

# A New Fissiparous Brittle Star, *Ophiacantha scissionis* sp. nov. (Echinodermata, Ophiuroidea, Ophiacanthida), from Jeju Island, Korea

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A new species of Ophiuroidea, *Ophiacantha scissionis* sp. nov., is described. It was collected from Munseom Island, Jeju-do, South Korea at a depth of 28–36 m, by SCUBA diving. *Ophiacantha scissionis* has unique and distinct morphological characteristics: small disk, densely covered by small trifold spines, radial shields completely concealed by disk spines, six arms with four arm spines proximally, fissiparous. In addition, this species is clearly distinguished from other species of *Ophiacantha* by mitochondrial *COI*. This species is usually hexamerous and reproduces asexually by fissiparity. It is the first report of fissiparous reproduction in the genus *Ophiacantha*.

**Key words:** Taxonomy, Phylogeny, Brittle stars, Ophiacanthidae, Mitochondrial *COI*.

## BACKGROUND

The class Ophiuroidea is the most diverse group in the phylum Echinodermata, with almost 2,100 described species (Stöhr et al. 2019). The genus *Ophiacantha* is eurybathic, distributed worldwide, and includes 131 extant species, making it the most diverse genus in the family Ophiacanthidae (Stöhr et al. 2019). *Ophiacantha* is polyphyletic, containing several groups of species that probably deserve their own genus and many other species that are difficult to place taxonomically (O'Hara and Stöhr 2006; O'Hara et al. 2018).

DNA barcoding employs sequence variation in a 658 bp region of the mitochondrial cytochrome *c* oxidase subunit I (*COI*) gene as a tool for specimen identification and species discovery (Hebert et al. 2003). An integrative approach to taxonomy (*i.e.*, using

morphological characters from preserved specimens, as well as one to several genes) has emerged as a powerful and necessary means for assessing species diversity and species boundaries (Puillandre et al. 2012). The class Ophiuroidea has been reported to have high interspecific divergence within genera (5.6–31.6%) and low intraspecific distance (< 6.4%) (Boissin et al. 2017). Therefore, DNA barcoding has proven an effective tool for species identification in the Ophiuroidea and other echinoderms (Hoareau and Boissin 2010; Layton et al. 2016; Boissin et al. 2017; Uthicke et al. 2010; Ward et al. 2008). This study reports a new species of *Ophiacantha* with a detailed morphological description and mitochondrial analysis. Moreover, this species is the first case of fissiparous reproduction in the genus *Ophiacantha*. Thus, we present morphological variations of fissiparity for the new species of *Ophiacantha*.

## MATERIALS AND METHODS

### Sample collection and preservation

Ophiuroids were collected from Munseom Island, which is located on the southern coast of Jeju-do, South Korea (Fig. 1). Samples were collected by SCUBA diving and carefully picked out from bryozoans, then immediately preserved in > 95% ethyl alcohol solution. The sorted samples were deposited at the Marine Echinoderm Resources Bank of Korea (MERBK).

### SEM and stereomicroscope photograph of brittle stars

The holotype and paratypes were lightly bleached following Stöhr et al. (2012), before being examined by scanning electron microscopy (SEM) and stereomicroscopy. Bleached specimens were dried in a drying oven for 6 hours at 55°C, then photographs were taken with a JEOL JSMmicroscope 6510 SEM and a Nikon SMZ 1000 stereomicroscope. The oral skeleton was interpreted following Hendler (2018).

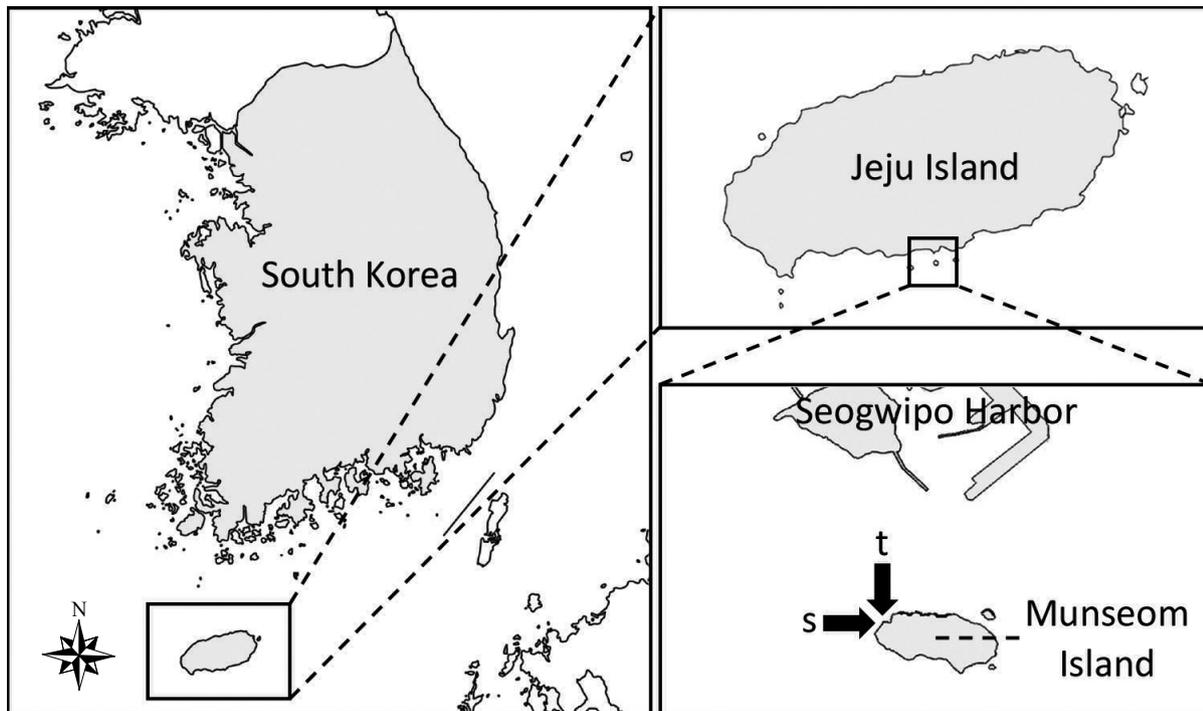
### Genomic DNA extraction and amplification of partial sequences of mitochondrial *COI*

Total genomic DNA was extracted from arm

tissue following the DNeasy kit protocol (Qiagen, Hilden, Germany). The partial sequence of the mitochondrial *COI* gene was amplified using a pair of primers conserved in echinoderms, OphiF1 (Driskell unpublished) and COIceR (Hoareau and Boissin 2010). PCRs were performed with initial denaturation step of 95°C/2 min, followed by 35 cycles of 95°C/30 sec, 52°C/60 sec and 72°C/60 sec with a final extension step at 72°C/7 min, after which the samples were stored at 4°C. PCR product quality was assessed by electrophoresis with 1.0% agarose gel and the NanoDrop 1000 (Thermo Scientific, Waltham, MA, USA). PCR products were sequenced using ABI Big Dye Terminator kits (Applied Biosystems, Foster City, CA, USA) on the ABI 3730XL DNA Analyzer.

### Analysis of phylogenetic relationships based on mitochondrial *COI*

For phylogenetic analyses, we used 27 sequences of ophiuroids for *COI*, including three sequences of the new species and 24 sequences of ophiuroids from GenBank, including 16 other *Ophiacantha* species, and 3 Ophiothamnidae, 1 each of Ophiopholidae and Ophiotrichidae, and 2 Euryalidae as outgroups (Table 1). Phylogenetic analyses for the *COI* dataset were performed using two methods: maximum likelihood (ML), using RAxML 8.2 (Stamatakis



**Fig. 1.** Sampling locations of *Ophiacantha scissionis* sp. nov. s, sampling site of paratypes and specimens of *O. scissionis* sp. nov.; t, type locality of holotype and specimens of *O. scissionis* sp. nov.

2014), and Bayesian inference (BI), using MrBayes 3.2.6 (Huelsenbeck and Ronquist 2001). The best-fit nucleotide sequence substitution models for each gene were estimated using jModelTest 2.1.1 (Guindon and Gascuel 2003; Darriba et al. 2012). RAxML was used for the ML analyses with 1,000 bootstrap replicates with TIM1+I+G model, and was performed with rapid bootstrapping and searches for the best-scoring ML tree. Bayesian analysis was performed using 1,000,000 generations of Markov Chain Monte Carlo chains with HKY + I + G model, sampled every 1,000 generations, and the initial 250 generations were discarded as burn-in.

## RESULTS

### TAXONOMY

#### Class Ophiuroidea Gray, 1840

#### Superorder Ophintegrida O'Hara, Hugall, Thuy, Stöhr and Martynov, 2017

#### Order Ophiacanthida O'Hara, Hugall, Thuy, Stöhr and Martynov, 2017

#### Suborder Ophiacanthina O'Hara, Hugall, Thuy,

#### Stöhr and Martynov, 2017

#### Family Ophiacanthidae Ljungman, 1867

#### Genus *Ophiacantha* Müller and Troschel, 1842

#### *Ophiacantha scissionis* sp. nov.

(Figs. 2–11)

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*Material examined:* Holotype: MERBK-O-21898, Munseom Island, southern Jeju-do, South Korea (33°13'38.2"N, 126°33'47.4"E), depth 35.7 m, water temperature 19.3°C, 27 November 2018, SCUBA diving, T. Lee (Fig. 2). Paratype 1: MERBK-O-21899, Munseom Island, southern Jeju-do, South Korea (33°13'38.2"N, 126°33'47.4"E), depth 31.5 m, water temperature 19.3°C, 27 November 2018, SCUBA diving, T. Lee. Paratype 2: MERBK-O-21900, Munseom Island, southern Jeju-do, South Korea (33°13'38.7"N, 126°33'47.3"E), depth 32.8 m, water temperature 19.3°C, 28 November 2018, SCUBA diving, T. Lee. 29 specimens (MERBK-O-21901), Munseom Island, southern Jeju-do, South Korea (33°13'38.2"N, 126°33'47.4"E), depth 35.7 m, water temperature 19.3°C, 27 November 2018, SCUBA

**Table 1.** Classification and GenBank accession numbers of *COI* sequences in this study

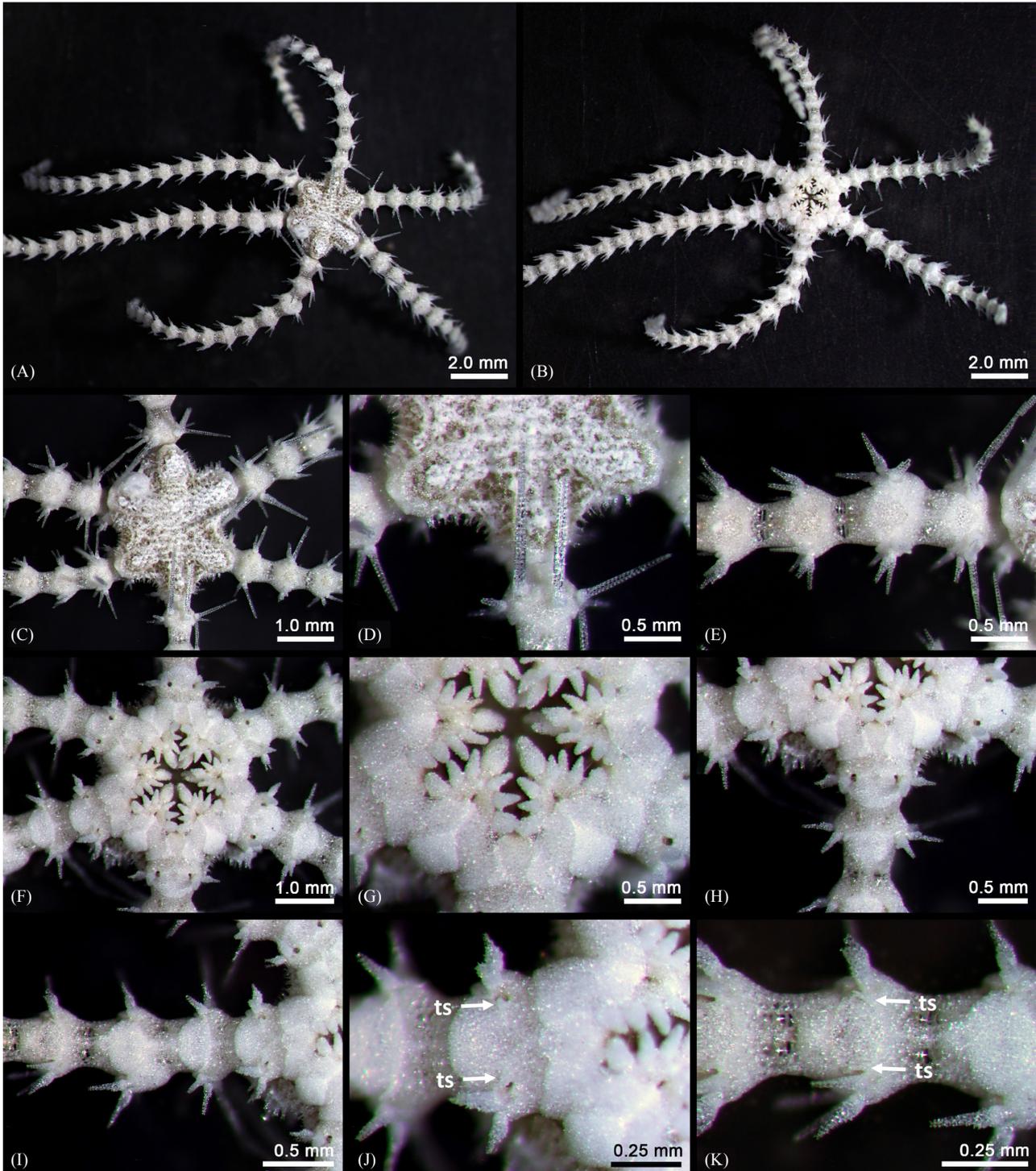
Species	Family	Order	Superorder	GenBank accession number	References
<i>Ophiacantha alternata</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895374	Hugall et al. 2016
<i>Ophiacantha antarctica</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895385	Hugall et al. 2016
<i>Ophiacantha brachygnatha</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895386	Hugall et al. 2016
<i>Ophiacantha densispina</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895380	Hugall et al. 2016
<i>Ophiacantha funebris</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895370	Hugall et al. 2016
<i>Ophiacantha linea</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	NC_023254	Park 2013
<i>Ophiacantha indica</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895373	Hugall et al. 2016
<i>Ophiacantha longidens</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895375	Hugall et al. 2016
<i>Ophiacantha otagoensis</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895388	Hugall et al. 2016
<i>Ophiacantha pentactis</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895376	Hugall et al. 2016
<i>Ophiacantha richeri</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895387	Hugall et al. 2016
<i>Ophiacantha rosea</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895383	Hugall et al. 2016
<i>Ophiacantha scissionis</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	MK495802-MK495804	This study
<i>Ophiacantha striolata</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895371	Hugall et al. 2016
<i>Ophiacantha vepretica</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895372	Hugall et al. 2016
<i>Ophiacantha vivipara</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895381	Hugall et al. 2016
<i>Ophiacantha yaldwyni</i>	Ophiacanthidae	Ophiacanthida	Ophintegrida	KU895384	Hugall et al. 2016
<i>Ophiactis savignyi</i>	Ophiactidae	Gnathophiurina	Amphilepidida	KU895153	Hugall et al. 2016
<i>Ophiolella elegans</i>	Ophiothamnidae	Ophiothamnidae	Ophiothamnidae	KU895364	Hugall et al. 2016
<i>Ophiothamnus bioical</i>	Ophiothamnidae	Ophiothamnidae	Ophiothamnidae	KU895365	Hugall et al. 2016
<i>Ophiothamnus hasbrotatus</i>	Ophiothamnidae	Ophiothamnidae	Ophiothamnidae	KU895366	Hugall et al. 2016
<i>Ophiopholis aculeata</i>	Ophiopholidae	Gnathophiurina	Amphilepidida	NC_005334	Smith et al. 1993
<i>Ophiothrix (Ophiothrix) exigua</i>	Ophiotrichidae	Gnathophiurina	Amphilepidida	KU895438	Hugall et al. 2016
<i>Asteromorpha capensis</i>	Euryalidae	Euryalida	Euryophiurida	AB758754	Okanishi and Fujita 2013
<i>Astroceras annulatum</i>	Euryalidae	Euryalida	Euryophiurida	AB758778	Okanishi and Fujita 2013

diving, T. Lee. 43 specimens (MERBK-O-21902), Munseom Island, southern Jeju-do, South Korea (33°13'38.7"N, 126°33'47.3"E), depth 32.8 m, water temperature 19.3°C, 28 November 2018, SCUBA

diving, T. Lee.

*Type locality:* Munseom Island, Jeju-do, South Korea, 33°13'38.2"N, 126°33'45.4"E, 35.7 m (Fig. 1).

*Description of the holotype:* Disk diameter



**Fig. 2.** *Ophiacantha scissionis* sp. nov., holotype, stereo-microscopic images. A, dorsal side; B, ventral side; C, dorsal side of disk; D, margin of disk and proximal arm; E, dorsal side of proximal arm; F, ventral side of disk; G, oral frame; H, ventral side of arm and oral frame on proximal arm; I, ventral side of proximal arm; J, first tentacle scales on ventral side of proximal arm; K, tentacle scales on middle arm. ts, tentacle scale.

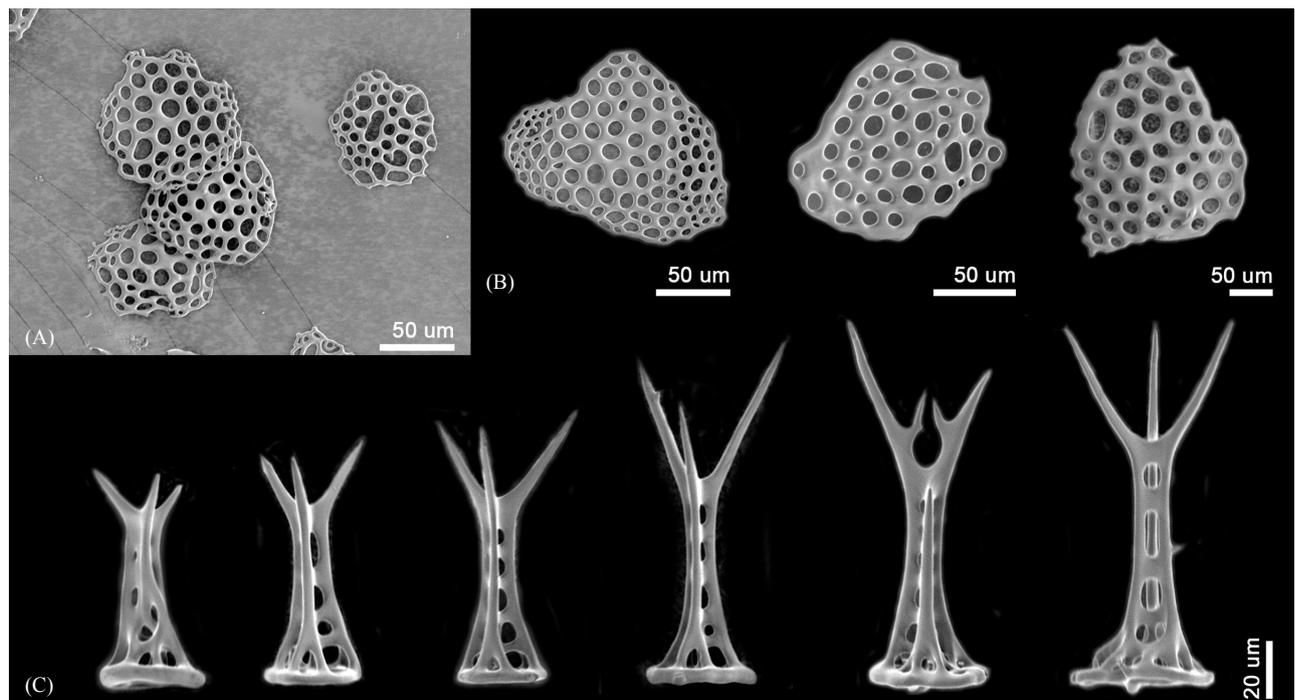
2.0 mm, moderately high, constricted interradially, six arms of almost same size, length of longest arm 9.8 mm (Figs. 2A, B). Arms distinctly moniliform (Figs. 2A, B, E). Disk covered with small, perforated, overlapping scales concealed by thin skin. Small spines densely cover aboral side of disk (Figs. 2C, D), distal part split into three sharp thorns, pillar of spine perforated, basal part usually circular.

Oral shields longer than wide (Figs. 2F, G), with straight or slightly concave margins. Adoral shields longer than wide (Fig. 2G), almost 2.5 times as long as wide. Jaw as wide as long (Fig. 2G), with one blunt and serrated ventralmost tooth. Oral papillae interpreted as proximalmost conical, pointed infradental papilla, 1–2 similar pointed lateral oral papilla(e), and distalmost a larger adoral shield spine with blunt tip (Figs. 2G, H).

First dorsal arm plate as wide as long with obtuse proximal angle and convex distal border (Fig. 2E). Succeeding plates separated, similar to first dorsal arm plate and guitar pick-shaped, wider than long. Lateral arm plate twice as long as wide, with distinctly concave proximal lateral side and distal side more convex than proximal side (Figs. 2E, I, K). Arm spines four proximally, straight, tapered to tip, slightly serrated. Uppermost arm spine longest, reaching to next dorsal arm plate, three times longer than other arm spines at same lateral arm plate (Fig. 2D). After third lateral arm plate, uppermost arm spine rapidly shortening, similar to

other arm spines at same lateral arm plate. One tentacle scale across entire arm, proximally a short and obtuse scale (Fig. 2J), further out a small spine-like scale (Fig. 2K). Color in life brownish-gray.

*Description of the paratypes:* Paratype 1 and 2 are six-armed specimens. The paratypes and other 72 specimens share the same morphological characteristics with the holotype, except for number of arms. Disk diameter 1.3–2.2 mm in two paratypes and 72 specimens, usually with six arms, rarely five and only one specimen with seven arms. Arm spines four to five proximally. Disk scales perforated irregular circles, covered with thin skin (Figs. 3A, B). Disk spines usually trifold but sometimes branched tips present (Fig. 3C). Genital plates small, narrow, tapered to tip and boomerang-shaped (Fig. 4A). Radial shield narrow, long and bent, almost a third of disk diameter long (Fig. 4B). Arm spines usually four proximally, dorsalmost longest (Fig. 4F), rapidly getting shorter ventralwards (Fig. 4C). Dorsal arm spines with serrated tips (Fig. 4F), ventral arm spines more coarsely serrated (Fig. 4C). Arm spine articulation not of typical ophiacanthid form, strikingly similar to amphilepidid form with two parallel lobes (dorsal lobe strongly bent), only weakly connected at their proximal ends, lacking a sigmoidal fold (Figs. 4D, E). Dorsal and ventral arm plates getting shorter and rounder from proximal to distal (Figs. 5A, B). Lateral plate and vertebrae getting longer from proximal

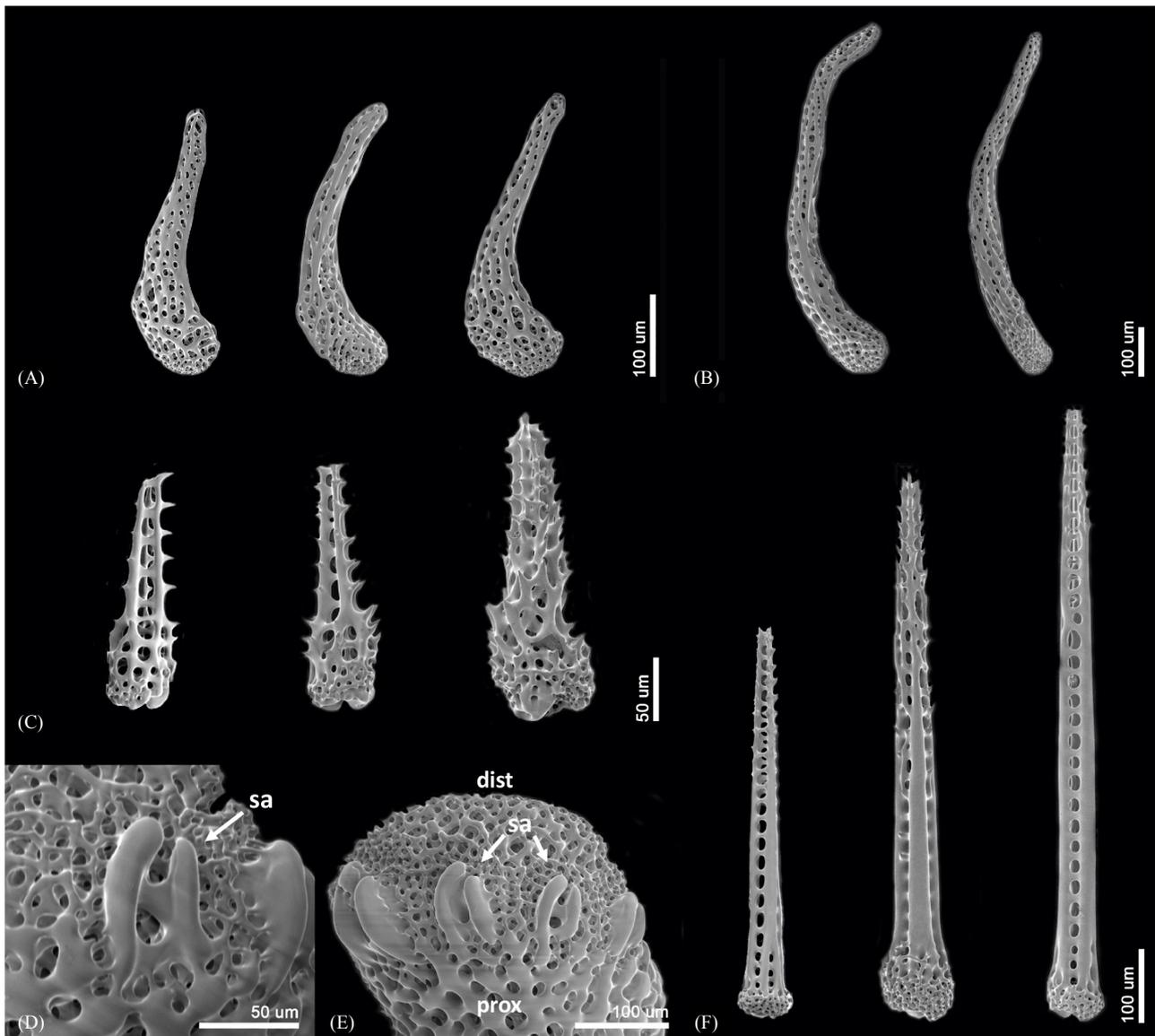


**Fig. 3.** *Ophiacantha scissionis* sp. nov., scales and spines of disk, SEM images. A, B, disk scales; C, disk spines.

to distal (Figs. 5C, F–H). Vertebrae elongated, with zygospondylous articulation (Fig. 6). Adoral muscle flanges larger than oral muscle flanges at proximal side (Figs. 6A, B) and oral muscle flanges of distal side wider than proximal side (Fig. 6C). Muscle flanges of proximal side slightly wider than distal side (Fig. 6F). Oral plates (half-jaws) elongated, almost twice as long as high (Figs. 7A–D), and adradial muscle attachment area small (Fig. 7B). On ventral surface of vertebra, a flat area of smooth and less perforated stereom with a conspicuous pore, interpreted as fossa and articulation surface for oral papillae (Fig. 7C). Adoral shields longer than wide and larger than oral shield (Fig. 7E). Oral

shields longer than wide and constricted at middle part (Fig. 7F). Dental plate small, convex, elongate, with three to four round tooth sockets with low smooth borders, not perforating the plate (Fig. 7G). Ventralmost tooth largest, second tooth smaller, both lanceolate in shape and larger than oral papillae (Fig. 7H). Infradental papilla and lateral oral papilla small, similar, slightly conical, and adoral shield spine larger than others, with blunt tip (Fig. 7I). First tentacle pore larger than others (Fig. 8). Tentacle scales getting longer and sharper from proximal to distal (Fig. 8).

*Habitat and ecology:* All specimens of *O. scissionis* sp. nov. were found on a bryozoan,

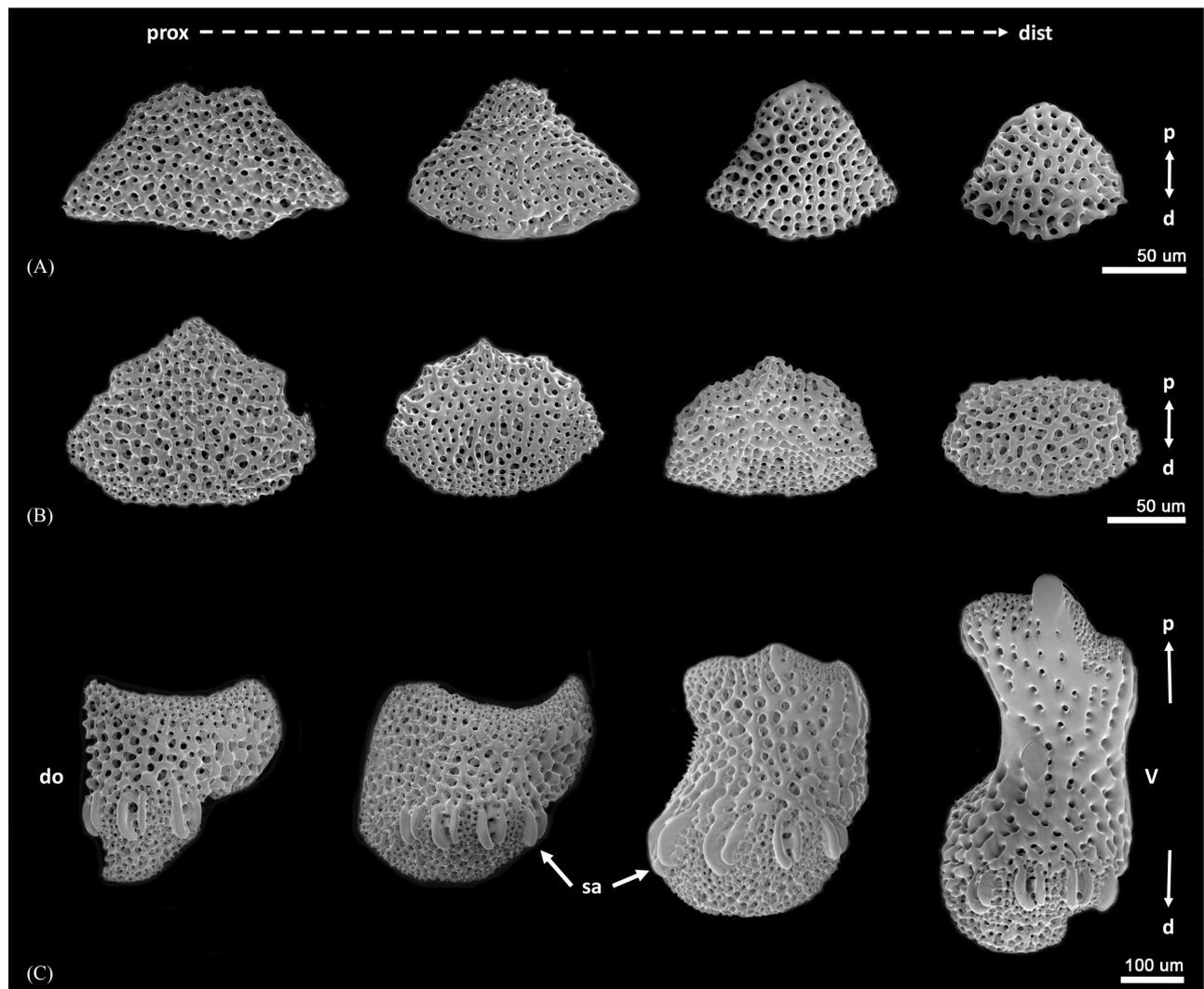


**Fig. 4.** *Ophiacantha scissionis* sp. nov., genital plate, radial shield, arm spines and arm spine articulations, SEM images. A, adradial genital plates; B, radial shields; C, lower arm spines of lateral arm plate on basal arm; D, E, arm spine articulations on lateral arm plate; F, upper arm spines of basal lateral arm plate. dist, distal side; prox, proximal side; sa, spine articulation.

*Bantariella bocki* (Silén, 1942). This bryozoan is distributed from southern Japan (Bonin Islands) to Jeju Island, South Korea; it has been suggested that the species is spreading due to increasing water temperatures (Seo et al. 2009). The Bonin Islands are located at similar latitude as Taiwan and at the boundary between subtropical and tropical waters (Seo et al. 2009). The sampling location, Munseom Island in Southern Jeju Island, is affected by a warm current (the Kuroshio current) all year round and the water temperature in the waters surrounding Munseom Island ranges from 16 to 26°C over a year (Ko et al. 2008). In deep water off Munseom Island, we observed that bryozoans covered black coral (*Myriopathes japonica* (Brook, 1889) and *M. lata* (Siberfeld, 1909)). Specimens of *O. scissionis* sp. nov. were not found on corals, they inhabited only the bryozoan *B. bocki*. It is at present unknown if the

ophiuroids obligately occur on these bryozoans and are spreading together with them. Several species of ophiuroid are known to live epizoid on black coral, e.g., species of *Ophiocanops* (Stöhr et al. 2008) and *Astrogymnotes* (Baker et al. 2001). Little is known about these associations, but the corals may provide raised vantage points from which the ophiuroids can collect food particles in the water column, and the brittle stars may hide from predators among the branches of the corals. Although *O. scissionis* sp. nov. seems not to be associated with the corals themselves, it probably indirectly benefits from them. Perhaps the filter feeding current created by bryozoans also transports food to the ophiuroids. More research is needed to understand these relationships.

*Remarks:* Most specimens of *O. scissionis* sp. nov. have an incomplete disk and six arms of different size.



**Fig. 5.** *Ophiacantha scissionis* sp. nov., arm skeleton, SEM images. A, dorsal plates; B, ventral plates; C, lateral plates. d, dist, distal; do, dorsal; p, prox, proximal; sa, spine articulation; v, ventral.

Three of the six arms are complete and long but the others seem to be regenerating, as does the disk. This species appears to reproduce asexually by fission. The series of oral papillae was interpreted based on their position on the jaw edge compared to *Ophiacantha bidentata* (Bruzelius, 1805), as shown by Hendler (2018), because no developmental series was available to trace the origin of each papilla. We agree that the term apical papilla has been applied to a variety of non-homologous structures and should be abandoned. The term infradental papilla has been redefined by Hendler (2018) to the proximalmost papilla on the oral plate, not on the dental plate as was long believed. The fossae and articulation surfaces of the oral papillae on the oral plate appear not well defined in *O. scissionis* sp. nov., except for the middle one. This may perhaps be a sign of incomplete regeneration in the selected specimen.

**Etymology:** The specific name is derived from the Latin term *scissio*, meaning split.

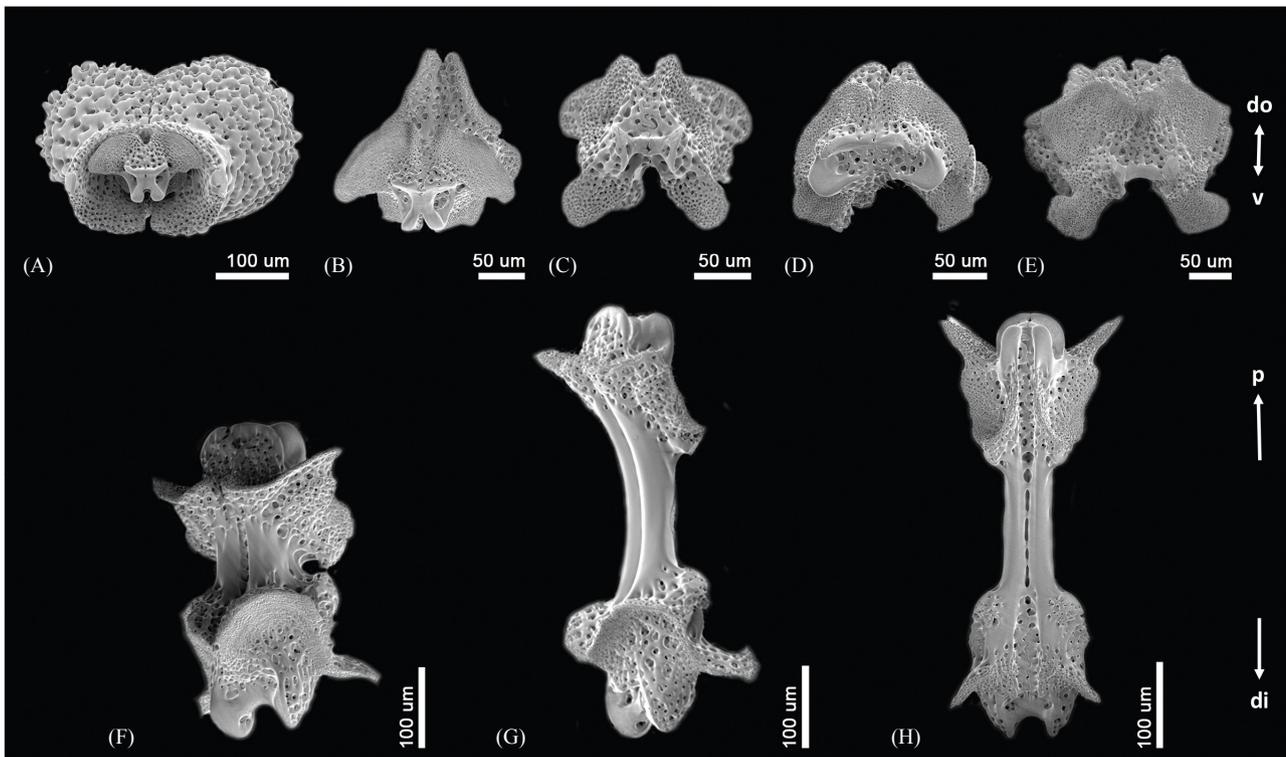
**Fissiparous morphological characteristics of *O. scissionis* sp. nov.**

Most specimens of *O. scissionis* sp. nov. have six arms (the whole animal being hexamerous), among

them, three arms complete and the others regenerating (Fig. 9). After division, the oral frame of a specimen consists of two complete jaws and two half split jaws, to either side of the complete jaw (Fig. 9). Also, often the three larger and older arms are not the same size, as these may be the result of several previous splits that are not on the same plane (Fig. 9B). Our specimens with five arms presented two division types, one is divided with three arms and the other is divided with two arms (Fig. 10). After that, the specimens grow five or six arms, becoming pentamerous or hexamerous. Some specimens presented a stage shortly after division (Fig. 11), and in these the arms began to regenerate prior to the oral frame (Fig. 11).

**Phylogenetic relationships and diversity based on partial sequences of *COI***

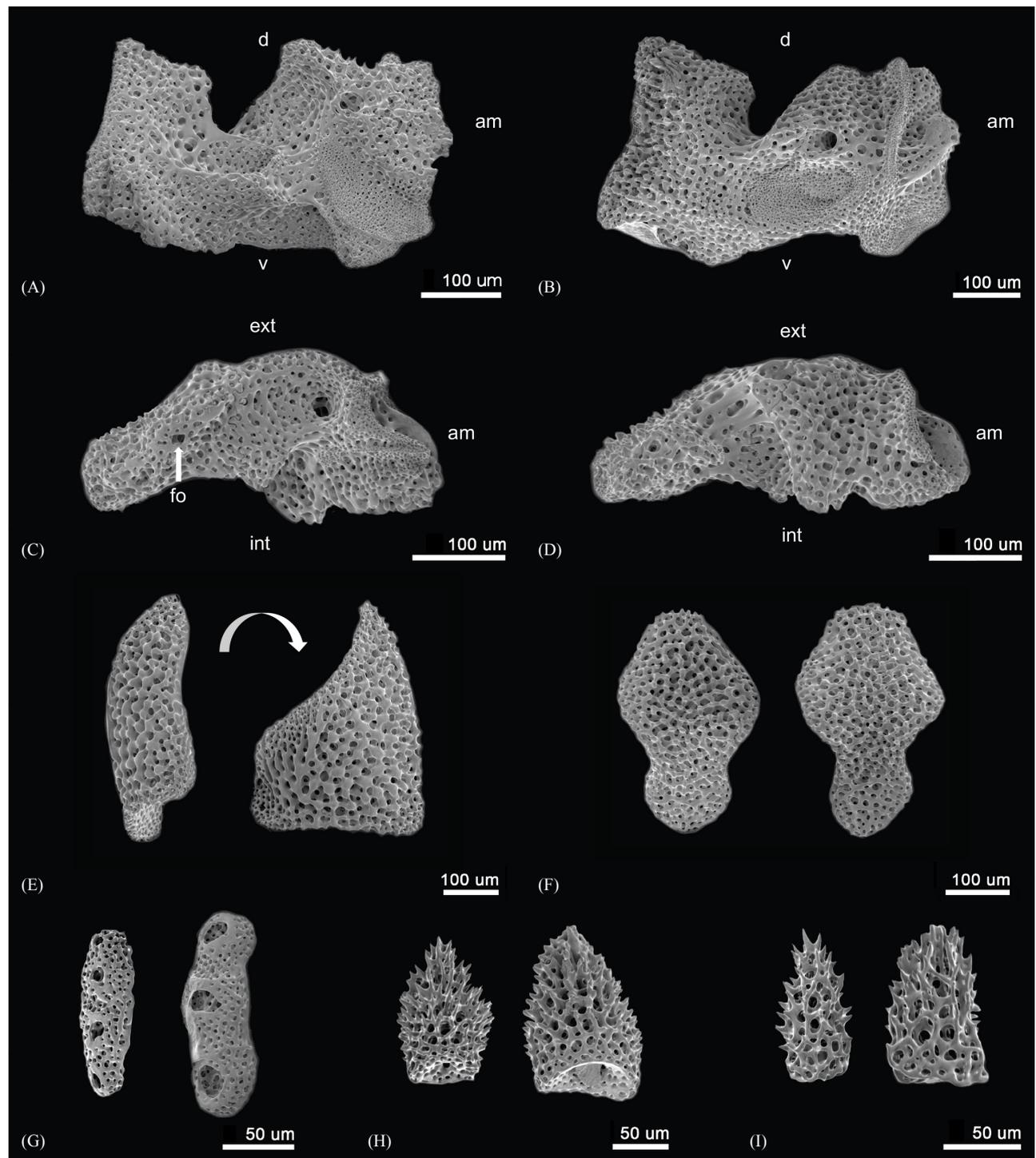
We investigated 17 species of *Ophiacantha* based on partial sequences of mitochondrial *COI*, including *O. scissionis* sp. nov. The dataset had a length of 663 bp and overlapped with the universal region of DNA barcoding in echinoderms (658 bp in anterior region of *COI*). The clade of the genus *Ophiacantha* is a monophyletic group, subdivided into two clades



**Fig. 6.** *Ophiacantha scissionis* sp. nov., vertebrae, SEM images. A, proximal cross section of arm skeleton; B, proximal side of vertebra; C, distal side of vertebra; D, proximal side of first vertebra; E, distal side of first vertebra; F, dorsolateral side of vertebra from proximal part of arm; G, lateral side of vertebra from middle part of arm; H, ventral side of vertebra from middle part of arm. di, distal; do, dorsal; p, proximal; v, ventral.

(Fig. 12). *Ophiacantha scissionis* sp. nov. is clearly distinguished from other species of *Ophiacantha* in both analyses (ML and BI), and its closest sister taxa are *O.*

*antarctica* Koehler, 1900, *O. brachygnatha* H.L. Clark, 1928, *O. otagoensis* Fell, 1958, *O. richeri* O'Hara and Stöhr, 2006 and *O. yaldwyni* Fell, 1958 (Fig. 12).



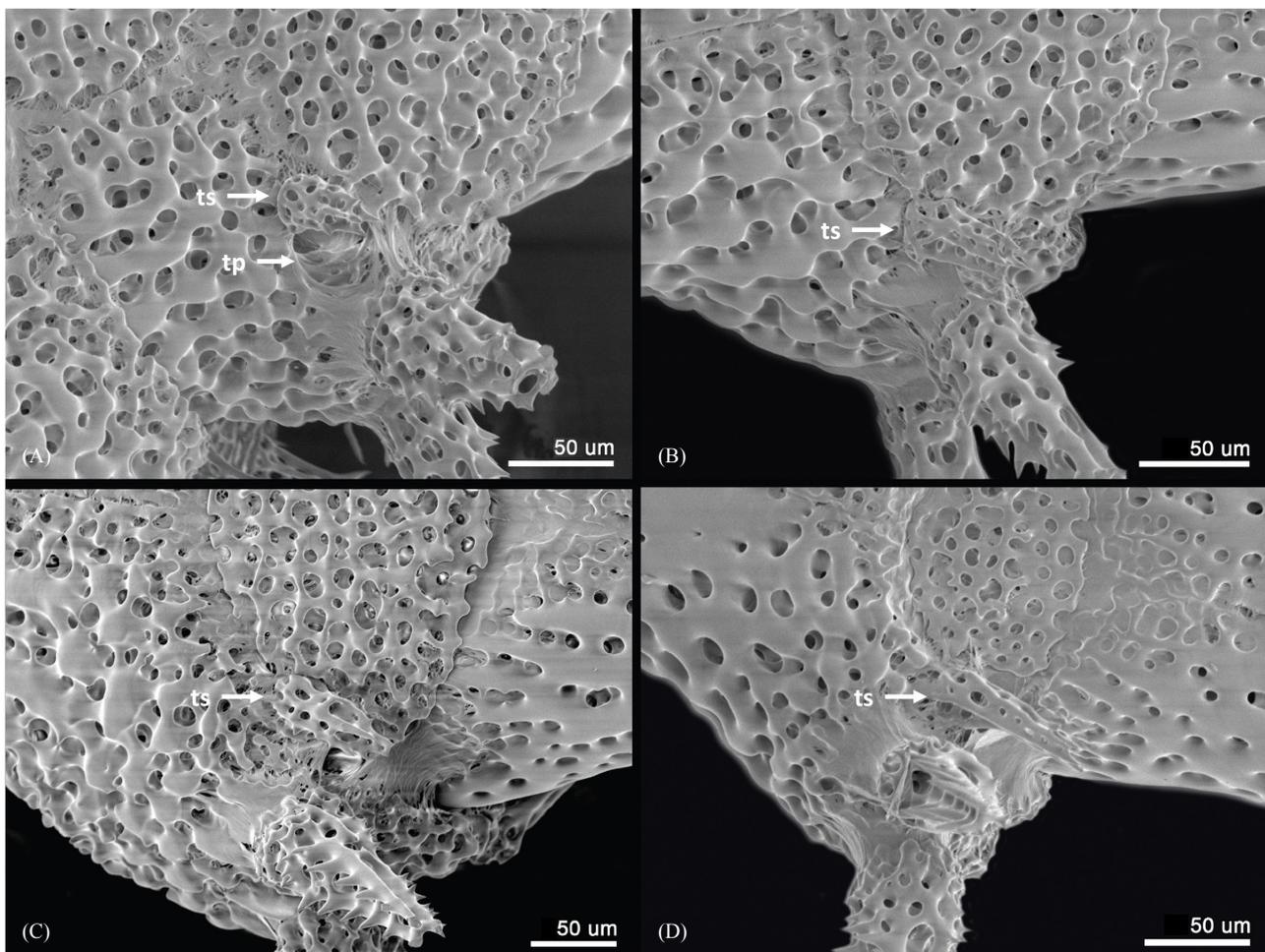
**Fig. 7.** *Ophiacantha scissionis* sp. nov., jaws, dental and oral plates, SEM images. A, adradial side of oral plate (half-jaw); B, abradial side of oral plate (half-jaw); C, ventral side of oral plate (half-jaw); D, dorsal side of oral plate (half-jaw); E, adoral shields; F, oral shields; G, dental plate; H, ventralmost teeth; I, infradental papilla (left) and adoral shield spine (right). am, articulation to arm vertebra; d, dorsal; ext, external; fo, fossa; int, internal; v, ventral.

The inter- and intra-specific pairwise distances (*p*-distance) of *Ophiacantha* estimated using the Kimura 2-parameter are summarized in table 2. The inter-specific *p*-distance of 17 species of *Ophiacantha*, including *O. scissionis* sp. nov., ranged from 12.3% to 38.5%, average 27.0% (Table 2). The inter-specific *p*-distance of 16 species of *Ophiacantha*, excluding for *O. scissionis* sp. nov., ranged from 12.3% to 38.7%, with average 26.8% (Table 2). The inter-specific *p*-distance between *O. scissionis* sp. nov. and other species of *Ophiacantha* ranged from 13.6% to 38.5%, average 27.4%, which is slightly higher than average values of *Ophiacantha*, with or without *O. scissionis* sp. nov. The lowest *p*-distance between *O. scissionis* sp. nov. and other *Ophiacantha* suggests a relationship with *O. otagoensis* (13.4–13.6%) and the highest with *O. striolata* (38.2–38.5%) (Table 3). The intra-specific *p*-distance of *O. scissionis* sp. nov. is 0.0–0.2% (Table 2).

## DISCUSSION

### Comparison between *Ophiacantha scissionis* sp. nov. and related species

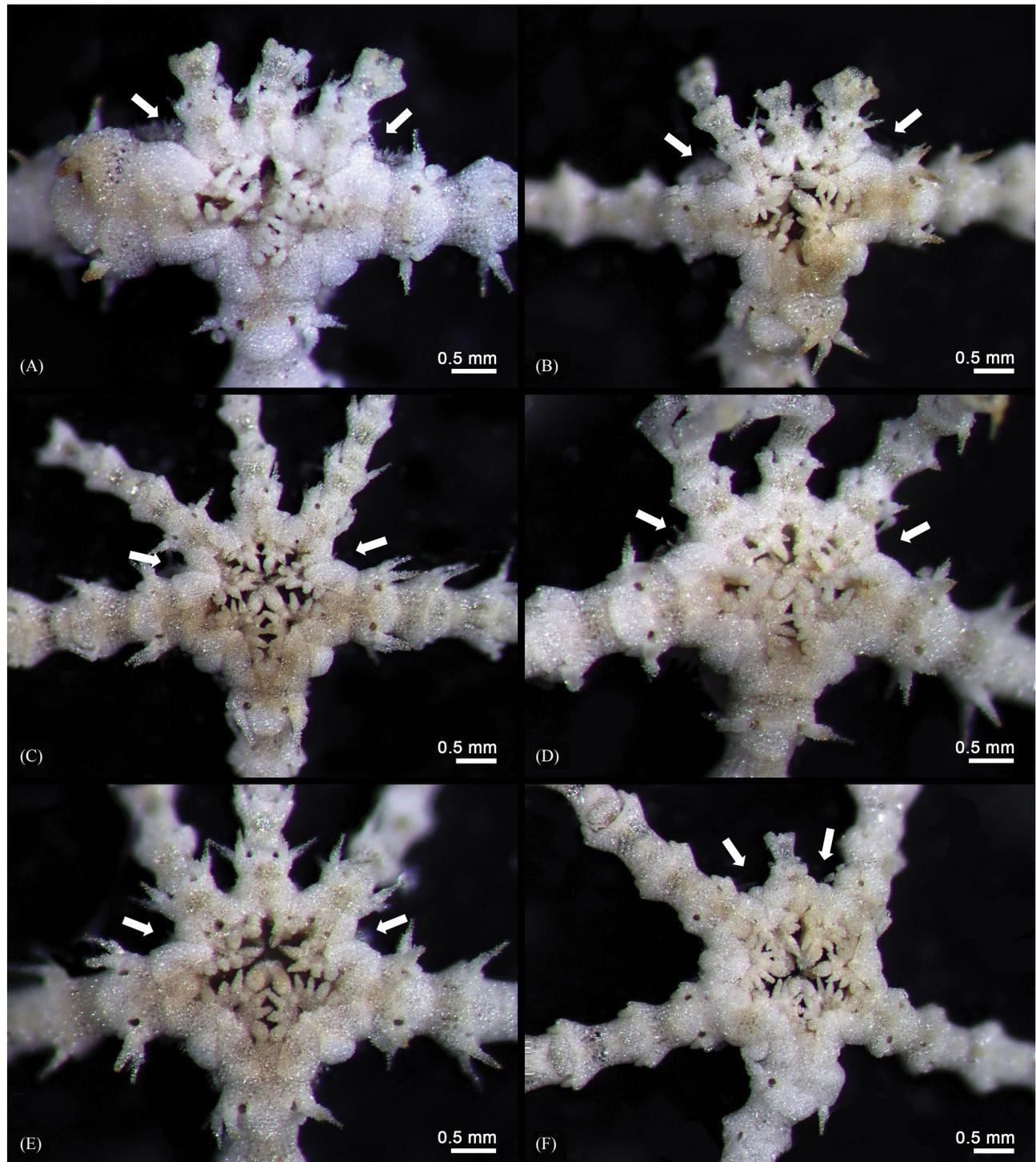
*Ophiacantha scissionis* sp. nov. is morphologically distinct with dividing disk and six arms, usually showing signs of regeneration. We compared morphologically similar species with *O. scissionis* sp. nov. (Table 3). Species with hexamerous or higher symmetry are rare in the genus *Ophiacantha*, only five of 131 recognized species, *O. anomala* G.O. Sars, 1872, *O. decaactis* Belyaev and Litvinova, 1976, *O. enneactis* H.L. Clark, 1911, *O. nodosa* Lyman, 1878 and *O. vivipara* Ljungman, 1871. Stöhr (2003) suggested that *O. anomala* and *O. nodosa* may be conspecific (because the characters of *O. nodosa* appear to fall within the variability of *O. anomala*; Stöhr unpublished results), thus *O. scissionis* sp. nov. was compared to four multi-



**Fig. 8.** *Ophiacantha scissionis* sp. nov., tentacle scales, SEM images. A, first tentacle scale and tentacle pore; B, second tentacle scale; C, third tentacle scale; D, tentacle scale on distal part of arm. tp, tentacle pore; ts, tentacle scale.

rayed species of *Ophiacantha*, excluding *O. nodosa* (Table 3). Among them, *O. vivipara* has 6 to 8 arms and 11 to 12 arm spines, whereas all others have fewer than 8 arm spines, including *O. scissionis* sp. nov. (Table 3). Moreover, the phylogenetic analysis supported that *O.*

*vivipara* is clearly a different species from *O. scissionis* sp. nov. *Ophiacantha decaactis* and *O. enneactis* have 10 and 9 arms, respectively, and their tentacle scales are larger and oval in shape (Belyaev and Litvinova 1976; Clark 1911), whereas *O. scissionis* sp. nov. has usually



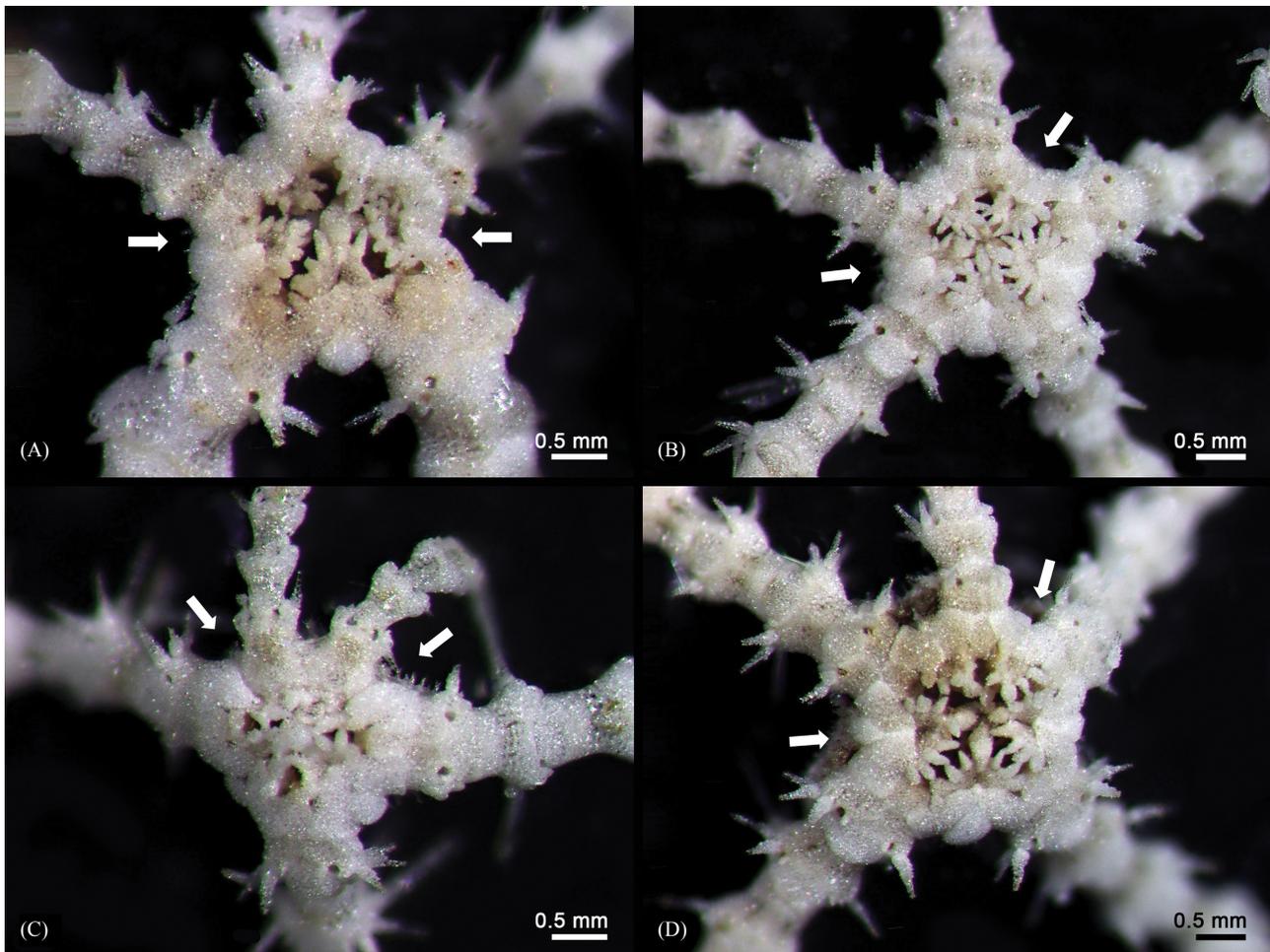
**Fig. 9.** *Ophiacantha scissionis* sp. nov., regenerating specimens with six arms, stereo-microscopic images. Arrow mark, split points for disk division.

six arms, rarely five or seven, and its tentacle scale is small, narrow and spine-like. *Ophiacantha anomala* differs from *O. scissionis* sp. nov. in the angle of the jaw, number of arm spines, shape of the tentacle scale and shape of the oral shield (Koehler 1914; O'Hara and Stöhr 2006). Among pentamerous species, *Ophiacantha scissionis* sp. nov. is similar to *O. moniliformis* Lütken and Mortensen, 1899 in the shape of the oral frame, number of arm spines and dorsal disk. *Ophiacantha moniliformis* has a narrow distal oral papilla, wider oral shield and slightly exposed radial shield (Lütken and Mortensen 1899; O'Hara and Stöhr 2006), in contrast *O. scissionis* sp. nov. has a wider distal oral papilla, slightly elongated oral shield and completely concealed radial shield. Previous studies reported that four species of *Ophiacantha* inhabited the waters of South Korea (Duncan 1879; Liao 2004; Shin 2012). Among these, *O. dallasii* Duncan, 1879 was collected at a depth of 91 m, East Sea, Korea (38°N, 129°E) and this species is distributed in the East Sea of Korea, South China

Sea, Philippines and Indonesia (Liao 2004). Some morphological characteristics of *O. dallasii* are similar to *O. scissionis* sp. nov.: four arm spines, trifid disk spines, shape of oral skeleton and small disk (< 3 mm). *Ophiacantha dallasii* is pentamerous and has longer arms than *O. scissionis* sp. nov. Although pentamerous individuals occur in *O. scissionis* sp. nov., these are mistakes in the process of fissiparous reproduction, whereas *O. dallasii* is not fissiparous, despite its small disk. Ultimately, *O. scissionis* sp. nov. has unique and distinct morphological characteristics and is clearly distinguished from other *Ophiacantha* species based on mitochondrial *COI* analysis.

**Diverse regeneration morphology of *Ophiacantha scissionis* sp. nov.**

As discussed above, four *Ophiacantha* species with multi-rayed symmetry (6–10) are known, and these are not fissiparous but viviparous (Belyaev and



**Fig. 10.** *Ophiacantha scissionis* sp. nov., regenerating specimens with five arms, stereo-microscopic images. Arrow marks split points for disk division.

Litvinova 1976; Stöhr 2003). Fissiparous ophiuroids possess the ability to produce solitary, mobile modules by binary fission (Mladenov and Emson 1988) and usually possess hexamerous symmetry (Emson and Wilkie 1980; Mladenov et al. 1983; Emson et al. 1985).

Recently divided specimens of *O. scissionis* sp. nov. usually have half a disk and three complete arms, suggesting that fissiparity sets in after the specimens have grown to a moderate size, about 1.5 mm to 2.0 mm disk diameter. Specimens of *O. scissionis* sp. nov.

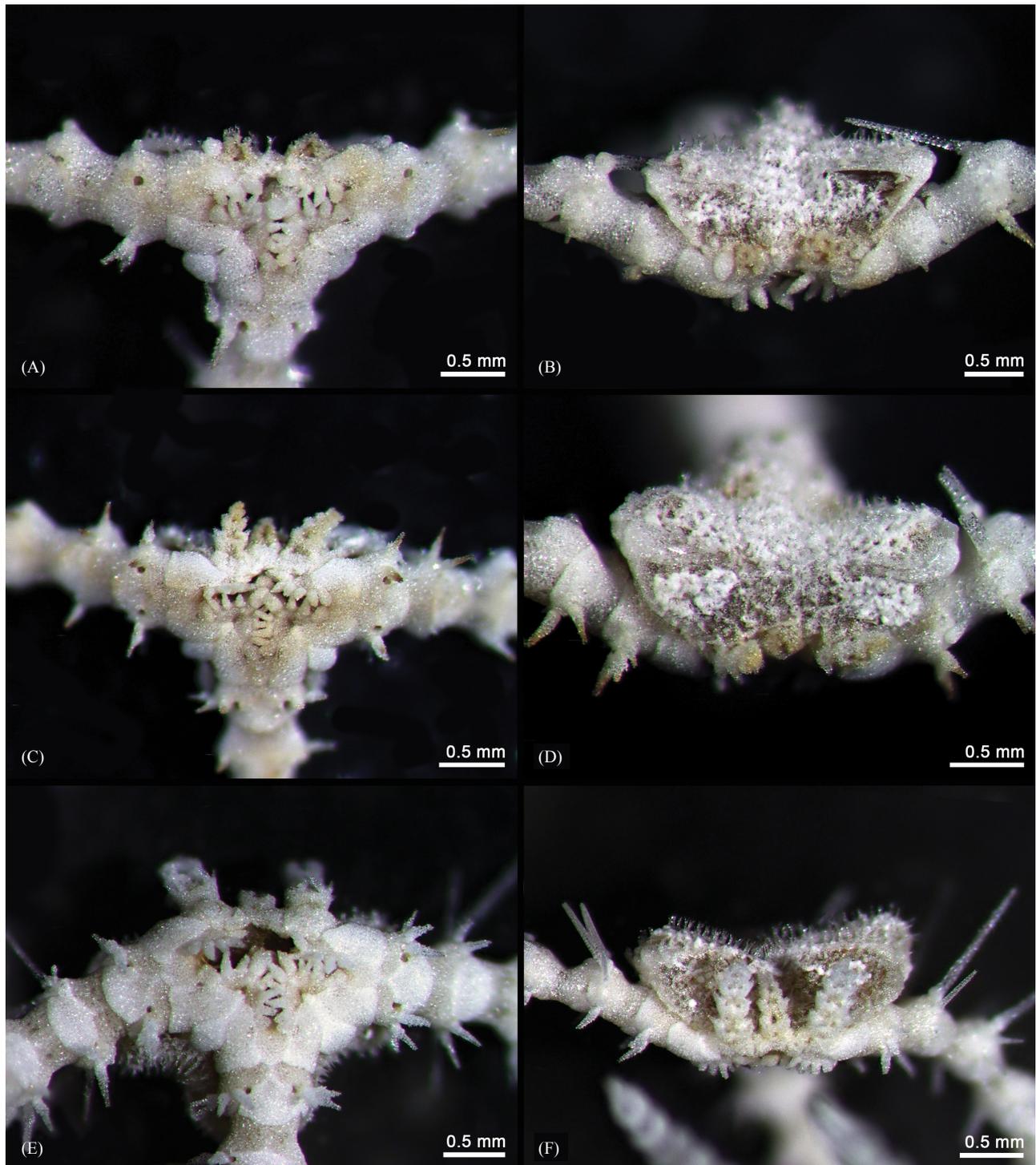
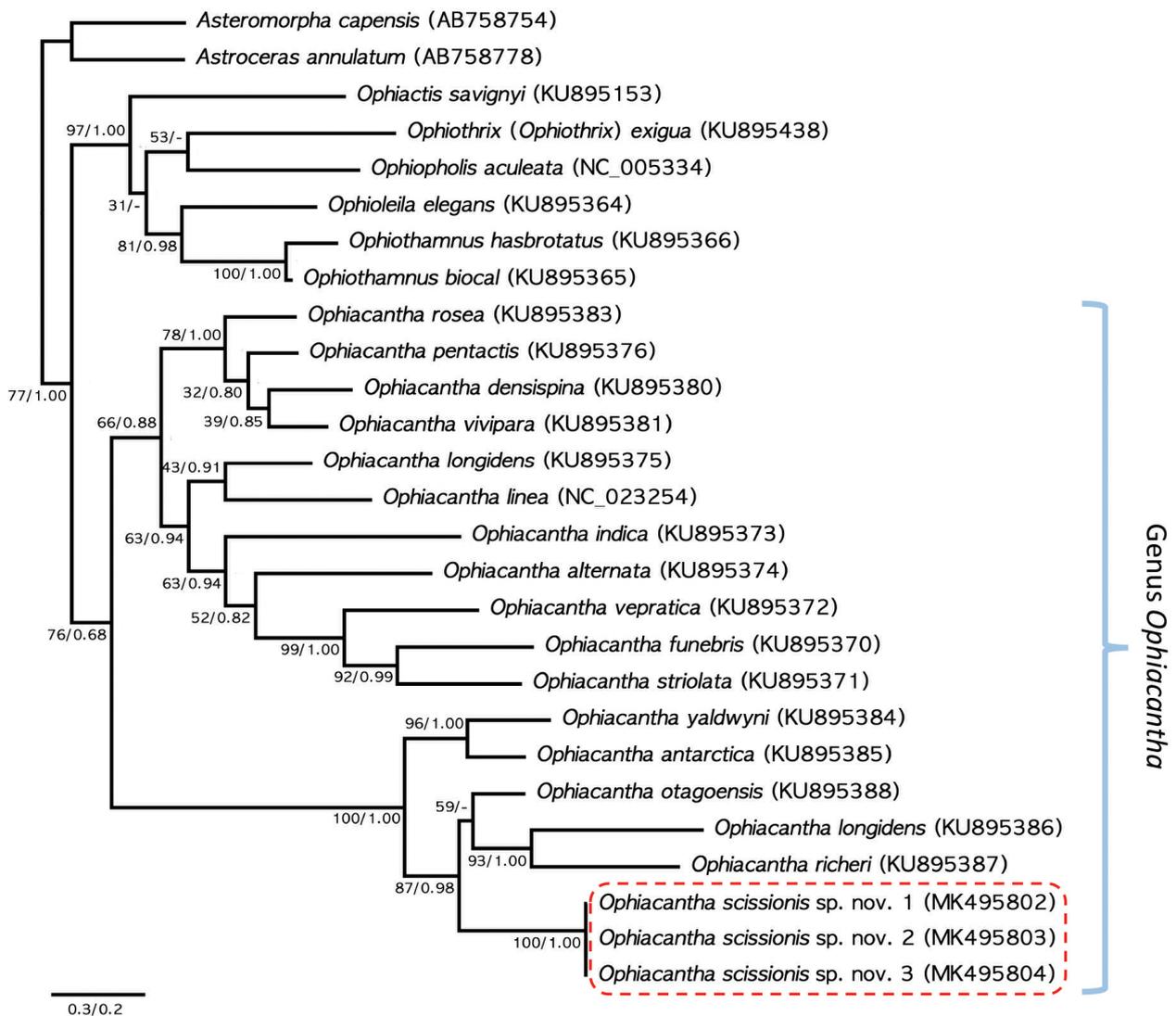


Fig. 11. *Ophiacantha scissionis* sp. nov., recently split and regenerating specimens, stereo-microscopic images.

usually have single fission planes and the number of fission planes is lower than in *Ophiactis savignyi* (Müller and Troschel, 1842) (Chao and Tsai 1995; Mladenov et al. 1983). Recently, divided specimens of *O. savignyi* commonly have three older arms which may vary in size and three equally short arms, which is evidence of multiple fission planes (Yamazaki 1950; Hyman 1955; Mladenov et al. 1983) and suggests that fission occurs again before the new arms have fully regenerated (Chao and Tsai 1995). Considering this hypothesis, *O. scissionis* sp. nov. may have shorter fission intervals than *O. savignyi*. Environmental fluctuations at the intertidal zone may trigger fission of asteroid and holothurian inhabitants since adjacent sublittoral

populations of the same species show less evidence of fission (Emson and Wilkie 1980; Lawrence 1980; Barker et al. 1992; Chao et al. 1993). But, exogenous factors (temperature, salinity and hypoxic conditions) did not initiate fission of *Ophiocomella ophiactoides* (H.L. Clark, 1900) in Jamaica, and fission in that species is possibly under internal control (Mladenov et al. 1983). The sampling location of *O. scissionis* sp. nov. is affected by the Kuroshio warm current all year round and water temperature and salinity range over 16–26°C and 32.2–4.4 psu over a year, respectively (Ko et al. 2008). The environmental conditions around Munseom Island, sampling location of *O. scissionis* sp. nov., indicate that concentrations of dissolved oxygen



**Fig. 12.** Maximum likelihood (ML) and Bayesian inference (BI) tree based on 663 bp of mitochondrial *COI* for 17 species of *Ophiacantha* and other ophiuroids as outgroup. The values of bootstrap support (ML) and posterior probability (BI) are indicated on each node as  $\leq 100$  and  $\leq 1.00$ , respectively.

**Table 2.** Pairwise distances for 17 species of *Ophiacantha*, calculated using the Kimura-2 parameter distance model, based on 663 bp of the mitochondrial *COI* gene

Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 <i>O. scissionis</i> 1																		
2 <i>O. scissionis</i> 2	0.2%																	
3 <i>O. scissionis</i> 3	0.2%	0.0%																
4 <i>O. alternata</i>	31.7%	31.5%	31.5%															
5 <i>O. antarctica</i>	18.5%	18.7%	18.7%	29.8%														
6 <i>O. brachygnatha</i>	21.3%	21.5%	21.5%	34.1%	23.0%													
7 <i>O. densispina</i>	26.9%	27.1%	27.1%	25.7%	25.0%	31.7%												
8 <i>O. funebris</i>	34.1%	34.3%	34.3%	26.6%	31.6%	32.9%	27.2%											
9 <i>O. indica</i>	33.0%	32.8%	32.8%	23.7%	30.4%	35.3%	25.2%	26.5%										
10 <i>O. linea</i>	29.4%	29.2%	29.2%	24.7%	27.0%	31.0%	23.9%	25.4%										
11 <i>O. longidens</i>	28.1%	28.3%	28.3%	24.2%	25.0%	30.1%	19.3%	25.9%	22.5%	18.8%								
12 <i>O. otagoensis</i>	13.6%	13.4%	13.4%	30.6%	17.2%	18.5%	25.6%	35.3%	32.0%	28.3%	27.6%							
13 <i>O. pentactis</i>	28.8%	28.6%	28.6%	25.0%	28.6%	31.0%	13.4%	26.8%	24.6%	22.5%	20.5%	26.5%						
14 <i>O. richeri</i>	18.7%	18.9%	18.9%	32.1%	22.2%	20.4%	32.0%	38.5%	36.9%	31.0%	32.9%	17.2%	32.5%					
15 <i>O. rosea</i>	29.3%	29.5%	29.5%	25.5%	29.3%	33.5%	14.6%	27.5%	25.3%	22.6%	20.3%	28.8%	13.4%	34.9%				
16 <i>O. striolata</i>	38.2%	38.5%	38.5%	25.7%	34.4%	33.8%	27.5%	20.9%	27.6%	24.8%	25.9%	33.7%	26.3%	38.2%	23.9%			
17 <i>O. vepratita</i>	35.1%	34.8%	34.8%	26.1%	32.7%	34.3%	26.4%	24.1%	30.4%	26.3%	26.8%	33.5%	22.5%	38.7%	23.4%	22.4%		
18 <i>O. vivipara</i>	30.9%	30.6%	30.6%	22.5%	28.3%	34.6%	14.3%	25.2%	27.0%	21.7%	20.5%	29.3%	12.3%	34.5%	15.3%	25.7%	21.5%	
19 <i>O. yaldwyni</i>	21.1%	21.3%	21.3%	30.7%	12.6%	22.1%	28.3%	34.2%	31.2%	30.7%	27.0%	16.2%	29.5%	23.0%	29.3%	33.8%	33.0%	29.1%

**Table 3.** Comparison of morphological characters within *Ophiacantha scissionis* sp. nov. and morphologically similar species of *Ophiacantha*

	<i>O. scissionis</i> sp. nov.	<i>O. anomala</i>	<i>O. dallasii</i>	<i>O. decaectis</i>	<i>O. enneactis</i>	<i>O. moniliformis</i>	<i>O. vivipara</i>
Number of arms	6, rarely 5 or 7	6	5	10	9	5	6–8
Fissiparous	yes	no	no	no	no	no	no
Disk diameter (mm)	2.0	12.0	3.0	8.8	5.0	5	19.0
Arm length (mm)	9.8	unknown	18.0	unknown	15.0	30	70.0
Disk spine	yes	yes	yes	yes	yes	yes	yes
Tip of disk spine	sharp trifid	multifid	sharp trifid	sharp 1 point	sharp 1 point	sharp trifid	dull 1 point
Disk granule	no	no	no	no	yes	no	yes
Tip of disk granule	-	-	-	-	2 or 3 points	-	rounded, conical form
Radial shield exposure	no	yes, slightly	no	yes, slightly	no	yes, slightly	no
Oral shield	longer than wide	wider than long	longer than wide	longer than wide	as long as wide	wider than long	as long as wide
Angle of jaw	wider than long	narrow	wider than long	very narrow, compressed	very narrow, compressed	a little wider than long	unknown
Oral papillae	apex 1, side 3 to 4	apex 1, side 3 to 5	apex 1, side 3 to 4	apex 1, side 3	apex 1, side 3	apex 1, side 3 to 4	apex 1, side 4 to 6
Distal oral papilla	broad	broad	broad	narrow	broad	narrow	broad
Number of arm spines	almost 4, rarely 5	6–8	4	7	6	4–5	11–12
Number of tentacle scale	1	1	1	1	1	1	1
Shape of tentacle scale	small spine	large oval-like	small oval-like	large oval-like	large oval-like	small spine	large spine
Collecting depth (m)	35.7	180–653	15–294	200–2000	868	888–1224	0–1100
Type locality	Munseom, Jeju- do, South Korea	Bodø, Norway	East Sea, Korea	Kamchatka Peninsula, Russia	Agattu Island, Alaska, USA	North Pacific, western Mexico	Falkland Islands, Patagonia, Argentina

and chemical oxygen demands were as low as those in the standard sea-water-quality class I (Ko et al. 2008), and therefore Munseom Island has higher biodiversity than other regions of South Korea (Choa and Lee 2000; Lee et al. 2000). Thus, we considered that fissiparous reproduction of *O. scissionis* sp. nov. may be a temporary strategy for the adaptation to dynamic environments or under internal control of some (yet unknown) factors.

## CONCLUSIONS

We collected 76 specimens of ophiuroids from Munseom Island, Jeju-do, South Korea and described them as a new species in the genus *Ophiacantha*, *O. scissionis* sp. nov. The morphological characteristics of this species differed distinctly from other species of *Ophiacantha*: usually hexamerous and reproduces asexually by fissiparity. It is the first report of fissiparous reproduction in the genus *Ophiacantha*. We provided detailed description of morphological characteristics and diverse forms of fissiparity. Moreover, we obtained sequences of the DNA barcoding region from mitochondrial *COI* and demonstrated that the species differs clearly from 16 species of *Ophiacantha*, whose sequences we obtained from GenBank.

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**Authors' contributions:** TL performed field collections and the DNA analyses, drafted the manuscript and wrote results and discussions. All authors contributed to drafting and revising the manuscript. All authors read and approved the final manuscript.

**Competing interests:** TL, SSt, YJB and SSh declare that they have no conflict of interest.

**Availability of data and materials:** Obtained sequences of new species in the study have been submitted in the GenBank of NCBI and granted accession numbers from NCBI.

**Consent for publication:** Not applicable.

**Ethics approval consent to participate:** Not applicable.

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