International Journal of Paleopathology 53 (2026) 65–68

Contents lists available at ScienceDirect

International Journal of Paleopathology

journal homepage: www.elsevier.com/locate/ijpp

Evidence of bony stress syndrome in a fossil cetacean

Oliver Hampe [a,b,*], Patrick Asbach [c]

[a] Museum für Naturkunde, Leibniz-Institut für Evolutions- und Biodiversitätsforschung, Invalidenstr. 43, Berlin 10115, Germany
[b] Institut für Geologische Wissenschaften, Fachrichtung Paläontologie, Freie Universität Berlin, Malteserstr. 74-100, Berlin 12249, Germany
[c] Charité – Universitätsmedizin Berlin, Klinik für Radiologie, Campus Charité Mitte, Charitéplatz 1, Berlin 10117, Germany

ARTICLE INFO

Keywords:
Repetitive biomechanical overload
Bone proliferation
Mysticeti
Miocene
Schleswig-Holstein

ABSTRACT

Objective: A finding in a fossil mysticete rib is used to get insights into biomechanical limits of extinct whales.
Materials: The investigated specimen from the Miocene (Serravallian/Tortonian boundary) of Groß Pampau, North Germany, comprises a 252 mm distal fragment of a right posterior rib exhibiting distinctive pathological features including extensive periosteal new bone formation and a prominent 69 mm bony spur.
Methods: The internal morphology was analysed with a clinical CT-scanner.
Results: Morphological examination and computed tomography analysis revealed irregular cortical thickening, excentric bone proliferation with a 17° anterior deviation, and trabecular bone continuity at the spur base, consistent with a healed stress fracture. Differential diagnoses including acute trauma, osteomyelitis, neoplasia, and dysbaric osteonecrosis were systematically excluded based on morphological criteria and the absence of associated lesions throughout the skeleton.
Conclusions: The combination of an isolated rib fracture with periosteal reaction and the presence of an adaptive bony spur strongly suggests a stress fracture etiology resulting from repetitive biomechanical overload, analogous to stress injuries observed in human athletes, e.g., intensive swimming activities.
Significance: Stress fractures are underreported in cetaceans. Our findings enhance our understanding of bone remodeling processes providing evidence for chronic, repetitive mechanical overload and highlight that fossil bone can be used to demonstrate long-term physiological strain in deep-time.
Limitations: To date, there have been few comparable studies on marine mammals.
Suggestions for Further Research: Further research into the locomotory behavior and biomechanical stress patterns of Miocene cetaceans is needed.

1. Introduction

Rib fractures commonly occur as a consequence of direct trauma to the chest. Different fracture patterns depend on the trauma mechanism, with blunt trauma to the ribcage often resulting in serial rib fractures. Besides concurrent injury to chest organs (e.g., lungs and blood vessels), the severity of injury depends on the number of fractured ribs and the number of fractures per rib, potentially leading to chest wall instability affecting respiratory mechanics (flail chest) (Sermonesi et al., 2024). Besides acute trauma, rib fractures can result from (chronic) stress injury (Boden et al., 2001) or can be secondary to other medical conditions such as osteoporosis, infection/inflammation (Rachidi et al., 2025), metastatic disease or, very rarely, to primary bone tumors (Zarqane et al., 2013). Stress fractures in (fossil) cetaceans provide indirect evidence of repetitive skeletal loading, offering insight into functional demands and habitual behaviors in extinct whales beyond morphology alone. Their identification also refines paleopathological diagnostic criteria by helping distinguish chronic overuse-related lesions from traumatic or taphonomic damage in marine vertebrates. Documenting such injuries therefore advances both reconstruction of whale biology and behavior.

2. Material and methods

The fossil under investigation comes from the Serravallian/Tortonian boundary (Bolboforma fragori/subfragoris Zone with an age between 11.8 and 10.6 Ma; after Spiegler and Gürs, 1996; Gürs and Spiegler, 1999) of Groß Pampau in Schleswig-Holstein, northern Germany. It is nearly complete, but heavily fragmented due to salt tectonics and Quaternary glacial pressure. The skeleton has been identified as

* Corresponding author at: Museum für Naturkunde, Leibniz-Institut für Evolutions- und Biodiversitätsforschung, Invalidenstr. 43, Berlin 10115, Germany.
E-mail address: oliver.hampe@mfn.berlin (O. Hampe).

https://doi.org/10.1016/j.ijpp.2026.03.004
Received 6 October 2025; Received in revised form 17 March 2026; Accepted 24 March 2026
Available online 3 April 2026
1879-9817/© 2026 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

mysticete *Praemegaptera pampauensis* originally presented by Behrmann (1995). Although its definitive systematic placement is unresolved, the general cranial morphology of *Praemegaptera pampauensis* closely resembles that of extant rorquals of the genus *Balaenoptera*, as shown by 2-dimensional warp analyses (see Hampe and Baszio, 2010).The holotype specimen of *Praemegaptera pampauensis* (MNUL.Pal.100.002), exhibiting the described pathology, is on display in the Lübeck Museum für Natur und Umwelt. The fossil was discovered and excavated during the years 1989/90 (Höpfner, 2014). The "Grabungsteam" worked under the direction of G. Höpfner, who also prepared the material, on behalf of the Lübeck museum.

The ribcage preservation of the specimen is fragmentary, with many ribs found disarticulated. Locality records suggest that *Praemegaptera pampauensis* likely had 12–13 pairs of ribs. The focus of this report is a 252 mm long distal part of a right posterior rib (probably the 8th to 10th; see Fig. 1a) with a maximum diameter of about 46 mm which shows a significant proliferation of the cross-sectional rounded shaft and a prominent bony spur extending distally (Fig. 1b, c). The total length of the spur measures 69 mm (including the base erupting from the rib body).

Clinical computed tomography (CT) analysis was performed using a 320-section multidetector CT (Aquillion ONE; Canon Medical Systems, Otawara, Japan). A helical scan mode was conducted with a rotation time of 1.0 s, tube voltage of 135 kV, and tube current of 150 mA. Axial slices were acquired at 0.5 mm thickness, with in-plane resolution of 0.35×0.35 mm^2.

3. Results

The rib fragment under investigation shows an unusual combination of two anatomically separated abnormal findings. There is a marked irregular thickening of the rib shaft, with bone proliferation forming longitudinal grooves over a 170 mm segment proximodistally (Fig. 1a, b). No pits or holes are evident at the bone surface. At the distal anterolateral aspect of the rib, a bony spur is present oriented in a distal direction (Fig. 1b, c). Distal to this spur, the rib displays a normal morphology.

Internal morphology shows that the eccentric thickening results from partially solid and mostly disorganised periosteal new bone formation, with the anterior rib cortex preserved (Fig. 2a-c). At the transition from the proximal to the middle third of the fragment, there is a 20 mm area where the remaining cortex is completely replaced by new bone formation, aligned with a 17° anterior deviation of the distal rib (Fig. 2a, b, d). The new bone formation is pronounced (up to 22 mm) in the direction of this deviation, with only minimal new bone formation on the lateral aspect of the rib and no new bone formation on the medial aspect, which is anatomically aligned. No aggressive periosteal reaction changes such as layered or sunburst patterns are observed. The bony spur measures 20 mm with a 10 mm base and shows a thin cortex (Fig. 2e). There is no cortex at the base of the spur, which is mostly composed of trabecular (cancellous) bone continuous with the rib's trabeculae. Distal to the spur, the internal morphology of the rib is normal (Fig. 2f). There are no lytic areas within the entire rib specimen. For comparison, the normal bone condition is shown in a recent minke whale (Fig. 3a, b).

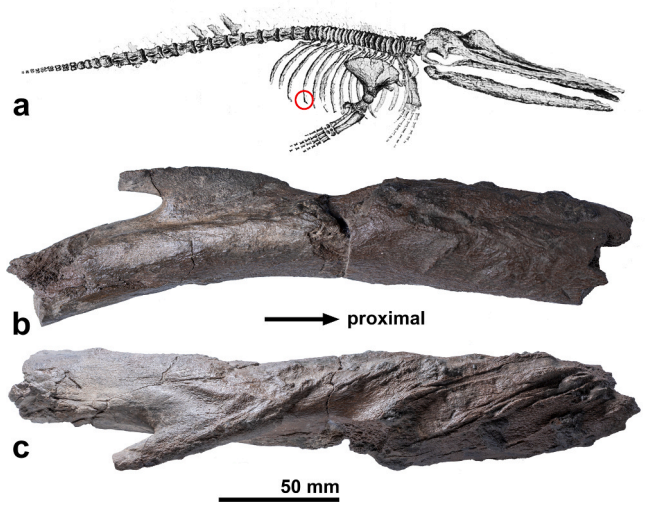

Fig. 1. *Praemegaptera pampauensis*, holotype, MNUL.Pal.100.002. (a) reconstruction of the skeleton from the perspective of G. Höpfner drawn in 1989 with the probable position of the pathological rib. (b) right distal rib fragment, probably belonging to the 8th to 10th rib in posteromedial view with bony spur and thickened proximal shaft. (c) in anterior view with longitudinal grooves proximal to the spur.

4. Discussion

4.1. Interpretation of rib pathology

The specimen represents an isolated rib fracture in *Praemegaptera pampauensis*. The rib fracture appears healed, evidenced by substantial new bone formation (Fig. 2). Rib fractures with extensive bony growths have been described in modern humpback whales (Groch et al., 2012). The partially solid nature of the new bone suggests a protracted period of healing. No additional injuries are observed elsewhere in the skeleton. Distal to the fracture, a relatively large bony spur (i.e., osteophyte, enthesophyte) is present (Fig. 1b, c, Fig. 2b, e), which typically occurs at the junction between muscles (or ligaments) and bone and is a reaction to increased load or friction at the muscle-bone interface. The spur thus represents an adaptive reparative process.

The combination of an isolated rib fracture and a bony spur as reaction of the bone to increased load is suggestive of a stress reaction. The two findings are very likely linked to each other given the general principal of parsimony. Stress reaction is a specific type of bone injury caused by a mismatch between bone stability and mechanical load or friction (overuse injury) (Connolly and Connolly, 2004). Stress-related bone responses can range from very mild periosteal reactions to alterations of the trabecular and cortical bone, with a cortical fracture being the most severe form (Fredericson et al., 1995). The biomechanical interpretation of the stress fracture and the bony spur suggests deep-time evidence that the phenomenon of repetitive submaximal loading related to long-term physiological strain has occurred in extinct cetaceans. Yet, stress fractures are virtually unknown in living whales, specifically rib stress fractures appear to be almost nonexistent as a formal diagnosis.

4.2. Stress fractures in humans and differential considerations

In humans, stress fractures typically affect the lower limbs, in particular the laminae of the lumbar spine, the femoral neck and the metatarsals (Boden et al., 2001; Connolly and Connolly, 2004). However, there are exceptions in relation to sports. Rib stress fractures have occurred in rowers, due to increased rib loading caused by muscle activity from the serratus anterior and the abdominal muscles (Warden et al., 2002). Rib stress fractures were also reported in competitive swimmers (Taimela et al., 1995, Schwanz et al., 2025). Whale axial musculature is quite similar to that of humans (Slijper, 1936; Huggenberger et al., 2019). For a stress fracture in the posterior rib area, the external oblique muscle would be the primary cause of overload. It pulls the rib cage downward to compress the abdominal cavity and is responsible for lateral movements (rather rare in cetaceans, except during jumping). Thus, such a stress fracture was potentially induced by repetitive activity, perhaps associated with locomotor or behavioral patterns.

Alternative causes, such as osteomyelitis with secondary fracture, are

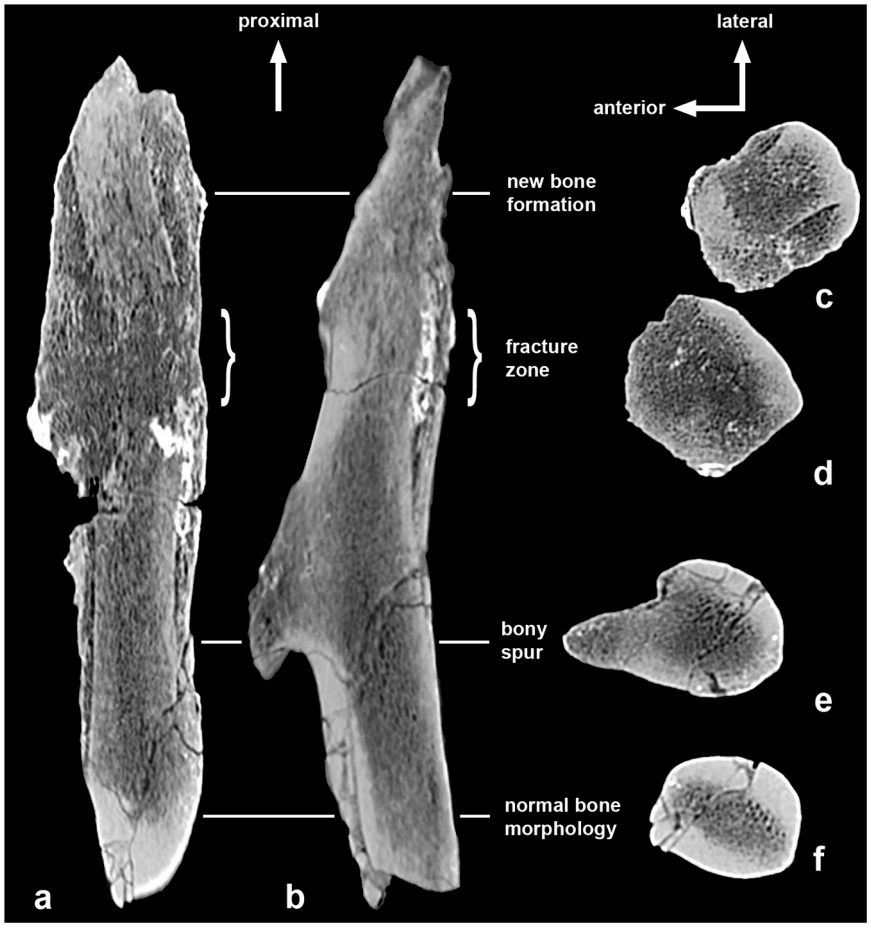

Fig. 2. CT-images of the pathological rib of the *Praemegaptera pampauensis* holotype reconstructed in different slice orientations. (a) transversal section showing a deviation of 17° of the distal part of the rib. (b) sagittal section at the level of the spur. (c) proximal cross-section showing new bone formation; (d) cross-section at the level of the fracture zone with reduced cortex; (e) cross-section at the level of the adaptive bony spur; (f) distal cross-section representing normal bone morphology and intact cortical layers.

unlikely due to the absence of circumferential new bone and sequestrum formation (Zarqane et al., 2013). Benign osseous tumors, e.g., chondroblastoma or giant cell tumor, are excluded by the absence of lytic changes (Zarqane et al., 2013). A fracture secondary to dysbaric osteonecrosis (Sharareh and Schwarzkopf, 2015) seems unlikely as no necrotic changes are seen.

4.3. *Differential considerations regarding whales*

Other traumatic etiologies appear equally unlikely, specifically caused by external impacts. Intraspecific combat associated with mating is documented for humpback whales and right whales (Ford and Reeves, 2008), but no severe injuries are reported in this circumstance. Such a trauma would probably lead to multiple rib injuries. A fracture related to predation of macroraptorial sperm whales (see Lambert et al., 2014, 2017) is also doubtful. *Hoplocetus ritzi*, a representative of these highly predatory sperm whales, existed in the area where our find was made (Hampe, 2006). Prior to the Pliocene epoch, these whales probably occupied the ecological niche of today's killer whales. However, rake marks on attacked recent mysticetes induced by orcas are found predominantly on the tail fluke (Corsi et al., 2022). A collision with a rock in a tidal zone, incurred by a possibly exhausted or sick animal, can also be excluded since there are no signs of reef structures or barriers in the Groß Pampau fossil site.

Diagnosing stress fractures in fossil specimens is challenging, particularly in distinguishing stress-related lesions from healed traumatic fractures, developmental anomalies, or postmortem damage. Here, however, the morphology, location, and surface characteristics of the lesion are strongly suggestive of a stress injury since similar lesions have been documented in humans and modern cetaceans (fin whales) display fractures on the spinal process of the lumbar vertebrae caused by excessive bending of the body (Daume et al., 2023). However, the data available is still too sparse to serve as a reliable proxy for habitual behavior in those marine vertebrates.

5. Conclusion

In conclusion, the combination of an isolated rib fracture with periosteal new bone formation is most consistent with a stress fracture attributable to increased biomechanical strain related to extensive or uncommon swimming activity. The associated bony spur likely reflects a secondary, adaptive response at a muscle attachment site. It appears that the bone was routinely loaded near and beyond its limits, subsequently resulting in a stress fracture. This finding opens the door to the future integration of finite element modeling. The bone remodeling response to repetitive strain bridges paleopathological inquiry with evolutionary medicine, functional morphology, and comparative orthopedics. To determine whether skeletal pathologies in fossil cetaceans can be used as indirect evidence of biomechanical loading, behavior, and, in possibly some cases, ecological pressures, transforms paleopathology from descriptive diagnosis into a tool for reconstructing the functional life history of extinct whales.

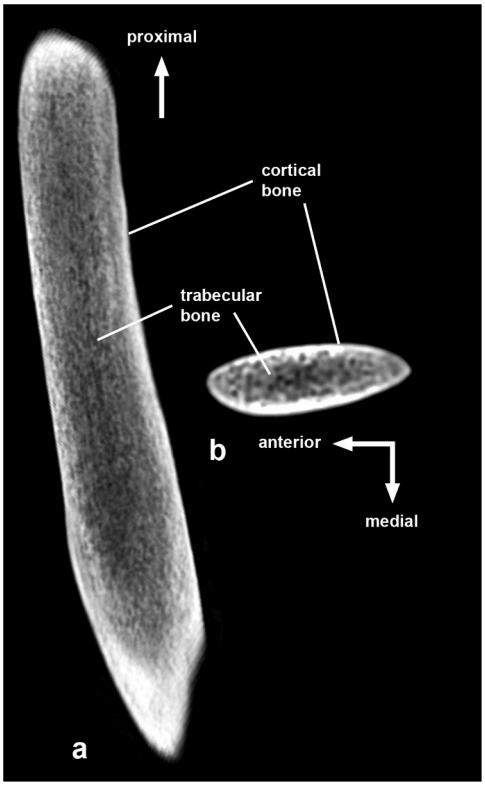

Fig. 3. CT-images of a healthy right 8th rib of a minke whale, *Balaenoptera acutorostrata*, ZMB_Mam_114514 (Zoological collection, Museum für Naturkunde Berlin). (a) transversal section through the distal part. (b) distal cross-section.

CRediT authorship contribution statement

Oliver Hampe: Writing – review & editing, Writing – original draft, Validation, Investigation, Conceptualization. **Patrick Asbach:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis.

Acknowledgements

We thank the Possehl Foundation for financial support enabling the excavation, transport, and preparation of the *Praemegaptera pampauensis* specimen. We gratefully acknowledge Gerhard Höpfner (Lübeck) for essential background information regarding the fossil mysticete. We are indebted to Susanne Füting for fossil bone loans and Jürgen Graack (both Lübeck) for technical support in the Lübeck museum. Christiane Funk (Berlin) provided the healthy minke whale rib. Finally, we would like to express our sincere thanks to the editor-in-chief and two anonymous reviewers for their comments and suggestions, which contributed significantly to improving the manuscript.

References

Behrmann, G., 1995. Der Bartenwal aus dem Miozän von Gr.-Pampau (Schleswig-Holstein). Geschiebekunde. aktuell 11 (4), 119–126.
Boden, B.P., Osbahr, D.C., Jimenez, C., 2001. Low-risk stress fractures. Am. J. Sports Med. 29 (1), 100–111.
Connolly, L.P., Connolly, S.A., 2004. Rib stress fractures. Clin. Nucl. Med. 29, 614–616.
Corsi, E., Calambokidis, J., Flynn, K.R., Steiger, G.H., 2022. Killer whale predatory scarring on mysticetes: a comparison of rake marks among blue, humpback, and gray whales in the eastern North Pacific. Mar. Mamm. Sci. 38 (1), 223–234.
Daume, H.V., Herr, H., Mallison, H., Glaubrecht, M., Kaiser, T.M., 2023. Osteopathological analysis provides evidence for a survived historical ship strike in a Southern Hemisphere fin whale (*Balaenoptera physalus*). Plos One 18 (2), e0281316.
Ford, J.K.B., Reeves, R.R., 2008. Fight or flight: antipredator strategies of baleen whales. Mamm. Rev. 38 (1), 50–86.
Fredericson, M., Bergman, A.G., Hoffman, K.L., Dillingham, M.S., 1995. Tibial stress reaction in runners: correlation of clinical symptoms and scintigraphy with a new magnetic resonance imaging grading system. Am. J. Sports Med. 23 (4), 472–481.
Groch, K.R., Marcondes, M.C.C., Colosio, A.C., Catão-Dias, J.L., 2012. Skeletal abnormalities in humpback whales *Megaptera novaeangliae* stranded in the Brazilian breeding ground. Dis. Aqua. Org. 101, 145–158.
Gürs, K., Spiegler, D., 1999. Regional Neogene North Sea Basin stages (Langenfeldian). Aardk. Mededel 11, 21–24.
Hampe, O., 2006. Middle/late Miocene hoplocetine sperm whale remains (Odontoceti: Physeteridae) of North Germany with an emended classification of the Hoplocetinae. Fossil Rec. 9 (1), 61–86.
Hampe, O., Baszio, S., 2010. Relative warps meet cladistics: a contribution to the phylogenetic relationships of baleen whales based on landmark analyses of mysticete crania. Bull. Geosci. 85 (2), 199–218.
Höpfner, G., 2014. Aus der Urzeit aufgetaucht. Bilddokumentation über sensationelle Wal- und Haifunde aus Schleswig-Holstein, SatzPartner, Lübeck.
Huggenberger, S., Oelschläger, H., Cozzi, B., 2019. Atlas of the Anatomy of Dolphins and Whales, Academic Press, London.
Lambert, O., Bianucci, G., Beatty, B.L., 2014. Bony outgrowths on the jaws of an extinct sperm whale support macroraptorial feeding in several stem physeteroids. Naturwissenschaften 101 (6), 517–521.
Lambert, O., Bianucci, G., Muizon, C. de, 2017. Macroraptorial sperm whales (Cetacea, Odontoceti, Physeteroidea) from the Miocene of Peru. Zool. J. Linn. Soc. 179 (2), 404–474.
Rachidi, F., Elhadi, A., Bittner-Schwerda, L., Schären-Bannert, M., Köller, G., Schinköthe, J., Majcher, A., Diehl, B., Hansmann, F., Kühn, T., Starke, A., 2025. Case Report: Clinical, laboratory, and pathological findings in cows with osteomyelitis of the ribs and sternum and endocarditis valvularis thromboticans. Front. Vet. Sci. 12, 1589472.
Schwanz, K.L., Karnovsky, S.C., Malafronte, J., Borg-Stein, J., Tenforde, A.S., McInnis, K. C., 2025. Rib bone stress injuries: a narrative review with protocol for rehabilitation and prevention. Curr. Sports Med. Rep. 24 (6), 153–163.
Sharareh, B., Schwarzkopf, R., 2015. Dysbaric osteonecrosis: a literature review of pathophysiology, clinical presentation, and management. Clin. J. Sports Med. 25 (2), 153–161.
Sermonesi, G., Bertelli, R., Pieracci, F.M., Balogh, Z.J., Coimbra, R., Galante, J.M., Hecker, A., Weber, D., Bauman, Z.M., Kartiko, S., Patel, B., Whitbeck, S.S., White, T. W., Harrell, K.N., Perrina, D., Rampini, A., Tian, B., Amico, F., Beka, S.G., Bonavina, L., Ceresoli, M., Cobianchi, L., Coccolini, F., Cui, Y., Dal Mas, F., De Simone, B., Di Carlo, I., Di Saverio, S., Dogjani, A., Fette, A., Fraga, G.P., Gomes, C. A., Khan, J.S., Kirkpatrick, A.W., Kruger, V.F., Leppäniemi, A., Litvin, A., Mingoli, A., Navarro, D.C., Passera, E., Pisano, M., Podda, M., Russo, E., Sakakushev, B., Santonastaso, D., Sartelli, M., Shelat, V.G., Tan, E., Wani, I., Abu-Zidan, F.M., Biffl, W.L., Civil, I., Latifi, R., Marzi, I., Picetti, E., Pikoulis, M., Agnoletti, V., Bravi, F., Vallicelli, C., Ansaloni, L., Moore, E.E., Catena, F., 2024. Surgical stabilization of rib fractures (SSRF): the WSES and CWIS position paper. World J. Emerg. Surg. 19 (1), 33.
Slijper, E.J., 1936. Die Cetaceen. Vergleichend-anatomisch und systematisch. Martinus Nijhoff, The Hague.
Spiegler, D., Gürs, K., 1996. Der miozäne Glimmerton von Groß Pampau, Schleswig-Holstein (Mollusken, Foraminiferen und Bolboformen). Meyniana 48, 135–164.
Taimela, S., Kujala, U.M., Orava, S., 1995. Two consecutive rib stress fractures in a female competitive swimmer. Clin. J. Sports Med. 5, 254–257.
Warden, S.J., Gutschlag, F.R., Wajswelner, H., Crossley, K.M., 2002. Aetiology of rib stress fractures in rowers. Sports Med. 32 (13), 819–836.
Zarqane, H., Viala, P., Dallaudière, B., Vernhet, H., Cyteval, C., Larbi, A., 2013. Tumors of the rib. Diagn. Interv. Rad. 94, 1095–1108.