Ose*dax* borings in fossil early Oligocene marine bird bones

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Aims
Ose*dax* is a marine annelid (family Siboglinidae) that consumes bones on the seafloor (Rouse et al. 2004). Its evolutionary origin and the range of substrates that it is able to consume are still unclear (Glover et al. 2008; Jones et al. 2008; Vrijenhoek et al. 2008, 2009). Using molecular clock estimates, its origin has been linked to the Cenozoic rise of whales (Rouse et al. 2004), recently supported by the discovery of fossil traces of *Ose*dax* in Oligocene whale bones (Kiel et al. 2010). Using an alternative calibration for the molecular clock, however, a Cretaceous origin also seems possible (Vrijenhoek et al. 2009). In this case, *Ose*dax* might have consumed bones of large marine reptiles such as plesiosaurs and mosasaurs and after their extinction at the end of the Cretaceous it was suggested (Vrijenhoek et al. 2009) that bones of turtles, marine crocodiles, and perhaps large fishes could have been utilized. Although the bacterial symbionts that provide *Ose*dax* with nutrition can survive on collagen and lipids as sole carbon sources (Goffredi et al. 2007), there was no evidence so far that *Ose*dax* consumes anything other than mammalian bone. Here, we show that *Ose*dax* colonized bones of large, flightless marine birds in the early Oligocene.

Method
The fossilized bones of the penguin-like bird *Tonsala hildegardae* (family Plothopteridae) were extracted from the enclosing rock by acid etching. One specimen was scanned using the SkyScan 1172 device of the experimental and theoretical petrology group at Kiel University with a beam energy of 70 kV, a flux of 141 µA and a copper-aluminum filter with a resolution of 8 µm using a 360-degree rotation with a step size of 0.75 degrees. Image analysis and volume rendering was done using the SkyScan software CT-analysre.

Results
Many of the bones show significant corrosion (Goedert and Cornish 2002), and almost all of the bones have at least a few boreholes. Protruding edges of some bones are corroded to the extent that much of the smooth surface has been corroded away, exposing the trabecular bone underneath (Fig. 1b). The bones also show scrape marks most likely produced by scavenging sharks. Boreholes are widely scattered on some of the bones, especially on the femora and tibiotarsi where they are restricted to the bone shaft and are absent from the more dense proximal and distal surfaces. The pelvis has a number of widely distributed boreholes, some in very thin bone such as portions of the ilium and ischium. A high density of boreholes (35 borings per square centimeter), some of them fused, with a maximum diameter of 0.3 mm, was seen on the smooth surface of the micro-CT scanned vertebra of *T. hildegardae* (Fig. 1b). Just below the head of the femur of *T. hildegardae*, the density reaches 40 borings per square centimeter.
The micro-CT scans show that these boreholes lead into a network of cavities underneath the surface (Fig. 1d). A regular cavity of the trabecular bone was also penetrated (Fig. 1e). The surface layer above the network of cavities is often only 0.1 to 0.2 mm thick (Fig. 1f). Most holes on the investigated bones do not exceed 0.3 mm in diameter. Exceptions include one hole on the proximal end of a femur of T. hildegardae, which reaches nearly 1 mm in diameter (near top of Fig. 1a), and one hole that reaches 1.5 mm in diameter near the distal end of the femur. Both of these large holes are situated at the transition zone between shaft and the head.

The boreholes and cavities documented here in bones of the early Oligocene pteropod bird *T. hildegardae* resemble those in whale bones from the same strata and those produced by *Osedax* today (e.g., Figs. 1d; 2a in Kiel et al. 2010). Pteropod bones have neurovascular foramina that can be of similar size as boreholes produced by *Osedax*, but they have smooth edges or start as a small sulcus whereas *Osedax* boreholes have sharp edges, as if made by a drill. Borings and cavities produced by other deep-sea invertebrates such as sipunculids, sponges, or bivalves differ in shape from *Osedax* borings (see discussion in Kiel et al. 2010) and from those reported here. Microbes can substantially damage bones in deep water, but their activities affect mainly the surface layer of the bone rather than the interior and individual borings are only a few micrometers in diameter (Allison et al. 1991; Kiel 2008). The borings documented here are thus interpreted as *Osedax* borings.

Compared to *Osedax* borings in Oligocene whale bones those reported here reach significantly higher densities, up to 40 borings per square centimeter in the bird femur compared to a maximum of 15.5 borings per square centimeter on a whale dentary (Kiel et al. 2010). The size of most borings in the bird bones is within the range of those on the whale bones (up to 0.45 mm in diameter), except for the two extremely large borings (up to 1.5 mm in diameter) on the bird femora. The shape of the cavities suggests that the producing *Osedax* species had a branching filiform root like the extant *O. roseus* (Rouse et al. 2008, their Fig. 4b) and the species that attacked Oligocene whale bones (Kiel et al. 2010). The maximum size of an individual specimen of *Osedax* in the bird bones is difficult to determine because all boreholes on the surface lead into interconnected cavities; however, an elongate tunnel (Fig. 1e) most likely produced by a single individual is 3 mm long. This is almost twice as large as the *Osedax* holes from coeval whale bones, which reach a maximum dimension of 1.7 mm (Kiel et al. 2010).
Figure 1. *Osedax* borings in early Oligocene bones of the plotopterid bird *T. hildegardeae*. (a) Femur showing numerous small holes, and a corrosion pit on the upper half. (b) Smooth lateral surface of a vertebra with a neurovascular channel (nvc) in the middle and a high density of *Osedax* borings; numbers indicate the boreholes shown in (d), (e), and (f); lines indicate the positions of the micro-CT scans shown in (c), (e), and (f). (c) Reconstructed image of a micro-CT scan horizontally through the vertebra, bone material (white to gray), holes and cavities (black). (d) Micro-CT-based rendering of the trace fossils, bone material in transparent blue, borings and cavities in yellow. (e), (f) Micro-CT scan images of the vertebra, showing a relatively straight boring that penetrated a regular cavity of the trabecular bone (e) and a cavity with only a thin “roof” of bone material (f); image from Kiel et al. (2011).
Conclusion
The boreholes documented here in fossil marine bird bones provide the first evidence that *Osedax* may be capable of growing on non-mammalian bones and to colonize carcasses as small as 80 cm in length. A possible Cretaceous origin of *Osedax* as suggested by molecular clock estimates was thought to require its ability to grow on fish or reptile bones, for which there is currently no evidence. The Oligocene traces documented here do not provide evidence for a Cretaceous origin of *Osedax*; however, marine birds have existed continuously since the Cretaceous and could thus have, in theory, provided an alternative food source for *Osedax* since that time.

References: