Zoodiversity, **54**(5): 433–438, 2020
DOI 10.15407/zoo2020.05.433

UDC 567.3:597.311.2(519.3)"6235'

NEW EXAMPLE OF *COSMOPOLITODUS HASTALIS* (LAMNIFORMES, LAMNIDAE) FROM THE MIOCENE OF SOUTH KOREA

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New Example of *Cosmopolitodus hastalis* (Lamniformes, Lamnidae) from the Miocene of South Korea. Yun, Ch.- g. — The discovery of an isolated juvenile tooth of an extinct lamnid shark *Cosmopolitodus hastalis* (Agassiz, 1843) from the Duho Formation (middle Miocene), Pohang City, South Korea. This tooth is approximately 11 mm in crown height, suggesting a juvenile affinity of an individual this tooth originated. In life, the shark is estimated to have been approximately less than 2 m in length. This is the second reported fossil record of *C. hastalis* in the Korean Peninsula and the first permineralized fossil remain as well. Although largely undescribed, fossil shark assemblage of the Duho Formation is similar to those of contemporaneous Japanese marine sediments, indicating epipelagic or pelagic sharks were already diversified throughout the East sea during the middle Miocene.

Key words: Lamniformes, Lamnidae, fossil shark, Duho Formation, Pohang, Miocene, South Korea.

Introduction

Lamnidae is a group of large lamniform sharks comprising only three extant genera (*Carcharodon*, *Isurus*, *Lamna*) (Ehret et al., 2009). However, the taxonomic diversity of this group was much higher during the Neogene, as evidenced by numerous fossil records from Neogene marine sediments with worldwide distributions (Ehret et al., 2009, 2013; Cappetta, 2012). Despite the abundance of fossil taxa, the phylogenetic relationships between extinct taxa or their biogeographical distributions remain controversial, which is partly due to the lack of non-dental remains or insufficient detailed descriptions of significant specimens (Ehret et al., 2009, 2013; Cappetta, 2012). Thus, any new descriptions about new or unstudied specimens of lamnid sharks, especially those from hitherto poorly sampled horizons is significant for contributing to clarify these issues.

Lamnid fossils have been discovered from the Neogene marine deposits in Korean Peninsula for many decades but unfortunately, very few of them have been properly described in research articles so far as many of the specimens are often deposited in private local museums or being "buried" in old natural history collections without any paleoichthyological identification (Choi & Lee, 2017; Kim et al., 2018). Up to now, only two Korean lamnid shark fossils had been described in the peer-reviewed scientific articles: one is an isolated tooth crown of *Carcharodon carcharias* from the Plio-Pleistocene Segwipo Formation of Jeju Island (Lee et al., 2014 b) and the other is a tooth mold of *Cosmopolitodus hastalis* from the Miocene Duho Formation of Pohang City (Kim et al., 2018). Unfortunately, while it is unquestionable that these are very significant discoveries, they are all described in Korean so detailed information of them are currently unavailable to international scientific community.

The Pohang Basin is one of the best localities for Cenozoic fish fossils in South Korea, including fossil sharks (Choi & Lee, 2017; Kim et al., 2018). Since Takai (1959) mentioned the presence of *Otodus* (*Megaselachus*) *megalodon* in the Pohang Basin, the number and diversity of lamniform sharks from the Duho Formation has been dramatically increased (Yang, 2013) while only one has been described so far (Kim et al., 2018). In this paper, the author reports a new specimen of *Cosmopolitodus hastalis* from the middle Miocene Duho Formation of South Korea. This is the second occurrence of this taxon in Korean Peninsula that has been recorded so far, and it also represents the first permineralized tooth record as well. The purpose of this paper is to describe the new specimen, discuss its taxonomic implications, and to introduce the fossil sharks from the Duho Formation to the wider paleontological community.

Geological setting

The Pohang Basin is the best exposed and thickest Cenozoic basin in South Korea, and composed of the non-marine Yangbuk and marine Yeonil Group (Jung & Lee, 2009). The Yeonil Group is divided into three formations: The Chunbuk Conglomerate, and the Hagjeon and the Duho Formations in ascending order (Jung & Lee, 2009).

Specimen G03_31001_061 was recovered from the Duho Formation that is exposed at the Chilpo Village, northern Heunghae town, North district of Pohang City in 2005 (fig. 1). The Duho Formation is the uppermost unit of the Yeonil Group, and it is composed of up to 250 m of yellowish brown to dark grey mudstones (Jung & Lee, 2009; Kim & Lee, 2011; Lee et al., 2012). Paleomagnetic studies and a microplankton analysis suggested that the sediments of the Duho Formation were deposited during the middle Miocene (Kim et al., 1993; Chun, 2004) and a SHRIMP U-Pb Zircon geochronological study provided an age between 21.89 ± 1.1 Ma and 21.68 ± 1.2 Ma for the start of the sedimentation (Lee et al., 2014 a). K-Ar dating of the volcanic rocks of the Yeonil Group estimated the age of the group to be about 15 Ma (Lee et al., 1992). The Duho Formation produced a variety of fossils, including plants, invertebrates, micofossils, and vertebrates (Choi & Lee, 2017; Kim et al., 2018). Interpretations about the depositional environment of the Duho Formation vary ranging from a shallow marine environment based on presence of benthic foraminifera and stomatopods (Kim & Choi, 1977; Yun, 1985) to a hemipelagic, deep sea accumulation based on the presence of deep water trace fossils like *Chondrites* and nearly complete fish skeletons with widely open mouths that are suggestive of sudden death caused by oxygen depleted condition (Kim & Paik, 2013; Nam et al., 2019).

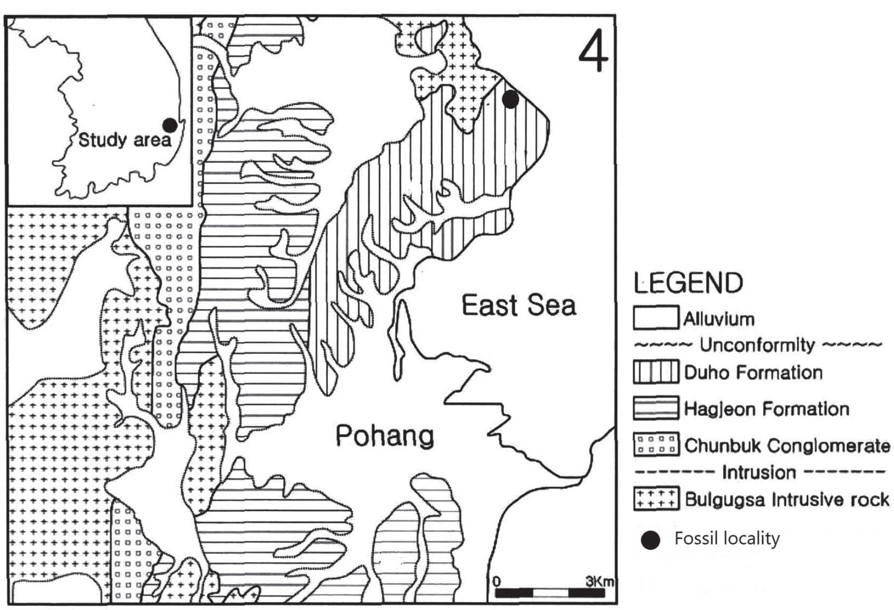

Fig. 1. Geological map of the locality where the specimen was discovered. Modified from Kim & Lee (2011).

Material and methods

The specimen is currently housed at the Kyung Hee University Natural History Museum, and bears the number G03_31001_061. Unfortunately, due to lack of appropriate preparation facilities at the museum and concerning that preparation without an appropriate tool may damage the specimen (especially considering that there are some cracks at the mesial part of the root), the tooth was not removed from the matrix and only the exposed parts are described here. Specimen G03_31001_061 was photographed using a NIKON D7100 digital camera at the museum.

For comparison with known Neogene lamniform sharks in the region, the data of Kuga (1985), Karasawa (1989) and Cappetta (2012) were used. Tooth nomenclature used in this study follows that of Kuga (1985).

Systematic Paleontology

Clade Lamnidae Müller and Henle, 1838
Genus †*Cosmopolitodus* Glikman, 1964
†***Cosmopolitodus hastalis*** (Agassiz, 1843)

Description. Specimen G03_31001_061 is a fossilized lamnid shark tooth that is still embedded in the matrix (fig. 2). A large portion of the labial surface and slight lingual part of crown apex are exposed. The tooth only bears a single cusp and lateral cusplets are absent, although a weakly developed mesial enameloid shoulder that overhangs the mesial tooth branch is present. The crown is wide, triangular and seemingly flattened labiolingually. The height of the crown is 11 mm, and the maximum width of the exposed portion is 8 mm which results in an estimated maximum width of the crown about 10 mm. The apex of the crown is strongly inclined distally, with the mesial edge being straight basally but convex apically and mostly straight, but proximally concave distal edge. The cutting edges are smooth and devoid of any serrations. The labial surface of the crown is flat, although the exposed lingual portion of the crown apex is slightly convex. A mesial portion of the root is exposed in G03_31001_061, and it is only slightly more extended mesially than the basal limit of the crown. The asymmetrical nature and morphology of the crown suggests this tooth was derived from the posterolateral position of the right palatoquadrate cartilage.

Remarks. The combination of unserrated cutting edges, absence of cusplets, triangular, wide, and labiolingually flattened morphology of the crown indicates that the tooth belongs to *Cosmopolitodus hastalis* (e. g., Kuga, 1985; Karasawa, 1989; Kim et al., 2018). As similar tooth morphology also occur in various other lamniform sharks including *Anotodus retroflexus*, *Cosmopolitodus plicatilis*, *Cosmopolitodus* "*xiphodon*", *Isurus oxyrinchus* and *Isurus planus* (e. g., Kuga, 1985; Karasawa, 1989; Cappetta, 2012), rejection of the referral of G03_31001_061 to these taxa is discussed here. On the whole, the observed tooth differs from the upper lateral tooth of *Anotodus retroflexus* in being more distally hooked, bearing a longer mesial enameloid shoulder and lacking a horizontal mesioventral margin of the root (Cappetta, 2012: Fig. 223I). Of note, *Anotodus retroflexus* may be a *nomen dubium* (Purdy et al., 2001). *Cosmopolitodus* "*xiphodon*" is a *nomen dubium* as the originally published stratigraphic information on the type specimens is incorrect (e. g., Ehret et al., 2013; Ebersole et al., 2017) so any new material should not be referred to this taxon. It is assumed that *Cosmopolitodus plicatilis* includes

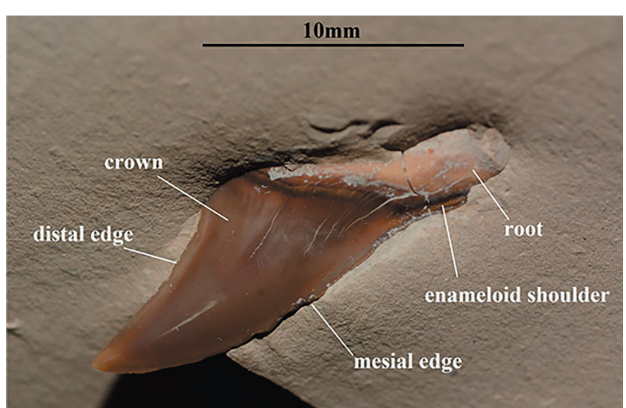

Fig. 2. A magnified labial view of G03_31001_061, a juvenile *Cosmopolitodus hastalis* tooth from the Duho Formation (middle Miocene).

the materials that were previously identified as "*xiphodon*" (Collareta et al., 2017). Regardless of the possibility that *Cosmopolitodus plicatilis* may represent a variation of *Cosmopolitodus hastalis* (cf. Ehret et al., 2013), specimen G03_31001_061 highly differs from much more mesiodistally broad, nearly symmetrical teeth of juveniles and adults of *Cosmopolitodus plicatilis* (Collareta et al., 2017). G03_31001_061 differs from upper lateral teeth of *Isurus oxyrinchus* in having more convex mesial edge, much concave distal edge and longer, narrower mesial enameloid shoulder (Long and Waggoner, 1996: Fig. 2 B; Boessenecker, 2011: Fig. 3.27). G03_31001_061 bears a weak enameloid shoulder on the mesial edge, which is more characteristic of *Cosmopolitodus hastalis* rather than *Isurus planus* which lack such feature (Kuga, 1985; Karasawa, 1989; D. Ehret, pers. comm.). Furthermore, the crown of G03_31001_061 is more constricted and less distally curved than *Isurus planus* which possess very wide, strongly inclined crown (Kuga, 1985; Karasawa, 1989). Finally, *Isurus planus* might represent a variation of *Cosmopolitodus hastalis* (Karasawa, 1989). Based on these observations, the author refers this specimen to *Cosmopolitodus hastalis*. The taxonomy of *hastalis* is highly controversial, which is beyond the scope of this paper: here, *hastalis* is considered as a species of the genus *Cosmopolitodus* (Ebersole et al., 2017). Nevertheless, G03_31001_061 represents the second record of *Cosmopolitodus hastalis* in Korean Penninsula after Kim et al. (2018).

Discussion

Cosmopolitodus hastalis is closely related to modern *Carcharodon carcharias*, and body sizes of both taxa are also similar as well, as they are more than 6 m in large adults (Ehret et al., 2013). Scaling based on measurements of posterolateral upper teeth of 12 *Carcharodon carcharias* individuals provided by Shimada (2003), it is likely that a total body size was less than 2 m for G03_31001_061, suggesting that this specimen is from a juvenile. Moreover, the crown is more gracile than adult teeth of *Cosmopolitodus hastalis*, which also supports the young ontogenetic status (Collareta et al., 2017). Juveniles of *Cosmopolitodus hastalis* are thought to mainly lived and foraged in shallow productive marine environments (Collareta et al., 2017), just like other extinct and extant lamniform sharks. Collareta et al. (2017) reported a skeleton of a juvenile *Cosmopolitodus hastalis* with stomach contents composed of small to medium sized fish remains, and suggested juveniles of this taxon mainly foraged on fishes like modern lamniforms. Various fossil fishes were reported from the Duho Formation (Choi & Lee, 2017; Kim et al., 2018) so it is probable that *Cosmopolitodus hastalis* juveniles of the Duho Formation also foraged on this fishes as well. However, given that juvenile lamniforms also occasionally feed on marine mammals (Grainger et al., 2020), the presence of small cetaceans in the Duho Formation (Choi & Lee, 2017; Kim et al., 2018) suggests also occasional foraging on marine mammals.

Although the vast majority of fossil shark remains that were excavated from the Duho Formation remain undescribed, at least the occurrence of several fossil taxa had been mentioned in the literature and conference abstracts. These records are summarized here, to provide a reconstruction of the fossil shark diversity of the Duho Formation fauna, though this should be considered as preliminary pending on official descriptions on these materials. Kim et al. (2009) mentioned the presence of *Galeocerdo* sp., and Takai (1959) mentioned the occurrence of *Otodus* (*Megaselachus*) *megalodon* in the Duho Formation. Additionally, *Isurus* sp., *Carcharhinus* sp., and *Otodus* sp. are noted as present at the Duho Formation by Kim and Kim (2011). Lastly, the photograph of the shark teeth provided in Yang (2013) clearly suggests that these teeth are assignable to *Isurus planus* (pers. obs.). In summary, there were multiple shark taxa including *Carcharhinus* sp., *Cosmopolitodus hastalis*, *Galeocerdo* sp., *Isurus* sp., *Isurus planus*, *Otodus* sp., and *Otodus* (*Megaselachus*) *megalodon* in the Duho Formation fauna. Of note, Choi & Lee (2017) listed *Otodus obliquus* as present in the Duho Formation, but definite records of this taxon only occur in the Paleocene to Eocene deposits of Europe, North America, Africa and Asia (Cappetta, 2012). Thus, it is very likely that this is a misidentification, possibly with other otodontid or lamniform taxa.

This reconstructed shark assemblage of the Duho Formation is compared with contemporaneous fossil shark assemblages in the center of the Japanese archipelago, to estimate the diversity and distribution of the fossil sharks during the middle Miocene of the western Pacific. It is found that the assemblage of the Duho Formation is largely similar to Japanese assemblages, as species of *Carcharhinus*, *Cosmopolitodus hastalis*, species of *Galeocerdo*, species of *Isurus* such as *planus*, and *Otodus* (*Megaselachus*) *megalodon* are quite common in Japanese localities, although this is expected as these are cosmopolitan taxa (Karasawa, 1989; Yabumoto and Uyeno, 1994). Although the number of elasmobranch species in Japanese assemblages generally exceed that of the Duho Formation (Karasawa, 1989) it is expected that additional specimens of unrecorded taxa would be excavated in the Duho Formation in the future especially considering that fossil shark remains of the Pohang Basin are largely unsampled. Regardless, the similarity of the shark fossil fauna of the Duho Formation with those in central Japan strongly suggests that such epipelagic or pelagic sharks like carcharhinids and lamniforms (Kajiura et al., 2010), already diversified throughout the East sea of the middle Miocene when this sea was at the stage of early development and expansion (Pavlyutkin et al., 2016). Possibly, this wide distribution of sharks was affected by sea temperature increases throughout the Early Miocene to the middle Miocene by the invasion of warm oceanic currents in this area (Pavlyutkin et al., 2016), especially considering that carcharhinids and laminiforms inhabit warm-temperate waters (Cappetta, 2012).

The author thanks Beom-Cheol An and Do-Hong Kim for the discovery of such scientifically important specimen and permission for this study. Discussions with Jim Bourdon and Dana Ehret regarding about the specimen were also helpful. This manuscript was benefited by reviews from Jürgen Kriwet and an anonymous reviewer.

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Received 13 July 2020
Accepted 26 October 2020