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Crinoid diversity in the subtidal non-coral reef habitats of Singapore

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Abstract. Seabed sampling by dredging and trawling in non-coral reef areas off the island of Singapore to depths of 160 m showed that crinoids were present in more than 30% of the 354 subtidal locations sampled. Approximately 1500 specimens were collected, accounting for 26 nominal species. All belonged to the order Comatulida. Six families were recorded, amongst which the dominant families were Comatulidae (73%) and Himerometridae (23%). The majority of specimens were found in the Singapore Strait that serves one of the busiest container ports in the world and where extensive reclamation have been carried out over the last 50 years. Mean species diversity per survey was generally low (2.7 ± 2.2 species) although one survey recorded at least 12 species. Most species occurred over a wide range of depths and some species, including *Comatula* cf. *solaris* and *Zygometra comata*, both of which can be found between depths of 7 m to 130 m. Of the 26 species recorded, 11 had been previously recorded from coral reefs in Singapore. Mean species density was 0.03 ± 0.05 m^{-2} and was lower than values known from coral reef habitats in the Indo-Pacific region. Maximum density however, was 0.4 individuals m^{-2}, at east of the Singapore Strait. This value is comparable to coral reefs elsewhere in the Indo-Pacific region, showing that non-coral reef habitats can support similar densities of crinoids. This is the first extensive study focusing on the distribution and characterization of crinoids in Singapore's non-coral reef habitats. While many crinoids can be found in coral reef habitats, non-coral reef habitats with sufficient productivity and water movement appear to be able to support high densities of crinoids despite chronic anthropogenic disturbances caused by shipping and land reclamation.

Key words. Crinoidea, feather star, non-coral reef, dredging, species distribution

INTRODUCTION

Singapore's crinoids are surprisingly well documented, with a total of 39 species recorded in the last 150 years (Messing & Tay, 2016). Most of the early specimens were hand collected from the shorelines by the German zoologist Carl von Martens in the 1860s and Consul for Denmark, Svend Gad, in the early 1900s (AH Clark, 1931). These specimens were subsequently documented by AH Clark in his monographs (AH Clark, 1931, 1941, 1947, 1950). In the 1990s and 2000s, small-scale surveys via SCUBA diving and dredging were undertaken by university researchers, though the focus tended to be on the crinoid commensals rather than their hosts (Eeckhaut et al., 1994; Tan, 2012). Lim & Chou (1987) provided a brief introduction to crinoids in Singapore's coral reefs, documenting a total of eight species. The only crinoid-focused distribution survey was by Lim (1986) at several coral reefs in the western part of the Singapore Strait, recording ten species. Although the intertidal shores and subtidal coral reefs were examined to some extent in the abovementioned studies, no comprehensive work has been done to characterise the distribution of crinoids on non-coral reef habitats.

In shallow waters of the tropics, crinoids, particularly those of the unstalked form, are generally known to be associated with coral reefs (Messing et al., 2006). Coral skeletons provide crinoids with structures to cling onto, as well as crevices and overhangs to hide in. Hence, studies involving unstalked crinoids have largely focused on coral reefs, particularly in areas where crinoids are visible and abundant. However, crinoids are now also known to occur in other habitats. Stevens & Connolly (2003) was the first to quantitatively sample for crinoids in a soft-sediment environment, dispelling the then common assumption that crinoids were only characteristic of reefal environments. Another study by Messing et al. (2006) also surveyed a sandy slope within the Great Barrier Reef. Both studies found that crinoids were not just present on hard substrata, but could also occur in significant numbers on soft sediment environments. Mekhova & Britayev (2015) also documented crinoids living on soft sediment in the Gulf of Tonkin in the South China Sea.

As part of a study of Singapore's marine biodiversity (Comprehensive Marine Biodiversity Survey, 2010–2015; see Tan et al., 2015), a wide-ranging survey of Singapore's subtidal seabed was undertaken via dredging and/or trawling. This paper presents the results from surveys of subtidal non-coral reef areas in the Singapore and Johor Straits that

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Table 1. List of crinoid species and their depth ranges recorded from Singapore between 2012 and 2014 (Messing & Tay, 2016; Tay, unpubl. data). Species documented from previously known coral reef surveys in Singapore are indicated with an asterisk (Lim, 1986; Eeckhaut et al., 1994; Tan, 2012).

Family	Species	Depth range (m)
Comatulidae	*Comatula* cf. *solaris** Lamarck, 1816	10.3–130.5
	Comatula cf. *pectinata* (Linnaeus, 1758)	11.0–125.5
	Comatula sp.	12.2–73.6
	Capillaster multiradiatus (Linnaeus, 1758)	11.0–130.5
	Capillaster sentosus (Carpenter, 1888)	21.3
	Capillaster cf. *tenuicirrus* AH Clark, 1912	13.8–64.2
	*Phanogenia typica** Lovén, 1866	18.4–29.7
Zygometridae	*Zygometra comata** AH Clark, 1911	17.6–130.5
Himerometridae	*Himerometra robustipinna** (Carpenter, 1881)	14.0–28.0
	Himerometra cf. *bartschi* AH Clark, 1908	7.0–27.8
	Heterometra cf. *crenulata* (Carpenter, 1882)	7.0–130.5
	Heterometra schlegelii (AH Clark, 1908)	11.0–64.3
	Heterometra sp.	17.2–64.3
	Amphimetra cf. *discoidea* AH Clark, 1911	7.0–49.0
	Amphimetra ensifer (AH Clark, 1909)	11.0–34.2
	Amphimetra sp.	14.0–23.6
Mariametridae	*Dichrometra flagellata** (Müller, 1841)	27.2–29.7
	*Lamprometra palmata** (Müller, 1841)	11.0–29.9
	*Stephanometra tenuipinna** (Hartlaub, 1890)	18.3
	*Stephanometra indica** (Smith, 1876)	24.8
Colobometridae	*Colobometra perspinosa** (Carpenter, 1881)	17.7
	Decametra mylitta AH Clark, 1912	17.8–19.5
	Decametra sp.	16.9–130.5
	*Oligometra serripinna** (Carpenter, 1881)	17.2–29.9
	*Pontiometra andersoni** (Carpenter, 1889)	11.0–39.9
Antedonidae	*Dorometra* cf. *nana* (Hartlaub, 1890)	20.7–130.5

mainly comprise unconsolidated substrata including coral rubble, mud and sand where crinoids were thought to be neither diverse nor abundant.

MATERIAL AND METHODS

A study of the subtidal seabed around mainland Singapore was conducted between 2013 and 2015 as part of the Comprehensive Marine Biodiversity Survey project. Surveys took place in areas outside of coral reefs, where the substratum comprised any combination of mud, sand, gravel, rocks and biogenic material. Singapore's marine waters within the port limit were divided up into grids measuring one nautical mile by one nautical mile and each accessible grid was surveyed at least twice. A total of 354 surveys were conducted over three years. Each survey dredged over a narrow strip covering approximately 500 m^2 of the seabed by means of a naturalist's dredge, beam trawl or otter's trawl, depending on the terrain of the area. The depths surveyed ranged from 3.8 m to 160.0 m. Mesh size of the nets used on the dredge and trawls was 7 × 7 mm.

Specimens were sorted immediately after collection and put into containers with seawater for transport back to the laboratory, where the specimens were relaxed by immersing them mouth down in 95% ethanol before being transferred to 75% ethanol for preservation. Any commensals found were preserved separately. Identification of crinoid specimens was based on Clark & Rowe (1971), augmented by descriptions of local specimens provided in Messing & Tay (2016, this volume).

Statistical analyses only took into account surveys where crinoids were recorded. Juveniles and undetermined species of crinoids were excluded from such analyses.

RESULTS

Nearly all crinoids were confined to the Singapore Strait, a waterway south of mainland Singapore serving one of the busiest container ports in the world that is affected by land reclamation activities in the vicinity. Crinoids occurred in more than a third (139) of the 354 surveys carried out. A total of 1501 specimens were recorded from this seabed study over three years, accounting for 26 nominal species (Table 1). Of the 1501 specimens, 71.0% were identified to genus and 66.0% were identified to species. The remaining species comprised of juveniles (1.6%) and undetermined adults

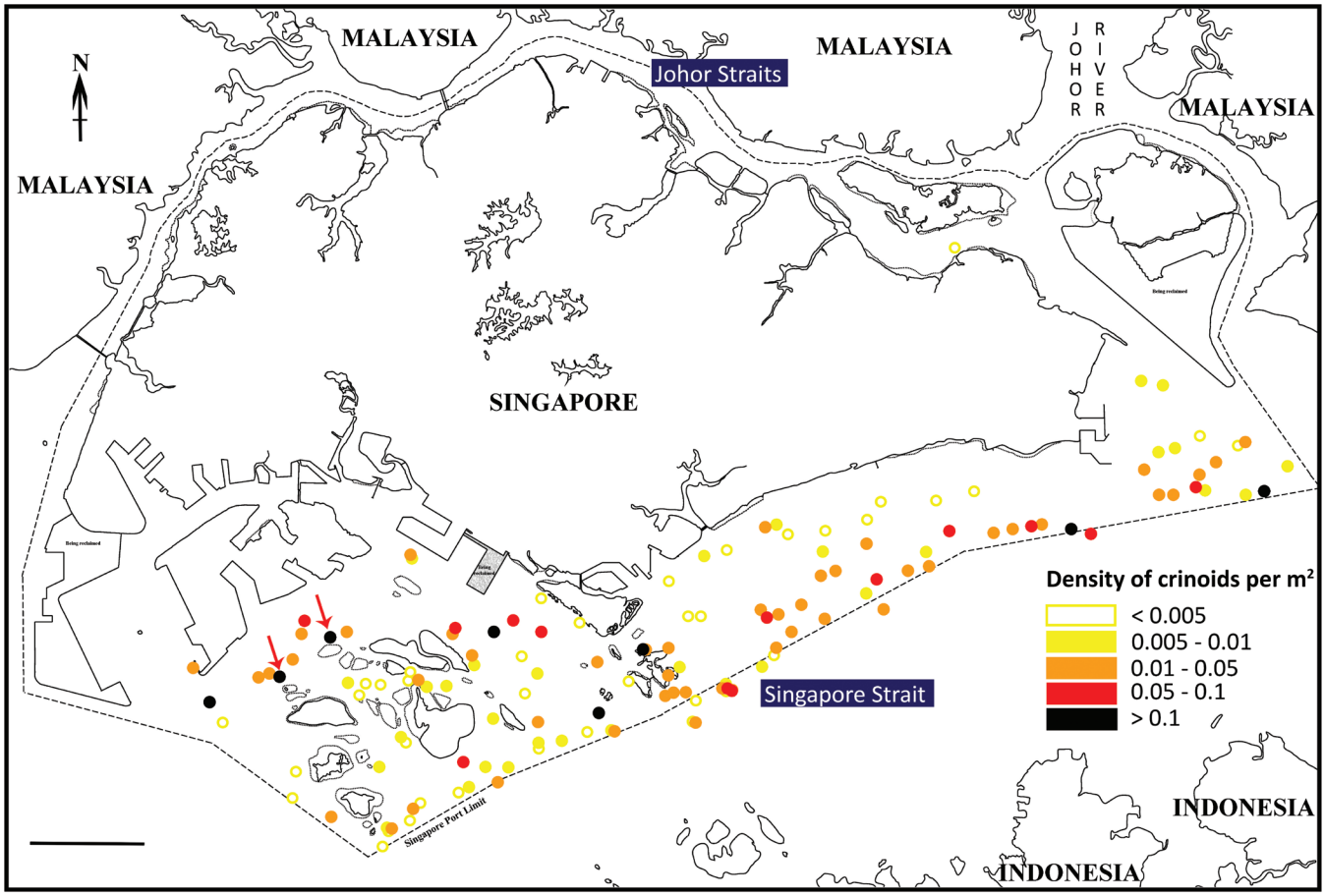

Fig. 1. Density and distribution of crinoids in Singapore waters, based on dredge and trawl surveys between 2012 and 2014. Arrows indicate areas with particularly high species diversity (11 to 12 species per dredge). Scale bar = 5 km.

(27.4%), including those that were too badly damaged to be identified. All crinoids belonged to the order Comatulida and were of the unstalked form, also commonly known as feather stars. No stalked crinoids were found, nor had any been previously recorded in Singapore.

Species diversity. Six families of crinoids were recorded from this survey. Members of the family Comatulidae were overwhelmingly dominant, accounting for 72.6% of specimens. Members of the family Himerometridae comprised the next largest group (22.7%). About 3.8% comprised the family Colobometridae, while the remaining three families (Antedonidae, Mariametridae, Zygometridae) each accounted for approximately 1.0% of the total number of specimens obtained. Overall species diversity was low, with a mean diversity of 2.7 ± 2.2 species per survey (n = 139). A total of 88 surveys had either one or two species in the trawl/dredge nets, which accounted for 63% of the 139 surveys with crinoids present. A further 49 surveys comprised three to eight species per survey, and the remaining two surveys had 11 and 12 species. The two surveys with the highest species diversity were both located in the western part of the Singapore Strait, southeast of Jurong Island (Fig. 1). Seabed conditions at these two locations were largely similar, with depths of between 17 m and 22 m, having a sandy and rocky substratum. They were also located within the live firing and military restricted area where waters are closed to the general public and anchoring of vessels is prohibited, unlike many other areas around Singapore. Recent observations using SCUBA have found the nearby coral reefs to be in relatively good condition (Tay, unpubl. data).

Crinoids from Singapore's subtidal non-coral reef occurred over a wide range of depths ranging from 7.0 m to 130.5 m. A species distribution graph showed that crinoid families had different depth distributions (Fig. 2). Crinoids from the family Comatulidae were widespread across all depth classes while those from the family Mariametridae appeared to be limited to shallow waters (<30 m). The family Comatulidae was also the most abundant family recorded in the 15–30 m and 30–45 m depth classes.

Species-depth distribution varied among the 26 species recorded. While almost all species could be found in shallow waters less than 30 m, only a small number were in deep waters greater than 100 m. Some species were observed only in shallow waters of less than 30 m, such as *Himerometra robustipinna* Carpenter, 1881. No exclusively deep-water species were found. However, several species with a wide depth range were found in deeper waters of more than 100 m, including *Comatula* cf. *solaris* Lamarck, 1816, *Capillaster multiradiatus* Linnaeus, 1758 and *Heterometra* cf. *crenulata* Carpenter, 1882. Crinoids were both less abundant and less diverse in deeper waters.

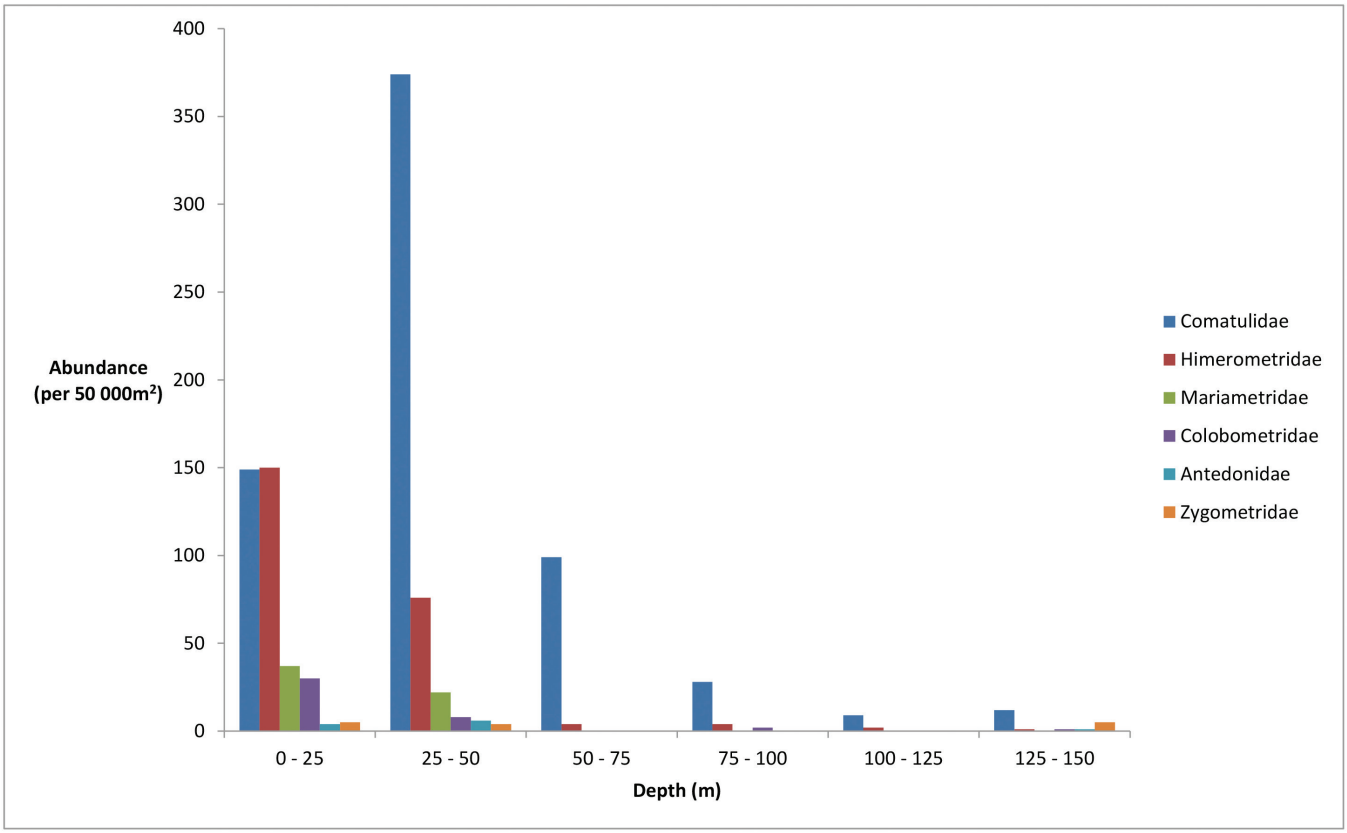

Fig. 2. Depth distribution and abundance (individuals 50 000 m^{-2}) of crinoid families in Singapore waters.

Species density. Crinoid densities are at best only semi-quantitative due to the methods used to collect the specimens. Nevertheless, we can still obtain a fairly good idea of the distribution of crinoids in Singapore based on the extensive data collected. Crinoids occurred in numbers ranging from one to 50 individuals per survey, but three survey sites had extremely high numbers of crinoids, with 74, 100 and 150 individuals respectively. The assemblages were made up of several species, with *Capillaster multiradiatus* and *Comatula* spp. being dominant. The substratum of the three sites comprised of sand and/or gravel.

As a very approximate means of comparison against previous studies, we calculated that crinoid densities in Singapore's non-coral subtidal habitats ranged from 0.3 to 40.0 individuals per 100 m^2, with a mean of 3.0 ± 5.0 individuals per 100 m^2. The maximum density was well within the range of densities reported in other studies of coral reef habitats (see Table 2). The mean density in Singapore was comparatively lower than most other places surveyed. This may be because most coral reef studies have surveyed locations where crinoids are known to be abundant.

The most widespread and abundant species recorded from this study was *Comatula* cf. *solaris*. Accounting for a quarter of the total identified specimens, its density ranged from 0.3 to 10.0 individuals per 100 m^2, with an average of 6 individuals per 100 m^2 and occurring in nearly half of all surveys (47%).

Commensalism. Commensals were associated with about 7% of crinoids. Commensals were found on most of crinoid species recorded, with the exception of a few uncommon species. Brittle stars (*Ophiomaza* sp.) were the most common commensal found, followed by the myzostome worms (Polychaeta; Myzostomidae). Other commensals included polynoid and hesionid worms (Family Polynoidae and Hesionidae), shrimps (*Synalpheus stimpsonii* de Mann 1888; *Periclimenes commensalis* Borradaile, 1915) and crabs (*Harrovia longipes* Lanchester, 1900), all of which have previously been recorded on crinoids in Singapore (Lim, 1986; Eeckhaut et al., 1994; Tan, 2012). However, squat lobsters (*Allogalathea elegans* Adams & White 1848; *Allogalathea longimana* Cabezas, Macpherson & Machordom, 2011) and amphipods (*Leucothoe* sp.) found during this survey, comprise of animals recorded as associated with crinoids for the first time in Singapore. Common associations between crinoid hosts and commensals included the crab *Harrovia* sp. with the crinoids *Pontiometra andersoni* and *Phanogenia typica*, as well as snapping shrimps (Caridea) with the crinoid *Himerometra robustipinna*.

DISCUSSION

A total of 26 crinoid species were recorded from seabed surveys in this study. This was slightly more than the 24 species recorded from the three-week long Singapore Strait workshop (Messing & Tay, 2016), which included diving and intertidal surveys. All 24 species were documented in this present seabed study, in addition to two other species, *Himerometra* cf. *bartschi* AH Clark, 1908 and *Decametra mylitta* AH Clark, 1912 that were not observed during the workshop. Mekhova & Britayev (2015) recorded eight species of comatulids in the Gulf of Tonkin from similar substrata

Table 2. Crinoid densities between non-coral reef and coral reef habitats. Density units are individuals m^{-2}.

Location	Habitat type	Mean density (indiv. m^{-2})	Maximum density (indiv. m^{-2})	Source
Singapore	Non-coral reef	0.030 ± 0.050	0.40	Present study
Lizard Island, Australia	Non-coral reef	0.028	0.10	Messing et al., 2006
Moreton Bay, Australia	Non-coral reef	0.11	0.88	Stevens & Connolly, 2003
Singapore Strait	Coral reef	0.13	1.85	Low, unpubl. data
Enewetak Atoll, Marshall Islands	Coral reef	0.071	0.14	Zmarzly, 1984
Discovery Bay, Jamaica	Coral reef	0.22	0.22	Meyer, 1973
Central Great Barrier Reef, Australia	Coral reef	7.10	70.00	Fabricius, 1994

as that of our study, and all except two species were also present in Singapore.

Species distribution. The dominance of Comatulidae over other families is a feature commonly seen in the tropical shallow waters (Meyer, 1973; Messing, 2003). This characteristic was more variable in non-coral reef habitats. On a sandy bottom, one study showed Comatulidae as the most abundant family (Messing et al., 2006) while another study recorded Zygometridae as the dominant and only family present (Stevens & Connolly, 2003).

Among the 26 species recorded in this study, some 11 species of crinoids were previously documented from Singapore's coral reefs (Table 1; species marked with asterisks). Coral reef surveys were typically conducted using SCUBA at less than 20 m depth. The majority of these 11 species were only found in shallow waters, with the exception of *Comatula* cf. *solaris*, *Zygometra comata* AH Clark, 1911 and *Pontiometra andersoni* Carpenter, 1889. *Himerometra robustipinna* and *Lamprometra palmata* Müller, 1841 were recorded in relatively high numbers in both coral and non-coral habitats despite having rather limited depth ranges (14–28 m and 11–30 m respectively). Both species were absent from waters of more than 30 m, and in fact, recent intertidal surveys (Tay, unpubl. data) have found these two species to be common species on Singapore's intertidal shores. Hence, the two species may be restricted to the shallow waters of Singapore and are possibly exclusively shallow-water species in Singapore. More surveys in deep waters would need to be conducted in order to confirm these findings. Elsewhere in the region, they have been reported at depths of up to 60 m (AH Clark, 1941; Lane et al., 2000).

Using Marr's (1963) classification of seabed substrata, Singapore's seabed can be generally divided into three types: (1) Mud, sometimes sticky, often mixed with some sand, gravel or stones; (2) Sand, often with bits of fragments, gravel and small rocks; and (3) Rock with gravel. Marr found that crinoids on the Antarctic Shelf were not very selective as to their choice of substratum. This was true for the majority of species recorded from our survey, but a small number of species appeared to avoid muddy substrata altogether: *Phanogenia typica* Lovén, 1866, *Oligometra serripinna* Carpenter, 1881, *P. andersoni* and *Dichrometra flagellata* Müller, 1841. The near absence of cirri in *P. typica* would mean that this species depends on tiny spines on the arm pinnules to attach itself to hard substrata. In a muddy environment, this species would have difficulty raising itself above the bottom to avoid sedimentation. *Oligometra serripinna*, on the other hand, had previously been recorded to be present in soft substrate environments, although they can cling to gorgonians to raise themselves off the substratum (Mekhova & Britayev, 2015).

Fauna associated with crinoids. While a few studies on crinoid commensals have been conducted in Singapore (Lim, 1986; Eeckhaut et al., 1994), very little quantitative data is available. However, based on our results, the percentage of crinoids associated with symbionts was lower compared to those from the coral reefs of Singapore and nearby regions (Eeckhaut et al., 1994; Britayev & Mekhova, 2011). This could be due to crinoids becoming stressed during collection, causing the commensals to release their hold on their hosts.

Crinoids are known to cling onto hard substrata such as rocks and boulders. In environments where such objects are lacking, crinoids could be found attached to other animals. In this study, crinoids were often dredged up attached to sea fans and sponges, and smaller individuals have also been found on basket stars. A video of the seabed taken in a high-density crinoid area in the Singapore Strait off Jurong Island saw many large specimens of crinoids perched on the barrel sponge, *Xestospongia testudinaria* Lamarck, 1815 (Fig. 3). These sponges can grow up to 1.5 m in height (Fromont & Bergquist, 1994), and the crinoids appeared to use the availability of such vantage points where increased current flow, lower sediment load, and a better grip on the sponge surface prevail over less ideal conditions on the seabed.

Other observations. During our study, only one specimen (which was too badly damaged to identify) was found in the Johor Straits, a narrow, estuarine channel dividing mainland Singapore and mainland Peninsular Malaysia (Fig. 1). The almost complete absence of crinoids in the Johor Straits can be attributed to the lower and fluctuating salinity values in the Johor Straits, due to substantial freshwater input from the Johor River and several other rivers into the Straits in combination with poor circulation (Wood et al., 1997; Gin et al., 2000). Salinity in the Johor Straits generally ranged

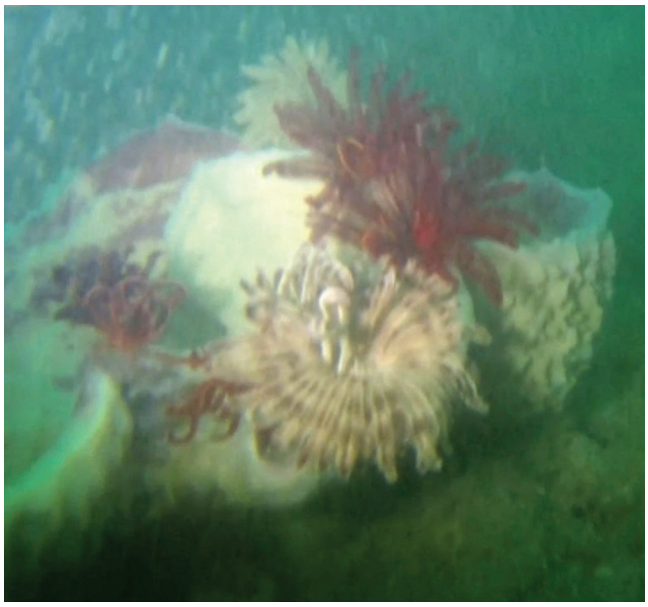

Fig. 3. Crinoids on a barrel sponge (*Xestospongia testudinaria*) in the Singapore Strait (photograph extracted from underwater video).

from 19–30 ppt as compared to 29–32 ppt in the Singapore Strait. Among the five echinoderm classes, members of the Crinoidea have never been found in brackish waters (Russell, 2013). Indeed, crinoids are known to be extremely stenohaline (Stickle & Diehl, 1987). This supports our finding that crinoids are largely restricted to the Singapore Strait.

Conclusions. A total of 26 crinoid species can be found on Singapore's non-coral reef habitats, distributed largely across the Singapore Strait. *Himerometra robustipinna* and *Lamprometra palmata* are probably exclusively shallow-water species in Singapore waters. While the presence of crinoids was not entirely surprising, it was interesting to find several areas with large numbers of crinoids with high species diversity in highly disturbed areas. Although these numbers may be unremarkable based on studies conducted elsewhere in the Indo-West Pacific, it is still important to appreciate that such habitats can support fairly high numbers of crinoids.

This study agrees with Stevens & Connolly (2003) that crinoids are not essentially coral reef fauna. Subtidal non-coral reef areas are also important habitats for crinoids. Our results clearly show the presence of crinoids on the non-coral reef areas in Singapore, with some areas of high diversity and density that are associated with sponges. Dredging is however, not the most ideal method to estimate crinoid densities on the seabed. Underwater videography could provide a less destructive alternative, although species identification can become difficult without the benefit of physical specimens.

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