.2	18.0	356.257	25.4	0.60%
—	4.80	2.20	8.294	—	27.5	23.0	496.766	25.7	0.60%
—	2.48	1.47	2.863	—	22.0	21.0	362.855	27.0	1.27%
—	2.40	1.63	3.073	—	24.0	18.4	346.833	24.4	1.13%
—	2.10	1.90	3.134	—	21.0	17.5	288.635	41.0	0.92%
—	1.90	1.83	2.731	—	19.0	15.0	223.839	23.2	0.82%
N 21 E	1.65	2.10	2.721	S 86 W	18.0	13.5	190.852	29.0	0.70%
N 69 E	2.60	2.20	4.493	N 26 E	28.5	20.0	447.678	15.6	1.00%
S 12 W	1.65	1.80	2.333	N 80 W	20.9	13.6	223.242	38.1	0.96%
—	2.40	2.20	4.147	S 68 W	22.5	18.0	318.087	19.5	0.77%
N 19 E	1.75	1.40	1.924	S 33 W	21.5	15.8	265.956	15.5	1.38%
N 16 E	1.92	2.00	3.016	N 67 W	21.5	19.4	327.590	27.5	1.09%
S 26 W	2.31	2.22	4.028	N 81 W	20.5	18.9	304.303	30.8	0.76%
N 26 E	1.70	3.00	4.006	N 28 W	24.0	22.0	414.691	36.0	1.04%
Average	2.35	1.99	3.72	—	22.6	17.8	318.2	26.2	1.01%

stratification of the dune sand is relatively subtle compared to that of backbeach. Upon emergence, hatchling loggerheads tend to head down slope on the dune surface and may wander in interdune swales until they reorient toward the sea.

BACKBEACH NESTS: Backbeach nests are formed when turtles nest at, or above, the spring high tide line, often in, or below, fresh or old wrack mats, and/or in heavy mineral layers (fig. 13.5B, C).

The backbeach is the preferred location for nesting by Georgia loggerheads (see Bishop and Meyer, chap. 14: fig. 14.1). Most turtles crawl and nest between the spring high-tide line and the storm high line, depositing their clutch immediately shoreward of the normal reach of tidal inundation. Because this is also the location for the accumulation of beach debris as flotsam, the location of skeletal tree "boneyards," and scarps or ephemeral dunes, these nests will often be obstructed, complex nests. In areas undergoing erosion where scarps or bluffs lie behind the beach, turtles will often attempt to crawl up the scarp face, then be turned by its steepness or height, and crawl for some distance along the base of the scarp before they nest.

Backbeach nests are vulnerable to tidal inundation on spring tides, which normally does not significantly affect the nest except for decreasing hatching success. However, these nests are extremely vulnerable to saltwater or freshwater inundation and/or erosion during nor'easters, thunderstorms, and hurricanes. These normal effects of the habitat, along with depredation, may be the driving force for the evolution of deposition of multiple clutches by sea turtles.

WASHOVER FAN NESTS: Washover fan nests are formed when turtles nest on a washover fan; nests are deposited in laminated sands and egg chambers are often deposited in damp or wet sand susceptible to repeated inundation and to being washed out or buried by the formation of accreting ephemeral sand dunes (fig. 13.5F).

Washover fans are typically areas where the eroding beach is backed by marsh meadows and, on high spring tides and especially during storm surges, the eroding beach washes over the backbeach berm and/or through the ephemeral sand dunes. When loggerheads nest on beaches backed by washover fans, they often cross onto the washover fan, dig a washover fan nest, and become disoriented, especially after nesting and attempting to return to the sea. This disorientation results in excessive wandering as the nesting turtle apparently attempts to reorient to the sea without slope clues provided by the beach surface. Turtles observed nesting in this habitat have been documented wandering as far as 465 m (1535 ft) after nesting (nest 94-026). Upon emergence, hatchlings usually radiate over 360° in searching for a beach slope to lead them to the sea, and exhibit extensive disorientation across the surface of the washover fan, often ending up in the marsh.

FOREBEACH NESTS: Forebeach nests are formed when turtles nest above high tide level on a neap tide; the nest is deposited below spring high tide line level and will be inundated by spring high tides and storm tides; this part of the beach is very firm and often wet below, eggs are deposited in shallow egg chambers, often barely covered (fig. 13.6C).

Forebeach nests are deposited seaward of the spring high tide line. This occurs during neap tides when the sand above high tide level is solar heated, allowing the turtle to trigger as she crosses from wet, tidally inundated sand onto the warm, solar-heated sand above the high (neap) tide line. The differential position of the high tide line on neap and spring tides in the Georgia Bight at St. Catherines Island is 0.6 m, translating to a lateral distance of approximately 6 m. Because the underlying beach sand is firm and well packed, nests on the forebeach are often small and shallow, barely having a covering pit. Clutches of eggs are close to the surface and vulnerable to depredation as well as certain inundation by the sea.

OBSTRUCTED AND UNOBSTRUCTED NESTS

Two conditions relative to surface obstructions on the beach produce different styles of nests, those that were obstructed in some way during deposition and those that were not obstructed.

OBSTRUCTED NESTS: Turtles often encounter obstructions (wrack, grasses, exposed or buried logs, buried soil, root zones, or peat) as they attempt to dig a body pit or egg chamber, often resulting in wandering crawlways, multiple attempts to dig egg chambers, and chaotic nesting behaviors; this results in complex nests, clutches of eggs often placed in odd places (outside the covering pit beneath the wrack mat, beneath clumps of grass, beneath and alongside logs), and thin bioturbated covering layers (fig. 13.5B).

Loggerheads nesting on the backbeach often encounter obstructions when they attempt to nest. These obstructions may consist of trees in skeletal “bone yards,” the backbeach storm scarp, or wrack mats. Each of these obstructions to nesting interrupts and introduces chaos into the turtle’s nesting behavior. Such nests are much less predictable than unobstructed nests, primarily because the turtle is turned from her entrance orientation and often wanders along or among the obstructions until she finds a suitable nesting site. When such a site is found, the nesting behavior begins regardless of direction the turtle is facing and regardless of nearby obstructions. Obstructed nests tend to involve larger areas and be extremely unpredictable in orientation during egg laying. Under such conditions, nests are often deposited against, or under, buried logs, beneath the edge of surrounding wrack mats, and in other unexpected areas. One of the most common nesting obstructions on St. Catherines Island is a prominent backbeach storm scarp that has formed on virtually all high areas of the island whether on dune fields, linear accretional dune ridge systems, or Pleistocene island core.

Turtles often nest in sand overlying buried wrack mats or in the wrack mat overlying beach sand. When they do so, they usually complete their nesting ethogram; however, the presence of a wrack mat interferes significantly with nesting activity, causing the egg chamber to be often isolated from the covering pit and underlie the turtle’s crawlway or even be deposited in the surrounding wrack mat. These nests are easy prey for raccoons but difficult for humans to locate due to lack of visual clues. Hatchling turtles can be trapped beneath the wrack mat and may be unable to reach the surface.

Unobstructed Nests: Turtles may encounter no significant obstructions to nesting, resulting in elliptical nests with clearly defined entrance and exit crawlways, flipper scarps, and a hummocky bioturbated surface covering layer (fig. 13.5C, E, F).

Loggerheads nesting on open beaches crawl onto the beach until they sense that conditions are correct for nesting and dig an unobstructed nest. At that point the turtle begins wallowing out a body pit (fig. 13.3A) that is roughly the shape and size of her body, shallow at the front and deeper behind. Because the turtle is usually facing away from the ocean as she crawls, unobstructed nests will almost always have the egg chamber centered on the seaward side of the entrance crawlway just inside the nest area. Once the turtle deposits her clutch and backfills the egg chamber, she will characteristically enter a covering behavior in which she moves forward and rotates as she throws sand with her flippers, this activity increases the size of the bioturbated nest area and camouflages the body pit and egg chamber with the scent of the turtle. The nest thus becomes a large elliptical area partially overlying the body pit, or if the turtle turns as she moves forward in her covering behavior, forming a U-shaped nest. In some cases the rotation is so complete that the turtle exits across the body pit and egg chamber almost on line with her entrance crawlway. When the turtle exits the nest area she often crawls parallel to or even crosses her entrance crawlway, forming a large crosscutting crawlway X (fig. 13.5A, C), allowing the exit crawlway to be easily identified as the younger of the two crosscutting crawlways.

SUMMARY OF GEORGIA LOGGERHEAD NEST MORPHOLOGY

Loggerhead nest traces in Georgia consist of entrance and exit crawlways, and the nesting structure or covering pit at the surface, hiding the buried components of the nesting suite, the body pit, the egg chamber, and the egg chamber discontinuity (see fig. 13.2). Loggerhead nests on St. Catherines are typically 55 cm deep, normally reaching only a few centimeters into the basal heavy mineral bed or into the inactive sediment underlying the active beach. The upper half of the nest consists of a broad depression having diffuse, disjunct, gently dipping boundaries. The lower half of the nest is a bulbous, cylindrical egg chamber about 18–27 cm in maximum diameter, with near vertical to undercut, sharply defined boundaries. The eggs are deposited in the urn-shaped egg chamber, usually restricted to the lower 20–30 cm (fig. 13.6A, B) of the egg chamber. Most of the egg chamber is occupied by eggs prior to hatching and, upon hatching, a volume decrease opens a small air chamber at the top of the egg chamber, which subsequently backfills with sand as the emerging turtles bump into it with their heads, forming a shrinkage stope that acts like an elevator allowing the hatchlings to mine their way to the surface, and eventually emerge.

Typical nest morphology (fig. 13.2) has thus been constructed from direct observation of new nests and from trenched hatched nests. This morphology consists of a nesting depression (the body pit) wallowed out by the turtle in loose surficial sand (upper part having gentle, poorly defined sides) until she reaches damp sand into which she can dig an egg chamber (the lower part having vertical walls and containing the egg clutch) with her rear flippers. The nest is subsequently backfilled by the female with homogenized surface bioturbated sand, and subsequently disrupted further as the hatchlings work their way upward through the sand plug during their emergence. Both processes lead to vertical cylindrical sedimentary structures approximately 20 cm in diameter and 20–30 cm high, which dramatically cut across horizontally laminated sedimentary structures of the backbeach and dunes and are characterized by being filled with mottled (bioturbated) sand that stands in stark contrast (in both horizontal and vertical aspects) to the surrounding laminated sands (fig. 13.3D).

The upper, active layer of backbeach sedi-

Fig. 13.6. Eroded loggerhead sea turtle nests on St. Catherines Island exposed in vertical aspect giving a geological perspective expected in fossilized sea turtle nests. **A,** Active dune nest [06-119a] on north end of South Beach, McQueen Dune Field, with clutch exposed in scarp formed by 9/11 nor'easter of 2006; **B,** inactive dune nest [2005] with shells of hatched eggs eroded by September nor'easter of 2005; **C,** doomed forebeach nest [06-024] deposited in front of storm scarp 14 m below spring high tide line (foreground); **D,** a trenched, unobstructed forebeach loggerhead nest [97-072] deposited about a meter in front of the scarp on South Beach, showing covering pit and egg chamber (back-filled with white quartz sand) in laminated back beach sediment (floored by 30 cm heavy mineral deposit). Scale = 10 cm.

ment often consists of predominantly quartz sand floored by a thick, basal heavy mineral layer (fig. 13.6D), which is horizontally laminated, having sparse layers of quartz sand and may be cut by quartz sand-filled ghost crab burrows. Normally overlying the basal heavy mineral layer is 20–40 cm of quartz sand horizontally interlaminated with sparse layers of heavy mineral sand. The upper layer usually consists of approximately 10–30 cm of quartz sand interlaminated with festoon cross beds marked by thin laminations of heavy mineral sand.

The sequencing of postdepositional erosional events is important in producing a suite of final sedimentary structures after each nesting event. A typical nest may be modified significantly by beach erosion, with deposits of interlaminated quartz and heavy mineral wave-deposited sand often deposited across the body pit or the egg chamber. Beach deposition often covers nests with prograding dunes, giving rise to the possible preservation of more or less complete sea turtle nest sequences under prograding conditions. Both scenarios should lead to sea turtle nesting suites (sedimentary structures) in Cretaceous and Cenozoic rocks, which might be easily overlooked or misinterpreted by sedimentologists.

Nearly all nests deposited in a given year are located along the line of the backshore either at the base of spring-tide storm scarps, on the front face of primary dunes, or just over the top of backbeach berms or washovers, all within a few meters of the backshore boundary (fig. 13.6). Upon hatching, the hatchlings work their way en masse to the surface and emerge in the cool of the night when sand temperature drops. The emergence may be synchronous as a single cohort of emergent hatchlings, or consist of several emergences spaced over several days. Occasionally the mass of turtles working their way toward the surface are caught by a rain event that dampens the surficial sand, causing it to become cohesive and resulting in an enlarged air cavity, or stope, above the hatchlings. Normal emergence is marked by formation of an emergence crater at the surface and an apron of hatchling crawlways fanning outward toward the sea from this crater.

Conclusions Regarding Georgia Loggerhead Nesting Structures

The following points about Georgia loggerhead nesting structures can be made:

(1) Nesting sea turtles leave a suite of distinctive traces on the beaches used for nesting, consisting of ephemeral crawlways and more permanent nesting structures.

(2) Nesting females leave large crawlways on the beach as they unsuccessfully (nonnesting crawls) or successfully nest on the backbeach.

(3) Nests consist of a body pit that forms a broad depression in the drier sand, a narrow, cylindrical egg chamber with vertical walls, and a covering pit.

(4) Nest morphology varies with substrate and obstructions presented to nesting, and by species.

(5) Nests form discordant sedimentary structures with a homogenized, bioturbated texture cutting across and downward into backbeach structures characteristic of nearshore dunes and backbeach sediments.

(6) Nests may be preserved intact or attenuated by erosion into very small structures.

(7) Hatchlings leave unidirectional, small scale, subparallel crawlways on the beach when they scamper for the sea.

(8) Crawlways would be difficult to recognize in vertical exposures while egg chambers should be easily recognizable.

(9) Suites of traces of nesting structures allow the rapid assessment of nesting and the location of the clutch of eggs.

SEA TURTLE NESTS AND THE FOSSIL RECORD

Turtles have a geological record that extends back to the Triassic, 200 million years into the past (Lee, 1993). Sea turtles have a geological record that dates back 105 million years at least into the Early Cretaceous (Pritchard, 1979; Hirayama, 1998; Kear and Lee, 2006). In spite of this significant fossil record, only one fossil sea turtle nest has thus far been described in the literature. There may be several reasons for this near lack of known fossil sea turtle nests, including low preservation potential of backbeach sediments, difficulty in recognition of fossil sea turtle nests by geologists, and/or low numbers of preserved nests.

In contemplating the paleontological record, the question was posed, “What would the nest of a Cretaceous sea turtle look like?” The range of Cretaceous sea turtles includes small turtles the size of modern sea turtles (i.e., *Toxochelys*) as well as giants such as *Archelon*. The nests of smaller sea turtles would probably look much like loggerhead nests described from St. Catherines Island (Brannen and Bishop, 1993). The sedimentary structures produced by the larger species such as some the Protostegids and *Archelon ischyros*, a sea turtle 3.5 m in carapace length and with a flipper span of 5 m would be spectacular and on a scale difficult to envision, perhaps having a crawlway 4–5 m wide, a body pit 2 m wide and 3 m long, bottomed by an egg chamber 1.5 m deep and 50 cm in diameter, covered by a pit of enormous size, 15 m wide and 30 m long. The resultant suites of sedimentary structures might be difficult for even a seasoned sea turtle worker to recognize.

SEA TURTLE NEST STRUCTURES OF THE FOX HILLS FORMATION

The Fox Hills Formation is a body of marine and marginal marine sand, silt, and clay deposited along the prograding Cretaceous shoreline as the sediments from the emerging Rocky Mountains were carried eastward into the Western Interior Seaway by eroding streams (Roehler, 1993). The Fox Hills is underlain by the marine Pierre Shale, consisting predominantly of offshore mud and sand lithosomes, and overlain by the terrestrial Laramie or Lance formation consisting of mudstone, sand, and coal beds, deposited on the terrestrial edge of the prograding shoreline.

The Fox Hills consists of fine- to medium-grained sandstone deposited within the shore facies of the Western Interior Seaway in a very dynamic, shallow marine environment marked by abundant burrows (*Ophiomorpha nodosa*) of ghost shrimp, and sedimentary structures characteristic of shallow marine sedimentation.

A Cretaceous Beach

A prominent ridge occurs in the eastern 1/2, sec. 23 and the NE 1/4 of sec. 26, SW 1/4 sec. 24, and NW 1/4 of sec. 25, T 8S, R 58 W, Elbert County, Colorado, on land owned by Frasier Farms and United Pacific Minerals. Outcrop exposures (fig. 13.8B) are found along the top of the ridge, particularly on the northeast side, and in a prominent bluff at its north end. Sediments of the ridge consists of a sequence of horizontally bedded quartz sands (occasionally containing *Ophiomorpha* burrows), overlaid by interlaminated quartz and heavy mineral sands, a thin sandy clay that is usually covered, capped by festoon cross-bedded sandstone. On January 18, 1997, an unusual sedimentary structure in the outcrop was called to the senior author's attention by James Barron. Subsequent fieldwork done in January and February 1997 documented the local stratigraphy and validated the sedimentary structure as the first, and thus far only, recognized suite of fossil sea turtle nesting structures.

A section measured on the east face of the prominent ridge about 100 m south of its north face documents that this sedimentary sequence consists of: (1) a basal sandstone with faint horizontal and cross-bedding (fig. 13.7C), (2) a strongly laminated sequence of heavy mineral layers interbedded with bioturbated sands overlain by a bed of anatomizing sandstones with scour-flute casts on their bases, and (3) a thin homogeneous interval capped by festoon cross-bedded sandstone. This sequence is interpreted to represent a forebeach, backbeach, and backbeach dune field (as depicted in fig. 13.7A). Three complete and a partial fourth sedimentological couplets were delineated within the interlaminated facies of the backshore; each sedimentological couplet consists of a basal interlaminated quartz and heavy mineral layer overlain by a bioturbated bed with indistinct burrowing marked by a mottled pattern stained limonite brown. Samples were examined and collected for petrological and palynological analysis; channel flute orientations in the upper channel facies were measured and found to average N26°E ($N = 7$) while two large channels in the forebeach facies have an orientation of approximately N85°W, and orientations of swash lineations exposed on float blocks from the interlaminated facies averaged N75°E. Sections were subsequently measured at the north face of the prominent ridge and approximately halfway down the length of the ridge to further document the changes in this facies tract.

Although the unusual sedimentary structure was immediately recognized in the field as a sea turtle nest, its origin was initially intentionally denied as alternative hypotheses of formation were formulated and evaluated. A subsequent critical evaluation of photographic evidence in the laboratory attempted and failed to invalidate the structure as a sea turtle nest; the initial deduction was further validated by comparison with photographs of trenched sea turtle nests on St. Catherines Island (fig. 13.9).

Fossil Sea Turtle Nesting Structures

After initial interpretation of the sea turtle nest structure, the outcrop was revisited and mapped (fig. 13.8) and a second nest structure discovered in a float block broken from the cliff face 4.6 m (15 ft) to the northeast (fig. 13.8D), a dichotomous scour and fill structure (without the expected cross-bedded fill) at a level consistent with it being the body pit of another sea turtle nest at approximately the same horizon 1.5 m (5 ft) to the east (fig. 13.8B). A curious foldlike structure 9 m (30 ft) to the southwest constrained within otherwise horizontal backbeach sediments is interpreted as a nesting sea turtle's crawlway seen in cross-sectional view parallel to the crawlway path, cutting across the flipper push-marks (fig. 13.8A).

Neither the body pit structure nor the crawlway structure by itself would have presented incontrovertible evidence for sea turtle nesting, but when placed in context with two fossil egg chambers, the two structures provide the first trace fossil evidence of nesting by sea turtles. This evidence can now be used to interpret similar structures in the fossil record. During March 1997, the outcrop was revisited to plan for collection of the sea turtle nest structure and the taking of outcrop peels. Collection was accomplished during May 1997 by the Museum of Geology, South Dakota School of Mines and Technology. It yielded six surface peels, two collected nest structures, and documentation of the nest structures, a body pit, a crawlway, and two associated sets of backshore sedimentary structures.

The sedimentary structures, which represent the first described suite of fossil sea turtle nesting structures (figs. 13.8, 13.9A, C, E, G) were documented using techniques developed to document Recent sea turtle nests on St. Catherines Island (Brannen and Bishop, 1993). Six beds are involved in the larger sedimentary structure recording the collapse of otherwise horizontal beds into a cavity within the beach facies. The ledge exposing the structure has a small reentrant beneath the nest, which exposed the bottom of the cavity where open voids are present, and when probed were found to be elliptical holes, inferred to be egg molds (fig. 13.9G). The lower four beds involved in the collapse structure are slightly laminated quartz sandstone and burrow-mottled quartz sandstone; the uppermost mottled bed has sagged into the underlying sand layer and becomes indistinguishable from it within the structure. The bed overlying the mottled layer, a laminated sand layer, has sagged as a coherent layer forming two downward-pointing foldlike structures. The next two beds above it, the first beds of the active beach facies, with interlaminated quartz and heavy mineral sands, have collapsed downward, forming a single foldlike structure. An overlying light-colored quartz sand layer maintains a horizontal upper surface but has also formed a small foldlike structure above the nest's egg chamber and is overlain by a brownish, mottled sand that has been disrupted on its upper surface by a overlying thick chevron truncating horizontal layers on either side. Continuous horizontal layers of the backbeach facies immediately overlie this bed. A smaller nest structure was found on a float block that had broken off the cliff and could be matched against its breakage fracture on the cliff face. This is a scour and fill structure, representing a washed-out nest that preserves only the lower few centimeters of the egg chamber.

Comparison of Fossil and Recent Sea Turtle Nest Structures

The nest structures from the Fox Hills (figs. 13.8, 13.9A, C, E, G) are comparable in morphology, size, and origin to structures seen in loggerhead sea turtle nests excavated by trenching on St. Catherines Island (fig. 13.9B, D, F, H). Nest 93-049 was deposited on July 10, 1993, on North Beach, St. Catherines Island by a loggerhead entering the beach and crawling 67 m in a sinusoidal path southward along the beach toward a dune, turning toward the backbeach, rotating north, pitting, nesting and covering, then crawling northward and looping back 180° and making what initially looked like a major body pit, then crawling back across her nest, and exiting eastward into the ocean. The entrance crawlway was 15–20 m shorter than the exit crawlway.

The clutch of eggs from Nest 93-049, failed to hatch after a normal incubation interval of 50–60 days, was trenched on September 10, 1993, to assess the reasons for its unsuccessful development. This clutch of 117 nonviable eggs was in an advanced stage of development when they died. The trench showed (fig. 13.9F) the unhatched eggs in the egg chamber packed tightly by sand filling in the normal porosity of the egg mass. The sand filling was apparently derived from surrounding and overlying laminated sands of the backbeach facies that had become fluidized by rising groundwater from a set of spring tides that had allowed waves to wash across the nest on four occasions, and from heavy rain and heavy surf during an early September nor'easter. The resulting sea turtle nesting structure exhibits

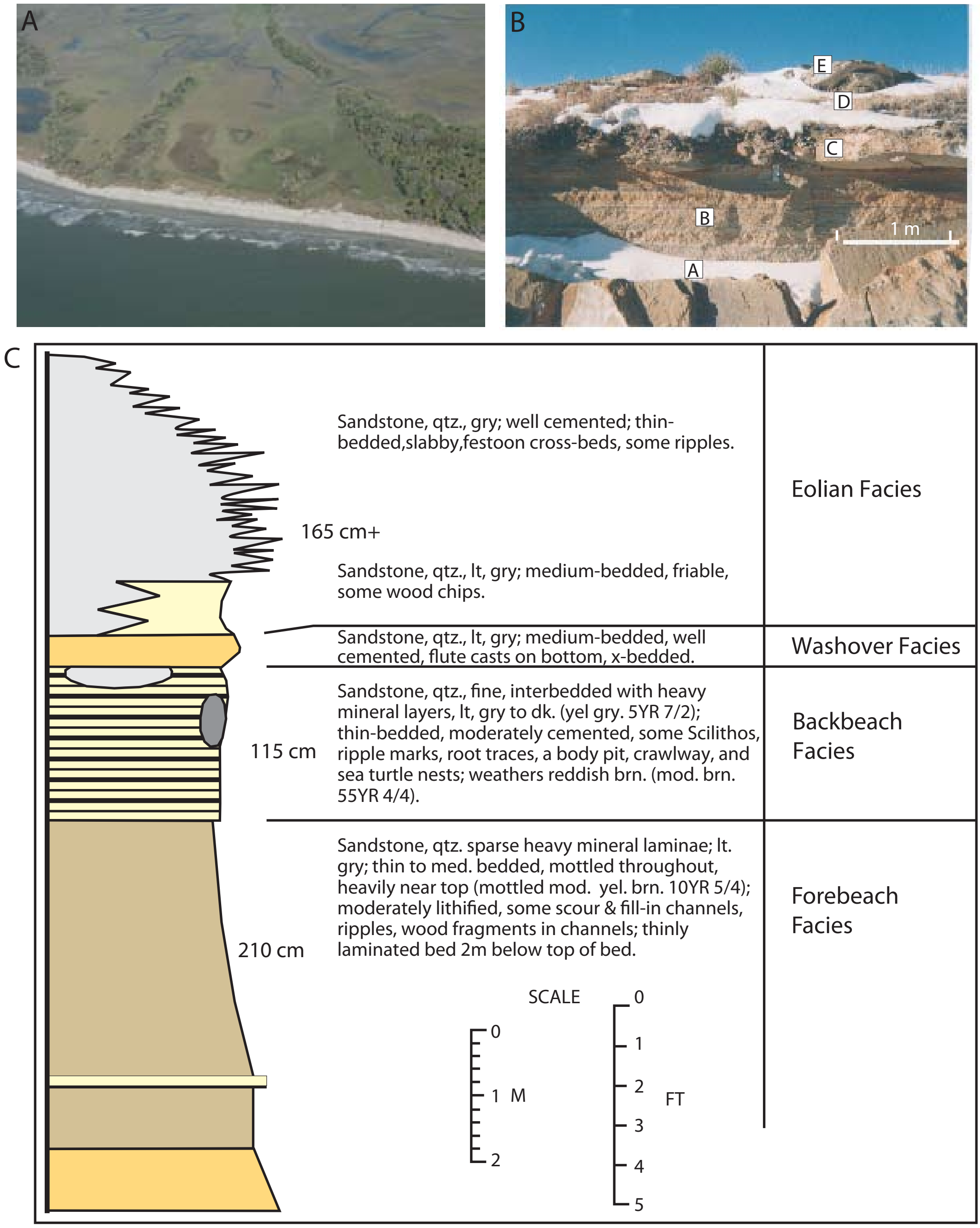


Fig. 13.7. Photograph of analogs: **A,** Beach facies tract on South Beach, St. Catherines Island; **B,** outcrop of beach facies tract, Elbert County, Colorado (labels: A, foreshore; B, backshore; C, washover fan; and D, terrestrial dunes); **C,** diagrammatic measured section at "Titanium Ridge," Elbert County, Colorado; all illustrating Walther's law.

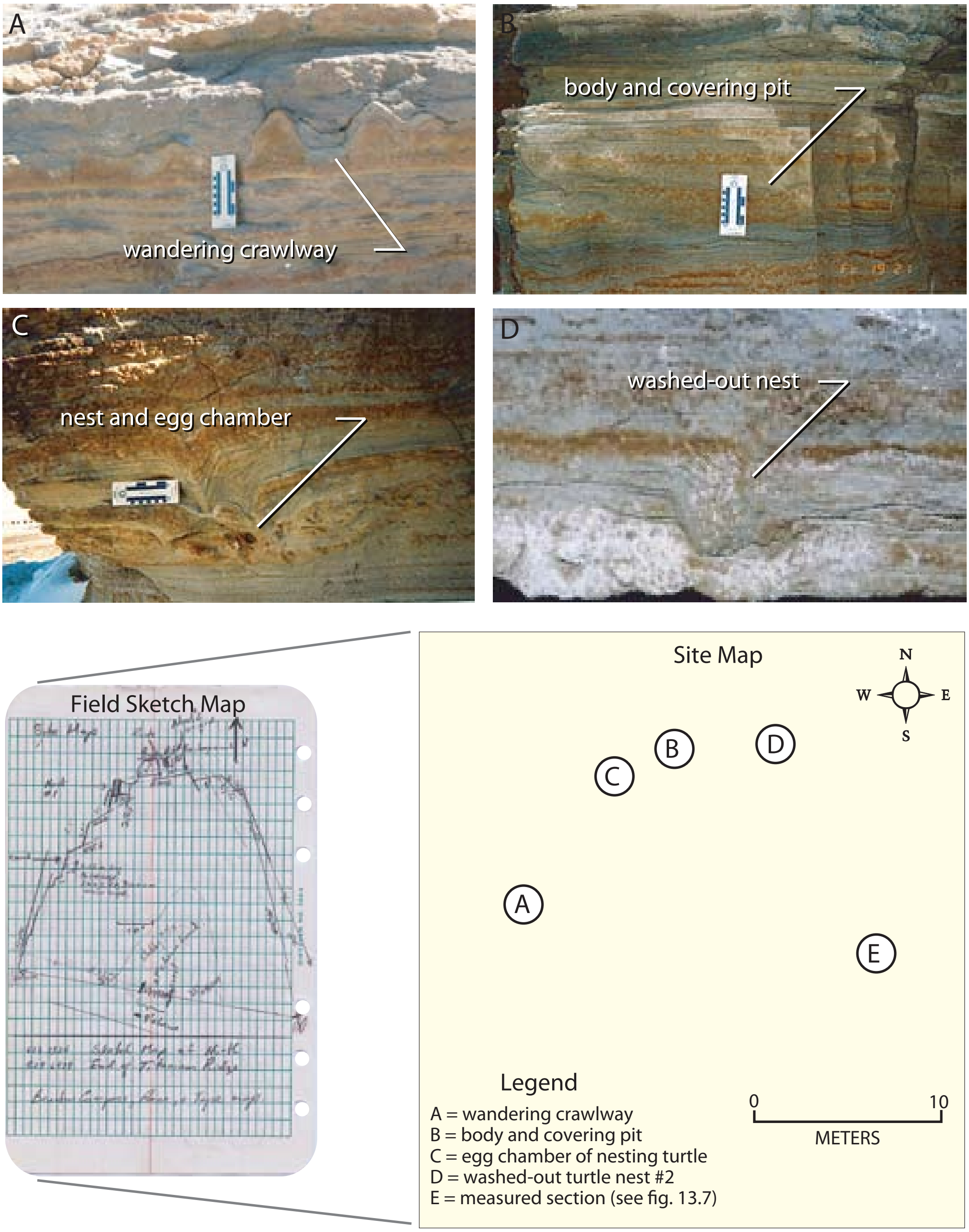
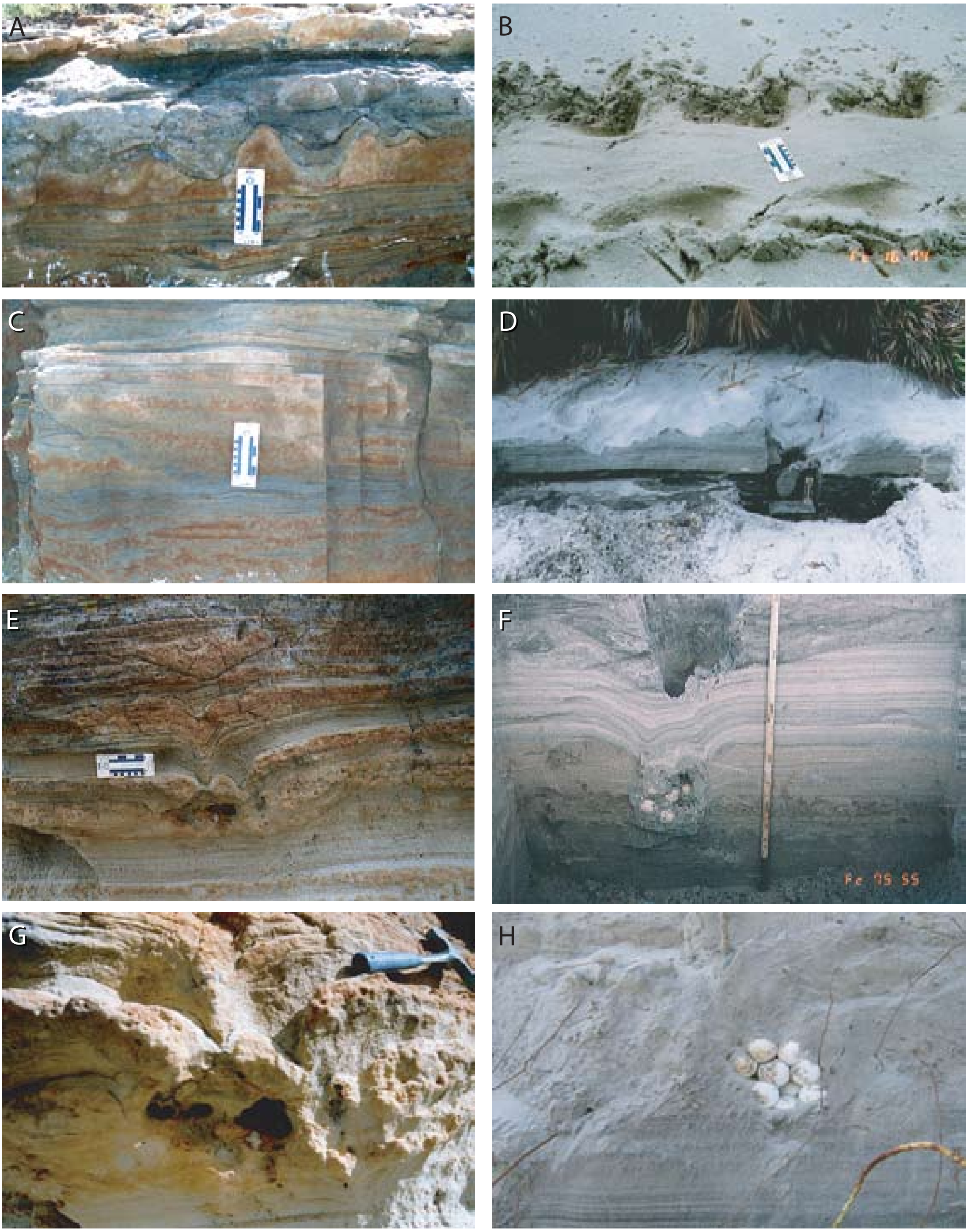


Fig. 13.8. Map view of sea turtle nesting structure suite at north end of “Titanium Ridge,” Elbert County, Colorado, showing relative positions of **A,** wandering crawlway; **B,** body and covering pit, in situ; **C,** egg chamber of nesting Cretaceous sea turtle; **D,** position of talus block with second (washed out) sea turtle nest. Bottom figures show field sketch of the north end of “Titanium Ridge,” (left) and the locations (right) of the elements of the sedimentary structure suite shown in figures 13.8A–D).


A
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the egg mass of the clutch still intact with the egg chamber delineated into ghostly laminated inactive beach overlain by the sag structure of the laminated quartz and heavy mineral sands of the backbeach facies.

The covering pit structure from the Fox Hills (fig. 13.9C) is a scourlike depression 103 cm across at the top and 25 cm deep at its center, cut into the laminated backbeach facies and filled by bioturbated sand. Comparison with a Recent loggerhead nest 97-079 (fig. 13.6D) shows a favorable correlation (figs. 13.8, 13.9) in the sedimentary structure morphology, lithology of the sediment involved, and the size of the nesting components. In the Recent nest, the eggs were moved and the egg chamber backfilled with white quartz sand that contrasts with a 33 cm heavy mineral placer into which the eggs were deposited.

The Fox Hills crawlway structure, exposed in vertical cross section (fig. 13.9A), is 106 cm long and consists of a series of six "chevron folds" representing six flipper push marks with maximum amplitude of 9.5 cm. This is comparable to crawlway structures made by loggerhead sea turtles crawling across soft sand flats on St. Catherines (fig. 13.9B), which, if buried, would result in a similar structure if seen in vertical exposure.

CONCLUSIONS

The sedimentary structures in the Fox Hills of Elbert County interpreted as sea turtle nesting traces, including two egg chambers (one with egg molds), a covering or body pit, and crawlway, compare favorably in morphology, size, and association with loggerhead nest structures previously documented on St. Catherines Island, Georgia. Both sets of traces are associated with backbeach sedimentary features including horizontal, interlaminated quartz and heavy mineral layers, washover fans structures, root traces, and desiccation features. The presence of these Fox Hills sea turtle nest structures in Elbert County documents the exact position of the Cretaceous seashore at that time of geological history.

Although sea turtle nest structures will always be ephemeral structures, their geological range and abundance should have preserved numerous examples in the stratigraphic record. Each documented example will locate the exact position of an ancient shoreline.

NOTES

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Fig. 13.9 (*left*). Direct comparison of Fox Hills nest structures (left) with analogous recent loggerhead nest structures (right). **A–B.** Sea turtle crawlway structures: **A,** Fox Hills crawlway seen in vertical view showing cross section of flipper push marks; **B,** loggerhead crawlway in soft back beach sand seen in oblique view showing deep flipper push marks. **C–D**. Vertical cross sections of ancient and modern sea turtle body and covering pits. **C,** Fox Hills body pit excavated into backbeach sandstone; **D,** loggerhead nest showing body pit excavated into backbeach sand about 1 m in front of storm scarp. **E–F.** Egg chamber structures of ancient and modern sea turtle nests: **E,** Fox Hills sea turtle nest with collapse structures into egg chamber at bottom; **F,** recent loggerhead sea turtle nest filled by fluidized, collapsed sand into egg. chamber. **G–H.** Egg molds in ancient nest and eggs in egg chamber of modern nest. **G,** Slightly compressed egg molds in Fox Hills nest; **H,** uncompressed eggs exposed in scarp eroded 9/08/06 into loggerhead nest [06-119]. Scales = 10 cm; bar scales = ~1.0 m.