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A large fossil baleen whale from the Shikiya Formation (early middle Miocene) of Wakayama, Japan

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Abstract. A new large Chaeomysticeti indet., WMNH-Ge-1140240005 from the Shikiya Formation of Kumano Group (early middle Miocene; about 16 to 15 Ma) of Wakayama, Japan is described here. It preserves a large rostrum (about 50 cm width at the base of the rostrum), which has gently tapered lateral margins of the rostrum, narrow mesorostral groove at the level of the narial fossa, and wide premaxillae and maxillae. There are no diagnostic features pertaining to the specimen at the family level, but it is comparable to "cetotheres" *sensu lato* such as *Pelocetus calvertensis* and *Diorocetus hiatus* by having wide premaxillae that occupy 1/3 width of the rostrum anterior to the narial fossa in dorsal view, which implies that WMNH-Ge-1140240005 is a possible member of "cetotheres" *sensu lato*. Its size is possibly between the two large species *Pelocetus calvertensis* and *Diorocetus hiatus* of the early middle Miocene, and larger than the reported middle Miocene mysticete specimens from Japan ("*Diorocetus*" *chichibuensis*, "*Diorocetus*" *shobarensis*, *Parietobalaena* sp. (SMNH-VeF-62)). The rostral width of WMNH-Ge-1140240005 suggests that this animal was medium-sized compare to extant species, but the largest in the class of baleen whales of its time.

Key words: Caeomysticeti, "cetotheres" *sensu lato*, Kumano Group, Langhian, Mysticeti

Introduction

Modern baleen whales, mysticetes, are the largest animals on Earth. However, the largest mysticetes from the Oligocene to middle Miocene were less than 10 meters long (Slater *et al.*, 2017; Tsai and Kohno, 2016). The causes of gigantism of the Mysticeti have been thought to be the emergence of large predators since the early middle Miocene (Lambert *et al.*, 2010), increasing nearshore productivity from the late Miocene (Pyenson and Vermeij, 2016), the onset of upwelling regimes of the late Pliocene (Slater *et al.*, 2017), efficiency of filter feeding (Friedman, 2012; Potvin *et al.*, 2012), and long- distance migration related to iron-mediated changes in glacial marine productivity (Marx and Fordyce, 2015). Tsai and Kohno (2016) suggested that "intrinsic factors" such as developmental constraints were responsible.

Several middle Miocene mysticetes are known from Japan, such as "*Diorocetus*" *chichibuensis*, "*Diorocetus*" *shobarensis*, *Parietobalaena* sp. (SMNH-VeF-62), *Taikicetus inouei* and *Pelocetus* sp. (Egashira and Kimura, 1998; Kimura *et al.*, 2007; Kimura and Ozawa, 2002; Kimura *et al.*, 1998; Otsuka and Ota, 2008; Tanaka *et al.*, 2018; Yoshida *et al.*, 2003). All of them belong to an extinct mysticete group, "cetotheres" *sensu lato* of Marx *et al.* (2017). Among them, only *Taikicetus inouei* (the skull preserves the median line and right side of the zygomatic process) and *Pelocetus* sp. (HMN-F00003) attain a skull width of about 60 cm, and their estimated body lengths are about 6 meters using the Pyenson and Sponberg (2011) formula for stem Balaenopteroidea. Tsai (2017) reported a fetal specimen of a middle Miocene whale, *Parietobalaena yamaokai* of Otsuka and Ota (2008), and estimated its size at adulthood as possibly over 10 meters.

Here, we report a Mysticeti rostrum and mandible from the early middle Miocene, Shikiya Formation, Kumano Group of Wakayama, Japan. The specimen is fragmentary, but the rostral width suggests that this animal was medium-sized compared to extant species, but the largest in the class of baleen whales of its time.

Institutional abbreviations.—AMP, Ashoro Museum

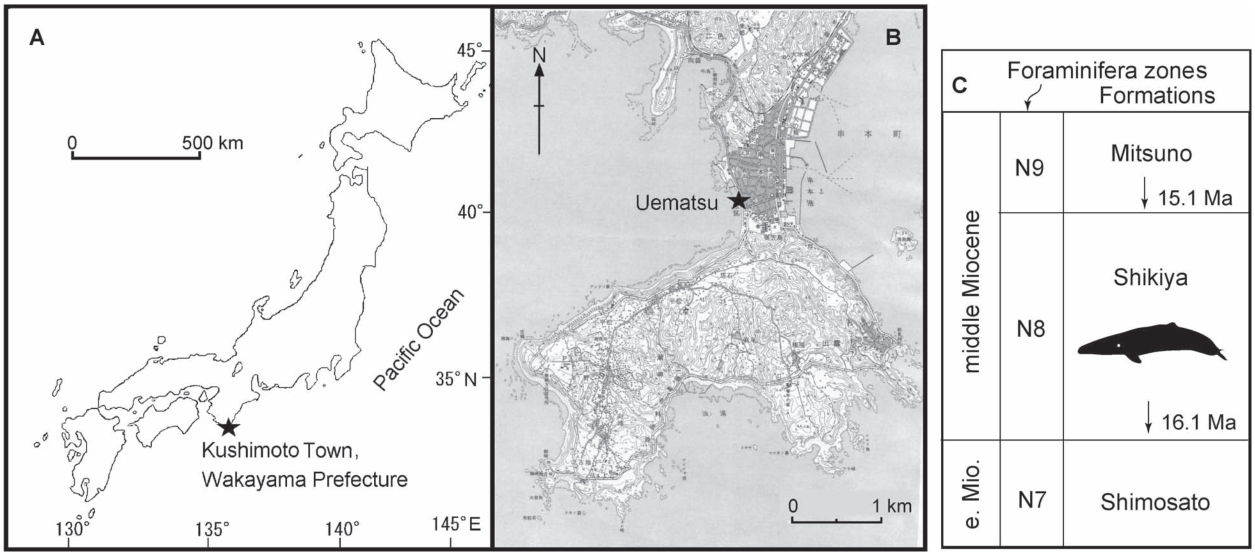

Figure 1. **A,** locality map; **B,** detailed locality map, modified a map from Geospatial Information Authority of Japan; and **C,** stratigraphic classification of the Kumano Group, modified from Honda *et al.* (1998).

of Paleontology, Hokkaido, Japan; HMN, Hiwa Museum of Natural History, Hiroshima, Japan; OU, Geology Museum, Dunedin, University of Otago, New Zealand; SMNH, Saitama Museum of Natural History, Saitama, Japan; USNM, Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington, DC, USA; WMNH, Wakayama Prefectural Museum of Natural History, Wakayama, Japan.

Systematic paleontology

Order Cetacea Brisson, 1762
Unranked taxon Neoceti Fordyce and de Muizon, 2001
Suborder Mysticeti Gray, 1864
Infraorder Chaeomysticeti Mitchell, 1989
Chaeomysticeti fam., gen. et sp. indet.

Figures 2, 3, Table 1

Referred specimen.—WMNH-Ge-1140240005, a large rostrum and a middle part of a left mandible was collected by Yukio Sako in 1973, and was prepared by one of the authors, Masaaki Ohara and preparators of WMNH.

Remarks.—WMNH-Ge-1140240005 is identified as Chaeomysticeti by lacking teeth in the maxilla and mandible, and in having the palatal foramina and sulci, the palatal keel and a dorsoventrally flattened maxilla. WMNH-Ge-1140240005 is comparable to "cetotheres" *sensu lato* such as *Pelocetus calvertensis* and *Diorocetus hiatus* by having wide premaxillae, which occupy 1/3 width of the rostrum, anterior to the narial fossa in dorsal view. The size of WMNH-Ge-1140240005 is intermediate between the two species; about 80% of the type of *Pelocetus calvertensis* (USNM11976) and about 120% of the matured referred specimen of *Diorocetus hiatus* (USNM23494) (see more in Discussion).

Table 1. Measurements in cm of the skull and left mandible, WMNH-Ge-1140240005, Chaeomysticeti indet. The asterisk (*) means restored measurement from the right-side one.

	cm
total preserved length	110.0
maximum preserved width	50.0
rostrum width at antorbital notch	52.0*
maximum width of vomer	13.0
maximum height of vomer	12.0
maximum length of premaxilla	84.5
maximum width of right premaxilla	6.0
maximum width of premaxillae	15.0
mandible	
total preserved length	90.0
maximum height	9.0
maximum width	5.0

Locality.—WMNH-Ge-1140240005 was dug up from a cliff at so-called Sugano-hama of Uematsu, Kushimoto Town, Wakayama Prefecture, Japan (Figure 1A, B): coordinates 33°27′54.34″N, 135°46′32.71″E .

Horizon and age.—The Kumano Group is about 4000

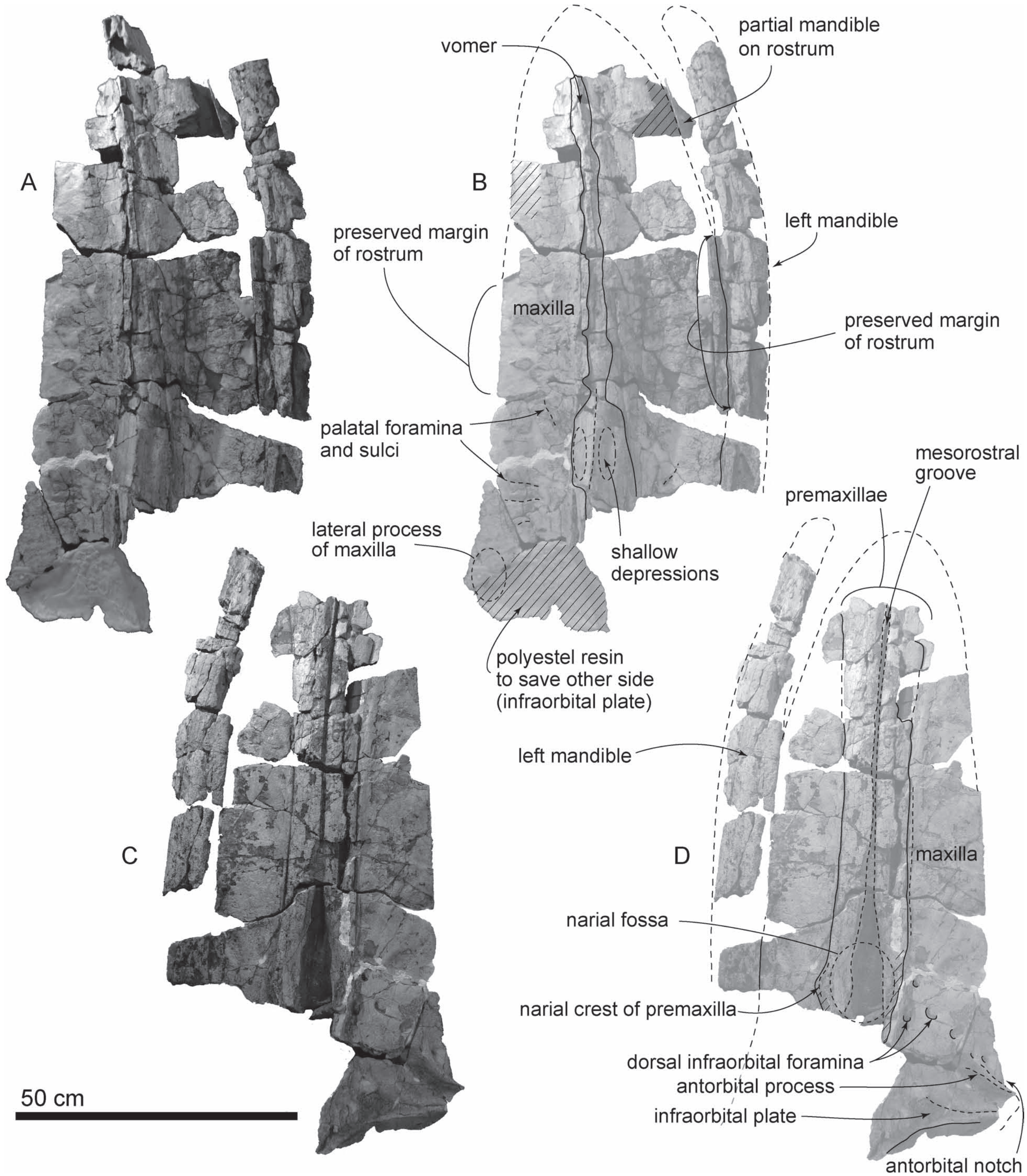

Figure 2. The skull and left mandible, Chaeomysticeti indet., WMNH-Ge-1140240005. **A, B,** ventral view; A, photo; B, key features; **C, D,** dorsal view; C, photo; D, key features.

m thick, and contains three formations, namely the Shimosato, Shikiya and Mitsuno formations from bottom to top (Hisatomi, 1981). The original horizon of WMNH-Ge-1140240005 is within the Shikiya Formation, which is the only exposed sediment at the locality (Figure 1).

The Shikiya Formation is equivalent to the plank-

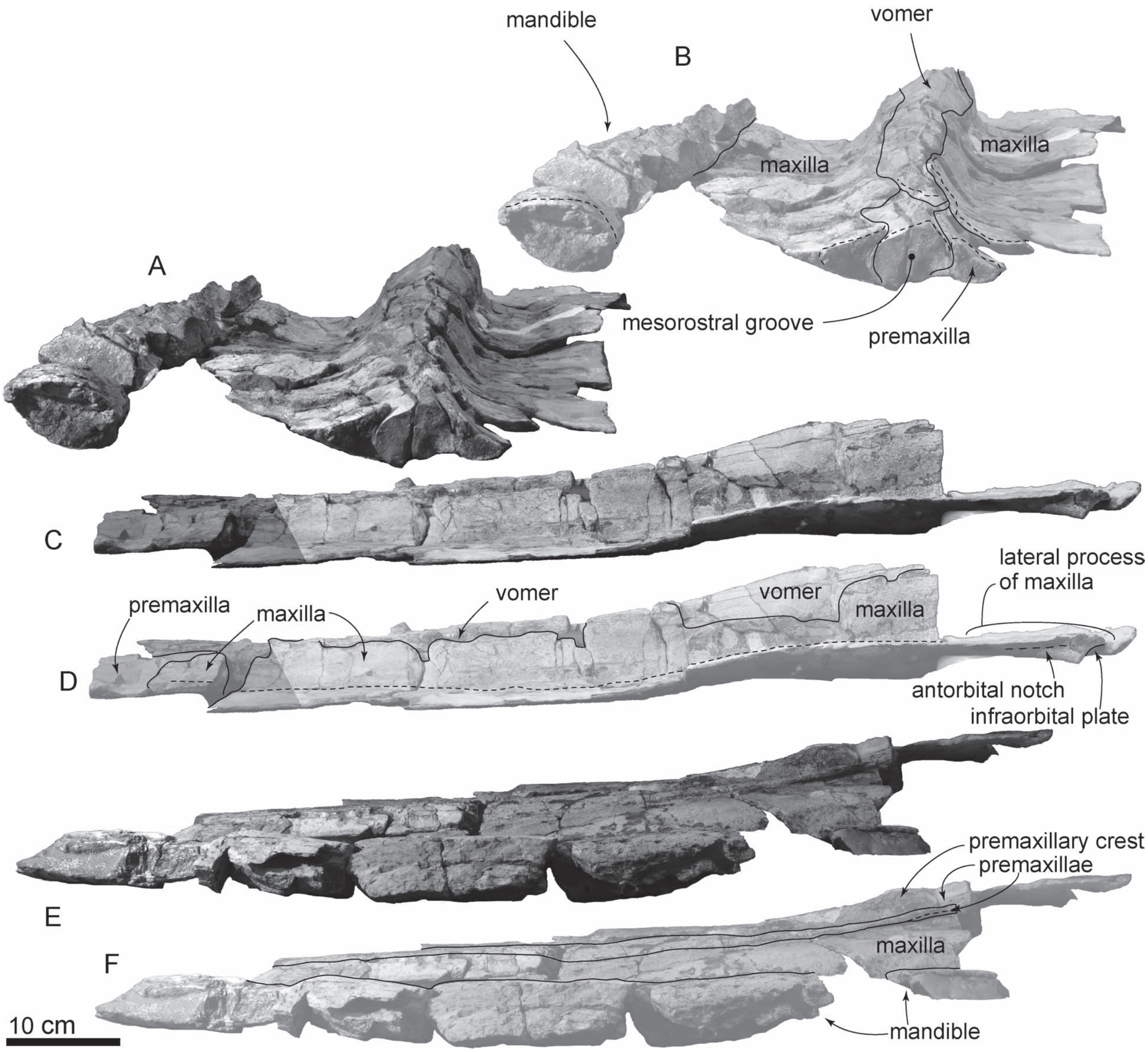

Figure 3. The skull and left mandible, Chaeomysticeti indet., WMNH-Ge-1140240005. **A, B,** anterior view; A, photo; B, key features; **C, D,** right lateral view; C, photo; D, key features; **E, F,** left lateral view; E, photo; F, key features. The smaller scale bar for C to F.

tonic foraminiferal zone N8 of Blow (1969) (Hoshi *et al.*, 2003). Some key foraminiferal species of Zone N8, *Lepidocyclina*, *Miogypsina*, *Globigerinoides japonicus*, *Globigerinoides sicanus*, *Praeorbulina glomerosa curva*, *Praeorbulina transitoria*, *Globoquadrina* cf. *langhiana* and *Globorotalia quinifalcata* were reported by Ikebe *et al.* (1975), but not the genus *Orbulina*, which is the diagnostic taxon for N9 (Hoshi *et al.*, 2003). The emergence of *Praeorbulina glomerosa* is estimated as 16.1 Ma, and the bottom of N9 is estimated as 15.1 Ma (Berggren *et al.*, 1995; Saito, 1999). Thus the estimated age of the Shikiya Formation is about 16 to 15 Ma (the early middle Miocene).

The Shikiya Formation has been regarded as forearc-basin sediments (Hisatomi, 1981). The basin was shallower in the north and inclined to the south. Deposits of the Shimosato and Shikiya formations filled the basin. The fossil locality was in the southern part of the basin, which was the deeper part on the shelf. A gastropod subspecies, *Entemnotrochus rumphii kushimotoensis* from the locality and formation was described by Tomida and Sako (2016). The study suggested that the taxon was accompanied by lower sublittoral to bathyal mollusks and lived in a tropical marine climate. The fossil fauna from

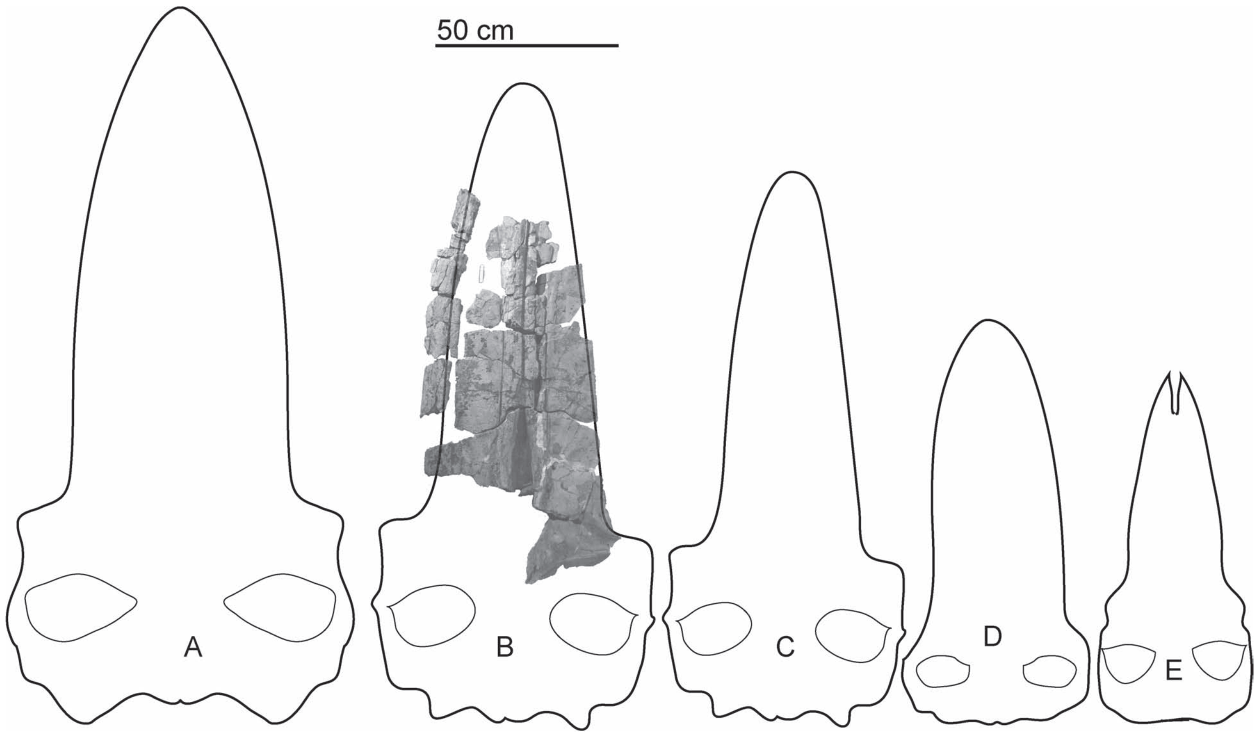

Figure 4. Size comparisons. **A,** *Pelocetus calvertensis*, type modified from Kellogg (1965); **B,** Chaeomysticeti indet., WMNH-Ge-1140240005 of this study; **C,** *Diorocetus hiatus*, mature referred specimen USNM 23494 modified from Kellogg (1968); **D,** "*Diorocetus*" *shobarensis*, type modified from Otsuka and Ota (2008); **E,** *Isanacetus laticephalus*, type modified from Kimura and Ozawa (2002).

the area is comparable to the tropical Kurosedani Fauna (Honda *et al.*, 1998).

General description

Morphological terms follow Mead and Fordyce (2009).

Estimated body size.—The estimated body size of WMNH-Ge-1140240005 is calculated using the Pyenson and Sponberg (2011) formula for stem Balaenopteroidea, which utilizes the bizygomatic width. The preserved width at the base of the rostrum is 52 cm. The zygomatic process is not preserved, but if WMNH-Ge-1140240005 had similar proportions to *Diorocetus hiatus* (USNM 23494) and *Pelocetus calvertensis* (USNM 11976) (see Remarks), the zygomatic width was about 70 cm. Using the estimated bizygomatic width (70 cm), the estimated body size of WMNH-Ge-1140240005 was about 7 m (and at least larger than 5.5 m). The size can be stated as "large" sensu Tsai and Kohno (2016), i.e. more than 5 m long.

Rostrum.—WMNH-Ge-1140240005 has a broad and flat rostrum. The palatal keel is formed by the maxilla and vomer, and runs anteroposteriorly on the medial line of the ventral surface of the palate. Because of deformation, the rostrum is slightly flattened and skews to the left. The surface of the specimen is eroded.

Premaxilla.—The premaxillae are wide and occupy 1/3 width of the rostrum in dorsal view (Figure 2C, D). The preserved anteriormost part of the premaxilla is anteriorly widened. The premaxillae are very close anteriorly (about 1 cm), but their posterior ends diverge and form the narial fossa. At the level of the latter, the lateral margin of each premaxilla rises and forms an anteroposteriorly long crest near the narial fossa, termed the narial crest of the premaxilla [new term], which projects dorsolaterally leaving open a shallow depression on the medial surface for the narial fossa. A possible homologous structure can be seen on many mysticete specimens, such as extant balaenopterids, *Cetotherium riabinini* (see Figure 6 of Gol'din *et al.*, 2014), *Tiucetus rosae* (see Figure 2 of Marx *et al.*, 2017) and *Incakujira anillodefuego* (see Figure 4 of Marx and Kohno, 2016) as a mediolaterally narrow ridge.

Maxilla.—The maxilla is dorsoventrally thin; especially the lateral margin is thinner than the medial part of the maxilla. In dorsal view, the maxilla has an anteroposteriorly long depression medially for the contact with the premaxilla. At the level of the narial fossa, several dorsal infraorbital foramina open continuously medial to the lateral process of the maxilla. At the anterior margin of the lateral process, the antorbital notch runs transversely.

Posterior to the notch, on the dorsal surface of the maxilla, there is a depressed area for the frontal in part of the orbital plate (Miller, 1923) of the maxilla. The area is very small and even the longest distance is 8.7 cm. Ventrally, the maxilla covers the lateral surface of the vomer. Posteriorly, the maxilla increases in height (about 13 cm at the preserved posterior end) (Figure 2B, D). Ventrally, the palatal sulci are located about at the level of the narial fossa, and are very faint (about 0.4 cm deep and 1.0 cm wide).

Vomer.—The vomer forms an anteriorly shallower and posteriorly deeper, dorsally widely opened mesorostral groove. The ventral margins of the maxilla are broken, so it is difficult to know whether the vomer is exposed ventrally or not. The posterior end of the vomer has a couple of shallow depressions beside an anteroposteriorly long ridge. These structures might be for contact with the maxillae.

Mandible.—The left mandible weakly curves, and does not show teeth. Its anterior and posterior ends were preserved in contact with the rostrum (Figure 2). The broken cross section shows dorsoventrally as a long ellipse, and its ventral side is sharper than the dorsal side. The medial side of the mandible is flatter.

Discussion

Comparisons to middle/late Miocene whales.—Figure 2 of Marx and Fordyce (2015), phylogeny and geological time scale of the Mysticeti shows that there are only three families (Balaenidae, Cetotheriidae, Balaenopteridae), and so-called "cetotheres" *sensu lato* (Marx *et al.*, 2017) during the middle to late Miocene.

A stem balaenid, *Peripolocetus vexillifer* is known from the Langhian (early middle Miocene) of the Temblor Formation of California (Kellogg, 1931), but does not preserve a comparable rostral part. The balaenids are characterized by having an arched and narrow rostrum (Marx *et al.*, 2016), which is different from the one of WMNH-Ge-1140240005.

Early members of the Cetotheriidae, *Joumocetus shimizui* and *Titanocetus sammarinensis* have posteriorly wider triangular rostra (Capellini, 1901; Kimura and Hasegawa, 2010), which are different from the gently tapered rostrum of WMNH-Ge-1140240005. *Kurdalagonus mchedlidzei, Metopocetus durinasus, "Cetotherium" megalophysum* and *Cephalotropis coronatus* do not have preserved rostra (Cope, 1896; Tarasenko and Lopatin, 2012), but their preserved frontals imply that the base of their rostra was obviously smaller than the one of WMNH-Ge-1140240005. The late Miocene cetotheriids, *Cetotherium riabinini* and *Brandtocetus chongulek* are smaller than WMNH-Ge-1140240005 (the two species' bizygomatic width is about 40 to 30 cm: see Table 1 of Gol'din and Startsev (2014)). *Cetotherium riabinini* shows a much narrower premaxilla and base of the rostrum (see Gol'din *et al.*, 2014).

There are two early members of the Balaenopteridae in the middle Miocene. *"Balaenoptera" ryani* of Hanna and McLellan (1924) does not preserve a comparable rostral part, but is much smaller than WMNH-Ge-1140240005. *Plesiobalaenoptera quarantellii* of Bisconti (2010) shows an anteriorly gradually tapering rostrum, and its width is about 40 cm, which is about 20% smaller than that of WMNH-Ge-1140240005. The late Miocene whale *Uranocetus gramensis* was placed basal to the Balaenopteridae (Marx *et al.*, 2017; Steeman, 2009; Tanaka *et al.*, 2018). *Uranocetus gramensis* has a very similar size of the width of the base of the rostrum (51.7 cm, Steeman, 2009) and morphology of wide maxilla and premaxilla. However, *Uranocetus gramensis* shows a stronger degree of mesorostral groove expansion at the level of the narial fossa. In addition, *Uranocetus gramensis* has the premaxilla, which has a weakly curved sigmoidal lateral margin. On the other hand, WMNH-Ge-1140240005 shows a weakly curved C-shaped lateral margin of the premaxilla.

WMNH-Ge-1140240005 is comparable to the two "cetotheres" *sensu lato Pelocetus calvertensis* and *Diorocetus hiatus* of the early middle Miocene (see Remarks). WMNH-Ge-1140240005 is comparable to *Pelocetus calvertensis* in the premaxillae being wide in dorsal view. The genus *Pelocetus* includes a second species, *Pelocetus mirabilis*, which was established by Ginsburg and Janvier (1971) using a mandible from France. The first Northwestern Pacific record of the genus *Pelocetus, Pelocetus* sp. (HMN-F00003), was reported from the middle Miocene, Korematsu Formation of Hiroshima, Japan by Kimura *et al.* (2007). *Pelocetus* sp. (HMN-F00003) and WMNH-Ge-1140240005 are possibly more or less the same size based on the preserved bizygomatic width. WMNH-Ge-1140240005 differs from *Pelocetus calvertensis* in having a narrower mesorostral groove, especially at the level anterior to the narial fossa, and wider premaxillae.

Several other supposed members of "cetotheres" *sensu lato* are "*Aglaocetus*" *patulus*, "*Diorocetus*" *chichibuensis*, "*Diorocetus*" *shobarensis*, *Isanacetus laticephalus*, *Parietobalaena campiniana*, *Parietobalaena palmeri*, *Parietobalaena* sp. (SMNH-VeF-62), *Pinocetus polonicus*, *Uranocetus gramensis*, *Parietobalaena yamaokai*, *Tiphyocetus temblorensis*, *Thinocetus arthritus* and undescribed OU 22705 (Marx *et al.*, 2017). These species show a smaller size and much more tapered rostrum compared to WMNH-Ge-1140240005, except for *Uranocetus gramensis*, *Diorocetus hiatus* and "*Diorocetus*" *shobarensis*. A large-sized "*D.*" *shobaren-*

sis established by Otsuka and Ota (2008) is similar to WMNH-Ge-1140240005 by having a wide rostrum. However, the width of the premaxillae on the rostrum is much narrower than in WMNH-Ge-1140240005. The size of WMNH-Ge-1140240005 is about 120% of "*Diorocetus*" *shobarensis*, HMN-F00005 (Figure 4).

Gigantism of mysticetes.—All reported middle to late Miocene "cetotheres" *sensu lato* from Japan (*Joumocetus shimizui*, *Parietobalaena yamaokai*, "*Diorocetus*" *chichibuensis*, *Isanacetus laticephalus*, and *Taikicetus inouei*) are smaller compared to WMNH-Ge-1140240005. Tsai (2017) reported a potentially large but juvenile specimen of *Parietobalaena yamaokai* from the middle Miocene of Hiroshima, Japan. However, WMNH-Ge-1140240005 is much larger than the type subadult specimen, HMN-F00022, which is about the same size as *Isanacetus laticephalus* (see Figure 4E). There are two more similarly large-sized (compared to WMNH-Ge-1140240005) Miocene mysticetes known: *Pelocetus* sp. (HMN-F00003) as discussed above, and a "cetothere" *sensu lato* (MFM 18124) from Gifu Prefecture (Kimura, 2002; Kimura *et al.*, 2000), which has a 177.7 cm long mandible. These facts suggest that, around the coasts of Japan, there was/were large unknown species of the Mysticeti of that size in the early middle Miocene. The size falls between *Pelocetus calvertensis* and *Diorocetus hiatus*. Previously, large-sized "cetotheres" *sensu lato* were known, such as *Pelocetus calvertensis* and *Diorocetus hiatus*. As Tsai and Kohno (2016) mentioned there are multiple origins of gigantism among lineages of the mysticetes. Indeed, recently large-sized fossil mysticetes, Llanocetidae (Fordyce and Marx, 2018) and Aetiocetidae (Tsai and Ando, 2016) of the Oligocene, and Balaenopteridae during the Pleistocene (Tanaka and Taruno, 2019) have been reported. The new material emphasizes that gigantism of "cetotheres" *sensu lato* had already happened in the early Middle Miocene.

Conclusion

Chaeomysticeti indet., WMNH-Ge-1140240005 from the Shikiya Formation of Kumano Group (early middle Miocene) of Wakayama, Japan comprises a large-sized rostrum (50 cm width at the base of the rostrum) and left mandible. The specimen shows gently tapered lateral margins of the rostrum, a narrow mesorostral groove at the level of the narial fossa, and huge width of both premaxillae and the mesorostral groove. There are no diagnostic features pertaining to the specimen, but it can be compared to the two "cetotheres" *sensu lato Pelocetus calvertensis* and *Diorocetus hiatus* by having wide premaxillae, which occupy 1/3 width of the rostrum, anterior to the narial fossa in dorsal view. This implies that WMNH-Ge-1140240005 is a possible member of the "cetotheres" *sensu lato*, but this would require more preserved parts to identify. The estimate size is about 7 meters, which is larger than the reported Middle Miocene mysticetes from Japan ("*Diorocetus*" *chichibuensis*, "*Diorocetus*" *shobarensis*, *Parietobalaena* sp. (SMNH-VeF-62), *Parietobalaena yamaokai* and *Taikicetus inouei*), excepting the not directly comparable *Pelocetus* sp. and *Taikicetus inouei*. WMNH-Ge-1140240005 is additional evidence for large-sized Mysticeti during the middle Miocene in the Northwest Pacific Ocean. The preserved rostral width suggests that this animal was of medium size compared to extant species, but within the largest class of baleen whales (more than 5 m long) for its time (see Figure 6 of Pyenson and Sponberg, 2011). The new material emphasized that gigantism of "cetotheres" *sensu lato* had already happened in the early middle Miocene.

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Author contributions

Y. T. conceptualized this study and wrote the original draft. M. O. and T. K. contributed discussion and revised the draft.