



Dinosaur Tracksites of the Paluxy River Valley (Glen Rose Formation, Lower Cretaceous), Dinosaur Valley State Park, Somervell County, Texas

Rastros de dinosaurios del valle del río Paluxy (Formación Glen Rose, Cretácico Inferior), Dinosaur Valley State Park, Condado de Somervell, Tejas

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Abstract

In 1940 R.T. Bird of the American Museum of Natural History collected segments of a sauropod and a theropod trackway from a site in the bed (Glen Rose Formation; Lower Cretaceous) of the Paluxy River, in what is now Dinosaur Valley State Park (Glen Rose, Texas, USA). However, Bird left undocumented thousands of other dinosaur footprints from this and other Paluxy tracksites. In 2008 and 2009 our international team carried out fieldwork to create detailed photo-mosaics of extant Paluxy tracksites, using GIS technology to combine these with historic maps and photographs. We also made photographs, tracings, LiDAR images, and measurements of individual footprints and trackways. Paluxy dinosaur tracksites occur in more than one tracklayer, but the largest and most spectacular footprints occur in the Main Tracklayer, a 20-30 cm thick, homogeneous dolomudstone that is thickly riddled with vertical invertebrate burrows (*Skolithos*). There are two dinosaur footprint morphotypes in the Main Tracklayer: spectacular sauropod trackways (*Brontopodus*) and the far more numerous tridactyl footprints, most or all of which were made by large theropods (possible ornithomimid prints occur in a tracklayer stratigraphically higher than the Main Tracklayer). Tridactyl footprints are highly variable in quality; Paluxy tracksites collectively constitute a natural laboratory for investigating how trackmaker-substrate interactions create extensive extramorphological variability from a single foot morphology. Trackways of bipedal dinosaurs show a "mirror-image" distribution, suggesting movement of animals back and forth along a shoreline. In contrast, most sauropod trackways head in roughly the same direction, suggesting passage of a group of dinosaurs. The trackways collected by R.T. Bird suggest that at least one theropod was following a sauropod.

Key words: dinosaurs, ichnology, Glen Rose Formation, Texas, Cretaceous

Resumen

En 1940 R.T. Aves del Museo Americano de Historia Natural extrajo los rastros de un saurópodo y de un terópodo de un yacimiento situado río Paluxy (Formación Glen Rose, Cretácico Inferior), en lo que hoy es Dinosaur Valley State Park (Glen Rose, Texas, EE.UU.). Sin embargo, dejó sin documentar miles de icnitas de dinosaurios de éste y de otros yacimientos del Río Paluxy. En 2008 y 2009, nuestro equipo internacional llevó a cabo el trabajo de campo para crear fotomosaicos detalladas de los yacimientos del río Paluxy. Se utilizó la tecnología SIG para combinar los fotomosaicos con los mapas históricos y fotografías. También hicimos fotografías, calcos, imágenes LiDAR y las mediciones de las huellas individuales y de los rastros.

Las icnitas de dinosaurios del río Paluxy se encuentran en más de una capa, pero las huellas más grandes y más espectaculares se han conservado en una sola capa de unos 20-30 cm de espesor. Litológicamente se trata de un carbonato bioturbado de madrigueras verticales de invertebrados (Skolithos). Hay dos morfotipos de icnitas de dinosaurios en esta capa: espectaculares rastros de saurópodos (Brontopodus) y huellas tridáctilas, mucho más numerosos, la mayor parte o la totalidad de las cuales fueron realizadas por grandes terópodos (impresiones posibles de ornitópodos se encuentran en una capa estratigráficamente más alta). La conservación de las icnitas tridáctilas es muy variable. Los yacimientos del río Paluxy en su conjunto, constituyen un laboratorio natural para investigar cómo se producen interacciones entre el sustrato y los miembros de los dinosaurios. Un solo dinosaurio produce una gran variedad de morfotipos distintos de la morfología de su pie. Los rastros de los dinosaurios bípedos tienen una distribución que sugieren el movimiento de los animales de un lado a otro a lo largo de la costa. En contraste, la mayoría de rastros de los saurópodos van en la misma dirección, lo que sugiere el paso de un grupo de dinosaurios. Los rastros recogidos por R.T. Bird sugieren que al menos un terópodo paso después de un saurópodo.

Palabras clave: Dinosaurios, icnología, Formación Glen Rose, Tejas, Cretácico

INTRODUCTION

Although Native Americans (cf. Mayor, 2005), Spanish explorers, and early Anglo-American settlers may have observed them, the first person known to have seen dinosaur footprints in the carbonate bedrock of the Paluxy River or its tributary streams was a truant schoolboy, George Adams, at the beginning of the 20th Century (Farlow, 1987; Jasinski, 2009). Young Adams called the tridactyl footprints to the attention of his teacher, who recognized them as dinosaur tracks. Brief descriptions of these trace fossils were published by Ellis W. Shuler (1917, 1935, 1937), who created two ichnotaxa, *Eubrontes* (?) *glenrosensis* and *E. titanopelopatidus*, to accommodate them (regrettably, the type specimen of *Eubrontes* (?) *glenrosensis* was incorporated into the wall of an outdoor bandstand, where it has suffered due to weathering; Adams *et al.* 2010). Subsequently tridactyl tracks were found to be common throughout the area of outcrop of the Glen Rose Formation and other Lower Cretaceous units across central Texas (Wrather, 1922; Gould, 1929; Albritton, 1942; Langston, 1974, 1979; Skinner and Blome, 1975; Farlow, 1981; 1987; Sams, 1982; Pittman, 1989; Hawthorne *et al.*, 2002; Rogers, 2002; Farlow *et al.*, 2006).

But the Paluxy hid even bigger ichnological secrets. By the mid-1930s local residents were aware of enormous footprints of quadrupedal animals that their discoverers assumed were elephants (Jasinski, 2009). These ichnites were made known to Science by Roland T. Bird, a fossil collector for Barnum Brown of New York's American

Museum of Natural History (AMNH) (Bird, 1985). Visiting an Indian trading post in Gallup, New Mexico on his way home from the field, Bird saw putative footprints of a tridactyl dinosaur and a gigantic human in loose slabs of rock. Upon inquiry he learned that they had come from Glen Rose, Texas, and so he stopped there for a look. Although the "tracks" Bird had seen in Gallup turned out to be forgeries carved by a local entrepreneur (George Adams himself) for sale to unsuspecting tourists, Bird discovered that the tridactyl footprints were based on authentic originals in the bed of the Paluxy River. He was also shown indistinct, elongate, "mystery" prints in the riverbed that the locals called "man tracks" or "moccasin tracks." Most importantly, Bird learned of the huge "elephant" footprints, which he immediately recognized as having been made by sauropods.

Bird described the tridactyl and sauropod footprints in a brief popular article (Bird, 1939), in which he also talked about the mysterious "man tracks." The last were mentioned in the hope of amusing oil magnate Harry Sinclair, an important patron of Barnum Brown's dinosaur-hunting forays (Farlow, 1985).

Bird returned to Texas in 1940, with federal support in the form of a Works Progress Administration work crew, to collect portions of trackways of a sauropod and an apparently following theropod (Bird, 1941, 1944, 1954, 1985). The footprints and the surrounding rock were quarried out in pieces, and eventually reassembled behind the skeleton of an *Apatosaurus* at the AMNH. A second segment of the two trackways was assembled in an outbuilding of the Tex-

as Memorial Museum (TMM) in Austin, and individual footprints were collected for other institutions.

Unfortunately, Bird's 1939 exercise in grantsmanship resulted in dramatic "blowback." Religious fundamentalists who literally interpreted the events of the biblical book of Genesis concluded that Bird's "man tracks" were genuine, particularly large examples of which had been made by the giants (*Nephilim*) of Genesis 6:1-4 (Attridge, 2006). The co-occurrence of human and dinosaur footprints in the Glen Rose Formation was further cited as evidence against both the antiquity of the earth and scientific descriptions of the evolution of life (Numbers, 2006). The "man tracks" figured prominently in creationist publications, most notably Stanley Taylor's 1970 film *Footprints in Stone* and Morris' (1980) book. However, some creationists were skeptical of the "man track" claims (Neufeld, 1975), and in the 1980s, the scientific community also responded, providing evidence that those human prints that were not out-and-out fakes or the caprices of weathering were in fact preservational variants of tridactyl dinosaur footprints, particularly of prints made during an unusual style of locomotion for the huge reptiles (see Milne and Schafersman, 1983; Cole and Godfrey 1985; Hastings, 1986, 1987; Kuban, 1986, 1989a, b; Farlow, 1987 and references cited therein), an interpretation that will be further documented in this paper.

At the same time, interest in the dinosaur footprints of the Glen Rose Formation in and of themselves, and not in the context of the "man track" controversy, was renewed (Farlow, 1987, 1993; Farlow and Hawthorne, 1989; Pittman, 1989; Hawthorne *et al.* 2002; Rogers, 2002; Farlow *et al.*, 2006), as part of revived worldwide interest in dinosaur trace fossils more generally (e.g. Gillette and Lockley, 1989; Thulborn, 1990; Lockley, 1991; Leonardi, 1994; Lockley *et al.*, 1994b; Gierlinski, 1995; Lockley and Hunt, 1995; Sanz *et al.*, 1997; Leonardi and Mietto, 2000; Lockley and Meyer, 2000; Fuentes Vidarte y Torcida Fernández-Baldor (Eds.), 2001; Pérez-Lorente *et al.*, 2001; Lockley, 2002; Moreno and Pino, 2002; Huh *et al.*, 2003; Pérez-Lorente (Ed.), 2003; García-Ramos *et al.*, 2004; Torcida Fernández-Baldor and Huerta Hurtado (Eds.), 2006, 2009; Moratalla, 2009; Whyte *et al.*, 2010). The Paluxy River sauropod tracks were formally named *Brontopodus birdi* by Farlow *et al.* (1989), and recognized as the prime example of "wide-gauge" sauropod trackways (Farlow, 1992b; Wilson and Carrano, 1999; Romano *et al.*, 2007; Marty *et al.*, 2010).

Dinosaur Valley State Park (DVSP) was created in 1970 to protect the dinosaur tracks of the Paluxy River and surrounding natural areas (Jasinski, 2009). Although the park hosts thousands of visitors each year, paleontologists who have not seen the park may not be aware that Bird's collecting activities merely scratched the surface of DVSP's ichnological riches. During the 1980s and 1990s Kuban (sometimes working with one or more associates) mapped dozens of trackways at several sites. In the same period Farlow repeatedly visited the park to carry out field work, but was overwhelmed by the enormity of the task

that adequate documentation of the Paluxy's tracksites would entail. In 2008 and 2009, however, a serendipitous coming together of financial support, technological resources, and manpower made possible intensive documentation of several major tracksites exposed in the bed of the Paluxy in DVSP by an international team of workers. The present paper summarizes the goals of this work, describes our field and laboratory activities, and presents our preliminary findings.

METHODS AND GOALS

Supported by grants from funding agencies in the U.S., Spain, and the U.K., we assembled an international team to document thoroughly dinosaur tracksites within the boundaries of DVSP that still preserved significant footprint assemblages, and that also were not covered by gravel and sand river deposits so large as to be impossible, or too disruptive to the park's aquatic and riparian ecosystems, to clean. Additional Paluxy tracksites than those described here are known to exist or have existed (Kuban, 1986; Farlow, 1987; Hawthorne, 1990), but will not be discussed in this paper.

Our project has several long-term goals, which have only partly been accomplished thus far:

- 1) to create an updatable database of footprint and tracksite information;
- 2) to determine the number of kinds of footprint morphotypes and the number of individual animals responsible for the tracksites;
- 3) to document the range of variability of footprint shapes within each morphotype, and the sediment factors responsible for that variability;
- 4) to determine the appropriate nomenclature to apply to the tridactyl footprints;
- 5) if possible, to determine the interval of time over which tracklayers accumulated footprints;
- 6) to determine what the animals were doing as they made the tracks.

Our efforts were aided by drought conditions in 2008 and 2009 that either exposed tracksites that are normally underwater, or at least lowered water levels covering the footprints enough to make photography possible. Even so, working conditions were not always ideal. By late morning breezes usually became strong enough to create ripples in the water surface, reducing visibility of submerged footprints. In 2009 a strong thunderstorm moved along the valley of the Paluxy, dumping enough rain onto the watershed to create a river rise high and powerful enough to shut us down for a few days, and submerging for the duration of our fieldwork some important sites that had hitherto been R.T. Bird (1985) experienced similar frustrations.

Field methods included both low-tech and high-tech approaches. Often assisted by volunteers from across the state of Texas, we began by cleaning sediment off tracksites, using brushes, push brooms, power hoses, shovels,

and wheelbarrows. Once a site was cleaned, if the tracksite surface was above water we drew a meter-square chalk grid over it. We then used a Trimble GeoXH GPS system with Trimble Hurricane antenna to georeference footprints and other features of tracksite surfaces, and photographed overlapping sections of tracksites that were then stitched together using Arcview 9.3 to create photomosaics of tracksite surfaces. We also took thousands of photographs of individual footprints and trackways, both at ground level and from an elevated platform. Where possible, we traced the surface outlines of individual footprints or trackways on sheets of plastic, and directly measured footprint and step lengths and individual footprint bearings. Casts were made of some of the better preserved tridactyl dinosaur footprints. In order to characterize vertical burrows in the Main Tracklayer, an oriented sample, about 20 cm thick and 40 cm by 30 cm wide, was collected in place as it was in the process of eroding from the edge of the Main Tracklayer in the Blue Hole Parlor site. This sample was cut into two perpendicular vertical slabs and into 8 horizontal slabs, each 2 cm thick, with the exception of the bottom and top slab, which were cut a little thicker. For comparison with previous stratigraphic studies (e.g. Hawthorne, 1990), a stratigraphic section was measured

along the river bank outside the eastern boundaries of the park. It was measured to centimeter precision by marking 10 cm intervals on the exposure. Beds were observed, photographed, described, and sketched in the field from this framework.

To document the AMNH-TMM footprint slabs, the fully portable RIEGL LMS-Z420i 3D laser scanner was chosen for its ability to rapidly acquire spatial data (12,000 x, y, z and intensity points per second). A 6.1 megapixel Nikon D100 digital camera was mounted on the scanner and, once calibrated, provided images that were used to extract an RGB colour channel and reflection intensity information for the point cloud, to texture map the final model, and to produce a photorealistic representation of the track blocks (e.g. Bates *et al.*, 2008). Both track blocks were scanned from multiple perspectives to provide more detailed 3D shape information by eliminating “shadows” (areas not visible to the laser) caused by irregularities in the exposure surface. Both perpendicular and oblique scan perspectives were necessary to eliminate shadows occurring in the tracks themselves. Point clouds captured from different perspectives were aligned using PolyWorks (Bates *et al.*, 2008) to form a merged network of scans aligned to extremely high precision (standard deviation less than

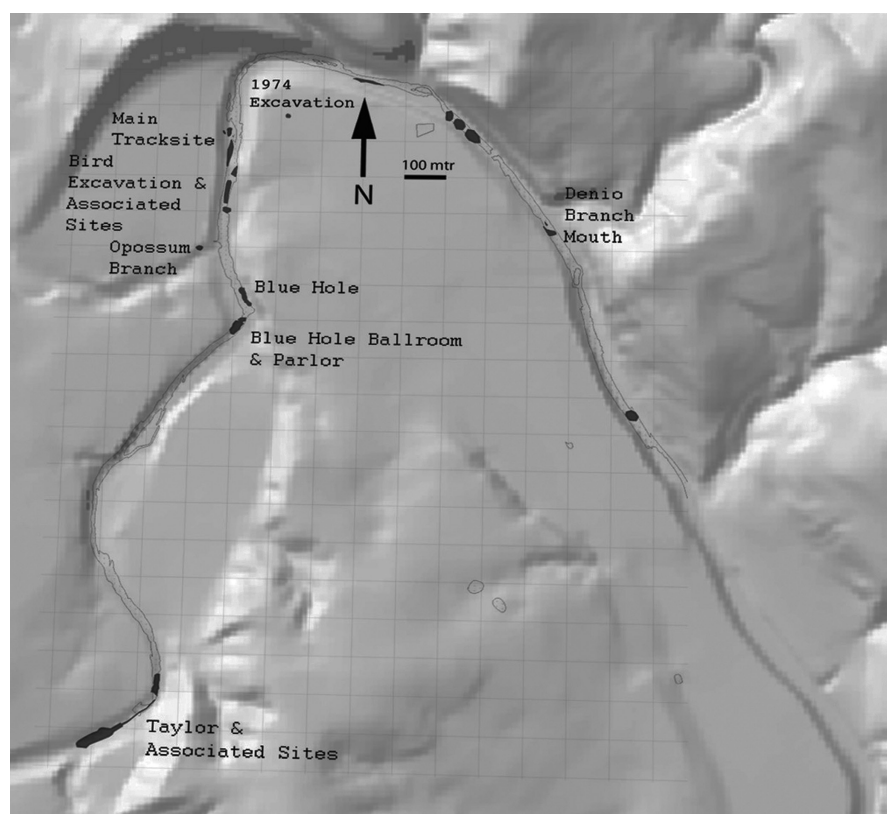


FIGURE 1. Digital elevation map of the Paluxy River valley in and around Dinosaur Valley State Park (Somervell County, Texas), indicating the major tracksites documented in this study, other track occurrences known to have existed (unlabeled), and a test excavation dug in 1974, away from exposures in the river bed, through overlying strata, to reach the Main Tracklayer.

10⁷). Merged point clouds of the two separate track blocks were then surfaced using Geomagic to produce high-resolution triangulated meshes, which were contoured and shaded according to topography. The polygonal meshes of the AMNH and TMM blocks were imported into Maya (a CAD package) and rotated until they matched R.T. Bird's 1940 maps and photographs of the two dinosaur trackways.

GEOGRAPHIC AND GEOLOGIC SETTING OF TRACKSITES

The dinosaur tracksites described in this study (Fig. 1) occur within DVSP, where the Paluxy River flows to the north before making a hairpin turn southward. The river has cut its way through overlying strata to expose track-bearing layers in and just above its bed. The local stratigraphic section comprises the lower and middle (Thorp Spring) members of the Glen Rose Formation (Nagle, 1968; Perkins *et al.*, 1987; Pittman, 1989; Winkler *et al.*, 1989; Hawthorne, 1990). Detailed stratigraphic sections (Fig. 2 and Hawthorne, 1990) indicate that tracklayers occur at four horizons, two of which are described in this paper.

Most of the dinosaur tracksites in the park (Figs. 3-12) occur in the Main Tracklayer, a ca. 20-30 cm thick, sandy, homogeneous dolomitic wackestone (cf. Shelton *et al.*, 1993). In addition to containing dinosaur footprints, the Main Tracklayer is thickly riddled with openings for vertical invertebrate burrows (Fig. 13A-C). Similar long, unbranched, tubular trace fossils are commonly assigned to the ichnogenus *Skolithos* (cf. Alpert, 1974; Droser, 1991; Schirf and Uchman, 2005), and indicate an intertidal to shallow subtidal depositional environment (Seilacher, 1967; Curran, 1984; Droser, 1991; Vossler and Pemberton, 1988; Skoog *et al.*, 1994), consistent with the presence of dinosaur tracks. *Skolithos* is also associated with dinosaur footprints in a shallow-water, carbonate setting in the Middle Jurassic Sundance Formation of Wyoming (Kvale *et al.*, 2001).

A second kind of possible trace fossil (or tool mark?) was observed only once in the Main Tracklayer, at the Blue Hole Ballroom. This was a large, horizontal, somewhat linear feature in the surface of the bed, composed of repeated shallow depressions separated by short gaps (Fig. 13D). Similar features were observed at another site in the Glen Rose Formation (Farlow *et al.*, 2006), where they were provisionally attributed to large gastropods.

With only one or two trace types, the diversity of invertebrate traces in the Main Tracklayer is quite low. However, we have observed at least two other distinct invertebrate trace fossil morphotypes (cf. *Thalassinoides* and cf. *Diplocraterion*) in exposures along the river between the Blue Hole Ballroom and the Taylor Site (Fig. 1), and probably stratigraphically between them as well (Fig. 2), but these localities require further documentation (cf. Hawthorne, 1990).

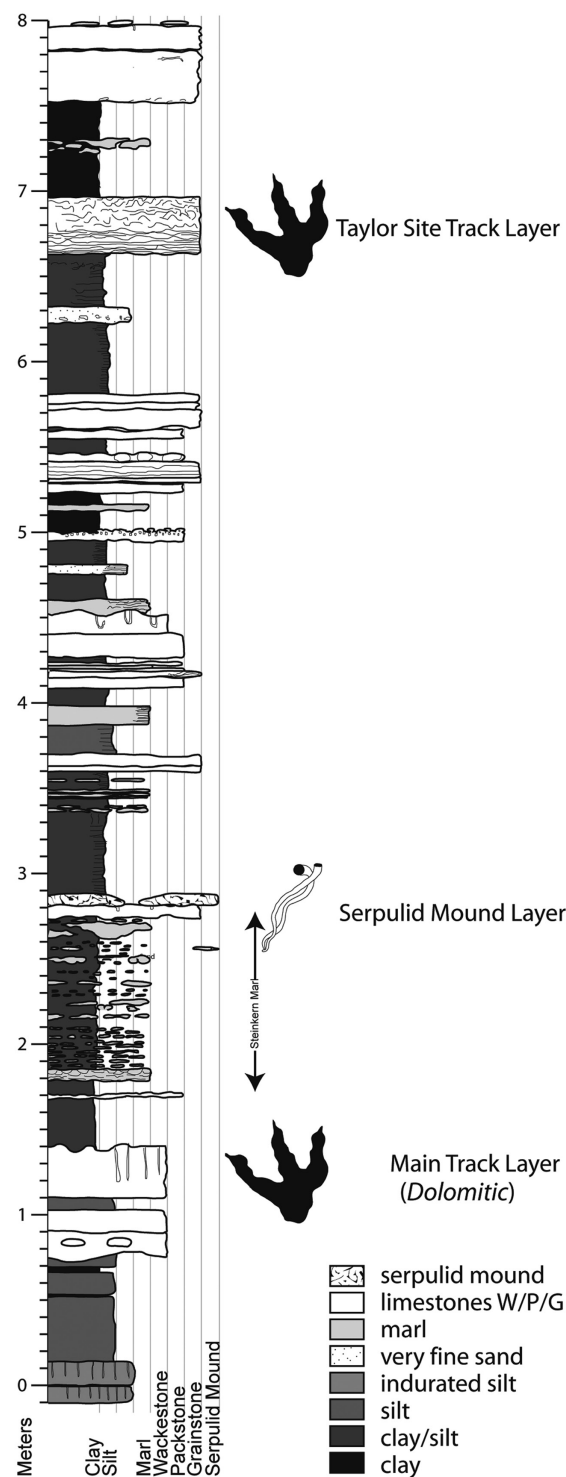


FIGURE 2. Stratigraphic section of the lower Glen Rose Formation in and around Dinosaur Valley State Park, based on our observations, and comparisons with Hawthorne (1990); also see Pittman (1989). Bed lithologies are labeled by shading / pattern, and (particularly for different kinds of limestone [wackestone / packstone / grainstone]) by horizontal distance to the right of the vertical axis of the section. Most of the park's tracksites are in the Main Tracklayer, a dolomitic wackestone. The Taylor Site is stratigraphically higher. Hawthorne (1990) identified two additional track horizons in the Paluxy River section.

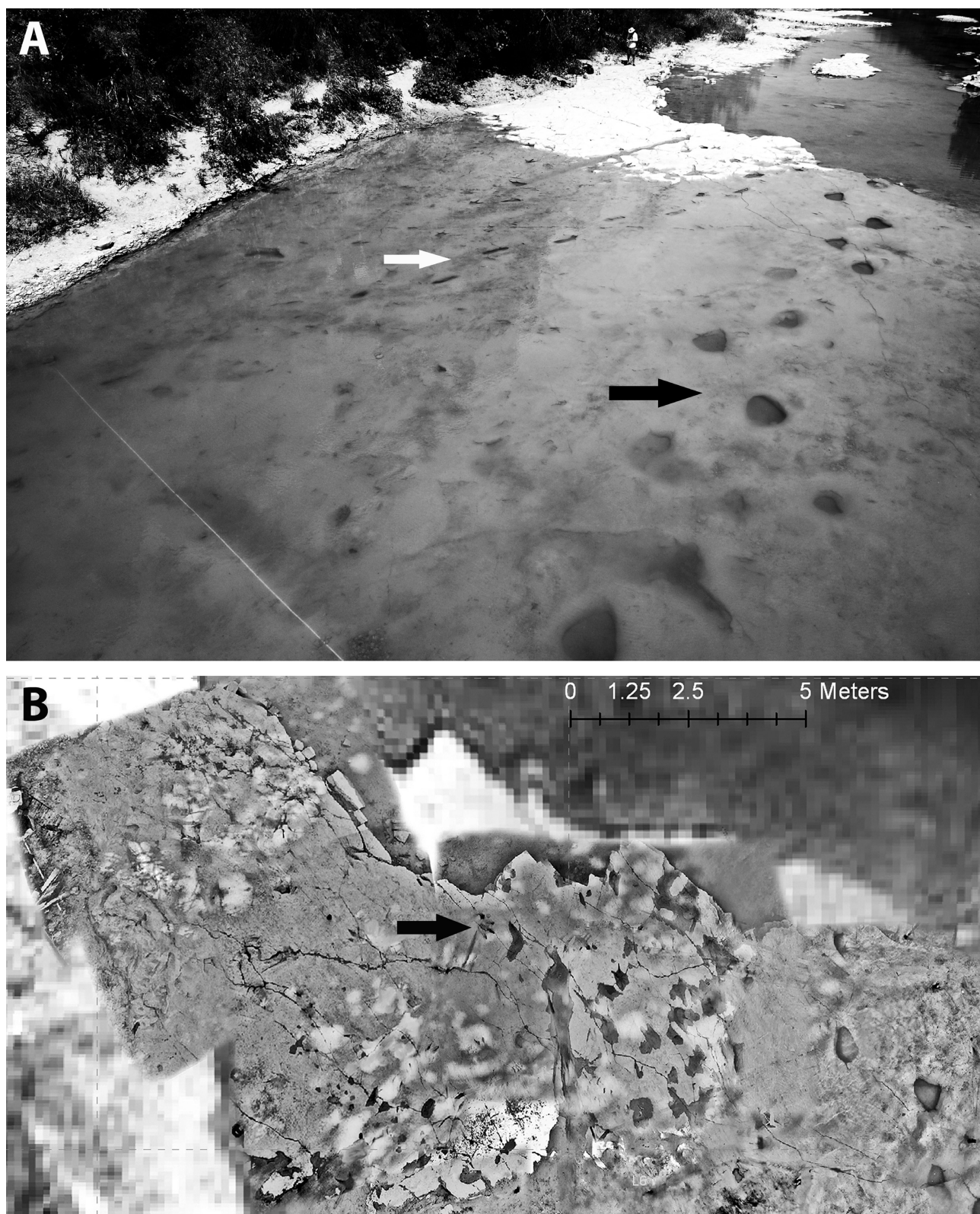


FIGURE 3. Denio Branch Mouth Tracksite. A) View from an elevated platform across the site, looking upstream (northward). Most of the site was under shallow water at the time this photograph was taken, but a dry portion of the site, containing several tridactyl prints, is visible at the top of the photograph. A sauropod trackway (black arrow) marked only by poorly preserved pes prints heads southward (?) across the site, while a trackway composed mainly of “elongate” footprints (white arrow) heads in the opposite direction. B) Photo-mosaic detail of the northmost edge of the site; one of several tridactyl footprints is indicated by an arrow.

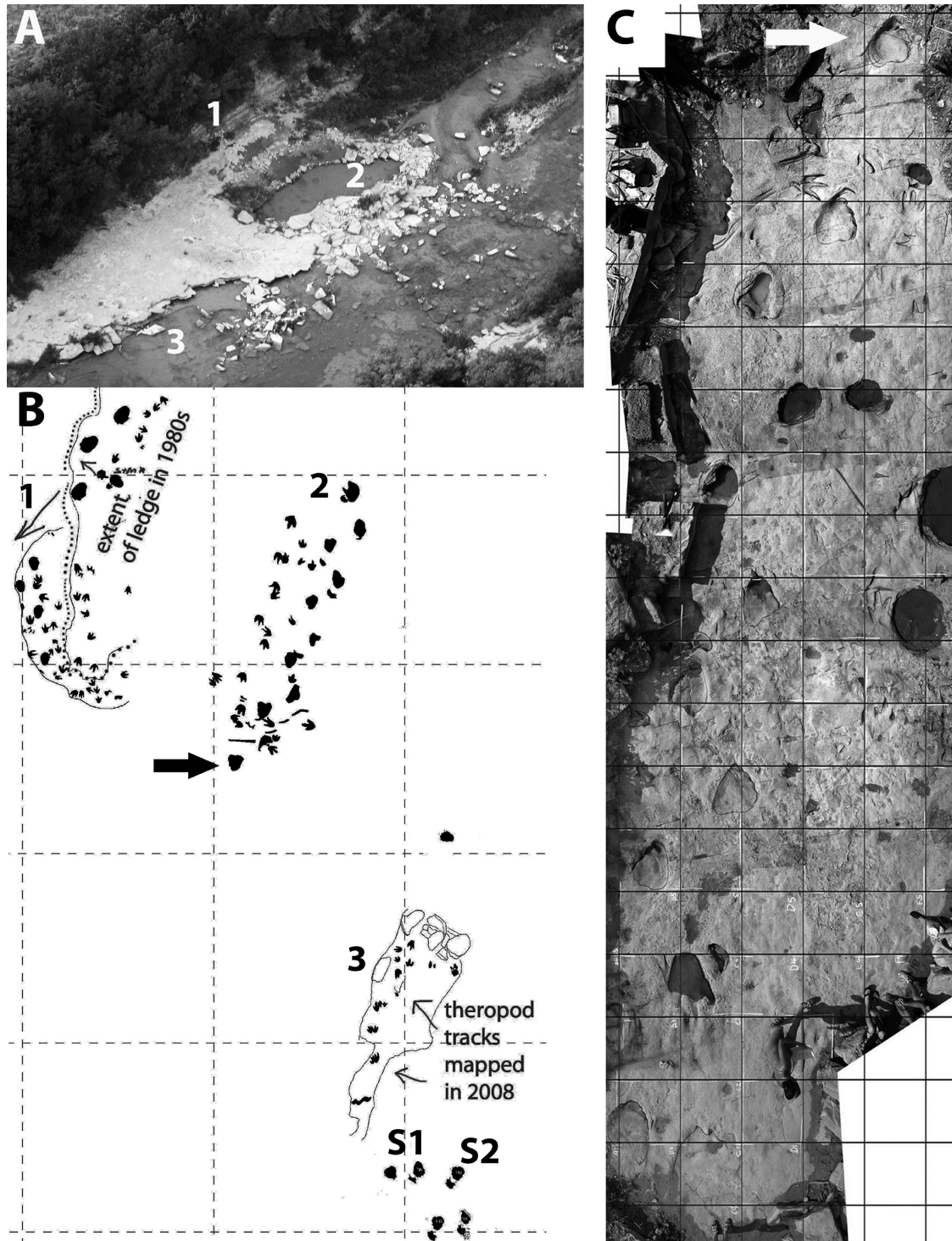


FIGURE 4. The Main Tracksite (so named because it contains the footprint exposures most easily seen by the casual observer). A) Aerial view, looking northward. Exposures of the Main Tracklayer (1, 2, 3) peek out from beneath an overlying hard limestone shelf. B) Footprints in the three exposures of the Main Tracklayer; north to the top of the map. Extensive change in the footprint surface, due to erosion of previously exposed tracks, and uncovering of new tracks, has occurred over the last two decades; note the changing position of the shelf layer in exposure area 1 between the 1980s (small arrow) and the present (large arrow). The final footprint in the trackway of a small sauropod in exposure area 2 is indicated by a heavy black arrow. Exposure area 3 is contiguous with the West Bank of the Bird Site. Additional theropod footprints that do not appear in the map were documented here in 2008. The locations of the beginnings of two of the sauropod trackways mapped by Bird in 1940 (S1 and S2) are plotted on the map. C) Photomosaic (1-m grid) of exposure area 2. South to the top of the image. Note the well-preserved sauropod trackway (S0; Main Site Trail of Farlow *et al.* [1989: Table 42.2]) from panel B; a white arrow labels the final exposed footprint in this trackway. Tridactyl prints are also scattered across this exposure.

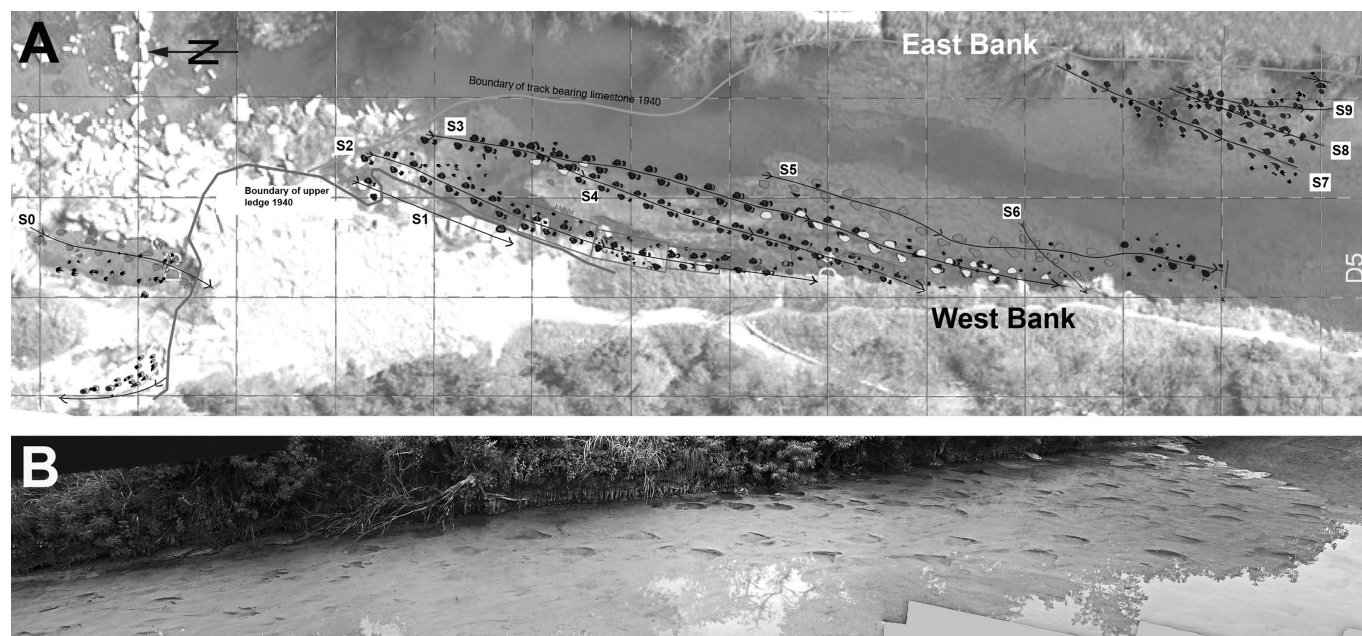


FIGURE 5. The Bird Site. A) Aerial view of the Bird Site and the Main Tracksite (left edge of photograph), with Bird's and our trackway maps superimposed. Sauropod trackways S1 – S5 numbered according to Farlow *et al.* (1989: Figure 42.1). Note erosional destruction of a significant part of the Main Tracklayer between 1940 and 2009-2010. B) Oblique view of East Bank sauropod trackways S7 – S9 from an elevated platform on the West Bank.

Dinosaur tracks in the Main Tracklayer are preserved as concave epireliefs with distinct outlines. They are often quite deep, with sauropod prints sometimes punching through the bed to reach the underlying silt layer. Tridactyl footprints nearly always show some collapse or roofing over of toe marks, or other features suggestive of rather plastic substrate conditions at the time footprints were emplaced.

The Taylor Site (Figs. 2, 14) Tracklayer is a grainstone, strongly laminated at its base and bioturbated at its top. Preservation of tracks is very different from that in the Main Tracklayer. The Taylor Site contains numerous trackways of elongate footprints with metatarsal impressions, most of which are largely filled in with a bluish-gray sedimentary rock. This reduces their topographic relief with respect to the surrounding rock, and contributes to the human-like shapes that creationists have identified as human tracks. However, when well cleaned the infilled prints clearly show tridactyl digital patterns. Cores taken at the margin of the fillings show that the original footprints were several centimeters deep before sediment filled them. Moreover, with repeated exposure due to low river levels during droughts, the iron-rich infilling sediment has in places oxidized to a reddish-brown color, making print outlines even more distinct (Kuban, 1986, 1989b; Farlow, 1987). Some of the Taylor Site prints presently occur as convex epireliefs that are topographically somewhat higher than the surrounding rock. One of the Taylor site trackways contains more than two hundred individual footprints.

DINOSAUR FOOTPRINT MORPHOTYPES

Remarkably, despite the large areal extent of tracksite exposures along the Paluxy, only two distinct dinosaur footprint morphotypes have been recognized, making this a low-diversity vertebrate ichnological assemblage.

Sauropods (Figs. 3A, 4B, C, 5-8, 12A, B, 15)

The sauropod footprints are of course what captured R.T. Bird's attention, and are among the world's best-preserved sauropod trace fossils (Farlow *et al.*, 1989). Well-preserved manus prints (Fig. 15F) are rather horseshoe-shaped, being deepest along the anterior margin and shallowest at the center and rear of the print. Digits II-IV seem to have been bound together and separated from digits I and V. There is no indication of a claw on digit I. However, manus prints are often squashed from the rear, or even obliterated by pes prints (Figs. 3A, 4C, 12A-B).

Sauropod pes prints are much larger (commonly about a meter in length) than manus prints, and somewhat triangular in shape. Well-preserved pes prints (Figs. 7, 15F) show three large, laterally directed claw marks, and sometimes additional nail or callosity marks lateral to the large claw marks. The footprint is deepest along its medial margin, particularly at the front and rear edges of the print, and shallowest toward its lateral margin. Pes prints are as deep as, or deeper than, associated manus prints.

Both manus and pes prints are usually well offset from the trackway midline (Figs. 3A, 4C, 6B, 15A, B, D, E), pes impressions being more so than manus impressions, making

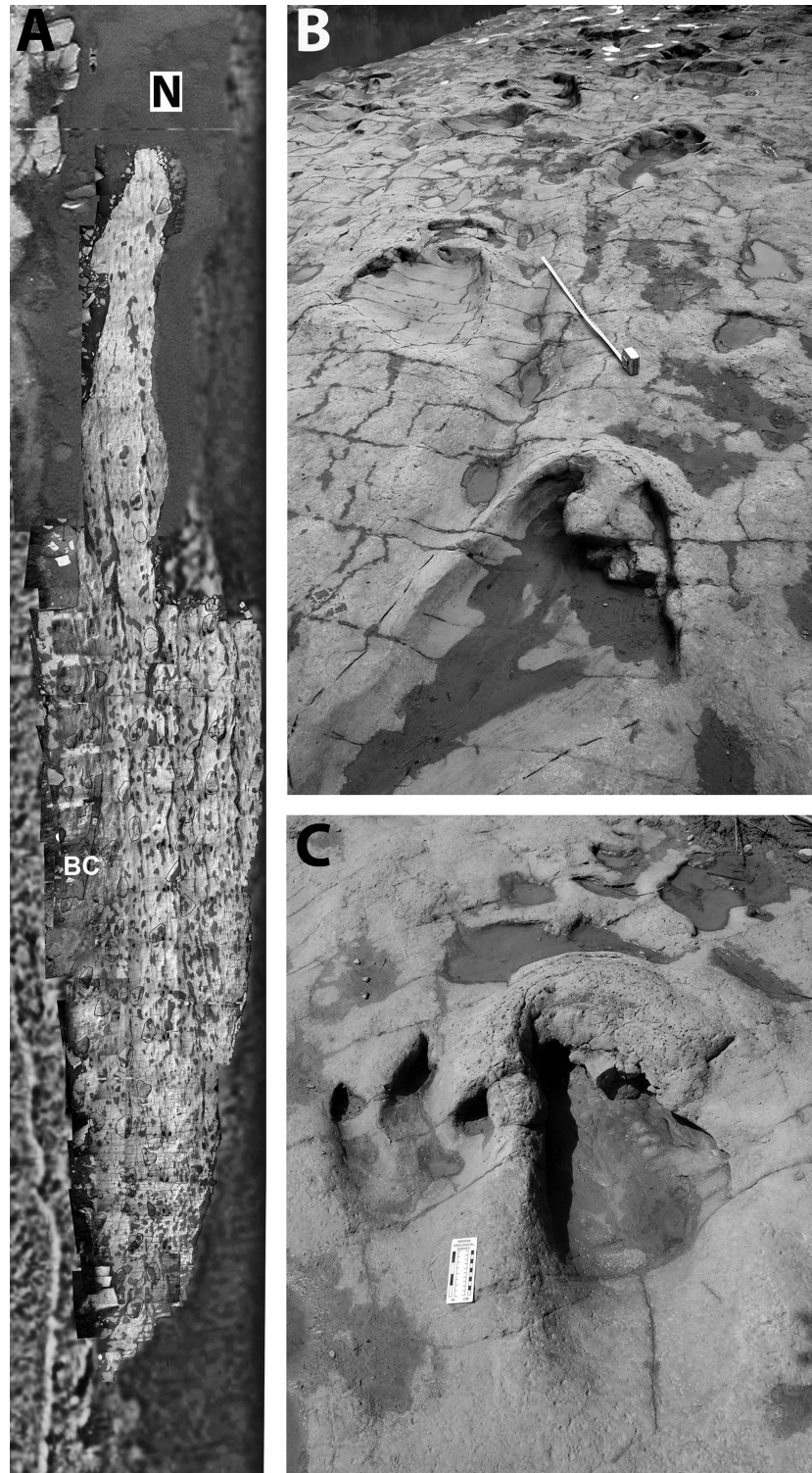


FIGURE 6. West Bank of the Bird Site. A) Photomosaic of the tracksite surface. Many individual sauropod and theropod footprints are outlined in black. North (N) at the top of the image; BC marks the site from which the Brooklyn College (New York) manus-pes set (Fig. 7) was collected. B) Ground-level oblique view of a sauropod trackway; the animal was moving southward and away from the viewer. Tape measure exposes 1 m of tape. C) Sauropod footprint with a theropod print impressed into its margin; scale in photograph marked in cm and inches.



FIGURE 7. Well-preserved left sauropod manus-pes set collected by R.T. Bird for Brooklyn College. A) Photograph of the manus-pes set (courtesy of John Chamberlain); scale bar marked off in 10-cm increments. B) Detail of the photomosaic of the West Bank of the Bird Site (Fig. 6A; the image is here rotated 180 degrees from its position in Fig. 6A, with south here toward the top of the image) showing the Brooklyn College manus-pes set as originally located in sauropod trackway S4 (BC); also see Bird (1985: 179).

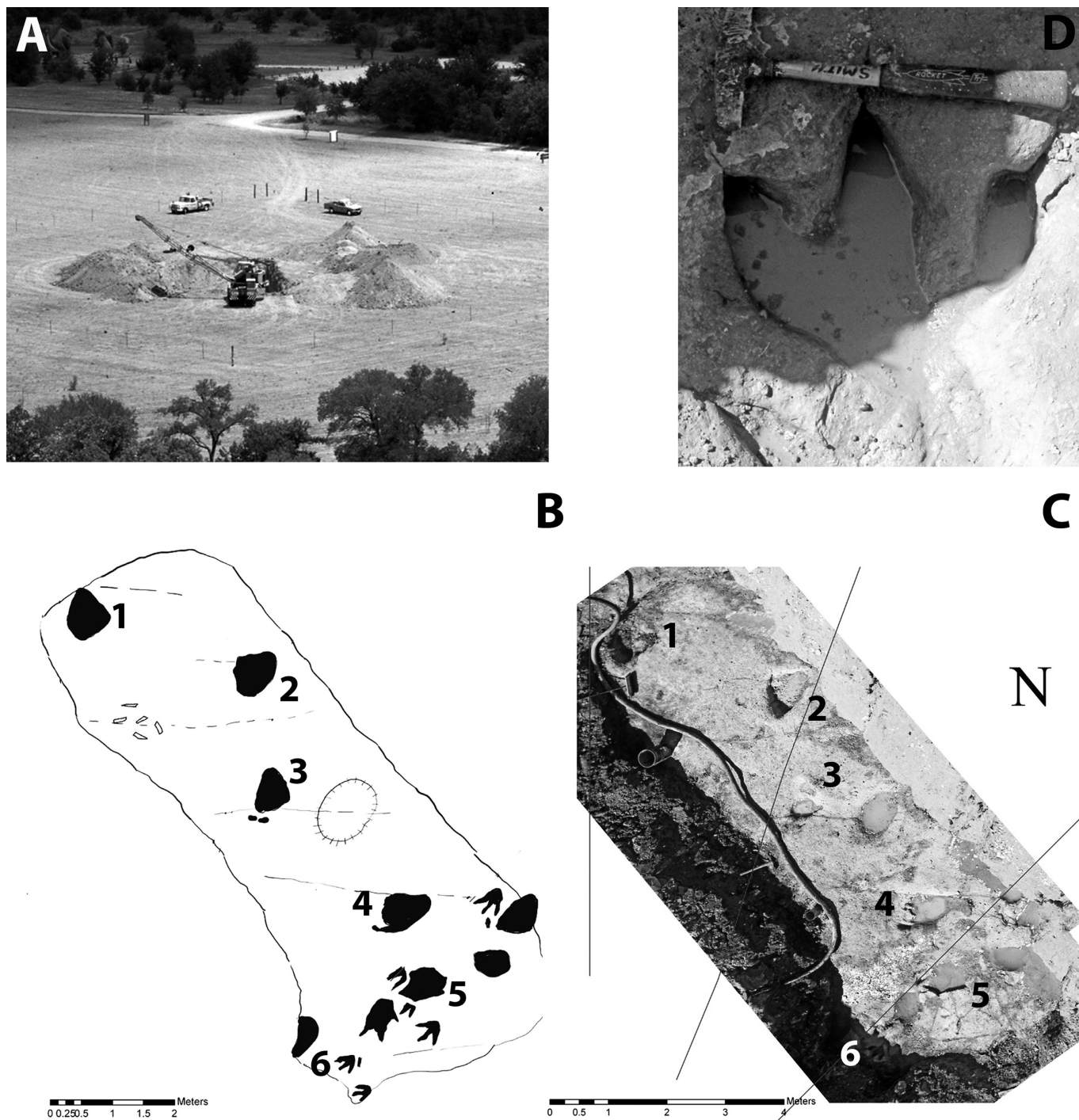


FIGURE 8. Footprints discovered during a 1974 test excavation in a field well away from the river bed. A) Digging the pit. B-D) Footprints exposed, probably in the Main Tracklayer. B) Map and C) photograph of the uncovered track surface. Several footprints are identified by number in both panels. D) Tridactyl footprint (print 6 in panels B and C).

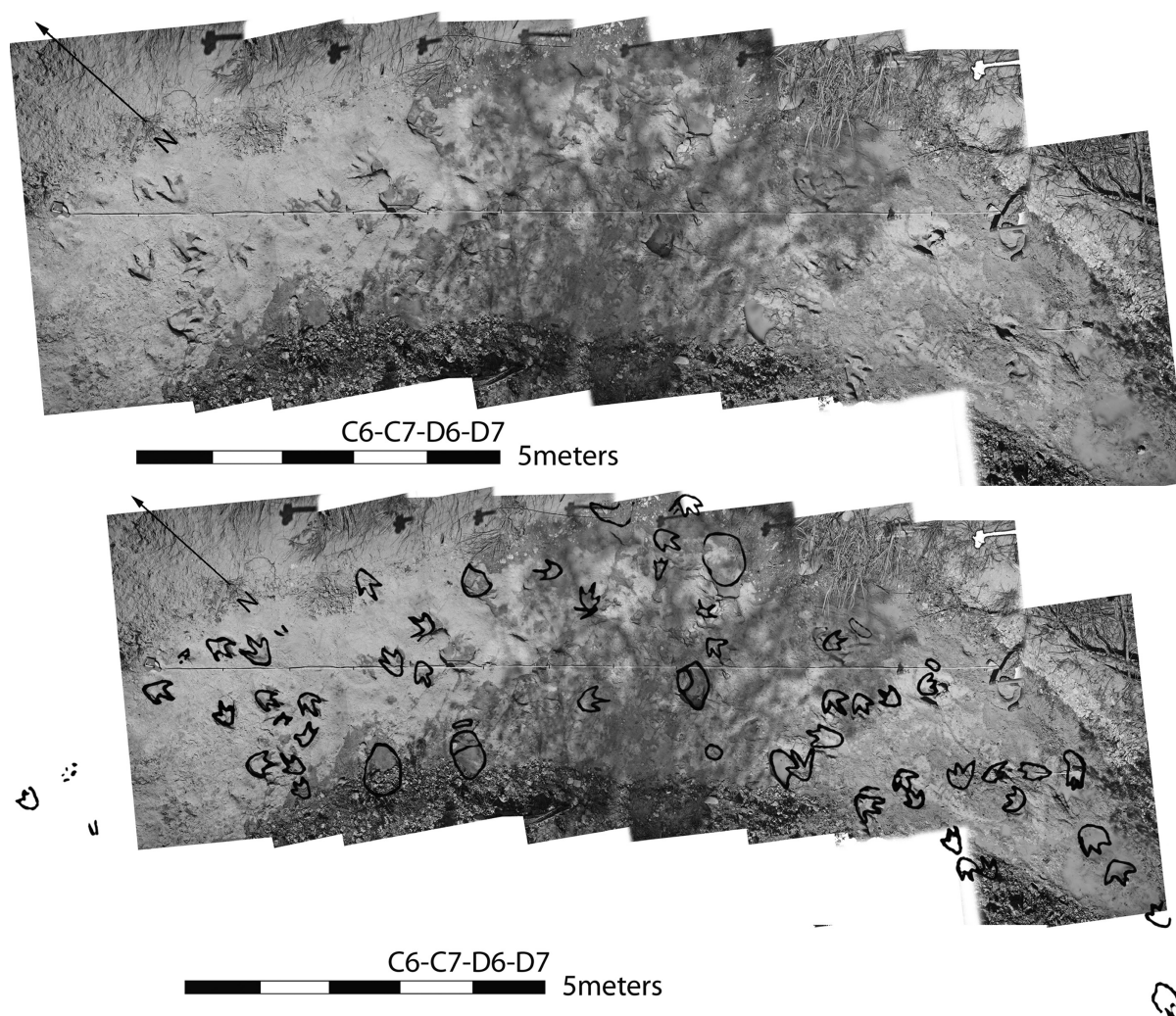


FIGURE 9. The Opossum Branch tracksite, exposed in the bed of a small tributary of the Paluxy River. The tracklayer is either the Main Tracklayer itself, or stratigraphically very close to it. A) Photomosaic of much of the tracksite surface. B) Map of footprints superimposed on the photomosaic.

Brontopodus the paradigm of “wide-gauge” sauropod trackways (Farlow, *et al.*, 1989; Farlow, 1992b; Wilson and Carrano, 1999; Wright, 2005; cf. Romano *et al.*, 2007; Marty *et al.*, 2010). Both manus and pes prints are rotated outward with respect to the trackmaker’s direction of travel. The pace angulation of pes prints is about 100-120°.

A plausible candidate for the *Brontopodus*-maker is *Paluxysaurus* (previously assigned to *Pleurocoelus*), known from skeletal (including pedal) material from stratigraphic units of about the same age, from the same region (Langston, 1974; Gallup, 1989; Rose, 2007). Another candidate is *Sauroposeidon* (Wedel *et al.*, 2000), but nothing is known of its pedal skeleton.

Tridactyl Footprints (Figs. 4C, 8D, 9, 10C, 12C, 14, 16-18)
With regard to three-toed footprints of bipedal dinosaurs, Paluxy River tracksites collectively constitute a natural

laboratory for investigating extramorphological effects of substrate conditions and trackmaker movements in creating a variety of footprint shapes from a uniform foot shape. Although some tridactyl prints in the Main Tracklayer are beautifully preserved, even showing traces of digital pads in the toemarks (Fig. 16B, F), most show some toe tip pinching, toemark collapse, or other plastic deformation. Toemarks are often roofed over, such that their lengths in surface expression are considerably less than their lengths as toe tunnels beneath the rock surface (Fig. 17J; when the river level is up, it is amusing to watch small fishes swim in and out of such dinosaur toe tunnels). Sometimes toemarks are indicated by little more than gashes extending forward from the footprint (Figs. 17, 18E). In some trackways the animal impressed portions of the metatarsal region of the foot (Figs. 17E, F, K; 18), either deliberately or inadvertently as the foot interacted with substrate condi-

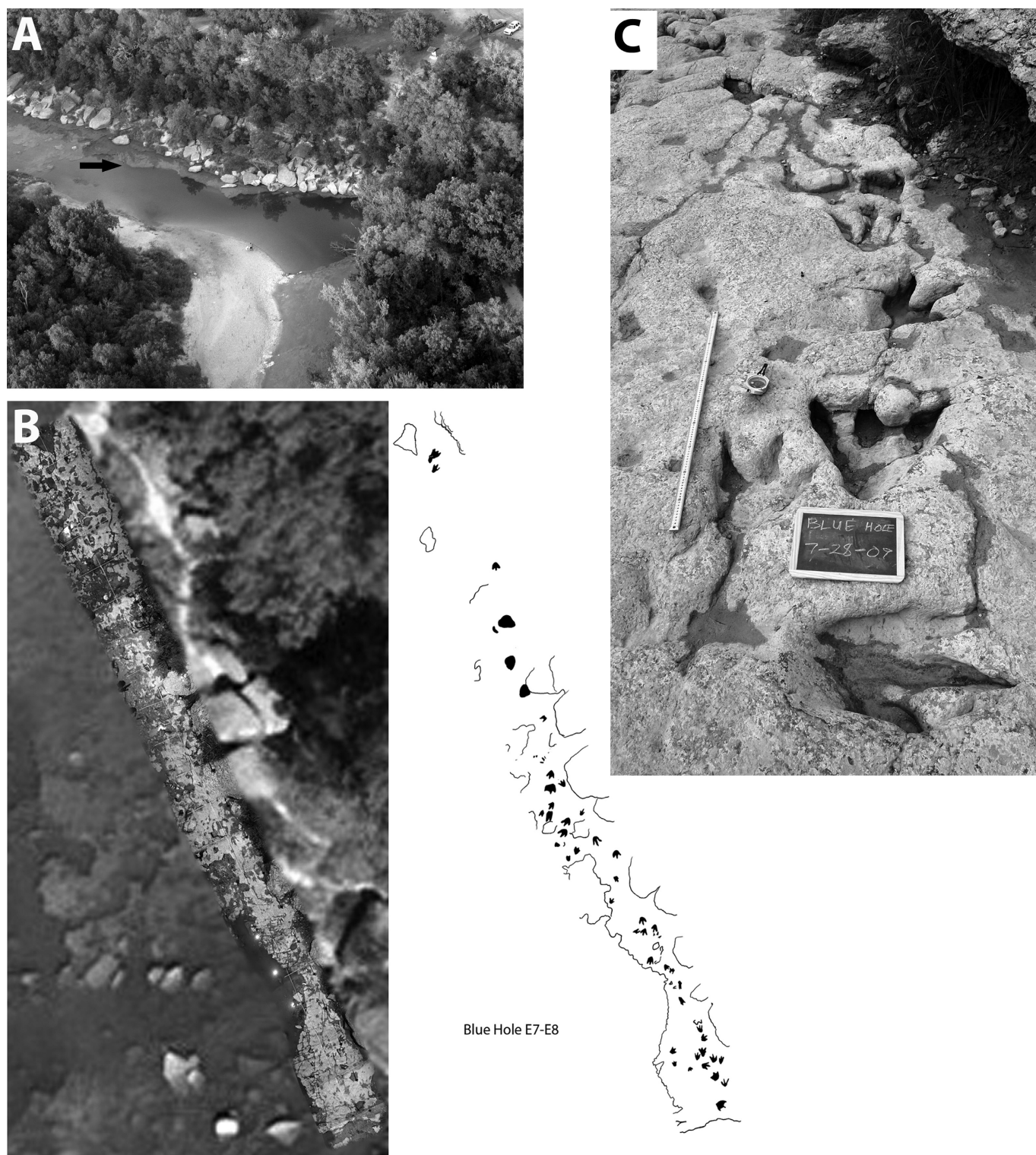


FIGURE 10. The Blue Hole, a popular swimming area at DVSP. A) Aerial photograph; upstream (south) toward the viewer. Black arrow indicates a ledge exposing the Main Tracklayer along the downstream side of the Blue Hole. B) Photomosaic and map (north to the top) of several dinosaur tracks exposed in the Main Tracklayer indicated by the arrow in panel A. C) Ground level oblique view of several typical Blue Hole Site tridactyl footprints.

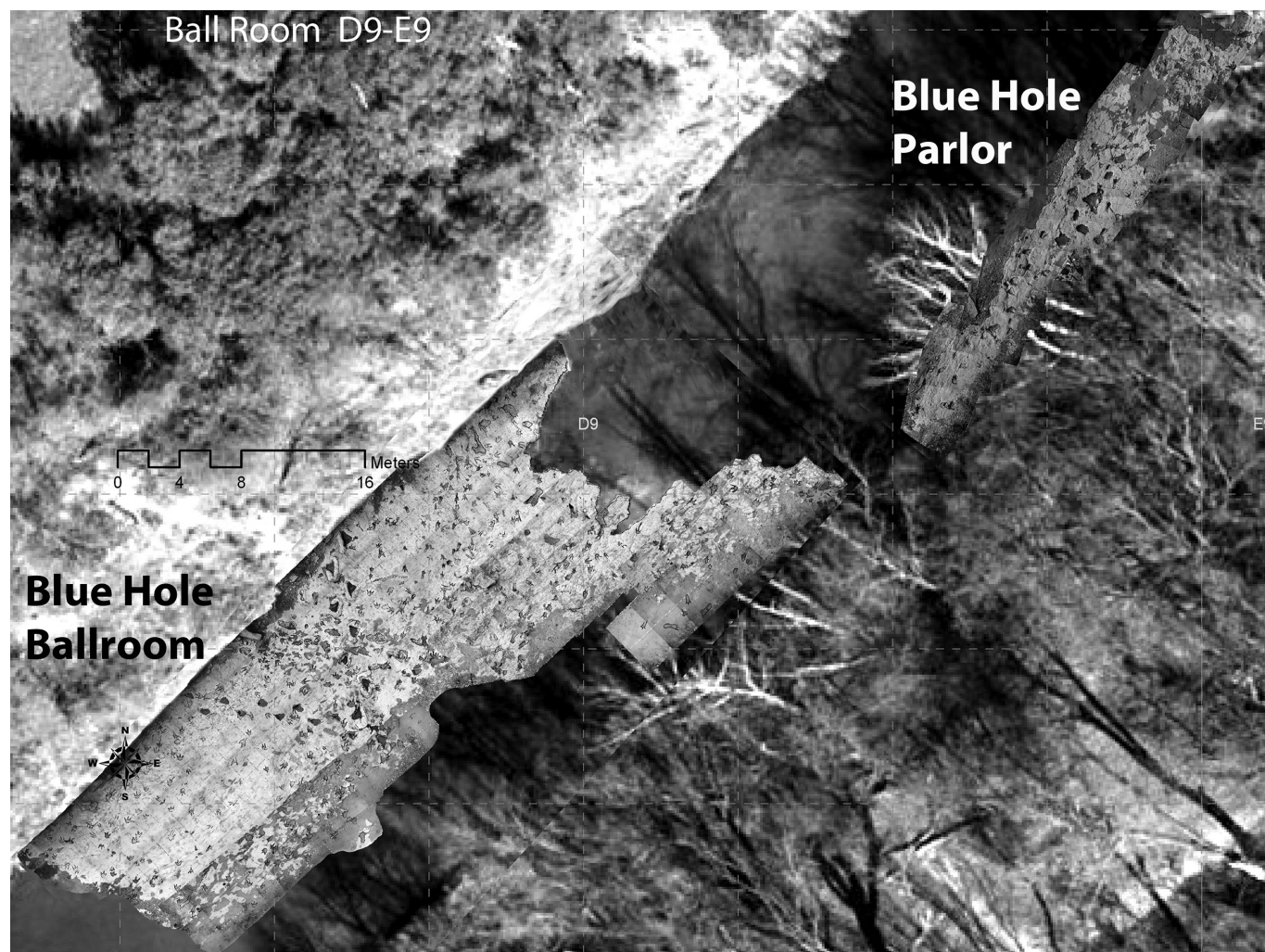


FIGURE 11. Aerial photograph showing location of the Blue Hole Ballroom and Blue Hole Parlor, two extensive exposures of the Main Tracklayer.

tions, making “elongate” footprints (Kuban 1986, 1989a; cf. Pérez-Lorente, 1993; Lockley *et al.*, 2003; Romero-Molina *et al.*, 2003; Romano and Whyte, 2003; Boutakiout *et al.*, 2009; Gierlinski *et al.*, 2009). These extramorphological features complicate anatomical interpretation of tridactyl prints. For example, toemark pinching, collapse, and/or roofing make toe marks in surface expression look shorter and blunter than they really are (Fig. 17H, L).

Those of the alleged Paluxy River “man tracks” that are not erosional markings or human carvings are elongate metatarsal tracks in which the digit impressions are subdued by one or more factors (infilling, erosion, toemark collapse), causing the remaining metatarsal portion to appear more human-like (Kuban, 1986, 1989a, b; Hastings, 1987); arguably such prints might be considered to be a footprint morphotype different from the more typical tridactyl prints. Although topographic expression of the toemarks is nearly lost in the “man tracks”, they nonetheless show triangular distal ends that suggest a tridactyl shape (Fig. 18C). Furthermore, as already noted, the toemarks

of some Taylor Site prints are accentuated by color differences between infilling material and the surrounding rock (Kuban, 1989b). Some color-delimited tridactyl prints at this site have positive relief relative to the surrounding rock (Fig. 17M; also see Fig. 16A, B for color differences between a well-preserved footprint and surrounding rock in the Main Tracklayer).

The best-preserved Paluxy tridactyls have long, narrow, pointed toemarks, with a slightly S-shaped digit III impression whose terminal end is medially directed (Fig. 16B, C, F). Typically they are 45-60 cm in total length. Footprints of this size and shape are consistent with having been made by a large theropod (Langston, 1974; Farlow, 1987, 2001; Pittman, 1989; Farlow *et al.*, 2006). A plausible candidate is *Acrocanthosaurus*, known from Lower Cretaceous rocks of Oklahoma and Texas (Stovall and Langston, 1950; Harris, 1998; Currie and Carpenter, 2000).

The skeletal fauna of the Trinity Group includes other bipedal dinosaurs (Winkler *et al.*, 1989). Conceivably some of the smallest Paluxy tridactyls could have been made by

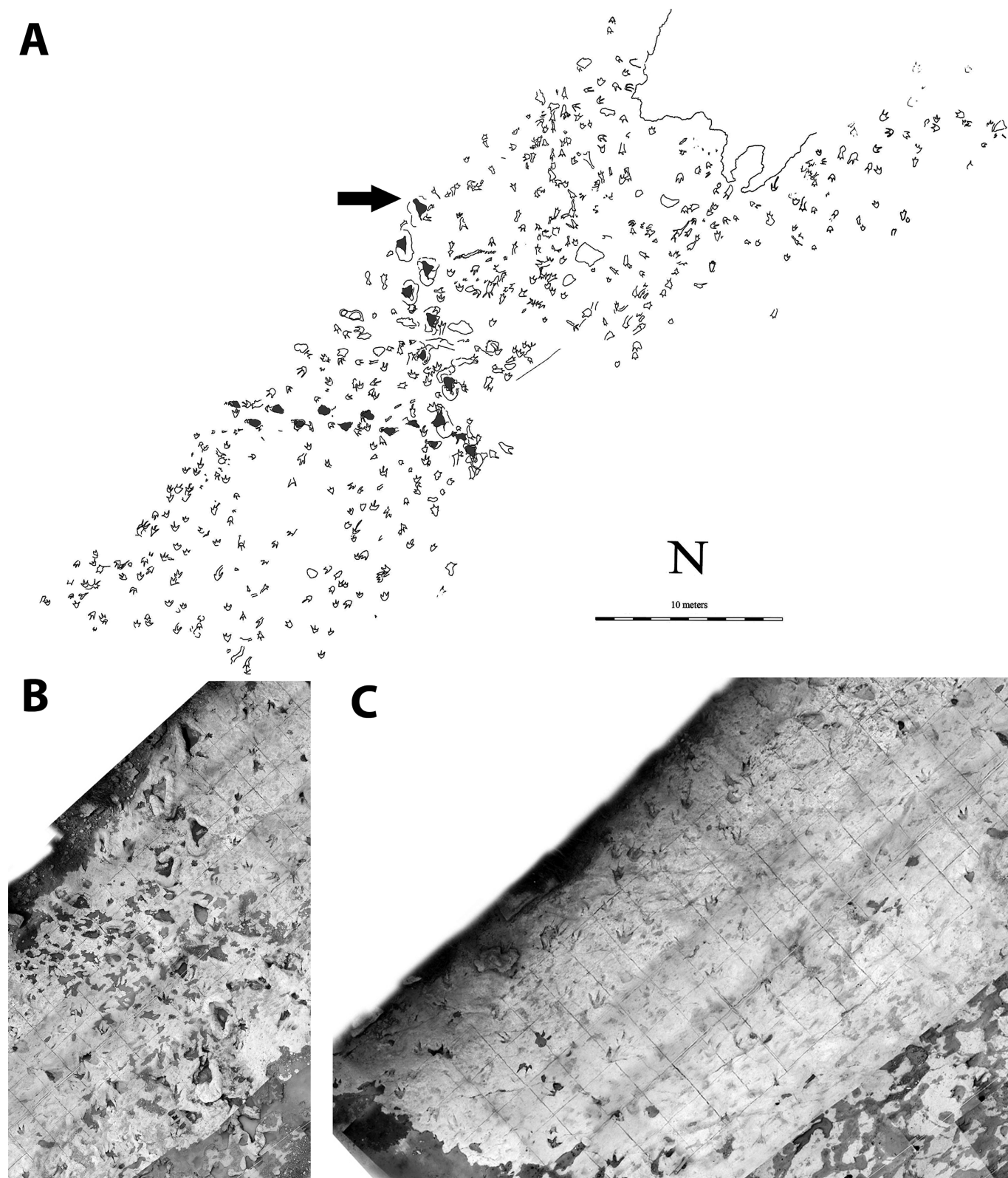


FIGURE 12. The Blue Hole Ballroom. A) Map of the tracksite; north to the top of the page. Black arrow indicates the beginning of the trackway of a large sauropod. A distinct trackway of a smaller sauropod (dark fill) crosses the trail of the bigger dinosaur near the end of the latter trackway, moving from east to west across the site. A second, less distinct trackway of a small sauropod crosses the trail of the large sauropod about midway along the latter's length. B and C) Details from a site photomosaic, marked off in a meter grid. B) Portion of the tracksite emphasizing the trail of the large sauropod. C) Southwest portion of the tracksite featuring numerous tridactyl footprints.

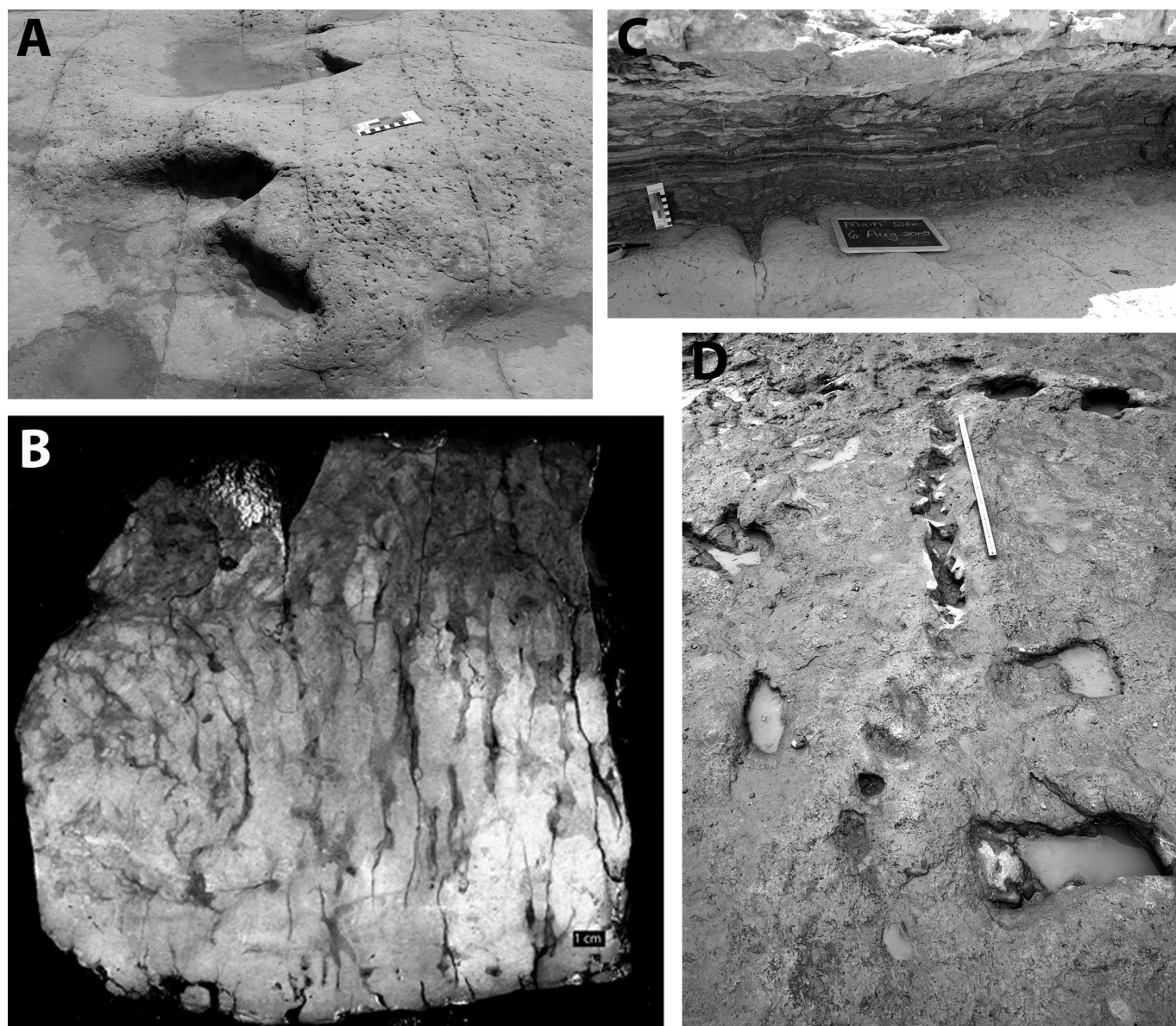


FIGURE 13. Sedimentary features associated with the Main Tracklayer. A and B) Vertical invertebrate burrows (cf. *Skolithos*). A) Tracklayer surface densely marked by burrow openings adjacent to tridactyl footprints, Bird Site; scale marked in cm. B) Vertical section through a sample of the Main Tracklayer (top of the layer upward), Blue Hole Parlor; 1-cm bar indicated in the lower right-hand portion of the photograph. Numerous vertical burrows (darker than the surrounding sediment) snake in and out of the plane of the cut. The left-hand portion of the section shows some distortion of bedding, possibly due to a dinosaur footprint. C) Contact between the Main Tracklayer and overlying beds, Main Tracksite; scale marked in cm. A tridactyl print is emerging from the riverbank. Note numerous pinprick vertical burrow openings dotting the tracklayer surface. D) Horizontal surface trace of a large invertebrate, or possibly a tool mark, Blue Hole Ballroom; a meter stick provides the scale.

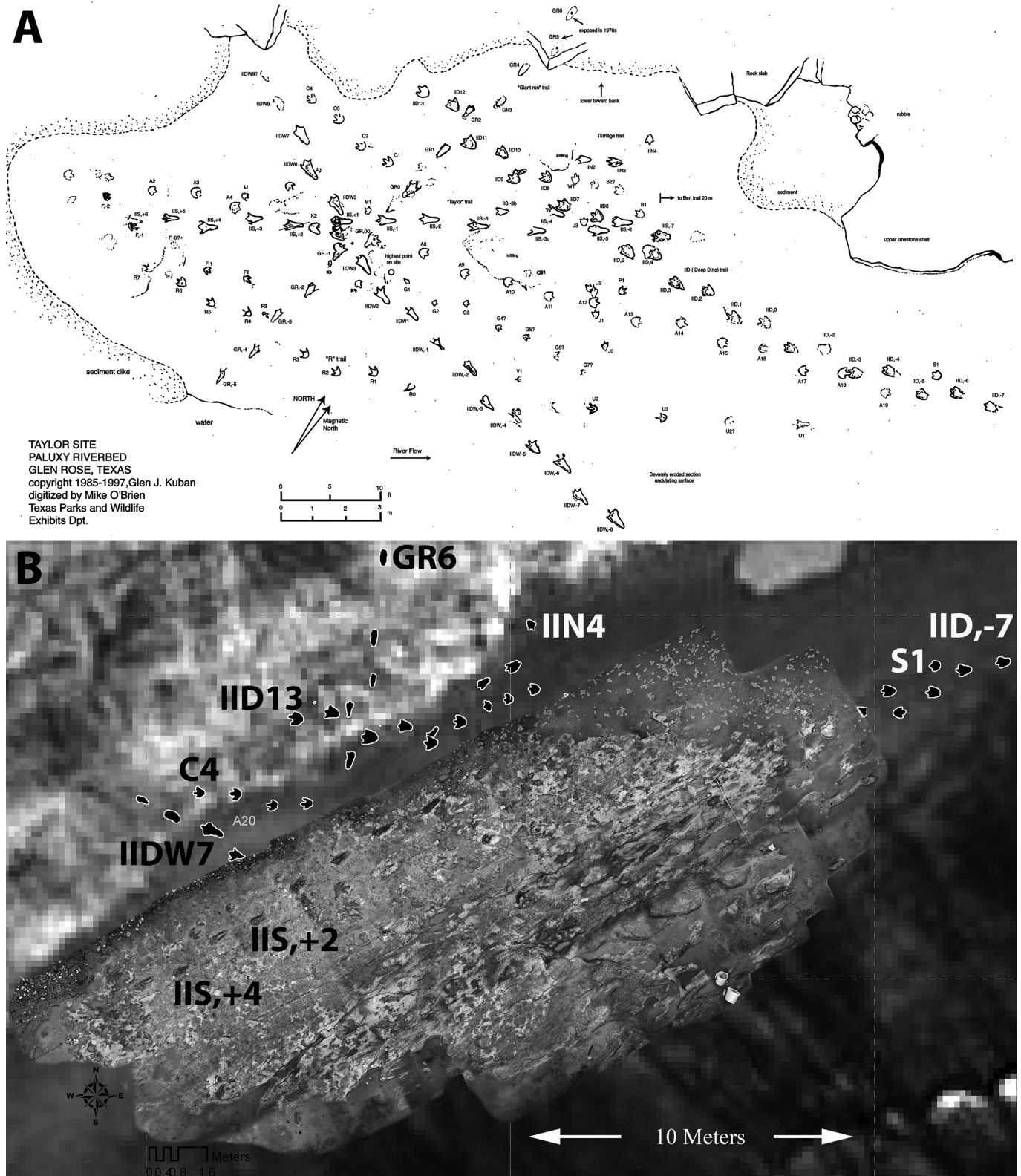


FIGURE 14. The Taylor Site, a footprint exposure stratigraphically several meters higher than the Main Tracklayer. A) Map of the site by Glen Kuban, with labels for individual footprints. B) Photomosaic of that portion of the tracksite recognized in 2009; numerous footprints mapped by Kuban in previous years were not seen. Some individual prints beyond the limits of the 2009 exposure, mapped by Kuban, are superimposed on the image. Footprint labels from Kuban's map are added to the photomosaic, which in this view is rotated about 30 degrees counterclockwise from Kuban's map.

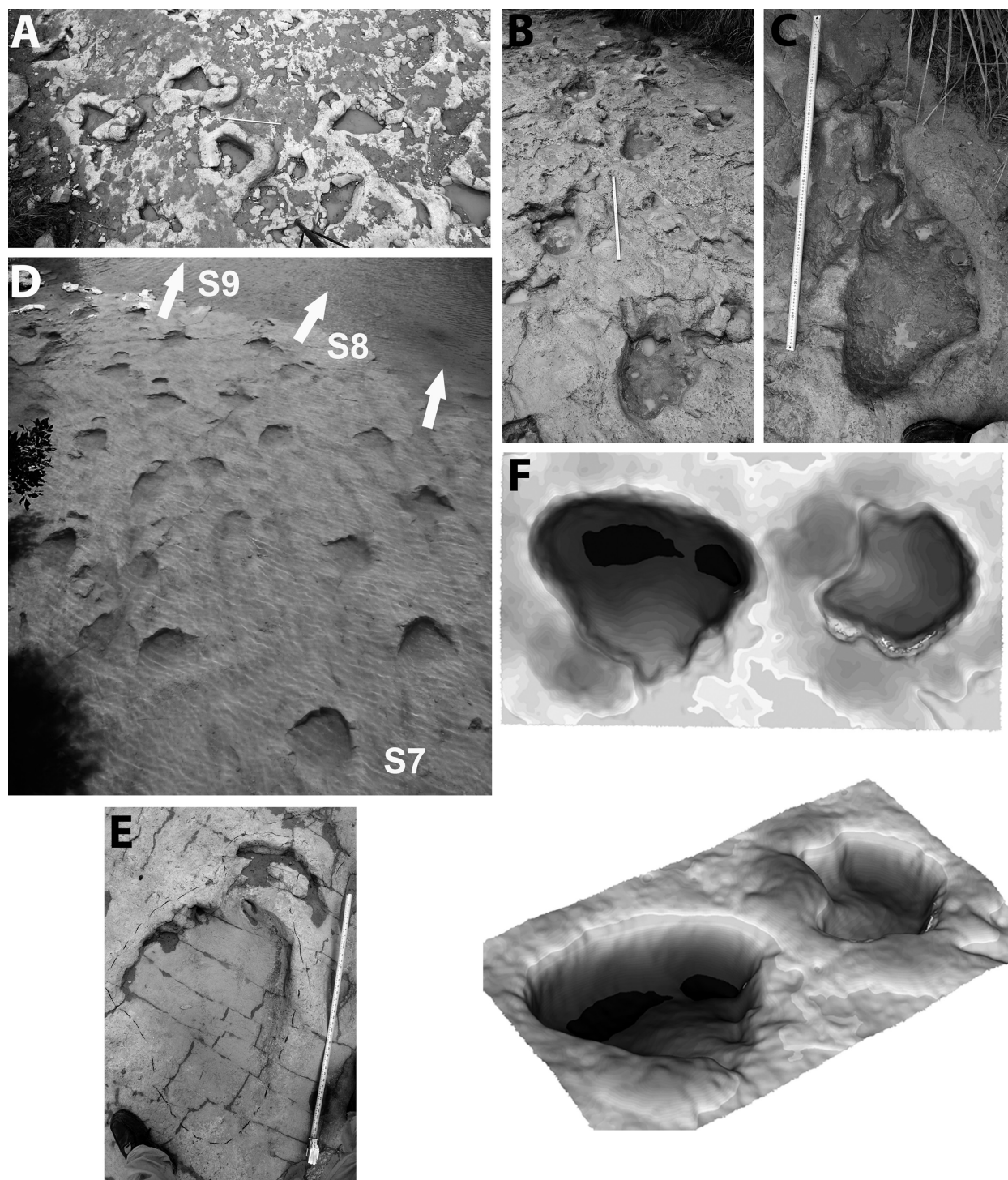


FIGURE 15. Sauropod footprints and trackways. A) Trackway of the large sauropod, Blue Hole Ballroom; meter stick provides scale. The animal was moving from left to right, with pes prints obliterating manus prints. B, C) Portions of the more distinct small sauropod trackway from the Blue Hole Ballroom; meter stick provides scale. B) Ground-level oblique view of the last several footprints in the sequence. C) Overhead view of the final right pes print (and possible deformed manus impression ahead of it?). D) View from an elevated platform of three sauropod trackways in the East Bank of the Bird Site (Fig. 5). White arrows indicate direction of travel of trackmakers. From left to right these are the “East” (S9; mean pes print length 76.5 cm), “Middle” (S8; mean pes print length 62.0 cm), and “Wet” (S7; mean pes print length 90.0 cm) sauropod trackways of Farlow *et al.* (1989: Table 42.2). Manus prints occur in trackways S8 and S9, but not trackway S7. E) Overhead view of left manus-pes set, West Bank Bird Site; tape exposes 1 m. F) Overhead and oblique LiDAR images of right manus-pes set S2M (trackway S2) from the American Museum trackway slab collected by R.T. Bird; pes print length about 87 cm. Shading indicates print depth, with darker shading indicating greater depth.

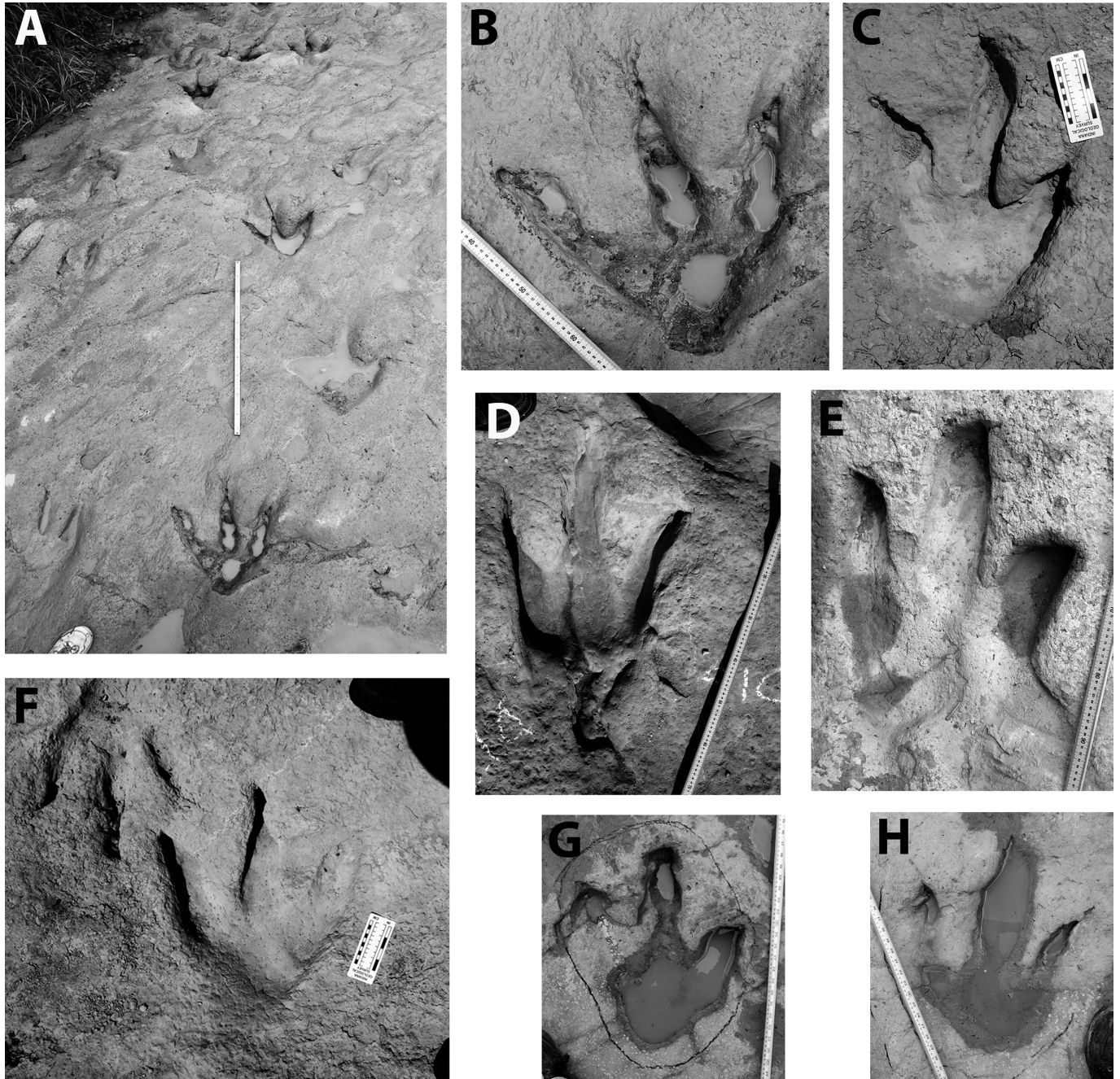


FIGURE 16. Well-preserved tridactyl footprints. A, B) Particularly well-preserved trackway, Blue Hole Ballroom A) Ground-level oblique view; meter stick provides scale. B) Overhead view of the splendid left print seen in the foreground of panel A; meter stick marked in 1-cm intervals. Note distinctly darker color of rock inside than outside the print. C) Print from Opossum Branch; scale marked in centimeter and inch intervals. D) Footprint with distinct hallux impression, south end of exposure area 2 of Main Tracksite. E) Large tridactyl, Blue Hole. F) Two very nice tridactyls, Opossum Branch. G, H) Somewhat distorted tridactyls, West Bank Bird Site.

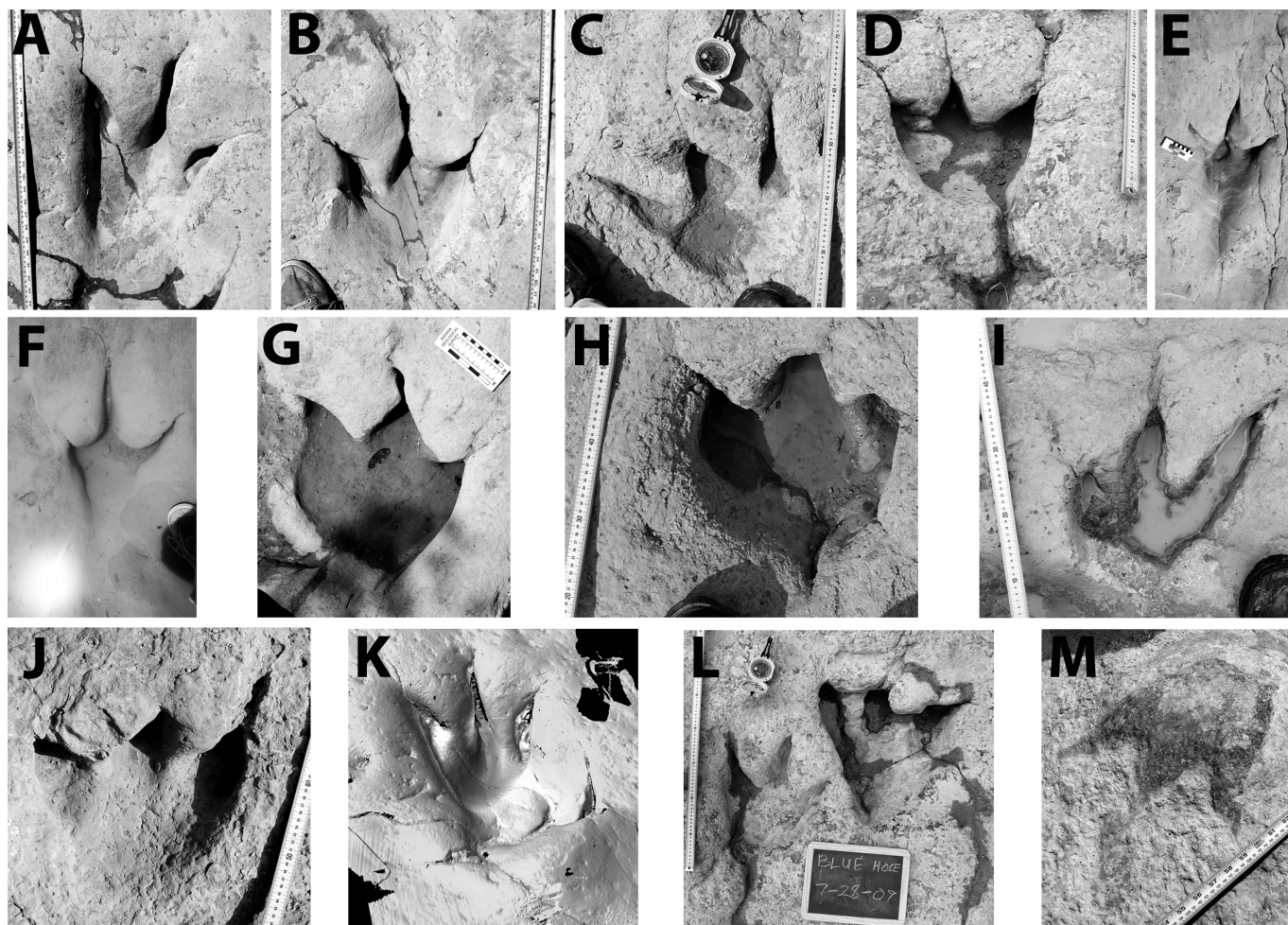


FIGURE 17. A-L), Moderately to greatly distorted tridactyl footprints, Main Tracklayer; scale in most panels provided by portions of a meter stick or tape marked in 1-cm intervals, or by a small scale marked in centimeter and inch, or only in centimeter, intervals. In all of these prints there is at least some pinching off or collapse of toe impressions. Some of the prints also show probable impressions of the metatarsal region of the trackmaker's foot. Footprints from Denio Branch (A, B, E, F, K), the Blue Hole (C, D, H, L), Opossum Branch (G), West Bank Bird Site (I), Main Tracksite (J). M). Tridactyl print from the Taylor Site. In contrast to prints from the Main Tracklayer, which are preserved as concave epireliefs, this print is preserved as a convex epirelief delimited from surrounding rock by darker color.

gracile ornithopods. Although some large tridactyls in the Main Tracklayer look ornithopod-like in surface expression (Fig. 17H), the complicating effects of sediment-foot interactions mean that at present there are no Main Tracklayer prints that can unambiguously be identified as having been made by large ornithopods. However, the A Trackway of the Taylor Site (Fig. 14A), preserved at a higher stratigraphic level than the Main Tracklayer, shows distinctly ornithopod-like prints over several steps, and may well have been made by an ornithopod.

Possible (but questionable) large ornithopod prints occur in the Upper Glen Rose Formation at a site in south Texas (Farlow *et al.*, 2006). Huge footprints possibly made by enormous ornithopods occur in clastic sedimentary rocks correlative to the Glen Rose Formation at a site in Comanche County (Farlow and Hawthorne, 1989).

Large theropod footprints from the Glen Rose Formation are generally similar to those of large theropods from other ichnofaunas around the world (Lull, 1953; Langston, 1974; Thulborn, 1990; Sanz *et al.*, 1997; Olsen *et al.*, 1998; Lockley *et al.*, 1998a, b; Lockley and Meyer, 2000; Farlow, 2001; Pérez-Lorente *et al.*, 2001; Lockley, 2002; Farlow and Galton, 2003; Moratalla *et al.*, 2003; Mossman *et al.*, 2003; Pérez-Lorente (Ed.), 2003; Weems, 2003; Day *et al.*, 2004; Farlow *et al.*, 2006; Rainforth, 2007; Lockley *et al.*, 2008). Shuler (1935, 1937) tentatively assigned the Paluxy River tridactyls to two species of the Early Jurassic Connecticut Valley ichnogenus *Eubrontes*; Langston (1974) suggested that the Early Cretaceous ichnogenus *Irenesauripus* might be more appropriate. Evaluating the ichnotaxonomy of Glen Rose Formation tridactyls is one of the long-term goals of the present project.

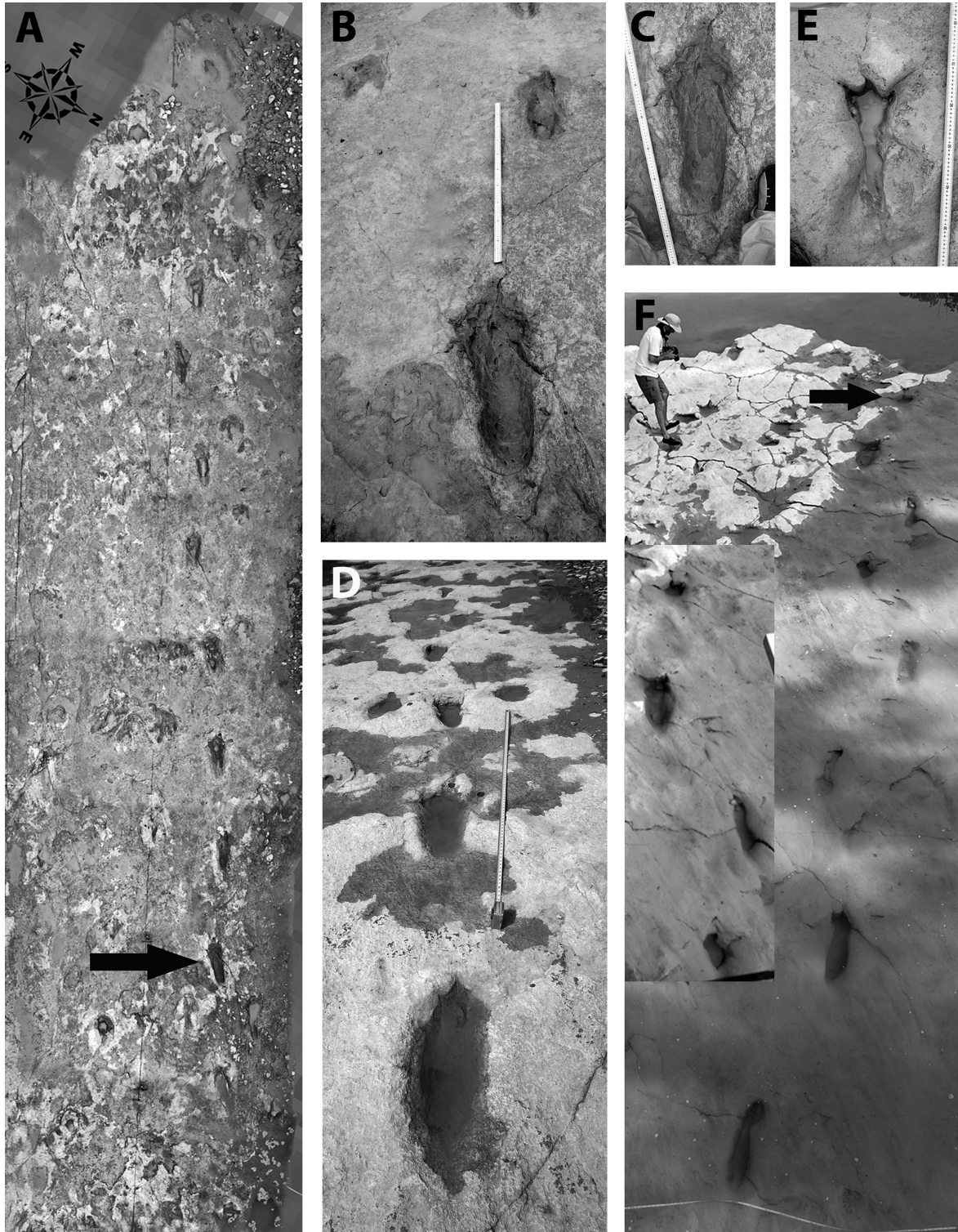


FIGURE 18. Trackways of “elongate” footprints. A-D) Trackway IIS, Taylor Site (Fig. 14). A) Photomosaic of the trackway; black arrow indicates print IIS,-3). B) Ground-level oblique view of print IIS,-3 and the following footprint in sequence, IIS,-2; meter stick provides scale. C) Overhead view of print IIS,-3. D) Ground-level oblique view further along the IIS trackway (IIS,-1 and following prints); the 2 m of exposed tape are adjacent to print IIS,+1). E) Print from the Blue Hole Ballroom. F) Final portion of elongate trackway from Denio Branch Site (Fig. 3A); human figure provides scale. Most of the footprints in this trackway show little indication of toe marks in the prints, but the final print (black arrow) is clearly tridactyl, as seen (inset) in the photograph from an elevated platform.

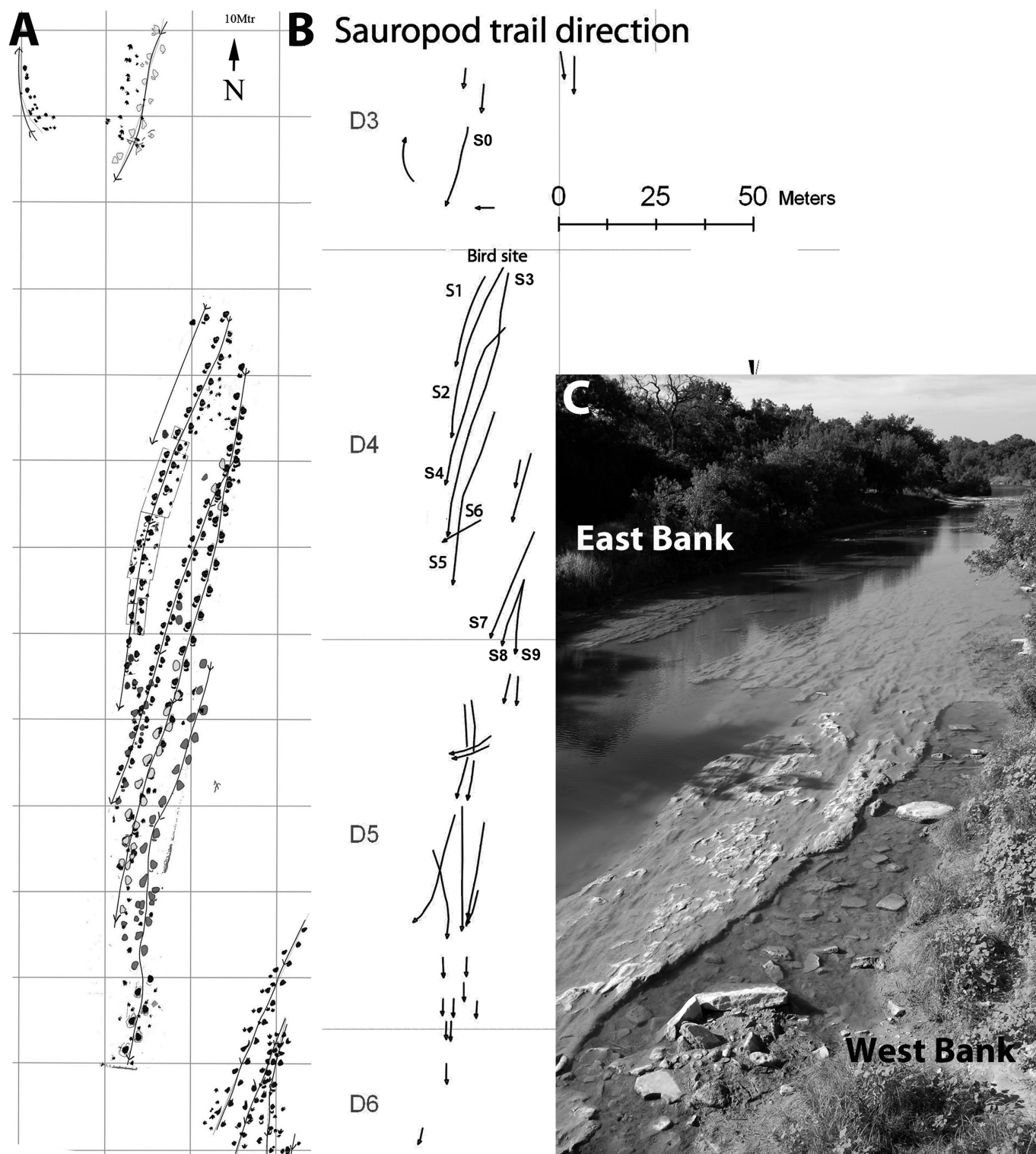


FIGURE 19. Direction of travel of sauropods, Main Tracksite and Bird Site (Figs. 4-6, 15D). A) Composite map of sauropod movements from Bird's 1942 Rye Chart (Farlow *et al.*, 1989) and our observations. Main Tracksite trackways are at the top, the West Bank of the Bird Site is in the middle, and the East Bank of the Bird Site is at the lower right. B) Sauropod movements summarized as arrows. Information is provided for the sauropod trackways illustrated in panel A, and also for trackways further to the south (upstream). Note the strong preference for southward movement by the sauropods. C) View of the Bird site, looking south (upstream). Location of Bird's 1940 trackway quarry in the immediate foreground.

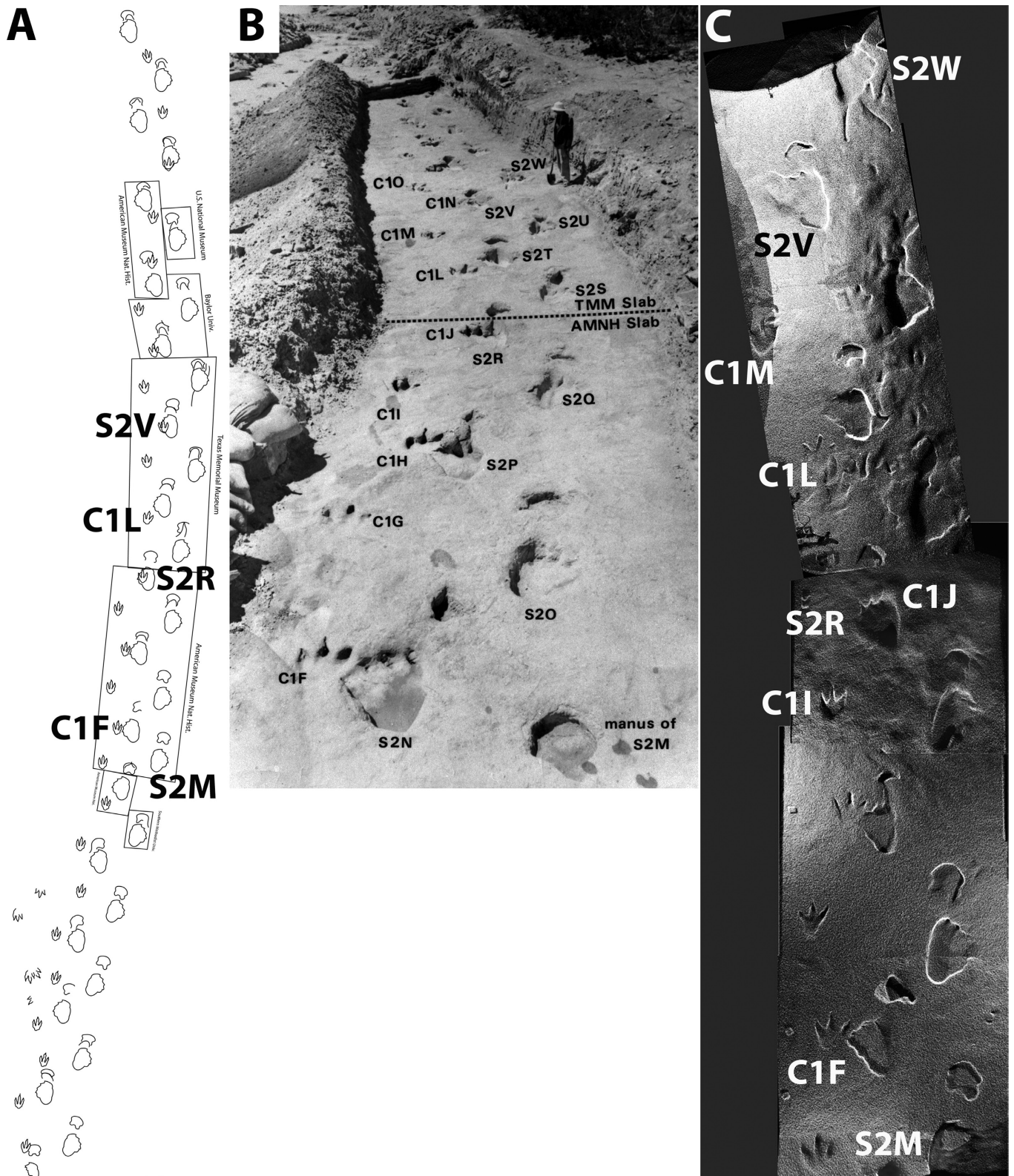


FIGURE 20. The AMNH-TMM theropod-sauropod chase sequence. A) Portion of the 1942 Rye chart showing the chase sequence, the two main trackway blocks collected for the AMNH and the TMM, and individual prints collected for other institutions. Selected key footprints of theropod C1 and sauropod S2 are labeled for comparison with other panels of this figure. B) One of Bird's photographs of the chase sequence; image used by permission of the AMNH. C) Composite LiDAR image of the American Museum (AMNH FARB 3065; cf. Bates *et al.*, 2009a) and Texas Memorial Museum (TMM 40638-1) trackway blocks.

WHAT WERE THE DINOSAURS DOING? PALEO-ECOLOGICAL AND BEHAVIORAL INTERPRETATIONS

The joint occurrence of sauropod and theropod footprints, particularly in coastal carbonate rocks, is a recurrent feature of dinosaur trace fossil assemblages (cf. Lockley *et al.*, 1994b; Pittman and Lockley, 1994; Dalla Vecchia *et al.*, 2000, 2001; Moreno and Pino, 2002; Marty *et al.*, 2003; Hunt and Lucas, 2007; Lockley, 2007; Marty, 2008; Petti *et al.*, 2008). However, given the huge sizes of the trackmakers, and the carnivorous diet of the theropod, it is unlikely that any of Paluxy trackmakers was restricted to the shoreline habitat in which their prints are preserved (Farlow, 1992b, 2001; Meyer and Pittman, 1994; cf. Dalla Vecchia *et al.*, 2000), and skeletal fossils of the likely trackmakers are known from more inland clastic facies (Stovall and Langston, 1950; Harris, 1998; Currie and Carpenter, 2000; Rose, 2007; cf. Wright, 2005; Mannion and Upchurch, 2010).

The homogeneous character of the Main Tracklayer suggests that it was deposited in a single event. The density of *Skolithos* burrows might provide a clue as to how long the muddy deposit that became the Main Tracklayer was exposed before burial. If the ichnofabric proves to have little sign of second-generation burrowing (e.g. vertical burrows that cut across older burrows), this will support the interpretation that the dinosaur track-making event(s) occurred over a relatively short time interval. In that event, the number of dinosaur trackways as a function of the size of tracklayer exposures might serve as a proxy for the local abundance of dinosaurs on the landscape (cf. Farlow *et al.*, 2010).

The Paluxy tridactyl prints and trackways show a mirror-image pattern of arrangement, with most heading generally northward or southward, in approximately equal numbers (Farlow, 1987), a commonly observed dinosaur tracksite pattern that suggests that trackmakers were moving back and forth along the local coastline (Lockley, 1991; Farlow *et al.*, 2006). This pattern provides no information about whether the theropod trackmakers were travelling singly or in groups. In marked contrast, the Paluxy sauropod trackways show a strong preference for moving southward (Fig. 19). This suggests that the sauropods were moving through the area as a herd (Farlow, 1987). The total number of animals in the hypothetical herd would have been greater than the number of sauropod trackways exposed in the riverbed, because modern lateral river erosion continually exposes new trackways, and how far away from the river valley dinosaur trackways occur in the Main Tracklayer (cf. Fig. 8) is unknown. If the sauropods were travelling in a group, at least some of them were not walking side-by-side, with one animal right beside its neighbor, because some of the sauropod trackways cross each other (Figs. 5, 12, 15D, 19). R.T. Bird (1954, 1985) believed that one or more of the large theropods was pursuing the sauropod herd, and that

the theropod in the AMNH-TMM trackway slab actually attacked the fleeing sauropod (Farlow, 1987; Thomas and Farlow, 1997). The theropod clearly walked across the site after the sauropod did, because the big carnivore's footprints are repeatedly impressed into the margins of the sauropod tracks (Fig. 20), as also occurs in other sauropod-theropod footprint associations at the Bird Site (Fig. 6C). Equally interesting, over much of the exposure of the two trackways, both the sauropod and the theropod trackway follow the same curving path, with the theropod trackway hugging the left edge of the sauropod trackway (Fig. 20). Bird's imagination was captured by a missing left footprint (which would have borne the label C1K) of the theropod that coincides with the shortest stride involving the right feet (from C1J [whose toemarks are only partially impressed in the front margin of sauropod pes print S2R] to C1L; Fig. 20) of the big carnivore. Bird concluded—and the late paleoartist David Thomas concurred—that at this point in the trackway the theropod had actually attacked the sauropod, only to be dragged off its feet by the forward motion of the much bigger herbivore (Bird, 1985:173; Thomas and Farlow, 1997). As the meat-eater took an involuntary forward hop, its left foot was unable to touch the ground, and so print C1K was never made.

Although we think it quite possible that the theropod was indeed closely following the sauropod, we are skeptical that Bird's putative hop actually occurred. Had the carnivore been pulled off its feet after partly impressing right print C1J, to come down on the same right foot to make print C1L, we would expect footprint C1L to be very unusual. There might be a spectacular skid mark as the theropod's right foot contacted the substrate as it swung forward. Given the weight of the theropod (Bates *et al.*, 2009b), print C1L would likely have been particularly deep, probably passing completely through the Main Tracklayer as many of the sauropod footprints do. Unfortunately, there seems to be nothing unusual about footprint C1L.

FOOTPRINT CONSERVATION

Once uncovered by the river, the footprints are ephemeral features. Exposures of the Main Tracklayer adjacent to Bird's 1940 quarry have been greatly reduced in size (Fig. 5); this and routine erosion have blurred or destroyed many of the footprints that Bird saw. Footprints that O'Brien, Kuban, and Farlow saw at the Main Tracksite in the 1980s have been lost (Fig. 4B). The Park Overlook site (which was positioned along the river between the Main Tracksite and Denio Branch Mouth Site), which in the 1980s contained a beautiful theropod trackway, is essentially gone. Although river erosion contributes to footprint destruction, an even greater threat is freezing of the rock surface during the winter time, if water levels are so low that the prints are exposed. At such times, the footprints shatter (Farlow, 1992a). As long as the river flows freely, there is a rough balance between the rate at which "old" tracks are effaced

by erosion, and “new” tracks are exposed by river action. A proposal in the 1980s to dam the Paluxy upstream from DVSP would have threatened this balance (Farlow, 1992a), but fortunately came to naught. For now, then, the dinosaur footprint resource at DVSP seems safe. However, the continued erosional loss of presently exposed footprints adds impetus to our goal of creating a database of tracksite information that can continually be updated.

Ironically, even some of the footprints collected by Bird are under threat. The portion of the “chase sequence” that Bird collected for the TMM (part of the type trackway of *Brontopodus birdi*; Farlow *et al.*, 1989) was not assembled inside the museum, but rather inside a small outbuilding on the museum grounds. The rock slabs were placed over a sand layer atop a concrete slab lying on the ground, with the building built around them. Since Bird’s time the porous rock of the Main Tracklayer has allowed moisture to seep up from below, causing weathering of the tracklayer surface, and gradual effacement of the footprints (Shelton *et al.*, 1993). Indeed, some of the footprints in this specimen that were still clear in the 1980s (Farlow, 1987) have now become indistinct. The cost of moving the huge specimen indoors is great enough to have made the TMM reluctant to do this. Furthermore, the little outbuilding has itself been designated a national historic landmark, causing some to regard the building as more significant than the dinosaur tracks it was erected to protect. Discussions are presently underway that may, however, lead to better conservation of the remaining footprints in this slab.

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APPENDIX

Billy Paul Baker. An Appreciation

Billy Baker was born on 6 July 1949, and died 4 November 2010. He is remembered for an exceptionally meritorious career with the Texas Parks and Wildlife Department as Park Superintendent at Dinosaur Valley State Park in Glen Rose. Billy's service of more than 37 years included respected roles in law enforcement, search and rescue, and numerous community organizations. Throughout this time, Billy was always intensely interested in the dinosaur tracks of the park, and was unstintingly generous of time and resources to further the research that made this paper possible. He will be missed by all who had the opportunity to know him.

