

Brittle stars from a submarine cave of Christmas Island, northwestern Australia, with description of a new bioluminescent species *Ophiopsila xmasilluminans* (Echinodermata: Ophiuroidea) and notes on its behaviour

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Abstract. Three species of ophiuroids are reported from a shallow water submarine cave on Christmas Island in northwestern Australia, including a new bioluminescent species, *Ophiopsila xmasilluminans*, which is described herein on the basis of 15 specimens. This new species occurs on sandy bottoms in the cave with disc buried and arms extended above the substratum. This species possesses a disc entirely covered by thick skin with small and delicate embedded scales and granules; 3 oral papillae, basically flat, fan-shaped but sometimes innermost or middle papilla spiniform; diamond shaped oral shield with rounded edges, as long as wide; long and flat arm spine; inner tentacle scale narrow, flat and long, arms approximately 18 times the disc diameter. We describe bioluminescence and burying behaviour, which suggest adaptation to submarine cave environments. Also reported herein is a rarely encountered species, *Ophiomora elegans*, based on a single specimen. *Ophiomora elegans* was previously known only from southern Mozambique, the east coast of Africa and the Ryukyu Islands. We also include a new record of *Ophioconis clavicularis*, which was previously known only from the Ryukyu Islands.

Key words. brittle star, endemism, new species, submarine cave, bioluminescence, Christmas Island

INTRODUCTION

Recent investigations of anchialine and cave dwelling habitats has revealed a multitude of undescribed invertebrate species from various international locations (e.g., Bribiesca-Contreras et al., 2013; Fujita, 2018). Okanishi & Fujita (2018a, b, 2019) have recently described new records and undescribed species of Ophiuroidea (Echinodermata) from submarine caves in the Ryukyu Islands in southwestern Japan.

Tan et al. (2014) recently reported three cave-dwelling brittle stars from Christmas Island, located in northwestern Australia. Detailed descriptions of these species are pending. One of those species, collected from the “Thunderdome Cave” locality, was identified as *Ophiopsila pantherina* Koehler, 1898. In situ observations of this species by Tan et al. (2014) showed that this species emitted visible flashes of green light. Following detailed morphological observations of the species, we have determined this to be undescribed

species in the genus *Ophiopsila* Forbes, 1843, which is described herein.

The original monotypic genus *Ophiopsila* (Ophintegrida: Amphilepidida: Ophiopsilidae) was erected by Forbes (1843) for the eastern Mediterranean species *Ophiopsila aranea* Forbes, 1843. Over the next 90 years, 14 species were described (H. L. Clark, 1915, 1918; A. H. Clark, 1921). Subsequently, Koehler (1930) listed the pre-1929 species with descriptions of 6 new species. Since 1930, 6 additional species have been added to the genus (A. M. Clark, 1952, 1974; Murakami, 1963; Baker, 1974; Guille & Jangoux, 1978; Liao & A. M. Clark, 1995), and thus *Ophiopsila* currently comprises 27 nominal species.

Two of the species reported by Tan et al. (2014), *Ophioconis cupida* Koehler, 1905 and *Ophiomora elegans* Koehler, 1907 have undergone further taxonomic refinements. “*Ophioconis cupida*” has been re-identified as *Ophioconis clavicularis* Okanishi & Fujita, 2018b, which has been described recently from the Ryukyu Islands, Japan. In addition, we provide a redescription of *O. elegans*, which had been known only from southern Mozambique on the east coast of Africa (Koehler, 1907) and more recently reported from the Ryukyu Islands in Japan (Fujita et al., 2015).

Recent descriptions of ophiuroids have included comprehensive range of photographs and/or drawings of relevant diagnostic morphological characters as well as SEM images of each ossicle, which provides a consistent suite of characters

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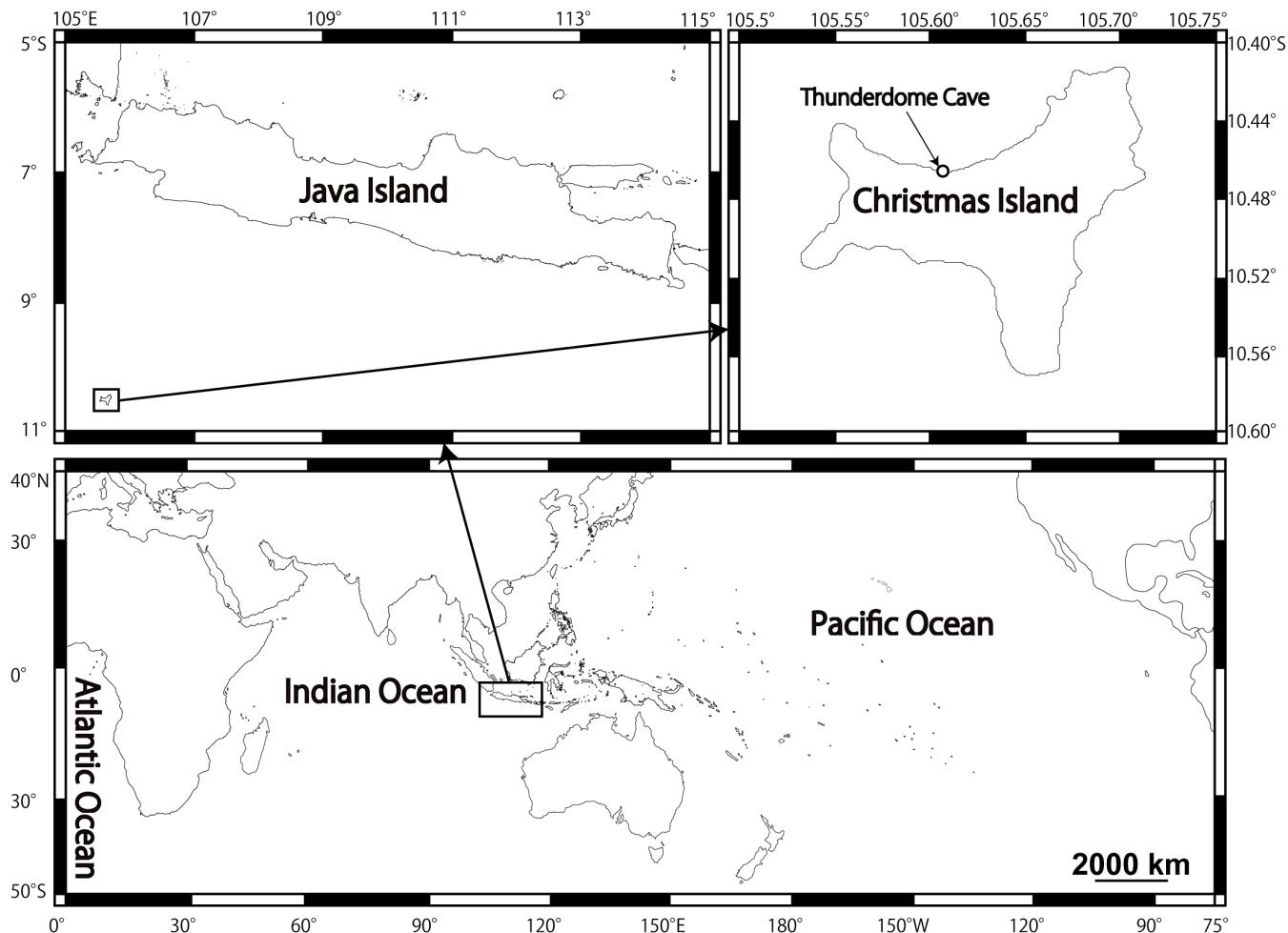


Fig. 1. Sampling location of three ophiuroid species examined in this study.

for comparison and identification (e.g., Martynov, 2010; Thuy & Stöhr, 2016; Okanishi & Fujita, 2018a). To date, drawings and photographs showing diagnostic characters of *Ophiopsila* have been limited (e.g., Guille & Jangoux, 1978). Scanning electron microscopy (SEM) images of ossicles were previously unavailable. Similarly, only drawings of characters of *Ophiomora elegans* were available. Here, we present detailed photographs of many parts of the body for *Ophiomora elegans* and the new species as well as SEM images of separated ossicles. Additionally, based on in situ observations during the survey, we provide photographs of living colour for the three species and brief descriptions of bioluminescence and sand-dwelling behaviour of this new species.

MATERIAL & METHODS

The materials examined in this study were collected and observed in situ by the last author (YF) during SCUBA diving at the submarine “Thunderdome Cave” in Christmas Island (10°45.956'S, 105°60.465'E), northeastern Australia (Fig. 1). Detailed information on the cave system at Christmas Island is provided by Tan et al. (2014).

The holotype (WAM Z99800) of *Ophiopsila xmasilluminans* new species was anaesthetised in a 10% aqueous solution of magnesium chloride, then fixed in 99% ethanol. Photographs were taken during anaesthetisation and fixation. A part of the arm of a paratype (RUMF-ZE-00153) was dissected to remove internal ossicles. For observation by SEM, the ossicles were isolated using domestic bleach (approximately 5% sodium hypochlorite solution), washed in deionised water, dried in air and mounted on SEM stubs using double-sided conductive tape. The whole body of another paratype (RUMF-ZE-02087) was dried in air and mounted on stub. The preparations (RUMF-ZE-00153 and RUMF-ZE-02087) were sputter-coated with gold-palladium and examined and photographed with Jeol JSM 5510LV SEM of the Misaki Marine Biological Station of The University of Tokyo (MMBS). Part of the disc and a proximal portion of the arms of a paratype of the new species (RUMF-ZE-02086) and *Ophiomora elegans* (RUMF-ZE-00142) were bleached (approximately 5% sodium hypochlorite solution) to remove skin and observe internal ossicles. The examined type specimens of the present new species and other specimens of *Ophiomora elegans* and *Ophioconis clavicularis* were deposited in the following collections: ZRC, the Zoological Reference Collection of the Lee Kong Chian Natural History Museum, National University of Singapore; WAM, the Western Australian Museum, Perth; RUMF, the Ryukyu University Museum, Fujukan, Okinawa,

Japan. Morphological terminology follow Stöhr et al. (2012), Okanishi & Fujita (2018b), and Wilkie & Brogger (2018), and systematics follows O’Hara et al. (2018).

Three video clips on the in situ observation of *Ophiopsila xmasilluminans* new species were filmed (Supplementary file 1: <https://youtu.be/SQrY7mN7UbM>; Supplementary file 2: <https://youtu.be/vVXIDRyNzvs>; Supplementary file 3: <https://youtu.be/AkbrMHpxXXw>).

TAXONOMY

Class Ophiuroidea Gray, 1840

Superorder Ophintegrida O’Hara et al., 2017

Order Amphilepidida O’Hara et al., 2017

Suborder Ophiopsilina Matsumoto, 1915

Superfamily Ophiopsiloidea Matsumoto, 1915

Family Ophiopsilidae Matsumoto, 1915

Genus *Ophiopsila* Forbes, 1843

Type species. *Ophiopsila aranea* Forbes, 1843.

Other included species. *O. abscissa* Liao, 1982, *O. annulosa* (Sars, 1859), *O. bispinosa* A. M. Clark, 1974, *O. brevisquama* Koehler, 1930, *O. californica* A. H. Clark, 1921, *O. caribea* (Ljungman, 1872), *O. dilatata* Koehler, 1930, *O. fulva* Lyman, 1878, *O. glabra* Koehler, 1930, *O. guineensis* Koehler, 1914, *O. hartmeyeri* Koehler, 1913, *O. maculata* (Verrill, 1899), *O. multipapillata* Guille & Jangoux, 1978, *O. multisepia* Koehler, 1930, *O. novaezealandiae* Baker, 1974, *O. pantherina* Koehler, 1898, *O. paucispina* Koehler, 1907, *O. picturata* Koehler, 1930, *O. platispina* Koehler, 1914, *O. polyacantha* H. L. Clark, 1915, *O. polysticta* H. L. Clark, 1915, *O. riisei* Lütken, 1859, *O. seminuda* A. M. Clark, 1952, *O. squamifera* Murakami, 1963, *O. timida* Koehler, 1930, *O. vittata* H. L. Clark, 1918 (see also taxonomic history mentioned in the Introduction above).

Diagnosis. Extremely long tentacle scales that cross on the mid-line of the oral side of arm; arm spine articulations of lateral arm plates with two smooth, parallel, straight lobes; in the proximal space between them a short ridge; inner side of the lateral arm plates with two merged knobs.

Ophiopsila xmasilluminans new species

(Figs. 2–10)

Ophiopsila pantherina non Koehler, 1898: —Tan et al., 2014: 413, fig. 19.

Type material. Holotype: (WAM Z99800) submarine cave (known as “Thunderdome Cave”) at Christmas Island, northwestern Australia, depth approximately 10 m, SCUBA diving, coll. Y. Fujita, 27 March 2011. Paratypes: 1 specimen (ZRC.ECH.1332), same data as holotype; 12 specimens (RUMF-ZE-00148, RUMF-ZE-00153, RUMF-ZE-02086, RUMF-ZE-02087, ZRC.ECH.1333, ZRC.ECH.1334, ZRC.ECH.1335, ZRC.ECH.1336, WAM Z99801, WAM Z99802, WAM Z99803, WAM Z99804), same data as holotype; 1

specimen (RUMF-ZE-00152), same locality as holotype, 30 March 2011.

Diagnosis. Disc surface entirely covered by thick skin with embedded small and delicate scales and granules; 3 oral papillae, basically as scales, but sometimes spiniform for one on innermost or middle position; diamond-shaped oral shield with rounded edges, as long as wide; long and flat arm spines, 6 in maximum number; inner tentacle scale narrow, flat and long; arms approximately 18 times longer than disc diameter.

Description of external morphology (holotype WAM Z99800 and paratype RUMF-ZE-02087). Disc. Pentagonal, 6.3 mm in diameter (Fig. 2A), aboral surface covered by small round scales, approximately 30 µm in length on central disc and by scales around radial shields, approximately 50–100 µm (Fig. 3A). These ossicles embedded in thick skin (Figs. 3A, 5A). Radial shields bar-like, 5 to 6 times longer than wide, two-thirds or half the length of disc radius (Fig. 3B, 5A). On oral surface, adoral shields bar-like, wider than long (Figs. 3E, 5C), approximately 500 µm in length, 150 µm in width, in contact with the first ventral arm plates (Fig. 3E). Oral plates short, invisible from outside, approximately 300 µm in length, 80 µm in width, contacting each other. Oral shields pentagonal, approximately as long as wide (Figs. 3E, 5C). All oral shields similar in size and shape: oral shield serving as madreporite unrecognisable in external view (Fig. 3D, E). Interradial oral disc covered only by skin (Figs. 3F, 5B). Genital slits long, almost extending to disc edge (Figs. 3F, 5B), approximately 0.2 mm (Fig. 3F). Abradial genital plates visible on side of genital slit, near disc edge, bar-like, approximately 1 mm in length and 0.1 mm wide (Fig. 3F). Near the oral shield, small scales lie immediately outside of the genital slits, approximately 0.1 mm wide and long (Fig. 3F). Two flat, subequal trapezoidal oral papillae and an spiniform oral papilla just below the inner trapezoidal papilla at each opening for the second tentacle of adoral shield (Fig. 3E), sometimes the middle papilla spiniform (Fig. 5C; see also “Variation” section below). Teeth triangular, pointed, forming tooth papillae consisted of 7 to 9 papillae on oral half side of dental plate, and at least two flat, block-like papillae forming vertical row on aboral half of plate (Figs. 3E, 5C). Second tentacle pore completely inside the mouth slit.

Arms. Five, three arms lacking distal one-fourth to one-third, and two arms remaining almost entire length, 85 mm long. Arms approximately 1.3 mm wide and 1.0 mm high in proximal portion, square in cross section. Arms tapering gradually distally (Fig. 2).

On proximal to middle portion of the arms, ventral arm plates oblong, slightly longer than wide, distal and lateral sides concave, contiguous (Figs. 4D, 7D). Dorsal arm plate oblong, slightly longer than wide, distal edge slightly rounded, contiguous (Figs. 4A, B, 5G, H). Lateral arm plates slightly protruding from arm, separated by dorsal and ventral arm plates (Figs. 4A, B, D, E, 5G, H). On distal portion of the arms, ventral arm plates long, pointed distally, concave on lateral side, and having small points on proximal side (Figs.

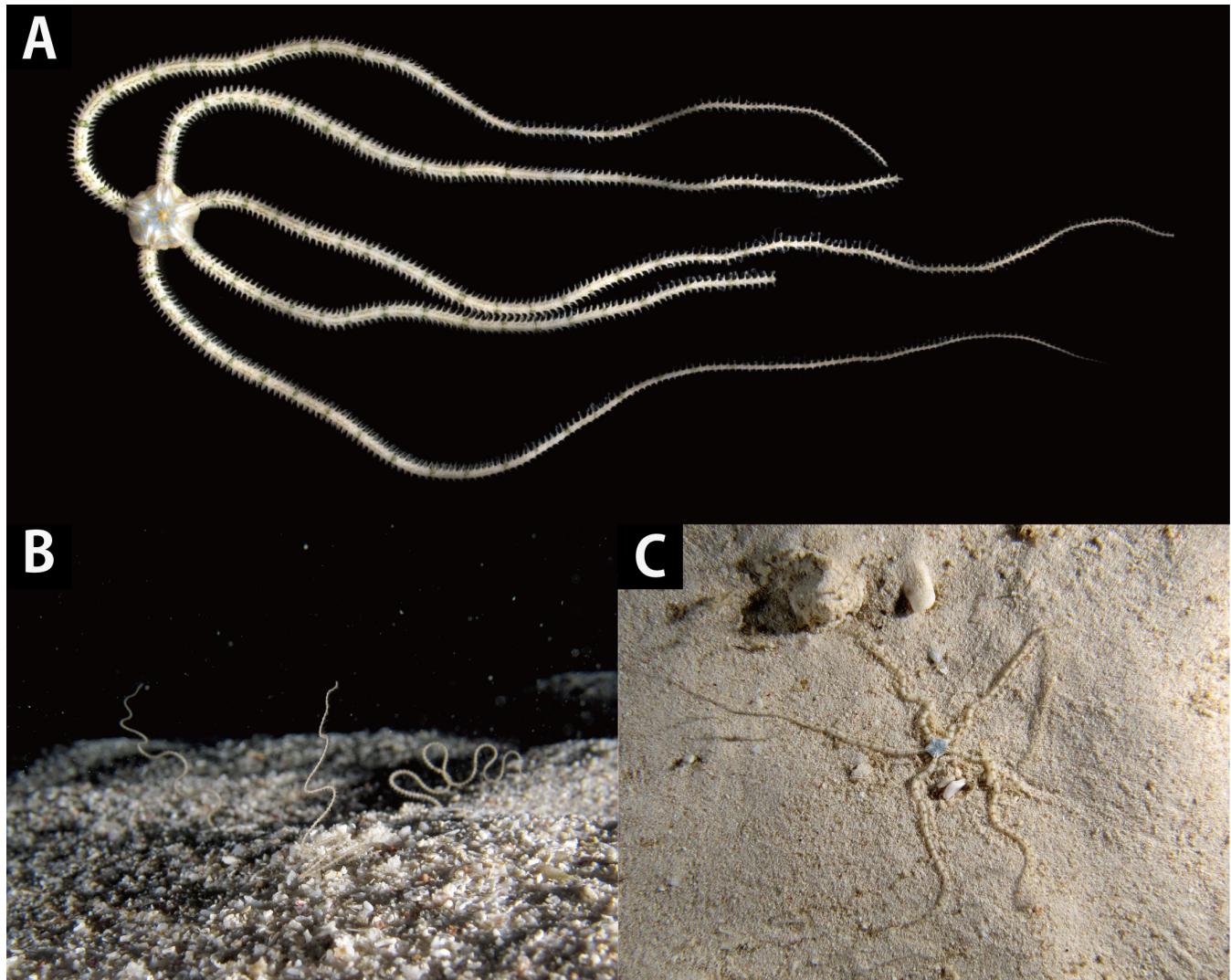


Fig. 2. *Ophiopsila xmasilluminans* new species, living, anesthetised (A: one paratype, RUMF-ZE-00152), in situ (B, C: specimens not collected): A, aboral view; B, with buried disc and extended arms; C, an excavated specimen.

4F, 5I, 8E, F). Dorsal arm plates also longer than wide, oval, and pointed distally (Figs. 5I, 8I). Lateral arm plates bearing arm spines, on proximal portion, 7 or 8 long and flat spines, aboral- and oral-most ones the longest, approximately 1.5 to 2 times longer than corresponding arm segment, and others as long as the corresponding arm segment (Figs. 4A, G, 5E, G). On middle portion, 5 or 6 spines, long and thin, oral-most one the longest, approximately twice as long as corresponding arm segment, and others three-fourth length of corresponding arm segment (Figs. 4B, E, 5H). On distal portion of arms, 2 spiniform arm spines, oral (inner) one longer, approximately two-thirds length of corresponding arm segment and the other one-fourth length of the corresponding arm segment (Fig. 4C, F). Tentacle scales 2, flat, spiniform, inner one longer, two-thirds to the same length of the corresponding arm segment, and outer one half to one-third the length of the corresponding arm segment (Figs. 4D, 5C–E) on proximal to middle portion of arm. On distal portion of arm, scales more flattened, inner spine half the length of corresponding arm segment, and the other one-fourth length of the corresponding arm segment (Figs. 4C, F, 5I). Detailed descriptions of ossicles are provided below.

Description of ossicle morphology (holotype, WAM Z99800). Vertebrae with zygodorsal articulation, large aboral and oral muscle flanges on both distal and proximal sides (Fig. 6C, D). Aboral muscle flanges wider than oral muscle flanges. Longitudinal deep furrows on both aboral and oral sides (Figs. 6A, B, 7G, H, 8A). Transverse furrow on proximal portion of the arm (Fig. 6B). Radial water and nerve holes unrecognisable on oral furrow (Figs. 6A, 7H). Depression for tentacles located on lateral distal side of the vertebra (Figs. 6A, 7H, 8A).

Proximal dorsal arm plates trapezoid, as long as wide, distal edge becoming rounder, wider than proximal width (Fig. 7C). On distal portion of arm, dorsal arm plate rhomboid with rounded edge, longer than wide, pointing to proximal edge, in form of a water drop (Fig. 8I). Proximal lateral arm plates strongly arched, sickle-shaped, with pointed oral-proximal and aboral-proximal protrusion with strong constriction, and strongly pointed on oral-distal side (Fig. 6E, F). On inner surface, irregular series of perforations forming a vertical line on the center (Fig. 6E) and two well defined, confluent knobs on oral side (Fig. 6E). Seven or eight equal-sized spine articulations on distal edge (Fig.

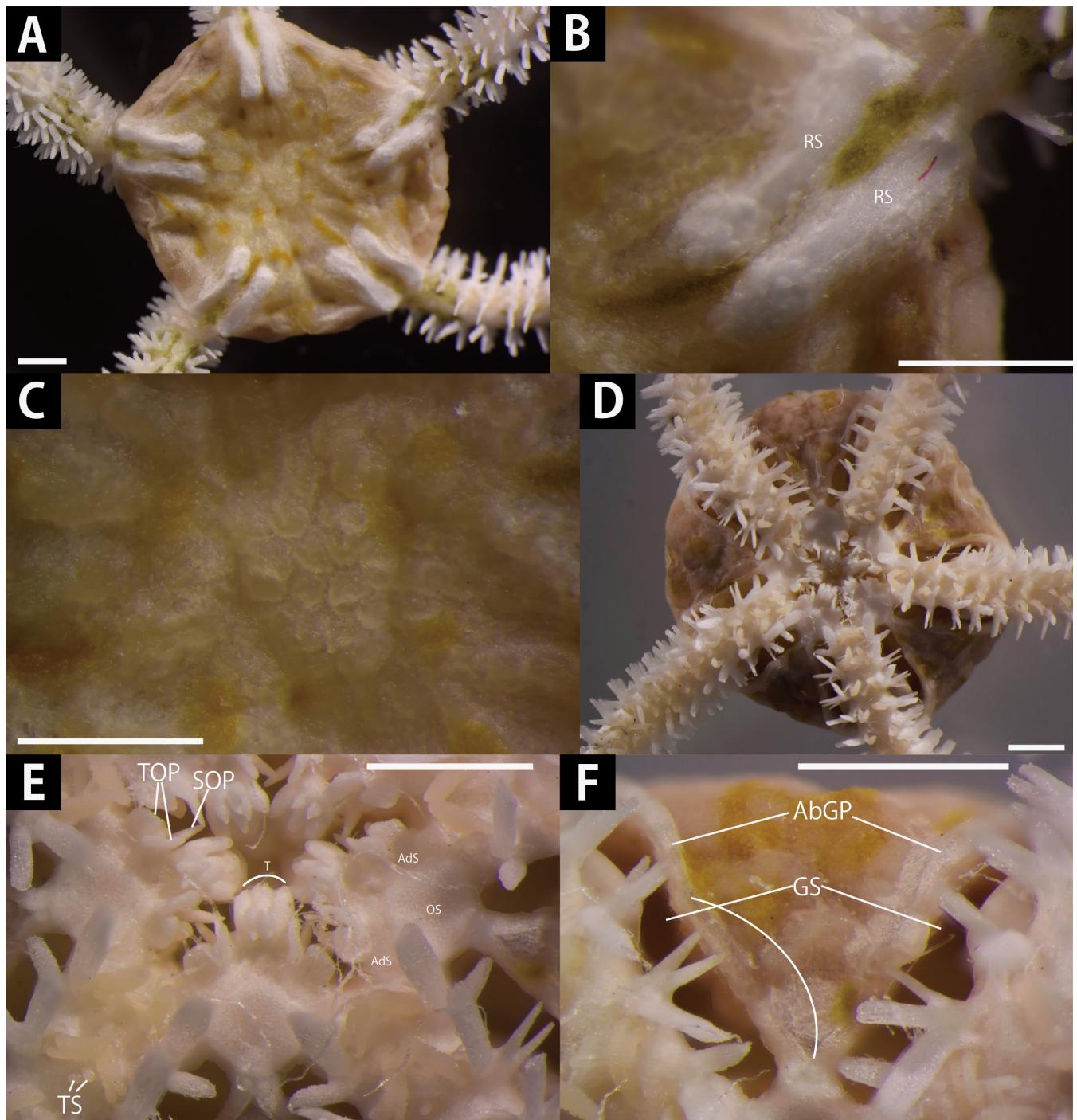


Fig. 3. *Ophiopsila xmasilluminans* new species (Holotype, WAM Z99800). A, aboral disc; B, aboral periphery part of disc; C, aboral central part of disc; D, oral disc; E, jaws; F, lateral interradial part of disc, an arch indicates small scales lying along a genital slit. Abbreviations: AbGP, abradial genital plate; AdS, adradial shield; GS, genital slit; OS, oral shield; RS, radial shield; SOP, spine-shaped oral papillae; T, teeth; TOP, trapezoidal oral papillae; TS, tentacle scale. Scale bars = 1 mm.

6G), composed of parallel, horizontal and equal-sized dorsal and ventral lobes, with muscle and nerve openings inside of lobes (Fig. 6G). A short ridge in proximal space between a pair of lobe (Fig. 6F). Distal lateral arm plates elongated parallelograms with slightly pointed oral-proximal and aboral-proximal protrusions (Fig. 8B). On inner surface, a perforation recognisable centrally, no conspicuous ridge defined (Fig. 8C). Up to three equal-sized spine articulations on distal edge (Fig. 8D), composed of parallel, horizontal and equal-sized dorsal and ventral lobes, muscle and nerve openings unrecognisable (Fig. 8D).

Arm spines long, cylindrical on proximal portion of the arm (Fig. 7A) and on distal portion, spiniform (Fig. 8G) with serrate minute spinelets on lateral surfaces, more conspicuous and numerous than those of proximal portion of arm.

Inner tentacle scales long, flat, thinner on basal side and wider on external side on proximal portion of arm (Fig. 7B), distal tentacle scales shorter (Fig. 8H). Ventral arm plates on proximal portion of arm octagonal, spearhead-shaped, longer than wide, with strongly concave lateral and proximal edges, proximally wider than distally (Fig. 7D), becoming

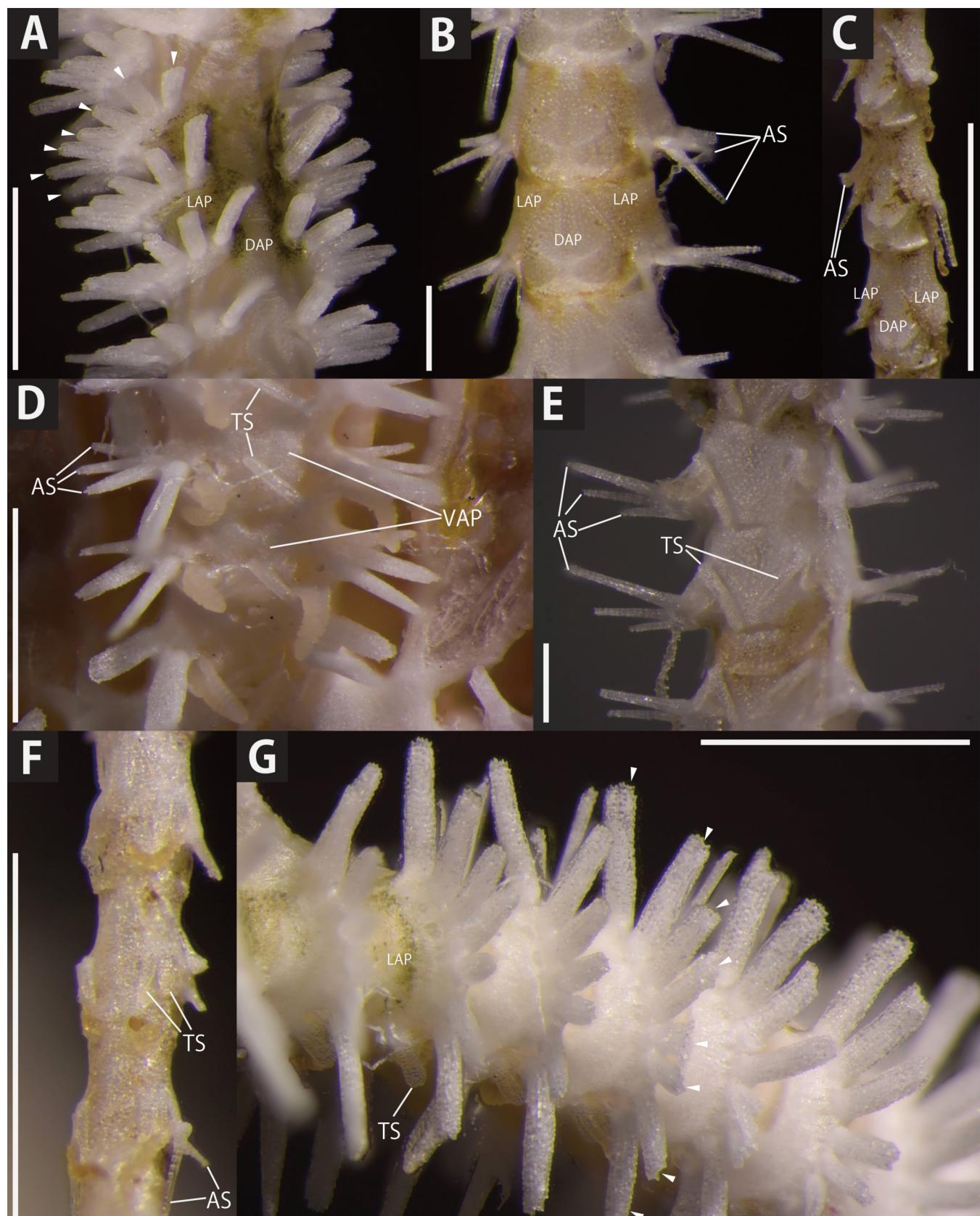


Fig. 4. *Ophiopsila xmasilluminans* new species (Holotype, WAM Z99800). A, aboral proximal portion of the arm; B, aboral middle portion of the arm; C, aboral distal portion of the arm; D, oral proximal portion of the arm; E, oral middle portion of the arm; F, oral distal portion of the arm; G, lateral middle portion of the arm. Arrowheads indicate arm spines (A, G). Abbreviations: AS, arm spine; DAP, dorsal arm plate; LAP, lateral arm plate; TS, tentacle scale; VAP, ventral arm plate. Scale bars = 1 mm.

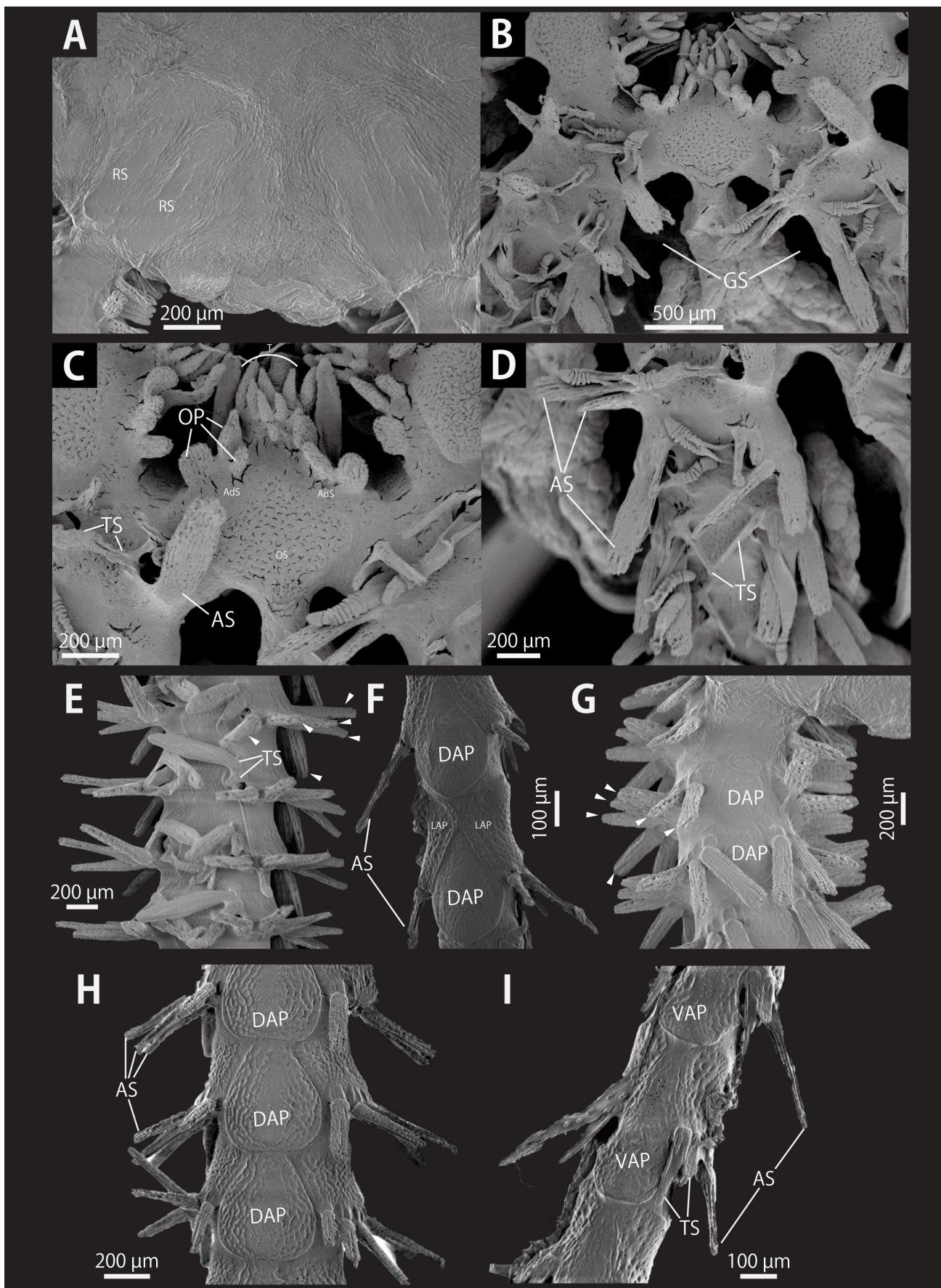


Fig. 5. *Ophiopsila xmasilluminans* new species (one paratype, RUMF-ZE-02087), SEM photographs of external body. A, aboral periphery of disc; B, oral periphery of disc and lateral interradial disc; C, a jaw and oral frame; D, oral proximal portion of the arm; E, oral middle portion of the arm; F, aboral distal portion of the arm; G, aboral proximal portion of the arm; H, aboral middle portion of the arm; I, oral distal portion of the arm. Arrowheads indicate arm spines. Abbreviations: AdS, adoral shield; AS, arm spine; DAP, dorsal arm plate; GS, genital slit; LAP, lateral arm plate; OP, oral papillae; OS, oral shield; RS, radial shield; TS, tentacle scale; VAP, ventral arm plate.

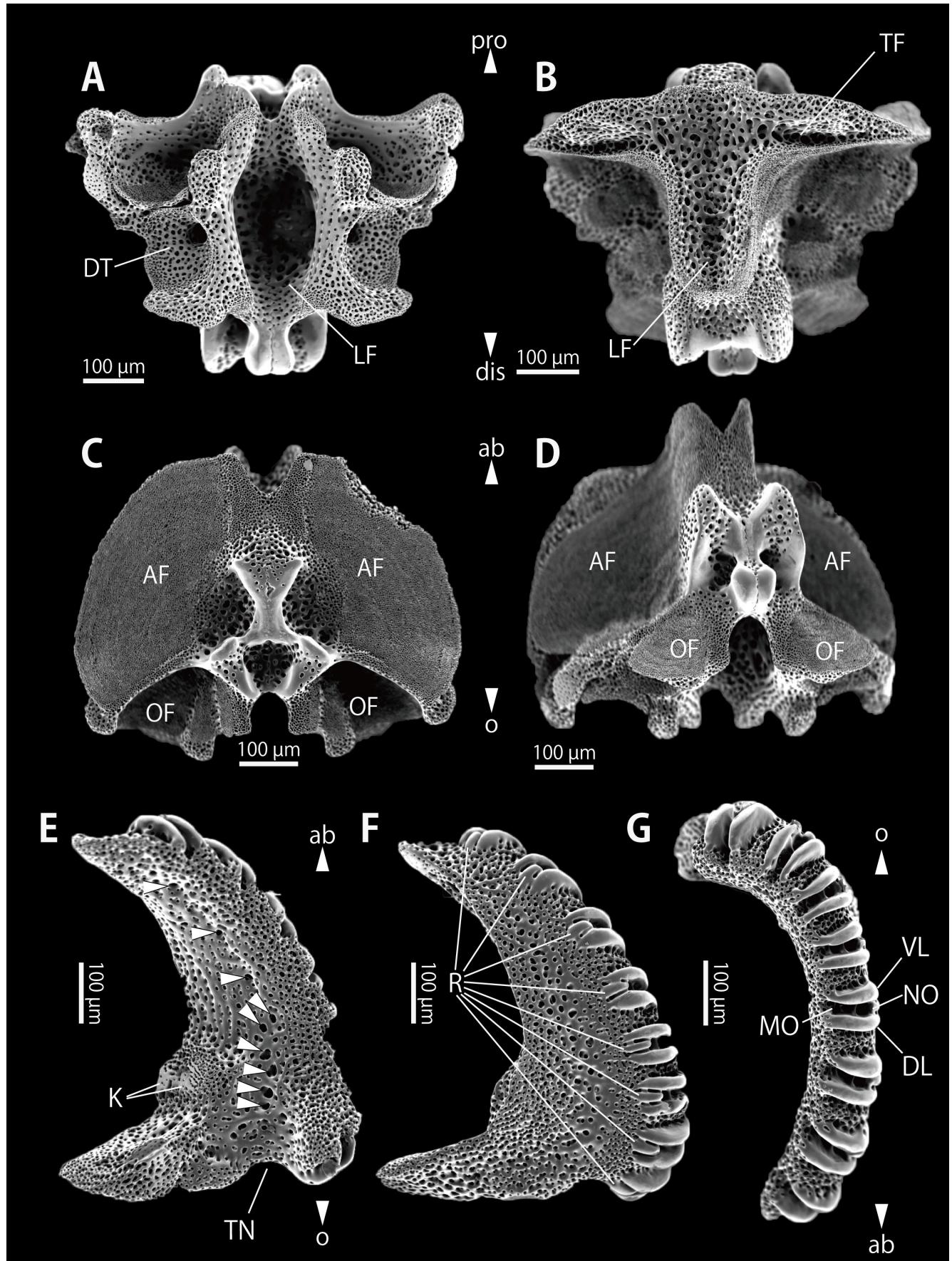


Fig. 6. *Ophiopsila xmasilluminans* new species (Holotype, WAM Z99800), SEM photographs of internal ossicles of arm at proximal portion of the arm. A–D, vertebrae, oral (A), aboral (B), proximal (C) and distal (D) views; E–G, lateral arm plates, inner view (E), external view, arrowheads indicate perforations (F) and distal view (G). Arrowheads indicate orientations: ab, aboral side; dis, distal side; o, oral side; pro, proximal side. Abbreviations: AF, aboral muscle flange; DL, dorsal lobe; DT, depression for tentacle; K, knob; LF, longitudinal furrow; MO, muscle opening; NO, nerve opening; TF, transverse furrow; TN, tentacle notch; OF, oral muscle flange; R, ridge; VL, ventral lobe.

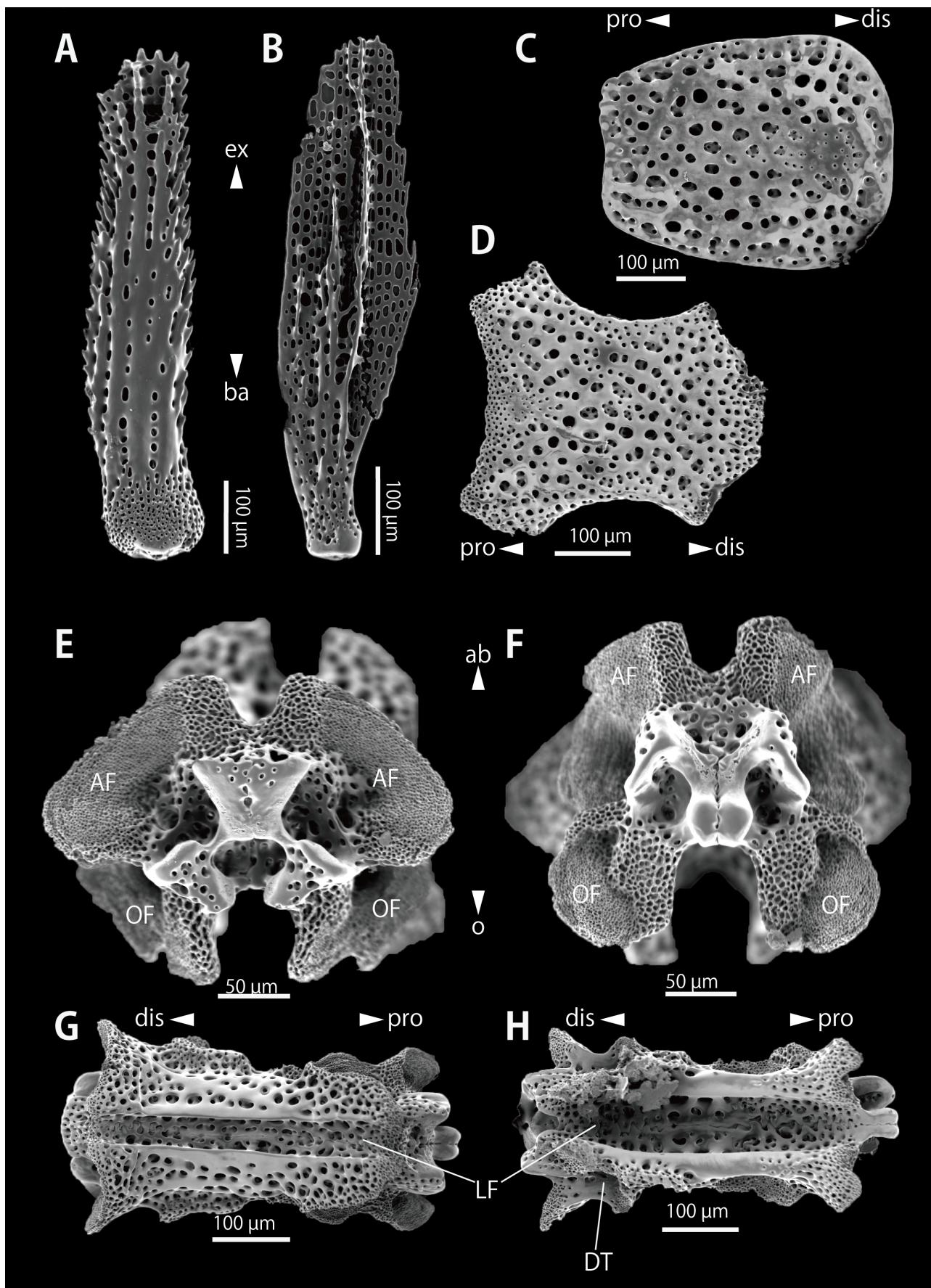


Fig. 7. *Ophiopsila xmasilluminans* new species (Holotype, WAM Z99800), SEM photographs of internal ossicles of arm. A, arm spine from middle portion of the arm; B, inner tentacle scale from middle portion of arm; C, dorsal arm plate from proximal portion of arm; D, ventral arm plate from proximal portion of the arm; E–H, vertebrae at distal portion of the arm, distal (E), proximal (F), aboral (G) and oral (H) views. Arrows indicate orientations: ab, aboral side; ba, basal side; dis, distal side; ex, external side; o, oral side; pro, proximal side. Abbreviations: AF, aboral muscle flange; DT, depression for tentacle; LF, longitudinal furrow; OF, oral muscle flange.

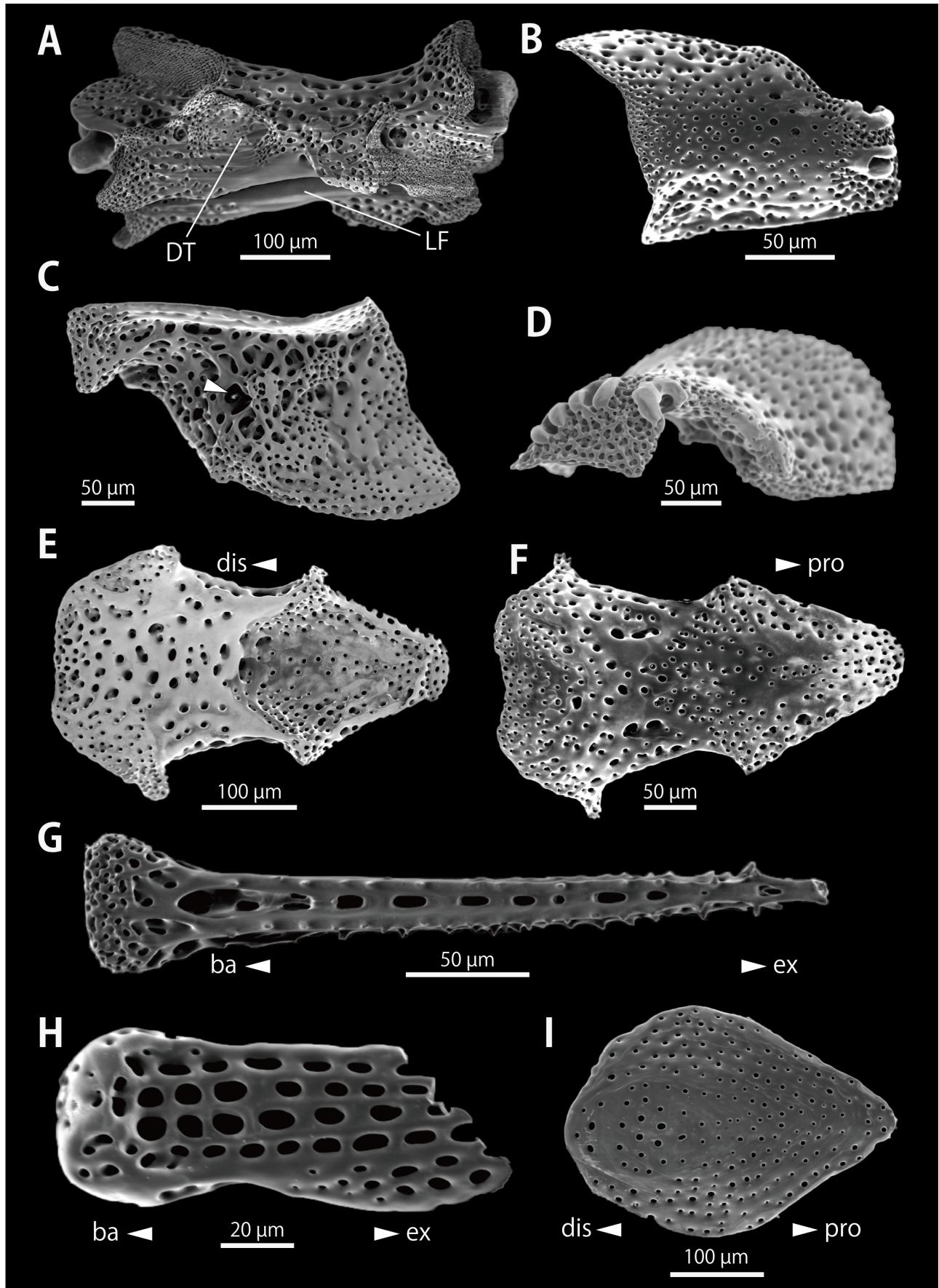


Fig. 8. *Ophiopsila xmasilluminans* new species (Holotype, WAM Z99800), SEM photographs of internal ossicles of arm at distal portion of the arm. A, vertebra, lateral view; B–D, lateral arm plates, external view (B), internal view, an arrowhead indicates a perforation (C) and distal view (D); E, F, ventral arm plates, internal (E) and external (F) views; G, arm spine; H, tentacle scale; I, dorsal arm plate. Arrowheads indicate orientations: ba, basal side; dis, distal side; ex, external side; pro, proximal side. Abbreviations: DT, depression for tentacle; LF, longitudinal furrow.

spear shaped distally, pointing to proximal side, concave lateral edges (Fig. 8E, F).

Description of interbrachial frame and oral shields morphology (a paratype, RUMF-ZE-02086). Morphology of interbrachial frame showed the typical morphology of “Type B” as defined by Wilkie & Brogger (2018): two oblong peristomial plates adjoining at their abradial edges on aboral side of oral plates (Fig. 9A); oral plates with deep neural grooves on aboral-distal area (Fig. 9B, C); abradial muscle attachment area of oral plate large and located on a human ear-shaped fringe that projects beyond the lateral profile of the whole plate, the attachment area with radiating interruptions of microstructually differentiated stereom (Fig. 9B); abradial muscle attachment area spoon-shaped and aboral portion expanding like the ‘bowl’ and oral portion narrowing like ‘handle’, and two depressions for tentacles presenting distal side of the muscle attachment area (Fig. 9C); dental plate entire, not divided into several plates, one or two aboral tooth sockets in the form of wide perforations that are divided into two lateral halves by a complete vertical bar (Fig. 9D, E). One of five oral shields have two opening pores, smaller one on oral side (Fig. 10A) and larger one on aboral side (Fig. 10B, C). These pores connecting a spiral canal inside of the shield, which recognised under stereomicroscopic observations (Fig. 10A–C). No canal and pores recognised in the normal oral shield (Fig. 10D).

Colour in life. Aboral periphery of disc and radial shields generally creamy white, with concentric non-continuous yellowish bands on aboral periphery and yellowish spots scattered on aboral center of disc. Green bands present on every 4 to 6 arm segments. Oral disc also creamy white, yellowish spot on oral interradial disc (Fig. 2).

Variation. A morphological variation was observed in 12 of 15 examined specimens of *Ophiopsila xmasilluminans* new species. The innermost oral papillae of holotype and 6 paratypes (WAM Z99800, d.d. = 6.3 mm; ZRC.ECH.1333, d.d. = 5.3 mm; ZRC.ECH.1334, d.d. = 5.5 mm; ZRC.ECH.1335, d.d. = 5.7 mm; WAM Z99801, d.d. = 5.3 mm; WAM Z99803, d.d. = 5.6 mm; WAM Z99804, d.d. = 5.3 mm) is situated below the other papillae (Fig. 3E) whereas those of 5 paratypes (ZRC.ECH.1332, d.d. = 7.0 mm; RUMF-ZE-00153, d.d. = 5.0 mm; RUMF-ZE-02087, d.d. = 5.0 mm; ZRC.ECH.1336, d.d. = 5.1 mm; WAM Z99802, d.d. = 5.0 mm) form a horizontal raw on oral edge of adoral shields (Fig. 5C).

Etymology. The specific name is an adjective in apposition formed as a compound of the island name “*xmas*” and the Latin participle, *illuminans*, meaning “lighting”, referring to its sampling locality name (Christmas Island) and luminescence.

Common Japanese name. Dohkutsu-hikari-kumohitode.

Distribution. Known only from the type locality, a submarine cave called as “Thunderdome Cave”, northern coast of Christmas Island, northwestern Australia, approximately 10

m depth (type locality, Fig. 1). Tan et al (2014) noted that *Ophiopsila pantherina* [= this new species] was also found at “Thundercliff Cave”, which is located near Thunderdome Cave. However, specimens of this species were only collected from Thunderdome Cave by the last author (Yoshihisa Fujita).

Habitat. All type specimens of *Ophiopsila xmasilluminans* new species were collected in sandy bottoms in the submarine cave, with buried disc and arms extended into the water (Fig. 2B).

Remarks. This new species falls within the genus *Ophiopsila* by virtue of having: extremely long tentacle scales that cross on the mid-line of the oral side of arm; arm spine articulations of lateral arm plates with two smooth, parallel, straight lobes; in the proximal space between them a short ridge; inner side of the lateral arm plates with two merged knobs (Guille & Jangoux, 1978; O’Hara et al., 2018).

Among the 28 species of *Ophiopsila*, the present new species is similar to *O. pantherina* Koehler, 1898, originally described from King’s Island, Mergui Archipelago, Myanmar and *O. timida* Koehler, 1930 from Kei Island, Philippines (Koehler, 1898; Koehler, 1930), in sharing combination of following characteristics: small round scales on disc; contiguous radial shields; 2 or 3 oral papillae on each adoral shield; and narrow and/or long inner tentacle scales on proximal portion of the arm. This new species can be distinguished from these similar species by the covering of the disc, number and shape of oral papillae, shape of oral shield, shape of arm spines, shape of inner tentacle scales and length of arm (Koehler, 1898, 1930; H. L. Clark, 1918; A. H. Clark, 1921; Murakami, 1963; Baker, 1974; A. M. Clark, 1974; Liao & Clark, 1995). These characters are compared among the three species as follows:

(1) Disc surfaces: Disc of this new species is covered by thick skin with embedded small round scales on aboral side, and only by skins on oral side. Both aboral and oral disc surface of *O. pantherina* and *O. timida* are also covered by small round scales (Koehler, 1898; 1930).

(2) Oral papillae: Three oral papillae on each side of the jaw in this new species; two in *O. pantherina* and *O. timida*. Oral papillae are flat, broad scales or inner papillae or middle one sometimes spiniform; all broad scales in *O. pantherina* and spiniform in *O. timida*.

(3) Oral shield: Oral shields diamond shaped with rounded edges, as long as wide in the new species and *O. pantherina*; elliptical, 2.5 times longer than wide in *O. timida*.

(4) Arm spines: Shapes of arm spines on proximal portion of arms long and flat in this new species, spiniform in *O. pantherina*, and cylindrical with thorny tips in *O. timida*.

(5) Tentacle scales: Inner tentacle scales of this new species and *O. timida* are narrow, cylindrical and long, and scale long and flat in *O. pantherina*.

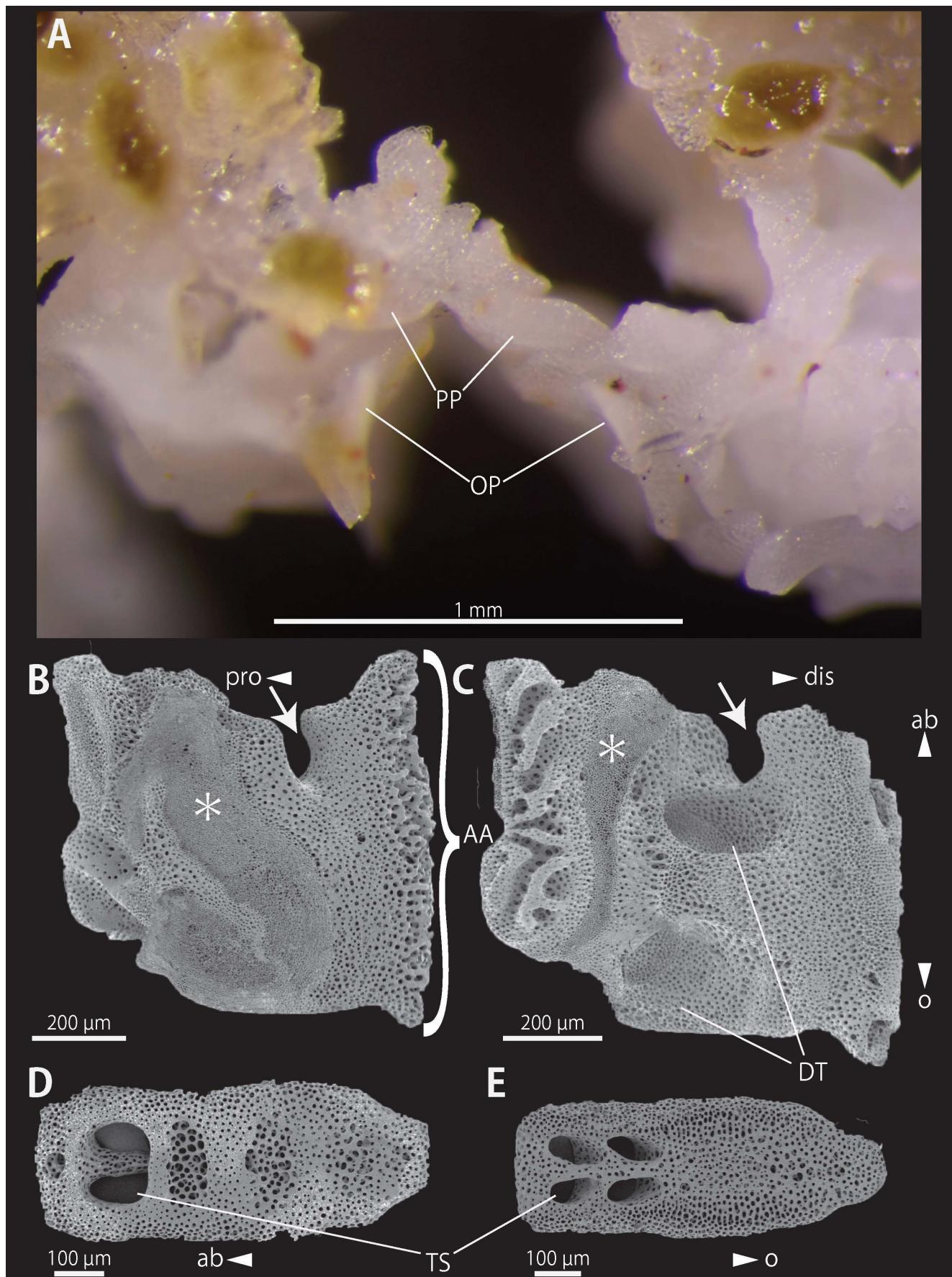


Fig. 9. *Ophiopsila xmasilluminans* new species (one paratype, RUMF-ZE-02086), Stereomicroscopic (A) and SEM (B–E) photographs of internal ossicles of interbrachial frame. A, aboral side of a single interbrachial frame unit, one peristomial plate (right) slipping into neural groove in the handling of dissection; B, C, oral plates, adradial (B) and abradial (C) side, arrows indicate neural grooves, asterisks indicate muscle attachment areas; D, E, dental plates, distal (D) and proximal (E) side. Arrowheads indicate orientations: ab, aboral side; o, oral side. Abbreviations: AA, attachment area; DT, depression for tentacle; OP, oral plate; PP, peristomial plate; TS, tooth socket.

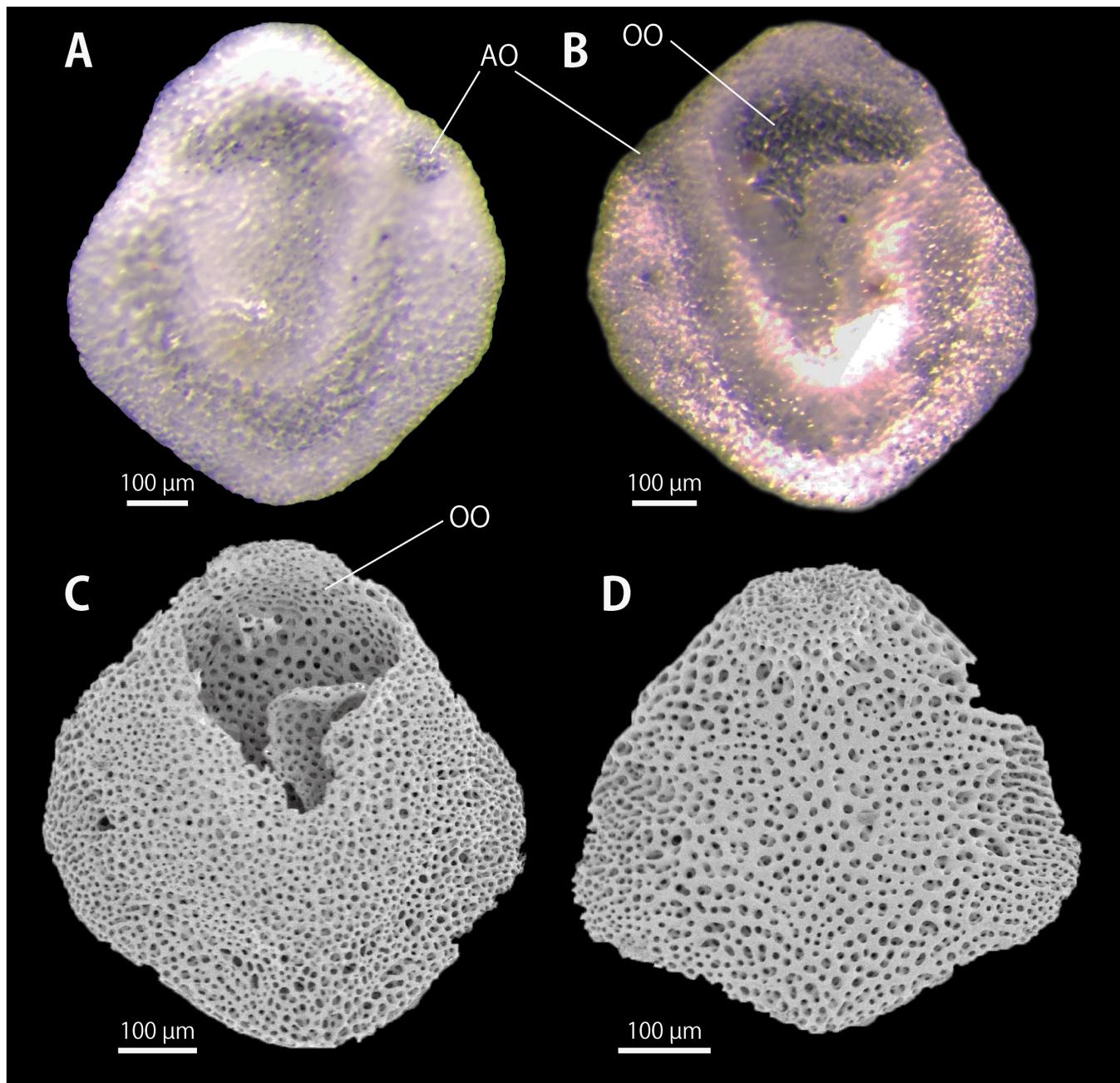


Fig. 10. *Ophiopsila xmasilluminans* new species (one paratype, RUMF-ZE-02086), Stereomicroscopic (A, B) and SEM (C, D) photographs of madreporic (A–C) and normal (D) oral shields. A, D, oral sides; B, C, aboral sides. Abbreviations: AO, aboral opening; OO, oral opening.

(6) Length of arm: relative length of an arm with maximal length of this new species exceeds 18 times disc diameter; whereas those of *O. pantherina* and *O. timida* are 8.5 and 8 times, respectively. The arms of the new species are the longest in *Ophiopsila*. Other than this new species, the arms are 14 times longer than the disc diameter in *O. brevisquama* Koehler, 1930 and *O. riisei* Lütken, 1859 (Lütken, 1859; Koehler, 1930).

Ecological note. Tan et al. (2014) noted that this new species is bioluminescent, with flashing arms. Our in situ video observations reveal that this species partly flashes its arms where touched (Supplementary file 1). An autotomised and separated arm further flashed and showed active wiggling, suggesting a sacrificial-lure function, which has also been

reported for other luminous brittle stars (Mallefet et al., 2004; Supplementary file 2). We did not measure the spectrum, but the bioluminescence colour observed in the field was green. Although two species of brittle stars are known to show blue emission (*Amphiura filiformis* and *Amphiura arcystata*: e.g., Emson & Herring, 1985; Jones & Mallefet, 2013), the luminescence of other known brittle stars (Widder et al., 1983), including a congener of the new species, is green (*O. californica*; Brehm & Morin, 1977; Shimomura, 1986). No bioluminescence has previously been observed for cave-dwelling brittle stars, but considering that other coastal congeners also show the same bioluminescence (*O. aranea*, *O. californica*, *O. pantherina* and *O. riisei*; see Grober, 1988; Vanderlinden & Mallefet, 2004; Woolsey et al., 2013), this flashing behaviour is not restricted to cave dwellers. The

bioluminescence of ophiuroids has also been considered to be an aposematic signal (Grober, 1988), an effective defense against predation, most likely for determent (Deheyn et al., 2000; Jones & Mallefet, 2013; Woolsey et al., 2013), or acting as a “burglar alarm”, for enemies of the predator at night (Mallefet, 2009). It is difficult to say which hypothesis is likely given that we did not carry out quantitative experiments in this study. The flashing of *O. xmasilluminans* new species might have a similar function to a “burglar alarm” because its habitat is the interior part of the cave, where it is almost dark, without any daylight. On the other hand, the “lure” hypothesis cannot be rejected because light is also emitted from the autotomised arm (Supplementary file 1, 2). Indeed, potential predators having developed eyes, such as decapods and fishes, live sympatrically in this cave (Tan et al., 2014). To our knowledge, no bioluminescent species have previously been discovered in submarine anchialine caves (Bell, 1887; Gibson-Hill, 1947; Marsh, 2000), although it is difficult to say whether *O. xmasilluminans* new species is a cave-endemic, since adequate inventory surveys around the cave have not yet been done. Our present study suggests that further extensive surveys in these submarine caves and their surrounding environment might reveal the presence of new locally-endemic bioluminescent species which have adapted to distinctive dark or anchialine environments.

In *Ophiopsila*, sand burying behaviour is known for *O. pantherina* (Woolsey et al., 2013), but it is different from *O. xmasilluminans* new species: *O. pantherina* extend almost their entire arms (Woolsey et al., 2013) into the water, but *O. xmasilluminans* new species buries the proximal portions of its arms in the sand and extends only the distal portions into the water (Fig. 2B). As suggested in previous studies of ophiuroids (Bribiesca-Contreras et al., 2013), extraordinarily long arms of species could be an adaptation to cave life. Long arms also possess more tentacles than other species and it may help ophiuroids to find food resources in cave environments, with less predators. More detailed morphological examination of the arms is required to understand the peculiar behaviour of this new species.

Order Ophiacanthida O’Hara et al., 2017
Suborder Ophiidermatina Ljungman, 1867
Superfamily Ophiidermatoidea Ljungman, 1867
Family Ophiomyxidae Ljungman, 1867
Genus *Ophioconis* Lütken, 1869

Type species. *Pectinura forbesi* Heller, 1862.

Remarks. See included species and diagnosis for recent for Okanishi & Fujita, 2018b.

***Ophioconis clavicularis* Okanishi & Fujita, 2018b**
(Fig. 11A)

Ophioconis clavicularis Okanishi & Fujita, 2018b: 164–173, figs 2–6.
Ophioconis cupida non Koehler, 1905: Tan et al., 2014: 414; Fujita et al., 2015: 47.

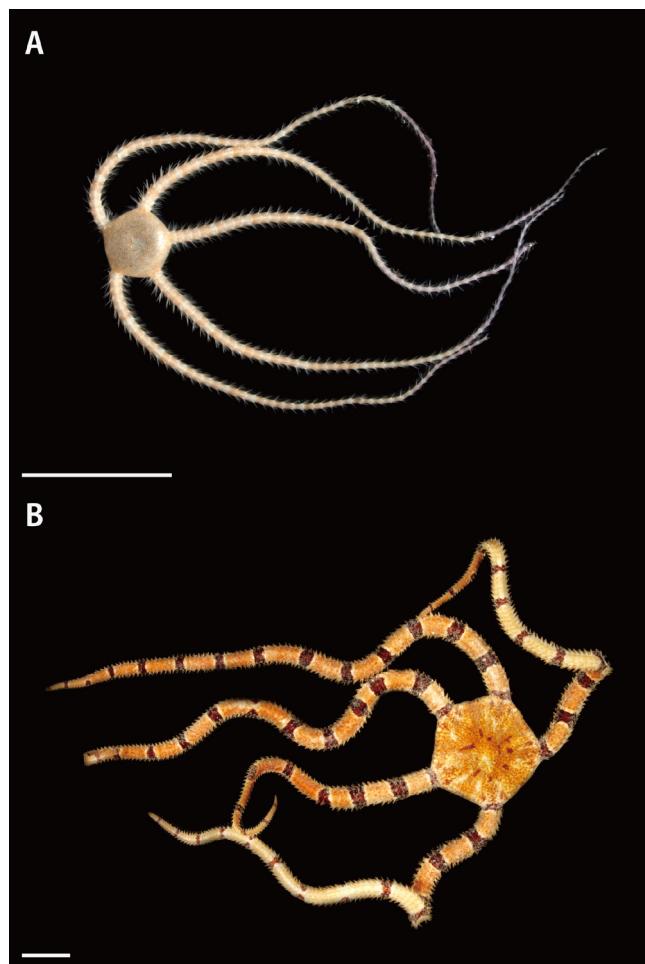


Fig. 11. Aboral views of *Ophioconis clavicularata* (RUMF-ZE-00155) (A) and *Ophiomora elegans* (RUMF-ZE-00142) (B), anesthetised living specimens. Scale bars = 1 mm.

Material examined. RUMF-ZE-00155, 2 specimens, submarine cave known as “Thunderdome Cave” at Christmas Island, northwestern Australia, depth approximately 10 m, bait trap with Pacific saury [*Cololabis saira* (Brevoort, 1856)], SCUBA diving, coll. Y. Fujita, 28 March 2011. Partly bleached to remove integuments.

Distribution. Known from the Ryukyu Islands, southwestern Japan, approximately 20–35 m depth (Okanishi & Fujita, 2018b); Christmas Island, northwestern Australia, a submarine cave known as “Thunderdome Cave”, approximately 10 m depth (This study, Fig. 1).

Common Japanese name. Konbou-awahada-kumohitode.

Remarks. Morphological features of examined two specimens correspond to the diagnostic characters of *Ophioconis clavicularata* Okanishi & Fujita, 2018b, disc covered by granules; four, sometimes five, flat, polygonal oral papillae on each side of jaw; broad and flat teeth with hyaline distal end; spiniform and conical arm spines, two times longer than the corresponding arm segment at the maximum length; oral-most arm spines on proximal portion of arms flattened and clavate; four tentacle scales on third tentacle pore; and ventral arm plate longer than wide, with concentrate lamellar striations.

The type specimens of *O. claviculata* were collected at Ryukyu Islands, southwestern Japan, 20–35 m depth and thus, its occurrence in northwestern Australia is a large extension of the geographical range to westward.

Ophiacanthida incertae sedis
Genus *Ophiomora* Koehler, 1907

Type species. *Ophiomora elegans* Koehler, 1907 (monotypic).

Diagnosis. Body covered by thick integument including no granules, scales nor plates, excepting the single transverse row of stout plates on marginal disc; extremely small, short genital slits, carrying small ossicles with thorns inside of the slits; instead of dorsal arm plates; small fragmented mosaic plates covering aboral surface of the arm; oral papillae and tentacle scale present distinctly; vertebrae having streptospondylous articulation form.

***Ophiomora elegans* Koehler, 1907**
(Figs. 11B, 12, 13)

Ophiomora elegans Koehler, 1907: 342, 343, pl. 14; H. L. Clark, 1915: 174; Tan et al., 2014: 413; Fujita et al., 2015: 50, 97.

Material examined. RUMF-ZE-00142, submarine cave “Thunderdome Cave” at Christmas Island, northwestern Australia, depth approximately 10 m, SCUBA diving, coll. Tan Heok Hui, 27 March 2011. Partly bleached to remove integuments.

Diagnosis. The same as the genus.

Description of external morphology (RUMF-ZE-00142). Disc. Circular, 22 mm in diameter, covered by thick skin, embedding small granules, approximately 200–400 µm in length (Figs. 11B, 12A). On aboral surface, removing the skin, radial shields exposing, bar-like, 3 to 4 times longer than wide, almost reaching to disc center (Fig. 12B). Stout polygonal plates also exposing and forming a single transverse row on lateral disc margin (Fig. 12B). On oral surface, removing the skin, adoral shields trapezoid, wider than long (Fig. 12D), approximately 1 mm at outer edge and 700 µm at inner edge in length, 1 mm in width, in contact with the first ventral arm plates (Fig. 12D). Oral plates thin, approximately 800 µm in length, 400 µm in width, contacting each other. Oral shields triangular, approximately as long as wide (Fig. 12C, D). One circular oral shield serving as madreporite and having at least three pores (Fig. 12C). Interradial oral disc covered only by skin (Fig. 12C). Genital slits small, along between 3rd and 4th arm segments (Figs. 12F, 13B), approximately 200 µm in length (Fig. 12C). Abradial genital plates visible on side of genital slit, bar-like, approximately 1.5 mm in length and 0.3 mm in width (Fig. 12E). Thorny granules inside of the genital slit, near the abradial genital plates (Fig. 12E). Four flat, subequal trapezoidal oral papillae at each adoral shield horizontally (Fig. 12C, D). Teeth triangular, forming single vertical row on dental plate (Fig. 12D). Second tentacle pore completely inside the mouth slit.

Arms. Five, all arms entire almost entire length, 50–75 mm long. Arms approximately 4.0 mm wide and 2.0 mm high, flatten. Arms tapering and flattening gradually distally (Figs. 11B, 13A, B, D–G).

Throughout the arm, dorsal arm plates absent and small fragmented plates, approximately 300–500 µm in length on aboral side (Fig. 13A). On distal portion of the arm, lateral arm plates contacting on mid line each other (Fig. 13B). On oral side, removing the skin, ventral arm plates polygonal, slightly wider than long, lateral sides concave, contiguous on proximal portion of the arm (Fig. 13C). On middle to distal portion of the arm, ventral arm plates triangular, pointing to proximal portion, and separated by each other (Fig. 13D). Lateral arm plates bearing arm spines, on proximal portion, 3 or 4 spines, long and pointed, and aboral-most spine approximately 1.5 times as long as corresponding arm segment, and other spines as long as corresponding arm segment (Fig. 13D, F). On middle portion of arm, 3 subequal long and pointed spines, approximately as long as the corresponding arm segment (Fig. 13G). On distal portion of arms, 2 subequal cylindrical and oval arm spines, approximately half to one-thirds length of corresponding arm segment (Fig. 13E). Tentacle scales 1, flat and fan-shaped, two-thirds to the same length of the corresponding arm segment, and outer one half to one-fourth length of the corresponding arm segment throughout the arms (Figs. 12F, 13D, E).

Colour in life. Body basic creamy white. On aboral surface, dense orange small spots appear except proximal portion of the arm where the spots are sparsely scattered (Fig. 11B). Deep purple bands present at intervals of 6 to 8 arm segments. Oral disc also creamy white with the deep purple bands on arms continuous from aboral surface (photo not shown).

Common Japanese name. Gama-kumohitode.

Distribution. Known from the type locality, the Fernando Veloso, near Inhaca Island, southern Republic of Mozambique, eastern coast of Africa (Koehler, 1907); Kumejima Island, the Ryukyu Islands, southeastern Japan, submarine cave, approximately 18 m depth (Fujita et al., 2015); Christmas Island, northwestern Australia, submarine cave known as “Thunderdome Cave”, approximately 10 m depth (this study, Fig. 1).

Remarks. In original description, Koehler’s examined single specimen had a disc diameter of 13 mm, almost 10 mm smaller than our examined specimen (22 mm in disc diameter). Koehler (1907) distinguished *Ophiomora* from other genera in the Ophiomyxidae in having small genital slits with carrying few calcareous ossicles beside them and one tentacle scale on each tentacle pore (Koehler, 1907). These characters are also recognised in our specimen (Fig. 11E, F). Considering the distinct characters, although this genus is now *incertae sedis* in the order Ophiacanthida, we maintain *Ophiomora* as a valid genus. Our extensive second description of this species revealed that this species has radial shields, which were stated in the original Koehler

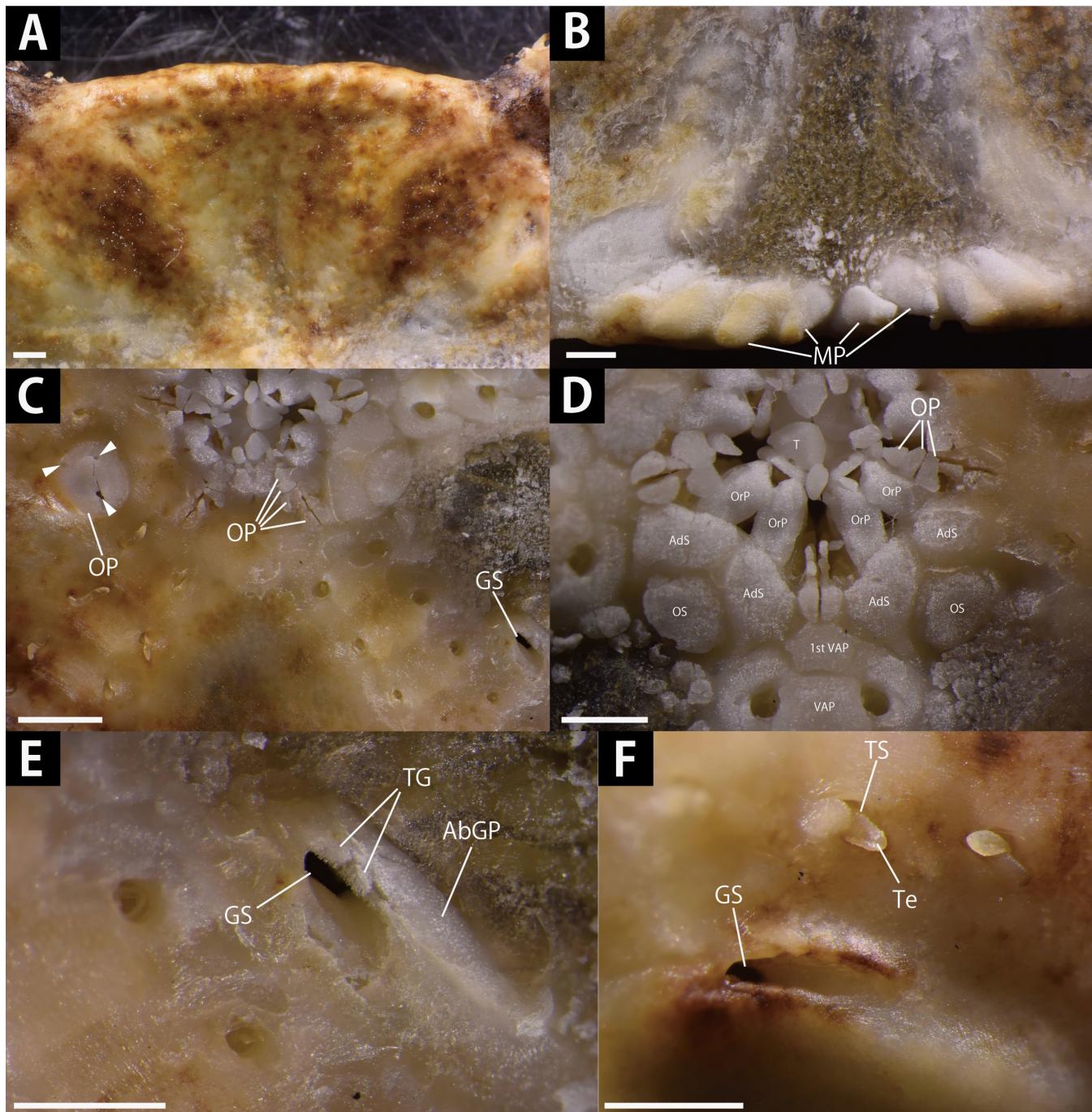


Fig. 12. *Ophiomora elegans* (RUMF-ZE-00142). A, aboral periphery part of the disc; B, aboral periphery part of the disc, skin removed; C, oral disc, skin partly removed; D, jaws, skin partly removed; E, interradial oral disc, genital slit, skin partly removed; F, genital slit and proximal portion of the arm. Abbreviations: AbGP, abradial genital plate; AdS, adradial shield; GS, genital slit; MP, marginal plate; OS, oral shield; OP, oral papillae; OrP, oral plate; T, teeth; TG, thorny granule; TS, tentacle scale; Te, tentacle; VAP, ventral arm plate. Scale bars = 1 mm.

(1907) as absent. However, of course, to determine the precise taxonomic position of this species, reexamination of the single type specimen of *Ophiomora elegans* is required.

The sampling locality of the present specimen (Christmas Island, northwestern Australia) is located midway between the type locality (East Africa) and the recent record from Japan. This geographical evidence indicates this species is widely distributed in the Indo-Western Pacific region (Koehler, 1907; Fujita et al., 2015).

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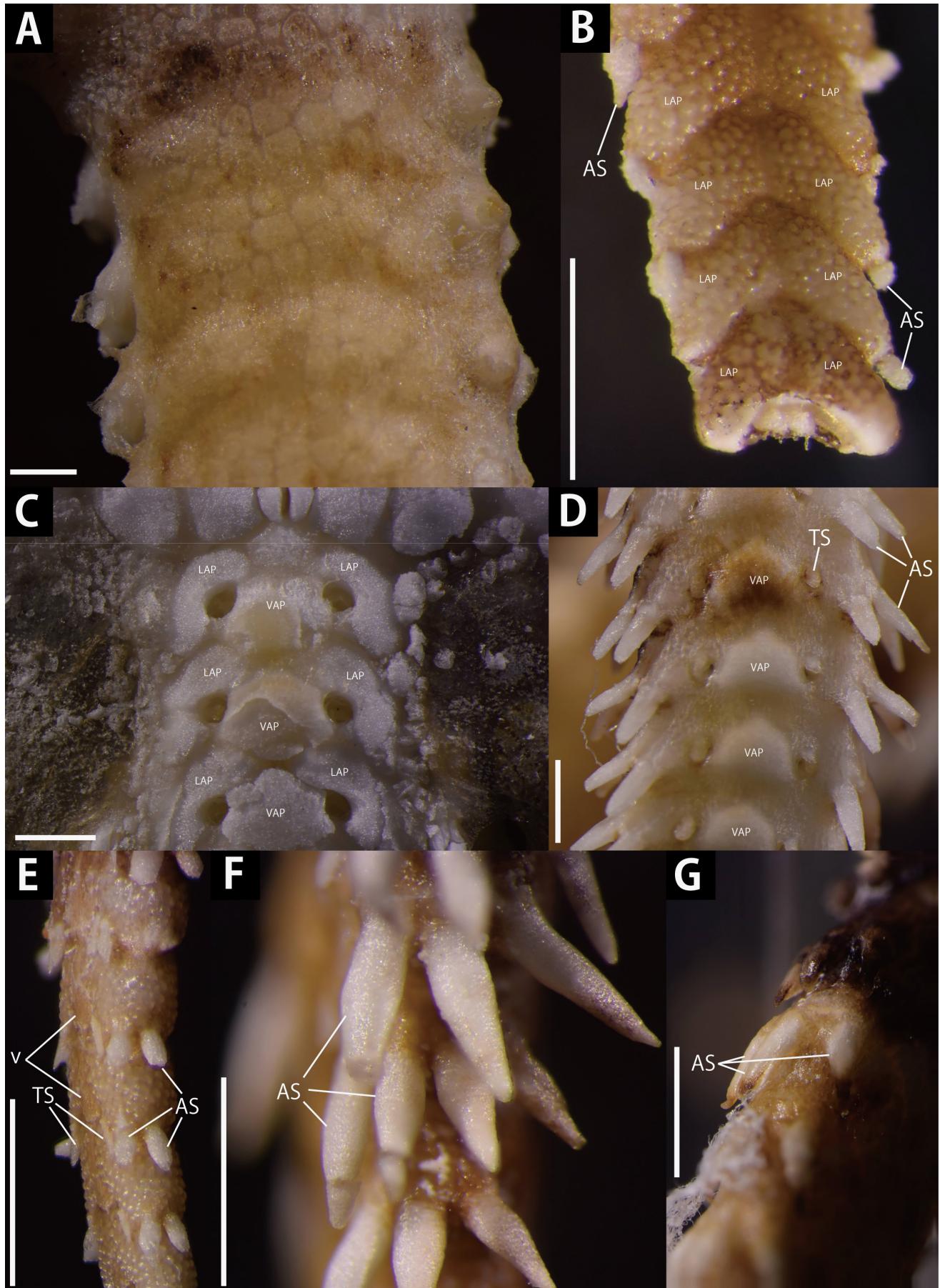


Fig. 13. *Ophiomora elegans* (RUMF-ZE-00142). A, aboral proximal portion of the arm; B, aboral distal portion of the arm; C, oral proximal portion of the arm; D, oral middle portion of the arm; E, oro-lateral distal portion of the arm. F, lateral proximal portion of the arm; G, lateral middle portion of the arm. Abbreviations: AS, arm spine; LAP, lateral arm plate; TS, tentacle scale; VAP, ventral arm plate. Scale bars = 1 mm.

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