

Paleopathology in Late Cretaceous Hadrosauridae from Alberta,
Canada: with comments on a putative *Tyrannosaurus* bite injury
on an *Edmontosaurus* tail

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Darren to add: Hadrosaur tail drag paper

Minor corrections:

Then 6 lines down from paragraph, “then” → “and”

Centra – review numbered comments re consistent grammar – sentences or not.

Vertebrae-Caudal, line 3 – should read “vert. An”

Abstract

Late Cretaceous hadrosaurs from southern Alberta, Canada provide the best preserved and most numerous examples of dinosaurian osteopathy globally and are ideal for invasive or non-invasive studies such as histology, X-ray, CT or MRI scanning. Enough specimens have been observed in the field and museum collections to demonstrate predictable patterns of osteopathy, not only in representative types, but in some cases, in regards to body position and relative ontogenetic stage. Hadrosaurs account for about 60% of all dinosaur paleopathology seen in Royal Tyrrell Museum collections (higher % in the field), the world’s largest repository for examples of dinosaur paleopathology, likely only surpassed by that secured from the Pleistocene La Brea tar pits in California.

While osteopathy was observed in animals of all ages (including neonate), most were found affecting ribs and especially the caudal vertebrae of adults. Examples often show active healing of fractures, but there are few cases of complete bone repair.

Paleopathology among Alberta Hadrosauridae are reviewed and prior interpretation of an instance of caudal osteopathy in an *Edmontosaurus* tail as being the result of failed predation by *Tyrannosaurus* discussed and refuted.

Introduction

The fossil record provides glimpses into animal behavior, as well as its morphology (Rothschild and Martin, 1987, 1993, 2006). Study of paleopathology in its strictest definition examines diseases or pathologic conditions. Analyzing paleopathology as a population phenomenon allows unique insights into habitat and behavior (Rothschild and Martin, 1989; Rothschild and Martin, 1993; Rothschild, 1997; Tanke and Currie, 2000; Rothschild et al., 2001; Happ, 2008; Rothschild and Martin, 2006; Rothschild and Molnar, 2008; Peterson et al., 2009; Tanke and Rothschild, 2010; Rothschild et al., 2012).

Frequent observation of hadrosaur osteopathy mostly secured from 75 million year old (Dinosaur Park Formation, Campanian) sediments in Dinosaur Provincial Park (DPP), in southern Alberta, Canada, stimulated this review. It also discusses the suggestion of caudal neural spine injuries in an *Edmontosaurus* from Montana as evidence of a failed predation attempt by *Tyrannosaurus*. Much of the sample awaits further study and quantification. So many specimens are now known that only select representatives could be used for this review. Like the contemporaneous Albertan ceratopsian osteopathy review recently published (Tanke and Rothschild, 2010), this

paper is less about medical analysis and diagnoses, but is written to present a broader overview of the types of hadrosaur paleopathology found in the province and thus serve as a comprehensive, comparative source for hadrosaur workers globally. For a detailed literature review (up to 2001) of Albertan (and elsewhere) hadrosaur pathological conditions, see Tanke and Rothschild, 2002. A few more relevant recent works of significance are noted below as pertinent. All specimens herein are unspiciated adult-sized DPP hadrosaurs, unless otherwise noted. Given the large area of the DPP badlands (~80² km), and wide spacing of specimens at different stratigraphic levels, we consider the possibility that any two (or more) disarticulated vertebrae coming from the same individual unlikely.

Abbreviations

AB – Alberta, Canada; AEHM, Amur Natural History Museum of the Far Eastern Institute of Mineral Resources, Blagoveschensk, Russia; Blasi – Museo Palaeontológico de la Universidad de Zaragoza; CMN – Canadian Museum of Nature, Ottawa, Ontario; DMNH – Denver Museum of Natural History, Denver, GNSM – Gwacheon National Science Museum, Seoul; MOR – Museum of the Rockies, Bozeman, MT; NHMUK – Natural History Museum, London; RAM – Raymond M. Alf Museum of Paleontology, Claremont, CA; ROM – Royal Ontario Museum, Toronto, Ontario; TMP – Royal Tyrrell Museum of Palaeontology, Drumheller, Alberta; UAD – Uncollected Articulated Dinosaur; field site designation by TMP; UNO – University of New Orleans, New Orleans, LA; USNM – United States National Museum, Washington, D.C.; ZPAL MgD – Institute of Paleobiology, Polish Academy of Sciences, Warsaw.

Materials and methods:

Examples of paleopathology representing all Late Cretaceous vertebrate species were sought in the field (DPP primarily) and collected mostly as isolated specimens to build up a good comparative collection, steadily built up over several decades. Presently there are about 1200 pathological dinosaur specimens catalogued in the TMP. These comprise the world's largest such collection; of these nearly 60% are hadrosaur. This number does not include pedal phalanges with osteochondrosis (Rothschild and Tanke, 2007), which would substantially increase this percentage. Museums curating DPP dinosaur material were also visited, and pathological specimens there examined. TMP specimens were prepared for gross examination using standard small fossil preparation techniques and hand tools (e.g. water, brushes, dental picks), and mechanical airscribes as required. Many fossils were found fully exposed on the surface and required only a light scrub with brush and water to remove adhering lichens, silt, and sand. Some were further cleaned and detailed with an airabrasive unit charged with sodium bicarbonate (baking soda) or aluminum oxide powders. Some TMP specimens underwent further non-invasive study. Fluoroscopy work was done with a portable Xi Tec, Model 1000 fluoroscope at 40-65 KVp on all catalogued hadrosaur caudal vertebrae (Rothschild et al., 2003). CT scans of some specimens were made at the Drumheller Health Centre with a Toshiba Aquilion 16 scanner with settings of 120 kV and 450 mAs, images taken at .5 mm slices. A few small specimens were sliced and made into histological thin sections to determine the quality of the end product and were found to show excellent cellular details. All specimen photographs were taken by the senior author.

Previous work:

Work on hadrosaur osteopathy got off to a slow start in Alberta. Despite hadrosaurs being known from the province for over 120 years, only scattered notations of osteopathy appeared in the scientific literature. These notations were brief and included within larger anatomical descriptions, popular books, reports, or soft science news stories (e.g., Parks, 1922; Moodie, 1923, 1930; Langston, 1961; Swinton, 1970; Sawyer and Erickson, 1985; Monastersky, 1990; see literature review in Tanke and Rothschild, 2002). Roy Lee Moodie (1880-1934), the father of paleopathology studies in the western hemisphere, wrote one short paper dedicated to the topic (Moodie, 1930), and had a general overview manuscript on Albertan dinosaur osteopathy written, but he died before it was published. Only recently has dedicated work on their paleopathology been conducted (Rothschild and Tanke, 2007; Straight et al., 2009). With this paper, the authors hope to establish a firm foundation on which future studies of hadrosaur osteopathy worldwide and that in large ornithopods generally may be conducted and compared.

Description

Skull and teeth

Hadrosaur skulls appear delicate, yet serious pathological conditions in them are preserved. Among the first good dinosaur specimens collected and described from the province were an unassociated hadrosaur maxilla (CMN 362) and dentary (CMN 361; [fig. 1](#)) with deeply eroded or expanded pockets of bone and premortem tooth loss (in the

dentary).

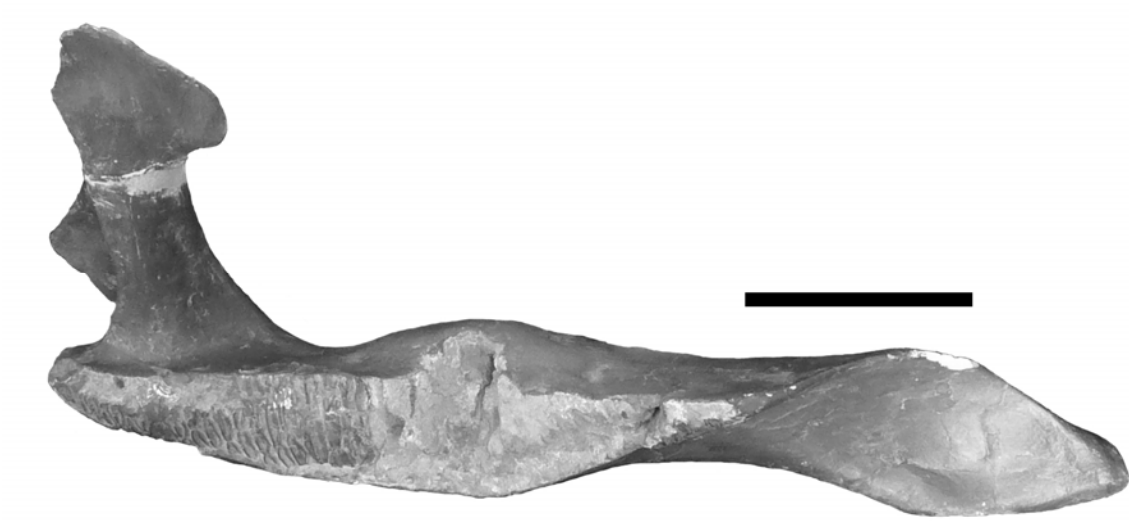


Figure 1. CMN 361, adult hadrosaur left dentary in dorso-lingual view showing noticeable swelling at mid-length. Scale bar = 10 cm. Image courtesy of Margaret Currie and the Canadian Museum of Nature.

While Lambe (1902) figured but did not describe their pathological conditions, Moodie (1930) later considered these as dental abscesses, a diagnosis with which we concur. It is curious that Lambe should find two examples in one field season and none have been reported subsequently, despite intensive fieldwork and hundred of hadrosaur jaws seen or collected.

Prosaurolophus (TMP 1993.081.0001; DPP quarry 213) skull preserves what appears to represent a massive fracture with extensively thickened but evidently non-infectious callus 120 X 95 mm on the external left dentary, centered about 180 mm posterior to the hypothetically restored symphysis. There is slight ventral shifting and angulation of the distal portion. A shallow groove atop the new bone growth, roughly dorso-ventrally

orientated may represent the original fracture line. The lingual portion of this dentary is still in the hard rock as is the other dentary, so it is unknown if it too was affected; further preparation of this interesting specimen is required. *Brachylophosaurus* skull TMP 1990.104.0001, from Milk River, AB exhibits a deep circular pit of unknown etiology on the right postorbital. Additionally there is a minor disruption and depression of the bone grain texture on the external right dentary, about 10 cm anterior to the coronoid process just above the ventral edge. Directly below the anterior tooth rows of the left dentary, close to the ventral aspect of the lingual edge, there is an area 9.4 cm long with disruptive bone texture with noticeable swelling anteriorly. The anterior-most left dentary teeth (about 6 rows) appear smaller than the same teeth in the other dentary. These combined features are suggestive of a well-healed bilateral jaw fracture, though a CT scan would be needed to test this hypothesis. Another anomalous skull bone is an isolated asymmetrical occipital (TMP 1993.066.0011); it would have been interesting to know how this condition affected the development of the rest of the skull.

Hadrosaur teeth are common finds in DPP. Despite large museum and field samples, dental developmental conditions appear to be extremely rare. Dental caries and premortem tooth fractures are unknown. Absence of caries and fractures is not surprising, given how quickly the teeth were replaced and how individual teeth are not fully exposed, but are instead tightly packed together to form complex grinding tooth batteries. Tooth TMP 1985.036.0161 (fig. 2) has a dorso-ventrally “compressed” appearance. The etiology of this condition is unknown, but appears it appears developmental and suggestive of prior tooth bud damage resulting in the deformity.

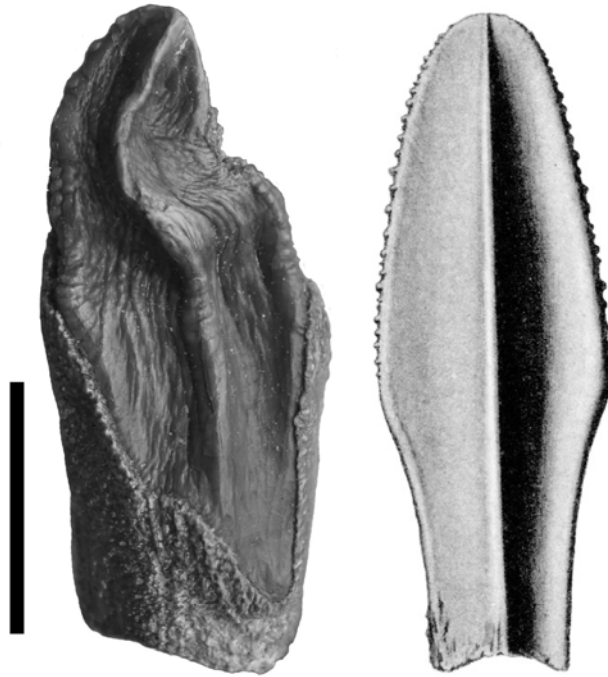


Figure 2. TMP 1985.036.0161, pathologic hadrosaur tooth (left) compared to one of normal morphology (image from Lambe, 1902). Scale bar = 1 cm.

Dental anomalies in hadrosaurs outside the province are also extremely rare, Prieto-Márquez (2012:522; fig. 9c) briefly notes a splitting of the single median ridge into two smaller and finer ridges.

Vertebrae

Vertebrae, especially those from the tail, are the most frequently injured part of the hadrosaur body, and this survey will focus more closely on them. Rothschild et al. (2003) reported on occurrences of benign neoplasia (hemangioma, desmoplastic fibroma, osteoblastoma) and malignant neoplasia (metastatic carcinoma) in Asian and American hadrosaurs. Frequency of occurrence was similar to that observed in modern animals (Natarajan et al., 2007). As no cases were identified in Albertan hadrosaurs this aspect

will not be discussed further. A proximal caudal vertebra with a “tumor” figured in Norman and Milner (1989) and identified as coming from Alberta (Capasso, 2004). However, this specimen (NHMUK R4862) is actually from Wyoming (Chapman, pers. comm., 2012), and thus will not be further considered here. This analysis will concentrate on vertebral pathologies recognized in Albertan hadrosaurs supplemented with reports pertinent to their osteopathy.

Vertebrae – cervical

Osteopathy from the neck is unreported in the literature or rarely observed. This is expected any source of bone injury (trauma) in this body region would likely prove fatal. TMP 1986.012.0022, a fragment of a cf. *Edmontosaurus* cervical vertebra from Drumheller, exhibits minor pitting and erosions of the diapophysis articulating face.

Vertebrae – dorsal

A scoliotic congenital deformity of an embryonic or neonate *Hypacrosaurus* (TMP 1987.079.0012) was recovered near Warner, AB. One dorsal centrum, 8.5 mm wide and 6.5 mm tall, has a deep rounded pit of small diameter on the exposed articular face. The opposing face is slightly bevelled and articulates to a wedge-shaped centrum, with one neural arch base instead of two. Both vertebrae are fused ventrally over a distance of 1 mm. A third incomplete articulated centrum also appears to have been wedge-shaped. While scoliosis related to wedge-shaped centra (hemi-vertebrae) have been cited as congenital defects in mammals (including *Homo*; Brothwell, 1967; Baker and Brothwell, 1980; Rothschild et al., submitted), this appears to be its first recognition in an embryonic dinosaur. Recently a hemi-vertebra case was reported in the Late Jurassic *Dysalotosaurus* from Tanzania (Witzmann, et al., 2008). Another possible scoliotic example, TMP

1991.036.0289 is unusual in that there is asymmetrical growth, with one side of the neural arch base being about 16 mm taller than the other (fig. 3), resulting in it being strongly tilted laterally. Subadult centra TMP 1980.16.0016 and TMP 1992.036.1165 exhibit a circular pit or an elongate curved depression on one endplate respectively, possibly osteochondrosis.



Figure 3. TMP 1991.036.0289, dorsal vertebra in anterior view, showing bilateral asymmetry. Scale bar = XX cm.

Parasaurolophus (ROM 786) has the tips of three neural spines angled together, with the posterior pair joined at the tip by a roughened bony pad. Parks (1922) suggested that this pad served as a ligamentous attachment point for a flap of skin between the tip of the posteriorly elongated crest and the back. However the anomaly (see Naish, 2008 for more discussion) is no doubt related to nearby rib fractures- see below. There is no complimentary roughened bone on the distal end of the crest that to which such a flap would attach. Despite this, many *Parasaurolophus* life reconstructions have been influenced by the minor pathology and show the skin flap. What would be of interest to

add in life reconstructions are the numerous lower tail injuries in hadrosaurs leading to amputations or kinks (see below). cf. *Edmontosaurus* dorsal centrum TMP 1984.164.0001 bears three deep circular holes (one with an overhanging margin) on one endplate. These lesions require further study. TMP 1993.036.0148, a fragmentary neural arch, bears prominent erosions of the articulating facets of the pre- and postzygapophyses, especially the former. The causative agent is unknown. Infection or the form of arthritis referred to as spondyloarthropathy are the most likely candidates. TMP 1993.031.0183, recovered from an *Edmontosaurus*-dominated bonebed near Drumheller, AB appears to show a congenital defect where two dorsal centra share one neural arch. The specimen is crushed, incomplete and in a poor state of repair, but worthy of more detailed study.

Vertebrae – Sacral

Osteopathy has not been reported or observed from this region. Several large, broad and flat neural spine fragments with fully remodelled fractures and angulation in TMP collections (e.g. TMP 1990.036.0409) may derive from the sacrum, but are too incomplete for verification.

Vertebrae – Caudal – General comments

Caudal injuries are quite common in hadrosaurs. They are the most common type of dinosaur osteopathy found in the province. An adult hadrosaur tail is composed of some 75 vertebrae and a fewer number of chevrons, an adult *Corythosaurus* with a complete tail had this many vertebrae (Gilmore, 1946). Isolated caudal centra and complete vertebrae, especially the former are extremely abundant, numbering in the thousands with new specimens exposed annually in the high erosion badlands environment. Because of

this, some comments can be made about osteopathy types and frequencies of occurrence, although actual quantification work still needs to be done. Hadrosaur caudal vertebrae were divided into several ontogenetic size classes based on combination of relative size (and compared to mounted skeletons), degree of neural arch fusion, and bone texture. Neonate to juvenile-sized material (animals <2.5 metres long) are found in DPP (Tanke and Brett-Surman, 2001), including occasional centra. None of the animals in this size class express osteopathy, perhaps the animals did not survive major wounding incidents. The sample size is presently too small to make meaningful comparisons with larger hadrosaurs. Subadult material (animals 2.5-4.5 metres long) is abundant, although the neural arch, the area most frequently injured, has often not ontogenetically fused to the centrum or been preserved in this size grouping. The centrum only therefore only provides limited data regarding osteopathy frequency. However, subadult to adult centra comparisons can be made and it can be seen that centrum osteopathy is quite rare in subadults also. One reason for this may be segregation of subadults (“bachelor herds”) from adults as part of hadrosaur life history (Forster, 1990; Varricchio and Horner, 1993). Adult (4.5+ metres long) hadrosaur caudal vertebrae are extremely abundant. Thousands exist in museum collections and in the field. They provide the best resource for quantification of osteopathic conditions.

In the descriptions and discussions below, the hadrosaur tail is arbitrarily divided into three sections. “Proximal” are vertebrae at the base of the tail. These vertebrae (about 16 in number; Gilmore, 1946) bear caudal ribs of varying lengths (elongate to low, rounded bumps), and have elongate, erect, and laterally flattened neural spines, angled slightly posteriorly. Some neural spines may developed parallel rows of smooth grooves and

ridges near the tip, forming a fluted effect. Neural spines (especially proximally) are longer in lambeosaurines than in hadrosaurines. There are well developed chevron facets (except those closest to the tail that lack chevrons) and zygapophyses. Centra have a tall trapezoidal shape when viewed en face; except those closest to the sacrum, where they are round. “Medial” is the arbitrary term used herein for vertebrae in the centre region of the tail. Caudal ribs are absent. Neural spines are shorter, tend to be more rounded in cross-section and are inclined posteriorly then dorsally. There are well-developed but smaller chevron facets and zygapophyses, and centra have a more hexagonal-shape when viewed en face. “Distal” refers to vertebrae located at the end of the tail. These are readily identified by their smaller size (< ~5 cm overall length), more noticeable taper, and “rounded hexagonal” to round endplates. They have a simple, spool-like morphology (more so distally), with greatly reduced to absent neural spines, smaller zygapophyses without actual articulating facets, and reduced or absent chevron facets. Orientation of centra lacking a complete neural arch was based on presence of prezygapophyses (or their bases), antero-postero tapering of the centrum, and location of chevron facets.

Hadrosaur caudal vertebral osteopathy is so prevalent; we are surprised at how little it was noted by earlier workers- it really is hard to miss.

Vertebrae – Caudal – Proximal and chevrons

One of the most common injuries encountered in hadrosaurs are damaged and healed or healing caudal neural spines, especially those more proximally situated (fig. 4).



Figure 4a-b. TMP 1966.017.0008, proximal hadrosaur caudal neural spine in left lateral view (left) and anterior view (right). Scale bar = 1 cm.

Injuries of this variety are the most prevalent osteopathy in Albertan hadrosaurs and one of the most common types of osteopathy among all Albertan dinosaur families. Typically, the neural spine is broken once and buckled, forming sigmoidal curves in various stages of repair (i.e. TMP 1979.014.0746). Occasionally two healing fractures are present on one spine; e.g. TMP1981.019.0154, TMP 1986.036.0520 (Straight et al., 2009); TMP 1991.036.394, TMP 1993.666.0043, and TMP 1994.012.0901, TMP 1998.059.0001 (Straight et al., 2009), in each specimen all fractures are in the same stage of repair, indicating all were incurred at the same time. Numerous examples are from isolated vertebrae or spines, but articulated specimens preserving the pathology are also known in Alberta and elsewhere (Table 1). In TMP 1987.036.0401, the distal end of the neural

spine was snapped off and had slid or pulled (via muscle contractions?) partway down the side of the injured spine, where it subsequently fused, but at an angle (fig. 5).



Figure 5. TMP 1987.036.0401, proximal caudal neural spine showing fracture with healing and angulation of tip. Semi-circular depressions are vascular, not toothmarks. Scale bar = 1 cm.

The injured neural spines exhibit different morphologies at the tip. They can appear normal, or acquire roughened swollen, saddle-like (TMP 1985.047.0009; fig. 6) or club-like shapes (e.g. TMP 1967.008.0053, TMP 1985.036.0024; TMP 1993.666.0043), occasionally with deep hollowed-out pockets. Some (e.g. TMP 1981.027.0051) exhibit extreme angulation at the tip (fig. 7).



Figure 6. TMP 1987.047.0009, proximal neural spine in anterior or posterior view. The large elongate depression is vascular, not a toothmark. Scale bar = 1 cm.



Figure 7. TMP 1981.027.0051, proximal caudal neural spine in anterior view showing strong lateral angulation at tip. Scale bar = 5 cm.

The broken segment often is dislocated and fuses in an abnormal position, typically to the side and usually up to 45° off the vertical plane. Fracture callus textures ranges from rough and fibrous (similar to undersides of ankylosaur scutes), to smooth, where healing is advanced or completed. A few specimens showing advanced healing fracture then a more recent fracture also undergoing repair have been seen. A number of pseudoarthroses (non-unions of fracture components) positioned above the zygapophyses complex were observed (i.e. TMP 1991.036.0589, TMP 1992.036.0390, TMP1993.066.0030). Proximal caudal ribs protrude laterally from the vertebrae. Only one (TMP 1990.002.0033) from Sandy Point, AB was injured, and represented by an irregular rugose mass.

Chevrons are underrepresented in the sample and rarely seen in the field, except in articulated skeletons. TMP 1994.012.0768, proximally located in life, bears a well healed longitudinal fracture distally. TMP 2005.012.0071, a distal chevron, bears a slight swelling distally that may represent an old healed fracture. Diffuse idiopathic skeletal hyperostosis (DISH) is known in several dinosaur families (Rothschild, 1985; Rothschild and Berman, 1991; Rothschild and Martin, 1993; Rothschild and Martin, 2006; Tanke and Rothschild, 2010), where two or more vertebrae fuse together through the ossification of lateral spinal ligaments, but centrum endplates and zygapophyseal articulations are uninvolved. Only one Albertan specimen, a single proximal caudal (TMP 1992.036.0714; fig. 8a-b), appears to express this condition.



Figure 8a-b. TMP 1992.036.0714, proximal caudal vertebra in anterior view (a) and right lateral view (b). Scale bar = 1 cm.

As it has not fused to the next vertebra, diagnosis cannot be confirmed. In dinosaurs, particularly sauropods (Rothschild and Berman, 1991), DISH is believed to help support the weight of the tail. If so, one might expect to find more examples in hadrosaurs than is the case although these animals do have a complex lattice-work of tendons (which sauropods lacked) to support the tail. One of the authors (BMR), has previously hypothesized that the tendon lattice served a similar function to DISH and would render the latter redundant, perhaps explaining its rarity in those groups (Rothschild and Martin, 2006).

A curious case involves two proximal caudal vertebrae and their associated chevron from an unspeciated lambeosaurine (TMP 1978.004.0001; [fig. 9](#)) collected from Sandy Point, AB. The bones are fused together by the presence of a large, ovoid mass, 110 mm

long and 70 mm wide on the left side. The lesion appears to be a syndesmophyte, diagnostic of spondyloarthropathy. More of the tail expresses healing injuries; see Table 1.



Figure 9. TMP 1978.004.0001, articulated and fused proximal caudal vertebrae and chevron, left lateral view. Scale bar = 10 cm.

A similar, but highly eroded and broken specimen (TMP 1989.036.0347) has massive thickening of the endosteum. Although tumor is possible, infection is the most likely explanation for these pathologic findings. X-ray examination should clarify the question.

Vertebrae – Caudal – Medial

Mid-caudal osteopathy generally resembles that in proximal caudals with occurrences of healing fractures at or close to the tip of the neural spine, though some can be more medially located (fig. 10).



Figure 10. TMP 2011.012.0134, mid-caudal vertebra in left lateral view (left) and antero-dorsal view (right) showing poorly healed fracture of mid-neural spine. Scale bars = 1 cm.

Pseudoarthrosis of the basal neural spine occurs regularly (i.e. TMP 1989.036.0321), with the fracture occurring between the neural arch and zygapophyses. Healing fractures (swellings) can also be found at the base of the neural arch where it surrounds the neural canal. Caudal postzygapophyseal destruction occasionally complicates infectious processes. In TMP 1973.008.0365, the neural spine base probably suffered a greenstick

fracture, which subsequently healed in association with deep holes eroding into the postzygapophyses. The rough and pitted bone surface texture on the anterior edge and tip of a mid-caudal neural spine (TMP 1989.017.0007) was associated with infectious damage to the postzygapophyses. Curiously, the prezygapophyses do not seem affected. TMP 2011.012.0132 is unusual in that the neural spine curves laterally for no apparent reason, though does bear a healing fracture near the tip.

TMP 1978.009.0064 and TMP 1980.016.0973 from Sandy Point, AB each consist of two completely fused caudal centra. Cross-sectional examination of the former revealed normal trabeculae. There was no line of separation between the centra, although remnants of the disk space were faintly visible on the surface in a few places. The latter specimen also exhibits prominent, deep meandering cracks running dorso-ventrally on both endplates. An injury early in development is suggested. These cases, while visually impressive, are not as massively swollen as in American specimens described by Partridge (2007) and Depalma et al., submitted.

A form of osteopathy, not seen in proximal caudals, is centrum endplate with the development of narrow (usually), and relatively flat-bottomed cracks with rounded edges indicating repair located. These cracks are associated with adjoining healing bone, suggesting that the centrum was split fully in two by a traumatic event. They resemble healing near vertical cracks in cervical vertebrae centra of extant soay sheep *Ovis aries*, where head-butting behavior was implicated (Clutton-Brock et al., 1990). A few hadrosaur specimens show multiple cracks radiating in varying directions, indicating the centrum was more seriously injured and broken into multiple pieces; three pieces are evident in TMP 1991.050.0140. Endplate cracks occur vertically, diagonally (Tanke and

Rothschild, 2010, their figure 2), or transversely and usually are linear. Centra split completely down the middle with healing (e.g. TMP 1982.014.0003; fig. 11x-x) create a 50/50 bone ratio, but most other examples are broken roughly 60/40 and a few 95/5.

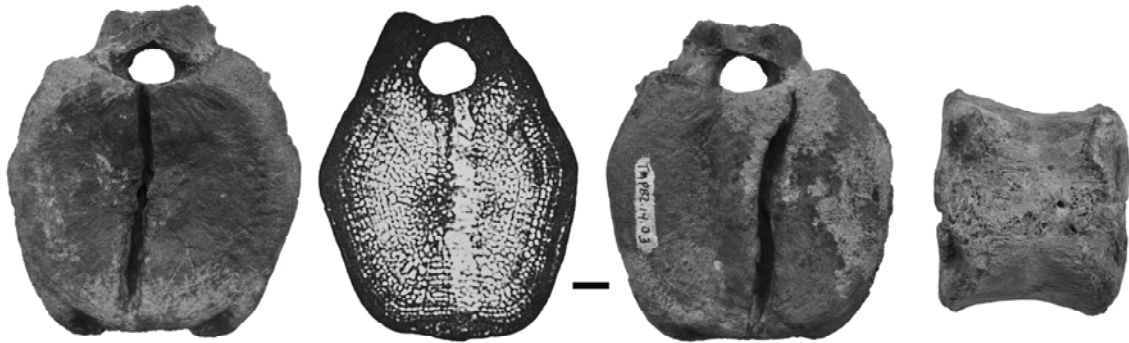


Figure 11. TMP 1982.014.0003, mid-caudal vertebra, in a) posterior, b) transverse CT scan, c) anterior and d) ventral views. Scale bar = 1 cm.

The direction of the crack is often mirrored on the opposing endplate, though single endplate cracks and curving cracks (TMP 1967.019.0031; fig. 12) are known.



Figure 12. TMP 1967.019.0031, showing broadly curving inverted crack on endplate. Scale bar = 1 cm.

The authors have observed medical cases in *Homo* resulting in similar centrum splitting (fig. 13) involving falls resulting in spinal compression or motorcycle accidents.

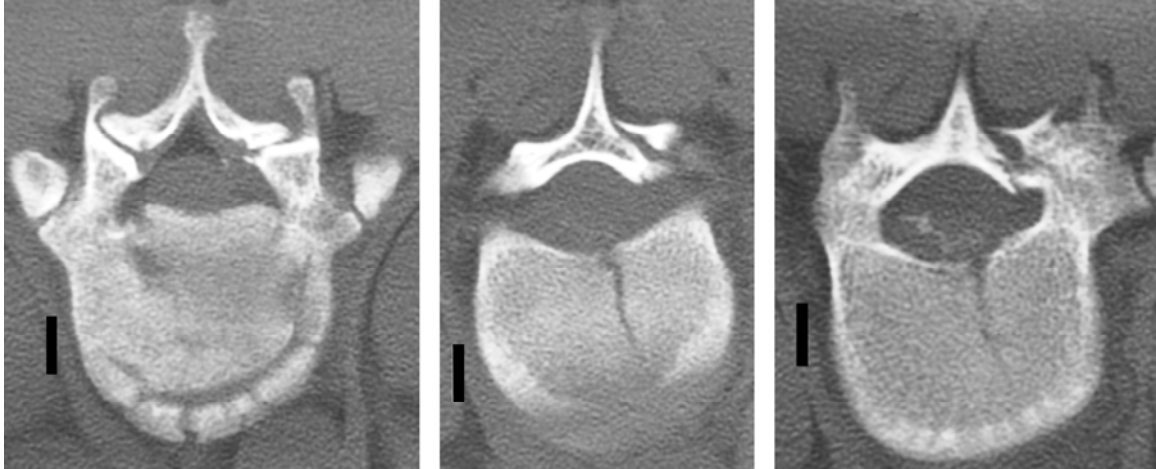


Figure 13. *Homo* with centrum trauma related to a fall resulting in compression fractures of the centra and unilateral fracture of the neural arch. The young male individual fell off a ladder, landing on his buttocks and suffered a compression fracture of the spinal column. Scale bars approximately = XX cm.

Deep, wide, and tapering cracks with healing but not infilled with new reparative bone have also been seen (fig. 14a-c). Taphonomic artifact, such as cracking from drying due to loss of bone grease prior to burial (Miller, 1975), is excluded as explanation for the cracks, in view of obvious bone healing modifications observed in all specimens.



Figure 14 a-c. TMP 1992.036.0300, distal caudal centrum in a) left lateral, b) anterior, and c), right lateral views showing deep penetrating crack across centrum face. Scale bar = 1 cm.

CT scans, taken in transverse (**fig. 11b**) and coronal planes through afflicted centra confirm the internal continuation of disrupted bone beyond the endplate cracking, suggesting a traumatic injury broke the centrum into two or more segments which were in the process of healing when the individual perished. Most specimens healed back together in proper alignment, but in TMP 1991.036.256, one half of the centrum shifted longitudinally several mm before healing was achieved.

Gangloff and Fiorillo (2010:fig. 14A) figured (upside-down) a subadult mid-caudal centrum with two short and curved opposing shallow endplate depressions. They attribute these depressions to osteochondrosis. Endplate depressions of this morphology are common on DPP hadrosaur medial and distal caudal vertebrae and some bear a marked resemblance to centrum lesions in *Homo* attributed to “burst fracture It results from a vertical compression that ruptures the intervertebral disc through the vertebral end plate, forcing disc tissue into the vertebral body”. (Lovell, 1997:143, fig. 3; Lovell, 2008:355, fig. 11.8). There are so many Albertan examples that it raises the question of whether or not they are related to ontogeny, normal anatomy, or represent true osteopathy.

Confusing the issue are vertebrae with these depressions and endplate cracking (i.e. TMP 1990.117.0009; **fig. 15**) suggesting multiple origins (developmental anomalies and/or trauma) of these unusual lesions.

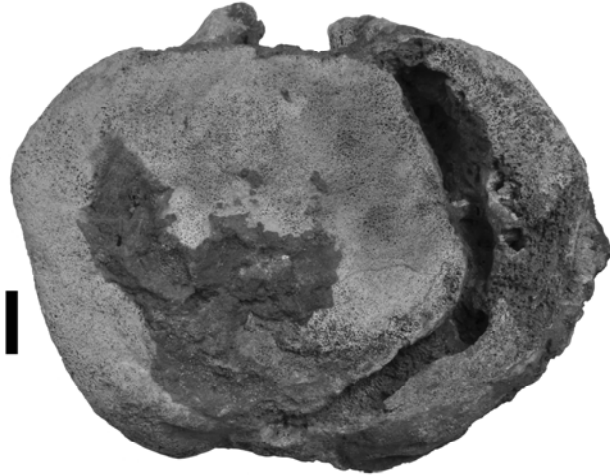


Figure 15. TMP 1990.117.0009, distal caudal centrum with deep curving crack; trauma predisposed to related osteochondrosis lesion? Scale bar = 1 cm.

In that specimen, the lateral quarter of the centrum appears to have spalled off and fused back on, the crack following the same lines as the osteochondrosis lesion. Possibly these lesions or developmental artifacts created plane(s) of weakness that allowed the vertebra to break apart along these lines when traumatized (see below). Some rare specimens (i.e. subadult mid-caudal TMP 1980.008.0321; [fig. 16a](#); TMP 2011.012.418; [fig. 16b](#)) have depressed defects that penetrate so deeply, they fully pierce the centrum from one endplate to the other. The former appears to possibly be developmental in origin while the latter somewhat resembles insect boring damage to dinosaur bones reported from a number of western North American and overseas localities (e.g. Rogers, 1992; Roberts et al., 2007; Kirkland and Bader, 2010; Saneyoshi et al., 2011). However, Albertan dinosaur bones with possible insect boring traces are extremely rare- the senior author is only aware of a few possible examples, affecting a distal hadrosaur humerus (TMP 1993.049.0001), a small distal caudal centrum (TMP 1967.009.0145), and a hadrosaur

ilium fragment (TMP 1966.017.0005). Complicating the matter of open-ended centrum cracks is TMP 1993.036.0059; fig. 16c, which appears trauma-related.

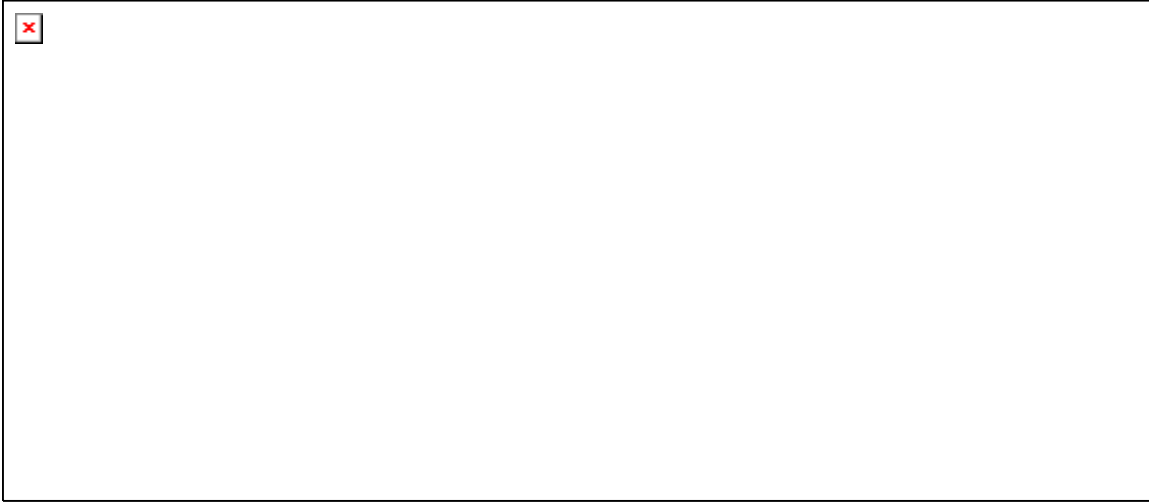


Figure 16a-c. TMP 1980.008.0321 (left); TMP 2011.012.0418 (middle); and TMP 1993.036.0059, all showing fully penetrating crack defects. The bilateral asymmetry in c is related to osteopathy. Scale bar = 1 cm.

The deep crack through the distorted centrum presents finished bone with rounded edges showing that some split centra did not fully fuse back together leaving the crack open. Further detailed study of these unusual lesions and their etiologies is required. Splitting of centra through the neural canal must have resulted in spinal cord damage and paralysis, but was not immediately detrimental as the specimens demonstrate at least some individuals lived an extended time after being injured.

Some non-pathologic mid-caudal centra have a normal smooth low longitudinal ridge at/near mid-height on the side of the centrum. In pathologic specimens of this variety, this ridge may become more prominent forming a keel and/or with the development of

associated osteophytes occurring uni- or bilaterally occurring on or dorsal to the keel, osteophytes ventral to the keel have only rarely been observed.

Other endplate anomalies include circular, symmetrically-placed, low, rounded lesions (TMP 1979.008.0096) and a strong unilateral keel (TMP 1981.041.0139). In the latter, articulation with the preceding vertebra must have been seriously compromised, yet no eburnation was present.

Vertebrae – Caudal – Distal

Distal caudal vertebrae exhibit the widest variety of injuries and affected specimens are fairly common. The senior author (DHT) has seen approximately one specimen every five days of fossil prospecting work in DPP. These vertebrae often exhibit massive comminuted crush trauma (fractures) and other conditions. Vertebrae can express some or nearly all of the conditions summarized below:

Centra:

1. A repeat of the crack (cleft) phenomenon seen in medial caudals (additionally with a visible healing longitudinal crack on the neural canal floor in some specimens; e.g. TMP 1966.030.0005, TMP 1993.036.0285, TMP 1993.150.0005), often associated with a longitudinal smooth and rounded ridge on ventral midline (often best detected by feel), representing a remodelled/ing fracture callus. Some cracks run longitudinally through a neural arch base (e.g. TMP 1980.016.0225). Lesions on endplates, ventral centrum, neural arch and canal floor, while of different appearance/texture, can be seen on close inspection to be all connected. Endplate cracking can occur vertically, transversely, or diagonally. The angle or direction of the defect is often mirrored on the opposing endplate (complete fracture), though single endplate crack phenomenon (incomplete

fracture) is known. Centra are split roughly in half, but in some specimens, only an edge is affected.

2. An overall swollen or lumpy condition, with the cortical bone perforated by numerous small openings giving it a spongy appearance (osteomyelitis). Some specimens are so deformed as to no longer resemble a vertebra, although the endplates are still present, often with centrally-positioned notochordal projections (figs. 17, 22a,c). Some centra have thin and finely textured patches of periosteal reaction which easily flakes off, revealing the normal bone underneath.

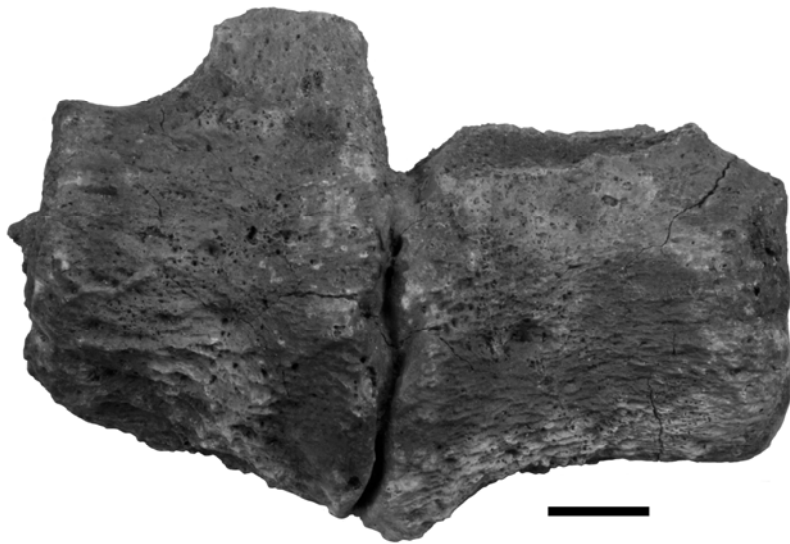


Figure 17. TMP 1980.016.0162, two fused distal caudal vertebrae in left lateral view, showing slight angulation, osteomyelitis, and pointed notochordal projection on anterior centrum. Scale bar = 1 cm.

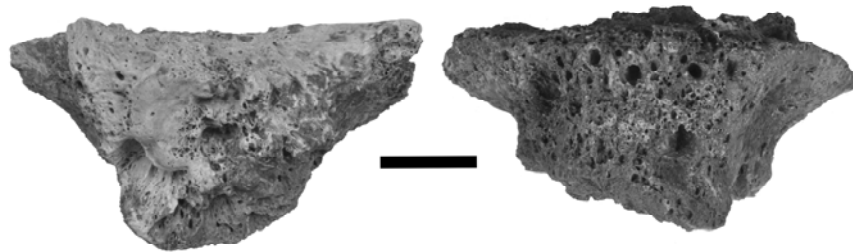
3. When viewed dorsally, the normally straight centrum may be slightly curved with both endplates curving laterally in the same direction.

4. Fusions of adjoining vertebrae, sometimes at angles show the tail healed with a noticeable upward or lateral kink. A lateral kink of the distal pathological tail “stump” composed of three fused and badly infected vertebrae (and estimated to be missing at least 10 more pre-mortem) shows a slight lateral curve to the right in the Late Cretaceous theropod *Majungasaurus* from Madagascar (Farke and O’Connor, 2007). Tanke and Rothschild (2011:146) noted fusions of up to four vertebrae (but typically two); a new specimen (TMP 2011.012.0374; fig. 18a-b) from the extreme tip of the tail shows five vertebrae with fusions occurring along the central vertical midlines only. The specimen superficially resembles a dinosaur pygostyle (e.g. Barsbold et al., 2000) but is truly pathological.



Figure 18. TMP 2011.012.0374, five fused distal caudal vertebrae in left lateral view (top) and ventral view (bottom). Scale bar = 1 cm.

Other vertebrae fuse completely, although lines of demarcation between the centra are still defined in some specimens. Other osteopathic fusions of tail tips were observed in TMP 1992.036.0136 (two vertebrae) and TMP 1997.012.0160 (three vertebrae). Fused specimens abraded by river sediments prior to final burial may be hard to identify and resemble simple amorphous “lumps” of bone with little symmetry. Even well-preserved examples may no longer resemble a vertebra (TMP 2011.012.0417; [fig. 19a-b](#)) though a partial rim of a centrum endplate was all that was left to identify it as a vertebra. CT scanning of this specimen revealed greatly thickened trabecular bone but no centrum could be distinguished.



[Figure 19a-b](#). TMP 2011.012.0417, badly deformed and osteomyelitic distal caudal vertebra in ?anterior view (left) and ventral view (right). Scale bar = 1 cm.

5. Moderate to deeply concave endplate(s) with numerous small pitted subcircular erosions ([fig. 20](#)) and/or centrally-positioned pointed notochordal projections ([fig. 17](#) and [22a,c](#)).



Figure 20. TMP 1993.036.0062, distal caudal centrum with endplate erosions. Scale bar = 1 cm.

Some large endplate erosions can penetrate deep inside the centrum and expand internally (TMP 2011.012.0420; **fig. 21**). Endplates may also exhibit a(n) asymmetrical bulge(s).



Figure 21. TMP 2011.012.0420, associated distal caudal vertebrae (posterior view, left) and anterior view, right) showing deep endplate erosions. Though found apart at the same site, these two vertebrae may have formed a pair. Scale bar = 1 cm.

6. Development of osteophytes, singly, small groupings, or sometimes spectacular crowded, radiating (when viewed en face) spicular growths entirely encircling the vertebra and greatly increasing its diameter (e.g. TMP 1991.036.0409; TMP 2006.012.0048; TMP 2008.012.0066; fig. 22a-c), suggestive of rampant osteomyelitis. Small singular osteophytes sometimes have an accessory blood vessel opening onto the bone surface.



Figure 22a-c. TMP 2008.012.0066, distal caudal centrum wholly encased in osteomyelitis forming radiating spicular growths. The bases of notochordal projections are seen on both endplates. Scale bar = 1 cm.

7. Anteriorly positioned neural arch (e.g. TMP 1965.030.0007; TMP 1992.030.0181; TMP 1994.012.0791; TMP 1994.012.0697; TMP XXXX; **fig. 23**), suggesting posterior elongation of the centrum during healing, as per #2 below. Some specimens suggest posterior and anterior centrum elongation post-trauma.

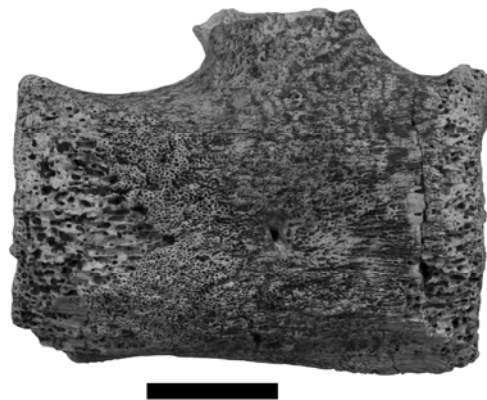


Figure 23. TMP XXXXXX, distal caudal centrum, right lateral view, showing anteriorly placed neural arch. Osteomyelitis is also evident on side of centrum. Scale bar = 1 cm.

Editor/reviewer- this specimen is now misplaced in TMP collections- may have to be replaced with a similar specimen.

8. Bilateral or coronal asymmetry of endplate(s). Asymmetry of fossils worldwide is often the result of compaction of over thick overlying sediments which crushes the fossil or cause plastic deformation. Such diagenetic changes and their effects on morphology are a concern to vertebrate palaeontologist's worldwide (e.g. Ross, 1978; White, 2003; Forrest, 2004; Boyd and Motani, 2008). Crushing of DPP dinosaur bone is regularly seen, especially in those with hollow bones such as maniraptorans, ornithomimids, and tyrannosaurids, which can be crushed flat. Larger ornithischian limb bones, with thin cortical bone and weak, thin-walled trabecular bone can also be deformed. In all these cases, the crushing exhibits sharp edges and sometimes slickensides in the surrounding clay matrix and passing through the bones. Isolated specimens such as skull elements, vertebrae and phalanges appear to be better ossified (skull elements) and/or have more structural integrity, and while often waterworn and rounded, don't exhibit diagenetic dessication cracks or crushing (Eberth and Currie, 2005). Those specimens that appear altered by crushing or plastic deformation always show true pathological conditions and therefore we interpret them as being asymmetrical due to biological responses to injury.

9. Attenuation of endplate margins with a low and sharp-edged encircling ridge (TMP 1966.030.0005); the same specimen (and others: TMP 1966.011.0050, as well as seen in the field) show a marked color difference between endplates (grey) and centrum body (off white) in eroded out specimens, the significance of which is unknown. Tanke and Currie also noted differing color of lesions versus normal bone in facebite lesions in

tyrannosaurids (Tanke and Currie, 2000); Erickson and Sawyer (19XX) noted similar color differences in pathologies affecting Paleocene *Leidyosuchus* crocodiles. DPP baenid turtle shells with possible fungal infections also often show marked color differences with light gray to white-colored lesions on tan to dark gray normal-colored bone. The significance of color differentiation is unknown, but is real and perhaps worthy of further investigation.

10. May be hollowed out inside in cases of pyogenic osteomyelitis. An isolated extreme distal centrum (TMP 2011.012.0417; fig. 24a-c), with a hollowed interior indicative of osteolysis, is missing half its length with the “broken” edge exhibiting signs of rounding and repair, suggesting the very tip of the tail was lost premortem. TMP 2011.012.0374 (fig. 18a-b), may also be missing part of the posterior-most centrum.

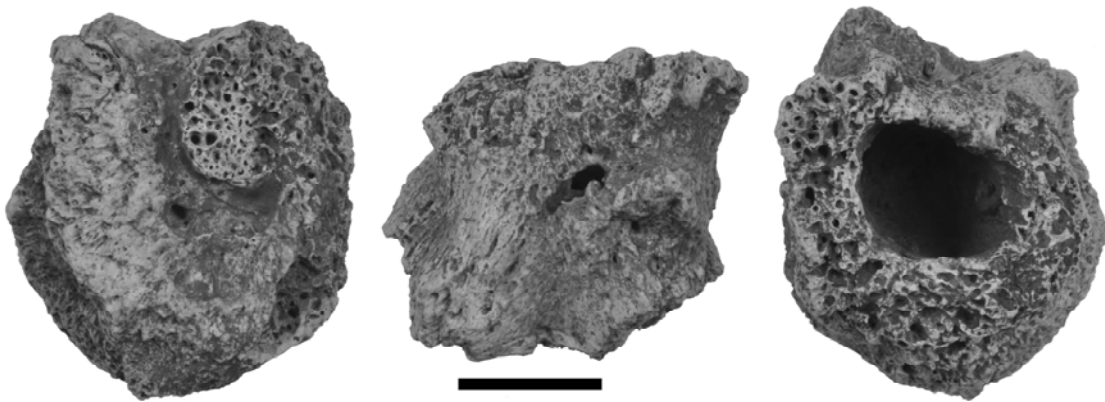


Figure 24a-c. TMP 2011.012.0417, distal caudal centrum in presumed proximal (left), dorsal (middle) and distal views (right). The centrum is hollowed out internally and with rounded distal end suggestive of pyogenic infection and distal tail loss. The foramen in the center figure connects to the cavity inside the centrum. Scale bar = 1 cm.

11. Hypertrophic development of normal anatomical features like muscle attachment points, dorso-ventrally arranged ridging on endplates, and chevron facets.
12. Strong lateral compression, so when viewed end on the normal round morphology is flat-sided and more rectangular in profile (e.g. TMP 1992.036.1168; TMP 1994.012.0900).
13. Antero-posterior “squashing” of the centrum, so that when viewed dorsally, one side of the centrum is longer than the other. For example, in TMP 2011.012.0291, one side is 51 mm while the other is 42 mm long; in TMP 1996.666.0009 (fig. 25a-c) the same measurements are 61 and 39 mm. Such specimens could be misidentified as scoliosis and would cause spinal curvature, but the shorter side of the former specimen also exhibits bilateral anomalies and a ventral ridge, all suggestive of trauma. The second vertebra exhibits endplate cracking, again suggestive of trauma.



Figure 25. TMP 1996.666.0009, distal caudal centrum showing both endplates (left, right) and in dorsal view (middle). Scale bar = 1 cm.

14. Some specimens may exhibit smooth-surfaced cortical bone with a high degree of polish (e.g. TMP 1973.023.0011), similar to that seen in contemporaneous saurischian bone.

15. Some centra exhibit a small hairline cleft or slit on the midline which occupies the upper eighth to half of the endplate, the cleft widening slightly as it nears the neural canal (fig. 26a-b). These can occur on one or both endplates. They seem to be developmental in nature and resemble “Type 2” articular surface lesions in cattle phalanges from European archaeological sites where their presence was suggested as being a “benign developmental condition” (Thomas and Johannsen, 2011), though further study of these curious lesions among hadrosaurs is required.

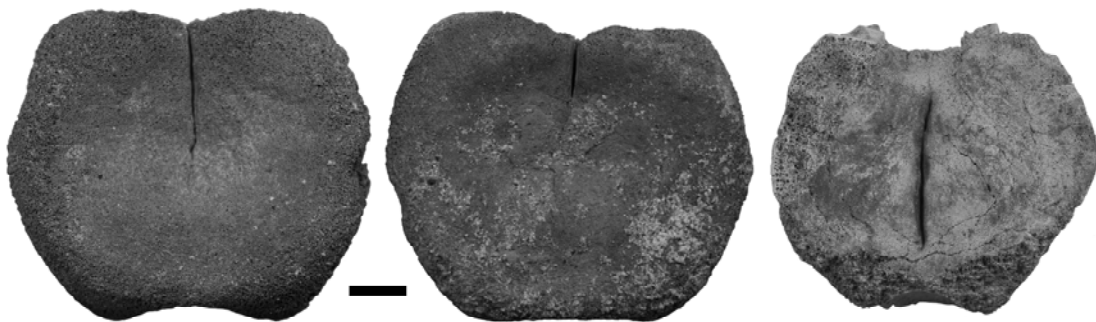


Figure 26a-c. Distal caudal vertebrae exhibiting vertical midline slits or cracks of endplates of varying etiologies. (a-b) TMP XXXXXX (developmental), and c) TMP 1994.12.0509 (trauma). Scale bar = 1 cm.

Editor/reviewer, a and b missing in TMP collections, may have to be replaced with a different specimen.

Endplate cracking in the same region due to trauma (fig. 26c) suggests several etiologies for the cleft phenomenon. Further complicating the interpretation are other specimens where these clefts are absent and instead a low and very narrow (~ .25 mm) osseous ridge appears (e.g. TMP 1988.036.0185, TMP 1990.036.0193).

16. Broken specimens may exhibit trabecular bone with thicker walls compared to specimens that are normal.

17. Unusually long centrum, anteriorly, posteriorly, or both.

18. Development of extra blood vessel openings at/near basal walls of neural canal and/or on floor of neural canal itself.

19. Presence of elongate, low and sharply defined ridges on sides of centrum, ~ 1 mm wide X 1 mm high. These ridges resemble the lines of fracture callus seen on neural arch bases and are here interpreted as fracture lines as well. Such ridges can run longitudinally along the sides of the centrum (e.g. 1992.036.1167), at angles (TMP 1993.036.0060), or even with the ridges intersecting, forming an “X” motif (TMP 1987.036.0221; fig. 27).

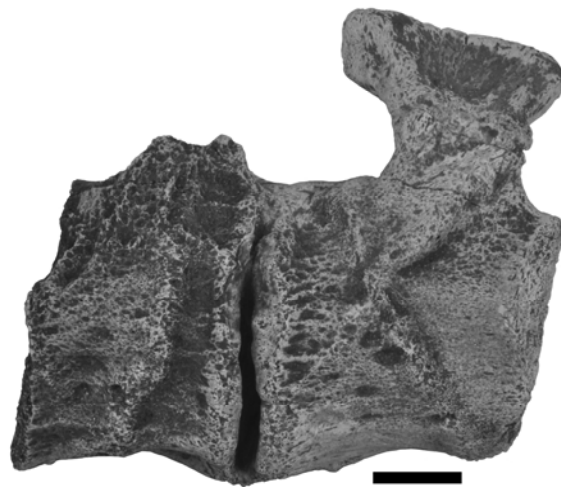


Figure 27. TMP 1987.036.0221, two fused distal caudal vertebrae in right lateral view exhibiting raised ridges on sides of centra bodies. Ridges on the right centrum intersect, forming an “X”. Scale bar = 1 cm.

20. TMP 1971.027.0002, TMP 1987.036.0162 (fig. 28a-c), and TMP 2005.012.0046 are examples of non-traumatized vertebrae with a thickened ring of new bone that encircles the centrum. The endplates are normal on one side but pitted and grooved on the other. These specimens have some attributes of early stage DISH but have failed to fuse to the next vertebra. Perhaps these are examples of infectious fusion which can mimic DISH.



Figure 28a-c. TMP 1987.036.0162, distal caudal vertebra in distal (left), right lateral (middle), and proximal (right) views. Scale bar = 1 cm.

Neural arch:

1. Often has a mangled appearance, that no longer resembles normal morphology.
2. Can be positioned more anteriorly than normal; suggestive of post-traumatic posterior elongation of the centrum.

3. A single raised fracture callus lines (ridges) may occur uni- or bilaterally at the neural arch base, just dorsal to where it fuses onto the centrum.

4. The neural arch bases on a single vertebra can be “offset”; one side being more anteriorly placed than the other. The thickness of the bone forming the basal walls of the neural canal borders may be thicker on one side than the other, sometimes markedly so. Some neural arch bases may be thin on one side and thicker on the other.

5. Noticeable thinning of the neural arch bone immediately surrounding the neural canal. Alternatively, in cases of serious osteomyelitis, the neural arch walls surrounding the neural canal can be greatly thickened.

6. Bone non-union (pseudoarthrosis) development at/near base of neural spine (e.g. TMP 1989.036.0321; TMP 1991.036.0301). In TMP 1993.036.0601, consisting of 3.5 distal-most caudal vertebrae, it appears a non-union has formed through the most proximal centrum in a dorso-ventral plane.

7. A taller neural arch (hypertrophic dorsally-oriented growth of the walls of bone lateral to the spinal cord), relative to non-pathological specimens.

Some of the more serious cases suggest spinal cord damage, and extreme distal tail infection with amputations or sloughing of the distal segment (see below).

Osteopathy in articulated or associated tails

The single caudal vertebrae examples described herein are interesting cases, but tell us nothing about how other vertebrae within the same series may have also been affected.

Multiple caudal vertebrae osteopathy is known and summarized in Table 1. Here were

briefly describe two DPP specimens that exhibit serious caudal trauma and disease response.

TMP 1980.023.0002; DPP quarry 126, is an unspciated adult hadrosaur skeleton which Langston (1961) suggested the end of the tail of which was fused into a “solid bar of bone”. Vandalism to this remote, outdoor exhibit necessitated the removal of the end of the tail for specimen safety. Nine vertebral units (single or paired fused vertebrae) were removed and later prepared; eight of which preserve progressively more serious osteopathy distally suggestive of premortem loss of the tail tip. The first two vertebrae were articulated and in situ, but the rest of the distal tail was disarticulated in situ, (partially prepared or not at all), or loose on the surface in the exhibit. Some had lost their neural arches after being uncovered. For purposes of description, the vertebrae are labelled A-I here. The vertebrae were re-associated based on relative size and length of the centra (fig. 29a-b); it is not certain this reassembly is 100% correct, there may be a vertebra missing between C and D.

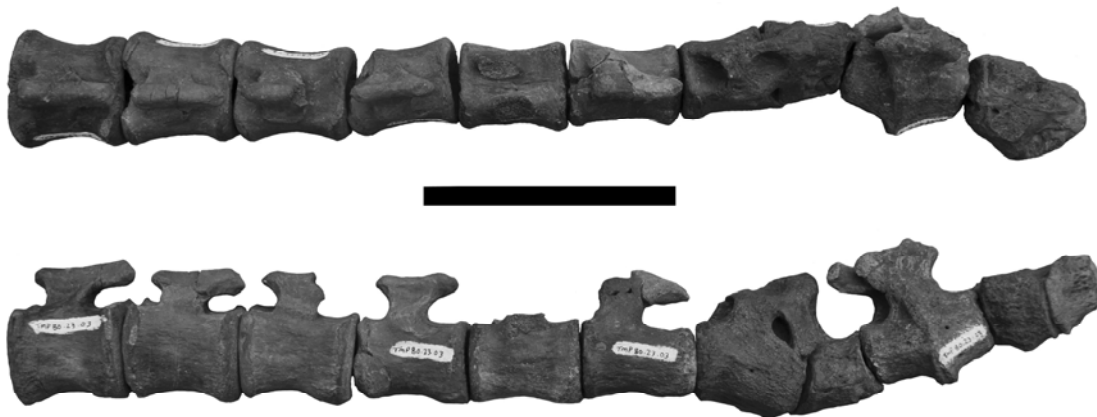


Figure 29a-b. TMP 1980.023.0002, rearticulated distal tail in dorsal (top) and left lateral (bottom) views. Anterior is to the left. Scale bar = 10 cm.

Vertebra A is of normal, non-pathologic morphology. Vertebra B and C both show longitudinal fracture calluses on both sides of the neural arch, near their bases and are more prominent in C. Vertebra D shows low and mildly rugose postero-dorsal ridging on both sides of the neural arch, starting at its base and joining to the sides of the neural spine near its base. Vertebra E is missing the neural arch, but shows offset neural arch bases, with the right side more anteriorly placed than the left. The centrum shows a wrinkled bone texture on the floor of the neural canal and a low longitudinal ridge on the ventral midline. The centre region of the posterior endplate is finely pitted. Vertebra F bears the same postero-dorsal ridging seen in D, a low ventral midline ridge, and a dorsally elevated neural arch which is noticeably positioned anteriorly. Vertebrae G-I are all badly malformed, some fused together and all with cortical bone textures indicative of osteomyelitis. G consists of two fused vertebrae, though atypically, they appear fused at the neural arches, not the centra whose degree of fusion (if any) cannot be determined because of intervening matrix. G bears a deep circular depression on the anterior endplate. The neural arch is slightly anteriorly placed. The centrum is markedly swollen and twisted slightly to the right and has a short low longitudinal ridge on the ventral midline. The left neural arch base of the posterior-most of the vertebral pair appears to have been broken away from its base at the time of trauma and angled anteriorly where it fused to the malformed neural arch of the preceding vertebra. The centrum is also twisted, but this time to the left; so despite both vertebrae being asymmetrically twisted in opposing directions, each vertebra cancels out the other's twist and the pair are thus in a relatively straight line. The distal endplate is antero-posteriorly bevelled, malformed, and

concave. Vertebral unit H is difficult to interpret. It appears to represent either one vertebra or two. The centrum/centra are swollen and exhibit osteomyelitis. A strongly developed dorso-ventral ridge is present on the left side. The neural arch is hyperdeveloped dorsally with oversized prezygapophyses, especially that on the right side. The bevelled distal endplate of G results the articulation of G and H to curve laterally to the left at noticeable angle. The distal articular end of unit H is antero-posteriorly bevelled. Vertebral unit I appears to consist of two fused centra; the neural arches of which are now lost. The centra are swollen, exhibit osteomyelitis, and like vertebral unit H, bear a dorso-ventral keel on the left side, but with a shallow, smooth-bottomed groove along the keel's edge, probably marking the line of separation between the two centra. There is a healing crack, roughly dorso-ventrally oriented, on the proximal endplate. As noted, the neural arches are missing, but the two on the right side were co-joined; only one is present on the left side. Units H and I articulate at an angle, adding more to the slight curvature at the tip of the tail of this individual. The posterior endplate is malformed, with a deep pit bisected by a low dorso-ventrally oriented ridge. The last vertebra appears truncated, suggesting possibly 30 cm or so of the tail tip was lost premortem. There was no evidence of a cartilaginous regenerated section as seen in a fossil crocodylian with a premortem tail tip amputation (Buffetaut, 1985). Premortem tail wounding and amputations in larger African mammals such as the black rhinoceros *Diceros bicornis*, and related to predation attempts, are known (e.g. Plotz and Linklater, 2011), but the present hadrosaur examples appear to be the result of serious post-trauma infections related to crush fractures (trampling), not predation. It is possible the missing

distal-most caudals in TMP 1980.023.0002 were lost during burial (the tip of the tail was disarticulated), excavation, improper care, and/or vandalism.

The second specimen (TMP 2011.012.0420) is an uncollected hadrosaur skeleton, possibly lambeosaurine, in DPP (UAD 91). Eleven disarticulated, but associated distal caudal vertebrae, were collected on the surface. Of these, eight express pathological conditions including fracture callus at the base of a neural arch and a bulging endplate, but six preserve large cavernous erosions that expand and penetrate deep into the centrum body (fig. 27a-b). These unusual lesions have not been recognized among many hundreds of pathological hadrosaur centra examined and appear to represent a type of osteopathy new to DPP hadrosaurs. They will be considered more fully elsewhere (Tanke and Rothschild, in prep.).

Ribs

Ribs fractures with well-aligned healing or with signs of infection are known from various sites and affect animals of all ages (neonates excepted), but predominate in adults. Single fractures are typical, though two affecting the same rib are known (e.g. TMP 1986.036. 0121, cf. *Edmontosaurus* TMP 1989.017.0004). *Prosaurolophus* (ROM 787) has six linearly disposed, well-healed right lower rib fractures. Parks (1935, Plate III) illustrated a healed mid-dorsal rib fracture in *Edmontosaurus* (ROM 807) collected near Drumheller. *Parasaurolophus* (ROM 786) has three healed rib fractures just superior to the left scapula (Parks, 1922). The injury appears to have affected the articulating vertebrae, as the neural spines tips are angled together and fused. TMP 1992.053.0021; quarry 206, a disarticulated cf. *Parasaurolophus*, preserves 19 dorsal ribs, three of which show healed breaks; two from the right side of the body, one positioned about mid-torso

and the second further back, preserved well healed and aligned fractures at mid-length (internally) and just below the head respectively. The left rib, posteriorly positioned in life, was injured just below the rib head. All are in the same state of repair, suggesting they were broken at the same time. A juvenile *Hypacrosaurus* dorsal rib (TMP 88.151.31) exhibits a swollen area on the posterior surface of the ribs neck. Two healed fractures (TMP 1989.017.0004) were present in an adult specimen from a ?hadrosaurine bonebed in Edmonton, AB. One was mid-shaft and the other located below the head. Both breaks probably occurred at the same time, as they were in the same state of repair. Some unfractured specimens (TMP 1987.048.0003; TMP 1993.666.0003) exhibited swelling and signs of osteomyelitis where the head of the rib articulates with the vertebra.

Shoulder girdle and forelimb

Shoulder girdle osteopathy is rare and appears of minor significance. cf. *Edmontosaurus* scapula fragment (TMP 1994.009.0001) bears a low rounded lesion with a drainage sinus. There is no indication of fracture or osteomyelitis. TMP 1966.031.0084 bears a low and smooth C-shaped lesion of undetermined etiology (likely and ossified subperiosteal hematoma or other residual damage from trauma) on the external left distal scapula (fig. 30).

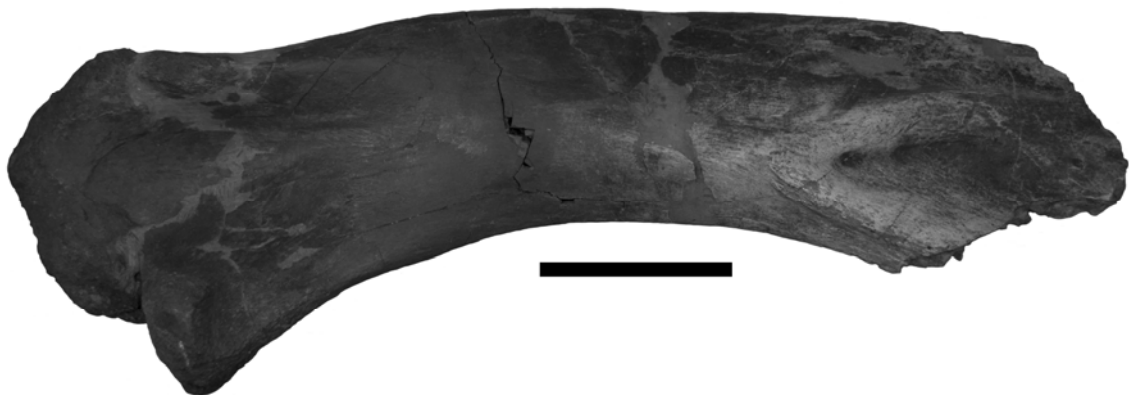


Figure 30. TMP 66.031.0084; left scapula, external view, showing raised C-shaped lesion on posterior blade. Scale bar = 10 cm.

A few traumatic forelimb injuries were noted and were quite serious in nature. The sole example of humeral pathology was collected upstream from Drumheller, AB. While Swinton (1970) cites it as *Hypacrosaurus*, Moodie (1923) incorrectly referred to it as a horned dinosaur. The bone (AMNH 5207; TMP cast TMP 1998.011.0001), was broken in two transversely or obliquely in a dorso-ventral plane, the two pieces then separated, rotated slightly and healed misaligned with subsequent osteomyelitis. It is so heavily modified (fig. 31a), that only the normal distal articulating end confirms it is in fact a humerus. Barnum Brown of the AMNH and collector of the specimen apparently called it “... the sickest fossil bone I have ever seen”.



Figure 31a-b. a) TMP 1998.011.0001 (cast of pathologic humerus AMNH 5207, compared with b) normal right humerus (reversed) of cf. *Parasaurolophus* (TMP 1992.053.0021) for comparison. Scale bar = 10 cm.

A well healed radius fracture with mild arching is figured in Sawyer and Erickson (1985). A more serious case (TMP 1996.012.0434; **fig. 32**) involves the complete fracture of both radius and ulna at mid-length. The periosteum of both bones was ruptured and reparative bone cells could freely proliferate into a large fracture callus, which permanently fused the bones together in life position.



Figure 32. TMP 1996.012.0434, radius and ulna, completely fused together at mid-length. Scale bar = 10 cm.

TMP 1966.017.0009 appears to represent a section of radius completely encased in an infectious fracture callus. Osteopathy was not observed in the few wrist elements located.

TMP 1996.012.0182 is a metacarpal with extensive osteomyelitis. The bone's surface texture looks so different in its pathological state, that its discoverer thought it was a plesiosaur sacral rib. TMP 1989.036.0317, another metacarpal preserves a thin irregular

layer of osteomyelitic new bone that easily flakes off of the normal bone. Despite a good sample size (N = 56), occurrences of manual osteopathy in TMP collections are rare, and are restricted to a few cases mild osteomyelitis (e.g. TMP 1989.036.0319) or osteophyte development (TMP 1991.036.0224). Spectacular healing fracture trauma of metacarpals III and IV has been reported from Montana in *Edmontosaurus* USNM V3814 (Moodie, 1926; Rothschild and Martin, 2006: fig. 17-8 (lower); TMP 1999.032.0001 (cast)). The rarity of metacarpal injuries suggests that they were either rare events or incompatible with survival. Some large metacarpals express low ridging and mild osteophyte development, but these appear restricted to very large animals and may be related to size and late ontogeny.

Pelvic girdle and hind limb

An articulated pair of lambeosaurine hadrosaur ischia both fractured proximally healed in a twisted position with massive callus formation (TMP 1979.014.0381; fig. 33). The shafts appear to have fused their entire length, including the expanded distal 'boot'. This specimen represents the most serious deep body fracture of a dinosaur so far recorded; it is indeed remarkable the individual survived.

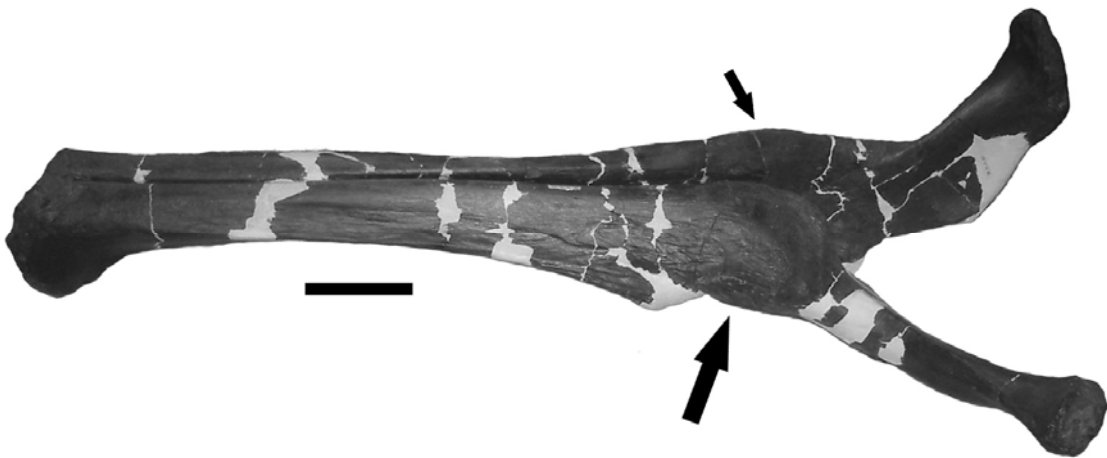


Figure 33. TMP 1979.014.0381, paired adult ischia with well healed fractures proximally (arrows). Scale bar = 10 cm.

Fractured ischia were reported by Charig (1979) and Blows (1989) in *Iguanodon*. Blows (1989) suggested such injuries in *Iguanodon* may have been caused by unsuccessful mating attempts but could conceivably have resulted from bad falls. The only other examples of pelvic osteopathy are Waldman's 1969 note of "a possible pathological condition" on the prepubis of a young *Kritosaurus* (CMN 8784) and an enlarged external face iliac pubic peduncle in *Parasaurolophus* (ROM 786), which partly overlapped the pubis (Lull and Wright, 1942). Hind limb injuries are rare. A thickened lesion, measuring 232 mm by 149 mm on tibia shaft (CMN 41201; Edmund, 1954; Lindblad, 1954; **fig. 34**) appears osteomyelitic and was active at time of death.



Figure 34. Transverse CT scan of distal of region CMN 41201, an adult tibia showing osteomyelitis. On the far right, it can be seen that the new bone is falling away from the normal bone. Scale bar approximately **XX** cm.

TMP 1991.036.0306, represented by two large pieces of tibia, also appears to have been badly infected. A complete fracture with massive pseudoarthrosis development at mid-length was observed in TMP 1995.405.0072, believed to be an incomplete fibula (fig. 35) preserved in two sections. A broken cross-section shows the original bone to be about 14.3 cm in diameter. Yet just 16 cm away the bone suddenly swells to form a massive pseudoarthrosis 48 cm in diameter, a jaw-dropping 335.7% increase over the normal bone!

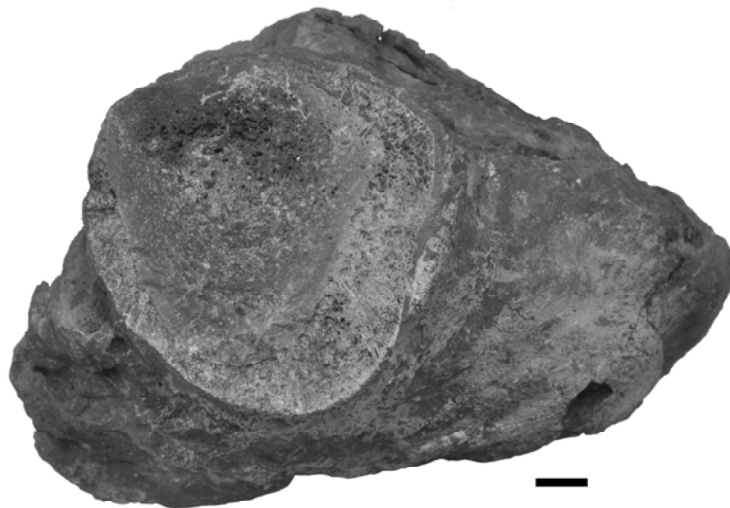


Figure 35. End on view of fibula shaft TMP 1995.405.0072, showing original bone in cross section and exuberant new bone development. Scale bar = 1 cm.

The paucity of major fracture trauma in large weight-bearing hind limb elements was as expected. Femoral or tibial fractures would be anticipated to impair mobility, resulting in death from trauma, dehydration, starvation, or predation. Osteopathy of bones in the ankle region was not observed, in contrast to what was recognized in the *Iguanodon* herd discovered in a coal mine a mile under Brussels (Rothschild, 1990).

Trauma was not observed among 72 metatarsals in TMP collections. Metatarsal III fragment TMP 2008.012.0062 is so badly infected as to suggest distal sloughing of the entire digit. If so, this animal may have left ichnites or trackways expressing limping or an injured/missing toe. Such examples are documented in theropods (citations in Tanke and Rothschild, 2002:85-86, 89-90; see also Ishigaki and Lockley, 2010), and one possible example of an infected and swollen toe in a hadrosaur was reported by Currie et al., (2003:fig. 7E) from Mongolia. In *Hypacrosaurus* (CMN 8501) from Rumsey, AB, right metatarsal IV is also pathologic, extensively covered by callus formation of an undetermined nature. Pedal injuries and infections, appear confined to fully mature individuals. The amorphous and barely recognizable deformed hadrosaur pedal phalanx (TMP 1975.008.0007) has several large openings present on the infected bone surface and is extensively hollowed out internally, suggesting massive pyogenic infection and perhaps sloughing off of the distal segment. Osteochondrosis regularly affects pedal phalanges, especially the proximal articular faces of the fourth digit. The lesions consist of circular to elongate-shaped shallow pits with a smooth or finely pitted floor, and occur singly or as multiple depressions. These common lesions are considered more fully in Rothschild and Tanke (2007). Stress fractures of pedal phalanges, well documented in contemporaneous ceratopsians (Rothschild, 1988; Rothschild and Martin, 2006; Tanke and Rothschild, 2010; fig. 25.22A), are unreported in hadrosaurs. This is perhaps surprising, given their larger size and their earlier presumed wide-ranging migratory habits (though see Benton, 1991; Bell and Snively, 2006; Fricke et al., 2009, and Chinsamy et al., 2012 for discussions).

Ossified tendons

Ossified tendons in hadrosaurs and other dinosaurs have been reported as pathological or protective (Moodie, 1927, 1928; Campbell, 1966; Reid, 1984; Rothschild, 1987a; Organ and Adams, 2005; Organ, 2006). Two ossified tendon sections, believed to be hadrosaurian (TMP 1966.017.0013, TMP 1985.047.0005), have mushroomed tumor-like “growths” of an as yet determined nature. The tendons may have been injured at the same time as the associated caudal vertebrae, although Organ (2006) noted caudal vertebrae fracture trauma in Montanan specimens, where nearby tendons were unaffected. While TMP 1966.017.0013 might represent an ossified haematoma, radiologic and histologic studies are awaited. TMP 1998.93.100 may also represent a healing ossified tendon fracture.

Eggs/skin

Zelenitsky and Hills (1997) reported on multilayered eggshell pathology in the oogenus *Spheroolithus albertensis* from near Warner, AB. Based on finds elsewhere (some associated with embryonic remains), *Spheroolithus* is believed to be hadrosaurian (Jackson and Schmitt, 2008).

Fossilized dinosaur skin impressions can preserve pathology; one of us (BMR) has a section of hadrosaur skin impression with a healing laceration. This interesting specimen will be described elsewhere (Rothschild et al., in progress). Lucas et al., 2000:85 suggested that the numerous tubercles in hadrosaur skin “increased the resistance of the skin to tearing and puncturing”. As Martill (1991) noted possible parasite damage to skin preserved in a Lower Jurassic *Scelidosaurus* from England. In reptiles, visible skin pathologies may be observed due to disease (Buenviaje et al., 1998; Alibardi and Toni, 2005). This can relate to physical trauma like cuts, tears and nicks received under varying

circumstances such as falls, or scrapes against protruding tree branches, or physical interactions with conspecifics or predators (i.e. Webb and Manolis, 1989:101). Hadrosaur skin impressions are regularly seen in Alberta associated with single bones or skeletons. Given the frequency of hadrosaur skin impressions in Alberta and the fossil record globally, it is just a matter of time before more examples of skin healing, scarring, or other damage are found.

Parasites/insects and intraspecific disease transmission

Add Current Biology paper This section reviews aspects of paleopathology that have been little explored in dinosaurs or is coming online and promise interesting results in the future. All animals today are host to a variety of endo- and ectoparasites and there is no reason to suppose hadrosaurs and other dinosaurs were not any different. Insects parasites and their kin have a long fossil record (excellent review in Labandeira, 2002), and their effects on dinosaurs is a growing field of study (Poinar and Poinar, 2005, 2007; Boucot and Poinar, 2010). Possible parasite damage in a skin specimen was noted earlier, but a new specimen from an early Cretaceous dinosaur coprolite from Belgium indicated the presence of protozoan cysts and helminth eggs, representing three Phyla of intestinal parasites (Poinar and Boucot, 2006). Biting sand flies (fam. Ceratopogonidae) that attacked reptiles are known from the Lower Cretaceous (Poinar and Poinar, 2004). Borkent (1995) speculated that sand flies found in Late Cretaceous Albertan amber, an annoyance to paleontology fieldworkers there today, also attacked dinosaurs. These species possessed hypertrophied mouthparts which Borkent suggested were used to bite ceratopsians and hadrosaurs where the skin was likely thin and softer such as under the frill and around the eye region respectively. From the same deposit, a mosquito (Poinar et

al., 2000) was secured. Mosquitoes have a long fossil record (Capasso, 1993; Poinar et al., 2000) and many mistakenly think that mosquitoes feed only warm-blooded prey, but extant species will attack reptiles and amphibians (e.g. Downes, 1958; Tempelis, 1975). Hadrosaurs and other dinosaurs may not have been immune. Tweet et al., 2006 noted possible evidence of parasite burrows in the stomach region of a Montanan *Brachylophosaurus*. Martill and Davis (1998) described parasite eggs on a Lower Cretaceous feather; Grimaldi and Engel (2006) and Smith et al., 2011 reported on the likelihood of lice infesting feathered dinosaurs and Dunlop (2007) reported on early Cretaceous parasitic mites. Fleas or flea-like parasites have a long geological record going back to the Middle Jurassic (Huang et al., 2012; Switek, 2012; see also Riek, 1970); recently described specimens (Huang et al., 2012; Gao et al., 2012) of a large size are so big they must have attacked large animals such as dinosaurs. A tick is recorded from 90 million-year-old amber in New Jersey (Klompen and Grimaldi, 2001). There can be little question that hadrosaurs and other dinosaurs of long ago were all hosts to a variety of parasites, just as animals (and ourselves) are today. As herding animals hadrosaurs would have greater chance of transmission of diseases between herd mates. Some of the spectacular ceratopsian and hadrosaur monospecific bonebeds in Alberta and Montana are sometimes attributed to disease (e.g. Grimaldi, 2009), but these sites appear to have been formed under extreme environmental or climatic conditions such as drought (Rogers, 1990) or seasonal flooding causing mass drownings (Brinkman et al., 2007; Eberth et al., 2010; Hunt and Farke, 2010). Most of the diseases hadrosaurs suffered from will remain unknown. For all we know they were afflicted by the common cold, but we would never know because the common cold (and most diseases today) do not result in

osteopathy. Some (e.g., Tanke and Farke, 2007; Wolf, 2009b) have reasonably speculated that diseases may have come and gone through evolutionary history so that even if we were to find evidence of them, we may not even recognize them for what they were. Many diseases today seem to be of short duration, and leave no osseous "imprint", denying the opportunity to recognize past afflictions. Many chronic diseases (e.g., cardiovascular and cerebrovascular disease) lack an osseous imprint or leave one that has subtle manifestations on macroscopic examination. There are few diseases affecting bone for which histological examination would add information or allow recognition beyond that offered by macroscopic examination of bone. In many cases, destructive histological examination is not practical as an epidemiological tool though the commonality of pathological hadrosaur bones in the province make this problem less of a concern. Further, DNA analysis probably cannot be confidently pursued this far back in time. Isolation of virus or its DNA from dinosaur bone would be difficult to interpret. First of all, contamination is a major concern. Second, one must verify that the isolated virus or fragment is a pathogen in general and then, for the specific species. Since so much of human DNA represents parts of viruses (e.g., the retroviral fragments in DNA from healthy humans), so it seems the isolation of viral/pathogen DNA from fossils would unlikely even be interpretable.

Discussion

This overview presents an overview of often common pathological conditions afflicting Albertan hadrosaurs. This is not to say their populations were unwell, but reflects their faunal dominance in Late Cretaceous ecosystems of southern Alberta. Hadrosaurs account for about 50% of the DPP dinosaur fauna (Currie and Russell, 2005) as skeletons

(Henderson and Tanke, 2010), in microvertebrate localities (Dodson, 1983), and overwhelmingly occur as numerous disarticulated elements recovered from multitaxic bonebeds and which formed the core of this research. Pathologic hadrosaur specimens in DPP occur with such frequency that one of us (DHT) has found up to half a dozen examples in a day. The types of dental, oral and skeletal osteopathy observed predominantly reflect the “bumps and knocks” incurred during the life of a hadrosaur, and are likely related to simple events such as falls, congenital defects, teratisms, and intraspecific encounters, be they accidental contact or behavior related. Because of their abundance in the field, caudal vertebrae are often ignored, which is unfortunate as they provide a wealth of knowledge about health and inferred lifestyle in hadrosaurs. One cannot help but be impressed by the large numbers of healing tail injuries. The frequency of these injuries is very real, and not enhanced by collecting biases and demand explanation as to their etiology(ies). Earlier interpretations of proximal caudal neural spine injuries (Tanke, 1989; Rothschild and Tanke, 1992; Rothschild, 1994) considered mating trauma, with the heavy weight of the mounted male resting on and crushing the female’s proximal tail. This suggestion was not well received in the scientific community; though see Isles (2009:176). It was mocked in newspaper (see Tanke and Rothschild, 2002:66 for citations) and radio press even though dinosaur mating trauma had been previously suggested (Gilmore, 1909, 1912; Blows, 1989; Vance, 1989; more citations in Tanke and Rothschild, 2002:91), and courtship/mating trauma and death are known in the modern world (see Baker and Brothwell, 1980; Droscher, 1976). If this interpretation is true, then lambeosaurines, with their more elongate neural spines may have been more prone to injury.

Over several decades, the role of tyrannosaurids, especially *Tyrannosaurus*, as obligate scavengers, active predators (or both), and cannibals has been a hot button issue and stimulated much debate (Farlow and Holtz, 2002; Meers, 2003; see Holtz, 2008 for a recent review; Witmer and Ridgely, 2009; Brusatte, et al., 2010; Hone and Watabe, 2010; Longrich et al., 2010; Bell and Currie, 2010; Bell, 2011). We don't want to belabour the issue of tyrannosaurid feeding behavior, but some comments are made here. A well-established fact is that tyrannosaurids (and some other theropods) used their teeth on live conspecifics (Tanke and Currie, 2000; Peterson et al., 2009; Bell, 2011), landing deep bites on the head, doing so regularly (44% of TMP articulated skull specimens; Tanke and Currie, 2000:180) and at their own peril. These wounds, while serious, were not immediately fatal, if the bite was in fact the cause of death. Knowing that tyrannosaur intraspecific head-biting occurred, it does not require a leap of faith to see them biting and killing hadrosaurs. However, caution is strongly urged in interpreting hadrosaur caudal osteopathy as examples of failed predation attempts by tyrannosaurids. For example, Carpenter (1988; 2000), described a series of five pathological caudal vertebrae (#'s 13-17) in an articulated *Edmontosaurus* (DMNH 1943) collected from the Hell Creek Formation of Montana. The wounds formed a curved line, suggesting the outline of a mouth. He therefore attributed the wounds to a *Tyrannosaurus* bite, an interpretation that has gained acceptance in the public and to some in the scientific community (e.g. Farlow and Holtz, 2002; Holtz, 2002; Glut, 2003:316; Holtz, 2003, Canudo-Sanagustín, 2004; Canudo et al., 2005a-b; Carpenter et al., 2005; Hone and Rauhut, 2010). Carpenter (2000) describes the distal end of neural spine #15 as being "sheared off" by a tooth with a deep groove or pocket now present on the remaining end. Simple, malaligned and well

healed fractures are present in the remaining pathologic segment. Two associated pits were interpreted as tooth puncture marks. But were these lesions actually inflicted a *Tyrannosaurus*' teeth or are they the result of something else?

The morphology of small theropod and tyrannosaur tooth marking on bone in DPP and large theropod toothmarks elsewhere are well documented (Currie and Jacobsen, 1995; Jacobsen, 1998, 2001; Probiner, 2008; Jacobsen and Bromley, 2009; Longrich et al., 2010; see also review in Hone and Rauhut, 2010). Claw marks (e.g. Worthy and Holdaway, 2002:figs. 8.18 and 8.39) on prey bone in DPP are presently unknown. Toothmarks are present on bones with flat or rounded morphologies and occur as punctures, tooth drags (gouges), parallel striae imprinted from tooth serrations, or combinations thereof. True, unquestionable tyrannosaur toothmarks, manifested as intraspecific head-biting lesions with subsequent healing (Tanke and Currie, 2000; Peterson et al., 2009; Bell and Currie, 2010) are also known. After all, the only animal large enough to bite an adult tyrannosaur on the head is an adult conspecific. These head-bite lesions, with their active and advanced healing, are still recognizable as tyrannosaur tooth marks, forming elongate straight to gently curving rows and in correctly spaced parallel groups, where more than one tooth has made contact with bone (Bell, 2011:fig. 3). The tooth strike lesions, first forming punctures or rough-edged troughs (gouges) when incurred, are later infilled and slightly overfilled with reparative bone tissues that form an elongate and raised osseous "blister", this feature being analogous to a fracture callus. It is important to separate unhealed versus healing predator on prey toothmarks. Carnivore teeth embedded in bone without healing (e.g. Currie and Jacobsen, 1995; Schwimmer et al., 1997; Mead, 1998; Buffetaut et al., 2004; Kellner, 2004; van Oorde,

2008; Ehret et al., 2009) or unhealed toothmarks are sometimes misdiagnosed, interpreted or categorized by others as paleopathology. These represent evidence of predation or scavenging behaviors only, nothing more. If there is no reactive bone response such as blister formation or other expressions of new bone growth at/near the toothmark wound, then there is no paleopathology. Simply put- if you are dead, your bone cannot heal. This simple point is often and consistently overlooked by others.

Other similar blister-like lesions are known in an interpreted *Tyrannosaurus* bite on a *Triceratops* frill (Happ, 2008; fig. 19.2) and on ceratopsian frills where conspecific rivalry and horn damage to frill bones is implicated (Farke et al., 2009; fig. 2-3). Circular and sub-circular fully penetrating lesions of the thin surangular and angular bones in tyrannosaurs, particularly *Tyrannosaurus*, have also been variously interpreted as intraspecific tooth puncture marks. Some (Brochu, 2003; Wolff, 2007, Wolff et al., 2009) have suggested they are disease related, a controversial perspective (see Bell, 2010:1265-1266), although they are indistinguishable from healing bone defects observed in humans and other animals (Rothschild and Martin, 2006). For this discussion, the elongate, furrow-forming tyrannosaur on tyrannosaur toothmarks (with healing) are the ones relevant to this discussion. Those lesions, now recognized for their true source, are therefore valuable for comparison to other dinosaur bones whose prior owners were attacked by a tyrannosaur. They were deeply bitten (with teeth contacting bone), but were able to escape and then partially recover from the wound. Such individuals should show similar healing blister formation in, straight or elongate furrows, likely in parallel arrangements. Tyrannosaurs broke and chipped their teeth (Farlow and Brinkman, 1994; Schubert and Ungar, 2005) during feeding, so they might also reveal the tips or fragments

of embedded tyrannosaur teeth (Farlow and Holtz, 2002; Holtz, 2002; Bell and Currie, 2010; Hone and Rauhut, 2010:fig. 3), but would also exhibit reactive healing bone around or encapsulating them, likely with exuberant and infectious bone growth (sensu Rothschild and Martin, 1990; Rothschild, et al., 2005; DePalma et al., submitted). Three and a half decades of museum and field examination by one of us (DHT) of hadrosaur (and other ornithischian bones) in DPP and elsewhere in Alberta, TMP and other museum collections and similar museum work done by BMR over 30 years has revealed only one “blister-like” or bone response to an embedded tooth (DePalma et al., submitted).

Unhealed predator toothmarks on bone are regularly seen, but few exhibit healing and are restricted to tyrannosaur cranial elements (Tanke and Currie, 2000; Peterson et al., 2009; Bell, 2011). This indicates that tyrannosaurs were better able to survive bites from conspecifics than were their prey, which is not unexpected. Today, if a predator is able to catch its prey and/or land a deep bite, then the prey animal is usually killed and consumed there and then. Many prey animals can escape being pursued because they can outrun or outwit the predator. No record of that interaction is recorded, as no bite was landed. Only a very lucky few wrench free from a deep bone damaging bite and manage to escape.

Seemingly anomalous openings that may appear to represent healing tooth puncture wounds in dinosaur bones are usually related to infection, increased blood supply at the wound site or other factors. Tanke and Rothschild (2010: fig. 2 left) figure a pathologic hadrosaur caudal vertebra (TMP 1992.036.0602) with a basal neural spine pseudoarthrosis and two small circular holes. These holes would traditionally be interpreted as toothmarks, but they are related to the osteopathy and are likely vascular in origin. Pseudo-toothmarks can also be created when a fracture callus overlaps, but does

not contact normal bone, creating subcircular to elongate overhanging lips of bone (i.e. TMP 1992.092.0068; TMP 1992.030.0097). These features could possibly be misinterpreted as healing toothmarks. Direct examination of the Denver *Edmontosaurus* (DMNH 1943) with the putative “bitten tail” disclosed healing neural spine lesions no different to those seen in the hundreds by one of us (DHT) in DPP and in TMP and other museum collections. There are no raised blister-like lesions as seen in healing tyrannosaur (and other theropod) facial bones or any other gouging or puncture-type lesions, with healing, as would be expected if a tooth gouged across the hadrosaur neural spine and the animal survived an extended period. There are no parallel tooth-induced lesions (though see Horner, 1992; plate 44B for a possible case in a *Kritosaurus* skull roof), nor do the neural spines exhibit embedded tyrannosaur teeth or the massive swelling that would occur in this situation (sensu Rothschild et al., 2005). Most telling in *Edmontosaurus* DMNH 1943 is neural spine #15 which is missing its distal end. Examination of Carpenter’s figures (Carpenter, 2000; figs. 4A-B, 5B) and close up inspection of the mounted skeleton by one of us (DHT) demonstrates a classic swollen fracture non-union (pseudoarthrosis) with infection. A non-union forms where a bone has fractured and repeated body movement or other conditions prevent the two (or more) segments from healing back together. Proper callus formation fails and the pieces heal separately forming a non-union or “false joint”. A non-union can only form if two or more bone adjoining pieces are present. Carpenter (2000:139-140) suggested neural spine #15 was “sheared off” during the supposed bite and removed. If so, the distal bone segment was gone and in its absence, a non-union could not develop. So what became of the missing distal piece? It is not included in the mounted skeleton and could be missing

for a number of reasons. We would posit the now missing neural spine #15 was there all along, allowing the non-union to develop. We hypothesize that it was later lost either through disuse atrophy, infection and sloughing off of the distal portion, lost as the skeleton decayed and perhaps water currents washed it away (less likely as the tail was articulated), accidentally lost in the field (not an uncommon occurrence), or it still exists, misplaced in a museum collection (again not an unknown situation in museums). But what of the several interpreted tooth puncture marks? They are now so remodelled that it is impossible to make such a diagnosis. Remodelled pus drainage channels or blood vessel openings could also be considered. X-ray examination will be of interest. Post-traumatic infection, complicating such fractures, can produce ragged-appearing new bone formations, as often occurs with internal vacuities opening onto the surface through irregular, branching tube-like networks. Examination of similarly injured neural spines in TMP collections shows that they too can develop “tooth puncture marks” (*sensu* Carpenter, 2000), but these holes are vascular, related to increased blood flow at a wound site and/or represent draining sinuses related to infections. These “tooth puncture marks” in TMP specimens are scattered over the wound site in irregular patterns (not in rows as would be expected from a bite (*sensu* Tanke and Currie, 2000; Bell, 2011; Peterson et al., 2009)), and are inconsistent with the shape, size and especially spacing of any known theropod teeth. In TMP 1981.016.0364, a proximal neural spine shows a number of “tooth punctures”, two of those located on the anterior and posterior edges of the spine near the tip. They are co-joined by a hollowed-out space deep inside the neural spine and show that it was infected and that the two “toothmarks” are actually related to a pyogenic infection with the openings allowing the discharge of pus. TMP 1985.036.0024 is

another proximal neural spine with two “toothmarks” and here again, the “toothmarks” are present and connected on the underside of new, post-traumatic bone growth, demonstrating the holes were actually formed due to increased vascular activity at the wound site.

Troubling for Carpenter’s interpretation are the large numbers of fractured neural spines with healing repeatedly seen in DPP and other Albertan localities, now curated in TMP collections. Along with fractured and healing hadrosaur centra, they are the most common type of dinosaur osteopathy found in Alberta. Similarly injured neural spines are known from elsewhere: South Dakota (Maltese, pers. comm., 2012; Table 1); Montana (Carpenter, 2000; Rothschild, 1997:433; Organ and Adams, 2005:604; Table 1); Spain (Canudo et al., 2005); and east Asia (Godefroit, et al., 2003, in press; P.J. Currie, pers. comm.). Specimens figured from California (Morris, 1981), Argentina (Juárez Valieri et al., 2010:fig. 5I (left), 5K (right); and China (Young, 1958) also seem affected.

If Carpenter’s interpretation is correct, then we have evidence of many lucky DPP (and worldwide) hadrosaurs being severely bitten and escaping. If only the DMNH 1943 *Edmontosaurus* (among all the hadrosaur specimens known today) showed the tail injury then the failed predation interpretation would be more plausible. But a number of circumstances had to happen to DMNH 1943 to allow this particular scenario (sensu Carpenter, 2000) to be preserved:

1. An adult *Edmontosaurus* would have a direct, close and personal encounter with a hungry adult *Tyrannosaurus*. Such events would likely only happen a few times in an edmontosaurs life and likely not have a good outcome. This is more likely if tyrannosaurs hunted in packs, as has been recently advocated (Currie and Eberth, 2010). If the

edmontosaur escaped to live another day without being bitten, then no record of the encounter would be recorded, i.e. no bitten tail.

2. The *Tyrannosaurus* would have to bite the *Edmontosaurus*' tail, strongly enough to cause bone breakage but not enough to bite all the neural spines off, yet remove neural spine #15, the centremost of the afflicted series. We consider that highly unlikely.

Tyrannosaurus, with its massive teeth, was a bone crusher (Chin et al., 1998; Erickson and Olsen, 1996; Erickson et al., 1996; see also Hone and Rauhut, 2010), not a nipper; we would envision the tail experiencing much more grievous injuries, if not being bitten off entirely.

3. The edmontosaur broke free, escaped, and then, wounded and bleeding, had to avoid the attentions other predators. It would have to live for an extended period of time, long enough show advanced healing of its injuries, but for how long is uncertain. Hadrosaur bone fracture healing rates are unknown. Early attempts to address this problem failed (Tumarkin et al., 1999) as histological work revealed that only later stage fracture repairs were preserved. Straight et al. (2009) discovered that fracture callus development in two unspiciated (?lambeosaurine) DPP hadrosaur proximal neural spines was more analogous to that in extant birds than extant crocodylians, suggesting a faster bone fracture healing rate than modern reptiles; more comparative work is needed in this area. Rothschild and Martin (2006:125) and Rothschild et al., 2012 suggested it would be difficult to see fracture callus formation in fossil vertebrates, even up to three weeks post trauma. Also during this time, the edmontosaur would also have to survive potential attentions of insects attracted to the wound site and the infectious "septic bite" often ascribed to tyrannosaurids (e.g. Abler, 1992, 1999).

4. The *Edmontosaurus* then had to die in or near an active fluvial system.

5. After death, the carcass had to dodge the numerous vagaries of taphonomy. It had to avoid bloating and floating away in a river channel then disarticulating, losing bones one by one (Behrensmeyer, 1991). It also had to escape being scavenged and torn apart, and had to be quickly buried before the bones were all washed away by water currents.

6. Then the skeleton had to avoid being uncovered again and washed away by the meandering river system and then had to become fossilized. As readers know, the fossil record is incomplete and we are often reminded how very few animals (or parts thereof) ever become fossilized.

7. 65 million years passed, and then modern erosion just happens to expose this particular specimen.

8. Man has coincidentally evolved and developed an interest in vertebrate paleontology and such a field worker happens to be in the right place at the right time and make the discovery before the skeleton (and specifically the bitten tail section) has eroded away.

Given these points, the authors consider the chance of a hadrosaur being seriously bitten by a tyrannosaur, escaping, partially healing, being buried, fossilized, and then discovered as extremely low, with ever increasing odds against it ever being preserved or found. So low of a chance in fact that healing tyrannosaur bites on hadrosaurs should therefore be rare indeed. There are some extremely rare examples in the fossil record where a prey animal was attacked and suffered a grievous wound, but escaped and healed. Such examples of sublethal predation in fossil and extant invertebrates are well known (e.g. Kelley et al., 2003), but among vertebrates, even going back to their origins (Lebedev et al., 2009) the record is quite small. Among extant animals a literature review

disclosed it is prevalent mostly in smaller vertebrates like fish, amphibians and reptiles (Bowerman et al., 2010). Healing bite wounds to the head and body in terrestrial or aquatic vertebrates may be related to intraspecific behavior (e.g. Everhart, 2008) and do not necessarily constitute attempted predation. Cases of possible failed predation with healing includes distal tail amputation in an Early Jurassic cf. *Massospondylus* (Butler, pers. comm., 2012, Butler et al., in prep.); a partial body amputation in a Miocene fish (Meunier and Gayet, 1991); Oligocene oreodonts with healing bite wounds to the cranium (Tanke and Currie, 2000); nipped off tail tips in juvenile marine mosasaurs (Mulder, 2001); and distal tail loss in a Pleistocene armadillo (Stangl et al., 2010; though frostbite may also be implicated). Several reports (Campagna, 2000; Glut, 2002:324) of partial healing of maniraptoran toothmarks to an *Edmontosaurus* dentary remain unstudied and thus unconfirmed. A good-quality cast of the specimen (TMP 2012.005.0001) is not instructive regarding the claims of partial healing. Failed predation does not necessarily wound or later prove fatal to the victim, and the predator itself occasionally ends up being the victim too (e.g. Frey and Tischlinger, 2012). These points in mind, true predator on prey injuries with healing among dinosaurs would be expected to be extremely rare. So how then does one explain the hundred of specimens identical to DMNH 1943 in the field (especially DPP), TMP and other museum collections with DPP material and similar finds worldwide? Tyrannosaur hunting strategy is often compared to that of the extant Komodo dragon *Varanus komodoensis* where the varanid bites a large prey animal then waits for it to succumb from shock, blood loss or sepsis within a few days (Montgomery et al., 2002). This is true, but in these cases there is often a large size disparity between the predator and prey (larger). The larger prey being bitten (water

buffalo, horses, goats) are not native to the islands where *V. komodoensis* lives and are introduced, so the hunting technique, specifically for larger prey may not be typical and not make a good comparison. After all Komodo dragons are lizards, not tyrannosaurs. If tyrannosaurs did in fact bite their hadrosaurian prey on the tail and then trailed it until it could be killed and consumed, then the numerous finds of healed or advanced healing of traumatized caudal neural spines in DPP (and elsewhere) demonstrate that many hadrosaurs did not die soon after being bitten, but lived for an extended time, perhaps well in excess of three weeks (Rothschild and Martin, 2006:125). Examples with full healing (but still showing angulation of the distal neural spine) would indicate some animals survived long after the attack was made. If so, partial and full healing of neural spines demonstrates that this “bite and wait” may not have been a successful hunting strategy for DPP tyrannosaurs and apparently for tyrannosaurids worldwide, where healing hadrosaur injured neural spines are also known. Such tail healing is observed over at least 10 million years of hadrosaur evolution suggesting tyrannosaurs did not evolve a better hunting style and many of their prey could escape and survive. Was the Late Cretaceous world one of numerous nervous hadrosaurs with nipped and injured tails and hungry, disgruntled tyrannosaurs? We think not.

For the record, there are several examples in DPP of true theropod tooth marks associated with an injured hadrosaur tail or caudal vertebrae. Associated fragmentary tail TMP 1992.036.0435 shows neural spine fracture healing and toothmarks. TMP 1981.019.0154 is a mid-caudal vertebra showing a pathological neural spine in a twisted condition, with two tyrannosaurid toothmarks on the left side of the centrum. Distal caudal vertebra TMP 1991.036.0212 shows toothmarks on the neural spine. Three small

theropod toothmarks are evident on two fused mid-caudal vertebrae (TMP 1978.009.0064) and mid-caudal centrum TMP 1991.036.0537 with osteomyelitis preserves toothmarks. As the toothmark damage in all these specimens is fresh and the neural spine/centrum injury is healing, attribution of hadrosaur caudal injuries to predation still proves elusive. Healed tyrannosaur bites are naturally an exciting explanation, but there are others cases of an exotic dinosaur pathology being simply explained. In one example, early newspaper reports of cancer affecting an *Allosaurus* distal humerus was rediagnosed as a badly infected bone fracture (Rothschild et al., 2003; Rothschild and Tanke, 2005; Rothschild and Martin, 2006). Other examples are those pathologies misdiagnosed as arthritis, an ailment virtually unknown in dinosaurs (Rothschild, 1990; Rothschild and Martin, 2006; Rothschild et al., 2012). There has to be a simpler explanation of the frequent hadrosaur tail injuries. While we don't deny tyrannosaurs were active predators (and scavengers when opportunity presented itself), we don't think the DMNH *Edmontosaurus* example and numerous DPP specimens and other similar occurrences worldwide represent(s) failed predation attempt(s). Further refuting this hypothesis are occurrences of numerous neural spines simultaneously injured in one animal (Table 1) in other hadrosaur specimens. Some of these specimens show damage over several metres of the tail (Table 1) and were evidently received at the same time, as all fractures are in the same state of repair. This would mean that a tyrannosaur with impossibly long jaws bit the tail and all teeth coincidentally contacted and broke a neural spine (the hadrosaur then escaping), or the victim stood around long enough for a tyrannosaur to repeatedly bite along the top of the tail like a corn on the cob with the hadrosaur realizing its predicament and escaping. The first scenario of course

never happened and the second seems illogical to us. The absence of associated and healing tyrannosaur toothmarks (e.g., lateral/longitudinal drag or puncture marks with post-traumatic osseous blister formation) complicates attribution of these injuries to unsuccessful predatory attacks.

Rather, a more parsimonious cause for these numerous injuries must exist. We posit a more benign etiology that reflects the rather delicate nature of the caudal neural spines combined with the known sociality of hadrosaurs. Some of the tail and other injuries may have been incurred during aggressive conspecific encounters resulting in kicking or lashing with the heavy tail (Rothschild, 1987a-b), but these behaviors are only speculative. Possibly the hadrosaurs were biting each other as part of some social behavior. Hadrosaurs lived in groups or herds and herding animals today often have complex intraspecific behaviors which may include biting, but a hadrosaur's gape seems too small, and biting strength perhaps too low inflict the injuries we've observed and, certainly could not have caused those located deeper within the tail. It is beyond the scope of this paper to discuss evidence supporting hadrosaur sociality, but most learned readers would agree that there is good evidence from trackways, communal nesting sites, grouped skeletons, and hadrosaur-dominated bonebeds to show that hadrosaurs lived in large groups at least part of, if not all of the time.

We suggest that DMNH 1943 does not represent a healing tyrannosaur bite wound, but rather, a simple trampling injury, whereby DMNH 1943 rested, laying prone on the ground and a conspecific stepped over its tail, "clipping" the tips of the neural spines with its foot (fig. 36, 37a-c). Hadrosaur tails were strongly buttressed laterally by complex tendon arrangements (Parks, 1920, Lull and Wright, 1942; Organ and Adams, 2005;

Organ, 2006), making them relatively rigid. Thus they would have little “give” when receiving a strong lateral blow (though non-union development of proximal caudal neural spines above the zygapophyseal complex indicates repeated movement was possible). However, the neural spine tips protrude above the tendon lattice-work and are unsupported, making them more exposed and vulnerable to potential traumatic impacts from the sides and above. Fractured and healing neural spines further down the tail and distal to the supportive tendon arrangement are also seen, suggesting other possible etiologies for these injuries. Carpenter (2000) interpreted the curve of the neural spine lesions on DMNH 1943 as representing the outline of the mouth of *Tyrannosaurus*, but the same curvature can be envisioned by the contracted foot of another hadrosaur as it stepped over the tail inadvertently striking a glancing, but serious bone-breaking blow (figs. 36, 37b-c), the broken spine tips deflected towards the direction of travel of the animal stepping over.

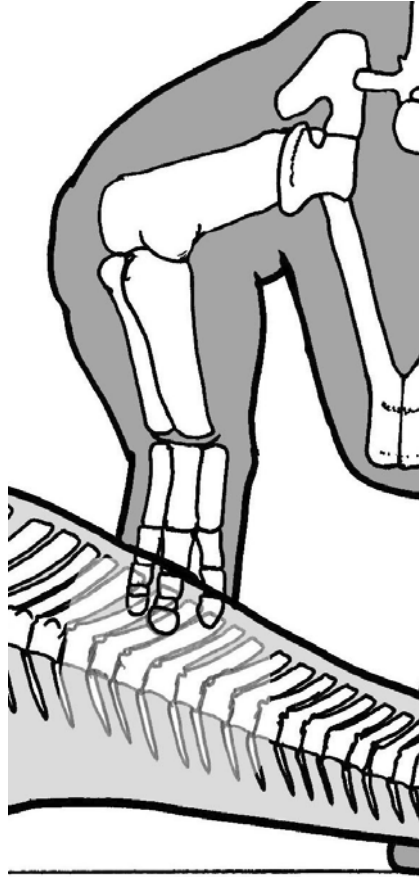


Figure 36. Alternative etiology explaining the caudal neural spine tips and angulation injuries in DMNH 1943 *Edmontosaurus*.

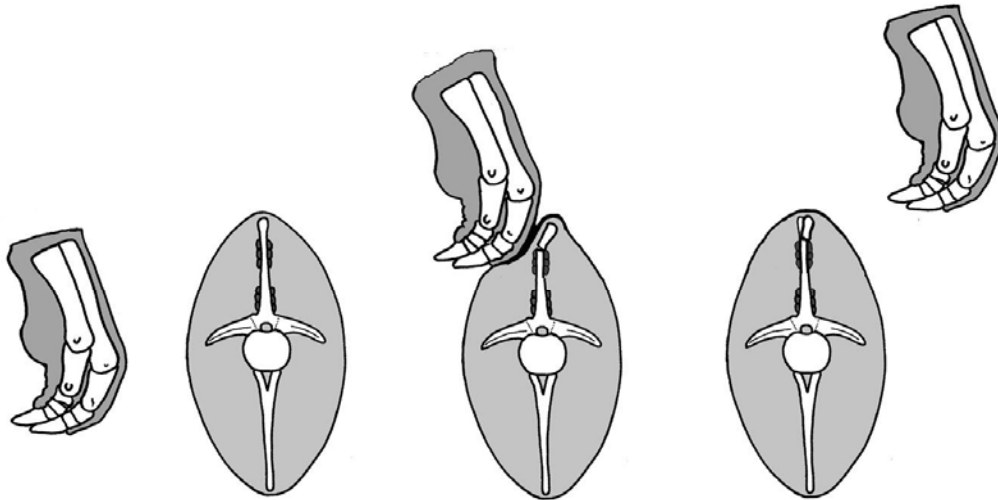


Figure 37a-c. Hypothesized sequence of events explaining caudal neural spine tip and angulation injuries in DMNH 1943 *Edmontosaurus* and hadrosaur specimens described herein.

Localized caudal neural spine traumas (such as DMNH 1943) may be easier to interpret but those that occur over long portions of the tail are perplexing and their etiologies harder to explain. Extensive linear neural spine fractures (contra Hanna, 2000) affecting many vertebrae cannot be explained as mating trauma, intraspecific trampling, or even putative failed predation attempts. They suggest other mechanisms of injury such as a biomechanical failure, but these explorations are beyond the scope of this paper.

The variety of injuries observed in hadrosaurs have also been seen in dinosaurs of a similar bauplan- the iguanodonts, although osteopathy in that group has not been extensively studied and mentioned mostly briefly (see citation listing in Tanke and Rothschild, 2002:79). The suite of injuries in that group, is similar to that in hadrosaurs, suggesting body shape and skeletal morphology may be as important as inter/intraspecific

behavior in the etiology of osteopathic conditions across related, but different dinosaur families. We would not be surprised if closer inspection for caudal osteopathy among other dinosaur families, especially those where the tail is long with relatively gracile skeletal morphology, great weight is involved, and herding or grouping behavior is known/suspected would also reveal examples similar to those in Albertan hadrosaurs.

As communal or herding animals, hadrosaurs would have a higher chance of being injured by conspecifics, be it accidentally or through aggressive behaviors. Whether in a bipedal or quadrupedal pose, hadrosaur tails were elevated off the ground (Galton, 1970). We do not advocate the obligate (and obsolete) “tail dragging dinosaurs” poses as portrayed years ago, but see it possible that they would on occasion place all or parts of their tails onto the ground. Supporting this, are examples that show that sauropods and bipedal dinosaurs did at least occasionally (see below), rested and/or dragged the tail and thereby risked injury from conspecific trampling. Many *in situ* dinosaur trackways are known globally. Very few show evidences of tail drag marks (see discussions and citations in Foster et al., 2000; Irby and Albright, 2002; Moratalla et al., 2003; Li et al., 2006; Pérez-Lorente and Herrero Gascon, 2007; Platt and Hasiotis, 2008; XXXX), but they don’t tell the whole story. Virtually all trackways described in the literature show animals going from point A to point B in straight or relatively straight paths, with long strides, and seemingly doing so with a purpose. Very few show them stopping, turning, resting, feeding/drinking, interacting with the environment, or other animals. From this we could infer all dinosaurs walked in relatively straight lines most of their lives and the known fossil record would overwhelmingly support this nonsensical hypothesis. We would posit then that hadrosaurs and other dinosaurs rested their tails on the ground more

than the fossil record indicates, but that activity is not frequently preserved because most trackways seen today are showing animals simply on the move with their tails held high and don't preserve traces of animals engaged in other activities where the tail was lowered. Few large ornithomimid or hadrosaur trackways are known with tail drag marks or suspected tail marks (Dollo, 1906; Parker and Balsey, 1989; Lockley et al., 2003; **there is one more, still being sought**), showing that they could and did lower their tails from time to time. Within large hadrosaur groupings, especially wherever crowding was an issue (i.e. nesting ground/rookery; Horner, 1984, 2000), the chance of bone-breaking accidents occurring would increase. Not only were eggs and nests in danger from trampling (Xing et al., 2009), but the hadrosaurs as well. A careless individual, laying fully on the ground or allowing its tail to contact the substrate (while brooding/guarding eggs or young), feeding (whereby rising high up on the hind limbs bringing the head towards vegetation simultaneously lowers the tail), drinking, resting/sleeping, or any activity involving lowering of the body), would bring the tail close to or in direct contact with the ground (see Maryńska and Osmólska, 1984:fig. 5A,D), making it vulnerable to others in the group. Another hadrosaur, partially stepping over the tail and clipping it, or, more distally, stepping directly onto the tail with all its weight resting on one foot (fig. **38**) could explain the serious caudal traumas described herein.

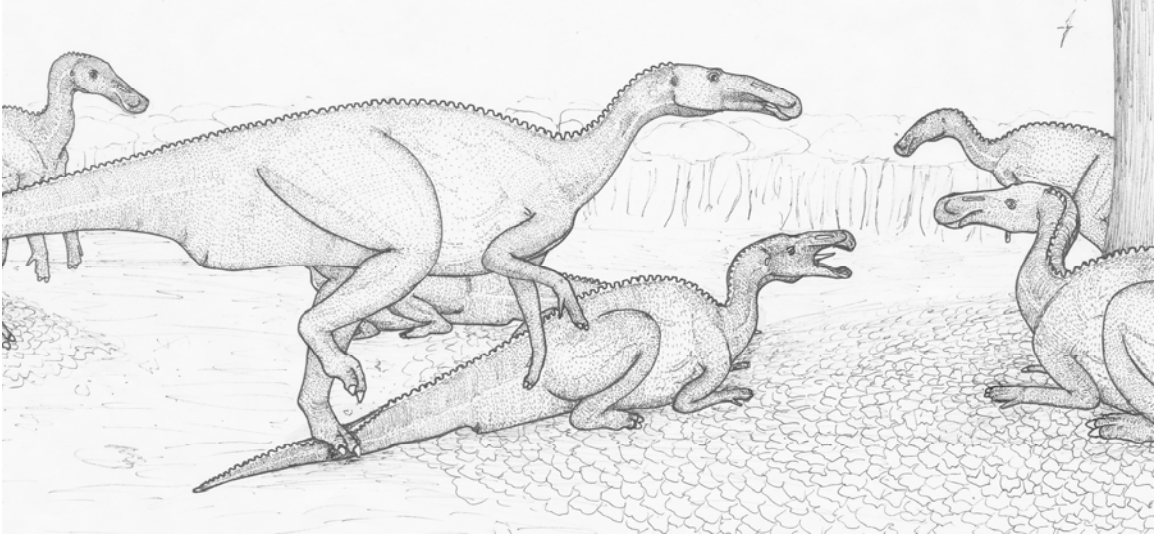


Figure 38. Intraspecific trampling of distal tail in *Edmontosaurus*. Illustration by Tracy Ford, Poway, CA.

Given the frequent observation of crush fractures to the distal half of the tail in TMP collections and in the field, such accidents appear to have been a regular occurrence. As predators, tyrannosaurs were naturally dangerous to hadrosaurs, but among their cohorts, hadrosaurs themselves could also make for rather dangerous company.

Summary/conclusions regarding osteopathy in Albertan hadrosaurs

1. Hadrosaur osteopathy is well known in Dinosaur Provincial Park and elsewhere in Alberta, where bone preservation and quantity are such that specimens are readily available for a variety of invasive and non-invasive studies.

2. Fractures predominate, with adults most frequently affected. It could be suggested that older animals acquired more injuries simply because they have been around longer than younger animals, but this is not so. Most of the injuries seen in adults are actively healing and demonstrate they were received when the animal was an adult.

Therefore these injuries are relatively new and do not reflect a cumulative effect of injuries received over long periods of time.

3. Hadrosaurs survived debilitating injuries such as dentary, forelimb and bilateral pelvic fractures; but no major hind limb bone fractures with healing are known.

4. Osteopathy in juveniles and subadults is not well known; the first, possibly related to relative fragility of the young animals (serious injury = rapid death or predation) and small sample size; the second, potentially related to segregation of young individuals from adults, as suggested for contemporaneous hadrosaur faunas in nearby Montana. Segregated subadults would thus avoid accidental or behavior-related contact with older and larger adults that could result in osteopathy/death.

4. Fractures often show advanced, but rarely total healing showing the afflicted animal survived its trauma for an extended period.

5. Total healing of fractures could make them invisible, but moderate angulation of the affected parts can still reveal the fractures original presence; i.e. neural spine tips in TMP 1981.019.0154; TMP 1981.023.0043, 1992.036.0362, TMP 1994.009.003.

6. The tail is most frequently injured body region, increasing in types and severity as one moves distally. Fractured (single (typical) or multiple) and healing neural spine tips are found proximally, often with lateral angulation; vertebral fusions are rare. Medial caudals show single or multiple fractures of the neural spine tip and fracture non-union above and below the zygapophyses is noted. Centra can have deep pre-mortem fracture-related cracks of variable orientation on one or both endplates. CT scans show similarly aligned disrupted bone, showing the centrum was split into two (or more) pieces which then healed. Intervertebral fusions are uncommon. Distal caudals show massive crush trauma

with fusions of seriously malformed vertebrae (up to five in number but usually two) are not uncommon. Osteomyelitis is known and some specimens suggested distal tail amputation or sloughing. Distal tail injuries appear related to intraspecific trampling.

7. Despite the spectacular story suggested by Carpenter (2000), the caudal neural spine osteopathy in *Edmontosaurus* DMNH 1943 was not caused by a tyrannosaur bite. It more likely represents an accidental partial trampling injury, where a large conspecific stepped over a prone DMNH 1943 and its foot clipped the top of the tail, breaking the neural spines. The outline of a stepping over foot matches the outline of the tyrannosaurs jaws as well. Paleopathological evidence of tyrannosaur bites on hadrosaurs (i.e. failed predation attempts with subsequent bone repair) are extremely rare, with only one known occurrence (DePalma et al., submitted).

8. As herding animals, hadrosaurs were most likely injured by large and heavy adult conspecifics who accidentally fell onto or stepped on the mid to distal tail (causing fractures and crushing trauma), or stepping over the tail of a prone individual (breaking neural spines). Animals with serious injuries are usually selected against by predators, yet we have documented numerous examples of serious, debilitating injuries. Perhaps an injured hadrosaur could gain some anonymity within a large herd and escape the immediate attention of top predators, or hunker down in dense vegetation, living off fat reserves until the injuries healed. However, examples of non-union of fractures in the tail and other elements suggest that some animals remained active, despite being injured.

9. As they all share the same bauplan and seem to share the same herding/nesting behavior, we would predict that wherever hadrosaurs (and probably iguanodonts) are found worldwide, the types of osteopathy described herein will also be found there. Other

dinosaurs, with herding behavior, a long tail, and great weight, may also show fracturing/crushing and healing of caudal neural spines and centra as well as pre-mortem distal tail amputations and infections described herein.

10. We would encourage paleontology artists who render hadrosaur reconstructions to include some with caudal injuries. This would include animals with distal ends of tails missing, swollen, or with the tail tip deflected dorsally or laterally at angles of about 10-25°.

Denouement

In the past twenty-five years there has been a rapid growth in the study of Albertan dinosaur paleopathology. Among saurischians, more focussed studies on pathological conditions and developmental anomalies in small theropods (Rothschild et al., 2001); tyrannosaurs (Farlow et al., 1991; Farlow and Brinkman, 1994; Erickson, 1995; Abler, 1997:741; Rothschild et al., 1997; Tanke and Currie, 2000; Rothschild et al., 2001; Schubert and Ungar, 2005; Wolff, 2008 (but see Beatty and Rothschild, 2009); Molinaro and Tanke, 2009; Bell, 2010; Bell and Currie, 2010); and ornithomimids (Sullivan et al., 2000; Rothschild et al., 2001; Bell et al., 2011) have been completed. Regarding ornithischians, ankylosaurs (Tanke and Farke, 2007; Arbour and Currie, 2011); ceratopsians (Rothschild, 1988; Rothschild and Tanke, 1992; Tanke and Farke, 2007; Currie et al., 2008; Farke et al., 2009; Tanke and Rothschild, 2010); and hadrosaurs (Tanke and Rothschild, 1992; Rothschild and Tanke, 2007; Straight et al. 2009; Tanke and Rothschild, 2011, this paper) have now been completed, thereby covering most of the major dinosaur groups in the province. So where do we go from here? Below we present some lines of research where the field of Albertan (and elsewhere) dinosaur

paleopathology could potentially go. Individual cases studies of osteopathy in Albertan dinosaur groups will continue, but there are broader issues that could be examined. With the large number of bones available in the province for study, and the countless numbers of new specimens exposed by erosion annually, Alberta will continue to be in the forefront of dinosaur paleopathology studies.

The diagnoses and discussions presented herein represent the current state of knowledge, predicated upon evidence-based interpretations. The pathophysiology and mechanism of injury, or especially diseases processes have not been clarified, so there is still much to do. It would be valuable to establish a “library” of osteopathic conditions and identify similar pathologies in the modern animal record, human or otherwise, to allow their characterization and evidence-based pursuit of mechanisms. Future work could address:

Epidemiology:

1. Comparison of character and frequency of pathologies in Alberta to those in other habitats. For example, are the frequencies and types of osteopathies seen in Alberta, the same with hadrosaurs elsewhere? Ramírez-Velasco (pers. comm., 2011) informed us that healing fibular fractures are regularly seen in Mexican hadrosaur material he examined; yet they are rare in Albertan material. Is such a disparity related to behavior, differing terrain, or other conditions?
2. Increase in sample size in hadrosaurs will allow comparison of juveniles and neonates with adults and subadults, perhaps permitting insights into possible different habitat selection. Helpful here would be if colleagues began a rigorous review, by recording and quantifying pathologic versus non-pathologic elements in hadrosaur-dominated bonebeds they are excavating. This quantification

approach would be instructive in any monospecific or low diversity dinosaur bonebeds whereby comparisons are made between sites.

3. Identification of spondyloarthropathy related to habitat.

4. Explore possible intraspecific transmission of disease. Diseases are more readily spread among animals in regular close proximity (those with herding behavior(s)) and the spread of disease would be more an issue for them.

Interdisciplinary collaboration:

1. Identification and localization of all fossilized skin scarring and close examination for evidence of healing.

2. Dermatologists to examine all fossilized skin impressions, to identify other evidences of skin disease.

3. Explanation of caudal vertebrae end plate depressions – awaits identification of etiology in humans with known histories for comparison. Biomechanical testing of replica specimens, cast in a material with the same properties as bone could be done to determine etiology and mechanism of injuries in crushed and split centra described above. Similar testing on centra in large extant vertebrates to determine mechanisms of injury may also be elucidating.

4. Identification of the types of trauma producing split and crushed caudal centra.

5. DPP specimens are so numerous; with more found annually, that invasive or destructive analyses may now be conducted without worry of negatively impacting the sample. For example, TMP 1998.059.0001 consists of several dozen bulk-collected neural spines with fracture callus development that were collected for such a purpose.

Anatomical effect of osteopathy:

1. Identification of alteration of stress indicators in individuals with loss of significant amounts of tail or multiple neural spine fractures.
2. Effect of hemivertebrae and other congenital or traumatic anomalies on posture.
3. Explore the possibility that absence of stress fractures indicates a foot anatomy (e.g., plantar versus digitgrade) or soft tissue development such as seen in extant heavy vertebrates (e.g. elephants *Loxodonta* and *Elephas*).
4. Quantification of TMP hadrosaur specimens, especially of the tail.
5. Many of the DPP caudal injuries show advanced but not total healing; why is this so?

Behavior:

1. Increase in sample size will allow comparison of juveniles and neonates with adults and subadults, perhaps permitting insights into possible different behaviors.
2. Localization of end plate depression to hypothesize the types of trauma to which it could possibly be related.
3. Localization of rib fractures to hypothesize the types of trauma to which it could possibly be related.
4. Analysis of frequency of union versus non-union of neural spine fractures by vertebral region – as assessment of bites versus other trauma.
5. Localization of split vertebrae to hypothesize the types of trauma to which it could possibly be related and compare to occurrence in other dinosaurs.
6. Analysis of tail damage; reviewing fracture, infection, premortem loss.

Disease:

1. Search for coprolites to assess occurrence and frequency of parasitism.
2. Identification of insects as vectors of disease from Alberta's large and still understudied amber faunas.
2. Identification of spondyloarthropathy related to habitat.
3. Distinguishing various causes of bone fusion and their relative frequencies.

Hadrosaurs are often derided by the public and even by some within the scientific community who describe them as “boring”, or the mindless “cattle of the Cretaceous”. However, their ability to survive grievous injuries and long term infections in a world full of predators and without medical intervention gives these authors a sense of awe and respect for these underappreciated and fascinating dinosaurs. The authors look forward to hearing from others who have hadrosaur osteopathy in their collections for potential future collaborations.

Identification	Catalogue #	Place collected	Total number of caudal neural spines injured vs. tail position (vertebrae number)	Information source
<i>cf. Edmontosaurus</i>	CMN 9872	Drumheller, Alberta	10; near tips of #'s 6, 12-15, 22, 25-26, 28-29	undescribed; pers. obser., DHT
<i>cf. Edmontosaurus</i>	TMP 1970.018.0001	Drumheller, Alberta	22; #'s 1-14, 16-17, 20, 25, 28, 31, 35-36	undescribed; pers. obser., DHT
<i>cf. Edmontosaurus</i>	MOR uncatalogued	Montana; “Warwick’s Duck” locality	22+; ? (unprepared, but possibly entire tail with pathologic neural spines, anterior caudals most seriously affected)	undescribed; D. Fowler, pers. comm., 2011
<i>Edmontosaurus</i>	RAM 7150	McCone County, Montana	44 caudals present (1 st 3-4 missing); of these #'s 14-16 and 21-29 (counting from the 1 st	pathology undescribed; A. Farke, pers. comm.,

			vertebra preserved) show injured neural spines	2012
cf. <i>Edmontosaurus</i>	UNO, number not provided	Wyoming	~13; total number and anatomical position uncertain (specimen only partly prepared; mid to distal caudals affected so far); “punctured fractured and/or infected caudal neural spines, fused caudal vertebrae”	Patchus and Derstler, 1998, 2002
<i>Edmontosaurus</i> “Big Ed”	GNSM PV 320201	20 miles NW of Buffalo, South Dakota	Fused centra: 9-10, 36- 37, 40-41; fused chevrons: 9, 20-21, 23- 25; damaged chevrons: 41, 49; damaged neural spines: 7-11, 17-26.	A. Maltese, pers. comm., 2012
<i>Edmontosaurus</i>	DMNH 1943	Dry Creek, Dawson County, Montana	5; #'s 13-16	Carpenter, 2000; Tanke and Rothschild, this paper
unspeciated	TMP 1981.035.0001; quarry 162	DPP, Alberta	5+; extreme end of tail, specimen not fully prepared	undescribed; pers. obser., DHT
unspeciated	TMP 1980.023.0002; quarry 126	DPP, Alberta	8 (+?); extreme end of tail	Tanke and Rothschild, this paper; fig. 26a-b
unspeciated	TMP 1998.059.0001	DPP, Alberta	3 +?; 4 associated proximal caudal vertebrae	undescribed; pers. obser., DHT
<i>Olorotitan</i>	AEHM 2/845 (type)	Amur region, eastern Russia	“proximal third of the tail” Godefroit et al., 2003; not specified in Godefroit et al., 2012, but wounding to proximal, medial and extreme distal caudals evident	Godefroit, et al., 2003:fig 1C-D; Godefroit, et al., in press; fig. 17B-E; Atuchin, pers. comm., 2012.
<i>Blasisaurus</i>	Blasi3/140	Arén, Spain	3; of 30+. Not articulated, but affected vertebrae are mid- caudals	Canudo- Sanagustín, 2004; Canudo et al., 2005a-

				b.
unspeciated	TMP 2011.012.0420; UAD 91 (= quarry 107?), Humber et al., 2005)	DPP, AB	11 distal caudal vertebrae found on surface, 8 have abnormal centrum shapes and/or deep internal vacuities; some have fractured and healing neural arch bases	Tanke and Rothschild, this paper; fig. 27a-b.
<i>Brachylophosaurus</i>	MOR 2919	Rudyard, Hill County, Montana	4 mid-caudals with healing fractures of neural spine tips	Freedman, pers. comm., 2012; Freedman, in prep.
<i>Barsboldia</i>	ZPAL MgD-1/110	Ömnogöv, Mongolia	Club-shaped distal caudal neural spines; are these normal morphology (Prieto-Márquez, 2011) or osteopathy?	Maryańska and Osmólska, 1981.
<i>Corythosaurus</i>	USNM 15493; quarry 26	DPP, Alberta	Mid-caudals ~ 27-31 appear pathologic in figures.	Gilmore, 1946; plates 17-18.
unspeciated lambeosaurine	TMP 1978.004.0001	Sandy Point, Alberta	Disarticulated proximal and mid-caudals; 12 of 16 show simple, non-infectious neural spine fractures near tips; centra normal.	Tanke and Rothschild, this paper.
<i>Lambeosaurus</i>	TMP 1982.038.0001; quarry 175	DPP, Alberta	Caudals 12-13 exhibit fractures near tips of neural spines, 12 especially so.	undescribed; pers. obser., DHT.
subadult <i>Brachylophosaurus</i> ; complete articulated tail	XXXX; specimen nicknamed "DAK"	north of Malta, Montana	Last sacral and first 2 caudal neural spines show fracture calluses	Anonymous, 2012; Ford, pers. comm., 2012.
Unspeciated tail section	More later	More later	More later	Freedman and Tanke, in prep.

Table 1. Listing of articulated/associated hadrosaur skeletons from Alberta, Montana, South Dakota, Wyoming, Mongolia, Russia, and Spain that exhibit multiple osteopathy

of the tail. *Barsboldia* and *Corythosaurus* USNM 15493 neural spines need to be examined for confirmation. Curiously *Edmontosaurus* or cf. *Edmontosaurus* predominates; the significance of this (if any) is unknown.

Acknowledgements

The authors thank Patty E. Ralrick for transcription of an earlier version of this paper, editing, and discussions. Tracy Ford did some citation searches, fact-checking, and drafted figures 36, 37a-c, and 38. The authors have benefitted from discussions and cooperation with Andrey Atuchin, Laurie Bryant, Richard Butler, Canadian Museum of Nature, Sandra Chapman, Allesandro Chiarenza, Margaret Currie, Philip J. Currie, Dinosaur Provincial Park staff, Fabio Della Vecchia, Andy Farke, Denver Fowler, Liz Freedman,; Ruben Guzman-Gutierrez, Graeme Housego, Anthony Maltese, Andrew Milner, David Norman, Ángel Ramírez-Velasco, Mark Van Tomme, Angelica Torices, Allison Tumarkin-Deratzian, and others over the many years this work has slowly come together. Jay Guidos provided photo-editing software. The authors are also grateful to Brandon Strilisky and the TMP Collections staff for their decades of assistance and support. Chris Capobianco and Sue Sabrowski provided photographic assistance. Sandra Mills, CT Technologist at the Drumheller Health Centre did the CT scan work. Thanks to our colleagues on the Facebook social group “WIKIPALEO” who provided digital copies of obscure or hard to find papers.

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