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Fossil lateral arm plates of *Stegophiura sladeni* (Echinodermata: Ophiuroidea: Ophiurida) from the Middle Pleistocene of Japan

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Abstract. Disarticulated fossil lateral arm plates of brittle stars from the Middle Pleistocene Miyata Formation, Miura, Kanagawa Prefecture, eastern Japan, are described. They are assigned to *Stegophiura sladeni* on the basis of their microstructural morphology. This is the first description based on disarticulated fossil lateral arm plates of brittle stars from Japan and intends to induce further exploration of the Japanese ophiuroid microfossil record.

Key words: brittle star, Kanagawa, Miyata Formation, Ophiopyrgidae, *Stegophiura*

Introduction

Brittle stars (Ophiuroidea: Echinodermata) are an abundant component of modern marine benthos from the intertidal zone to the deep see, and from the tropics to the polar regions (Stöhr *et al*., 2012). Approximately 2,100 extant species are currently known (Stöhr *et al*., 2020). Arms of brittle stars are subdivided into segment with a central arm ossicle each, called vertebra, surrounded by dorsal, ventral, and a pair of lateral arm plates (e.g. Okanishi, 2016). The lateral arm plate has a particularly diverse morphological spectrum, thus allowing for a detailed identification down to species level (e.g. Thuy and Stöhr, 2011).

Fossil ophiuroids from Japan have been recorded mainly based on articulated skeletons (e.g. Fujita, 1992; Ishida *et al*., 2011; 2015). The fossil record of disarticulated ossicles from Japan, in contrast, has not gained a lot of attention (Ishida, 2004), although there seems to be a high potential for new discoveries, as illustrated by a recent description of fossil basket star vertebrae (Okanishi *et al.*, 2019). As previously shown on the basis of material from outside Japan, the inclusion of microfossils, and in particular lateral arm plates, can dramatically increase the knowledge of the ophiuroid fossil record in a particular geographic and stratigraphic framework (e.g. Thuy, 2013). We therefore anticipate that the study of ophiuroid microfossils will greatly contribute to a better understanding of Japanese fossil brittle star faunas.

Here, we describe dissociated lateral arm plates retrieved from the sieving residues of sediments from the Pleistocene Miyata Formation in Kanagawa Prefecture, eastern Japan. We identify the species based on comparisons with similar plates extracted from recent specimens.

Material and methods

The Miyata Formation is subdivided into five members, namely Sugaruya Sand Member, Tsukuihama Sandy Gravel Member, Koenbo Sand Member, Sha'ana Tuffaceous Sand Member, and Itchoda Sand Member, in ascending order (Okumura *et al.*, 1977). Fossil ossicles were collected from the Sha'ana Tuffaceous Sand Member (corresponding to the Kamimiyata Tuffaceous Sand Member in Kanie and Ohkoshi, 1981), exposed at Sha'ana dai, Minami-Shita-ura Town, Miura City, Kanagawa Prefecture, about 1 km northwest of Miura-Kaigan railway station of Keikyu Line (139°38′47″E, 35°11′29″N) on 7 March 2012, 13 October, 2013 and 29 December 2017 (see also figure 1 in Okanishi *et al.*, 2019). The geological age of this member was estimated to be Middle Pleistocene (0.325±0.40 based on Electron Spin Resonance method; 1.22–0.44 or 1.02–0.46 Ma based on calcareous nannofossils, small *Gephyrocapsa* Zone or *Pseudoemiliania lacunosa* Zone or CN14a Subzone, respectively: see Yamaguchi *et al.* (1983); Kanie *et al.* (2000); Okanishi *et al.* (2019) for details). More recently, Kasama and Shioi (2019) recognized four levels in this formation, namely units A, D, B, and C in the ascending order, and estimated the Fission track (Ft) age of 0.41±0.07 Ma by using zircon minerals of the Funakubo Tuff (Fn) which is intercalated in the unit C.

Fossil ophiuroid ossicles were recovered from the semiconsolidated, massive sandy mud containing pumice, scoria, pebbles (approximately 2–15 mm in diameter) and molluscan fossils. Most of fossil bivalve shells are disarticulated, but articulated shells of several species, such as *Acila divaricata* and *Cyclocardia ferruginea* also occur in the outcrop. Additional gastropods (*Clio pyramidata*, *Homalopoma amussitatum*, *Niveotectura pallida*, *Puncturella nobilis*, etc.) abundantly occur. All ophiuroid fossils are fully dissociated into individual ossicles.

To collect the ophiuroid ossicles, sediment samples were air-dried and then disintegrated in water and washed using a sieve of 0.063 mm mesh size. Ossicles were handpicked from the residues under a stereo microscope and cleaned with hydrogen peroxide (30% solution). Photographs of Figures 1 to 3 were focus-stacked using the software CombineZM1 v.1.0.0.

Materials are deposited in the National Museum of Nature and Science (NMNS). Morphological terminology and systematics follow Thuy and Stöhr (2011) and O'Hara *et al*. (2018), respectively.

Specimens of Recent *Sterogphiura sladeni* from the collections of the Natural history museum Luxembourg (MnhnL) were used for morphological comparisons with the fossil materials. For a direct comparison of lateral arm plates, a proximal arm portion was cut off, macerated in household bleach, rinsed in distilled water and air-dried (Thuy and Stöhr, 2011). Selected lateral arm plates were mounted on aluminum stubs and gold-coated for scanning electron microscopy at the Natural history museum Luxembourg.

Systematic description

Superorder Euryophiurida O'Hara *et al*., 2017

Order Ophiurida Müller and Troschel, 1840

Suborder Ophiurina Müller and Troschel, 1840

Family Ophiopyrgidae Perrier, 1893

Genus *Stegophiura* Matsumoto, 1915

Species *Stegophiura sladeni* (Duncan, 1879)

Figures 1—3

Fossil material examined. — 72 dissociated lateral arm plates (NMNS PA19912—NMNS PA19983), all originating from bulk samples collected from the Middle Pleistocene Miyata Formation, Miura (Kanagawa, Japan).

Recent comparison materials. — A complete individual and a macerated arm portion (MnhnL

OPH106), from off Choshi, Japan, collected at a depth of 40 m.

Description. —In total 72 lateral arm plates range in size from 1.0 to 4.1 mm in height and 0.5 to 1.5 mm in length. The plates are higher than long, slightly curved, with a convex distal edge and a concave proximal edge (Figures 1A—C; 2A—C). In larger specimens (e.g. NMNS PA19944, 3.8 mm in height and 1.3 mm in length), a large vertically elongated, conspicuous ridge runs along the proximal edge of the internal side (Figure 1A). Up to six well defined, oval spurs composed of more densely meshed stereom form a vertical row parallel to the distal edge of the internal side (Figure 1B). A large tentacle notch opens on the ventro-distal edge of the plate (Figure 1A, B). No perforation is recognizable.

The external side of larger lateral arm plates has seven well defined, horizontally elongated spurs composed of more densely meshed stereom in a vertical row along the proximal edge with (Figure 1A). The row of spurs is distally bordered by a weakly depressed vertical area with a fine horizontal striation (Figure 1A).

Spine articulations without dorsal and ventral lobes but with muscle and nerve openings which are separated by a large, vertical ridge. Spine articulations are sunken into the distal edge, two near the ventro-distal edge of the lateral arm plate and one near the dorso-distal edge (Figure 1A—C).

In smaller lateral arm plates (NMNS PA19979; 1 mm in height, 0.5 mm in length), probably from median to distal portions of the arm, differ in the general plate proportions (lower than their proximal equivalents) and in having fewer (if any) spurs on the outer proximal and inner distal edge, and fewer arm spine articulations (Figure 2A—C)

Discussion

The examined 72 fossil lateral arm plates fall within *Stegophiura*, for they possess: spine articulations sunken into the distal edge; tentacle notch pointing to ventro-distal side, continuous slender and well defined ridge on inner side of proximal side; conspicuous incision on ventro-proximal edge. (Thuy and Stöhr, 2011; O'Hara *et al.*, 2018). The morphology of the studied fossils is similar to that of *Stegophiura sladeni*, based on a comparison with recent specimens as follows.

In this study, we compared our fossil lateral arm plates with those of recent species, namely *Stegophiura sterea* (Ishida *et al.*, 1996; Ishida *et al.*, 2018), *S. nodosa* (Thuy and Stohr, 2011), and *S. sladeni* (this study: Figure 3A, B). Fossil materials resemble those of *S. sterea* and *S. sladeni* in their distinctive row of spurs and *S. nodosa* lacks such spurs. The lateral arm plate of recent *S. sterea* illustrated in Ishida *et al*. (1996: plate 2H, I, 2.2 mm in height, 1.2 mm in width) has four and three spurs on the external and inner side, respectively. Our similar-sized fossil material (NMNS PA19937, 2.2 mm in height, 0.9 mm in width) resembles the recent material shown in Ishida *et al*. (1996) with respect to the number of spurs. However, the fossil lateral arm plates described-herein have two spine articulations on the ventro-distal side and one on the dorso-distal side, widely separated from the other two (Figure 1A, B). In contrast, *S. sterea* has four to five equally spaced arm spine articulations on the distal edge of the lateral arm plate (Matsumoto, 1915; Ishida *et al*., 2018).

The number and arrangement of the arm spine articulations and of the spurs on the outer proximal and inner distal edges of our examined fossil ossicles are similar to those of *S. sladeni* (Figure 3). The fossil lateral arm plates described in this study are therefore identified as *S. sladeni*, representing the first fossil occurrence of the species

Fossil *Stegophiura sladeni* can be useful as an indicator of the paleoenvironment of Sha'ana-dai during the Middle Pleistocene, assuming that habitat preferences of the species have been constant since the Middle Pleistocene. Living *Stegophiura sladeni* occur on sandy/muddy sea bottoms around Japan, in particular the southern Sagami Bay, the Sea of Japan and off Hong Kong at depths of 40—380 m (e.g. Irimura, 1982). Fossil articulated shells of *Acila divaricata*, *A. mirabilis*, and *Cyclocardia ferruginea*, species presently found on sandy and/or muddy bottoms at depths of 50–500 m, 20–200 m, and 50–400 m respectively (Okutani, 2017), suggest a paleobathymetry corresponding to mid-shelf to shallow slope settings, in line with the present-day distribution of *Stegophiura sladeni*.

The present report is the first descriptive study regarding the use of fossil lateral arm plates to investigate the ophiuroid fossil record in Japan. It follows in the footsteps of extensive studies exploring the ophiuroid microfossil record from other parts of the world, in particular Europe (e.g. Hess, 1960, 1962a, b, 1963, 1965a, b, 1966, 1975a, b; Hess and Palain 1975; Jagt, 2000; Thuy and Stöhr, 2011; Thuy, 2013). Approximately 350 species of ophiuroids are currently known from Japanese waters, accounting for three quarters of the total ophiuroid species diversity in the North Pacific (Stöhr *et al*., 2012; Okanishi, 2016). In addition, more than 50 species have been identified based on fossil articulated skeletons from Japan (e.g. Fujita, 1992; Ishida, 2004; Ishida *et al*., 2011; 2015), suggesting an even higher ophiuroid paleo-biodiversity is yet to be explored using fossil lateral arm plates. Our discovery is the first step to promote taxonomic studies on fossil lateral arm plates collected from the sieving residues of Japanese fossiliferous beds, to contribute to a better knowledge of the Japanese paleofauna and its changes throughout Earth history.

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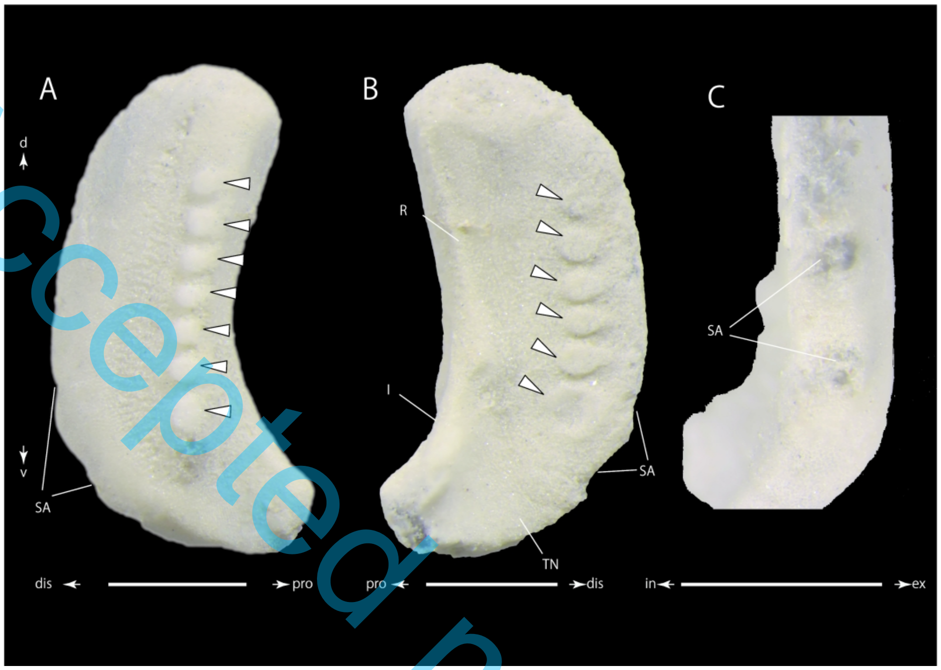
Figure captions

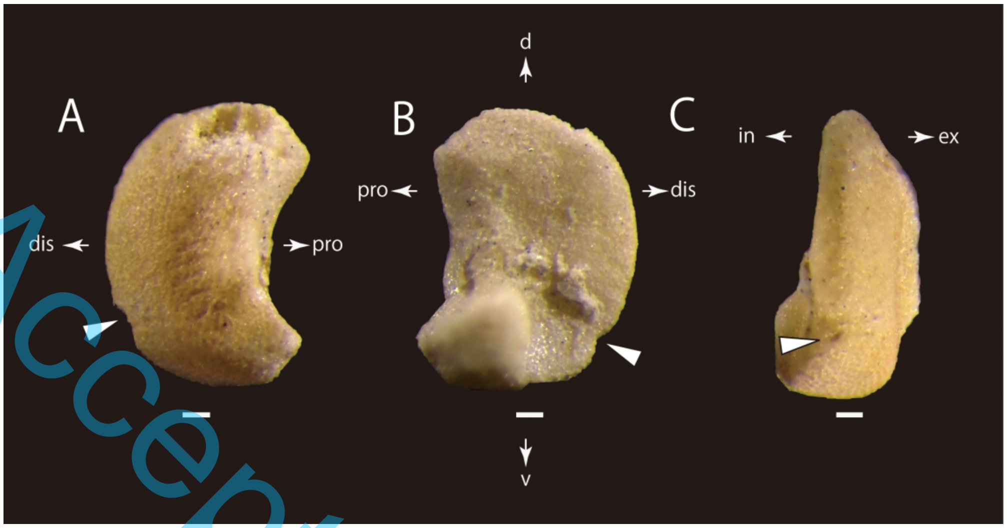
Figure 1. *Stegophiura sladeni* from the Miyata Formation, stereomicroscopic images of proximal lateral arm plates (NMNS PA19944). **A,** external view; **B,** internal view; **C,** distal-ventral view. Arrows show orientations, d, dorsal; dis, distal; pro, proximal; v, ventral. Arrowheads indicate spurs. Abbreviations: I, incision; R, ridge; SA, spine articulation; TN, tentacle notch.

Figure 2. *Stegophiura sladeni* from the Miyata Formation, stereomicroscopic images of distal lateral arm plates (NMNS PA19979). **A**, external view; **B,** internal view; **C,** distal-ventral view. Arrows show orientations, d, dorsal; ex, external; in, internal; pro, proximal; v, ventral side. Arrowheads indicate spine articulation.

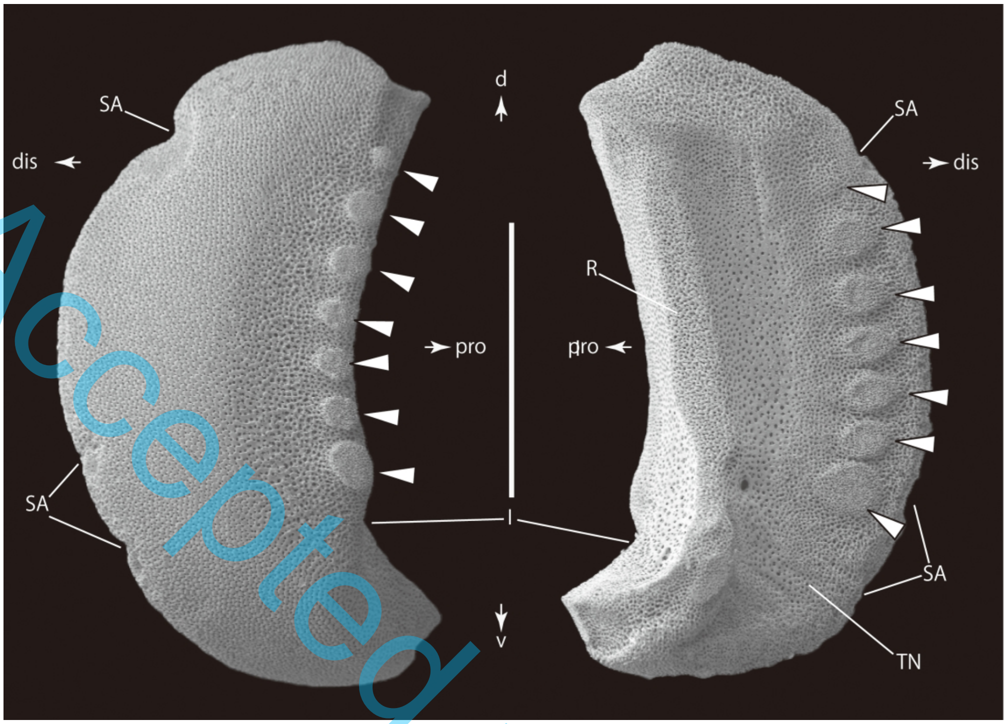
Figure 3. *Stegophiura sladeni* (MnhnL OPH106) from off Choshi, Japan, SEM images of proximal lateral arm plates. **A**, external view; **B,** internal view. Arrows show orientations, d, dorsal; dis, distal;; pro, proximal; v, ventral side. Arrowheads indicate spurs. Abbreviations: I, incision; R, ridge; SA, spine articulation; TN, tentacle notch.



Stegophiura sladeni from the Miyata Formation, stereomicroscopic images of proximal lateral arm plates (MO-2020-F33). A, external view; B, internal view; C, distal-ventral view. Arrows show orientations, d, dorsal; dis, distal; pro, proximal; v, ventral. Arrowheads indicate spurs. Abbreviation: I, incision; R, ridge; SA, spine articulation; TN, tentacle notch. Scale bars, 1 mm.



Stegophiura sladeni from the Miyata Formation, stereomicroscopic images of distal lateral arm plates (MO-2020-F68). A, external view; B, internal view; C, distal-ventral view. Arrows show orientations, d, dorsal; ex, external; in, internal; pro, proximal; v, ventral side. Arrowheads indicate spine articulation. Scale bars, 0.1 mm.



Stegophiura sladeni from the Miyata Formation, stereomicroscopic images of distal lateral arm plates (MO-2020-F68). A, external view; B, internal view; C, distal-ventral view. Arrows show orientations, d, dorsal; ex, external; in, internal; pro, proximal; v, ventral side. Arrowheads indicate spine articulation. Scale bars, 0.1 mm.