UPPER CRETACEOUS DINOSAUR TRACKS FROM THE UPPER AND CAPPING SANDSTONE MEMBERS OF THE WAHWEAP FORMATION, GRAND STAIRCASE-ESCALANTE NATIONAL MONUMENT, UTAH, U.S.A.

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Abstract—Tridactyl tracks were identified in the fluvial strata of the Upper Cretaceous Wahweap Formation in Grand Staircase-Escalante National Monument, southern Utah, U.S.A. An isolated track and a trackway are located within the upper member at the Cockscomb, and an isolated track is in the capping sandstone member at Wesses Canyon. The upper member tracks are tridactyl pes imprints consisting of a longer, blunt digit III and shorter, blunt digits II-IV. This trace corresponds well to an ornithropod dinosaur as the trackmaker. The capping sandstone member track is a tridactyl pes with an elongate digit III and shorter digits II-IV. Claw impressions are present on the terminus of digits II and III. This trace is consistent with the pes impression of a one meter tall theropod. The tracks further highlight the diversity of dinosaurs in the capping sandstone of the Wahweap Formation.

INTRODUCTION

During the Late Cretaceous, North America, in particular the western United States, was the site of a radiation of new dinosaurian genera. The Cretaceous Western Interior Seaway isolated the east coast (Appalachia) from the west coast (Laramidia) from ~ 95 to 68 Ma (Blakey, 2009). Laramidia's Late Cretaceous strata within Grand Staircase Escalante National Monument (GSENM) have been the locus of extensive exploration of dinosaur fossils (Fig. 1; Peterson, 1969; Gillette and Hayden, 1997; Kirkland et al., 1998; Foster et al., 2001; Kirkland, 2001; Titus et al., 2005; Gates and Sampson, 2007; Kirkland and DeBlieux, 2007, 2010; Getty et al., 2010; Sampson et al., 2010 and many more).

The Late Cretaceous Wahweap Formation has yielded a variety of vertebrate body fossils, mainly from the lower, middle and upper members (see above references). The capping sandstone member has not yielded any significant vertebrate bone. Vertebrate track sites have specifically been reported from the lower, middle, and upper members of the Wahweap Formation, and have rarely been described from the capping sandstone member (Foster et al., 2001; Hilbert-Wolf et al., 2009a; Simpson et al., 2010a, b).

This paper describes the recent discoveries of dinosaur tracksites from the upper and capping sandstone members, interprets the probable trackmakers and discusses their implications for sediment moisture content and faunal diversity in the Wahweap Formation.

GEOLOGICAL CONTEXT

The Cretaceous System of the Kaiparowits Basin in GSENM was deposited in the Cordilleran foreland basin, bounded eastward by the Cretaceous interior seaway, westward by the Sevier orogenic front, and southwestward by the Mogollon highlands (Eaton and Nations, 1991). In GSENM, the Upper Cretaceous rocks are represented by, from oldest to youngest, the Dakota, Tropic Shale, Straight Cliffs, Wahweap, and Kaiparowits formations (Fig. 1; Peterson, 1969; Eaton, 1991; Lawton et al., 2003; Titus et al., 2005). The Wahweap Formation is informally grouped into, from oldest to youngest, the lower, middle, upper, and capping sandstone members (Eaton, 1991). In the study area, the capping sandstone member consists of white quartzarenite beds and is readily distinguished from the tan-colored sublitharenite beds of the upper member (Eaton, 1991; Eaton and Nations, 1991; Pollock, 1999; Lawton et al., 2003).

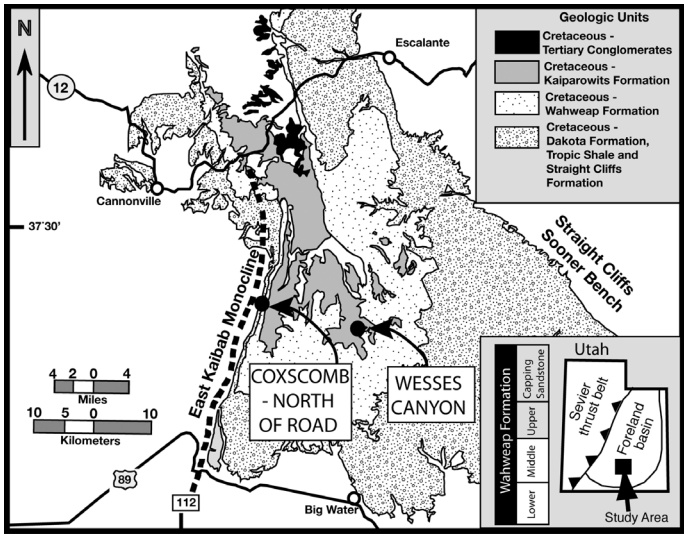

FIGURE 1. Geologic map of the Kaiparowits Basin, Utah, USA, showing location of the Coxcomb and Wesses Canyon and Cockscomb track sites. Geologic map after Sargent and Hansen (1982).

A Campanian age has been assigned to the Wahweap Formation based on microvertebrate biostratigraphy (Eaton, 1991, 2002). This assignment has been confirmed by Ar^{40}/Ar^{39} dating of tuffs throughout the Kaiparowits Formation and the lower/middle member of the Wahweap Formation (Roberts et al., 2005; Jinnah et al., 2009).

Pollock (1999) and Lawton et al. (2003) interpret the characteristic medium-grained, trough cross-bedded sandstones of the capping sandstone member as the product of amalgamated braided-stream channels, and lesser, fine-grained rippled sandstones, siltstones, and mudstones as associated overbank deposits (Fig. 2). In addition, Simpson et al. (2008) refined this interpretation by identifying thin deposits of small eolian dunes (Fig. 2C) and wind-reworked fluvial bar top units within the low-sinuosity, braided-stream deposits of the capping sandstone member (Fig. 2). Abundant soft-sediment deformation throughout the capping sandstone member is mainly the product of both local and regional seismogenic fault activity (Hilbert-Wolf et al., 2009a; Simpson et al.,

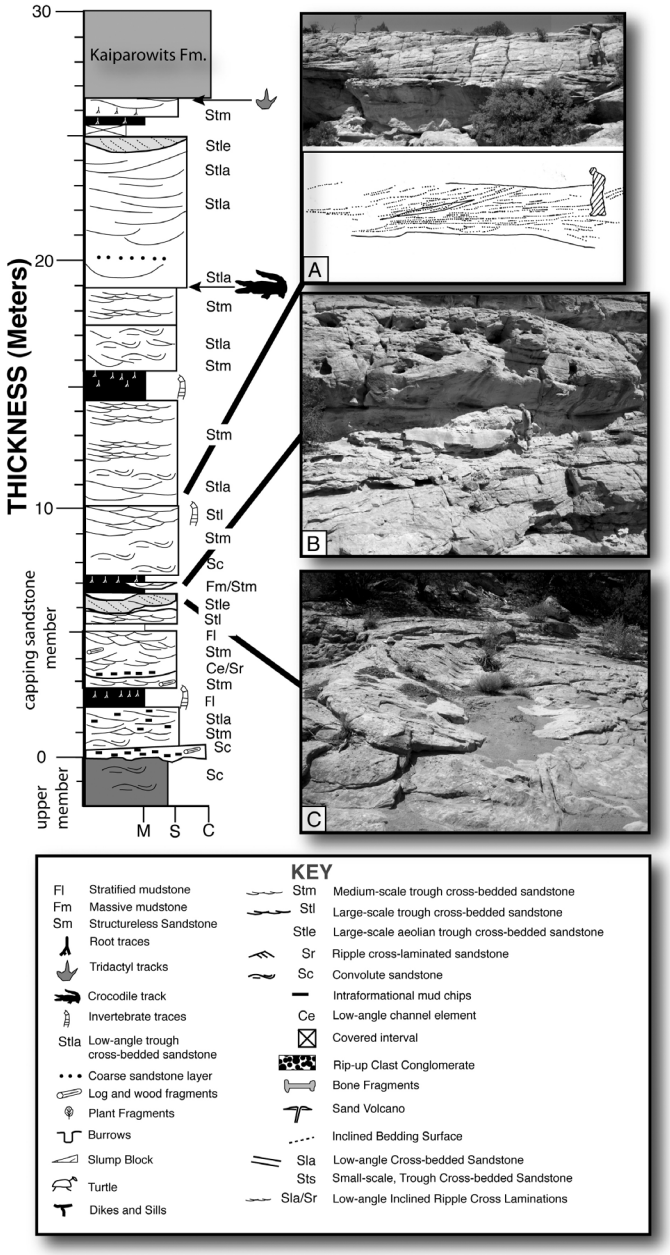

FIGURE 2. Measured stratigraphic column through the capping sandstone member of the Wahweap Formation in Wesses canyon (see Figure 1 for location). Note the dominance of trough cross bedding in the stratigraphic section. **A**, Photomosaic and interpretive line drawing of trough cross-bedded unit in which track was identified. Track was identified in low-angle toe sets. Person is 1.83 m in height. **B**, Isolated channel fill in finer-grained unit. Person is 1.83 m in height. **C**, Trough cross-bed set of eolian stratification. Note hat for scale in the upper right of the cross bed.

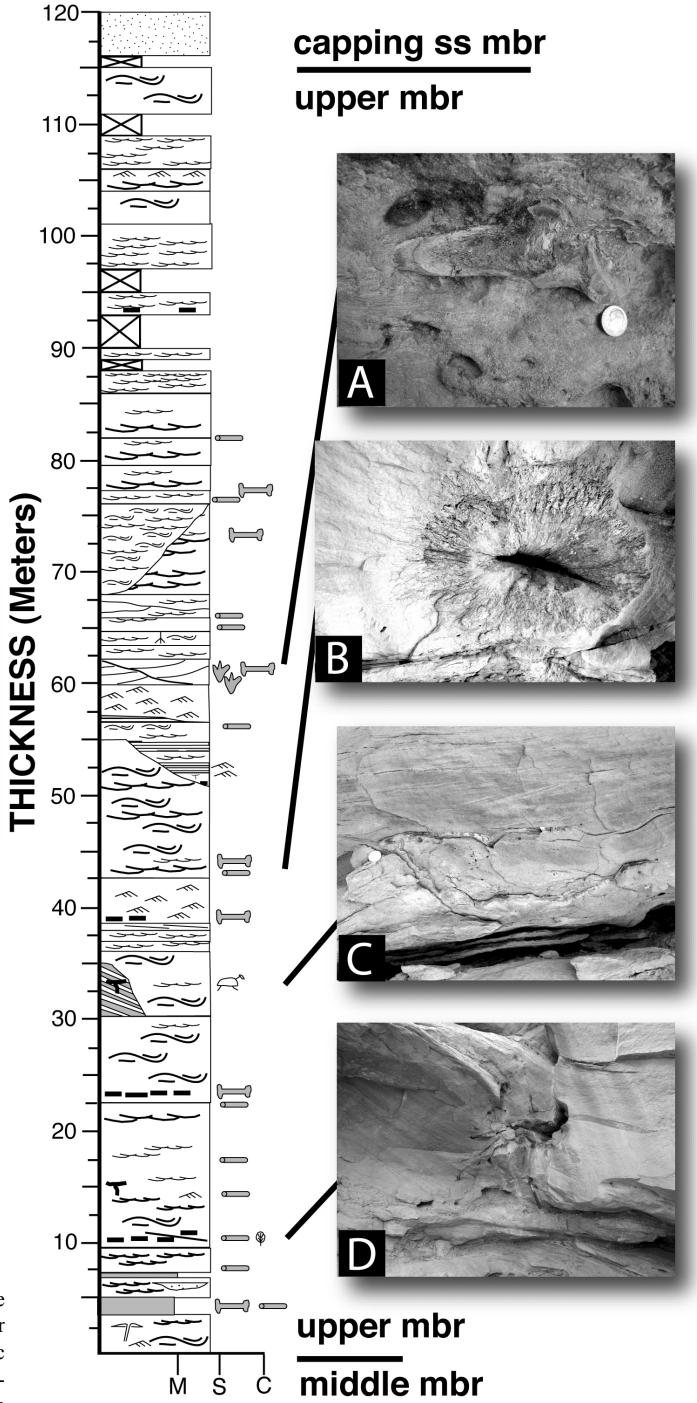

FIGURE 3. Measured stratigraphic column through the upper member of the Wahweap Formation in along the Coxscomb north of the road (see Figure 1 for location). Note the dominance of trough crossbedding coupled with soft-sediment deformation in the stratigraphic section. **A**, Unidentified bone. Coin is 2.5 cm. **B**, Cast of the base of a tree. Plant material is diagenetically removed. Approximate base diameter is 45 cm. **C**, Cross section through turtle skeleton. Coin is 2.5 cm. **D**, Rooted base of tree. Coin is 2.5 cm.

2009). An abrupt increase in grain size across a stratigraphic surface is ubiquitous in the upper half of the capping sandstone sections (Fig. 2) and is proposed as a regionally correlative surface by Hilbert-Wolf et al. (2009a).

The upper member is considered to be the product of low sinuousity, channel-dominated systems (Lawton et al., 2003; Wizevich et al., 2008; Jinnah and Roberts, 2009). The fluvial systems along the middle portion of the Cockscomb (Figs. 1, 3) developed in response to active localized normal faulting (Tindall et al., 2010). These fault systems, at least in the local area of the Cockscomb, controlled sedimentation style, higher versus lower sinuosity, and thickness (Wizevich et al., 2008; Hilbert-Wolf et al., 2009b; Tindall et al., 2010). Variations in seismic intensity inferred from sedimentary structures, seismites, were used to glean phases of normal fault movement (Hilbert-Wolf et al., 2009b) and their relationship to the switching from high to low sinuosity of fluvial systems (Wizevich et al., 2008).

TRACK DESCRIPTION AND IDENTIFICATION

Cockscomb-North of Road Locality

Description

These *in situ* tridactyl tracks form natural "casts" at the base of the channelized low-sinuosity, braided stream deposits that directly overlie deposits of a sinuous system (Figs. 2, 4A). The tracks are filled with fine- to medium-grained sublitharenite. Due to the overhanging nature of the outcrop, measurements were limited. Total track width is ~50 cm with a total track length of 53 cm and 90 cm step between left and right pes (Fig. 4C- D). Digit III is the longest, with a length of 23 cm. The pace angulation is estimated at 120° (Fig. 4C). A pronounced "heel" is present on the specimen (Fig. 4B, D).

Interpretation

This trace corresponds well to those ascribed to an indeterminate ornithropod (Lockley et al., 2003) and is consistent with measurements attributed to Late Cretaceous ornithopods (Milner et al., 2006). The shorter length of digit III compared to digits II and IV support an ornithopod interpretation. Heel impressions have been identified in ornithopod tracks (Milner et al., 2006). Exact assignment to a specific ichnogenus at this time is not possible. Most probably these tracks correspond to the ichnogenus *Hadrosauropodus* (see Lockley et al., 2003).

Hadrosaur body fossils have been reported from the Wahweap Formation (Eaton et al., 1999). In addition, hadrosaurs compose 34% of the fauna in associated and articulated skeletal deposits from the overlying Kaiparowits Formaion (Getty et al., 2010).

Wesses Canyon

Description

An isolated theropod pes impression (Fig. 5) was discovered at the Wesses Canyon near the top of the capping sandstone in medium-grained quartz sandstone one meter below the capping sandstone member-Kaiparowits contact (Figs. 1-2; Hilbert-Wolf et al., 2009b).

The track is a probable undertrack because of the absence of a preserved heel, metatarsal and skin impressions and well-defined track walls (Fig. 5). Digit III is the longest, ~ 16 cm, with an apparent claw impression located at the terminus. Digit III is slightly undulatory along its length with three apparent segments. Digit II is ~ 12 cm long, undulatory and with a possible toe impression. Digit IV is ~ 12 cm long and less well developed. The divarication angle between digits II and III is ~ 35°, and that for digits III and IV is ~25°. The total divarication angle is ~60°. The overall track width is ~ 20 cm with an overall length of at least 22 cm. The overall length measurement is problematic because of the absence of a metatarsal impression. Digit III displays three slight undulations in morphology along its length (labeled 1-3 in Fig. 5B).

Interpretation

Milner et al. (2006) report quantitative measurements of Late Cretaceous theropod tracks from the Iron Springs Formation in Utah. The Wesses Canyon tracks are comparable to those attributed to theropod tracks (Fig. 5). Relevant measurements include: 1) digit II length (8-15 vs 12 cm), 2) digit III length (10-20 vs 16 cm), 3) digit IV length (8-17 vs 12 cm), 4) width (11-20 vs 20 cm), 5) total track length (18-29 vs 22 cm), 6) divarication angle between digits II and III (35°-39° vs 35°), 7) divarication angle between digits III and IV (25°-37° vs 25°) and 8) a total divarication angle (60°-65° vs 65°). Track measurements considered to be problematic "theropod-like" are excluded from the ranges reported by Milner et al. (2006). In addition, preserved maniraptorian theropod digging traces found elsewhere in the capping sandstone are of similar track length (see Simpson et al., 2010b).

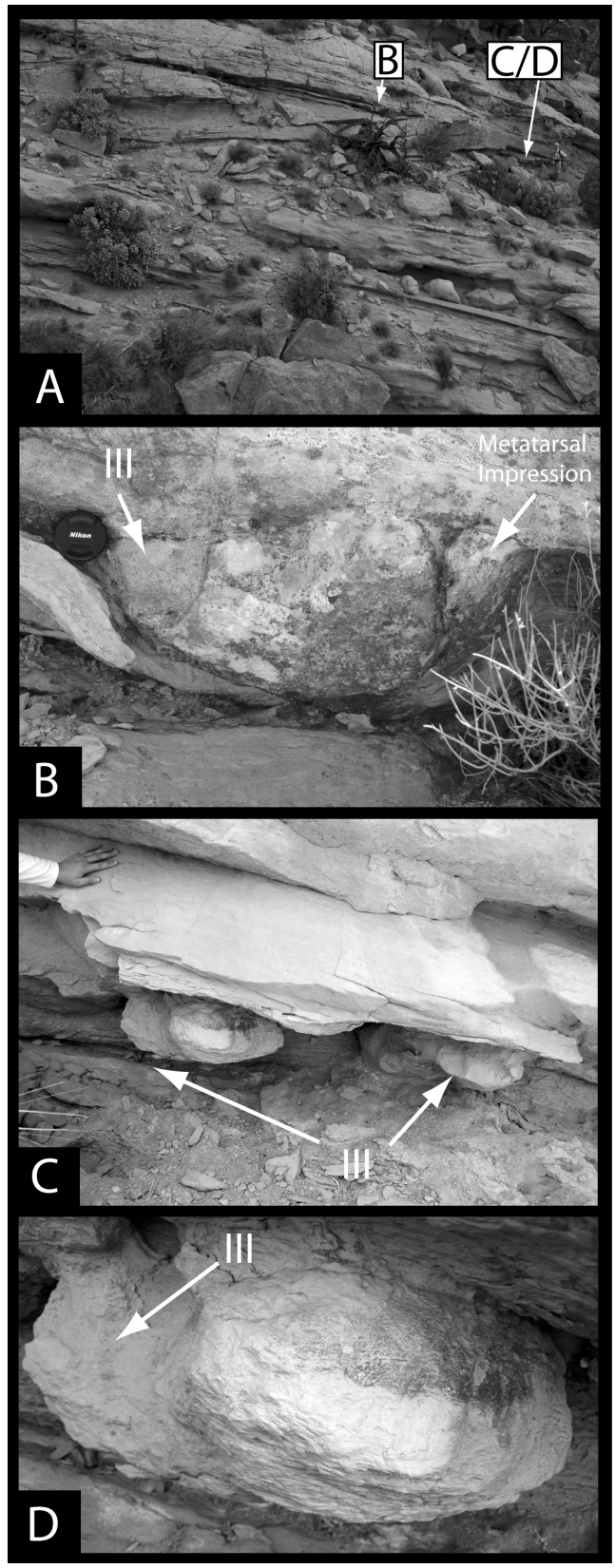

FIGURE 4. Field photographs along Cockscomb north of the road site. **A**, Photographs of heterolithic inclined crossbeds showing the location of the preserved orinthopod tracks shown in Figs. 4B-D. Person in upper right is 1.6 m tall. **B**, Natural cast of orinthropod track with parts labeled. Lens cap is 5.5 cm. **C**, Preserved orinthropod trackway at base of bed. Hand for scale. **D**, Close up of left track in **C**. Digits are labeled.

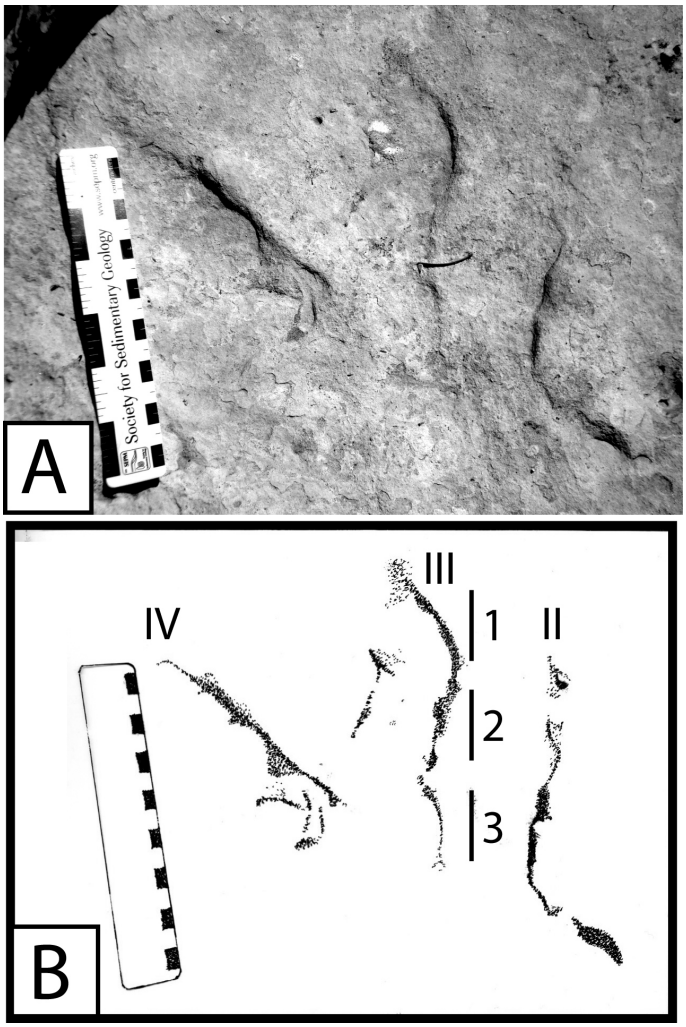

FIGURE 5. Theropod track from Wesses Canyon. **A**, Field photographs of theropod track. Scale is in cm. **B**, Interpretive line drawing of tracks with digits and segments labeled. Scale is in cm.

The three slight undulations in digit III are best interpreted to be the result of digital pad impressions, corresponding to the phalanx position along the digit as they interacted with the non-cohesive sediment (see Olsen et al., 1998; Milán et al., 2004, 2008).

This track may correspond to the ubiquitous ichnogenus *Grallator*, based on the size of the track (Olsen et al., 1998; Gaston et al., 2003; Milán et al., 2004, 2008). The Wesses Canyon theropod trackmaker is problematic, but relatively small in size. Through computer modeling, Henderson (2003) was able to demonstrate that the best reconstructed fit for the hip height of the trackmaker is 4 times the foot length. Applying this formula to our theropod track yields a maker of less than one meter high at the hip. Dromaeosaurids probably did not make this track because digit II is held aloft or very abbreviated when walking in reported track sites (*Dromaeopdus:* Cowan et al., 2010). Additional possible theropod dinosaurs reported from various units of the underlying Wahweap Formation include: immature tyrannosaurids, dromaeosaurids, and velociraptorids (Eaton et al., 1999). In the overlying Kaiparowits Formation, Getty et al. (2010) report that 9% of all associated and articulated skeltons are those of small theropods.

DISCUSSION

In experimental studies of tracks, Milán and Bromley (2006, 2008) produced similar looking defects in underlying sediment as those displayed in the upper member tridactyl pes. The analogous experimental track was produced by "drier" sand conditions (0.129lL of water /kg: Milán and Bromley, 2008). These conditions generated well-defined track walls that correspond to digit shape; the undertracks are wider and less well defined than the upper member tracks. Falkingham et al. (2010), through finite element analysis, found that foot shape is an important factor in depth of penetration into the sediment. Noncohesive sediment is displaced greater with increased track perimeter.

Tracks have yielded significant data as to the types of vertebrates present during the accumulation of the upper capping sandstone member whereas information from bone is lacking about this specific member. In addition to the small theropod track reported here, Simpson et al. (2010a) identified from Wesses Canyon the occurrence of *Crocodylopdus*, a crocodylomorph track from just above the stratigraphic marker surface (Fig. 2). These vertebrates represented, thus far from the capping sandstone track record, are typical subset of the fauna recorded from the lower, middle and upper members of the Wahweap Formation and the overlying Kaiparowits Formation.

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