FIGURE 11. Large flute cast preserved *in situ* in mudstone below the main track-bearing sandstone at the SGDS east of Riverside Drive indicating a current direction 125° to the southeast. Note the *Eubrontes* track, which was obliterated by weathering of this unconsolidated surface within a few weeks after exposure.

Grallator) and common, roughly diamond-shaped (triclinic) salt crystal casts that may represent borate salts such as trona or perhaps a soluble sulfate salt. Only one large flute cast was observed *in situ* at the initial SGDS discovery site: upon turning over of a large block of the main track-bearing sandstone, it was noted that a mold of a large flute cast was preserved in the underlying mudstone, indicating a paleocurrent direction to the east locally (Fig. 11).

A scenario for the development of the MTL in the area of the museum building on the southeast side of Riverside Drive would be: 1) a mud flat was exposed near the side of Lake Dixie that, while drying, formed extensive mudcracks and served as a substrate into which dinosaur tracks were impressed, 2) water flooded across this area from the west, eroding this surface and exposing salt crystals in the firm mud, 3) additional dinosaurs then impressed tracks into the softer mudstone exposed in the scoured areas, and 4) sands covered the entire mudflat surface. Thus, at least two episodes of dinosaur track formation and preservation are recorded on the MTL at the base of the main track-bearing sandstone (Fig. 10).

Across Riverside Drive, to the northwest, the MTL preserves more evidence of scouring and fewer mudcracks, indicating the direction toward deeper water to the west. Invertebrate burrows and crawling traces are common here, as are dinosaur swim tracks (Milner et al., this volume b; Fig. 12). Tool-marks and crescent marks produced by plant fragments penetrating this surface are also common and indicate a northward paleocurrent in this area (Milner et al., this volume c).

Deeper water also appears to be documented to the east of the SGDS at Jensen Ridge (Fig. 2), where the main track-bearing sandstone capped a small area on the north end of the ridge. The MTL at this site preserves a scoured surface with tool-marks, large flute casts and no tracks. This distribution of sedimentary feature suggests that the exposed mudflats exposed in the area of the museum building may have

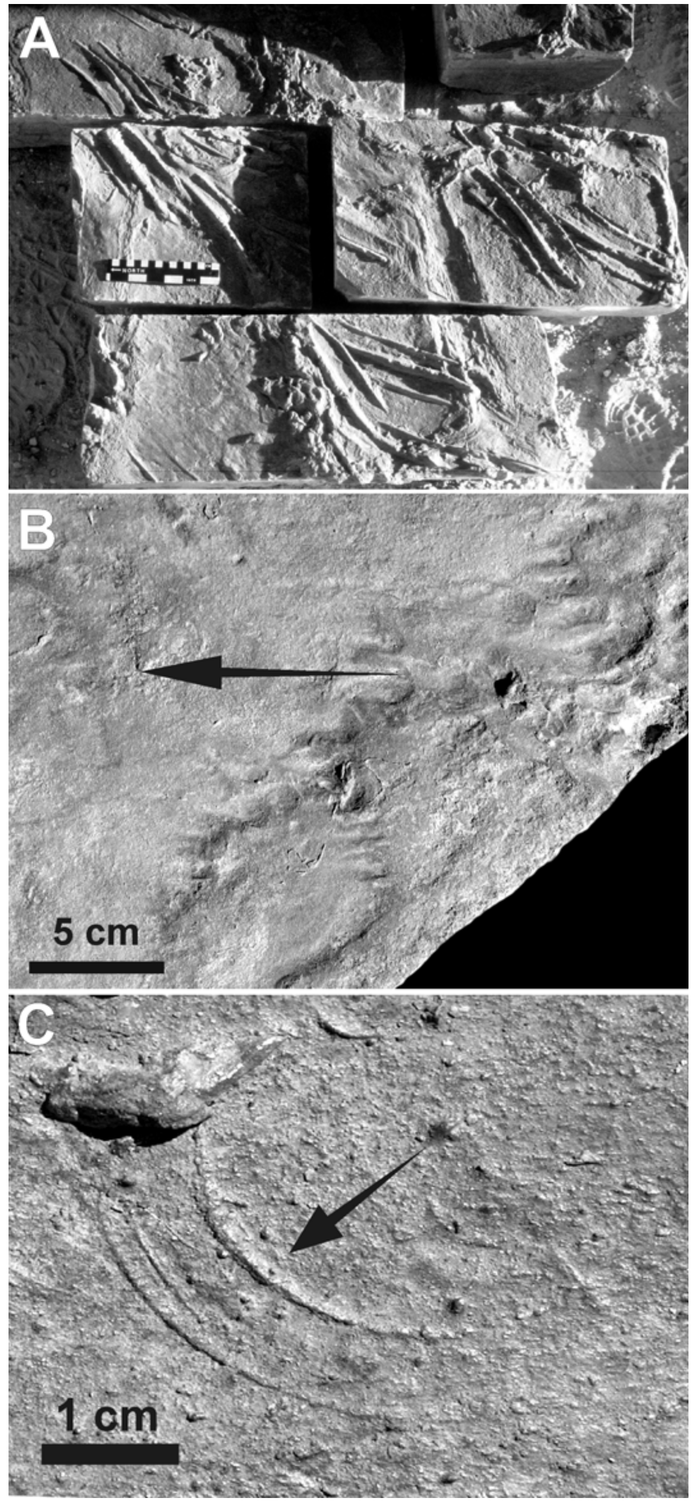

FIGURE 12. Sedimentary features preserved at the base of the main track-bearing sandstone northwest of Riverside Drive at the SGDS. **A**, Swim tracks from the main track-bearing layer (MTL) at the base of the main track-bearing sandstone west of Riverside Drive (SGDS.167). **B**, Flute casts from the MTL at base of main track-bearing sandstone west of Riverside Drive. **C**, Example of crescent structure formed by plant waving in current (scratch circle) (specimen number pending). Arrows indicate current directions.

been isolated from the actual shoreline of Lake Dixie, which is thought to be to the northeast.

At the SGDS museum, on the southeast side of Riverside Drive, a

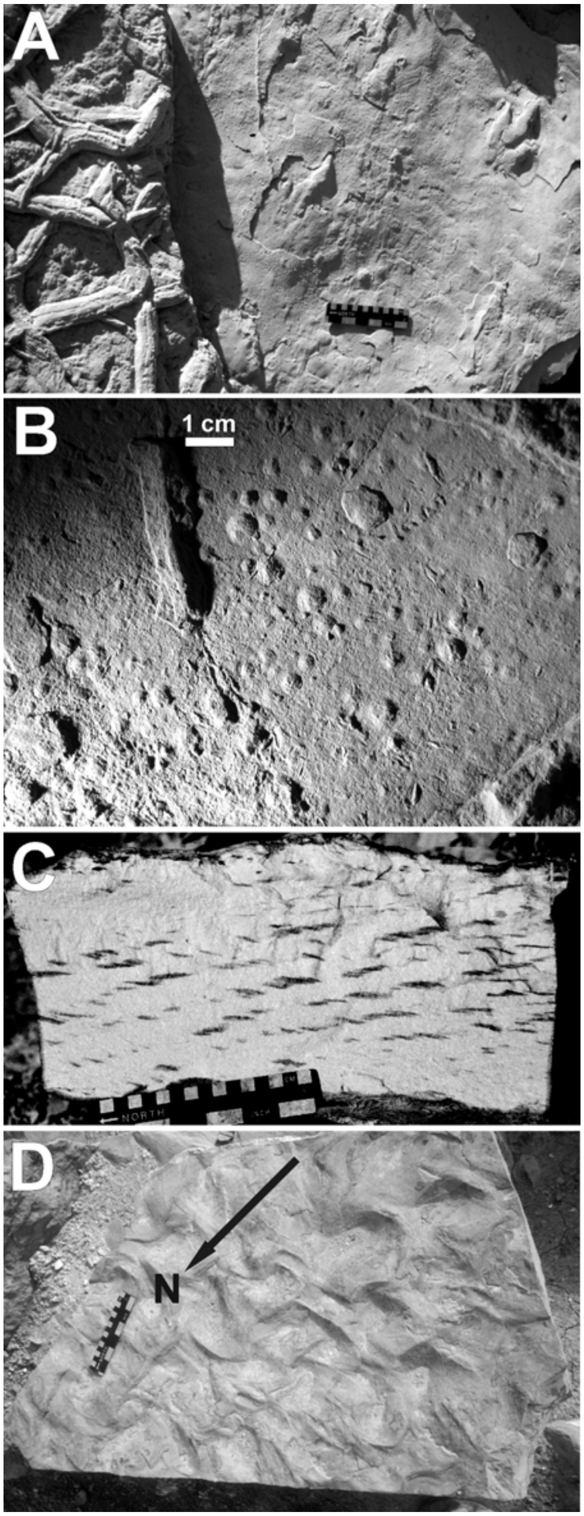

FIGURE 13. Sedimentary features preserved within the main track-bearing sandstone at the SGDS. **A**, Block showing the position of the "split layer" parting, with natural *Grallator* casts and asymmetric ripple marks about 10 cm above mudcracks preserved on the main track layer at the base of main track-bearing sandstone (specimen number pending). **B**, Close-up of the "split layer" parting surface with natural casts of rain drop impressions (SGDS.235). **C**, Cross-section of a portion of main track-bearing sandstone, displaying climbing ripple cross-bedding (SGDS.842). **D**, Interference ripples preserved on a major parting surface near the middle of the main track-bearing sandstone at the SGDS on the east side of Riverside Drive. Arrow points north.

parting referred to as the "split layer" by Milner et al. (this volume b) is developed about 10 cm above the MTL. The "split layer" preserves abundant small dinosaur tracks, invertebrate traces, and raindrop impressions (Fig. 13A, B). Fine puckering of the surface also suggests the presence of microbial mats and films binding the surface.

Internally, the main track-bearing sandstone preserves climbing ripple cross-bedding, indicating deposition under flowing water (Fig. 13C). Where partings occur, undulatory ripples are preserved (Fig. 13D). Although recognized across the entire area, the main track-bearing sandstone is cut completely away in small areas by later erosion, as discussed below. The main track-bearing sandstone typically varies from 10 cm to nearly one meter thick.

In the SGDS museum, a series of long ridges, spaced several meters apart and with as much as one-half meter of relief, are recognized at the top of the main track-bearing sandstone (Fig. 14). These ridges trend N70ºW. The relationship of the ridges and troughs to parting surfaces within the sandstone indicate that these are erosive megaripples formed by currents from the southwest crossing an initial sand bed about one meter thick (Reineck and Singh, 1975). The entire sandstone unit had been removed in one of the troughs between the erosive megaripples. Thin, ripple-marked sandstone beds 1-5 cm thick are present, mostly to the northeast of these megaripple crests, but also draping across them. These thin sandstone beds were formed from the sand eroded from the troughs between the megaripples. These thin sandstone beds are dominated by asymmetrical ripples demonstrating a southeast current direction, with fewer surfaces preserving either asymmetrical ripples indicating a northwest current direction or symmetrical wave ripples (Fig. 14). The northwest-southeast current directions indicated by the ripple-marks nearly parallel the crests of the erosive megaripples. Additionally, these thin ripple-marked sandstones preserve abundant dinosaur and crocodylomorph tracks together with relatively rare plant impressions (Fig. 15). Rill marks are also present, indicating water draining off this surface to the northwest (Fig. 14D) with microdeltas occasionally extending into the troughs from the sides of the megaripples.

The top surface of the main track-bearing sandstone (TS) is interpreted as a partially exposed beach, shoal, or spit along the coast of a large lake (Lake Dixie) that was being modified by waves impinging on it. The majority of the trackways mapped on the TS are directed either north or south (Milner et al., this volume b); because dinosaur trackways from other sites predominantly parallel ancient marine and lacustrine shorelines (e.g., Lockley, 1991), the shoreline is interpreted to also have been directed largely north-south. Therefore, the erosive megaripples preserved on the east side of Riverside Drive were formed at a high angle to the shoreline and may reflect the dominant angle at which large waves impinged on the shoreline, transporting sand along the shore. The smaller-scale, rippled sandstone beds preserved in the troughs and draped over the megaripples, together with other sedimentary structures, indicate that the megaripples focused water from smaller-scale waves onto the beach between the megaripples to the southeast. Subsequent drainage back off the beach was to the northwest, also between the megaripples. The predominance of asymmetric ripples indicating current directions to the southeast suggests that the dominant effect of sediment transport with "fair weather" waves was onshore. A simple model for the deposition of the main track-bearing sandstone is shown in Figure 14E.

One meter of reddish-purple shale overlies the main track-bearing sandstone (Figs. 9A, 16A). Near its base and middle, two thin volcanic ashes were recognized but proved to not be suitable for radiometric dating (B. Kowallis, personal commun., 2004). This shale also preserves partings that are covered with ostracodes (Schudack, this volume). The shale is, in turn, overlain by 70 cm of reddish-brown mudstone preserving disseminated ostracodes and conchostracan shells and isolated fish bones and scales (Fig. 3). These fine-grained sediments represent offshore lacustrine environments, and are penetrated from the top by sandstone-filled mudcracks up to 40 cm deep.

Where measured on the northwest side of Riverside Drive, a 65

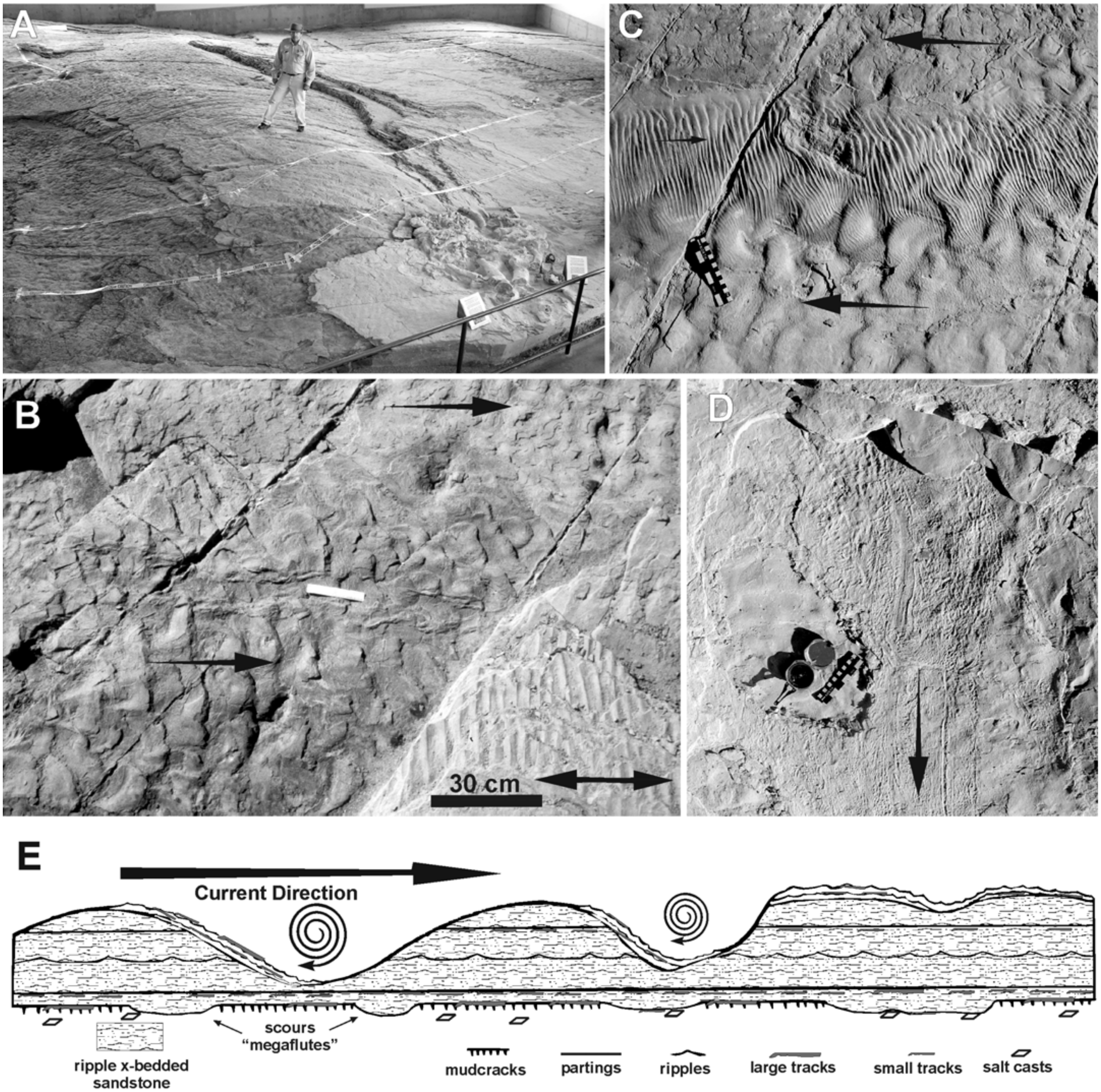

FIGURE 14. Sedimentary features preserved at the top of the main track-bearing sandstone at the SGDS in museum building (all SGDS.18). **A**, SGDS volunteer Monte Johnson standing on erosive megaripples at the top of the main track-bearing sandstone. **B,** Symmetric and asymmetric ripples on the top surface of the main track-bearing sandstone. Depressions represent poorly preserved *Grallator* tracks. Symmetrical ripple crests oriented N30ºE; joints directed N57°E. **C**, Large, northwest-directed, asymmetrical ripples superposed by small, northeast-directed, asymmetrical ripples on the north margin of the trough between the erosive megaripples. Joints directed N57°E. **D**, Branching rill marks formed by water draining NW, down the axes of troughs between the erosive megaripples. **E**, Model for the formation of the main track-bearing sandstone, based on Reineck and Singh, (1975, fig. 8), with the distribution of dinosaur tracks indicated.

cm thick, reddish-orange sandstone complex overlies these fine-grained strata; however, this sandstone pinches out to the south (Figs. 9, 16). The unit consists of four sandstone beds, each 10-25 cm thick and separated by mudstone partings. These sandstone beds preserve mudcracks and root casts with moderately well-preserved reptile tracks (*Eubrontes* and *Grallator* with rare *Anomoepus* and small quadruped tracks) on their upper surfaces (Fig. 16). This area is known as the Stewart-Walker Tracksite (SWS) (Milner et al., this volume b).

One of these surfaces preserves large depressions 25-60 cm across and 10-30 cm deep (Figs. 16B, D). These depressions were, at one point, thought to perhaps represent sauropod tracks, although the site is much older than any strata in North America preserving any tracks or body fossils of large sauropods. It has been proposed that perhaps these "pot holes" represent depressions made by fish nesting in the shallows, given their close association with fish swim traces (*Undichna*) on the same bedding surface. In at least one of these "pot holes," ripple marks indi-

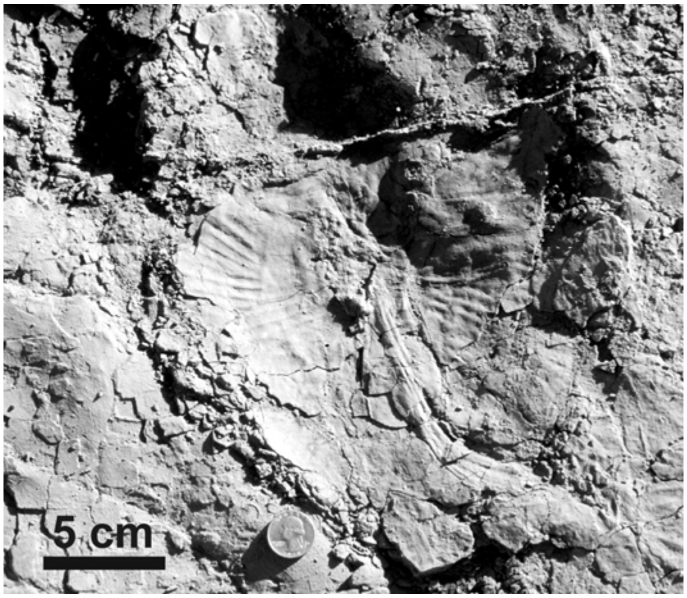

FIGURE 15. Unidentified plant impression preserved in a large *Eubrontes* track on the top surface of main track-bearing sandstone. This specimen is now preserved only as a cast at the SGDS (SGDS.913).

cate a subaqueous environment. These sandstones are interpreted as representing sand deposited near the lake margin.

These track-bearing sandstones are, in turn, overlain by 1.25 m of reddish-brown mudstone with scattered, thin layers of fine-grained sandstone (Fig. 3). These beds are lithologically similar to those at the contact between the Dinosaur Canyon and Whitmore Point members.

This intermixing of sedimentary features that indicate both subaerial and subaqueous environments documents significant lake level rise and fall during this interval of Whitmore Point Member deposition.

Middle Sandstone Dominated Interval

The next 7.64 m of section is characterized by interbedded, reddish-brown sandstone and mudstone (Fig. 17). The sandstones are much like those in the upper part of the Dinosaur Canyon Member in that they preserve mudcracks and dinosaur tracks and are internally ripple cross-bedded. However, these sandstones tend to be less well cemented, and the tracks are not quite so well preserved (e.g., the LDS Tracksite; Williams et al., this volume) (Fig. 17D). Invertebrate burrows are particularly abundant in this interval (Lucas et al., this volume b), along with common bones, fish scales and coprolites (Williams et al., this volume).

As with most of the ripple-bedded sandstones preserving tracks in the upper Dinosaur Canyon Member, these sandstones are interpreted as representing lake margin sand deposits emplaced by longshore currents. The sand entered the margin of the lake system outside the study area via fluvial channels presumably similar to those preserved in the lower part of the cliff-forming portion of the Dinosaur Canyon Member. Waves impinging on these sediments would have transported them laterally along the shore to some point where they were at equilibrium with overall energy conditions along the lakeshore.

Other outcrops of this interval of the Whitmore Point Member examined in the St. George area preserve notably less sandstone than to the west of Riverside Drive at the SGDS. The limited aerial extent of these sandstones at the SGDS suggests that they may represent an isolated spit or shoal that was only developed in the immediate vicinity of the SGDS.

Upper Shale Dominated Interval

The uppermost 6.55 m of the Whitmore Point Member consist of thin-bedded shale, siltstone, and fine-grained sandstone with minor, thin beds of limestone. This sequence consists mostly of coarsening upward cycles ~20-50 cm thick; each cycle is characterized by shale at its base containing fossil fish, conchostracans, and ostracodes, and capped by sandstone preserving algal laminae, stromatolites, mudcracks, mostly isolated bones and teeth, and locally abundant dinosaur tracks made up exclusively by *Grallator* (Figs. 18, 19). This bedding pattern may represent climatic cycles as are frequently reflected in finer-grained lacustrine facies. Other, less common features, such as sandstone dikes and soft sediment deformation features, also occur (Fig. 18).

Natural exposures of the upper shale interval northeast of Riverside Drive were relatively poor prior to preparation of the site for construction of Fossil Ridge Intermediate School. This process led to the development of low relief, clean exposures of these sediments on which we observed subtle sedimentary features such as mudcracks and poorly preserved dinosaur tracks (Fig. 18). Additionally, a great many vertebrate fossils were found (Kirkland et al., 2005; Milner et al., 2005; Milner and Lockley, 2006; Milner and Kirkland, this volume). Of particular interest was a sandstone bed near the top of the interval that preserved large bones, including many skull elements from large coelacanths (Milner and Kirkland, this volume) and isolated bones and teeth of theropod dinosaurs (Fig. 3). While the site preserving the dinosaur fossils has been set aside by the Washington County School District for further research, Fossil Ridge Intermediate School overlies most of these interesting strata. Attempts are underway to acquire additional acreage to preserve a large area of undeveloped properties to the east and south of Fossil Ridge Intermediate School and adjacent to the SGDS.

Many of the fossil vertebrates preserved in this interval are coated by reddish siderite concretions. They range from small, flat disks about one centimeter across, formed around isolated ganoid fish scales, to large masses tens of centimeters across, surrounding concentrations of isolated scales and bone (Fig. 20) and, in some cases, large, articulated fish. Some of these accumulations are unusual in being circular in cross-section and more than a meter long; they frequently contain concentrations of fish fossils and are thus referred to as "fish sticks" (Chin et al., 2003; Milner et al., 2005). The "fish sticks" are superficially similar to the chert-replaced tufa preserved at the base of the Whitmore Point Member and are currently under study by Karen Chin (University of Colorado).

Continued construction in the St. George area temporarily exposes new outcrops of the upper shale interval of the Whitmore Point Member. One particularly interesting exposure is below West Black Ridge (below the airport), along Bluff Street near 700 South, and is known as the "Dixie Lube Site." At this site, a vertical exposure of the upper Whitmore Point Member to lower Springdale Sandstone Member of the Kayenta Formation is visible (Fig. 19). Thin sandstone beds are exposed at the top of the Whitmore Point Member below the scoured surface at the base of the coarser-grained sandstones of the Springdale Sandstone.

At the SGDS, the Springdale Sandstone unconformably overlies fine-grained lacustrine sediments of the Whitmore Point Member. Elsewhere, such as at the Dixie Lube Site (Fig. 19) and at Zion National Park, fine-grained sandstone beds are present below this unconformity and may represent sand accumulating along the margin of a shrinking Lake Dixie. Although commonly mapped with the Springdale Sandstone Member of the Kayenta Formation, these sandstones are genetically part of the Whitmore Point Member of the Moenave Formation.

Springdale Sandstone Member, Kayenta Formation

At the SGDS, the overlying Springdale Sandstone lies on an erosional surface with a meter or more of relief and represents the J-sub K (J-0') unconformity of previous authors (e.g., Blakey, 1994; Marzolf, 1994; Lucas and Tanner, this volume). Locally, large clasts (10 cm and greater in diameter) of Whitmore Point lacustrine sediments are present in the basal Springdale Sandstone above this unconformity.

As nearly as can be determined, the Springdale Sandstone was measured herein close to the same path as Higgins and Willis (1995), who

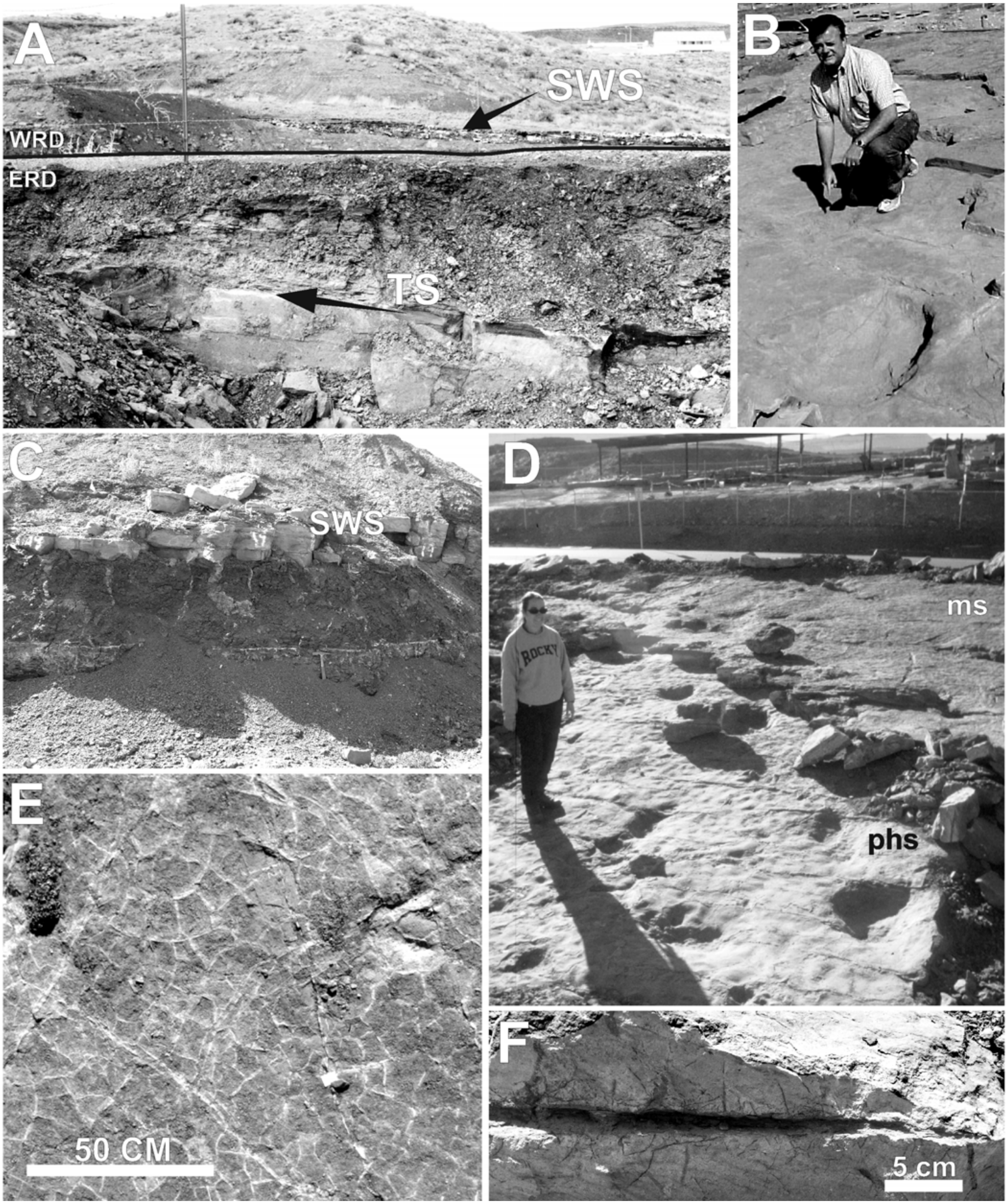

FIGURE 16. Sediments overlying the top of main track-bearing sandstone. **A**, Exposure on the east side of Riverside Drive in 2000 (fine-grained sediments have subsequently been removed from above the main track-bearing sandstone across the entire area). View to the west across Riverside Drive. **B**, Darcy Stewart by a "pot hole" (possible fish nesting structure) at the Stewart-Walker Tracksite on the east side of Riverside Drive. **C**, Close-up of sediments overlying the main track-bearing sandstone on the west side of Riverside Drive. The top surface of the main track-bearing sandstone is approximately at bottom of photograph. Rock hammer for scale. **D**, Upper sandstones at the Stewart-Walker Tracksite. **E**, Surface of the uppermost, mud-cracked sandstone at the Stewart-Walker Tracksite. **F**, Rhizolith in sandstone fill taken from the "pot hole" in **B** (SGDS.915). Abbreviations: ERD, east side of Riverside Drive; ms, uppermost mud-cracked sandstone; phs, sandstone with large "pot-hole" structures that may be fish nesting structures; SWS, upper sandstones preserving the Stewart-Walker Tracksite on the west side of Riverside Drive; TS, top surface of main track-bearing sandstone; WRD, west side of Riverside Drive.

FIGURE 17. Middle sandstone interval of Whitmore Point Member of the Moenave Formation west of Riverside Drive. **A**, Former construction site of the present-day Fossil Ridge Intermediate School exposing the middle sandstone interval. **B**, Resulting exposure of the middle sandstone interval from the northwest. **C**, Same exposure from the west. **D**, LDS Tracksite near the top of the middle sandstone interval. Abbreviations: bs, base of middle sandstone interval; ts, top of middle sandstone interval.

measured a total thickness of 35 m as compared to 27.85 m measured by us. The Springdale Sandstone is mostly pale yellowish-brown and stands out in contrast to the dominantly red to mauve-colored sediments above and below it (Fig. 21). It is a medium- to coarse-grained, 0.5-1.0 m scale, planar and trough cross-bedded fluvial sandstone with minor, discontinuous mudstone partings. Chert pebbles are locally concentrated at the bases of some of the larger cross-bed sets. Small amounts of petrified wood, including large logs, are also present in this member. Where the Springdale Sandstone was measured below Middleton Black Ridge, a couple of thin (2 cm) dikes (veins) of possible igneous material were observed in joints (Fig. 21B). The Springdale Sandstone represents an extensive braided river system that developed across southwestern Utah and north-central Arizona. Because it is well cemented, the Springdale Sandstone Member serves as a stable substrate for many of the homes that have been constructed east of the SGDS.

The lower, unnamed member of the Kayenta Formation conformably overlies the Springdale Sandstone (Higgins and Willis, 1995). The lower unnamed member is dominantly fine grained near its base and appears to represent a large lacustrine unit. Ganoid scales are present in these sediments at Zion National Park (DeBlieux et al., 2004, this volume). The uppermost Springdale below this contact consists of sheet sandstones with ripple marks interpreted to represent the fluvial Springdale reworked into lake margin deposits (Fig. 21). Dinosaur tracksites are common along this contact in the St. George and Zion National Park area (Miller et al., 1989; Smith et al., 2002; DeBlieux et al., 2004, this volume; Hamblin, 2006; Hamblin et al., this volume; Lockley et al., this volume). The abundance of dinosaur tracks at the top of the Springdale Sandstone Member apparently extends southeast to Tuba City, Arizona and has been referred to as the Springdale Megatracksite (Lucas et al., 2005a).

CONCLUSIONS

Lower Jurassic strata in the St. George area have received little attention, but the ongoing and rapid development of the region has provided, and is providing, numerous excellent, although short-lived, exposures that provide excellent research opportunities. The numerous dinosaur track sites preserved at the SGDS are all preserved in marginal and shallow lacustrine paleoenvironments, as indicated by the intimate association of mudcracks, ripple marks, and ripple cross-bedding. Additionally, the interbedding of coastal and shallow lacustrine facies indicates that lake levels fluctuated considerably over relatively short time spans, reflecting alternating periods of drought and high rainfall; larger time spans perhaps reflect climatic cycles.

The main track-bearing sandstone in particular preserves a complex history of rising and falling lake levels. The large-scale scours and erosive megaripples (Fig. 14) provide direct evidence of large waves supporting the hypothesis that Lake Dixie was a large lake that may have extended across the entire Whitmore Point outcrop belt when lake levels were high.

Although the present research provides considerable new data

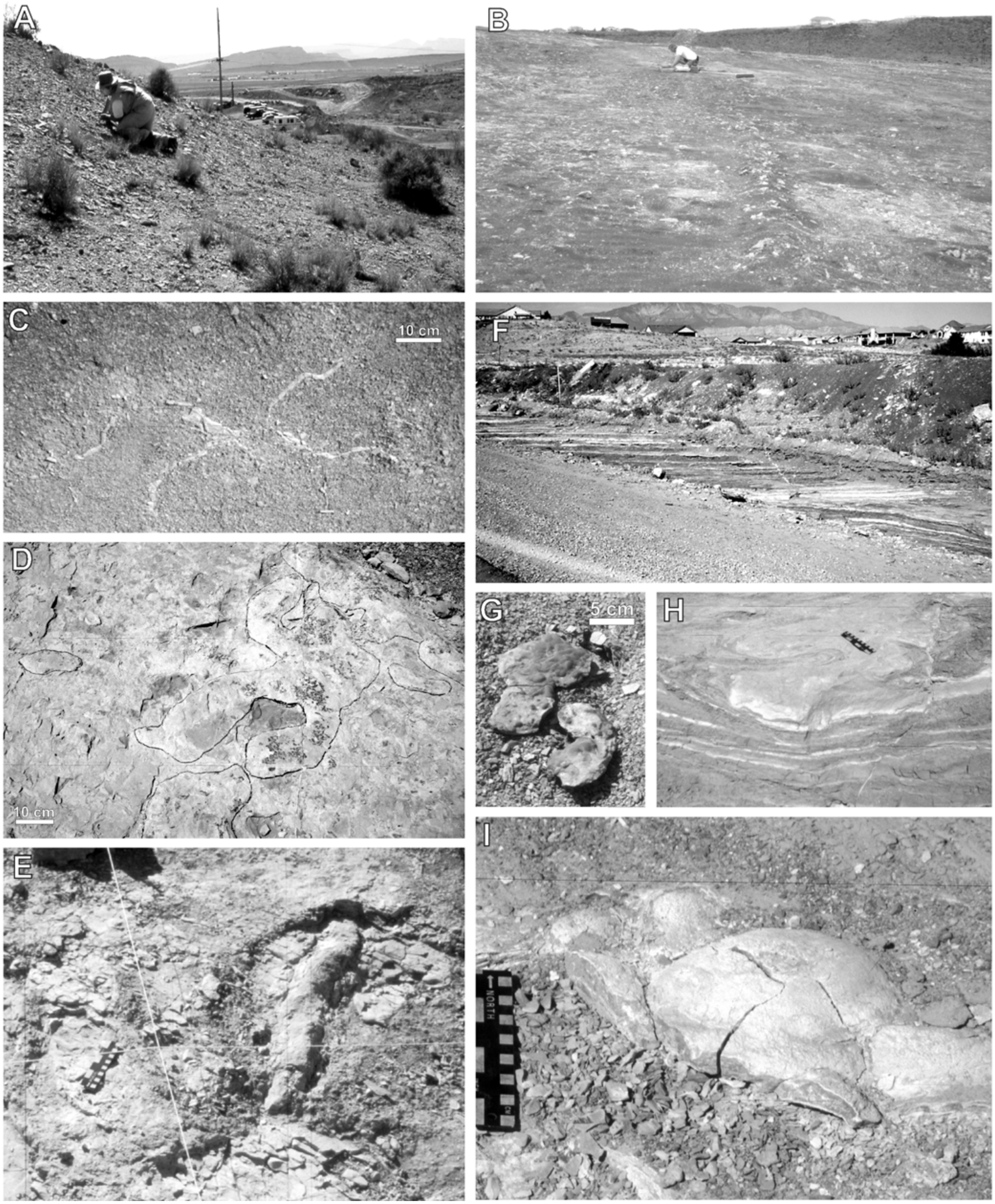

FIGURE 18. Upper shale interval of the Whitmore Point Member of the Moenave Formation west of Riverside Drive. **A**, Natural exposure of the Whitmore Point Member in 2000. **B**, Exposure of the Whitmore Point Member following initial leveling for Fossil Ridge Intermediate School. **C**, Mudcracks exposed on a weathered bedding surface. **D**, Flat siderite concretions exposed on a bedding surface. Small black flecks are ganoid scales. **E**, Elongate siderite concretion ("fish stick") naturally exposed parallel to bedding. **F**, Temporary exposure of the upper shale interval of the Whitmore Point Member in a gully along Mall Drive (currently below the sidewalk in front of Fossil Ridge Intermediate School. **G**, Typical siderite concretions from the upper shale interval. Dark lumps are built up around ganoid scales. **H**, Load and flame structures previously exposed along Mall Drive. **I**, Stromatolite layer previously exposed along Mall Drive.

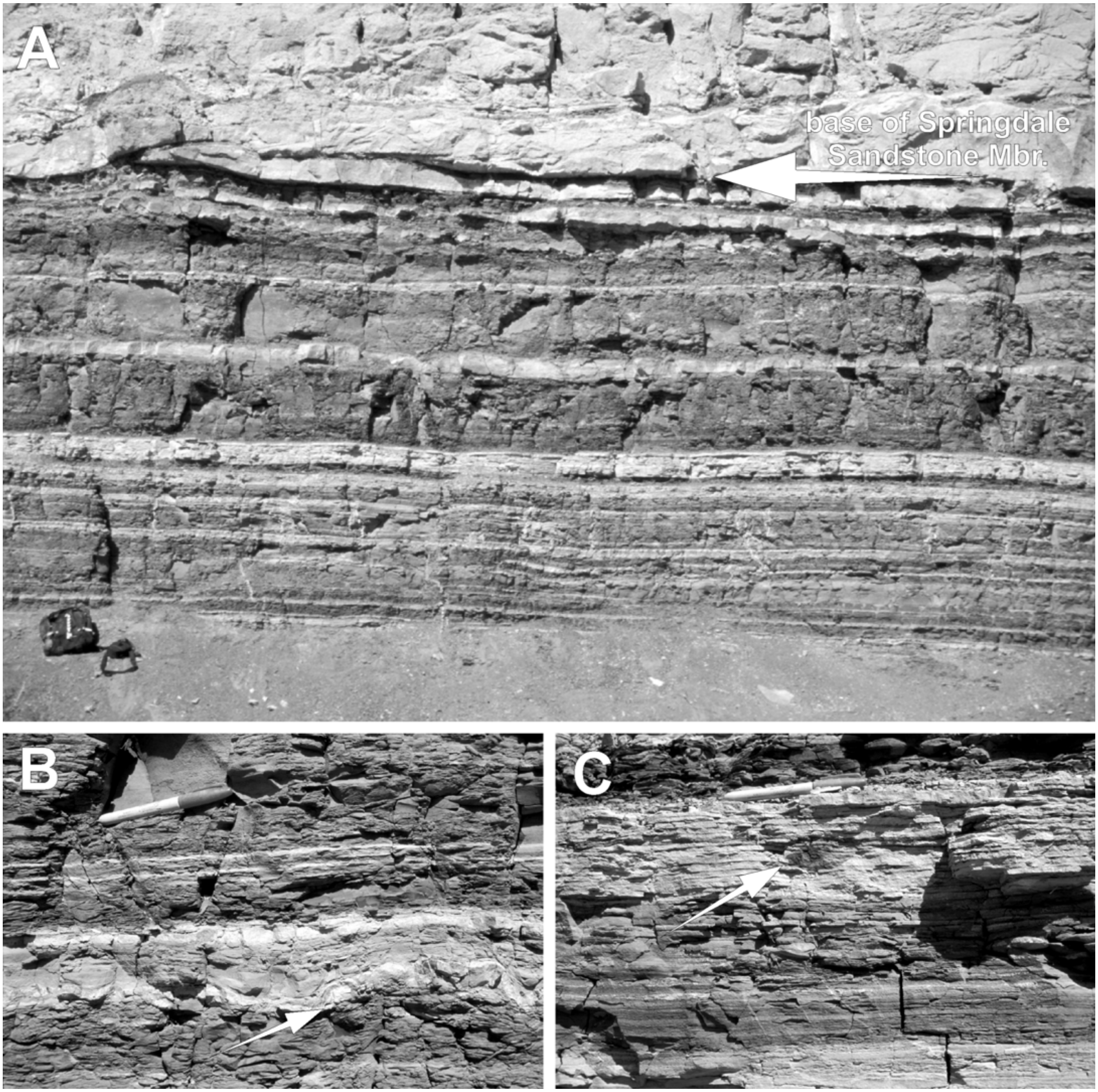

FIGURE 19. Upper shale interval of the Whitmore Point Member exposed below West Black Ridge along Bluff Street near 700 South (Dixie Lube Site). **A**, Vertical exposure of the upper shale interval showing its contact with the overlying Springdale Sandstone Member of Kayenta Formation. Backpack in foreground is about 50 cm (20 in) across. **B**, Stromatolite layer with "Sharpie" pen for scale. Arrow points to a stromatolite layer. **C,** Cross-section through a siderite concretion preserving bone with "Sharpie" pen for scale. Arrow points to a siderite concretion.

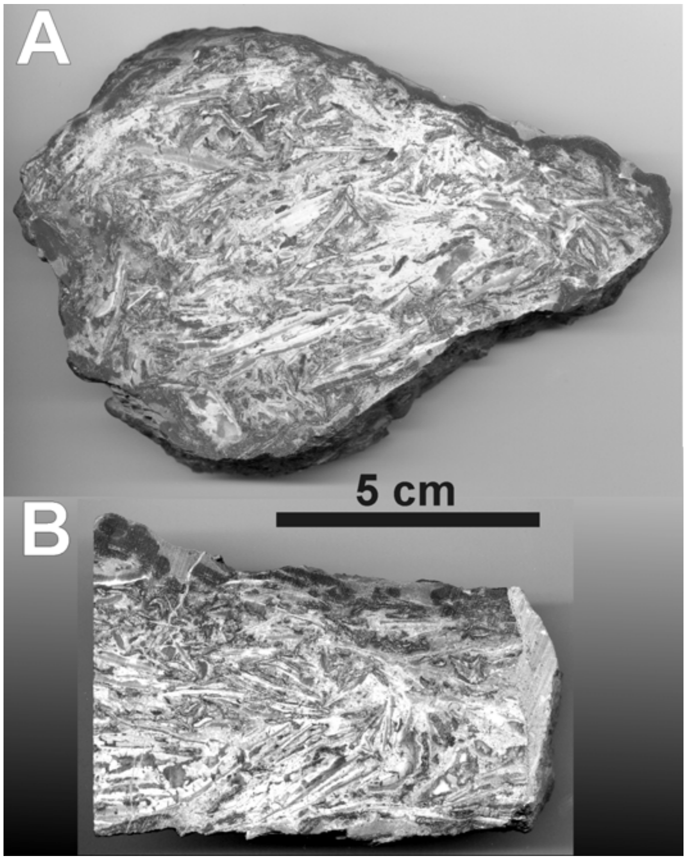

FIGURE 20. Cross-sections of typical masses of siderite concretions as in Figure 18G, preserving masses of disarticulated fish bones and scales. **A,** Cross section. **B,** Cross section at 90º to cross section in **A**.

concerning the Moenave Formation in this area, the extensive outcrop belt of these sediments across southwestern Utah calls out to future researchers to examine this fluvial-lacustrine system in more detail, putting these interesting rocks into a fuller temporal and paleogeographic context.

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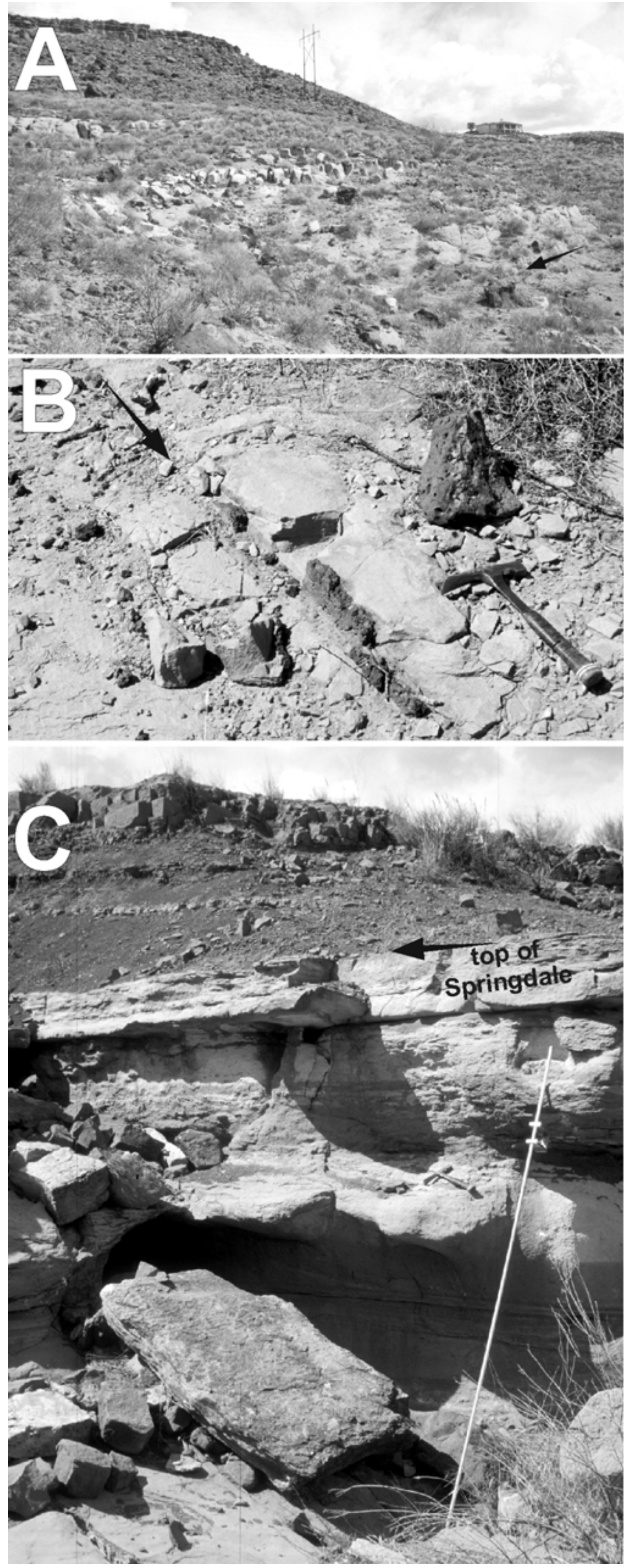

FIGURE 21. Springdale Sandstone Member of the Kayenta Formation below Middleton Black Ridge. **A**, Outcrop of the Springdale Sandstone; base indicated by arrow. The top of the member is obscured by basalt talus from a lava flow capping the ridge. **B**, Thin igneous dike (arrow) along a joint in the Springdale Sandstone. Hammer for scale. **C**, Contact between the Springdale Sandstone and unnamed lower shale member of Kayenta Formation.

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