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DESCRIPTION OF UNUSUAL PATHOLOGICAL DISORDERS ON PUBES AND ASSOCIATED LEFT FEMUR FROM A *DIPLODOCUS* SPECIMEN

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ABSTRACT

The main hypothesis of this study is that a *Diplodocus* was injured, resulting in a variety of paleopathologies described herein. Several bones have unusual pathologies, such as a left pubis bone with an abnormal growth and a left femur with an extended fourth trochanter. Pathologies present in these bones suggest an injury from an unknown cause, which the *Diplodocus* survived. The left pubis bone growth shows signs of possibly being purulent, and the right pubis shows evidence of healing after fracturing due to the presence of a callus. Osteomyelitis may have occurred in a growth from a pubis and enthesitis on the left femur, causing an extension to the fourth trochanter on the left femur from muscle strain. The extension of the fourth trochanter on the left femur suggests that the *m. caudofemoralis longus* on the left femur was also damaged by the injury, and the healing process involved fibrous entheseal changes to strengthen the muscle attachment site. It remains unknown if it was damaged in the same impact injury or from a different, unrelated scenario.

INTRODUCTION

Studies in paleopathologies of dinosaurs allow the opportunity to study the behavior of these extinct animals (Rothschild and Tanke, 1991; Waldron, 2009). Literature on pathologies in sauropod dinosaurs, however, appears to be limited (García et al., 2016; Gonzalez et al., 2017). Furthermore, some pathologies, such as fused caudal vertebrae observed in the tail of *Diplodocus* (Blumberg and Sokoloff, 1961), may instead be the result of sexual dimorphism (Rothschild and Berman, 1991).

Osteomyelitis is a type of bone inflammation and infection that has been documented in extant animals and humans (Patel et al., 2009). Osteomyelitis can be categorized as acute (a new infection), subacute (caused by an open wound), and chronic (a recurring infection; Hanna, 2002; Rothschild and Martin, 2006). It can be caused from direct trauma to the bone, but it is also possible for infection to spread from local soft tissue (Peterson and Vittore, 2012). Osteomyelitis in dinosaur specimens is not commonly documented but has been reported, including in another sauropod (García et al., 2016). This example was of osteomyelitis found in a titanosaur tail. It was diagnosed from sinuses observed on several caudal vertebrae, suggesting that they were purulent (Garcia et al., 2016).

Non-pathological ossified tendons have been documented in several dinosaur species to strengthen muscles (Organ 2006; Cerda et al., 2015), but disorders such as calcific tendonitis has not been reported in any dinosaurs. Enthesitis is the condition of enthesopathy, which is a disorder between ligament attachments to bone, causing inflammation at sites where tendons connect to bone (McGonagle et al., 1998). Enthesophytes are calcifications of tendon attachments. They have been reported in the phalanges of a camarasaurid (Tschopp et al., 2016) and in the ulna of a hadrosaur (Anné et al., 2016), caused by septic arthritis in the latter. The disorder has also been observed on a relatively large scale in the tibia of a sloth bear (Kompanje et al., 2000). Enthesophytes are different from osteophytes, which when they develop, occur in the joints between bones (van der Kraan and van den Berg, 2007). There were no known cases of enthesophytes or enthesitis on femora of sauropods or located on the fourth trochanter of dinosaurs before this study.

MATERIALS AND METHODS

The Foot Site (FS) quarry is in Morrison Formation (Late Jurassic) exposures in Thermopolis, Wyoming (Figure 1). The site was given the name 'Foot Site' as it is the location of the first articulated manus discovered in the area (Bedell and Trexlar, 2005). The name also applies to the site because of multiple articulated feet and foot elements discovered since excavation at FS began in 1997. The Wyoming Dinosaur Center (WDC) maintains a record of each individual fossil collected from their quarries (type of bone, taxon, date found/excavated, datum coordinates and map measurements of distance from bones to datum). Measurements of distance from the datum to bones have been used to map the position and layout of

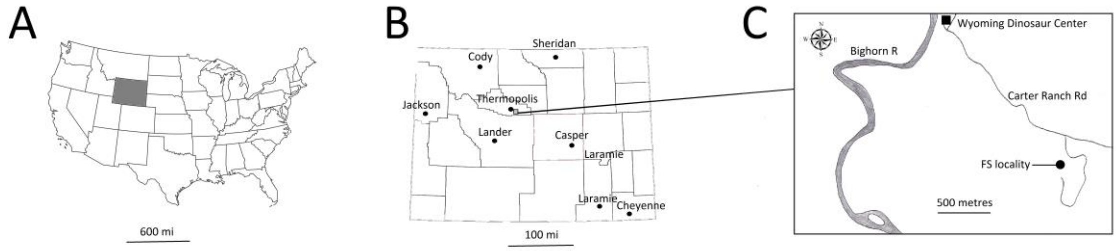

FIGURE 1. Location of the FS dig site quarry. **A**, Map of the United States of America with the State of Wyoming seen in grey. **B**, Map of the state of Wyoming with box in grey showing location of FS. **C**. Map of FS dig site quarry represented with black dot with proximity to the location of the Wyoming Dinosaur Center.

bones. Quarry maps have been created from drawings and are available at the WDC, although there appears to be missing information for some of the bones.

The bones in this study are in the collections of the WDC: the left pubis is WDC FS-317, right pubis is WDC FS-325, left ischium is WDC FS-313, and left femur is WDC FS-280. These bones were found disarticulated at the dig site and excavated separately but thought to be associated with each other based on the size proportions for the individual and that they appeared to articulate well with each other. All prepared bones from the FS quarry stored in the collections were photographed and recorded for any pathological damage.

DESCRIPTION

The pubes WDC FS-317 and WDC FS-325 were confirmed to be from the same individual *Diplodocus* as they had a clear connection point and were found within one meter of each other. Figure 2 shows anterior and posterior views of the pubes in articulation. WDC FS-317 is 62cm long and WDC FS-325 is 68 cm long. The pathological bone growth of the left pubis (WDC FS-317) connects to the medial shaft of the right pubis (WDC FS-325), which can be seen in anterior view (Figure 2A). The connection between the pubes is made on a callus, which is best seen on the shaft of the right pubis (Figure 3A). This indicates a semi-healed fracture on the right pubis based on the bulbous shape of the medial area of the right pubis, recovering after the fracture. Figure 3 shows the anterolateral sides of the pubes. The pathological growth that connects to the callus on WDC FS-325 shows signs of infection, indicated by pits on the exterior similar to what has been observed in titanosaur caudal vertebrae, indicating possible chronic osteomyelitis occurring in the pubes (García et al., 2016). The dorsal view of the growth shows these pits; the ventral view would be the connection with the right pubis (Figure 4), where a callus had formed.

WDC FS-313 is a left ischium (Figure 5) that appears to be associated with the pubes because of what is clearly a connection when in articulation. It is 62 cm long, and was found within one meter of WDC FS-317 and WDC FS-325. Despite being considered associated with the same individual, the ischium (WDC FS-313) shows no evidence of pathology. The left femur (WDC FS-280) appears to be seriously damaged (Figure 6). It is 120 cm long and has a unique disorder. A pathology relevant to the pubes is identified from the fourth trochanter, as it is much longer than what would be expected, at 45 cm in length (Figure 7). The distal end of FS-280 also appears to be affected by pathological disorders as the epicondyle flares outward.

DISCUSSION

Previous studies of *Diplodocus* pathologies have shown injuries in caudal vertebrae, usually assumed to be caused by trauma (Blumberg and Sokoloff, 1961). Other studies have described paleopathologies in other sauropods that document injuries inflicted on caudal vertebrae (Butler et al., 2013; Lovelace, 2014). However, no previous study on *Diplodocus* found pathologies related to the pelvic girdle. In the WDC specimens, the left ischium appears to be associated with the pubes but shows no sign of pathology, so the injuries were concentrated at specific areas around the left and right pubis bones of the animal. One can speculate that a fall or ‘stomp’ from another animal could be responsible for the injury, but currently it is not possible to confirm the cause of the pathologies. Whatever the cause, the individual *Diplodocus* survived the injuries; evidence of healing can be seen in the growth on left pubis, possibly to compensate for muscle strain, and the presence of a semi-healed fracture on the right pubis. It is unknown how long the animal lived after being injured or when it happened during its life.

Reconstructions of major sauropod muscles (Hallett and Wedel, 2016) indicate that the *m. rectus*

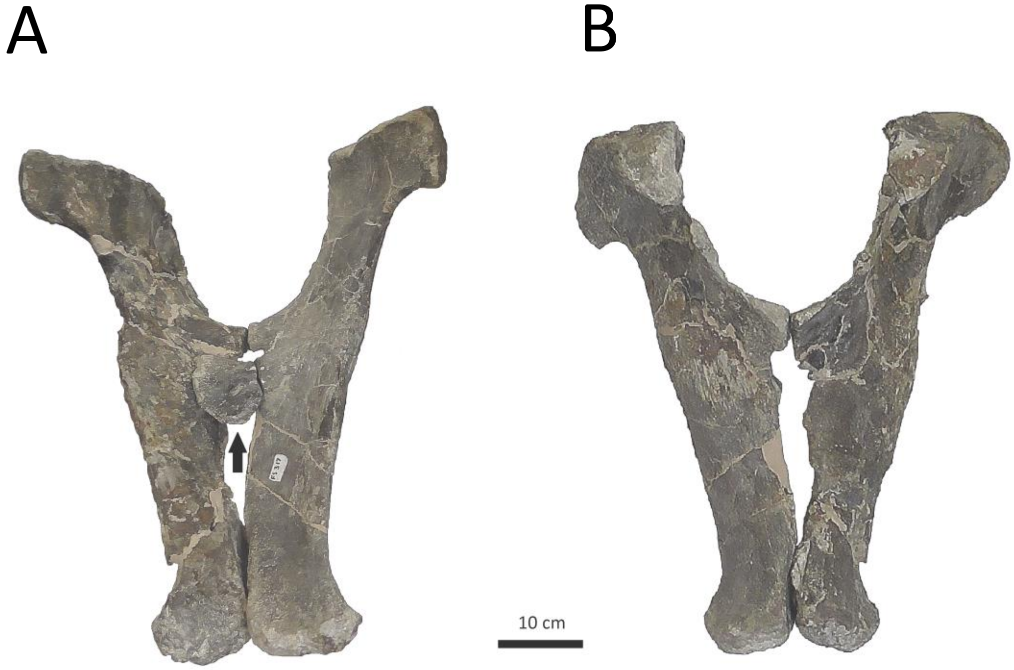

FIGURE 2. Articulated left pubis WDC FS-317 and right pubis WDC FS-325. **A**, Anterior view with articulated pathological growth, indicated by arrow. **B**, Posterior view without pathological growth of the pubes. Scale bar = 10 cm.

FIGURE 3. Anterolateral view of WDC FS-317 (right in image) and WDC FS-325 (left in image), with pathological growth extension removed. The callus on the right pubis (WDC FS-325) is indicated by the arrow. Scale bar = 10 cm.

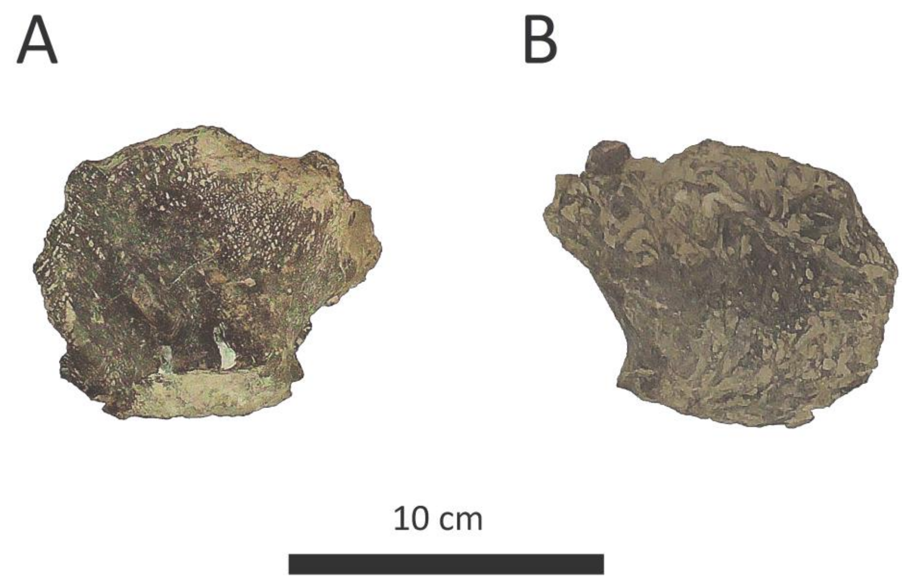

FIGURE 4. Closer view of the pathological growth from the left pubis (WDC FS-317). **A**, Dorsal view of the growth showing pit-like structures, that are possible signs of osteomyelitis. **B**, Ventral view of the growth that would have formed on the exterior surface. Scale bar = 10 cm.

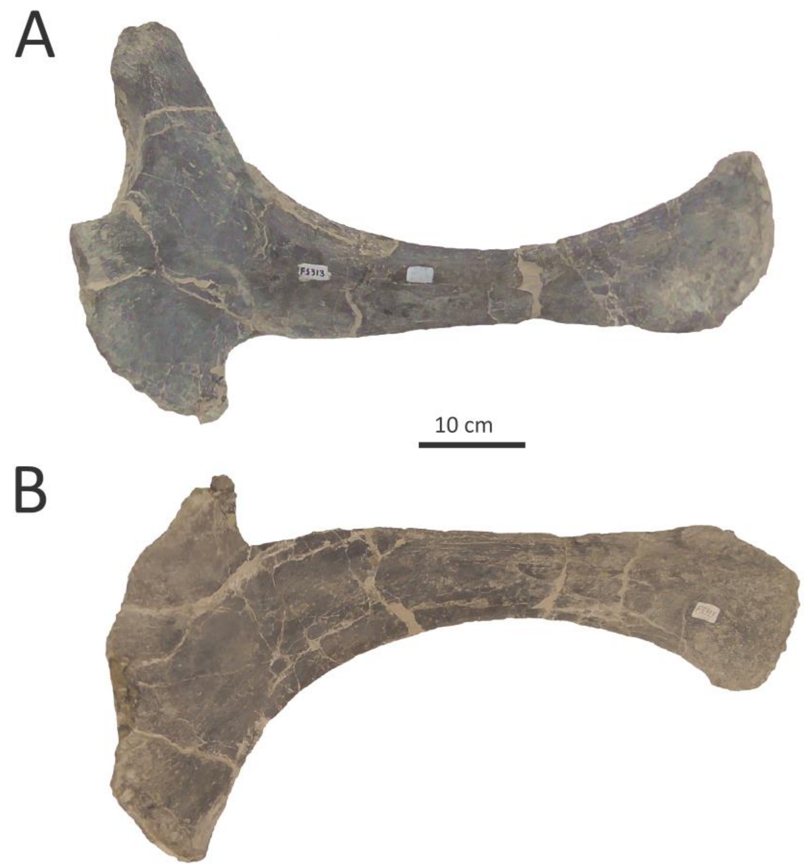

FIGURE 5. Left ischium, WDC FS-313, showing no signs of pathology. **A**, Left lateral view. **B**, Right lateral view. Note: Color of bone appears different on opposite lateral sides due to inconsistent lighting when images were taken. Scale bar = 10 cm.

abdominis would have connected with the pubes and caused tension on the distal end of these bones. If a traumatic fracture was to occur in this region, it is likely that the *m. rectus abdominus* would continue to force the distal end of the right pubis (WDC FS-325) away from the fracture, complicating the healing process. In response to this tension, a growth formed from the left pubis (WDC FS-317). This is a likely scenario as the growth has formed laterally onto the semi-healed fracture of the right pubis

This bone growth appears to have become infected during healing, based on pits on the exterior, which then formed onto the callus (Figure 8). The first evidence of osteomyelitis on a sauropod dinosaur consisted of similar pit-like structures in caudal vertebrae of a titanosaur (García et al., 2016). They were interpreted as indicating an area of exit for purulent discharge building up in the infected growth (Garcia et al., 2016). Contiguous osteomyelitis has been documented in other dinosaurs, including on a dermal spike of *Stegosaurus stenops* (McWhinney, et al., 2001). Periosteal reactive bone of the callus is preserved, as expected, in the WDC *Diplodocus* specimen, but it is unclear if the origin of the chronic infection in the bone began in the left pubis (WDC FS-317) or the fracture of the right pubis (WDC FS-325).

The unusual extension of the fourth trochanter of the femur (WDC FS-280) suggests that the *m. caudofemoralis longus* was severely damaged. The epicondyle of the left femur flares out, suggesting that the missing fibula and tibia or adjacent muscle attachments may have also been damaged. It is possible that this injury may have occurred from a different situation and may not be related to the trauma the pubes received that caused fracture of the right pubis and infected growth of the left.

Studies in titanosaurs suggest that the placement of the fourth trochanter in different positions corresponds to varied locomotion in different species of titanosaur (Ibiricu et al., 2014). But for *Diplodocus*, it is assumed that the more distal position of the fourth trochanter would allow a greater femoral retraction on the *m. caudofemoralis longus*, with less rotation of the femoral head (Bonnan, 2004). As the *m. caudofemoralis longus* is thought to be the main retractor muscle in non-avian dinosaur femora (Gatesy, 1990), it would be expected that any severe damage to the *m. caudalfemoralis longus* or its connection to the *Diplodocus* femur would require healing for subsequent locomotion. The *m. caudofemoralis brevis* may have connected the proximal end of the fourth trochanter (Gallina and Otero, 2009) to the rear of the ilia or ischiadic peduncle; whereas the *m. caudofemoralis longus* would be attached to the distal end of the fourth trochanter and the proximal caudal vertebrae. The analysis of the fourth trochanter extension of WDC FS-280 would indicate that the *m. caudofemoralis longus* enthesis would have been damaged, but the condition of the *m. caudofemaralis brevis* remain unknown, especially as the right ischium is missing. It remains unknown if this was affected by the injury or infection.

The elongation of the fourth trochanter of the femur (WDC FS-280) distally along the posterior of the femur may be the result of a combination of issues that affected the *m. caudofemoralis longus* attachment. Trauma inflicted from the injury to the *m. caudofemoralis longus* may have caused high levels of stress as the muscle retracted against the femur (Benjamin et al., 2006). As the fourth trochanter is more proximal in *Diplodocus* than in other sauropods (Bonnan, 2004), the strain on the injured *m. caudofemoralis longus* would cause a weakness, which may in turn affect motion as the muscle retracted against the femur with less force. It is a common assumption that a proximal fourth trochanter on the femur in other archosaurs may have had a pull focused on the femoral head (Bonnan, 2016), indicating that the healing of the *m. caudofemoralis longus* strain on WDC FS-280 could not be achieved to the same level of function as it was performing prior to the injury. As the *m. caudofemoralis longus* is widely accepted to have an importance in locomotion in reptiles (Hutchinson, 2004) it is very likely that the injury to the *m. caudofemoralis longus* could have become more severe as the animal continued to walk, increasing tension on this muscle (Benjamin et al., 2006).

The pathology on the pubes of the *Diplodocus* also may have caused complications in activities other than walking. Comparisons of bones in humans (Tihanyi et al., 2015; Weiss, 2015) and extant vertebrates suggests that the *Diplodocus* femur pathology is the result of fibrous entheseal changes in response to the trauma of the *m. caudofemoralis longus* in order to strengthen the muscle attachment to the tendon. As the extension is part of the fourth trochanter and the site attachment of *m. caudofemoralis longus* tension (Persons and Currie, 2010), it possibly represents a large enthesophyte, increasing the attachment site of the tendon. The enthesitis, however, is speculated to have caused the fourth trochanter extension of the femur in response to healing and strengthen the enthesis or muscle/tendon attachment at the contact site. Changes in fibrous entheses, such as the femur's fourth trochanter attachment, are not understood in as much detail as are fibrocartilaginous entheses due to irregularities in different cases (Tihanyi et al., 2015) and that the entity of entheses has been largely ignored (Waghray et al., 2015). This suggests that the pathologies are unique in this *Diplodocus* specimen, illustrating the animal's body attempted to repair soft tissue damage from repetitive muscle strain.

FIGURE 6. Left femur WDC FS-280. **A**, Anterior view. **B**, Posterior view, with arrows showing where fourth trochanter begins and ends. Left arrow is proximal, right arrow is distal. Scale Bar = 10 cm.

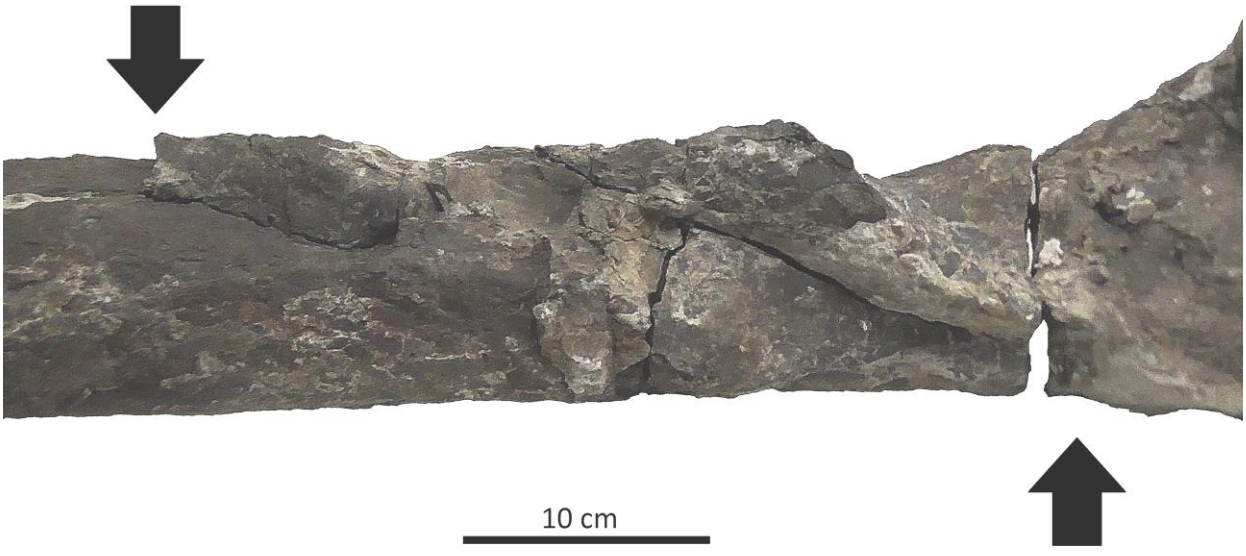

FIGURE 7. Posterior view of medial portion of left femur (WDC FS-280), showing fourth trochanter extension. Proximal side of fourth trochanter shown by arrow on upper left, distal side of fourth trochanter by arrow on lower right. Scale bar = 10 cm.

FIGURE 8. Dorsal view of pathological growth on WDC FS-325. White arrows point to pit structures identifying possible sites of osteomyelitis. Scale bar = 10 cm.

Examples of enthesophytes have been documented in a hadrosaur based on septic arthritis (Anné et al., 2016), suggesting that attachment sites on bone are prone to disorder when damaged, which was also described in a sloth bear (Kompanje et al., 2000). Based on the appearance of the fossilized fourth trochanter with other examples of dinosaur enthesitis (Anné et al., 2016), it seems to be the most likely condition in this *Diplodocus*.

Reconstruction of the *m. caudofemaralis longus* in diplodocids (Klein et al., 2011) suggest that *Diplodocus* would have been able to rear on their hind legs for great periods of time, meaning that the muscle would have facilitated browsing from higher areas. It is unlikely but possible that the *m. caudofemoralis longus* enthesis attachment allowed the animal the capabilities of this feeding technique. It is possible that the *Diplodocus* may have been partially disabled, no longer able to rear on its hind limbs or at least not to the same extent as before the injury. However, this is only speculation. The rearing ability of *Diplodocus* would also be influenced by the pubes development because rearing would cause additional strain while the animal supported its weight on its hind limbs. The pubic symphysis would be able to support the viscera (Klein et al., 2011) to allow this feeding behavior. It is possible that the *Diplodocus* individual could have survived without the ability to rear on its hind limbs, but with the incomplete pelvic girdle of this specimen and lack of a right femur, it is not possible to determine if the pathological condition of the bones made it incapable of this ability. It is possible that the pathological bone growth may be an example of an avulsion fracture, as seen in humans (Porr et al., 2011), and possibly became disconnected from the main bones of WDC FS-317 and WDC FS-325. This has been suggested based on the growth extension being found separated from the pubes. It is unclear if the pathologies in the pubes and femur were a short or long-term issue for the *Diplodocus*.

The pubes and associated left femur represent a significant discovery in the study of pathologies in dinosaur biology. Possible causes such as a fall or stomp from another animal cannot be proven. Despite being unable to completely understand the cause of the pathologies, this study has concluded that enthesitis occurred due to serious damage from an external stimulus that caused injury to the *Diplodocus*. This research suggests that fibrous entheseal changes occurred in the fourth trochanter of the left femur and the *m. caudofemoralis longus* was seriously damaged. The contraction of the *m. rectus abdominis* along with infection of the pubes (WDC FS-317 and WDC FS-325) caused a pathological bone growth potentially influenced by osteomyelitis that may have occurred to stabilise the fractured right pubis (WDC FS-325). As there are no other connection points along the shaft, it suggests that the pathological bone growth of the left pubis (WDC FS-317) was focused on this specific area of the right pubis where the callus had formed.

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REFERENCES

Anné, J., B. P. Hedrick, and J. P. Schein. 2016. First diagnosis of septic arthritis in a dinosaur. Royal Society of Open Science 3:160222. DOI: 10.1098/rsos.160222.

Bedell Jr., M.W, and D.L. Trexler. 2005. First articulated manus of *Diplodocus carnegii*. Pp. 302–320 in V. Tidwell and K. Carpenter (eds.), *Thunder-lizards: the Sauropodomorph*

Dinosaurs. Indiana University Press, Bloomington, Indiana.

Benjamin, M., H. Toumi., J. R. Ralphs, G. Bydder, T. M. Best, and S. Milz. 2006. Where tendons and ligaments meet bone: attachment sites (‘entheses’) in relation to exercise and/or mechanical load. Journal of Anatomy 208:471–490.

Blumberg, B. S. and L. Sokoloff. 1961. Coalescence of caudal vertebrae in the giant dinosaur *Diplodocus*. Arthritis and Rheumatism 4: 592–601.

Bonnan M. F. 2004. Morphometric analysis of humerus and femur shape in Morrison sauropods: implications for functional morphology and paleobiology. Paleobiology 30:444–470.

Bonnan, M. 2016. *The Bare Bones: An Unconventional Evolutionary History of the Skeleton*. Indiana University Press, Bloom-ington, Indiana, 528 pp.

Butler, R. J., A. M. Yates, O. W. M. Rauhut and C. Foth.. 2013. A pathological tail in basal sauropodomorph dinosaur from South Africa: evidence of traumatic amputation? Journal of Vertebrate Paleontology 33:224–228.

Cerda, I. A., G. A. Casal, R. D. Martinez and L. M. Ibiricu. 2015. Histological evidence for a supraspinous ligament in sauropod dinosaurs. Royal Society Open Science 2:150369 DOI: 10.1098/rsos.150369.

Gallina, P. A., and A. Otero. 2009. Procesos Transversos de vértebras caudales en dinosaurios Saurópodos: aspectos morfológicos, filogenéticos y funcionales, Ameghiniana 46:165–176.

García, R. A., I. A. Cerda, M. Heller, B. M. Rothschild and V. Zurriaguz. 2016. The first evidence of osteomyelitis in a sauropod dinosaur. Lethaia 50:1–10.

Gatesy, S. M. 1990. Caudofemoralis musculature and the evolution of theropod locomotion. Paleobiology, 16:170–186.

Gonzalez, R., P. A. Gallina and I. A. Cerda. 2017. Multiple paleopathologies in the dinosaur *Bonitasaura salgadoi* (Sauropoda: Titanosauria) from the Upper Cretaceous of Patagonia, Argentina. Cretaceous Research 79:159–170.

Hallett, M. and M. J. Wedel. 2016. *The Sauropod Dinosaurs: Life in the Age of Giants*. Johns Hopkins University Press, Baltimore, Maryland. 336 pp.

Hanna, R. R. (2002). Multiple injury and infection in a sub-adult theropod dinosaur *Allosaurus fragilis* with comparisons to allosaur pathology in the Cleveland-Lloyd dinosaur quarry collection. Journal of Vertebrate Paleontology 22:76–90.

Hutchinson, J. R. 2004. Biomechanical modeling and sensitivity analysis of bipedal running ability. I. Extant taxa. Journal of Morphology 262:421–440.

Ibiricu, L. M., M. C. Lamanna, and K. J. Lacovara. 2014. The influence of caudofemoral musculature on the titanosaurian (Saur-ischia: Sauropoda) tail skeleton: morphological and phylogenetic implications. Historical Biology 26:454–471.

Klein, N., K. Remes, C. T. Gee, P. M. Sander. 2011. *Biology of the Sauropod Dinosaurs: Understanding the Life of Giants*. Indiana University Press, Bloomington, Indiana 344 pp.

Kompanje, E. J. O., P. S. J. Klaver and G. T. De Vries. 2000. Spondyloarthropathy and osteoarthrosis in three Indomalayan bears: *Ursus ursinus* Cuvier, 1823, *Ursus thibetanus* Raffles, 1821, and *Ursus malayanus* Shaw and Nodder, 1791 (Mammalia : Carnivora : Ursidae). Contrib-utions to Zoology 69:259–269.

Lovelace, D. M. 2014. Developmental failure of segmentation in a caudal vertebra of *Apatosaurus* (Sauropoda). The Anatomical Record 297:1262–1269.

McGonagle, D., W. Gibbon and P. Emery. 1998. Classification of inflammatory arthritis by enthesitis. The Lancet 352:1137-1140.

McWhinney, L. A., B. M. Rothschild, and K. Carpenter. 2001. Post-traumatic chronic osteomyelitis in *Stegosaurus* spikes. Pp. 141–155 in K. Carpenter (ed.), *The Armored Dinosaurs.* Indiana University Press, Bloomington, Indiana 526 pp.

Organ, C. L. 2006. Thoracic epaxial muscles in living archosaurs and ornithopod dinosaurs. The Anatomical Record Part A, Discoveries in Molecular, Cellular, and Evolutionary Biology 288A:782–793.

Patel, M., Y. Rojavin, A. A. Jamali, S. J. Wasielewski and C. J. Salgodo. 2009. Animal models for the study of osteomyelitis. Seminars in Plastic Surgery 23:148–154.

Persons, W. S. and P. J. Currie. 2010. The tail of *Tyrannosaurus*: reassessing the size and locomotive importance of the *M. caudofemoralis* in non-avian theropods. The Anatomy Record 294:119–131.

Peterson, J. E. and C. P. Vittore. 2012. Cranial pathologies in a specimen of *Pachy-cephalosaurus*. PLoS ONE 7: e36227. DOI: 10.1371/journal.pone.0036227.

Porr, J., C. Lucaciu and S. Birkett. 2011. Avulsion fractures of the pelvis - a qualitative systematic review of the literature. Journal of Canadian Chiropractor Association 55:247–255.

Rothschild, B. M. and D. S. Berman. 1991. Fusion of caudal vertebrae in Late Jurassic sauropods. Journal of Vertebrate Paleontology 11:29–36.

Rothschild, B. M. and L. D. Martin. 2006. Skeletal impact of disease. New Mexico Museum of Natural History & Science 33:1–230.

Rothschild, B. M. and D. Tanke. 1991. Palaeopathology of vertebrates: insights to lifestyle and health in the geological record. Geoscience Canada 19:72–82.

Tihanyi, B., Z. Bereczki, E. Molnar and G. Pálfi. 2015. Investigation of Hungarian Conquest Period (10th c. AD) archery on the basis of activity-induced stress markers on the skeleton - preliminary results. Acta Biologica Szegediensis 59:65-77.

Tschopp, E., O. Wings, T. Frauenfelder and B. M. Rothschild. 2016. Pathological phalanges in a camarasaurid sauropod dinosaur and implications on behaviour. Acta Palaeontologica Polonica 61:125–134.

van der Kraan, P. M. and W. B. van den Berg. 2007. Osteophytes: relevance and biology. Osteoarthritis and Cartilage 15:237–244.

Waghray, N., A. J. Gandhalam, M. Imran, S. Yaseen and U. Chaudhary. 2015. Enthesis: a brief review. Apollo Medicine 12:32–38.

Waldron, T. 2009. *Palaeopathology*. Cambridge Manuals in Archaeology. Cambridge University Press, New York, 279 pp.

Weiss, E. 2015. The surface of bones: methods of recording entheseal changes, IOPscience, Surface Topography: Metrology and Properties 3. DOI: 10.1088/2051-72X/3/3/034003.