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ICHNOLOGY AND STRATIGRAPHY OF THE CRESCENT VALLEY MINE: EVIDENCE FOR A CARBONIFEROUS MEGATRACKSITE IN WALKER COUNTY, ALABAMA

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Abstract—Early Pennsylvanian trace fossil-bearing deposits from the Crescent Valley Mine of Walker County in Alabama are correlated with those from the nearby Minkin Paleozoic Footprint Site. These represent end-members of a megatracksite that spans an environmental gradient from the inland, freshwater part of a deltaic system at the Minkin site to more near shore environments at Crescent Valley, where variable salinity conditions and tidal processes prevailed. This is reflected by preservation of a depauperate ichnofauna at the Crescent Valley mine. Recorded trace fossils are identified and interpreted as amniote trackways (*Attenosaurus subulensis* and *Cincosaurus cobbi*), apterygote insect trackways (*Stiaria*) and jumping traces (*Tonganoxichnus*), myriapod trackways (*Diplichnites*-*Diplopodichnus*), invertebrate burrows (*Arenicolites* and *Treptichnus*), and bivalve resting traces (*Lockeia*). A continuum of trail morphologies from chevronate, to feather-stitch and leveéd forms is also observed. These are interpreted as recording the activities of juvenile xiphosurans and possibly bivalves in a shallow-water tidal environment. *Arborichnus*, present in deeper-water facies, is interpreted as recording the combined resting and swimming activities of adult xiphosurans. In contrast to the Minkin site, *Kouphichnium* is absent. The spatial and environmental separation of these different trace fossils attributed to xiphosurans reflects that of different phases in their life cycles. The environmental distinction from the Minkin site may explain the apparent absence of temnospondyl amphibians. The fish-fin trace *Undichna* is common at the Minkin site but absent from the Crescent Valley mine, which may be due to interrelated environmental and preservational conditions.

INTRODUCTION

The discovery of the Minkin Paleozoic Footprint Site by amateur collectors in 1999 (Buta et al., 2005) rejuvenated interest in the vertebrate trackways found in the Pennsylvanian-age rocks of Alabama. The Minkin site originated as a strip mining operation that exposed Carboniferous trackways and other trace fossils in the interval between two coal beds. The traces are preserved in a dark gray shale that was originally a tidal mud flat. The deposit is Westphalian A (313 Ma), about the same age as the oldest known amniote body fossils (Clack, 2012). By this time, the colonization of land was well underway. Permo-Carboniferous trace fossil-bearing strata representing coastal settings from other locations in the southern USA include the Tonganoxie Sandstone of Kansas (Buatois et al., 1997, 1998a), and the Robledo Mountains of New Mexico (Lucas and Heckert, 1995; Lucas et al., 1998; Minter and Braddy, 2009; Voigt et al., 2013). In this paper, we describe a new tracksite in Alabama that sheds further light on the nature of Carboniferous tetrapod communities. Further, it seems that the best-known Carboniferous track sites in Alabama are age equivalent, suggesting the existence of a megatracksite in Walker County.

Aldrich and Jones (1930) first described trace fossils from the Early Pennsylvanian strata of the Black Warrior basin in north-central Alabama. Workers at the Galloway Coal Company No. 11 mine, an underground slope mine located less than a mile south of Carbon Hill, had noticed tetrapod tracks in collapsed roof shale and exposed ceilings above the Jagger coal seam and brought them to the attention of knowledgeable authorities. Aldrich and Jones (1930) named nine ichnospecies of small vertebrate tracks, two ichnospecies of large vertebrate tracks, and two other uncertain forms. Haubold et al. (2005) concluded that seven of the ichnospecies these authors assigned to small vertebrate tracks were made by the same animal or animals and that there was only one distinct type, *Cincosaurus cobbi*, thought to have been made by an early amniote. No definite temnospondyl amphibian traces were recognized by Aldrich and Jones (1930), nor were invertebrate traces a significant part of their study. The largest and best-defined tracks found were assigned to the ichnospecies *Attenosaurus subulensis*. It is unfortunate that much of the original material figured by Aldrich and Jones (1930), including the holotypes of *C. cobbi* and *A. subulensis*, appears to be lost (Haubold et al., 2005).

The Crescent Valley Mine (CVM) is an active (at the time of this writing) surface coal mine in Walker County that was opened by National Coal Company in 2008 into the northern edge of the old Galloway No. 11 mine. The CVM was discovered in April 2011 to be a rich new track site, and its proximity to the original discovery site provides an opportunity not only to find more specimens like those seen by Aldrich and Jones (1930), but also to gain a more complete inventory of the trace fossil assemblage in the area. Over a period of 18 months, more than a thousand slabs of tracks and traces were collected from mine spoil piles, photographed, and posted on a website (http://bama.ua.edu/~rbuta/cvm/cvm.pl). Our goals with this paper are to describe the ichnofauna found at the CVM, present a modern examination of the rock layers exposed by the mining operation there, explain how the trace and plant fossils relate to the stratigraphy of the site, and compare the results with what was found at the Minkin site.

LOCALE

The location of the CVM relative to the boundaries of the old No. 11 mine is shown in Figure 1, which is based on an early 1930s map made around the time the mine was formally closed. This schematic also indicates the main trackway locales of Aldrich and Jones (1930). The trackways described by these authors were mostly found in an area called the Southwest Slope, 4th left entry, approximately 2 km southwest of the mine entrance. The old mine was of the room and pillar type,

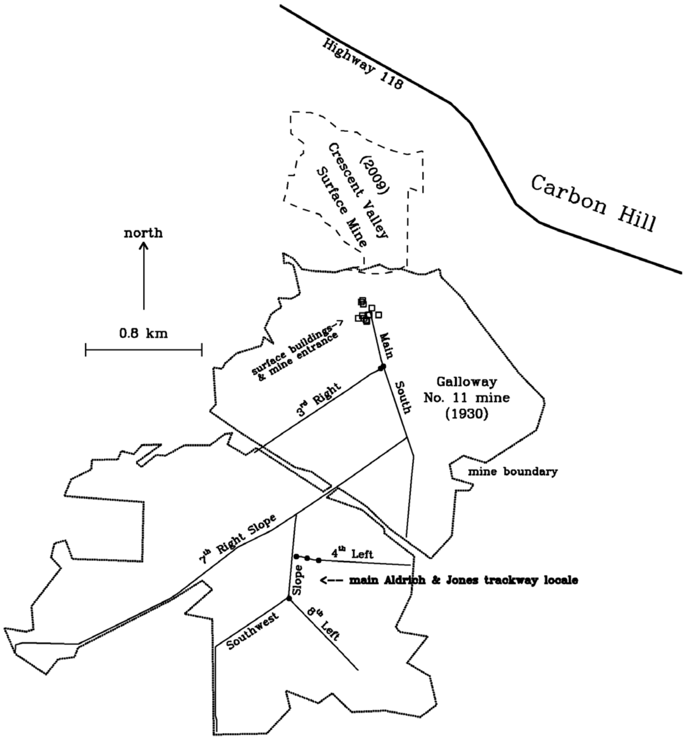

FIGURE 1. A schematic map of the No. 11 Mine of the Galloway Coal Company and its location relative to the Crescent Valley Mine. The No. 11 map is based on a 1930 original map. The first trackways in Alabama were mostly found along the "Southwest Slope," approximately 2 km from the mine entrance. The mine boundary is the dotted outline. Several special underground tunnels (such as the "4th left entry," cited as a primary locale for many of the main tracks illustrated by Aldrich and Jones) are indicated. The solid dots show points where figured Aldrich and Jones (1930) specimens were found. The CVM is highlighted by the dashed curve.

and was in operation long enough (ca. 1912 to 1933) that it left behind hundreds of coal-excavated chambers over an area of nearly 8 km^2. Several of these chambers were exposed when the CVM was opened in 2008. What originally attracted professional geologists to the No. 11 mine was reports of long trackways in the ceilings of some of the mine tunnels. In a repeat of history, when the CVM operation began, miners once again reported seeing tracks in the ceilings of exposed cavities from the old mining operation (D. Williams, foreman of Kansas Mine No. 2, 2011, private communication). To our knowledge, no professional geologists were contacted to view or photograph these finds, and all were destroyed by the subsequent mining operation. Figure 2 shows a photograph of one of the cavities exposed in 2011.

SITE SIGNIFICANCE

The Crescent Valley Mine provides exceptional insight into the geologic setting and habitat of the makers of *Cincosaurus cobbi* and other tetrapod trace fossils in Walker County. The traces occur in the Mary Lee coal zone of the Pottsville Formation, which is of Early Pennsylvanian (Langsettian) age and was deposited in the Black Warrior basin, an ancient foreland basin that flanks the Appalachian and Ouachita orogenic belts in Alabama and Mississippi (Mellen, 1947; Thomas, 1988; Pashin, 2004). The Pottsville Formation is locally more than 2,600 m thick and contains virtually all of the economic coal resources in northern Alabama (McCalley, 1886, 1900; Butts, 1926; Culbertson, 1964; Pashin and Gastaldo, 2009). The vast majority of the coal mined in the state comes from the Mary Lee coal zone, one of 13 major Pottsville coal zones. Numerous geological studies have been conducted of the Mary Lee, which was deposited in fluvial-deltaic environments on an ancient coastal

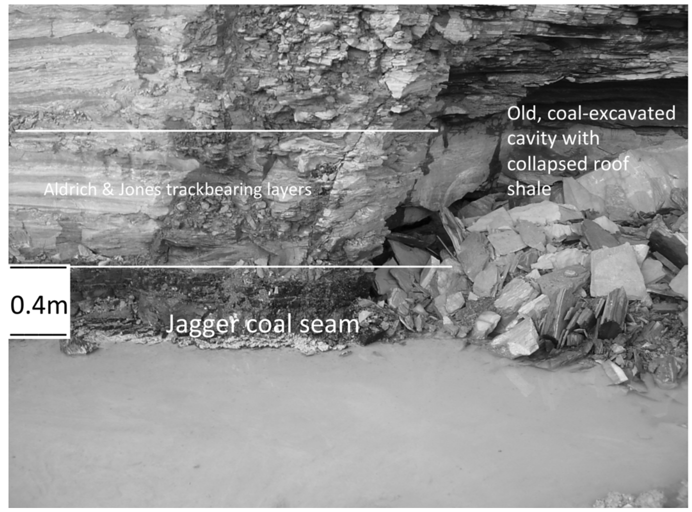

FIGURE 2. Photographs of part of the highwall in a (now reclaimed) pit at the Crescent Valley Mine. The dark band above the muddy water is the Jagger coal seam, 43 cm thick. The track-bearing layers should be within about 1 meter of the top of the seam. To the right is part of a cavity left in the rock when Jagger coal was extracted during the underground mining operation in the 1920s/30s. Most or all of the rocks seen in the cavity collapsed from the roof and some should include the track-bearing layers. This was confirmed when one large slab in the cavity was found to have 35 *C. cobbi* tracks in a 1 m long trackway (CVM 201).

plain flanking the ancestral Appalachian Mountains (e.g., Gastaldo et al., 1990, 1993; Pashin, 1994, 2005).

We have noted that the initial discovery of *Cincosaurus cobbi* and *Attenosaurus subulensis* came from the roof strata of the No. 11 Mine. Abandoned underground mine workings exposed in the CVM highwall, as in Figure 2, arguably are part of the same complex in which the tetrapod traces were discovered. The CVM thus offers an unparalleled opportunity to recover and examine these fossils from a vertical mine face that reveals the character of the strata in which the tracks were preserved. Here we use the rock types, the sedimentary structures, and the fossil content of the sedimentary rock to interpret the ancient environments of deposition in the area and the types of processes that operated in those environments. The CVM further provides a basis for comparison with the prolific Minkin Paleozoic Footprint Site to the east, which is another well-characterized *Cincosaurus cobbi* locality in the Mary Lee coal zone (Buta et al., 2005).

STRATIGRAPHIC ANALYSIS

Jagger Bedrock Through Jagger Coal

At CVM, four coal seams are being mined from the lower 20 m of a nearly vertical highwall (Fig. 3). Above the coal seams is a thick interval dominated by shale, and the total height of the highwall locally exceeds 40 m. At the base of the highwall is a thin, unnamed coal seam. This coal overlies a quartz-rich sandstone that miners in the Carbon Hill area refer to as the Jagger bedrock (Table 1). This sandstone is thought to have been deposited as part of a beach system in an area of high tide range (Gastaldo et al., 1993; Pashin, 1994). Above the unnamed coal is about 3 m of gray shale and mudstone containing abundant plant fossils, including the arborescent lycopod bark impression, *Lepidodendron*, and the horsetail fossil, *Calamites*. The coal and mudstone are thought to be the products of ancient swamps. The coal represents fossil peat, which is a wetland soil made primarily of organic matter, whereas the mudstone is a muddy wetland soil that accumulated during major flood events as sediment-laden streams overflowed their banks into the swamps (e.g., Demko and Gastaldo, 1992).

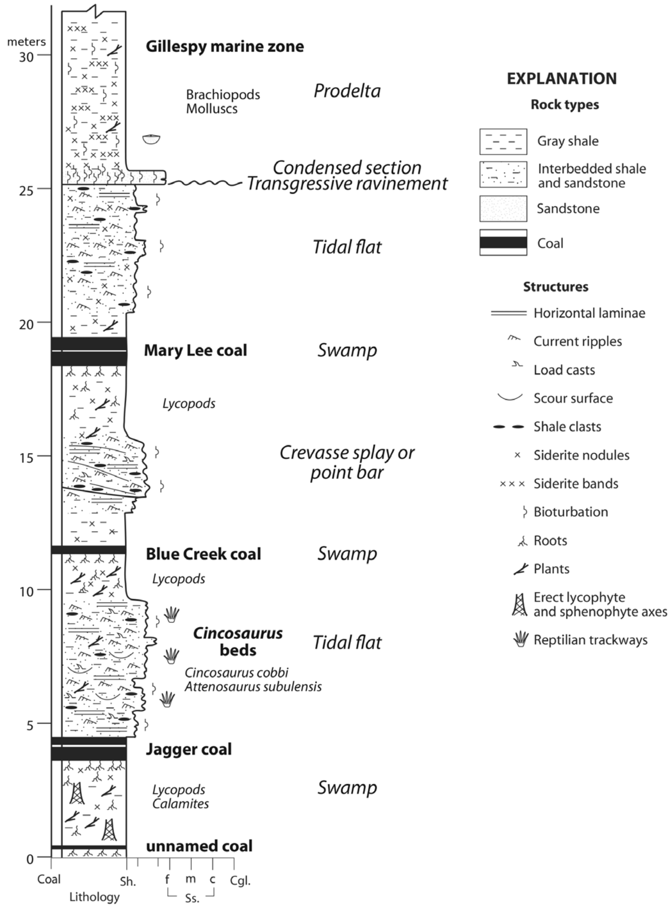

FIGURE 3. Schematic stratigraphic section showing the four coal seams being mined at the CVM. Standard terminology is used for different rock types and sub-units.

The Jagger coal overlies the plant-bearing mudstone (Fig. 3). With a thickness of about 1 m, the Jagger seam provides one of the principal mining targets in the Carbon Hill area. The coal is blocky and contains a very dark gray mudstone bed. Where measured, the mudstone bed is 0.15 m thick and is 0.30 m below the top of the coal seam. This coal represents renewed establishment of widespread peat-forming swamp environments in western Walker County. The mudstone layer within the coal can be correlated among outcrops and in the subsurface, and thus represents a significant interruption of peat deposition, which will be discussed later in the section on stratigraphic correlation. Pillars of the coal left over from older underground mining operations are exposed in the CVM highwall, and the strata forming the roof of the Jagger seam have collapsed into the voids among the old mine pillars (Fig. 2).

The *Cincosaurus* Beds

The roof strata above the Jagger coal are highly fractured and unstable. Examination of these strata in the highwall and in fresh mine spoils proved rewarding because they contain well-preserved specimens of *Cincosaurus cobbi* and reveal a distinctive depositional style. Because most if not all tetrapod trackways from the CVM were recovered from the interval between the Jagger and Blue Creek seams, these strata are called the *Cincosaurus* beds. This name also was applied to the trackway-bearing part of the Mary Lee coal zone at the Union Chapel Mine by Pashin (2005) (Table 1).

The *Cincosaurus* beds at CVM are dominated by thinly interbedded dark-gray shale and medium- to light-gray siltstone and sandstone (Fig. 4). Pinstripe, lenticular, wavy, and flaser bedding are present throughout the interval, and current-ripple cross-laminae are abundant. Most beds within the *Cincosaurus* beds form graded sandstone-shale couplets thinner than 3 cm. Other primary sedimentary structures in the *Cincosaurus* beds include load casts, flute casts, and a variety of other sole markings. Structures on the tops of the beds include sinuous ripple marks, wrinkle marks, and crater-like circular impressions. Prostrate plant fossils occur sporadically in the *Cincosaurus* beds and include lycopod axes and fern-like foliage. Progressive thickening and thinning of successive graded sandstone-shale couplets is a distinctive attribute of the *Cincosaurus* beds. Analysis of correlative strata at a nearby coal mine by Demko et al. (1991) and Sonett et al. (1996) indicates that this progression is cyclic, with an average periodicity of 18 couplets per cycle. A 1.8 m interval of sandy underclay gradationally overlies the trackway-bearing interval and is, in turn, overlain sharply by the Blue Creek coal (Fig. 3). The underclay contains abundant specimens of *Stigmaria*, which is a name applied to the root systems of lycopods rather than a unique taxon.

TABLE 1. Correlation of coal seams and the *Cincosaurus* beds in the Mary Lee coal zone.

Carbon Hill area, Crescent Valley Mine	Cordova area, Union Chapel Mine	Subsurface of Walker, Jefferson, and Tuscaloosa Counties	Blue Creek syncline, Jefferson and Tuscaloosa Counties
New Castle coal	absent	New Castle rider	absent
Mary Lee coal	New Castle coal	New Castle coal	New Castle coal
Blue Creek coal	absent	unnamed coal	absent
Cincosaurus beds	*Cincosaurus* beds	unnamed shale and sandstone	unnamed shale and sandstone
Jagger coal	Mary Lee coal	Mary Lee coal, Blue Creek coal	Mary Lee coal, Blue Creek coal
unnamed coal	absent	Jagger coal	Jagger coal
Jagger bedrock	Lick Creek Sandstone	Lick Creek Sandstone	Lick Creek Sandstone

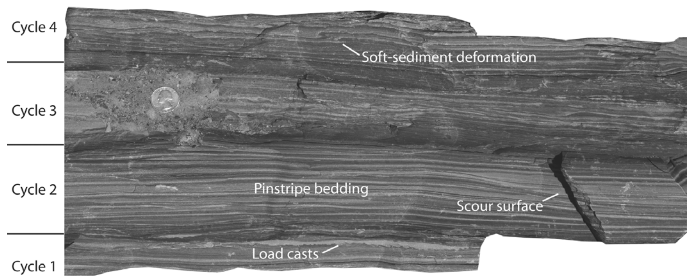

FIGURE 4. The *Cincosaurus* beds at the CVM included inter-bedded dark gray shale and medium to light gray siltstone and sandstone.

The graded sandstone-shale couplets indicate that sedimentation was episodic and dominated by suspension settling of sand and mud in response to decelerating flows. Load casts and other soft-sediment deformation structures indicate that the sediment was highly fluid at the time of sedimentation. Flute casts and other sole markings indicate that the base of many sandstone layers is erosional and that the tidal currents were at times capable of transporting larger objects than is indicated by the fine grain size of the sediment alone. Indeed, no plant fossils were observed in life position in the *Cincosaurus* beds; they were instead transported by currents to the site of deposition. This is a major contrast with the *Cincosaurus* beds at the Minkin site where erect axes of seed ferns and *Calamites* were observed (Pashin, 2005). Current-ripple cross-laminae in the *Cincosaurus* beds indicate that turbulent flows were common, whereas pinstripe bedding indicates frequent laminar flows as well. Circular impressions are abundant at the Minkin site and are thought to be principally gas-escape structures (Rindsberg, 2005), and some may be raindrop imprints (Pashin, 2005).

Demko and Gastaldo (1992) interpreted strata equivalent to the *Cincosaurus* beds as a freshwater to brackish tidal flat deposit, and observations at the CVM are consistent with a variable salinity, tidally-influenced, coastal plain system. The cyclicity of the sandstone-shale couplets is indicative of spring-neap tidal cycles. The 18-event periodicity of the cycles recognized by Demko et al. (1991) is suggestive of a strongly asymmetrical, mixed system of diurnal (daily) and semidiurnal (twice daily tides). A true diurnal system would have periodicity of 14 tides, and the occurrence of additional events may reflect occasional preservation of sediment deposited by the subordinate semidiurnal tide. Alternatively, this periodicity may be influenced by preservational bias related to erosional surfaces and discontinuous layering (Sonnett et al., 1996). The underclay below the Blue Creek coal signifies the encroachment of a muddy wetland into the area of the tidal flat, and the Blue Creek coal marks a return to peat deposition.

Blue Creek Coal Through Gillespy Marine Zone

The Blue Creek coal is about 0.37 m thick at the CVM. The coal is blocky and, in contrast to the other seams at the mine, lacks muddy partings. Above the Blue Creek coal is more than 6.1 m of shale, sandstone, and underclay. The shale and sandstone are similar to those lower in the section, although no confirmed tetrapod tracks have been recovered. The roof of the coal seam is dominated by shale with siderite nodules, and it is difficult to discern internal structures in this part of the section. In the overlying sandstone, grain size and bedding tend to fine and thin upward, respectively. The vertical trend is from flaser and wavy bedding to lenticular and pinstripe bedding. The sandstone-bearing part of this section exhibits the most lateral variation of any stratigraphic unit in the mine. Internal bedding surfaces are inclined, defining accretionary beds with a gentle, northward apparent dip. The sandstone-bearing interval fines upward into about 3 m of mudstone and underclay resembling that below the Blue Creek coal.

The Blue Creek coal signifies renewed establishment of peat-forming environments. The lack of mudstone partings indicates that this part of the swamp was not prone to influxes of muddy sediment. Sedimentary structures in the interbedded mudstone and sandstone section resemble the tidal flat deposits of the *Cincosaurus* beds. However, the accretionary bedding in this interval suggests sedimentation in a tidally-influenced point bar or crevasse-splay system. Similar deposits have been documented in other mines in the Carbon Hill area (Gastaldo et al., 1990). The underclay that caps the mudstone-sandstone interval marks establishment of yet another muddy wetland.

Above the underclay is the Mary Lee coal which, with a total seam thickness of 1.1 m, is the thickest coal exposed at the CVM. A dark gray mudstone parting with a thickness of 0.1 m is developed 0.5 m from the top of the seam and can be traced throughout the highwall. The roof strata above the Mary Lee resemble those above the Blue Creek seam. Gray shale immediately overlies the coal and grades upward into more than 4.5 m of thinly interbedded shale and sandstone that is dominated by lenticular and pinstripe bedding. The upper contact of this unit is sharp and marks the top of the Mary Lee coal zone at the CVM.

The Mary Lee coal was deposited as part of a widespread peat swamp, and the thin parting in the upper half of the seam marks an episode when muddy sediment flowed into the mire, thus interrupting peat accumulation. The thinly interbedded shale and sandstone above the coal is interpreted as another tidal flat deposit similar to the *Cincosaurus* beds. The sharp contact at the top of the Mary Lee coal zone is a widespread erosional surface that extends throughout most, if not all, of the Black Warrior basin (Liu and Gastaldo, 1992; Pashin, 2004). Indeed, the New Castle coal, which is a thin (< 7 cm) coal in the Carbon Hill area, is absent at the CVM. Stratigraphic cross sections indicate that the New Castle bed has been eroded at many locations near Carbon Hill (Gastaldo et al., 1990; Liu and Gastaldo, 1992). This surface has erosional relief less than 4.5 m and is thought to have formed as a ravinement generated by marine flooding and shoreface erosion during a major rise of sea level (Liu and Gastaldo, 1992).

Above the Mary Lee coal zone is a calcareous sandstone unit that is 0.52 m thick and contains a thin shaly parting 0.18 m from the base. The sandstone is mottled with burrows, and many of the burrows are filled with siderite. At the upper contact the sandstone grades into a thick interval of gray shale with pebble- to cobble-size siderite concretions. This shale is part of the Gillespy marine zone, which overlies the Mary Lee coal zone throughout the Black Warrior basin. The shale is bioturbated, and some of the concretions contain shells of brachiopods and molluscs, pyrite nodules, and plant fragments. Forming the upper 15 m of the mine highwall, the shale is largely inaccessible.

The calcareous sandstone above the Mary Lee coal zone is interpreted as a condensed deposit that formed during the most rapid part of the sea level rise. The calcareous sandstone is widespread in the Black Warrior basin, and the characteristics of the deposit vary among outcrops. Whereas only siderite-filled burrows were observed at CVM, other outcrops contain an array of marine body fossils, including brachiopods, molluscs, crinoid ossicles, and solitary rugose corals (Gastaldo et al., 1990; Liu and Gastaldo, 1992). The fossiliferous shale above the sandstone forms a thick, regionally extensive marine zone. The shale was deposited in prodelta and delta front environments during a major highstand of relative sea level that followed inundation of the entire Black Warrior basin (Pashin, 1994; Pashin and Raymond, 2004). Although this shale records the youngest Pottsville sedimentation at the CVM, several younger marine zones and coal zones are preserved farther south in the interior of the Black Warrior basin and provide many opportunities for paleontologic and sedimentologic discovery.

Crescent Valley Trace Fossil Beds

Most of the trace fossils from the Crescent Valley Mine have been recovered from mine tailings. Part of the challenge is therefore in assigning trace fossils to particular beds and facies. It is unclear if *Cincosaurus* and *Attenosaurus* are restricted only to the *Cincosaurus* beds, considering that similar strata occur at multiple stratigraphic levels. However, our surveys of the mine face and the mine tailings indicate that tetrapod tracks are rare outside of the *Cincosaurus* beds. Tracks were only found in spoil piles that the mine manager said were made of Jagger shale; piles made of shale from above the Blue Creek and Mary Lee coal beds did not yield tracks. Also, a limited amount of *in situ* collecting verified the location of the *Cincosaurus* beds. The cavity shown in Figure 2 yielded a large slab (CVM 201) with 35 footprints of *C. cobbi* along a trackway nearly a meter long. This was found in collapsed roof shale and would have come from the original Aldrich and Jones layers within a meter of the top of the Jagger coal bed. Higher layers than these also were found to contain tracks: several small slabs with *C. cobbi* tracks were pulled directly out of the highwall 2.5-3 m (8-10 ft) above the top of the Jagger coal bed at two different locations. This is still several meters below the Blue Creek coal bed.

The invertebrate trace fossils discovered from CVM are frequently found on small slabs and are rarely preserved together with vertebrate trackways. The principal exceptions are *Arenicolites* and *Treptichnus* burrows associated with *Cincosaurus*. Many of the other invertebrate ichnofossils occur in similar strata, but it is not possible to rule out that they may come from other parts of the Mary Lee coal zone. Indeed, considerable work remains to increase our understanding of the composition and interrelationships among the trace fossil assemblages at the CVM.

The occurrences of *Cincosaurus* and *Attenosaurus* differ markedly from those at the Minkin site, where the trace fossil assemblage is much more diverse and includes *Kouphichnium* and several additional vertebrate ichnotaxa, including those made by amniotes and anamniotes (Haubold et al., 2005). The *Cincosaurus* beds at the Minkin site were interpreted primarily as a fresh-water deposit in which tidal cyclicity is extremely weak. In contrast, the strong spring-neap cyclicity at CVM combined with the more restricted ichnofossil assemblage suggests stronger tidal influence and perhaps variable salinity, freshwater to brackish conditions. The makers of *Cincosaurus cobbi* and *Attenosaurus subulensis* were amniotes (Haubold et al, 2005), and thus better adapted to cope with saline water than temnospondyl amphibians, which are conspicuously absent from CVM. However, much remains to be learned about the environmental tolerances of early tetrapods, which may differ from those of modern taxa (Laurin and Soler-Gijon, 2010).

Staub and Esterle (1994) suggested that the Rajang Delta of Indonesia is a useful modern analog for Pennsylvanian coal-bearing deposits. Pashin (2005) noted that the combination of beach and deltaic deposits on the Rajang is similar to the deposits preserved in the Mary Lee coal zone (Fig. 5). The quartzose sandstone of the Jagger bedrock has been interpreted to include ancient beach sand, and the mud-rich coal-bearing strata of the Mary Lee coal zone represent a tidally influenced deltaic complex. Within this context, the Minkin site probably represents the inland part of the deltaic system, where fresh water conditions prevailed and riverine processes dominated over tidal processes. By contrast, the CVM appears to represent environments closer to the strandline, where brackish conditions and tidal processes prevailed.

Correlation of Coal Seams and the *Cincosaurus* Beds

Aldrich and Jones (1930) discovered *Cincosaurus cobbi* and *Attenosaurus subulensis* in the roof strata of the Jagger coal seam near the CVM. At the Minkin site, however, the *Cincosaurus* beds occur in the roof strata of the Mary Lee coal seam. Thus, at first glance, it would appear that the *Cincosaurus* beds occur at different stratigraphic intervals of the Mary Lee coal zone in different parts of the Black Warrior basin. However, one must be very careful when applying the names of coal seams in disparate areas, because coal seams commonly split and merge and are discontinuous (e.g., Ferm and Weisenfluh, 1989). In the case of the Mary Lee coal zone, nomenclature is complicated by the fact that mining began independently in different parts of the basin. Although four names (Jagger, Blue Creek, Mary Lee, New Castle) are applied to coal seams of the Mary Lee zone throughout the basin, it is not clear that those names were always applied consistently. Subsurface drilling for natural gas in the Pottsville Formation, however, provides a wealth of stratigraphic information that enables refinement of the correlations among coal seams (e.g., Pashin and Raymond, 1994) (Table 1).

During the late 1850s, coal mining began along the southeastern margin of the Black Warrior basin in an area called the Blue Creek syncline in Jefferson and Tuscaloosa Counties. Many of the seam names, such as Jagger and Blue Creek, originated in that area (McCalley, 1886; Semmes, 1929). Mining began shortly thereafter across the basin in Walker County, and miners immediately began applying the seam names that were already in use, and named additional seams, such as the New Castle coal. Table 1 shows the results of correlating coal seams from the Blue Creek syncline through the gas fields of Tuscaloosa and Walker Counties to the Union Chapel and Crescent Valley mines. This exercise demonstrates the complex nomenclature that has been applied in the Mary Lee coal zone, as well as distinct inconsistency in the application of the classic seam names. The end result is that the Mary Lee coal of the Minkin site correlates with the Jagger coal at the CVM and that the *Cincosaurus* beds constitute the same stratum at each locality. Accordingly, occurrences of *Cincosaurus cobbi* appear to be restricted to a narrow stratigraphic interval but cover much of Walker County (Fig. 6). Considering that the trackway beds cover an area of at least 400 km^2, Walker County can be classified as a megatracksite, following the terminology of Lockley and Meyer (2000).

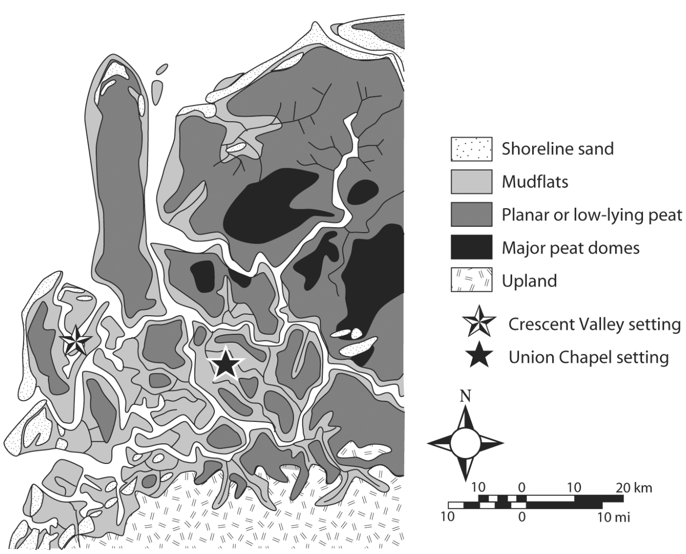

FIGURE 5. Schematic of the Rajang delta in Indonesia, a modern analog of Pennsylvanian coal-bearing deposits.

DESCRIPTION OF CVM TRACE FOSSILS

Methods

Standard trackway parameters have been used to characterize the vertebrate trace fossils found at the CVM. These include the pace, stride, trackway width, width of individual tracks, and pace angulation. Pace is the distance from the base of manus digit imprint III to the base of the same digit imprint on the next manus track. Stride is the distance from the base of manus digit imprint III to the base of the same digit imprint on the next manus track on the same side of the body. Track width was measured normal to the midline. Trackway width was measured between the outermost parts of tracks on each side of the mid-line, also normal to the

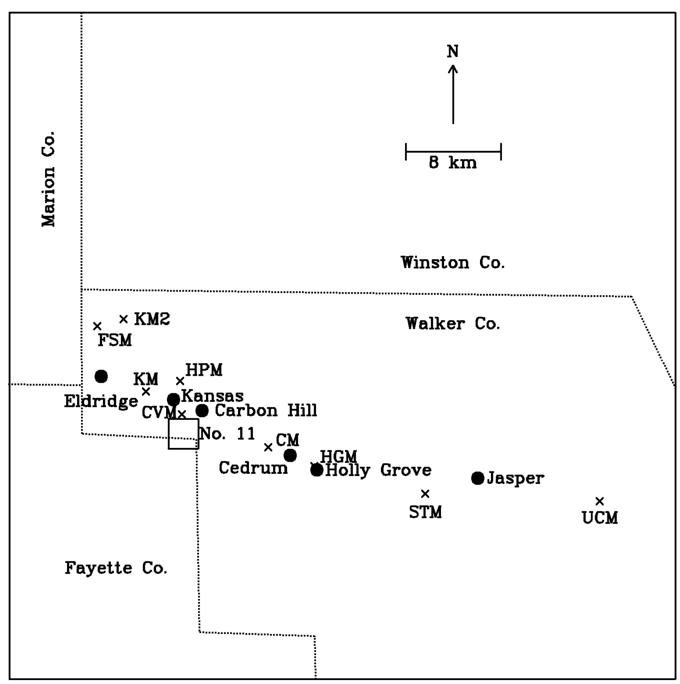

FIGURE 6. A map of all known track sites in Walker County, Alabama, relative to the cities of Eldridge, Kansas, Carbon Hill, Holly Grove, and Jasper. The mines shown are: CM-Cedrum Mine; CVM-Crescent Valley Mine; FSM-Fern Springs Road Mine; HGM-Holly Grove Mine; HPM-Hope Pit Mine; KM-Kansas Mine; KM2: Kansas Mine No. 2; No. 11 Mine-Galloway Coal Company mine where first tracks were documented; square indicates rough actual size; STM-Sugar Town Mine; UCM-Union Chapel Mine (=*Steven C. Minkin Paleozoic Footprint Site*).

mid-line. Pace angulation is the angle defined by connecting the bases of manus digit imprint III on three successive manus prints. Because most specimens are undertracks, measurements are not strictly comparable to those that would have been made on surface tracks. However, the only measurement likely to be greatly distorted is track length. This is because the tips of the grooves made by toes tend to disappear rapidly in undertracks as one moves down from the sediment surface.

All trackway measurements were made on digital photographs posted on the website http://bama.ua.edu/~rbuta/cvm/cvm.pl. All of these photographs were taken in full sunlight at medium to very low sun angle, usually in both full slab view and multiple close-ups. A mm ruler scale was included in all photographs, and every specimen was assigned a running CVM number and catalogued.

Vertebrate Trackways

Two vertebrate trackway ichnospecies have been recognized at the CVM: *Cincosaurus cobbi* and *Attenosaurus subulensis*. The former is attributed to an amniote and the latter to an anthracosaur (Haubold et al. 2005). *C. cobbi* is the most abundant tetrapod trackway found at the CVM. The ichnotaxonomy of *Cincosaurus* and similar trackways is in need of revision. Pending a full revision, and for simplicity, we follow the assignments of Haubold et al. (2005).

Attenosaurus subulensis Aldrich, 1930
Figs. 7-8

The holotype of this ichnospecies has been lost, but numerous specimens from the Minkin site allowed Haubold et al. (2005) to document its characteristics. The only reservation they had about referring Minkin site specimens to *Attenosaurus* is the possibility that *A. subulensis* (rare large tracks) and *Cincosaurus cobbi* (common small tracks) were made by different-sized members of a single tetrapod species. Haubold et al. (2005) did not attempt to test this hypothesis. Minkin site specimens referred to *A. subulensis* by Haubold et al. (2005) have: manus and pes tracks with five digit imprints; are larger than specimens referred to *C. cobbi* (up to 25 cm in pes track length); exhibit a wider trackway pattern; and have different digit imprint proportions (pes digit imprint IV is shorter than III). With one exception, CVM specimens of *A. subulensis* are too few and too fragmentary to add much to our knowledge of ichnospecific morphology, and they do not provide enough information to answer the question of whether the two ichnospecies are characterized by distinct size distributions. The CVM specimens extend the known paleogeographic range of the ichnospecies, but only slightly, because the CVM is very close to the Galloway No. 11 mine, where the original type specimens of *A. subulensis* were collected by Aldrich and Jones (1930).

The specimens shown in Figures 7A and B are single footprints on relatively large slabs with no other tracks included. Both are deeply impressed and may be *A. subulensis* surface tracks. The main track seen in Figure 7C is one of the largest footprints found at the CVM. The tracks in Figure 7D appear to be deep undertracks made when the animal was likely moving slowly.

The longest *A. subulensis* trackway found at the CVM was on a 1-2 ton slab, and comprises nine footprints, including seven pes tracks and two manus tracks, in a trackway 1.17 m long (CVM 1100, Fig. 8A-B). The three front tracks are impressed in a slightly higher layer than the rest of the tracks and are doubled. The other tracks are deeper single undertracks. From three of the large pes tracks we estimate a stride of 33.8 cm, a pace of 21.8 cm, and a pace angle of 157°. The ratio of pace to stride is 0.6. Pes tracks are 15.7 cm long x 6.9 cm wide; manus are 5 cm long x 4.8 cm wide, on average. Manus track width is 0.7 times pes track width. The three front tracks are all pes tracks averaging 18.8 cm x 7.6 cm. The reason for the doubling of these tracks is unknown, but they may be pes-over-manus prints.

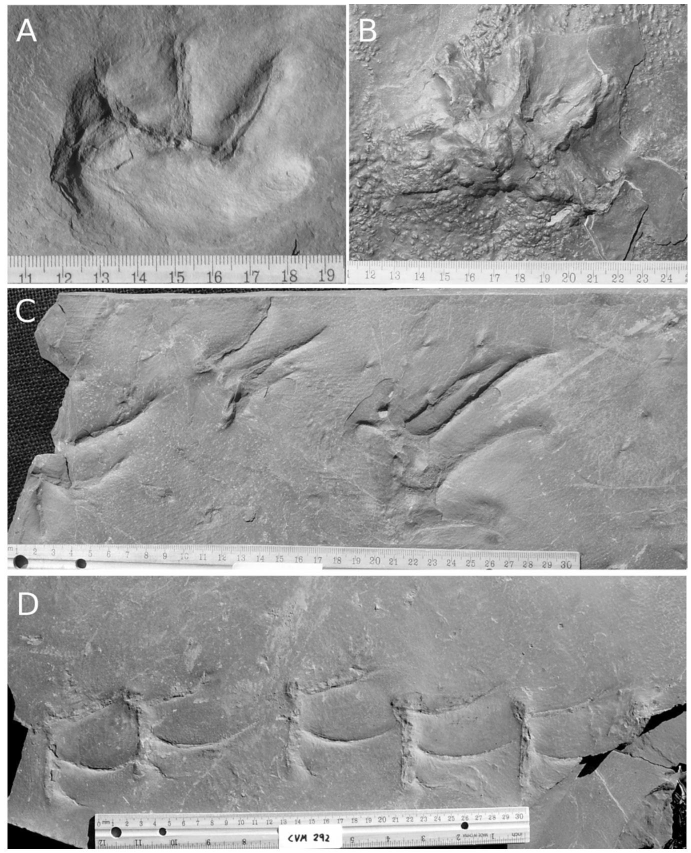

FIGURE 7. *Attenosaurus subulensis*, Crescent Valley Mine, scales in cm. **A**, Single track, negative epirelief, CVM 1036; **B**, single track, positive hyporelief, made on previously dimpled sediment surface, CVM 637; **C**, parts of three tracks, negative epirelief, CVM 641; **D**, five tracks, negative epirelief, CVM 292.

Cincosaurus cobbi Aldrich, 1930
Figs. 9-12

This taxon was revised by Haubold et al. (2005), which can be referenced for emended diagnosis and synonymy. Specimens from the CVM, like those from the Minkin site, are primarily undertracks. They have characteristics consistent with those of *C. cobbi* as described by Haubold et al. (2005) and by Aldrich and Jones (1930). These include: manus tracks with digit imprints splayed; track turned towards the mid-line, with the middle digit imprint at an angle of about 40° to 55° to the direction of travel; digit imprints I to IV successively longer; digit imprint V slightly shorter than III (CVM 1079, Fig. 9C); digit imprints straight or gently curved medio-posteriorly; and digit imprint I short and shallowly impressed. In the undertrack in Figure 9C, digit imprint I is visible only in some manus tracks, and four of the eight manus tracks in this trackway exhibit deeply impressed heel marks. Another shallow undertrack (CVM 786, Fig. 10C) has the best definition of manus digit imprints. This track shows clearly that digit imprint I is by far the smallest, and that digit imprint II is at least 3/4 length of the remaining three. This undertrack is probably slightly deeper than that illustrated in Figure 9C, as indicated by the faint and featureless heel impressions in the former.

Pes tracks in Figure 9C are limited to the imprints made by digits II to IV. There is no heel impression. The two medial digit imprints are long and sinuous, and parallel to the direction of travel. They were made by toes II and III. These are the most deeply impressed, and III is longer than II. Lateral to these, digit imprint IV angles outward at 15° to 35°. Digit imprint V is visible in two pes tracks; its angle of inclination is the

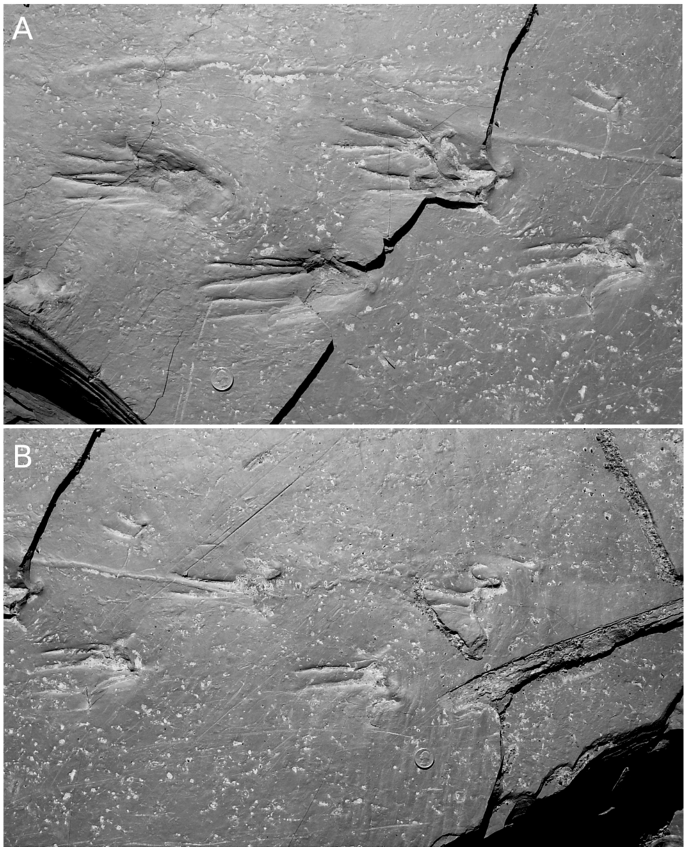

FIGURE 8. *Attenosaurus subulensis*. CVM 1100, the longest trackway of this type found at the CVM. The trackway is 1.17 m long and is shown in two parts. The pictures were taken on-site at low Sun angle. The quarter has a diameter of 0.955 in (2.426 cm). The three main tracks in **A** are doubled and are on a slightly higher layer than the other six. The tracks were in negative epirelief on part of a 1-2 ton slab and were not successfully retrieved from that slab.

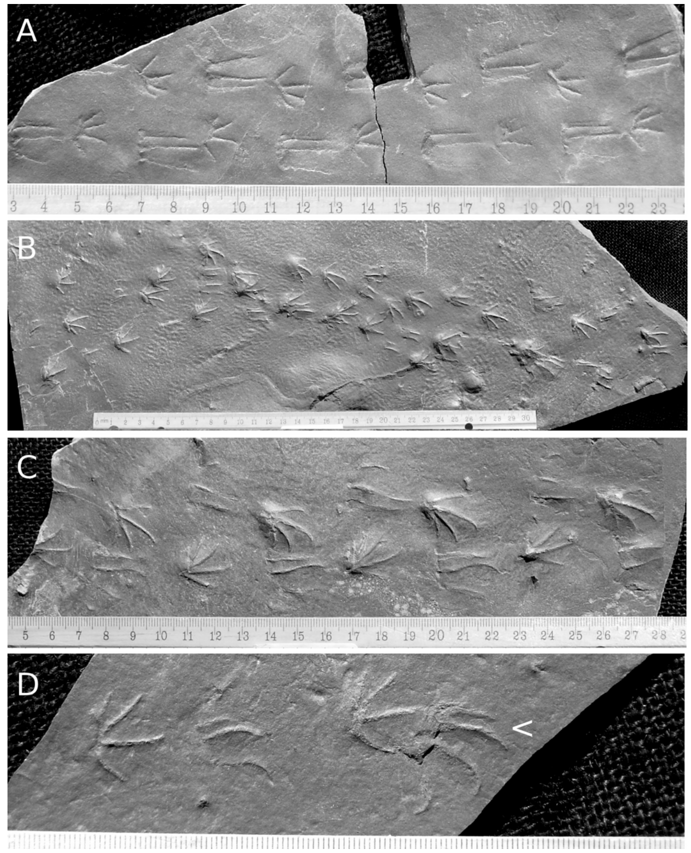

FIGURE 9. *Cincosaurus cobbi*, Crescent Valley Mine, scales in cm. **A**, Well-preserved undertrack made by an animal moving from left to right, manus in front of pes, negative epirelief, CVM 348-349; **B**, Two undertracks that cross, one made center left to lower right (equal spacing) and the other lower left to center right (manus in front), positive hyporelief, meandering horizontal burrow in lower left, foam marks, CVM 634; **C**, Well-preserved undertrack made by an animal moving from left to right, equal spacing, positive hyporelief, CVM 1079. **D**, Complete pes print (short arrow) in *Cincosaurus cobbi*, CVM 15.

same as that of IV. Some undertracks (CVM 348-9, Fig. 9A; CVM 325, Fig. 11A) indicate a short digit imprint I closer to the center line than the rest, and less deeply impressed. The specimen illustrated in Figure 9A, and other specimens, include up to four dimples at the bases of the digit imprints. At least one of the specimens collected at the CVM shows a complete pes imprint (Fig, 9D, white arrow). Pes dimensions are not determinable from the partial undertracks (the same is true for samples from the Minkin site; Haubold et al., 2005 did not quote any pes dimensions).

Figure 12 shows several possible surface trackways recognized as such because they have deeply impressed tail drag marks and sloppy indistinct footprints. The rows of footprints are relatively close together, indicating a narrow gait. The numbers of toes cannot be counted, and parameters such as pace and stride are not determinable.

Trackway parameters have been measured on eight figured specimens, which were chosen nonrandomly because they illustrated various characteristics of the tracks. An additional random sample of 38 specimens was measured in the same way. Every fifth specimen (by accession number, which corresponds to sequence of collection) was examined, but only 38 of these could be measured, because most of the more than 900 specimens contain too few well-preserved tracks to be analyzed (Table 2). The average trackway is 4.9 cm wide, pace averages 3.7 cm, and stride averages 5.9 cm. Manus tracks average 1.6 cm wide and 1.8 cm long; pace angulation averages 107º. Manus track length is a minimum, because digits commonly are truncated in undertracks. All specimens form a coherent array of values for every size measure (Fig. 13A).

Invertebrate Trace Fossils

The Crescent Valley Mine invertebrate ichnofauna consists of *Arborichnus*, *Tonganoxichnus*, *Lockeia*, *Arenicolites*, *Treptichnus*, *Stiaria*, and transitional *Diplichnites*-*Diplopodichnus* traces. Also present are chevronate, feather-stitch and leveéd trails that are similar to *Dendroidichnites*, *Protovirgularia* and *Nereites*, respectively. However, these three morphologies of trails are also observed to intergrade with one another and also extend to string-of-pits, crescent-shaped, and looping *Gordia*-like forms. *Kouphichnium* is notably absent.

Stiaria
Fig. 14A

Stiaria is comparatively rare from CVM in contrast to the material recovered from the Minkin site. Despite extensive collecting efforts, the only known specimen consists of several trackways preserved on a single surface (Fig. 14A). The trackways consist of series of two to three tracks with slightly staggered symmetry. Push-back mounds are present behind the tracks. A continuous medial impression is also present. The slightly staggered to almost alternate symmetry of the trackways and presence of a medial impression distinguishes them from *Paleohelcura*

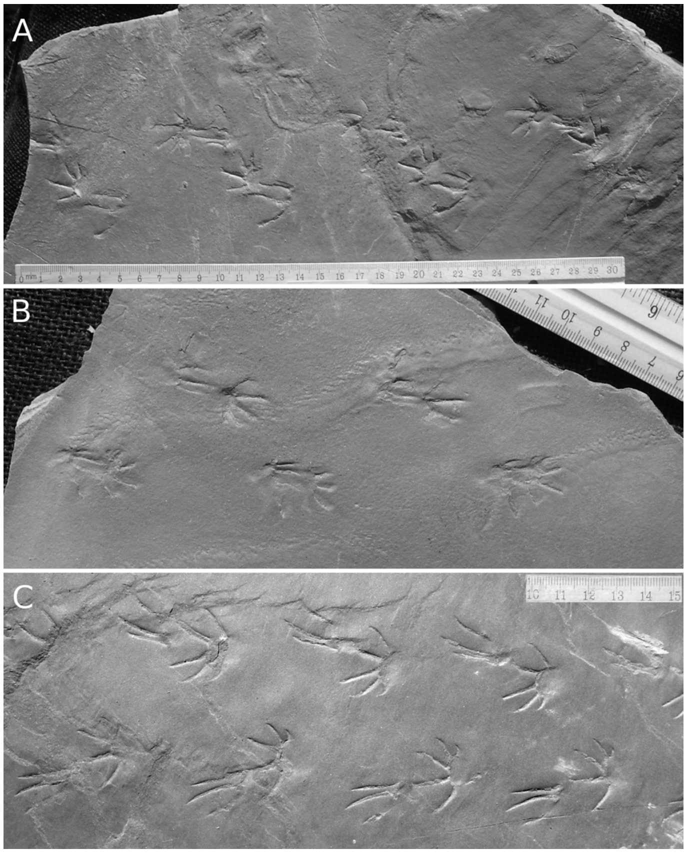

FIGURE 10. *Cincosaurus cobbi*, Crescent Valley mine, scales in cm. **A**, CVM 1081, interesting pattern of nearly overlapping tracks, possible loping gait; **B**, CVM 309, close track pairs with manus in front; **C**, CVM 786, close track pairs with manus behind.

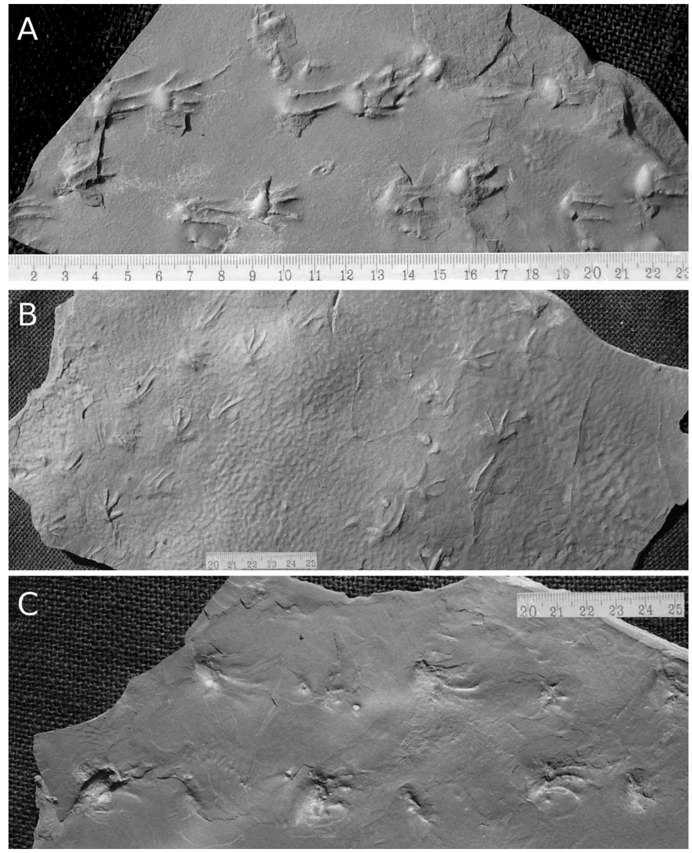

FIGURE 11. *Cincosaurus cobbi*, Crescent Valley mine, scales in cm. **A**, Well-preserved undertrack made by an animal moving from left to right, manus in front of pes, positive hyporelief, CVM 325; **B**, two well-preserved undertracks made by animals moving from bottom to top, pes in front on left, manus in front on right, positive hyporelief, foam marks, CVM 908; **C**, Interesting case of poorly defined shallow undertracks where pes print is large compared to manus; made by tetrapod moving from left to right, evenly spaced, negative epirelief, CVM 182.

(Gilmore, 1926; Brady, 1947, 1961) and identifies them as *Stiaria* (Smith, 1909; Walker, 1985; Buatois et al., 1998a; Minter and Braddy, 2009).

Tonganoxichnus
Fig. 14B

Tonganoxichnus is also comparatively rare from the CVM. Examples are partial, consisting of a pair of anterior medial linear imprints, one pair of lateral linear imprints and an elongate posterior medial imprint (Fig. 14B). Such a preservational style is similar to many examples from intertidal flat deposits from the type locality of *Tonganoxichnus* in the Carboniferous Tonganoxie Sandstone at Buildex Quarry in Kansas (Mángano et al., 1997) and the Permian Robledo Mountains Formation of New Mexico (Minter et al., 2007; Minter and Braddy, 2009).

Diplichnites-Diplopodichnus
Figs. 14C-D

In addition to *Stiaria* trackways, traces transitional between *Diplichnites* trackways and *Diplopodichnus* trails are also present (Figs. 14C, D). These consist of parallel grooves or ridges with superimposed tracks and are similar to material from tidal flat deposits of the Carboniferous Tonganoxie Sandstone of Kansas (Buatois et al., 1997, 1998a, b).

Chevronate, Feather-stitch and Leveéd Trails
Figs. 15-19A

Chevronate, feather-stitch and leveéd trails make up the majority of invertebrate trace fossils from CVM. The chevronate trails consist of a succession of nested chevrons (Fig. 15A, B) and are similar to examples of *Dendroidichnites* (Demathieu et al., 1992; Buatois et al., 1998a; Minter and Braddy, 2009). The feather-stitch trails are similar but there is a greater degree of separation between the chevrons (Fig. 15B, C). The interior angle between the limbs of the chevrons is also more open and, in some examples, almost forms a single line perpendicular to the mid-line of the trail (Fig. 15D). These trails are similar to some examples of *Protovirgularia* (e.g. Mángano et al., 1998) and some may indeed represent true *Protovirgularia*. The leveéd trails typically comprise a central furrow and then raised ridges of sediment on either side (Fig. 16A), and on occasion these ridges are formed of pads or beads of sediment (Fig. 16B). These traces are similar to some modern trails described as being *Nereites*-like (Martin and Rindsberg, 2007). However, true *Nereites* is an endichnial burrow with an axial tunnel and lateral lobes (Mángano et al., 2000). The chevronate, feather-stitch and leveéd trail forms are observed to intergrade in one “Rosetta stone” specimen (Fig. 17), which indicates that they may all form part of a continuum. However, it cannot be ruled out that particular examples represent truly distinct forms and this awaits further comprehensive study. Circular to ovate impressions are also observed along the lengths or at the terminations of some of the trails (Figs. 16B, 17). The different morphologies of the trails may reflect variations in substrate consistency and the position of the animal relative to the observed plane; whether it be crawling on or just above the surface, plowing through the substrate or shallowly burrowing. These trails also extend to string-of-pits (Fig. 18A), crescent-shaped (Fig. 18B, C) and looping *Gordia*-like forms (Figs. 18D, 19A). A further trace is similar to the chevronate trails but has alternate rather than opposite symmetry

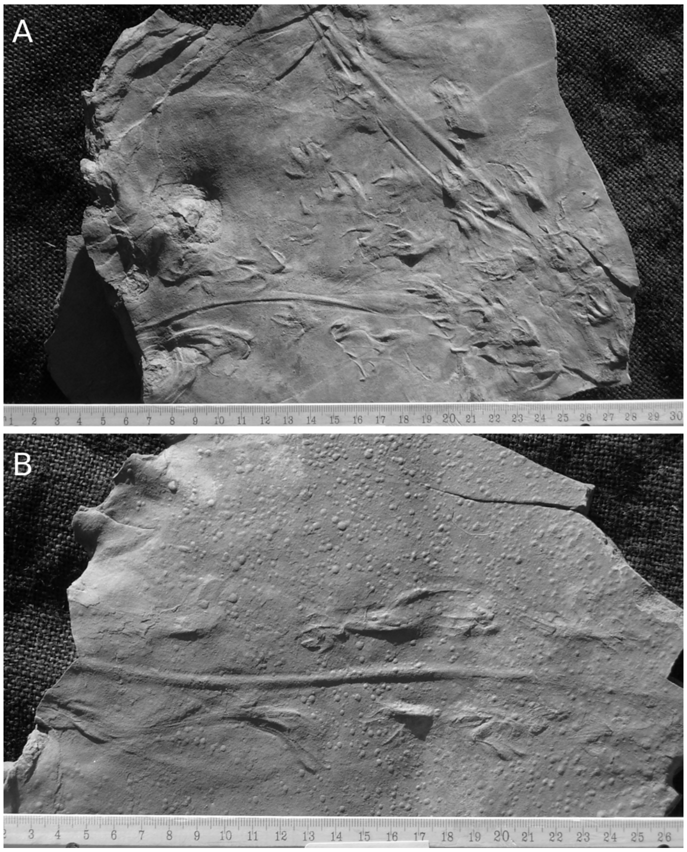

FIGURE 12. *Cincosaurus cobbi*, Crescent Valley mine, surface tracks, scales in cm. **A**, Two tracks with indistinct footprints and tail drag, negative epirelief, CVM 468; **B**, Track with indistinct footprints and tail drag, made on surface subsequently spattered with raindrop impressions, positive hyporelief, CVM 469.

(Fig. 18E). Such a pattern is suggestive of *Lithographus* (e.g. Minter and Braddy, 2009), but the form of the trace is not such that it may be assigned to this ichnogenus with confidence. It is tentatively included within the continuum of chevronate, feather-stitch and leveéd trails herein.

Invertebrate Burrows
Figs. 19B-D, 20A

The infaunal burrows, *Treptichnus* and *Arenicolites*, are also present and in some instances are preserved in association with examples of *Cincosaurus cobbi* (Fig. 19B, D). This scenario is common from the Minkin site (Rindsberg and Kopaska-Merkel, 2005). Examples of *Treptichnus* record the characteristic zig-zag course (Fig. 19B-D) whereas *Arenicolites* is observed as paired burrow tops (Fig. 19D) and the bases of vertical U-shaped burrows (Fig. 20A).

Arborichnus
Fig. 19E, 20A

The CVM section has also yielded examples of *Arborichnus*. In common with the Minkin site, these traces are recorded in a different lithology from those preserving tetrapod trackways and the majority of invertebrate trace fossils (Pashin, 2005). The specimens consist of bilaterally symmetrical scratch traces with five scratch marks on each side oriented perpendicularly to the mid-line of the trace. These traces conform to the diagnosis of *Arborichnus* (Romano and Melendez, 1985). In one specimen, the traces occur in a repeated linear succession (Fig. 19E) as for *A. repetita* (Romano and Meléndez, 1985); whereas they are more random in their distribution and the surface is cross-cut by later shallow U-shaped burrows (*Arenicolites*) in another (Fig. 20A).

TABLE 2. Measurements (in cm and degrees) of CVM trackways.

Specimen	Pace	Stride	Pace angulation	Trackway width	Track placement	Manus width	Manus length
15	3.7	5.2	89.0	5.6	Pes in front	1.9	1.6
40	3.8	5.9	100.4	4.8	manus in front	1.6	1.5
55	4.4	6.3	91.7	7.1	Pes in front	2.0	2.0
85	4.5	6.3		5.1		2.1	
95	3.8	5.9	87.5	5.2	variable	1.6	1.6
115	3.7	5.6	103.7	5.1	Manus in front	1.6	1.6
125	3.6	5.7	104.5	4.9	even	1.6	1.5
155	3.5	6.0	118.3	3.8	Manus in front	1.9	
165	3.3	6.1	137.2	4.8	Manus in front	1.6	1.8
170	2.3	3.9	125.5	4.8	variable	1.1	1.4
195	4.0	6.2	104.0	4.4		1.6	1.5
245	2.0	2.9	88.0	3.2	even	1.3	1.3
260	3.5	5.1	93	4.6	pes in front	1.7	4.2
265	2.9	6.8		4.8	Manus in front	1.8	1.7
285	1.4	2.0	97.5		Manus in front		
325	4.2	6.2	97.3	6.0	Manus in front	1.6	2.1
350	2.5	4	110	3.8	manus in front	1.2	1.4
420	4	6.7	112	4.2	manus in front	1.4	1.6
450	4.7				even	1.5	2.1
615	3.8	6.7	119.0	4.9	even		1.6
625	5.3	7.7	93.0	7.6	Manus in front	2.4	2.7
645	4.1	6.0	91.3	6.8	even	1.9	2.3
645	3.6	5.3	114	4.8	Manus in front	1.4	1.5
690	4.7	8	125	4.9	manus in front	2	3
750	4.4	8.2	138	3.5	unknown	1.6	1.8
760	2.6	4	87	3.6	manus in front	1	0.8
790	2.9	4.6	105.5	3.4	manus in front	1.3	
810	2.8	4.6	108.7	3.4	manus in front	1.1	1.5
865	5.5	9.5	120	6.7	Manus in front	1.8	2.4
905	3.3	6.0	128	4.8	Manus in front	1.5	1.6
915	3.2	5.4	115	3.9	Manus in front	1.6	
1035	4.3	6.1	91	6.3	Manus in front	1.7	1.8
2B left	3.5	5.6	110.8	4.6	pes in front	1.6	1.6
2B right	4.7	7.8	107	4.5	manus in front	2	1.9
3A	5.1	8.7	124.8	5.8	manus in front	2.2	1.8
3B	4.3	6.7	103	4.4	manus in front	1.5	1.5
3C	4.3	5.8	85	7.9	pes in front	2.8	2.4
1A	2.4	4.3	117.9	3.9	manus in front	1.4	1.5
1B	3.6	5.7	106	4.4	manus in front	1.8	1.9
1C	3.4	6	122.8	5.3	even	1.6	2
Mean	3.7	5.9	110.1	4.5		1.6	1.9

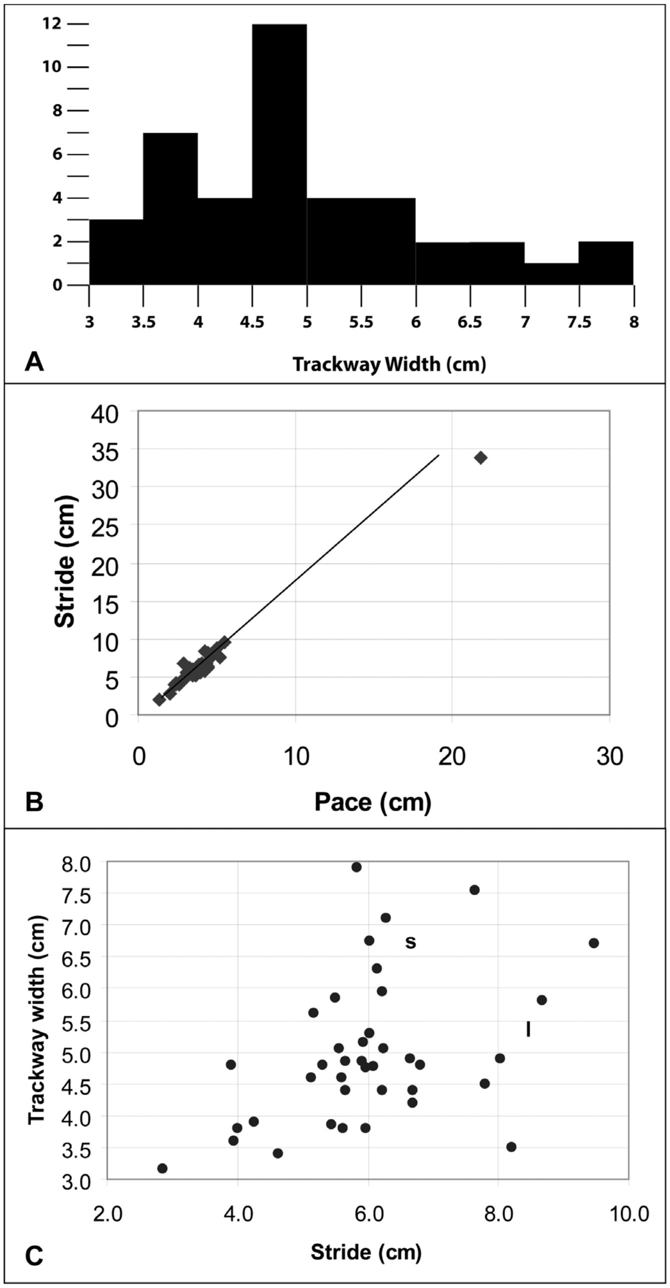

FIGURE 13. **A**, Size distribution of measurements of trackway width in *Cincosaurus cobbi* from the CVM. Unimodal distribution with coarse tail. **B**, Linear relationship between stride and pace in *Cincosaurus cobbi* from the CVM. Large specimen of *Attenosaurus subulensis* fits the trend. Trend line fitted by eye. **C**, Relationship between stride and trackway width for *C. cobbi* from the CVM.

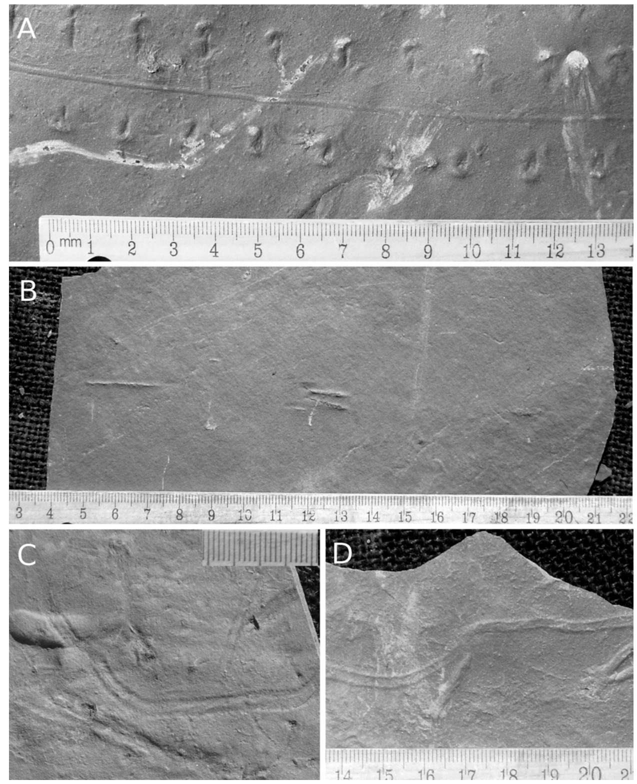

FIGURE 14. Invertebrate traces. **A**, *Stiaria*, CVM 655; **B**, *Tonganoxichnus*, CVM 960; **C**, *Diplichnites-Diplopodichnus*, CVM 221; **D**, *Diplichnites-Diplopodichnus*, CVM 728.

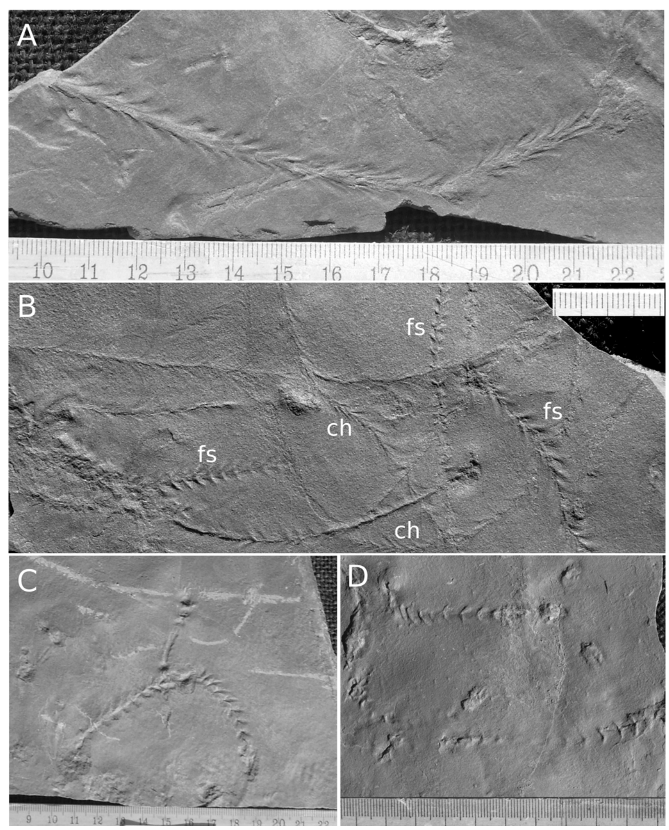

FIGURE 15. Chevronate (**A-B**) and feather-stitch trails (**B-D**). **A**, CVM 27; **B**, CVM 1120, chevronate (ch) and feather-stitch (fs) trails; **C**, CVM 523; **D**, CVM 224.

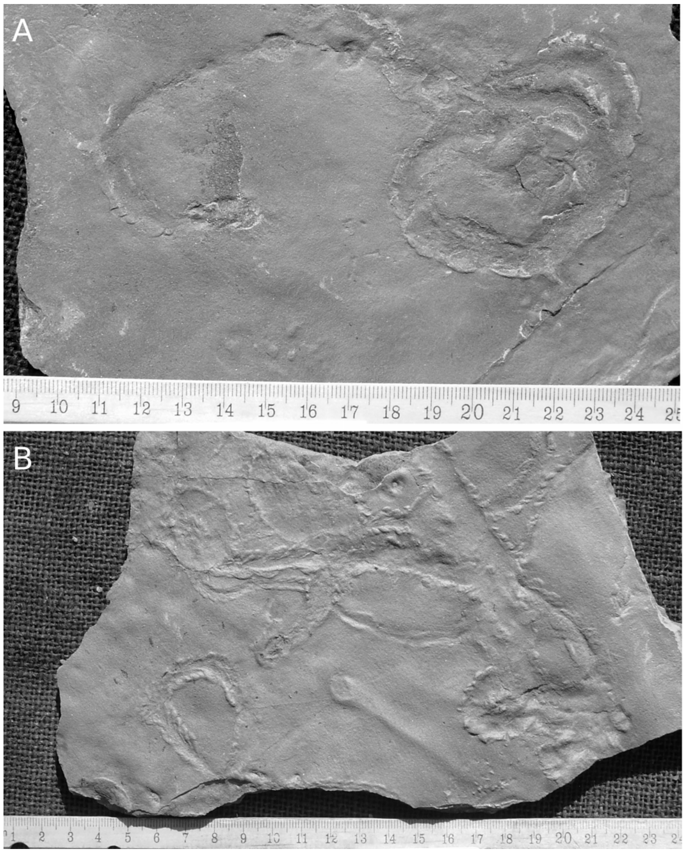

FIGURE 16. Leveéd trails. **A**, CVM 1024; **B**, CVM 955.

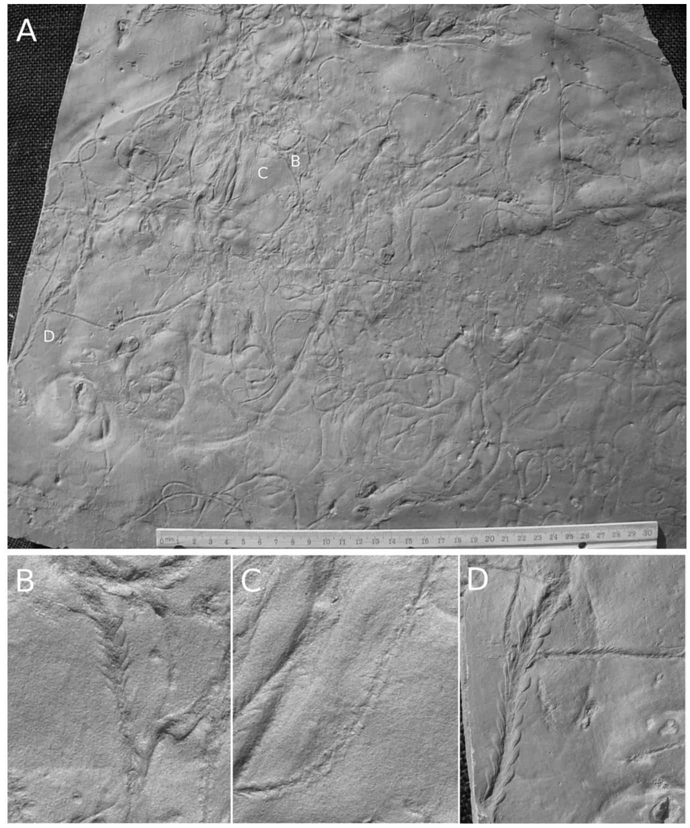

FIGURE 17. Inter-grading of chevronate, feather-stitch and leveéd trails in a single "Rosetta stone" specimen. The points labeled **B**, chevronate, **C**, feather stitch, and **D**, leveéd, are shown enlarged below.

Lockeia
Fig. 20B

Material identifiable as *Lockeia* has also been recognized at the CVM. It consists of small, isolated, thin, almond-shaped traces (Fig. 20B) and conforms to the emended diagnosis of *Lockeia* (Schlirf et al., 2001). The figured example also includes a semi-circular region at one end.

Problematica
Fig. 20C

Aldrich and Jones (1930) also described and named a structure as *Ctenerpeton primum*, considering it to be the impression of the abdomen of a lizard-like animal. However, it most likely represents an abiogenic chevron groove produced by a tool moving over the substrate in a flow (e.g. Dzulynski and Sanders, 1962). Similar structures have also been observed in the course of this study (Fig. 20C).

DISCUSSION

Our qualitative observations of CVM trace fossils indicate that vertebrate trackways are strongly dominated by specimens of *Cincosaurus cobbi*, and that the remaining specimens could all be assigned to *Attenosaurus subulensis*. A thorough examination of all vertebrate trackways found at the site did not turn up a single convincing example of a four-digit manus track, considered diagnostic of temnospondyl amphibian trackways. The 46 trackways of *C. cobbi* for which quantitative data were obtained (Table 2, omitting the large *Attenosaurus*) form a coherent array of values for every size measure, and the size distribution is roughly normal, plus the expected coarse tail corresponding to rare large (old) individuals (Fig. 13A). These measurements provide no evidence for the co-occurrence of two or more populations within *C. cobbi*, whether identified as differing species, genders, or age cohorts. Nearly every vertebrate trackway preserved at the CVM was made by a single kind of small amniote.

The measured CVM specimens of *C. cobbi* in Table 2 encompass a substantial (5-cm) size range in trackway width. To our knowledge, no comprehensive morphometric study of *C. cobbi* has been made that might explain this, and the CVM data are inadequate for that purpose. Still, a few observations are possible. The smallest *C. cobbi* manus tracks are greater than 1 cm wide. Perhaps fear of predation caused very small *C. cobbi* track makers to avoid the soupy mudflats on which tracks were preserved. Alternatively, the smallest known *C. cobbi* may have been made by hatchlings. It is possible that smaller animals were present, but that their tracks were eroded, rather than preserved. Smaller organisms made lasting impressions on the mud at the Minkin site; the trackways of temnospondyl amphibians and invertebrates much lighter than the makers of *C. cobbi* are common there. By contrast, only a few small arthropod trackways have been found at the CVM. Shallowly impressed tracks that are common at the Minkin site (for example, *Undichna*, *Diplichnites*, *Stiaria*) are rare or absent at the CVM. If water energy was slightly higher at the CVM, faint traces could have been destroyed. At least slightly higher water energy levels at the CVM are suggested by flute casts and ripple-cross strata, which are much more common than at the Minkin site.

The largest *C. cobbi* prints measured are less than 3 cm wide, which may correspond to the largest size commonly attained by the track makers, unless *Attenosaurus subulensis* and *Cincosaurus cobbi* were made by mature and immature specimens of a single tetrapod species. Haubold et al. (2005) deemed this unlikely because of the different relative lengths of digit imprints III and IV in the pes track. Specimens from the CVM shed no light on this matter of pes digit proportions. However, other proportions of the long *Attenosaurus* trackway from

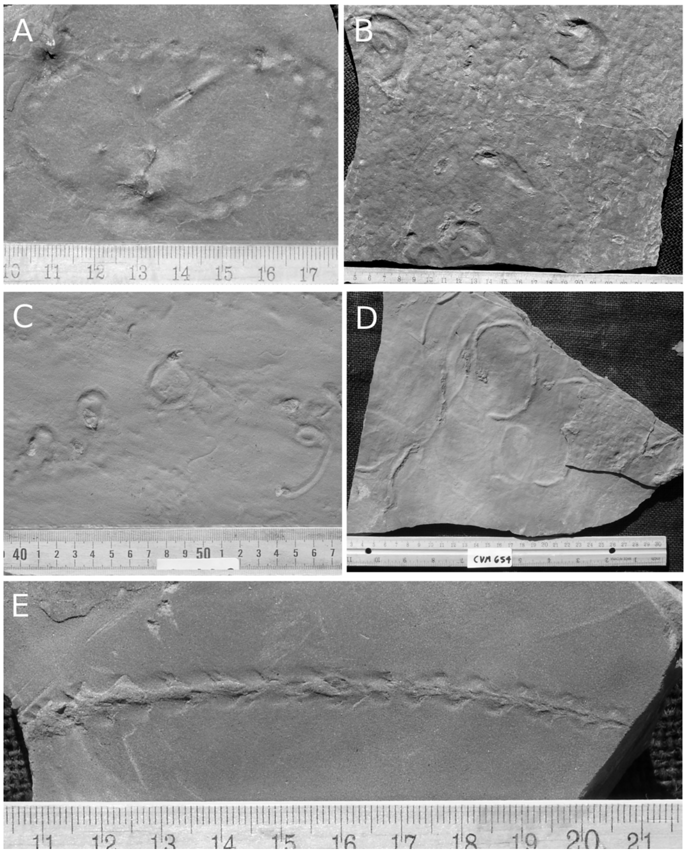

FIGURE 18. Other trail forms. **A**, String-of-pits, CVM 886; **B**, crescent-shaped, CVM 910; **C**, crescent-shaped, CVM 56; **D**, looping form, CVM 654; **E**, form with alternate symmetry, CVM 498.

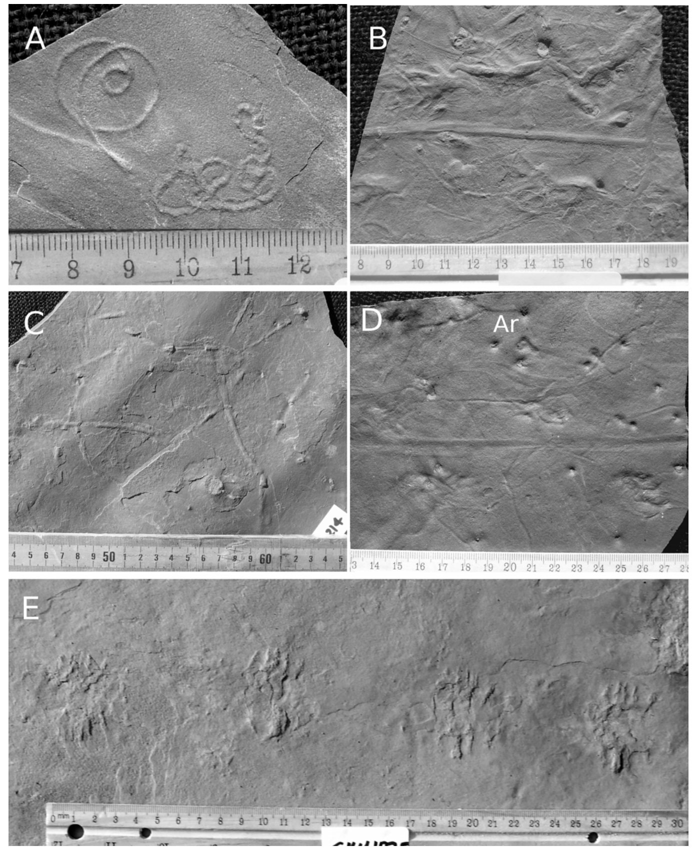

FIGURE 19. Other trace fossils. **A**, Looping form, CVM 872; **B**, *Treptichnus* and *Cincosaurus cobbi*, CVM 365; **C**, *Treptichnus*, CVM 214; **D**, *Treptichnus*, *Arenicolites* (Ar) and *C. cobbi*, CVM 1039; **E**, *Arborichnus*, CVM 1075.

CVM (Fig. 8) are consistent with those of *C. cobbi* from the CVM (Fig. 13B). Although a trendline drawn through the stride and pace data for *C. cobbi* passes very close to the single data point from the large *Attenosaurus* trackway, the size gap (Fig. 13B) is very large. We regard *C. cobbi* and *A. subulensis* as different ichnospecies made by different tetrapod species for two reasons: (1) the great size difference and, (2) the distinct toe morphology reported by Haubold et al. (2005).

Although *C. cobbi* is common at both sites, there were important ecological differences. Temnospondyl amphibians were common at the Minkin site, but conclusive examples have not been found at the CVM. As we noted previously, this suggests that the water at the CVM was perhaps brackish or of more variable salinity than at the Minkin site. In addition, a diverse suite of invertebrate trace fossils that is abundant at the Minkin site is poorly represented at the CVM (*Diplichnites gouldi* on 19 out of 2201 slabs in the Minkin site online database (http://bama.ua.edu/~rbuta/monograph/index.html), 59/2201 *Tonganoxichnus robledoensis*, 542/2201 *Kouphichnium* isp plus *Stiaria* isp, and many hundreds of *Treptichnus apsorum* and *Arenicolites* isp; Kopaska-Merkel, unpublished data). This also might be related to salinity. The presence of *Lockeia* and possible *Protovirgularia* also supports brackish water conditions, at least on occasion; although other trace fossils considered typical of brackish water conditions at this time such as *Teichichnus*, *Psammichnites* and *Asteriacites* (Buatois et al., 2005) are absent.

Spacing of tracks varies from one trackway to another (Table 2; Fig. 10). Some specimens of *C. cobbi* have manus tracks directly in front of pes tracks on either side of the trackway (Fig. 10B), and in some the relationship is reversed (Fig. 10C). The relative positions of manus and pes tracks are related to gait. Specimens with the pes track in front have a shorter stride relative to trackway width (1.0 vs. 1.3) and a smaller pace angulation (93º) than do manus-in-front trackways (110º). Stride is a function of animal size and gait. Trackway width and manus track width are measures of track maker size, so stride is proportional to either for a given gait (c.f., Martin, 2001). By contrast, pace angulation is roughly constant for a given gait. The relationship between stride and trackway width in specimens of *C. cobbi* from the CVM is complex (Fig. 13C). For smaller specimens (trackway width smaller than about 5 cm) most specimens form a single elongate cluster on a graph of stride versus trackway width. Larger specimens form two distinct groups, which are completely separate on the graph. Some individuals took relatively short strides (group "s"), whereas others took longer strides (group "l"). This latter group is characterized by longer manus prints (1.8 to 3.0 cm vs 1.6 to 2.7 cm) and less deeply impressed foot-pad impressions. No evidence of mud spraying behind rapidly moving feet was observed. Group "l" specimens may or may not record faster movement, but Figure 13C does appear to show a differentiation into two different gaits exhibited by larger individuals.

Slabs bearing multiple *C. cobbi* trackways may provide information about interactions between individuals. CVM 908 (Fig. 11B) has two trackways made by animals of about the same size and traveling in the same direction (trackways diverge at an angle of 20º). Both trackways are undertracks, and appear to have been made at a common depth. It is possible that two individuals were moving together. A large slab collected from the Minkin site bears multiple parallel trackways assigned to *Cincosaurus cobbi*, which have been inferred to record group behavior (Martin and Pyenson, 2005). A few other CVM slabs (e.g., CVM 634, Fig. 9B) show multiple trackways that may not be contemporaneous.

Most rock specimens collected at the CVM are relatively small, which limits the opportunity to observe trace fossils in close proximity. Co-occurrence of ichnotaxa on CVM slabs is rare (Figs. 9B, 19B, D, F). Fewer than 2% of samples contain multiple ichnospecies. By contrast, the *Cincosaurus* beds at the Minkin site preserve an ichnofauna that was both more diverse and more densely populated (Buta et al., 2005). For

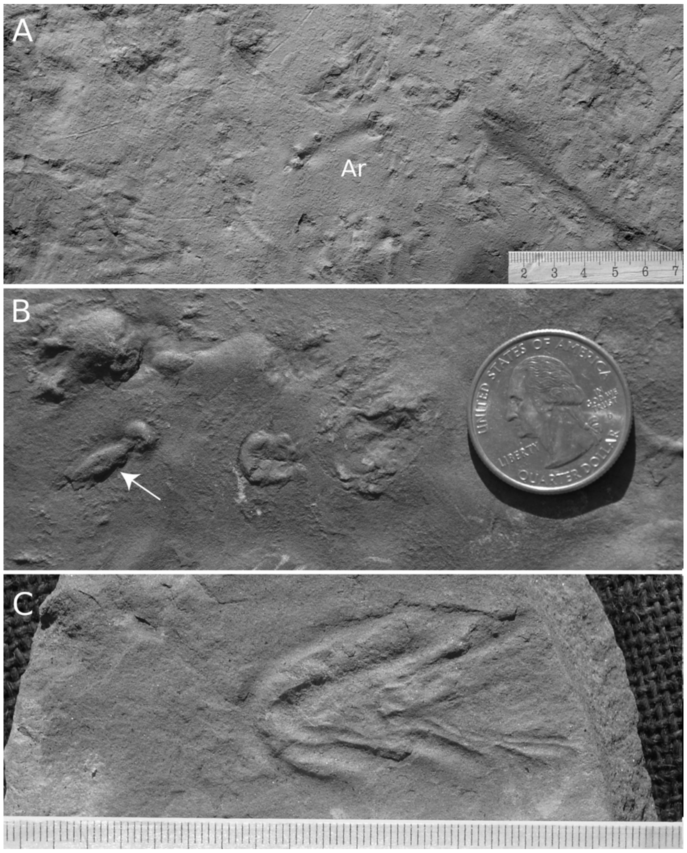

FIGURE 20. Other trace fossils. **A**, *Arborichnus* and *Arenicolites* (Ar), CVM 1077; **B**, *Lockeia* (arrow), field photograph; **C**, *Ctenerpeton primum*, CVM 430.

example, of the 94 specimens of *Undichna* sp. in the Online Trackway Database of Minkin site specimens, about 4% of the entire online database of 2201 specimens, 27 (nearly a third of *Undichna* specimens) co-occur with other ichnospecies (Kopaska-Merkel, unpublished observations). In contrast to the Minkin site, *Undichna* is absent from the CVM. This may be related to the environment and taphonomic conditions, with fish-fin trails and their preservation being most common in inland, freshwater-dominated, low energy parts of tidal flats compared to more seaward environments (Archer, 2004; Voigt et al., 2013).

Of the invertebrate trace fossils, *Tonganoxichnus* and *Stiaria* are both well attributed to apterygote insects including monurans (Mángano et al., 1997, 2001; Minter and Braddy, 2006, 2009). The example of *Tonganoxichnus* resulted as either a resting trace or combined landing and jumping trace; in contrast, the slightly staggered arrangement of the track series in the *Stiaria* indicates they were produced by the legs moving almost in phase as the animal hopped forward a short distance each time. The presence of angular sections in *Treptichnus* indicates that it was made by a short-bodied arthropod and not a vermiform animal. These types of traces are observed to be made by modern insect larvae (Uchman, 2005). *Arenicolites* is attributed to animals including worms and arthropods, and those from the Minkin site have been attributed to the same insect larvae or other arthropod that made *Treptichnus* (Rindsberg and Kopaska-Merkel, 2005). Those *Arenicolites* associated with *Arborichnus* and occurring in a different facies were likely made by different animals from those found with tetrapod trackways and the majority of trace fossils from the CVM.

The chevronate, feather-stitch and leveéd trails are observed to intergrade, which attests to them all being made by the same type of animal. *Dendroidichnites* is generally attributed to a multipodous arthropod such as a myriapod (Buatois et al., 1998a), *Protovirgularia* to a cleft-foot protobranch bivalve (Seilacher and Seilacher, 1994) and *Nereites* to a worm (Seilacher, 1986). The solution as to the producer likely lies in modern *Nereites*-like trails observed being made by juvenile limulids in intertidal sandflats on Sapelo Island, Georgia (Martin and Rindsberg, 2007). Indeed, circular to ovate impressions along the lengths or at the terminations of some of the trails from CVM (Figs. 16B, 17) may represent juvenile xiphosuran resting traces. Alternatively, the possibility that some of these traces were also produced by protobranch bivalves cannot be excluded. This is consistent with the presence of *Lockeia*, which is generally attributed to bivalves (Mángano et al., 1998).

The different morphologies of the trails may reflect variations in substrate consistency and the position of the animal relative to the observed plane, whether it be crawling on or just above the surface, ploughing through the substrate or shallowly burrowing. The trace with alternate symmetry that is tentatively included as part of this continuum (Fig. 18E) is indicative of an animal using an out-of-phase gait. This is characteristic of a hexapod, although the trace lacks other diagnostic features that would allow us to attribute it confidently to such an animal. It may be more parsimonious to include it within the variants of juvenile xiphosuran traces.

The attribution of at least some of the chevronate, feather-stitch and leveéd trails to xiphosurans raises a question. Why is there no *Kouphichnium* at CVM? This ichnogenus is present at the Minkin site but is less common than originally identified (Buta et al., 2005) because the majority of those specimens can be assigned to *Stiaria*. Resolution to this conundrum may be found in the life cycle of xiphosurans. Adults of the extant limulid, *Limulus polyphemus*, migrate onshore en masse to breed. Juveniles then remain in shallow waters for the first couple of moult stages before moving to deeper water (Rudloe, 1979; Shuster, 1979; Braddy, 2001; Martin and Rindsberg, 2007). The trace-fossil recording deposits at CVM may therefore represent such a nursery for juvenile xiphosurans in a shallow water tidal flat setting, where more brackish or variable salinity conditions and tidal processes prevailed. In contrast, *Kouphichnium* at the Minkin site represents the locomotion activities of adult xiphosurans, most likely associated with onshore migration and breeding, in the inland part of the deltaic system, where fresh water conditions prevailed and riverine processes dominated. The rarity of other invertebrate trace fossils such as *Stiaria* and *Tonganoxichnus* at CVM, which are common at the Minkin site, and contrastingly the presence of *Lockeia* and possible *Protovirgularia* at CVM supports this environmental delineation. *Arborichnus*, present at both the CVM and the Minkin site, represents combined swimming and grazing traces of larger adult xiphosurans in more distal facies after they have moved to deeper waters.

CONCLUSIONS

The Crescent Valley Mine near Carbon Hill is now among the best documented tracksites in Alabama. Crescent Valley strata record a different environment than at the Minkin site, which is located 37 km (23 mi) east. Indeed, paleoenvironmental conditions at CVM favored amniotes over temnospondyl amphibians as a dominant vertebrate group, excluded fish-fin traces, and acted as a nursery for juvenile xiphosurans. Although the CVM clearly merits long-term study, the site by law will be fully reclaimed in the near future.

The CVM database provides new and much needed insight into the original No. 11 mine discoveries, by on one hand providing many more specimens from the same area preserved under a wider variety of substrate conditions, and on another by filling the gap on invertebrate traces from the area, which were not described or named by Aldrich and Jones (1930).

We have also shown that the Minkin site and CVM trace fossils are from the same stratigraphic interval, which indicates that Walker County is a megatracksite. Significantly, the megatracksite incorporates an environmental transect from the inland part of a deltaic system, where riverine and fresh water conditions prevailed, to near shore environments, where brackish or variable salinity conditions and tidal processes prevailed. Any new site that opens up in the county and is documented as comprehensively as these mines can add considerably to our knowledge of coastal and coastal-plain environmental conditions and the paleoecology of a wide swath of coal age Alabama.

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