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Short communication

Infectious spondylitis with pathology mimicking that of tuberculosis in a cervical vertebra of a plesiosaur from the Upper Cretaceous of Patagonia, Argentina

Marianella Talevi [a, b, *], Bruce M. Rothschild [c], Matías Mitidieri [a, b], Marta S. Fernández [d]

[a] Universidad Nacional de Río Negro, Instituto de Investigación en Paleobiología y Geología, Av. Roca 1242, (R8332EXZ) General Roca, Río Negro, Argentina
[b] IIPG, UNRN, Consejo Nacional de Investigaciones científicas y Tecnológicas (CONICET), General Roca, Río Negro, Argentina
[c] Carnegie Museum of Natural History, 4400 Forbes Ave, Pittsburgh, PA, 15213, USA
[d] CONICET, División Paleontología Vertebrados, Facultad de Ciencias Naturales y Museo, UNLP, Av. 60 y 122, 1900 La Plata, Argentina

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ABSTRACT

Paleopathological studies have been used to understand the history of injury and disease in extinct populations, their putative causes and, on this basis, to infer paleoecology and behavioral aspects. The most common pathologies reported in the zoological/paleontological record are traumatic injuries, post-traumatic malformations, inflammatory arthritis, infection and congenital defects. Although pathologies in plesiosaurs are recognized since the 1870s, reports of infectious disease are comparatively scarce. Here we report the pathological cervical vertebra of a plesiosaur recovered from the Upper Cretaceous of Argentina. The anterior external surface shows an elliptical, subchondral erosion with new bone formation and slight adjacent filigree reaction. The right anteroventral surface of the centrum bears erosive processes with bone reaction and alterations that have the appearance produced by space-occupied masses. On the left anteroventral surface of the centrum, there are abnormal vascular channels, associated with a groove just ventral to the articular surface. The combination of these features indicates that the pathological aspect of the vertebra is due to an infection. The pattern of bone abnormalities is compatible with those described in Pleistocene mammals affected by the granulomatous tuberculosis infection and with the abnormal ribs and cervical vertebrae of an eosauropterygian from the Triassic. The case reported herein represents the first record of tuberculosis-like infection in a plesiosaur. As the vertebra was not part of an associated skeleton, we cannot infer if the cause of death could have been related to the compromised hunting ability (due to limited neck mobility) or the result of infection-related organ failure.

1. Introduction

Pathological studies have been used to understand the history of injury and disease among extinct populations, their putative underlying cause and, on this basis, some infer paleoecological and behavioral aspects (Moodie, 1918; Rothschild and Martin, 2006; Pardo Perez et al., 2017, 2019). Paleopathologies are generally identified if they damage the skeleton and the most common varieties include traumatic injury (e.g., fractures, tooth marks), post-traumatic malformations (e.g., vertebral fusions), modification of bone tissue by avascular necrosis, inflammatory arthritis, infection (e.g., osteomyelitis), congenital defects, and neoplasms (e.g., tumors) (Martin and Rothschild, 1989; Rothschild and Martin, 1993; Bell and Martin, 1995).

In the particular case of extinct marine reptiles, there have been reports of trauma with evidence of bone healing and remodeling, suggesting that the affected individuals managed to survive (Martin and Rothschild, 1989; Bell and Martin, 1995; Schulp et al., 2004; Pardo-Perez et al., 2017, 2018). This provides important information on the immune system and the healing potential in this group of fossil vertebrates. Osteological evidence of infections in

* Corresponding author. Universidad Nacional de Río Negro, Instituto de Investigación en Paleobiología y Geología, Av. Roca 1242, (R8332EXZ) General Roca, Río Negro, Argentina.
E-mail addresses: mtalevi@unrn.edu.ar (M. Talevi), spondylair@gmail.com (B.M. Rothschild), mmitidieri@unrn.edu.ar (M. Mitidieri), martafer@fcnym.unlp.edu.ar (M.S. Fernández).

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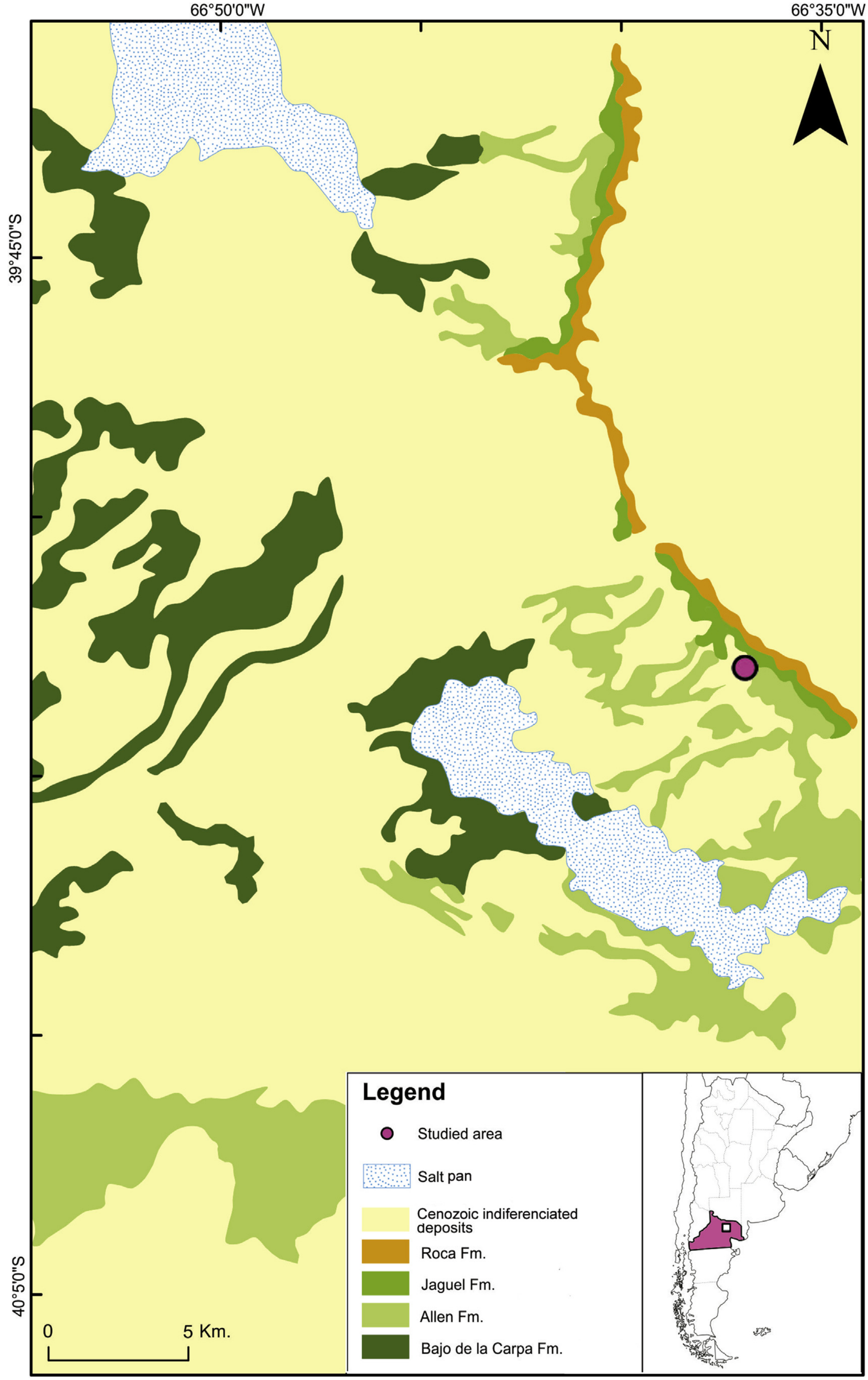

Fig. 1. Geological map of the study area. Pink region refers to Río Negro province, Argentina (Down right) and the white square refers to the region of geological map. Pink circle in the geological map refers to the location of the analyzed element.

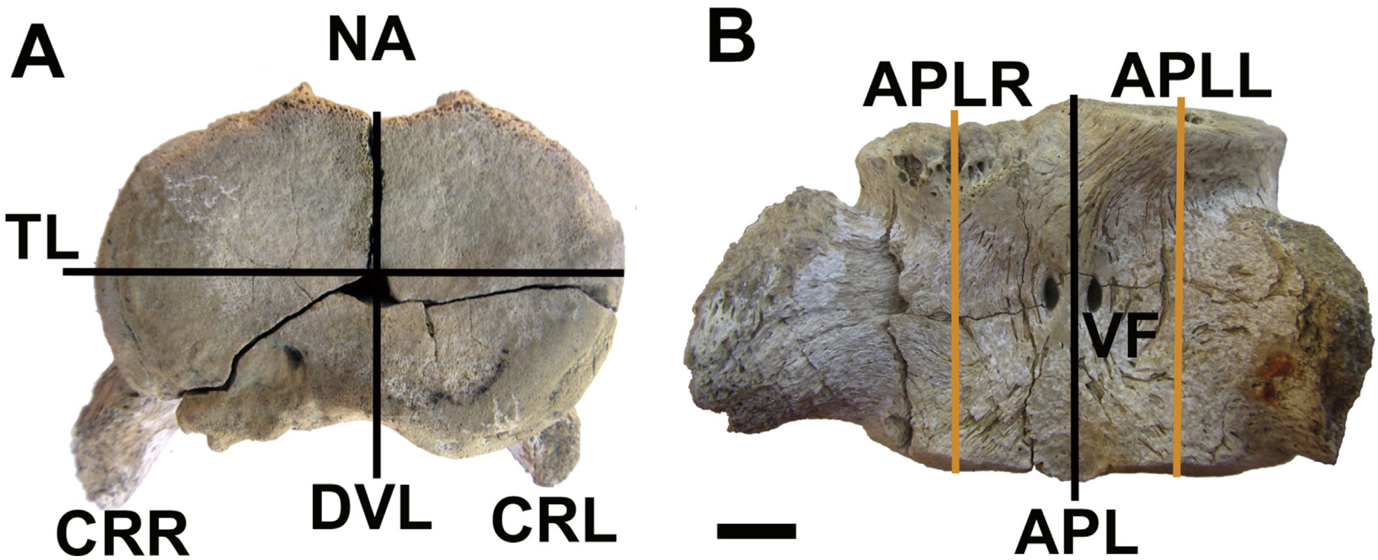

Fig. 2. MML-PV 1305. A. Cervical vertebra in anterior view and ventral view B. Abbreviations: Dorsoventral length (DVL); anteroposterior length (APL); anteroposterior length left (APLL); anteroposterior length right (APLR); Cervical ribs (CR); neural arch (NA); transverse length (TL); ventral foramina (VF). Scale bar 1 cm.

the fossil remains of marine reptiles further reveals the role that pathogens and their virulence (ability to infect a host) played in past ecosystems (Rothschild et al., 2012a; Schulp et al., 2006; Surmik et al., 2017; Surmik et al., 2018). Infectious diseases can also develop after trauma (e.g., abscesses), or they may be age-related (Moodie, 1923; Lingham-Soliar, 2004; Rothschild, 2012). Alternatively, bone pathologies may be the result of other factors that cause mechanical problems or physiological stress (e.g., ossification of vertebral ligaments) (Kompanje, 1999; Mulder, 2001; Rothschild and Martin, 2006; Cooper and Dawson, 2009; Rothschild and Everhart, 2015).

The analysis of the paleopathological characteristics of the marine reptiles presents a vast field of study that is still scarcely explored. The recognition of certain bone pathologies linked to the aquatic life environment has allowed us to know precise aspects of the physiology and palaeoecology of some groups of marine reptiles (Motani et al., 1999; Rothschild and Storrs, 2003). In ichthyosaurs, plesiosaurs and mosasaurs (Motani et al., 1999; Pardo Pérez et al., 2017; Rothschild and Martin, 1987; Rothschild and Storrs, 2003; Rothschild et al., 2012a; Rothschild et al., 2012b; Surmik et al., 2017), one of the most common pathologies is avascular necrosis which would indicate that under certain circumstances, these groups suffered from the so-called “Decompression Syndrome” as a consequence of the development of diving habits.

In the case of Mesozoic marine reptiles from Patagonia and Antarctica, publications on paleopathology are scarce. Talevi et al. (2019) described the first record of skeletal pathology (infectious arthritis and spondyloarthropathy) present in a mosasaur from the Maastrichtian of Antarctica. The objective of this contribution is to describe a pathology in a cervical vertebra of a plesiosaur recovered from the Maastrichtian (Upper Cretaceous) of northcentral Patagonia (Argentina). We identify this pathology as a tuberculosis-like infection representing the first report of this kind of malady in a cervical vertebra of a plesiosaur.

2. Materials and methods

The element MML-PV 1305 analyzed consists of a cervical vertebra. It can be assigned to Elasmosauridae indet. due to the presence of an elongated cervical vertebra, whose articular face presents a ventral concavity (Gasparini et al., 2007; Benson and Druckenmiller, 2014). The external characteristics (fusion of the neural arch to the vertebral body) would indicate that the cervical vertebra would have features of an adult specimen (O'Gorman et al., 2011; Talevi and Fernández, 2015). The element comes from the Allen Formation (upper Campanian–lower Maastrichtian) of Los Bajos de Trapalcó and Santa Rosa area, Río Negro province, Argentina (Fig. 1).

The specimen was analyzed through macroscopic examination and was scanned at the “YPF Tecnología” (Y-TEC) of the company YPF and Consejo Nacional de Investigaciones Científicas y Tecnicas (CONICET) in La Plata (Argentina) using an industrial X-ray computed microtomography (μCT, Bruker SkyScan 1773). The material was scanned at 130 kV, 61 mA, output file of 1120 pixels per projection, inter-slice distance of 50 mm and voxel size of 40.06 mm. The X-ray beam was filtered by a 0.25 mm-thick brass filter. A set of 600 projections were acquired by a flat panel detector (Hamamatsu 130/300) over a total scan angle of 360°. The resulting μCT slices were reconstructed using the commercial software NRecon version 1.6.9.8. Reconstructed slices were imported (as stack of BMP 8-bit files) to ImageJ to analyze the microCT images.

Institutional abbreviations. MML-PV, Museo Municipal de Lamarque-Paleovertebrados, Río Negro Province, Argentina.

3. Results

The analyzed element presents the following anatomical measurements: the dorsoventral length (DVL) is 44.3 mm; the anteroposterior length (APL), 59.3 mm; and the transverse length (TL), 71.2 mm (Fig. 2A-B). In the ventral region of the centrum, right anteroposterior length is 52 mm and left, 55 mm (Fig. 2B). The cervical ribs are incompletely preserved and the neural arch, absent. The articular facets are slightly concave in the shape of a dumbbell and two ventral foramina are evident in ventral view (Fig. 2A-B).

Macroscopic examination of the cervical vertebra reveals taphonomic artifact cracks in the subchondral bone with central

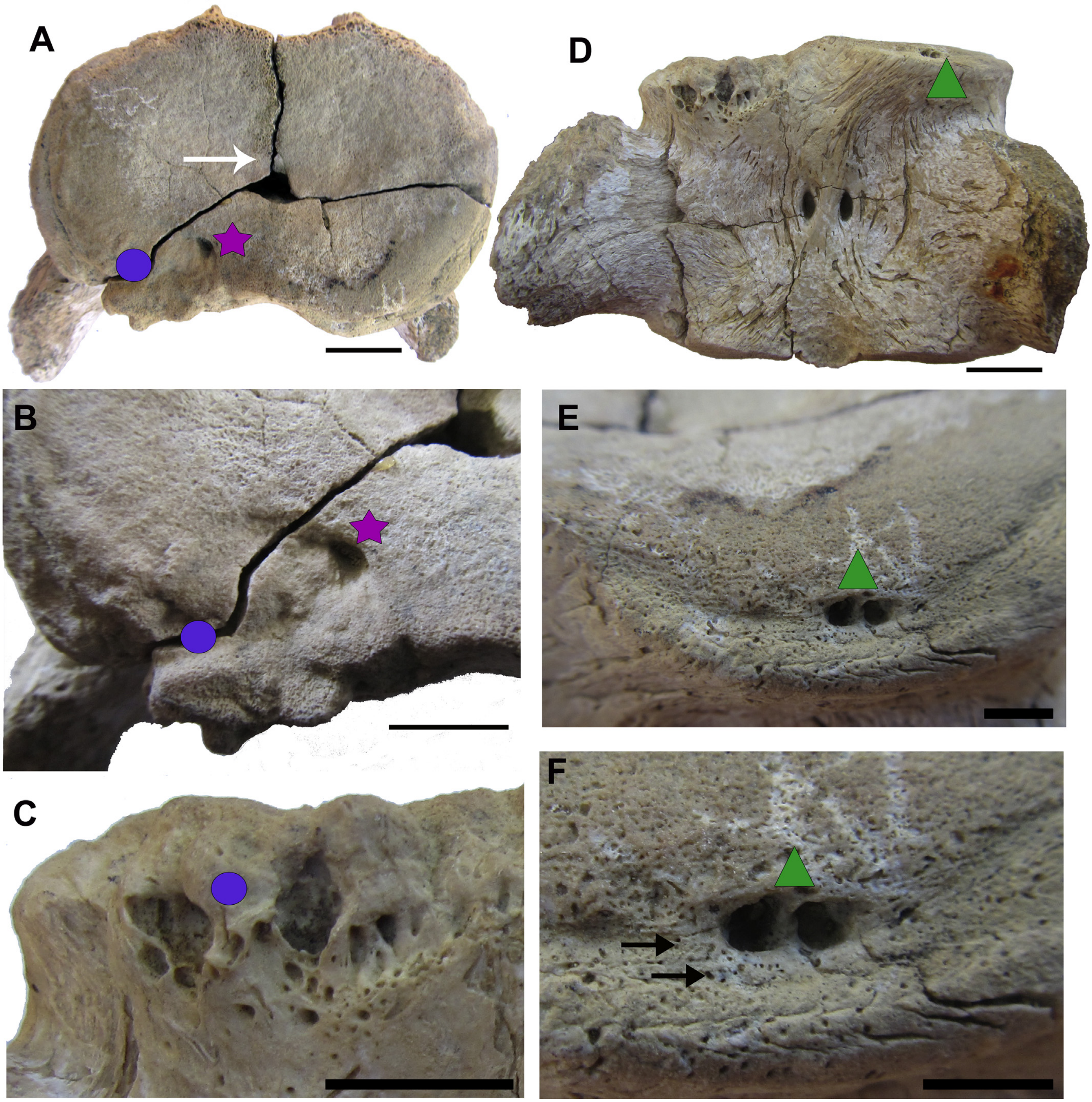

Fig. 3. MML-PV 1305. A. Cervical vertebra in anterior view. Taphonomic artifact cracks (white arrow) elliptical subchondral erosion (pink star) and protrusion (violet circle). B. Magnification of the area with elliptical subchondral erosion and protrusion. C. Ventral view protrusion with erosive process with minimal bone reaction. D. Cervical vertebra in ventral view. E-F. Lower right edge abnormal vascular foramen (black arrow), and groove (green triangle). Scale bar: A,B,C,D 1 cm; E,F 0.5 cm.

loss on the anterior view, as well as an elliptical subchondral erosion with minimal new bone formation and slight filigree adjacent reaction (Fig. 3A-B). In the lower right edge on the ventral view, a protrusion with the erosive process with the minimal bone reaction is observed, resulting in the appearance of space-occupied masses (Fig. 3B-C). Abnormal vascular foramen, associated with a groove just under the articular surface is observed in the lower left edge (Fig. 3D-E-F). X-ray examination reveals a central lytic area with the weakened and collapsed trabecular bone (Fig. 4A-B).

4. Discussion

Despite recognition of bone pathologies of Mesozoic marine reptiles in general and plesiosaurs in particular, since the 1870s (Mudge, 1878), reports of infectious diseases area still comparatively very scarce (Lingham-Soliar, 2004; Schulp et al., 2006; Surmik et al., 2017). Pathologies previously reported include septic necrosis, avascular necrosis, Schmorl's nodules [subsequently recognized as subchondral erosions of spondyloarthropathy, since plesiosaurs and mosasaurs have synovial joints, not disks

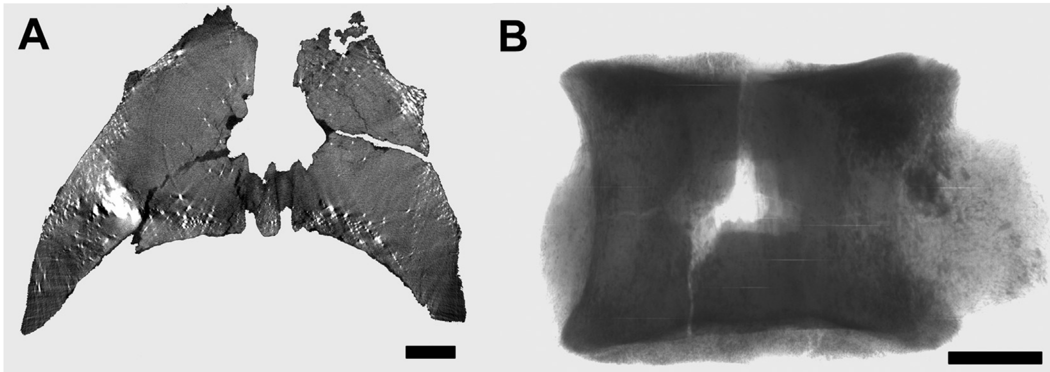

Fig. 4. MML-PV 1305. A. Reconstruction of cervical vertebra in anterior view. B. X-ray microtomographic image of cervical vertebra in dorsal view. Note the central lytic area with weakened and collapsed trabecular bone. Scale bar 1 cm.

(Rothschild et al., 2020)], osteoarthritis, vertebral fusions (Hopley, 2001; Rothschild and Martin, 1987; Rothschild and Storrs, 2003; Sassoon, 2019; Sassoon et al., 2012; Surmik et al., 2017) and numerous with tooth marks (Thulborn and Turner, 1993; Einarsson et al., 2010; Shimada et al., 2010; Rothschild et al., 2018). The vertebra described herein shows an elliptical subchondral erosion with new bone formation and adjacent slight filigree reaction as well as a groove just ventral to the articular surface and a central lytic area with weakened and collapsed trabecular bone. This kind of subchondral erosions indicates spondyloarthropathy or infectious spondylitis (Rothschild and Martin, 2006). However, the space-occupied regions observed on the right anteroventral surface (Fig. 3B-C) supports the proposal that the pattern observed in the MML-PV 1305 could be due to a granulomatous infection and refutes consideration of spondyloarthropathy. On the other hand, the combination of these features together with the slight filigree reaction permits its identification as an infection. The groove undercutting the articular surface that is visualized at the edge of the vertebra is similar to that noted with the granulomatous infection, tuberculosis, in Pleistocene *Bison*, *Bovis*, *Bootherium* and *Mastodon* (Rothschild and Martin 2003; Rothschild and Laub, 2006). As other osseous manifestations of disease have proven reproducibly stable through phylogeny and over geologic time (Rothschild and Martin, 2006; Rothschild et al., 2012a), documentation of such phylogenetic bracketing increases the likelihood of our interpretation. Space occupying masses have been sometimes referred to as pseudotumors (Elkin and Cooper, 1976) with caseous debris (Elkin, 1981). Those descriptions are now considered obsolete and are actually more characteristic of tubercular and other granulomatous diseases than of pyogenic infections in reptiles (Rothschild, 2021; Rothschild et al., 2012a). In the case of extinct reptiles, this kind of tuberculosis-like infection has apparently only previously been reported on ribs and vertebrae of an eosauropterygian from the Triassic of Poland (Surmik et al., 2018). The presence of bone reaction and protrusions, abnormal vascular foramen localized to the anterior and ventral surface area of the vertebra and vertebral damage with weakened and collapsed trabecular bone (similar to that noted with Pott's disease), suggest a tuberculosis-like infection, the first known such observation in a plesiosaur. As the vertebra are not part of an associated skeleton, we cannot infer if the cause of death could have been related to the compromised hunting ability (due to limited neck mobility) or the result of infection-related organ failure.

The results obtained from the work complement the state of knowledge about pathologies in extinct forms and their evolutionary prospecting, as well as paleoecological aspects of the organisms studied.

5. Conclusions

The cervical vertebra of a plesiosaur from the Upper Cretaceous of Patagonia (Argentina) described herein, shows pathological features characterized by an elliptical subchondral erosion with new bone formation and adjacent slight filigree reaction as well as groove just ventral to the articular surface. This condition is particularly conspicuous on the anterior and ventral surfaces of the vertebra. X-ray examination reveals a central lytic area with the weakened and collapsed trabecular bone. The combination of these features indicates that the pathological aspect of the vertebra is due to an infection and suggests a tuberculosis-like infection. Infections are extremely rare in Mesozoic marine reptiles and the case studied here represents the first known such observation in a plesiosaur.

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References

Bell, G.L., Martin, J.E., 1995. Direct Evidence of Aggressive Intraspecific Competition in Mosasaurus conodon (Mosasauridae:Squamata). Journal of Vertebrate Paleontology 15, 18.
Benson, R.B.J., Druckenmiller, P.S., 2014. Faunal turnover of marine tetrapods during the Jurassic–Cretaceous transition. Biological Reviews 89, 1–23.
Cooper, L.N., Dawson, S.D., 2009. The trouble with flippers: a report on the prevalence of digital anomalies in Cetacea. Zoological Journal of the Linnean Society 155, 722–735.
Einarsson, E., Lindgren, J., Kear, B.P., Siverson, M., 2010. Mosasaur bite marks on a plesiosaur propodial from the Campanian (Late Cretaceous) of southern Sweden. Geologiska Foreningens Stockholm Forhandlingar 132, 123–128.
Elkin, E., 1981. Pathology and histopathological techniques. In: Cooper, J.E., Jackson, O.F. (Eds.), Diseases of the Reptilia, vol. 1. Academic Press, London, pp. 75–91.
Elkin, E., Cooper, J.E., 1976. Tumors and pseudotumors in some reptiles. Journal of Comparative Pathology 86, 337–348.
Gasparini, Z., Salgado, L., Parras, A., 2007. Late cretaceous plesiosaurs from northern Patagonia, Argentina. Geological Journal 42, 185–202.
Hopley, P.J., 2001. Plesiosaur spinal pathology: the first fossil occurrence of Schmorl's nodes. Journal of Vertebrate Paleontology 21, 253–260.
Kompanje, E.J.O., 1999. Considerations of the comparative pathology of the vertebrae in Mysticeti and Odontoceti; evidence for the occurrence of discarthrosis,

zygarthrosis, infectious spondylitis and spondyloarthritis. Zoologische Mededelingen 73, 99–130.
Lingham-Soliar, T., 2004. Palaeopathology and injury in the extinct mosasaurs (Lepidosauromorpha, Squamata) and implications for modern reptiles. Lethaia 37, 255–262.
Martin, L.D., Rothschild, B.M., 1989. Paleopathology and diving mosasaurs. American Scientist 77, 460–467.
Moodie, R.L., 1918. Pathological lesions among extinct animals: a study of the evidences of disease millions of years ago. Surg Clin Chicago 2, 319–331.
Moodie, R.L., 1923. The Antiquity of Disease. University of Chicago Press, pp. 148–150.
Motani, R., Rothschild, B., Wahl, W., 1999. Large eyeballs in diving ichthyosaurs. Nature 402, 747.
Mudge, B.F., 1878. Geology of Kansas: First Biennial Report of the Kansas State Board of Agriculture. Topeka 60–63.
Mulder, E.W.A., 2001. Co-ossified vertebrae of mosasaurs and cetaceans: implications for the mode of locomotion of extinct marine reptiles. Paleobiology 27, 724–734.
O'Gorman, J., Salgado, L., Gasparini, Z., 2011. Plesiosaurios de la Formación Allen (Campaniano-Maastrichtiano) en el área del salitral de Santa Rosa (provincia de Río negro, Argentina). Ameghiniana 48, 129–135.
Pardo-Pérez, J.M., Kear, B.P., Gómez, M., Moroni, M., Maxwell, E.E., 2017. Ichthyosaurian palaeopathology: evidence of injury and disease in fossil "fish lizards". Journal of Zoology 304, 21–33.
Pardo-Pérez, J.M., Kear, B.P., Mallison, H., Gómez, M., Moroni, M., 2018. Pathological survey on Temnodontosaurus from the Early Jurassic of southern Germany. PloS One 13, 49–51.
Pardo-Pérez, J.M., Kear, B., Maxwell, E.E., 2019. Palaeoepidemiology in extinct vertebrate populations: factors influencing skeletal health in Jurassic marine reptiles. Royal Society Open Science 6, 190–264.
Rothschild, B.M., 2012. In: Rothschild (Ed.), Principles of osteoarthritis. Its definition, character, derivation and modality-related recognition. InTech, Rijeka. ISBN: 978-953-51-0063-8.
Rothschild, B.M., 2021. Bone alteration by disease: Its appearance, phylogeny and penetrance through geologic time. In: Garner, M.M., Jacobson, E.R. (Eds.), Diseases and Pathology of Reptiles, vol. II. CRC Press, pp. 483–501.
Rothschild, B.M., Everhart, M., 2015. Co-Ossification of Vertebrae in Mosasaurs (Squamata, Mosasauridae); Evidence of Habitat Interactions and Susceptibility to Bone Disease. Transactions of the Kansas Academy of Science 118, 265–275.
Rothschild, B.M., Martin, L.D., 1987. Avascular necrosis: occurrence in diving Cretaceous mosasaurs. Science 236, 75–77.
Rothschild, B.M., Martin, L.D., 1993. Paleopathology: disease in the fossil record. CRC Press, Boca Raton.
Rothschild, B.M., Martin, L.D., 2003. Frequency of pathology in a large natural sample from Natural Trap Cave with special remarks on erosive disease in the Pleistocene. Rheumatismo 55, 58–65.
Rothschild, B.M., Martin, L.D., 2006. Skeletal Impact of Disease. Museum of Natural History Press, Albuquerque, New Mexico.
Rothschild, B.M., Laub, R., 2006. Hyperdisease in the Late Pleistocene: Validation of an Early 20TH century hypothesis. Naturwissenschraften 93, 557–564.
Rothschild, B.M., Storrs, W., 2003. Decompression syndrome in plesiosaurs (sauropterygia: reptilia). Journal of Vertebrate Paleontology 23, 324–328.
Rothschild, B.M., Schultze, H., Pellegrini, R., 2012a. Herpetological Osteopathology. Springer, New York, United States of America.
Rothschild, B.M., Xiaoting, Z., Martin, L.D., 2012b. Adaptations for marine habitat and the effect of Triassic and Jurassic predator pressure on development of decompression syndrome in ichthyosaurs. Naturwissenschaften 99, 443–448.
Rothschild, B.M., Clark, N., Clark, C., 2018. Evidence for survival in a Middle Jurassic plesiosaur with a humeral pathology: What can we infer of plesiosaur behaviour? Palaeontologia Electronica 21, 1–11.
Rothschild, B.M., DePalma, R.A., Burnham, D.A., Martin, L.D., 2020. Anatomy of a dinosaur – clarification of vertebrae in vertebrate anatomy. Anatomy Histology Embryology 49, 12573. https://doi.org/10.1111/ahe.12573.
Sassoon, J., 2019. Congenital and late onset vertebral fusions in long necked plesiosaurs: The first report of spondylosis deformans in Sauropterygians. Palaeontologia Electronica 22, 1–15.
Sassoon, J., Noè, L.F., Benton, M.J., 2012. Cranial anatomy, taxonomic implications and palaeopathology of an Upper Jurassic Pliosaur (Reptilia: Sauropterygia) from Westbury, Wiltshire, UK. Palaeontology 55, 743–773.
Schulp, A.S., Walenkamp, G.H.I.M., Hofman, P.A.M., Rothschild, B.M., Jagt, J.W.M., 2004. Rib fracture in Prognathodon saturator (Mosasauridae, Late Cretaceous). Netherlands Journal of Geosciences, Geologieen Mijnbouw 83, 251–254.
Schulp, A.S., Walenkamp, G.H., Hofman, P.A., Stuip, Y., Rothschild, B.M., 2006. Chronic bone infection in the jaw of Mosasaurushoffmanni (Squamata). Oryctos 6, 41–52.
Shimada, K., Tsuihiji, T., Sato, T., Hasegawa, Y., 2010. A remarkable case of a shark-bitten elasmosaurid plesiosaur. Journal of Vertebrate Paleontology 30, 592–597.
Surmik, D., Rothschild, B.M., Dulski, M., Janiszewska, K., 2017. Two types of bone necrosis in the Middle Triassic Pistosaurus longaevus bones: the results of integrated studies. Royal Society Open Science 4, 170–204.
Surmik, D., Szczygielski, T., Janiszewska, K., Rothschild, B.M., 2018. Tuberculosis-like respiratory infection in 245-million-year-old marine reptile suggested by bone pathologies. Royal Society Open Science 5, 180225.
Talevi, M., Fernández, M., 2015. Remodeling bone and structural specializations in a elasmosaurid (sauropterygia: Plesiosauroidea) from the Upper Cretaceous of Patagonia, Argentina. Historical Biology 27, 60–67.
Talevi, M., Rothschild, B., Fernández, M., Reguero, M., Mitidieri, M., 2019. A pathological scapula in a mosasaur from the upper Maastrichtian of Antarctica: Evidence of infectious arthritis and spondyloarthropathy. Cretaceous Research 100, 1–4.
Thulborn, T., Turner, S., 1993. An elasmosaur bitten by a pliosaur. Modern Geology 18, 489–501.