



# Spondyloarthropathy in vertebrae of the aquatic Cretaceous snake *Lunaophis aquaticus*, and its first recognition in modern snakes

Adriana María Albino<sup>1</sup> · Bruce Rothschild<sup>2</sup> · Jorge D. Carrillo-Briceño<sup>3</sup> · James M. Neenan<sup>4</sup>

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## Abstract

Inflammatory arthritis is documented for the first time in snakes. Ossification of the intervertebral capsule and zygapophyseal joints resulting in segmental vertebral fusion was observed in the aquatic Cretaceous snake *Lunaophis aquaticus*. Such pathologic alterations are pathognomonic for the spondyloarthropathy form of inflammatory arthritis. A survey of 2144 snakes in recent collections, performed to identify Holocene prevalence, revealed only two occurrences in extant snakes. The findings in *Bitis gabonica* and *Elaphe taeniura* were indistinguishable from those noted in *Lunaophis aquaticus* and identical to those previously recognized in modern varanids. The pathology likely represents a form of reactive arthritis related to enteropathic infection. While the disease probably did not affect general locomotion, its vertebral column position may have compromised mating.

**Keywords** Spondyloarthropathy · Mesozoic · Marine snakes · South America · Venezuela

## Introduction

*Lunaophis aquaticus* is a representative of an early lineage of snakes that exploited tropical marine environments of Cretaceous South America (Albino et al. 2016). It is known by several precloacal vertebrae from sediments of the Cenomanian La Luna Formation in the Andes of Venezuela. A short portion of articulated vertebral column of the holotype reveals an osseous pathology previously unreported in any snake.

Reported cases of snake postcranial osseous pathology have been limited to those of traumatic, infectious, and neoplastic origin (Isaza et al. 2000; Rothschild et al. 2012). The report suggesting Paget's disease was diagnosed on the basis of disorganized osseous architecture (Frye and Carney 1974).

Although a viral cause has been suggested for Paget's disease (Altman and Singer 1980), the bone alterations in Frye and Carney (1974) have been reinterpreted as representing bacterial osteomyelitis (Rothschild and Martin 2006; Rothschild et al. 2012). The two are morphologically distinguishable on the basis of gross morphology, but not histology.

In this study, we describe the occurrence of spondyloarthropathy in vertebrae of *Lunaophis aquaticus*. Spondyloarthropathy is a form of arthritis in which the margins of vertebrae are bridged through either the outer layers of intervertebral disks or joint capsules (Resnick 2002; Rothschild and Martin 2006). This pathology has been previously recognized in extant varanids and crocodylians (Rothschild 2009) and in extinct mosasaurs (Rothschild and Everhart 2015), but not for either fossil or Recent snakes (Rothschild et al. 2012). We provide evidence supporting the diagnosis of this pathology in *Lunaophis*, which constitutes the earliest known instance of this kind of arthritis in snakes. Additionally, we surveyed extant snake collections to determine the occurrence and prevalence of the phenomenon.

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✉ Adriana María Albino  
aalbino@mdp.edu.ar

<sup>1</sup> CONICET, Departamento de Biología, Universidad Nacional de Mar del Plata, Funes 3250, B7602AYJ Mar del Plata, Argentina

<sup>2</sup> West Virginia University, Morgantown, WV 26501, USA

<sup>3</sup> Paläontologisches Institut und Museum, Universität Zürich, Zürich, Switzerland

<sup>4</sup> Oxford University Museum of Natural History, Oxford, UK

## Materials and methods

The pathologic fossil vertebrae investigated in this study are catalogued and stored at the collection of the Museo de Ciencias Naturales de Caracas, Venezuela (MCNC). The remains corresponding to the holotype of *Lunaophis aquaticus*

(MCNC-1827) include four isolated prelocal vertebrae (MCNC-1827-A, MCNC-1827-B, MCNC-1827-C, MCNC-1827-D), an isolated anterior vertebra (MCNC-1827-E), five mid- or posterior prelocal vertebrae (MCNC-1827-F), and a poorly preserved vertebral fragment (MCNC-1827-G). The pathologic vertebrae correspond to the segment MCNC-1827-F.

The vertebrae of *Lunaophis aquaticus* were found exposed in a quarry of the Cementos Andinos company, 10 km northeast of Monay city (9° 36.57' 06" N, 70° 24' 14" W), Trujillo State, Venezuela. The fossils come from strata corresponding to the Cenomanian La Aguada Member of the La Luna Formation (Albino et al. 2016; Guinot and Carrillo-Briceño 2018). Associated fauna from the same strata as *Lunaophis* indicates a marine environment (Albino et al. 2016; Guinot and Carrillo-Briceño 2018).

Snakes in the collections of the American Museum of Natural History (AMNH), Carnegie Museum (CM), National Museum of Natural History (NMNH), and Texas Memorial Museum (TMM) were examined by one of us (B.R.) by epi-illumination microscopy (Dino-lite, AM7915MZT, Dunwell Tech, Inc., 19803 Hamilton Ave #200, Torrance CA 90502) for vertebral bridging and fusion. Comprehensive expertise with this type of disease is displayed in Rothschild and Martin (2006) and Feldtkeller and Rothschild (in press).

Spondyloarthropathy was recognized on the basis of intervertebral margin ossification producing bridging/fusion of otherwise intact vertebrae (Resnick 2002; Rothschild and Martin 2006), in the absence of vertebral compression characteristic of fractures and the destructive bone changes with draining fibriscesses characteristic of osteomyelitis and mass effect of neoplasia (Resnick 2002; Rothschild and Martin 2006; Rothschild et al. 2012). Anterior longitudinal ligament ossification is a diagnostic characteristic of a phenomenon referred to as diffuse idiopathic hyperostosis (DISH), when capsule fusion is not present (Resnick 2002; Rothschild and Martin 2006). Its presence, however, does not rule out spondyloarthropathy, which is also associated with such ligamentous ossification (Resnick 2002; Rothschild and Martin 2006). The presence of intact intervertebral spaces allowed spondyloarthropathy to be distinguished from congenital block vertebrae (Burnham et al. 2013; Resnick 2002; Rothschild and Martin 2006; Rothschild et al. 2012).

## Results

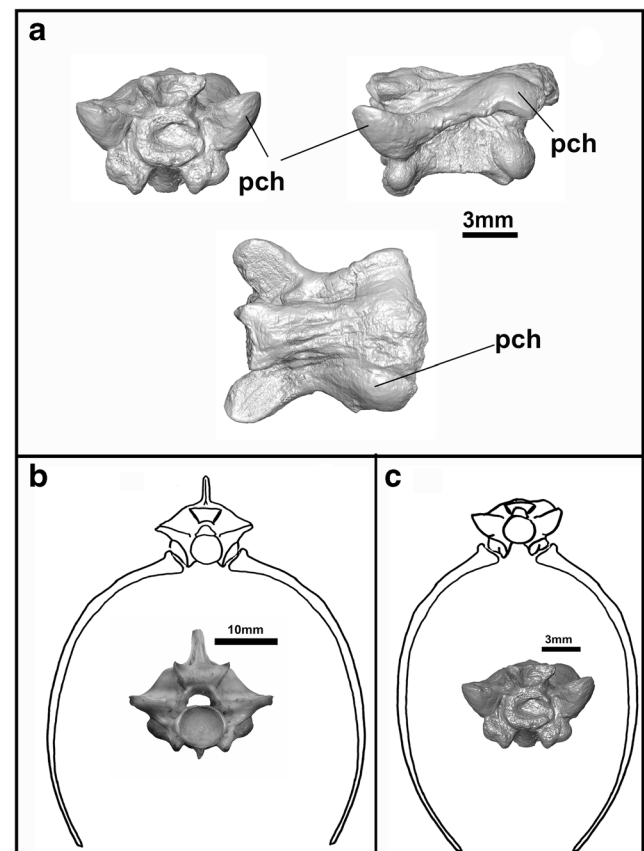
### Paleoecology of *Lunaophis aquaticus*

Examination of the vertebral morphology reveals that *Lunaophis aquaticus* resembles simoliophiids (Albino et al. 2016), the earliest sea-invaders in the evolution of snakes (Hsiang et al. 2015). *Lunaophis* represents the first aquatic

snake from the Cenomanian found outside of the African, Middle East, and European Tethyan and Boreal Zones, which is where the simoliophiids have been previously documented (Albino et al. 2016).

All simoliophiids display pachyostosis in which the centrum and neural arch are swollen in all dimensions, increasing the mass of the vertebrae (Lee and Caldwell 1998; Houssaye 2010; Rage et al. 2016). Pachyostosis is a non-pathological condition in these vertebrates in which the bones experience a thickening, generally caused by extra layers of lamellar bone (Houssaye 2009). It occurs in both aquatic and semi-aquatic vertebrates (Houssaye 2009). The pachyostosis in *Lunaophis* is less evident than in simoliophiids, and is concentrated on the prezygapophyseal bodies and on the posterior part of the neural arch, above the postzygapophyses (Fig. 1a).

In addition, the vertebrae of *Lunaophis* are characterized by the ventral position of the paradiapophyses, which are closely spaced, project ventrally from the centrum, and bear ventrally oriented surfaces (Fig. 1a). This morphology contrasts with the morphology of terrestrial, arboreal, and fossorial snakes, in which the paradiapophyses are well-separated from each



**Fig. 1** a Pachyostosis (pch) in a non-pathologic vertebra of *Lunaophis aquaticus* MCNC-1827-A (anterior, left lateral, and dorsal views). b Trunk vertebrae and articulated ribs of terrestrial *Boa constrictor occidentalis*, anterior view. c Trunk vertebrae and hypothetical articulated ribs of aquatic *Lunaophis aquaticus*, anterior view

other, do not project from the centrum, and have lateroventrally oriented surfaces determining a lateralized articulation of the ribs with the vertebra (Fig. 1b). The hypothetical ribs of *Lunaophis* would have been articulated with the paradiapophyses ventrally to the vertebral centra (Fig. 1c). Thus, the body of this snake was strongly compressed laterally, giving it an eel-like appearance as an adaptation for swimming. Aquatic habits are supported by the size of the snake (approximately 1.5 m), presence of pachyostosis, and depositional conditions of the La Aguada Member of the La Luna Formation.

### Spondyloarthropathy in vertebrae of *Lunaophis* and extant snakes

Spondyloarthropathy was recognized in MCNC-1827-F (Fig. 2a, b) on the basis of osseous fusion of the capsule surrounding intervertebral spaces (Resnick 2002; Rothschild and Martin 2006), while normal vertebral shape and configuration were retained. Examination of 2144 modern snakes revealed only one additional affected snake, the viperid *Bitis gabonica* CM145474S (Fig. 2c, d). Fusion of posterior (facet) joints is also present in *Lunaophis aquaticus* MCNC-1827-F (Fig. 2c). This is distinguished from congenital vertebral pathology which represents segmentation defects, predominantly failure of segmentation or failure of development of one of

the segments (e.g., hemivertebra or block vertebrae) that normally combine to form a normal vertebra (Burnham et al. 2013).

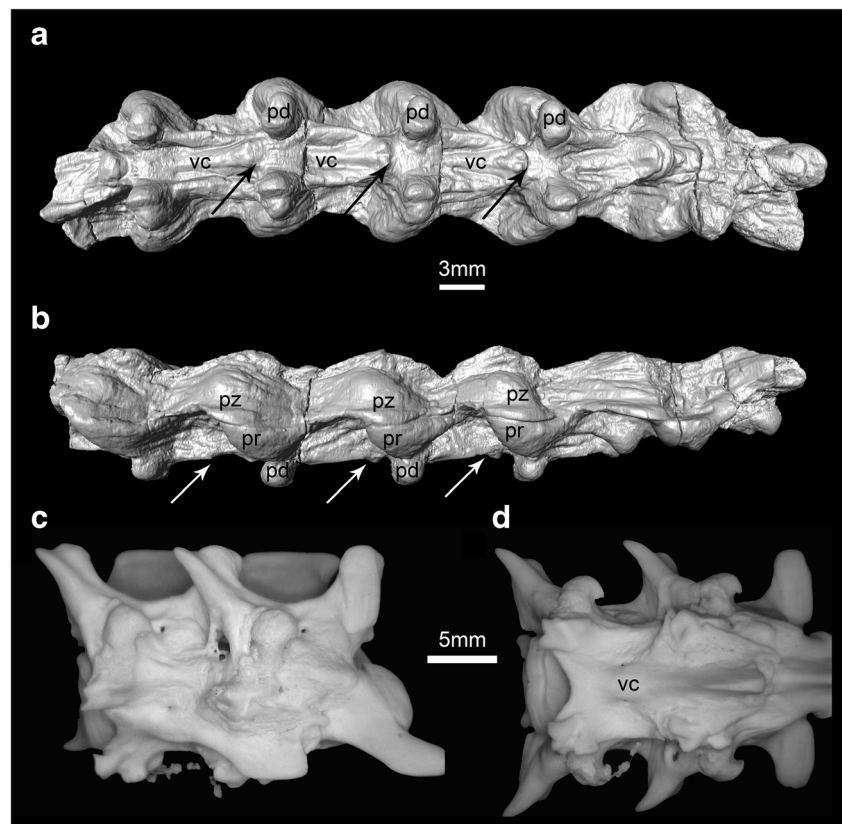
Fusion through the outer layers of the capsule joining vertebral centra (Fig. 2) is pathognomonic (diagnostic) for spondyloarthropathy (Resnick 2002; Rothschild and Martin 2006; Rothschild et al. 2012). It is accompanied by ligamentous ossification. Vertebral body shape and configuration appear otherwise unaltered.

### Discussion

These observations represent the first recognition of the inflammatory arthritis condition, spondyloarthropathy, in a fossil snake, and establish the geological depth of this disease. This condition is apparently rare in snakes, as there is only one recent case, other than that discovered in *Bitis gabonica* in the current study, noted to date. Marcus (1981) initially reported an anomaly affecting the extant snake *Elaphe taeniura* as osteoperiostitis, but Rothschild et al. (2012) suggest it would correspond to spondyloarthropathy, which is confirmed here.

Differential diagnosis—lack of vertebral disruption and draining sinuses rules out osteomyelitis (Jacobson 2007; Resnick 2002; Rothschild and Martin 2006). Maintenance of vertebral body shape and intervertebral spaces is incompatible

**Fig. 2** **a** Ventral view of *Lunaophis aquaticus* MCNC-1827-F vertebrae, fusion of vertebrae through intervertebral capsule. **b** Left lateral view of *Lunaophis aquaticus* MCNC-1827-F vertebrae, continuous fusion of longitudinal ligament. **c** Lateroventral view of *Bitis gabonica* CM145474S vertebrae, fusion of both zygapophyseal joints and intervertebral capsule, anterior to the left. **d** Ventral view of *Bitis gabonica* CM145474S vertebrae. pd paradiapophysis, pr prezygapophysis, pz postzygapophysis, vc vertebral centrum



with fracture or segmental defect evidencing congenital origin of the pathology. Presence of capsular calcification dismisses DISH as a diagnostic consideration. The associated ligamentous ossification in *Lunaophis aquaticus* MCNC-1827-F represents the enthesial reaction commonly found in individuals with spondyloarthropathy.

Spondyloarthropathy is a classification consisting of several diseases (Resnick 2002; Rothschild and Martin 2006): (1) a primary arthritis (ankylosing spondylitis). (2) A dermatologically related disorder, psoriatic arthritis. (3) Arthritis associated with inflammatory bowel diseases, ulcerative colitis, and Crohn's disease. (4) A reactive arthritis (previously referred to as Reiter's syndrome). (5) An undifferentiated form, not assignable to the first four categories. Ankylosing spondylitis generally starts in what would be the pelvic region and results in vertebral fusion proceeding uniformly in a cephalad (cranial) direction (Resnick 2002; Rothschild and Martin 2006). If the fused preloacal vertebrae of *Lunaophis aquaticus* represent the most posterior portion of that segment, early ankylosing spondylitis or inflammatory bowel disease could be considered as the specific variety of spondyloarthropathy. Reactive arthritis, psoriatic arthritis, and the undifferentiated form of spondyloarthropathy are not so limited in vertebral column distribution (Resnick 2002; Rothschild and Martin 2006). While psoriasis is characterized by erythematous skin reaction with scale shedding, this is quite different from snake dysecdysis, with residual tissue from normal skin shedding, and the hyperkeratosis that can complicate vitamin A deficiency (Marcus 1981). Skin disease in the form of psoriasis has not been recognized in snakes. However, reactive arthritis is worthy of consideration. The term "reactive" refers to the bone alterations that can take place subsequent to what is generally referred to as food poisoning by such organisms as enteropathic (intestinal wall invading) *Escherichia coli*, *Salmonella*, *Shigella*, *Campylobacter*, and *Yersinia* bacteria (Rothschild and Martin 2006). The originating infection is generally resolved, but is followed by an immunologic reaction producing the pathology. Such intestinal infections have been reported in snakes (Jacobson 2007) and gastritis has been related to parasitic infection (Brownstein et al. 1977), which can cause inflammatory bowel disease in humans (Nime et al. 1976). Reactive arthritis and ankylosing spondylitis are the most likely varieties of spondyloarthropathy responsible for the vertebral alterations in *Lunaophis aquaticus* MCNC-1827-F.

It is unclear that involvement of such a limited portion of the vertebral column would have impaired movement or ability to capture prey. It may, however, have impeded the physical act of mating. This form of arthritis may be quite painful and thus could have impacted the snake's quality of life.

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