



## Neoichnology of an Arctic fluvial point bar, North Slope, Alaska (USA)

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This study is the first to describe the neoichnology of an Arctic fluvial point bar (Colville River, Alaska, USA) and examine the sedimentological effects of tracemakers in this sedimentary setting. Seasonal extremes in discharge and sediment deposition in this system result in sandwaves, current ripples, gravel bars and mud veneers, with the latter forming extensive mudcracks. Organismal traces are abundantly represented in sandy mudflats on the downstream portion of the point bar and are characterized by: (1) abundant shallow horizontal invertebrate burrows and surface trails, directly comparable to *Treptichnus*, *Cochlichnus* and *Aulichnites*; (2) avian tracks and (3) large mammal tracks. *Treptichnus*-like burrows are attributed to dipteran larvae tracemakers, whereas *Cochlichnus*- and *Helminthoidichnites*-like trails were likely from nematodes or oligochaetes. Avian tracks are primarily from seagulls, geese, swans and plovers; mudcracks were connected directly to tracks, which developed as a result of increased amounts of sunlight available during the polar summer. Mammal tracks were dominated by those of caribou (*Rangifer tarandus*), but include grizzly bear (*Ursos arctos*) and other mammals. Caribou herds significantly impacted emergent and submergent mudflat surfaces through advection of saturated thixotropic muds and dry sand, while also fracturing mudcracked zones, and hence actively produced mud clasts. Vertebrates thus can cause considerable mixing, redistribution and erosion of sediments in Arctic point bars with only a few months of activity. Ichnodiversity was low but accompanied by high trace abundance, reflecting favorable hydrodynamic, solar and atmospheric conditions throughout a polar summer. In contrast, sedimentation and bioturbation are absent during winter months, when ice cover prevents organismal interactions with fluvial sediments. As a result, the ichnocoenose does not fit easily into paradigms of previously defined continental ichnofacies (e.g., *Mermia* and *Scoyenia*) and is more like a composite ichnofacies. These findings can thus serve as a starting point for more detailed studies of circumpolar point bars, while also adding new perspectives to the interpretation of trace fossils in circumpolar fluvial environments.

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### INTRODUCTION

Previous researchers studying the neoichnology in fluvial point bars have emphasized trace assemblages from more temperate settings (Pryor, 1967; Ratcliffe and Fagerstrom, 1980), with the highest-latitude example from nearly 46°N in New Brunswick, Canada (Lawfield and Pickerell, 2006). Similarly, fluvial and lacustrine ichnofacies, e.g., *Scoyenia* and *Mermia*, are based almost entirely on ancient, low-latitude examples from the geologic record, with little consideration of high-latitude ancient or modern ichnocoenoses (Frey *et al.*, 1984; Buatois and Mángano, 1995, 1998, 2002, 2007; Melchor *et al.*, 2006), with the noted exception of works by Uchman *et al.* (2004), Lawfield and Pickerell (2006) and Gingras *et al.* (2007). Moreover, some studies of modern traces and tracemakers in muddy point bars highlight marine-influenced (brackish-water) systems, which

more typically have an impoverished marine ichnoassemblage (Pearson and Gingras, 2006).

In contrast, this study represents a first attempt to describe the neoichnology of a circumpolar (70°N) fluvial point bar, specifically Poverty Bar of the Colville River on the North Slope of Alaska (USA). This study also examines the sedimentological impacts of seasonal infauna and epifauna in such systems, particularly the important role of vertebrates in affecting sedimentary processes, such as soft-sediment deformation, sediment advection, mudcrack development, and production of mudclasts. Furthermore, the ichnocoenosis and the associated physical sedimentary structures described here may provide a model for comparison to trace fossil assemblages and lithofacies of ancient circumpolar facies, such as those of Lower Cretaceous strata of coastal Victoria in Australia (Rich and Vickers-Rich, 2000; Rich *et al.*, 2002; Martin *et al.*, 2007; Martin *et al.*, 2008) and Upper Cretaceous strata of northern Alaska, some of which crop out adjacent to Poverty Bar

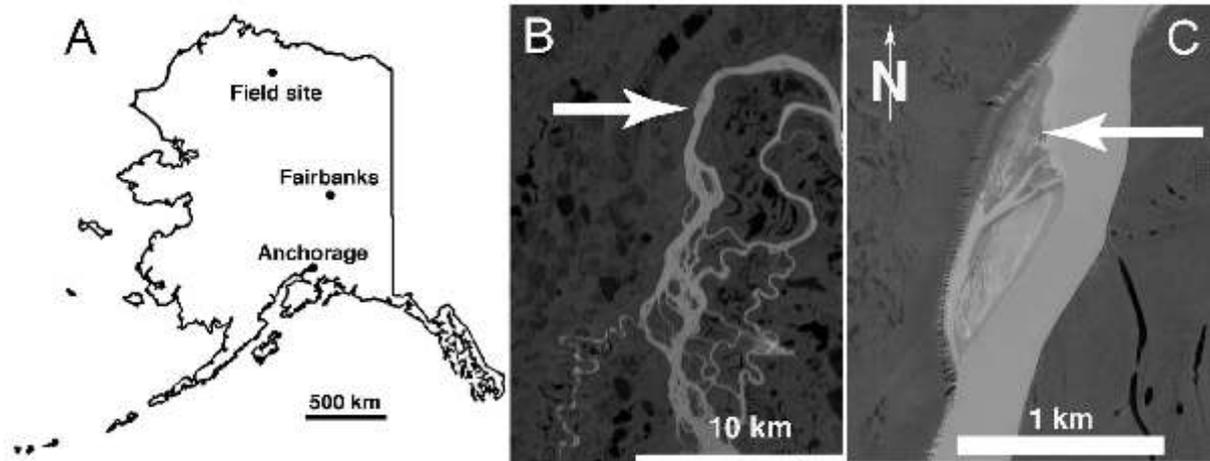


Fig. 1. Location of Poverty Bar, Colville River, North Slope of Alaska (USA)

A — location in North Slope relative to cities of Fairbanks and Anchorage; field site located at  $70^{\circ}4.4'N$ ,  $151^{\circ}33.85'W$ ; B — satellite image of drainage basin for Colville River, showing transition between braided (bottom) and meandering systems (top), location of Poverty Bar indicated; C — satellite image of Poverty Bar, with summertime view of sand- and mudflats in downstream (north) portion examined in this study; images for B and C taken on August 5, 2004, from Google Earth™

(Phillips, 2003; Flores *et al.*, 2007). This study, however, is not meant as a comprehensive overview of circumpolar fluvial neochronology. Instead, it is intended as a first, cursory report that will hopefully inspire more in-depth investigations of modern traces and tracemakers in circumpolar environments through its presentation of preliminary hypotheses that can undergo further testing with future research.

#### STUDY AREA AND DEPOSITIONAL SETTING

Poverty Bar, located at  $70^{\circ}4.4'N$  and  $151^{\circ}33.85'W$ , is a northeast-southwest trending point bar with an area of about 50 hectares (1.0 km long by 500 m wide; Fig. 1). The Colville River basin is located entirely within the Arctic Circle ( $>67^{\circ}N$ ) and drains northward from the Brooks Range and turns east into the Beaufort Sea, crossing the Beaufort Coastal Plain. Poverty Bar is located at the transition between braided and meandering systems in the Colville, with braided systems only about 7–8 kilometres south (upstream) of the study area.

The depositional regime of Poverty Bar and other point bars associated with the Colville River is controlled by seasonal extremes in discharge and accompanying sediment transport (Fig. 2). Mean annual temperature in the region is about  $-12^{\circ}C$  and precipitation is typically less than 100 mm/year, most of which occurs during the summer (Shulski and Wendler, 2007). As a result, the river is frozen and covered by snow and ice for 6–8 months of the year, effectively resulting in little to no discharge or sedimentation during these times. Moreover, permafrosts in the area inhibit infiltration, which enhances already high discharges accompanying spring thaws (Power and Power, 1995; Walker and Hudson, 2003). Recession of water levels by the end of the spring-summer thaw and meltwater runoff (July–September) results in lower flow regimes and bedload transport, resulting in finer-grained sedi-

ment deposition. Consequently, sediment transport and deposition is episodic, normally occurring from May–August (Walker and Hudson, 2003).

The Colville River is also known geologically because of extensive outcrops of the Prince Creek Formation (Late Cretaceous) along the west banks of the river in this area. The Prince Creek Formation has been studied mainly for its geologic significance as a formerly circumpolar deposit containing dinosaur bones (Rich *et al.*, 2002; Phillips, 2003; Flores *et al.*, 2007; Rich and Vickers-Rich, 2008). These outcrops are expressed as 15–20 m high bluffs that limit the westward extent of the river, and their steepness and instability tend to funnel larger vertebrates (e.g., caribou herds and brown bears) through the Colville River valley, which affects track formation and preservation, as well as sedimentological factors, explained in more detail later.

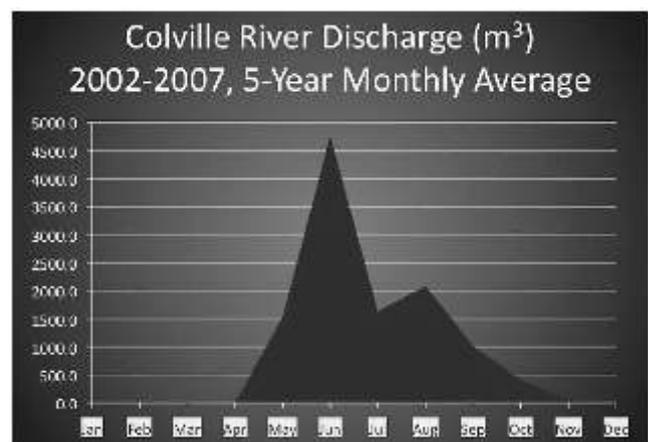


Fig. 2. Hydrograph of discharge ( $m^3$ ) in Colville River

Plotted for a five-year period (2002–2007) using average discharge for each month, from January through December; data from the U.S. Geol. Surv. ([www.usgs.gov](http://www.usgs.gov))

Poverty Bar sediments generally consist of a pebble-gravel foundation, which is exposed in its upstream portion but covered by poorly sorted sand (very coarse-very fine) and mud in its downstream portion. The latter sediments were deposited by ebbing flows toward end of spring-summer thaw and subsequent discharge in May–July 2007, which was waning by the time of my examining the point bar in late July–early August. Muddy layers were thixotropic where still saturated, although drying was probably accelerated as a result of extended daily sunlight from the polar summer. Much of the sand deposited originally by ebbing floods was being reworked by wind and redeposited on the distal bank of point bar at the time of these observations.

### PHYSICAL SEDIMENTARY STRUCTURES

Physical sedimentary structures were quite varied and noteworthy accompaniments to the traces on Poverty Bar (Fig. 3). These structures included prominent and well-developed megaripples (subaqueous dunes) with superimposed linguoid ripples indicating unidirectional flow in a downstream (north-northeastern) direction (Fig. 3A). Smaller-amplitude interference ripples were also evident in places, the probable effects of shifting wind directions on shallow water along the channel margin of the point bar (Fig. 3B). Mud veneers, presumably formed on recently submerged parts of the point bar, also covered most rippled beds. Mud layers varied in thickness from only a few millimetres to more than 20 cm where mud collected in ripple troughs of megaripples and ripples. Normal graded bedding was evident where sand-mud veneers were deposited over gravel-cobble sediments. By the time of my examination in late July–early August 2007, emergent parts of mudflats had also dried sufficiently to form mudcracks in places (Fig. 3C), some wide and deep enough (2 and 12 cm, respectively) to have been filled by aeolian silt and sand (Fig. 3D). Adhesion ripples were also common along some muddy surfaces, where windblown sand had collected on moist, firm surfaces. Tool marks were evident on some rippled surfaces, caused by tree branches transported by the wind; the lack of trees in this area, surrounded in upland areas by tundra, meant these branches were derived originally from far upstream and were part of the stream suspension load (Fig. 3C). Where formerly submerged, branches caused minor, rill-like drainage structures consistent with obstacle-related alterations to flow (Fig. 3E). Minor avulsion channels on parts of the point bar were accompanied by rill marks. Wind ripples were on the landward side of point bar, opposite of the main channel and closer to the bluffs. Lastly, some mudflat surfaces contained clusters of 2–7 mm diameter semicircular domes, which were likely caused by trapped air bubbles just below mud surfaces (Fig. 3F).

Transects across the bar revealed transitions between (from east to west): saturated shoreline muds and sands; dried, emergent mudflats; sandy gravels in cut-off chute deposits; and well-vegetated thalwegs containing a mixture of wind-blown silt and sand, gravel, and cobbles. These transitions also correspond with movement from the shoreline of the main river

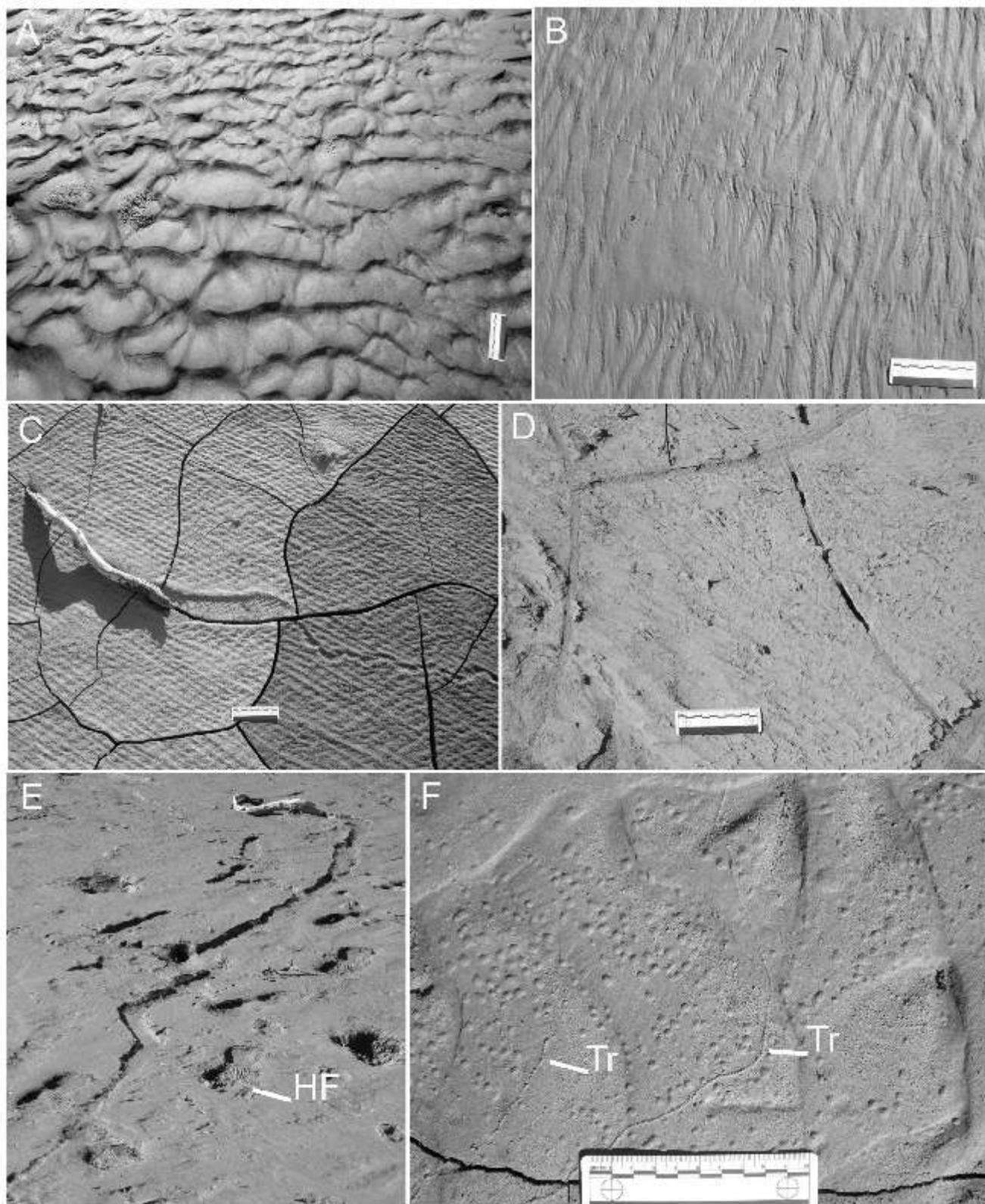
channel to bluffs of the Prince Creek Formation, which laterally (but temporarily) confine the river to the east. The majority of surface sediments on the upstream portion of the point bar, however, are composed of gravel and eolian sand. For the sake of facility, emphasis in this study was placed on describing traces preserved on sandy mudflats of the downstream (lee) portion of the point bar. This sampling bias was justified so that the ichnocoenose could be readily compared to those preserved in similarly fine-grained fluvial facies described from the geologic record (e.g., Frey *et al.*, 1984; Buatois and Mángano, 1998, 2007; MacEachern *et al.*, 2007).

### ICHNOCOENOSE OF POVERTY BAR

#### OVERVIEW

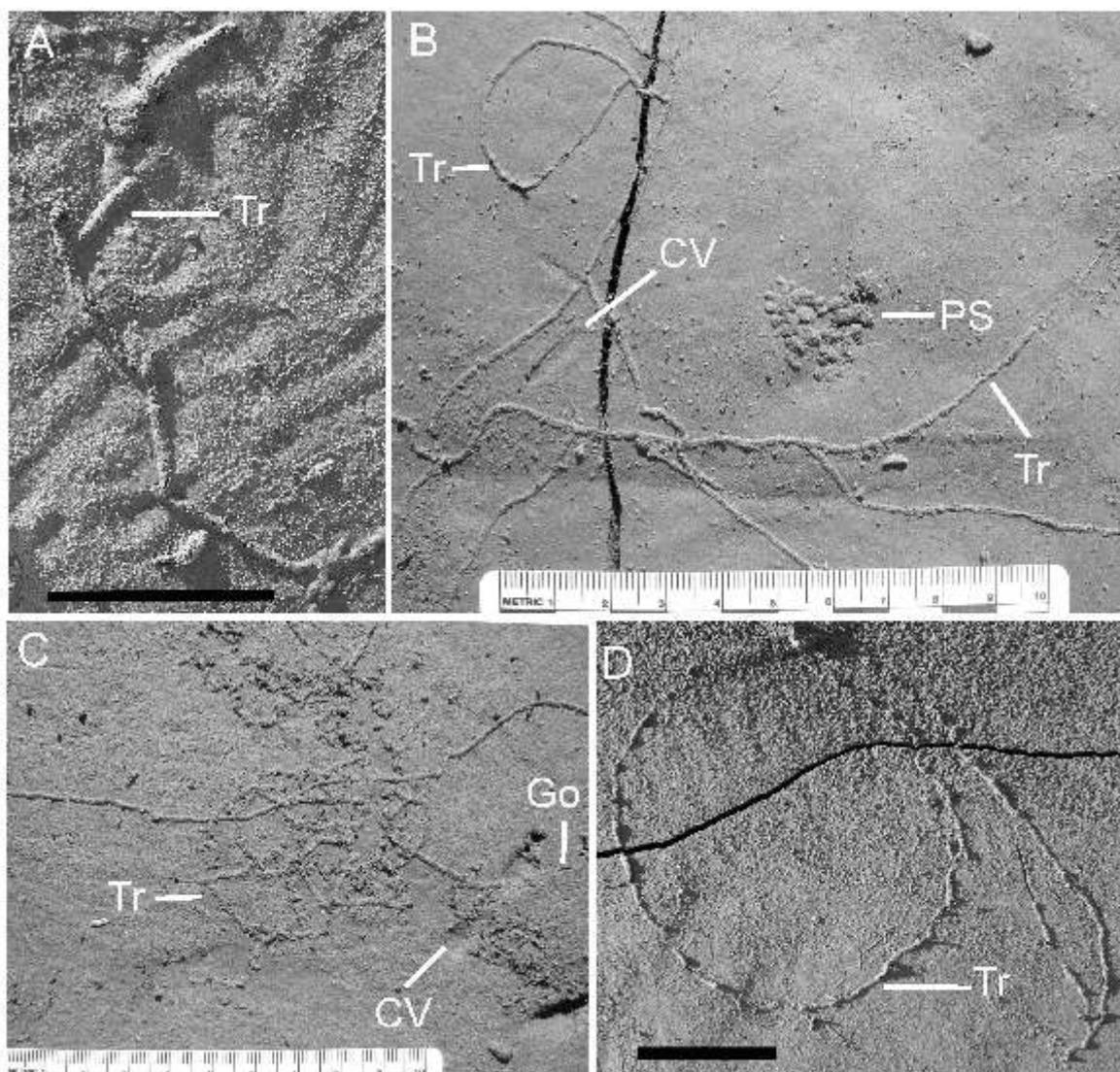
The ichnocoenose in the downstream portion of Poverty Bar is represented mostly by: (1) abundant shallow horizontal invertebrate burrows and surface trails; (2) avian tracks and (3) large mammal tracks. Invertebrate traces are the most common traces numerically, although mammal tracks are the most visible and seem to have caused the greatest volumetric changes to sediments. Invertebrate traces could be categorized as incipient *Treptichnus*, *Cochlichnus*, *Helminthoidichnites* and *Gordia*; no vertical or meniscate burrows (e.g., *Skolithos* or *Taenidium*, respectively) were observed (Figs. 4 and 5). Vertebrate traces were dominated by tracks (Figs. 6 and 7), specifically those of caribou (*Rangifer tarandus*), with relatively minor numbers of avian tracks and rare mammalian carnivore tracks, such as those by brown bears (*Ursos arctos*). Caribou, bears and avians also caused notable sedimentary alterations on point bar surfaces, elaborated later. Overall, the ichnocoenosis could be summarized as having high trace abundance, but low ichnodiversity.

Before providing detailed diagnoses of the traces, three important, and perhaps counterintuitive aspects of the ichnocoenose should be mentioned: (1) the assemblage was more typical of a lacustrine ichnocoenose, such as that of the *Mermia* ichnofacies (*sensu* Buatois and Mángano, 1995, 1998, 2002, 2007), rather than the fluvial ichnocoenose associated with the *Scoyenia* ichnofacies (Frey *et al.*, 1984; Buatois and Mángano, 2002; MacEachern *et al.*, 2007); (2) although invertebrate traces were the most abundant observed on point-bar surfaces, tracks of large mammals comprised the deepest tier, or elite traces (*sensu* Bromley, 1996), and thus were the ones most likely to be preserved in the geologic record and (3) vertebrate tracemakers, particularly artiodactyls (*Rangifer tarandus*) ursids (*Ursos horribilis*), and avians, also enhanced mudcrack and mud-clast formation, sediment advection, and sediment deformation, thus having a significant impact on the sedimentary processes of the point bar. The vertebrate-aided formation of mudcracks is particularly of note, considering the location of this point bar within the Arctic Circle: most previous such examples have been reported from more temperate or subtropical settings (Mason and Bruu, 1978; Master, 1991; Wallace and Wallace, 1992; Martin, 2005).



**Fig. 3. Physical sedimentary structures of Poverty Bar**

**A** — linguoid current ripples along channel margin, with direction of flow toward the viewer (north); **B** — low-amplitude current ripples with smaller, interference ripples developed in troughs; **C** — tool mark caused by aeolian transport of tree branch, on interference-rippled and mudcracked surface; **D** — large-scale mudcracks, partially filled by aeolian sand and silt; **E** — rill mark caused by drainage around obstacle (tree branch), human footprints (HF) for scale; **F** — air-bubble structures on rippled surface, accompanied by *Treptichnus*-like burrows (Tr); scale bar is 10 cm



**Fig. 4.** Invertebrate traces of Poverty Bar, part I: *Treptichnus* and associated traces

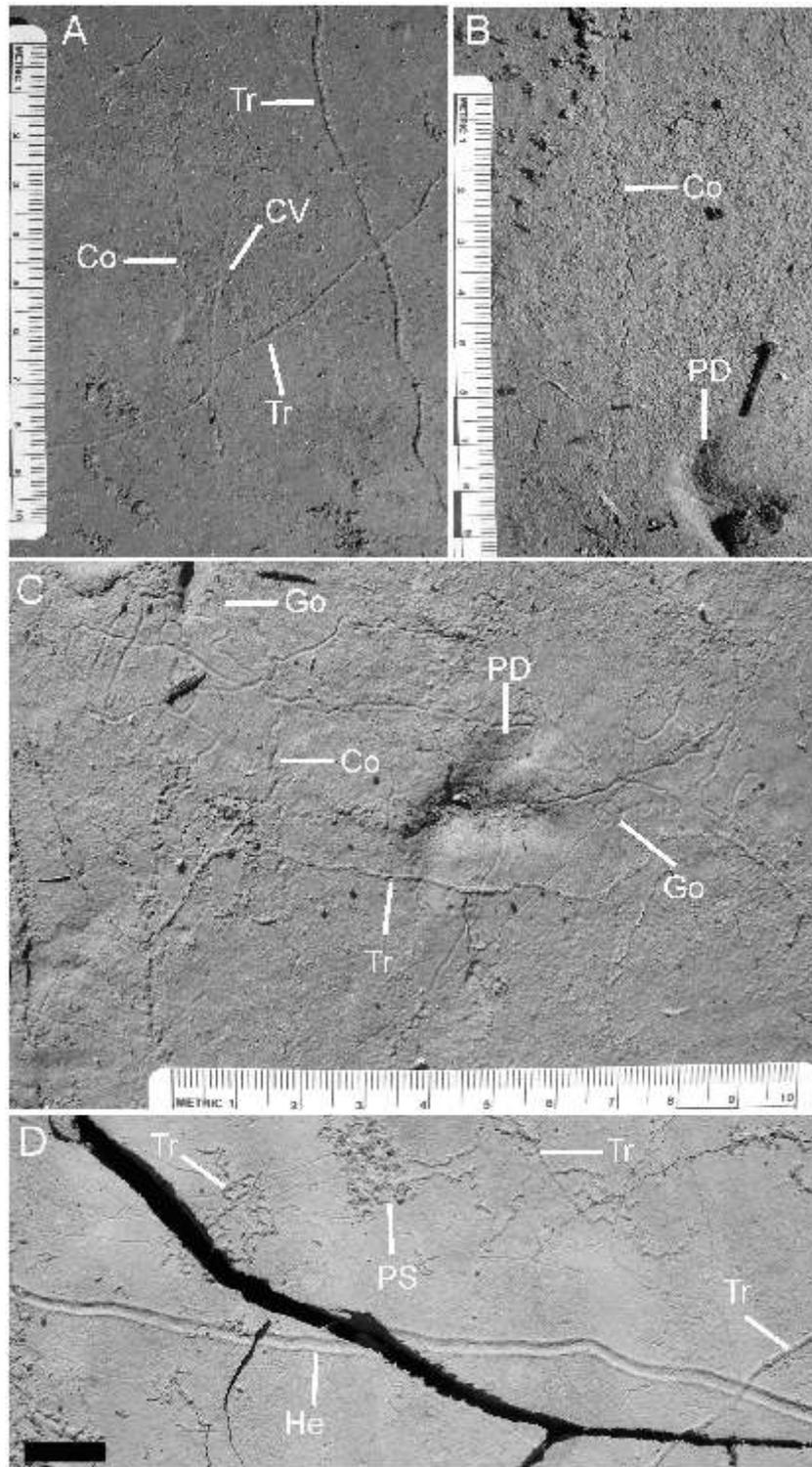
**A** — large-diameter *Treptichnus*-like burrow (Tr), showing offset shallow U-shaped burrows, scale = 10 cm; **B** — small-diameter *Treptichnus* with looping, intersecting and angular patterns, closely associated with possible pupation structures (PS) and killdeer (*Chadrius vociferous* = CV) track, scale in cm; **C** — *Treptichnus* with tight, angular loops, cross-cutting killdeer track (CV) and closely associated with minute *Gordia*-like trail (Go), scale in cm; **D** — large-diameter *Treptichnus* with large (25 × 30 cm) loop, scale = 10 cm

#### INVERTEBRATE TRACES

Invertebrate traces consisted of branching burrows directly comparable to *Treptichnus*, whereas some surface trails coincided morphologically with *Cochlichnus* and *Helminthoidichnites*; a few were also similar to *Gordia* (Figs. 4 and 5). The *Treptichnus*-like burrows were attributed to dipteran larvae tracemakers, whereas the *Cochlichnus*-, *Helminthoidichnites*-, and *Gordia*-like grazing trails were likely made by nematodes or oligochaetes. Unfortunately, none of the tracemakers were directly observed constructing these structures, but their morphological traits allow for preliminary diagnoses.

Linear to looping, interconnected, branching, and shallow U-shaped burrows (*Treptichnus*) were extremely abundant

throughout muddy surfaces of point bar (Fig. 4). Cross-overs of burrows are also quite common, causing false branching amidst actual branching. These burrows had a variety of diameters (<1 mm – 1.5 cm) and lengths of interconnected burrow segments (some nearly 2 m long), implying different but perhaps related species of tracemakers. Burrow geometries were quite varied, and some had repeated looping and cross-overs of burrows. Larger burrows also had slightly offset segmentation along their lengths, an identifying trait of *Treptichnus* (Rindsberg and Kopaska-Merkel, 2005; Uchman, 2005) and probably reflected tracemaker pauses before constructing successive segments (Fig. 4A). Closely associated with the burrows were clusters of short (1–3 mm), ovoid protrusions, which vary in size according to nearby burrows (Fig. 4B). Probable tracemakers of the burrows include dipteran larvae, such as



**Fig. 5. Invertebrate traces of Poverty Bar, part II: *Cochlichnus*, *Gordia*, *Helminthoidichnites* and associated traces**

**A** — *Cochlichnus*-like surface trail (Co), compressed by track of killdeer (*Chadrius vociferous* = CV) and cross-cut by *Treptichnus* burrow (Tr), scale in cm; **B** — *Cochlichnus* near eroded track of American golden-plover (*Pluvialis dominica* = PD), scale in cm; **C** — *Gordia*-like surface trail (Go) cross-cutting *Cochlichnus* (upper left), accompanied by small *Treptichnus*, another *Gordia* and American golden-plover (*Pluvialis dominica*) track; **D** — *Helminthoidichnites*-like surface trail (He) compressing *Treptichnus* (lower right) and cross-cut by mudcrack, accompanied by smaller, branching *Treptichnus* and pupal structures (PS); also note large number of smaller (<1mm diameter) surface trails resembling either *Helminthoidichnites* or *Treptichnus* in geometry

those of chironomids (midges) and tipulids (crane flies), which are very common in Arctic environments (Hershey, 1985; Oswood, 1989; Oliver and Dillon, 1997). Dipterans have been proposed as tracemakers for *Treptichnus* based on morphological clues (bioprints) on trace fossils, as well as modern (incipient) forms (Rindsberg and Kopaska-Merkel, 2005; Uchman, 2005). Accordingly, the ovoid structures adjacent to these burrows are interpreted as probable pupation structures made by the burrowing dipteran larvae.

Co-occurring with *Treptichnus* burrows on the same surfaces were regular and very small (<0.5 mm wide), meandering, sinusoidal surface trails, strikingly similar to the ichnogenus *Cochlichnus* (Fig. 5A, B). The symmetry of these traces is owed to their same-amplitude (about 1 mm) and wavelength (about 3–4 mm) forms, an amplitude: wavelength ratio that overlaps with those of some Oligocene specimens of *Cochlichnus* (Uchman *et al.*, 2004). Some trails have continuous lengths of more than 30 cm; trails also occasionally intersect, imparting false branching. Probable tracemakers were nematodes, which were proposed as the likely tracemakers of continental *Cochlichnus*, although dipteran larvae are also possible producers (Uchman *et al.*, 2004, 2008).

Relatively rare, small-diameter (<1 mm), looping (overlapping), non-meandering surface trails were uncommon but discernable in places on the mudflat surfaces, and were frequently near *Treptichnus* burrows (Fig. 5C). These traces most closely resembled the ichnogenus *Gordia*, which is characterized by its looping and non-meandering form (Wetzel and Bromley, 1996). These trails, like those of the *Cochlichnus*-like trails, were also probably made by small-diameter nematodes, but dipteran larvae have also been implicated in the formation of such traces (Uchman *et al.*, 2008).

Other surface traces included wider-diameter (1–2 mm), straight to slightly meandering, non-overlapping trails with smooth-walled grooves with rounded levees, some of which were more than 60 cm long (Fig. 5D). These traces are similar to the trace fossil *Helminthoidichnites*, which also consists of a central groove and rounded levees (Uchman *et al.*, 2008). In some instances, these trails overlie and compress the *Treptichnus*-like burrows, or cross-cut *Cochlichnus*-like trails, thus post-dating each of these. Tracemakers of these trails were likely larger worms, such as oligochaetes, but possibly could have been made by nematodes and insect larvae. Oligochaetes from freshwater ecosystems of northern Alaska include *Styloscolex opisthothecus* (Holmquist, 2007), but otherwise seem poorly documented. Small-diameter (<1 mm) trails throughout some surfaces also resembled either *Treptichnus* (with short, angular segments) or *Helminthoidichnites* (smoother and slightly meandering), with gradations between morphologies, and were likely made by a tracemaker similar in size to that of the *Gordia* trails.

An interesting aspect of the Poverty Bar invertebrate ichnoassemblage that should be pointed out is what is not there, such as archetypical invertebrate traces normally associated with fluvial ichnoecoenoses. For example, there was no evidence of back-filled meniscate burrows, adhesive or otherwise, such as those attributed to burrowing cicada nymphs or coleopteran larvae (Smith and Hasiotis, 2008; Counts and Hasiotis, 2009). Also, crayfish burrows, a common constituent

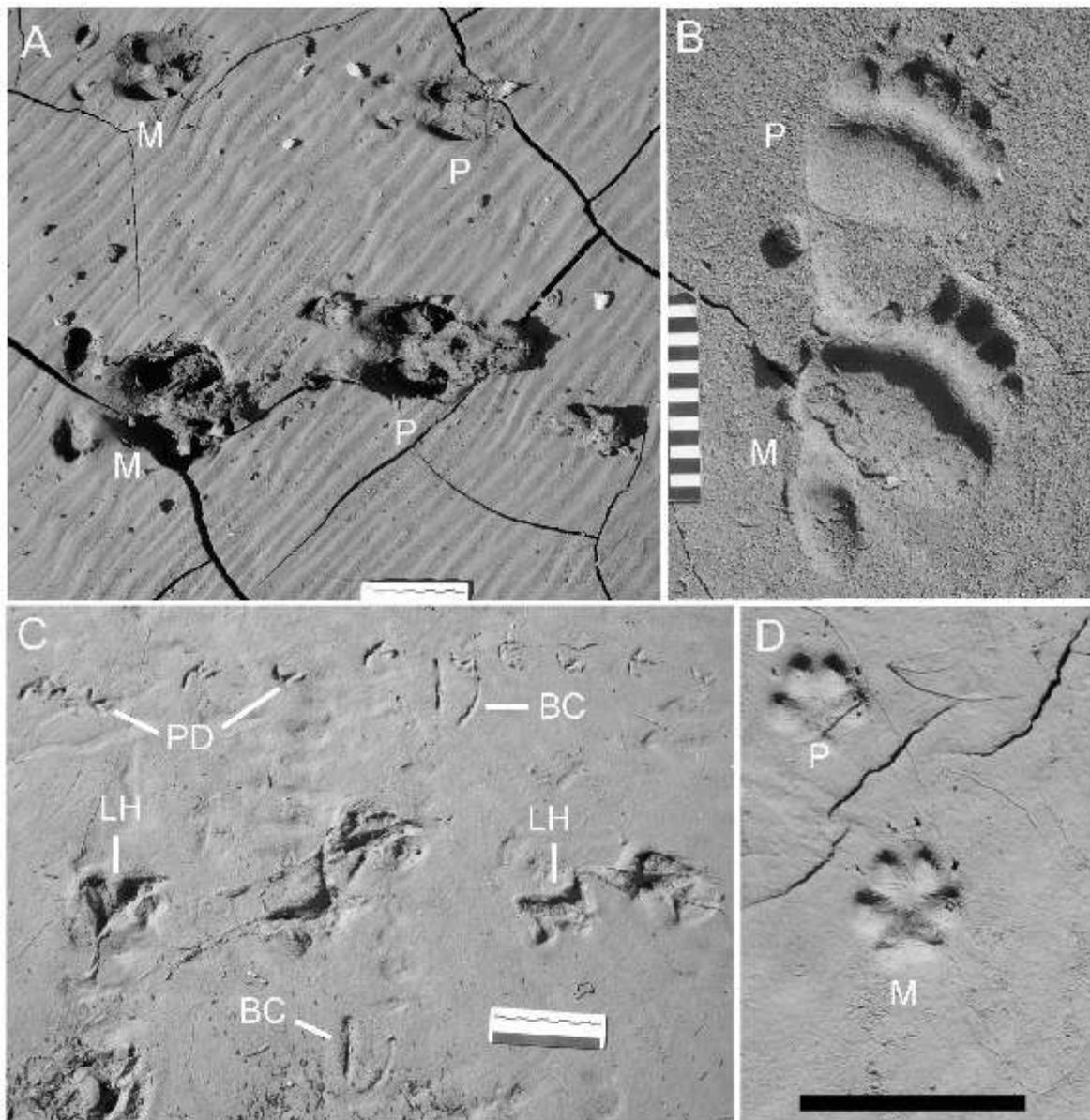
of fluvial ichnoassemblages (MacEachern *et al.*, 2007), were absent from the sediments. This was not surprising, though, as North American burrowing crayfish live at lower latitudes, with a maximum of 54°N for *Orconectes virilis* (Clifford, 1991). In Europe, however, the burrowing crayfish *Astacus astacus* nearly reaches the Arctic Circle, extending as far north as 67°N in Europe (Westman, 1973; Hobbs, 1988). Interestingly, vertical burrows of any type were apparently absent on the examined areas of the point bar, thus negating any ichnological resemblance to the *Skolithos* ichnofacies, which has been noted as a possible ichnofacies in association with high-energy freshwater deposits (Buatois and Mángano, 2007). Additionally, arthropod (insect) trackways would be expected on mudflat surfaces, but none were observed during my examination of the point bar, nor were any obvious in photographs taken from the site.

#### VERTEBRATE TRACES

Vertebrate tracks on Poverty Bar were dominated by those of caribou (*Rangifer tarandus*) and numerically were followed by avian tracks (Figs. 6 and 7). Of secondary importance are tracks of other mammal species, although brown bears (*Ursus arctos*) also imparted sedimentary effects on surface sediments that may have ichnological and sedimentological significance, described later (Fig. 8).

Caribou tracks (Fig. 6A) were identifiable as 8.5–13 cm long and 10–15 cm wide, dual, asymmetrical arcuate impressions imparted by digits III and IV; moreover, digit III is slightly reduced compared to digit IV. Hooves impart these unguigrade impressions, and as is typical of artiodactyls, hooves cut directly across substrate surfaces, making sharp edges and steep walls (as much as 15 cm deep) in tracks, depending on the nature of the substrate. The relatively wider posterior parts of the tracks and differences in digit sizes cause track asymmetry. Otherwise tracks have an outline similar to paired parentheses, and the overall compression shape of a track is semi-circular. With greater depth in the substrate, tracks also showed dew-claw impressions from vestigial digits II and V, posterior to digit III and IV. In caribou, these impressions are angled with respect to the line of travel, and become more perpendicular to that direction with increasing speed (Elbroch, 2005). Manus impressions were slightly larger than those of the pes, but both were somewhat rounded on anterior and posterior edges. On Poverty Bar, trackway patterns varied considerably, as caribou easily moved from slow walks to full gallops when unimpeded by obstacles or substrates. Hence same-side manus-pes pairs were superimposed (indirect or direct register) or separated by more than 20 cm. Trackway widths (straddle) were typically 25–40 cm, whereas walking stride (distance of successive footfalls from the same foot) was 55–80 cm; trackway width decreased with increasing stride lengths, reaching their narrowest (about 20 cm) once caribou were in full gallop, with strides of nearly 1.5 m. Smaller track sizes and strides were associated with juvenile caribou, which often accompanied adults and thus their trackways either paralleled or followed directly behind those of the adults (Fig. 6A).

Brown-bear trackways (Fig. 6B) were present in muddy, sandy and gravelly sediments of Poverty Bar; some trackways

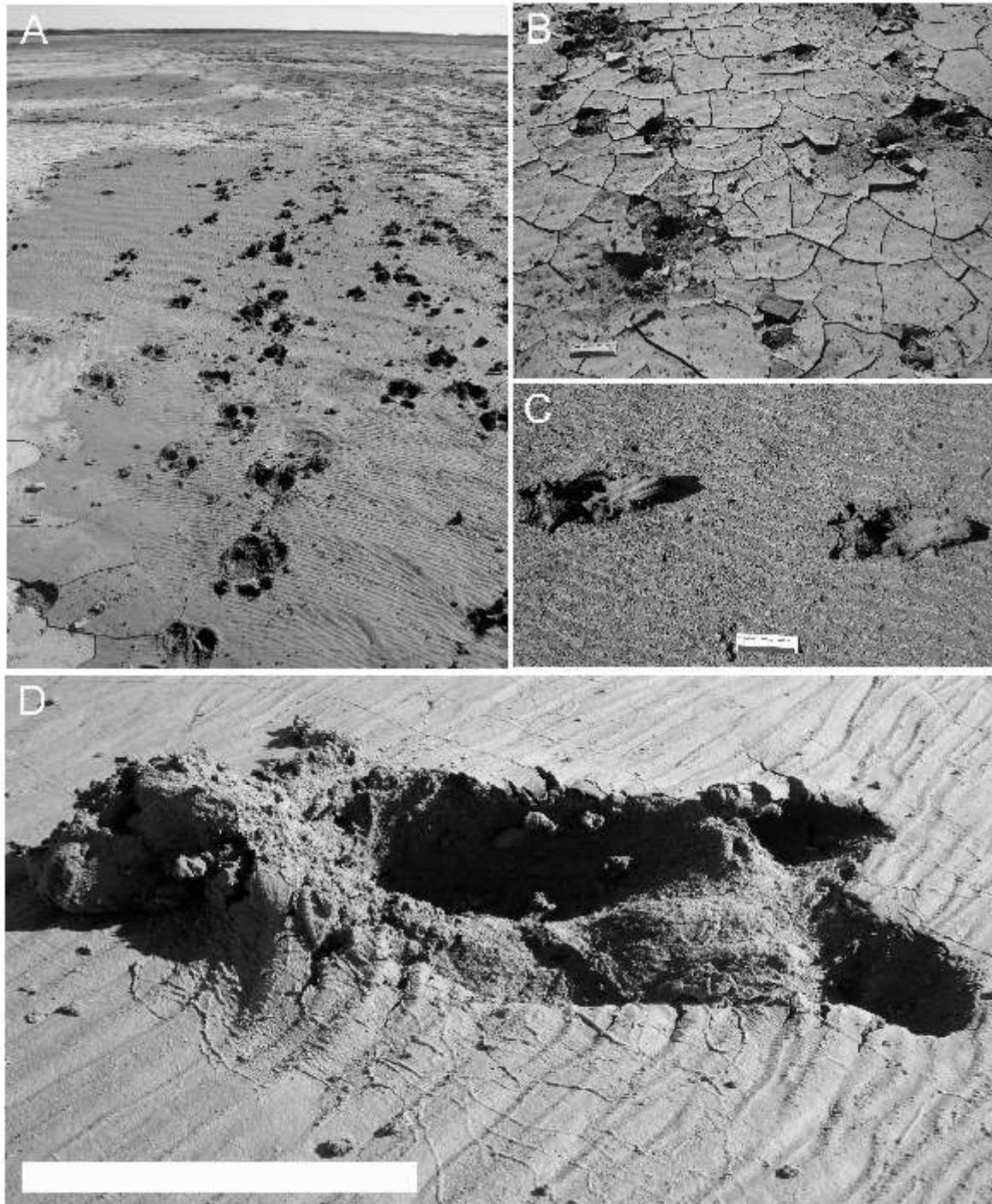


**Fig. 6. Vertebrate tracks of Poverty Bar**

**A** — tracks of caribou (*Rangifer tarandus*), adult (below) and juvenile (above), made in stiff, rippled mudflat undergoing initial desiccation. M = manus and P = pes; both tracemakers were travelling at a fast trot, sufficient to have made dew-claw impressions and pulled mud out of the track floor, scale = 10 cm; **B** — left side manus-pes pair of adult brown bear (*Ursos arctos*), tracemaker was moving at an amble, resulting in indirect register (overlapping) of pes in front of the manus, scale = 15 cm; **C** — avian tracks, representing glaucous gull (*Larus hyperboreus* = LH), Canada goose (*Branta canadensis* = BC) and American golden plover (*Pluvialis dominica* = PD), note differences in mud saturation reflected by degrees of clarity in track outlines, scale = 10 cm; **D** — left manus and pes of Arctic fox (*Alopex lagopus*), movement of tracemaker was at fast trot, scale bar = 10 cm

were extensive (hundreds of metres), but were not nearly as common as caribou tracks. Fortunately, all tracks preceded my investigation of Poverty Bar and some may have been several weeks old. This interpretation was based on their occurrence in formerly submerged muddy areas that were subsequently desiccated, evidenced by soft-sediment deformation structures associated with tracks and extensive mudcracks that cross-cut tracks. Brown-bear tracks were recognizable as 18–35 cm long and 12–22 cm wide footprints, with the pes considerably larger than the manus. Tracks were comprised of prominent oval to

subquadrate proximal and distal pad impressions in the posterior portion of the track, and five digits impressions in the anterior, the latter typically accompanied by clawmarks. Like all ursids, brown bears are plantigrade in their locomotion (Elbroch, 2005), and unlike artiodactyls have softer, fleshy pads that result in rounded edges on track outlines and relatively shallower impressions on firm substrates. Nonetheless, adult brown bears are much heavier than caribou; the largest can weigh more than 500 kg (Glenn, 1980); accordingly, tracks made in saturated, muddy substrates were quite deep (15–20 cm). The baseline gait



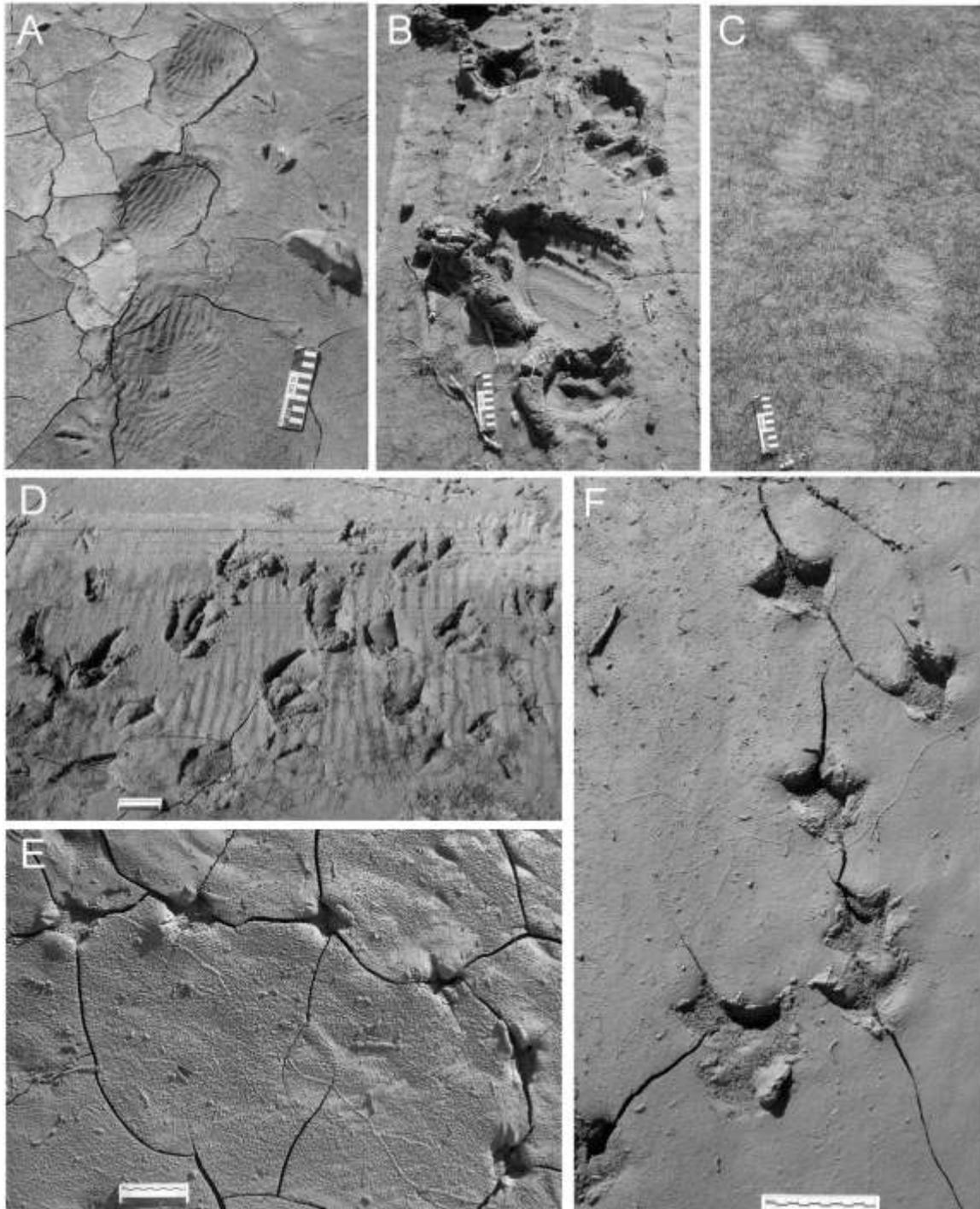
**Fig. 7. Sedimentary effects of vertebrate traces on Poverty Bar, part I: caribou (*Rangifer tarandus*)**

**A** — rippled mudflat surface of point bar affected significantly by caribou tracks; note subparallel movement of trackways (heading north-northeast), influenced by the surrounding topography and Colville River, and crossing of saturated (lighter) and dried (darker) areas of the mudflat; **B** — fracturing of dried mudflat surfaces, sediment advection, and transport of mud clasts as a result of caribou movement, scale = 10 cm; **C** — extrusion of mud plugs from caribou stepping into stiff mud, movement from left to right, scale = 10 cm; **D** — single caribou manus impression viewed from side, showing pressure-release structures associated with application and release of pressure with forward movement (from left to right), note small invertebrate burrows (*Treptichnus*) on the upraised area around the track, discussed further in the text, scale bar = 10 cm

for brown bears is an amble, in which the pes oversteps but indirectly registers on top of the front foot (Elbroch, 2005). Stride for this gait is normally about 55–65 cm, but with increasing speed (to a full gallop) can be as much as 1.1 m. Similar to that of cari-

bou, straddle was about 30–40 cm, with width narrowing in direct correspondence with greater speed.

Avian tracks (Fig. 6C) are primarily from glaucous gulls (*Larus hyperboreus*), Canada geese (*Branta canadensis*),



**Fig. 8. Sedimentary effects of vertebrate traces on Poverty Bar, part II: brown bear (*Ursos arctos*) and avians (*Larus hyperboreus*, *Branta canadensis*)**

**A** — brown-bear tracks (*Ursos arctos*), eroded and having served as site for ripple formation, scale = 15 cm; **B** — brown-bear tracks along edge of former avulsion channel with visible effects soft-sediment deformation, scale = 15 cm; **C** — brown-bear trackway through grassy area evident as bare patches, indicating negative impact on plant growth, scale = 10 cm; **D** — trampling by Canada geese (*Branta canadensis*) caused by flock movement up slope of former avulsion channel, scale = 10 cm; **E** — glaucous gull (*Larus hyperboreus*) tracks connected directly to mudcracks; direction of movement was from lower right to upper left, scale = 10 cm; **F** — glaucous gull tracks connected directly to mudcracks, in which digits I and III served as origination points for mudcrack development, scale = 10 cm

trumpeter or tundra swans (*Cygnus buccinator* or *C. columbianus*, respectively), American golden plovers (*Pluvialis dominica*) and killdeer (*Charadrius vociferous*). Tracks of all species were anisodactyl, with distal webbing

present in tracks of larger birds and proximal webbing in smaller ones. Plovers and killdeers were responsible for making the smallest bird tracks observed on point-bar surfaces, about 2.5–3.5 cm long and slightly wider than long; strides for

these species varied from 5–18 cm. Glaucous gull tracks were intermediate in size, about 5.0–5.5 cm long and as much as 6.0 cm wide; normal walking strides were 50–60 cm. Canada geese and swan tracks, despite their morphological similarity to gull tracks, were considerably larger: geese tracks were 10–12 cm long and 15–17 cm wide, whereas swan tracks were 15–17 cm long and wide. Normal walking strides for geese were 50–60 cm and 60–70 cm for swans. Avian trackways in nearly all instances showed normal bipedal walking with high pace angulations (nearly 170°), but included some rare instances of landing and take-off patterns at the start and end (respectively) of trackways. With such high pace angulations, trackway widths were accordingly quite narrow for all species, typically only slightly more than 1.5 times the track width of the tracemaker. Species of trackmakers were identified by use of Elbroch and Marks (2001) guide to North American bird tracks; only glaucous gulls and killdeer were directly observed during my time there.

Other vertebrate tracks observed on dried muddy surfaces of Poverty Bar included trackways of Arctic fox (*Alopex lagopus*; Fig. 6D), wolverine (*Gulo gulo*) and various small rodents. These traces, however, were relatively rare, with each species represented by only a few trackways. As a result, their sedimentary effects were minor. Moreover, their relative scarcity point toward how such traces could be easily overlooked in an ichnological survey of similar point bars, particularly if investigators are not trained for search images of small vertebrate tracks and other traces.

Based on my limited observations, the caribou had the largest sedimentological impact on the point bar. As large herding artiodactyls that frequently transect saturated sediments, these tracemakers significantly damaged the integrity of emergent and submergent mudflat surfaces on Poverty Bar (Fig. 7). For example, tracks in dried parts of mudflats also caused increased fracturing of dried, mudcracked areas, as well as advection of sand formerly underneath dried surfaces (Fig. 7A and B). Caribou tracks in saturated thixotropic muds also extruded cohesive plugs of mud from 5–10 cm below the sedimentary surface, which were deposited or draped anterior of the tracks (Fig. 7C). Additionally, where caribou traversed dried parts of the point bar, airborne suspension of clay- and silt-sized particles was increased, causing eolian transport and deposition of these sediments. Changes in gait affected the number of tracks within a horizontal distance and the depth of tracks in the substrate. For example, a slow-walking caribou imparted a larger number of tracks on a surface over the course of 10 m than a galloping caribou, but the galloping caribou left deeper impressions and pulled out more sediment from each impact area as a result of greater stress imparted by each footfall. Thus different gaits, especially when multiplied by large numbers of caribou interacting with exposed moist and dried point bar surfaces, resulted in much sediment advection and alteration of substrates during a relatively short amount of time (2–3 months). Furthermore, steep bluffs of the Prince Creek Formation on the west bank of the Colville River restricted the movement of the caribou to along the stream bank, so that trackways showed a high degree of parallelism. Repeated herding hence may have worn trails and encouraged minor avulsion channels on the lower (northern) parts of the point bar. Lastly, caribou are excellent swimmers, which meant their trackways frequently transected sub-

aqueous to subaerial environments and vice versa. In several instances, I witnessed several or individual caribou entering and exiting the Colville River via the point-bar shoreline, which increased bioturbation in these saturated sediments.

Similarly, perhaps the most ichnologically noteworthy aspects of the brown bear tracks were their effects on sedimentation, vegetation and sediment deformation (Fig. 8). Additionally, in at least one instance, brown bear tracks served as shallow depressions that were subsequently covered by water, in which wind-generated ripples developed (Fig. 8A). Bears that walked slope-parallel on the banks of former avulsion channels caused considerable movement of mud downslope and otherwise disturbed sediments in a grand way (Fig. 8B). Furthermore, one trackway was visible as patches devoid of vegetation forming a linear pattern (Fig. 8C). Patches corresponded with the size and compression shapes of manus-pes impressions of an adult brown bear, as well as an amble gait pattern; the tracemaker must have stepped on newly sprouted vegetation, thus preventing its growth. Considering the considerable masses of some adult brown bears, their visible effects on sediment and vegetation should be expected. Nonetheless, vertebrate ichnologists more often point toward large African herbivores (e.g., elephants and hippopotamuses) as models for vertebrate-caused sedimentary deformation (Cohen *et al.*, 1993; Deocampo, 2002; Platt and Hasiotis, 2008), rather than terrestrial carnivores of North America. Avian tracks were also partially responsible for sedimentary deformation of avulsion-channel margins (Fig. 8D), although relatively reduced in impact compared to disturbances caused by brown bears in similar places.

Interestingly, avian tracks were often connected directly with mudcracks and are deemed as responsible for initiating many of these sedimentary structures (Fig. 8E and F). In such instances, avian feet, by their penetration of mud surfaces, exposed underlying sediments to drying, which more easily facilitated mudcrack formation. This sort of mudcrack development is of course also enhanced by the increased amounts of sunlight available during polar summers. Nonetheless, avian tracks and trackways seem to have started a significant number of the mudcracks, a phenomenon noted in other areas (Mason and Bruu, 1978; Master, 1991; Wallace and Wallace, 1992; Martin, 2005), but not in a circumpolar environment. The alternative hypothesis, that avian tracemakers were following mudcracks, is unlikely, considering how these structures are precisely connected to distal ends of digit impressions, an exactness that defies easy explanation as a behavior.

A last observation about the vertebrate traces that should be noted is their possible influence on invertebrate burrows. In at least one instance, minute *Treptichnus*-like burrows were clustered locally in a 5-cm wide zone around the upraised deformations (pressure-release structures) of a caribou track (Fig. 7D). Perhaps these microtopographic variations of a sedimentary surface caused by vertebrate tracks translated into proportionally large differences for small, invertebrate tracemaker and thus affected their burrowing behaviour. Regardless, such direct associations between vertebrate tracks and invertebrate burrows demonstrate that the ichnoassemblage fulfills the definition of an ichnocoenosis as an ecologically consistent and contemporaneous collection of traces (Bromley, 1996).

## IMPLICATIONS AND APPLICATIONS OF RESULTS

Based on these results, the ichnodiversity of this circumpolar fluvial point bar was low, with only four incipient ichnogenera of invertebrate traces (*Treptichnus*, *Cochlichnus*, *Helminthoidichnites* and *Gordia*) and, with minor exceptions, vertebrate traces dominated by artiodactyl tracks made by a single species. Nonetheless, trace abundance was quite high, and parts of the point bar were bioturbated extensively on sedimentary surfaces by invertebrate burrows and vertebrate tracks, significantly altering physical sedimentary structures and sediment composition. Trace diversity and abundance, however, reflects favorable seasonal conditions and changes in hydrodynamic, solar and atmospheric conditions throughout a polar summer. In contrast, sedimentation and bioturbation would be nearly absent during winter months, or limited to small vertical burrows made only by a few organisms adapted to anoxic conditions, such as chironomid larvae that mine oxygen from algae during the winter (Gingras *et al.*, 2007). Perhaps the most significant conclusion of the study regards the considerable effects of small-scale and large-scale bioturbation on mixing, redistribution and erosion of sediments in this sedimentary environment during such a short, seasonally dependent time span. These findings should thus serve as a starting point for future, more detailed studies of the intersections between organismal activities and the sedimentology of circumpolar point bars, while also adding new perspectives to the interpretation of trace fossils from similar environments (e.g., Martin *et al.*, 2008).

The ichnocoenose does not easily fit any currently defined continental ichnofacies. With regard to its invertebrate traces, it contains elements of the *Mermia* ichnofacies, which has surface trails and shallow burrows, such as *Gordia*, *Cochlichnus*, *Helminthoidichnites* and *Treptichnus* (Buatois and Mángano, 1995, 1998, 2002, 2007), which match the main incipient traces in the Poverty Bar assemblage. The *Mermia* ichnofacies, however, lacks trackways; these are more typical of the *Scoyenia* ichnofacies, which is defined as having an abundance of invertebrate burrows, such as *Scoyenia*, *Taenidium* and adhesive meniscate burrows (MacEachern *et al.*, 2007). In contrast, the Poverty Bar ichnoassemblage is dominated by vertebrate tracks, none of which are aquatic species, either (although caribou are facultatively aquatic). In other words, the Poverty Bar ichnocoenose contains elements of both the *Mermia* and *Scoyenia* ichnofacies, which are interpreted broadly as representative of submerged lacustrine and intermittently emergent fluvial facies, respectively (MacEachern *et al.*, 2007). Because sedimentary structures, particularly biogenic ones, represent ichnofacies, ichnofacies are products of overall environmental conditions (including ecological factors), and not necessarily depositional environments. As a result, a low-diversity ichnocoenose of trails and horizontal burrows (*Mermia* ichnofacies) reflects animal behaviour in quiet-water, aqueous conditions. In contrast, subaerial exposure may bring conditions suitable to different behavioural activities and traces, such as the production of trackways (*Scoyenia* ichnofacies), thus making for a composite ichnoassemblage, representing mixed

elements of the two ichnofacies and formed within only a few months. Of further interest is how vertebrate tracks can also apparently encourage more burrowing (Fig. 7D), a sort of positive feedback that is undocumented from neoichnological studies dealing with the *Scoyenia* ichnofacies.

The absence of vertical burrows that might be typical of the *Scoyenia* ichnofacies, however, does not imply that environmental controls on vertical burrowing were absent, as hydrological data and the physical sedimentary structures of Poverty Bar clearly indicate high-energy subaqueous environments. The lack of vertical burrowing may be more attributable to the overall climate-related conditions, namely the very short time between formation of subaqueous sandy and muddy surfaces in late spring and the resumption of biological activity soon afterwards in early summer. The latter would have coincided with receding flood waters, when sedimentary surfaces would have become more exposed. As a result, lithofacies produced in such a situation would show relate high-energy aqueous facies overprinted by a low-energy and subaerially exposed facies. Furthermore, an unskeptical assessment of the ichnofauna as representing a *Mermia* ichnofacies would suggest low-energy conditions, although this ichnoassemblage could be overprinted by a *Scoyenia* ichnofacies. Thus in this instance, the overarching control on the formation of the ichnofacies is climate, which has been rarely considered when evaluating ichnofacies.

With regard to ancient facies, Uchman *et al.* (2004) noted a similarly mixed ichnoassemblage from fluvial-pond deposits in the Lower Freshwater Molasse (Oligocene) of Switzerland, in which a presence of vertebrate tracks suggested a *Scoyenia* ichnofacies; yet invertebrate trace fossils were more typical of the *Mermia* ichnofacies. Uchman *et al.* (2008) also noted a *Mermia* ichnocoenosis in a Pleistocene glacial lake deposit, but commented that its abundant arthropod trackways were atypical for a *Mermia* ichnofacies, as defined. Buatois and Mángano (2002) also recognized two possible ichnoassemblages in fluvial floodplains, one fitting a typical *Scoyenia* ichnofacies (tetrapod tracks and meniscate burrows) and the other more of an “impoverished” *Mermia* ichnofacies. Abundant shallow or superficial trails and burrows (e.g., *Treptichnus*, *Cochlichnus*) characterize the latter, although Buatois and Mángano (2002) also stated that tetrapod tracks would be rare in such a setting, which is contradicted by the Poverty Bar ichnocoenose. Again, ichnofacies distinctions are often based on ancient continental ichnoassemblages and at lower latitudes (Lawfield and Pickerell, 2006), so it is not surprising that the modern ichnocoenosis of Poverty Bar differs sufficiently that it cannot be placed neatly in any previously defined continental ichnofacies.

Thus I am in agreement with Keighley and Pickerell (2003) that current freshwater ichnofacies are “too broadly defined” and may “...allow for the inclusion of ichnocoenoses that are better considered representatives of composite ichnofacies.” As a result, future considerations of continental ichnofacies, particularly those associated with fluvial systems, should include the differences imparted by latitudinal or altitudinal factors. These seasonal effects on the sedimentological and ichnological content of freshwater environments are particularly acute in circumpolar environments, and should be of paramount importance whenever examining any suspected high-latitude trace fossil assemblage.

## FUTURE RESEARCH

The North Slope of Alaska contains hundreds, perhaps thousands of point bars emergent during summer months that likewise contain organismal traces from the intense biological activity accompanying this season. As a result, the first step of recommended future research should be an examination of other point bars within Colville River drainage basin and other North Slope rivers, if for nothing else to avoid an overdependence on the limited observations of this study. Other suggested research should attempt more precise identification of invertebrate tracemakers in circumpolar settings. For example, this study is vague about species of dipteran and nematode tracemakers, but exact about vertebrates. With such information in hand, finer comparisons can be made between Arctic ichnocoenoses and those of low-latitude fluvial point-bars. Finally, such better-defined modern ichnocoenoses can then be compared or contrasted with trace fossil assemblages of ancient fluvial facies from polar palaeolatitudes (e.g., Cretaceous of Victoria, Australia: Rich and Vickers-Rich, 2000; Rich *et al.*, 2002; Martin *et al.*, 2007, 2008). This situation can potentially lead to a better understanding of seasonality as a factor in continental tracemaker behavior, trace production and sedimentation in the geologic record.

## SUMMARY

This study is the first to describe the neoichnology of a circumpolar fluvial point bar, specifically Poverty Bar of the Colville River on the North Slope of Alaska (USA). The ichnocoenosis was observed on the downstream portion of downstream point-bar surfaces during late July–early August 2007. Trace numbers were high but of low diversity, largely consisting of shallow invertebrate burrows and trails attributed primarily to dipteran larvae and nematodes, as well as tracks made by artiodactyls (caribou) and ursids (brown bears). Extended daily daylight during summer months encouraged biological activity and some preservation of traces, although vertebrate tracks on point-bar surfaces were also responsible for major sedimentary alterations, such as: soft-sediment deformation; sediment advection; initiating the formation of mudcracks; breaking apart of mudcracked surfaces; and forma-

tion of mud clasts. The sedimentological effects of circumpolar tracemakers should be considered with any future study of either modern or fossil trace assemblages.

The invertebrate ichnocoenosis of Poverty Bar most resembles that of the *Mermia* ichnofacies, which is associated with lacustrine environments, but its abundant vertebrate tracks fit into the *Scoyenia* ichnofacies, which is connected with fluvial environments. As a result, the Poverty Bar ichnocoenosis more resembles a composite of the two ichnofacies, despite its fluvial setting. The mixture of this trace assemblage is thus more like a marginal and periodically emergent lacustrine environment, which is a direct effect of the extreme seasonality of hydrologic, sedimentological and biological factors in the Arctic Circle. Consequently, future neoichnological studies of fluvial systems, particularly of high-latitude ichnoassemblages, should take into account seasonal effects on trace production and preservation, as well as how such seasonality may contradict standard interpretations of freshwater ichnofacies in the geologic record (Keighley and Pickerell, 2003).

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