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Origin of larvae and juveniles of *Octomeris sulcata* Nilsson-Cantell (Crustacea: Cirripedia) newly found on the Sanriku coast of northern Japan

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Abstract: *Octomeris sulcata*, a warm water species of chthamalid barnacle dominant in the warm Kuroshio and Tsushima Currents, has never before been recorded from the Sanriku coast of northeastern Honshu, Japan. However, larvae and juveniles of *O. sulcata* were recently found in the marine plankton and attached to artificial PVC plates in Okkirai Bay. The growth of juvenile barnacles on the plates was monitored monthly for 22 months. Larval density was recorded monthly from 1990, and recruitment was studied in 1995 and 1996. Growth continued without any serious retardation and the average shell size reached 16 mm (rostral-carinal length of base) with 60% survival by the end of the observations. Second-stage nauplii were collected every autumn starting in 1993, and recruitment was observed on PVC plates to occur from late summer to autumn in both 1995 and 1996. These results and other biological observations, as well as the reported oceanographic conditions along the Sanriku coast, show that the larvae and juveniles of *O. sulcata* in Okkirai Bay had an autochthonous origin. The rarity of this species in the Sanriku region may be a result of competition for space with other barnacles. A hypothesis concerning its origin in the region is proposed, taking into account other organisms that display a similar distribution pattern.

Key words: range extension, barnacle larvae, *Octomeris sulcata*, recruitment, Sanriku coast

Introduction

The chthamalid barnacle species *Octomeris sulcata* was originally described from Kobe, Japan, by Nilsson-Cantell (1932). A few years later Hiro (1939a, b) reported this species to be seemingly endemic to Japan and Taiwan. Thereafter, this species has been found in many localities in Japan, Taiwan, and Korea (Utinomi 1949, 1970; Ooishi 1964; Hosomi 1966; Utinomi & Kikuchi 1966; Kitami 1968; Kado 1982; Kim 1995; Kado & Kim 1996; Kado, unpublished data; Yamaguchi, unpublished data) (Fig. 1). It has also been found in the Philippines, particularly in Manila Bay (Rosell 1973), which represents its southernmost limit. In Japan, *O. sulcata* is distributed along the Sea of Japan coast from southern Hokkaido to Yamaguchi Prefecture, along the west coast of Kyushu, on islands in the Sea of Japan, along the Pacific coast from the Boso Peninsula to Kyushu, and in the Nansei (Ryukyu) Islands. The above-mentioned areas are strongly affected by the warm-water Kuroshio Current.

In 1990, *O. sulcata* was noted for the first time along the Pacific coast of northeastern Honshu (Kado, unpublished data), namely, under a rock surface in the lower littoral zone of Kirikiri, Iwate Prefecture (Fig. 2). The specimen found there was just one single adult individual, and no others were found in the vicinity. Until then, no individual of this species had been collected in the Sanriku region (Pilsbry 1911, 1916; Hiro 1939c; Yamaguchi 1977a, b; Kajihara & Ura 1978; Kado et al. 1981; Horikoshi & Tsuchida 1981). Also no fossil evidence of this species has been found in the northeastern part of Honshu, although fossils have been obtained from areas facing the Sea of Japan and from the Pacific coast extending from the Boso Peninsula to the Nansei Islands (Yamaguchi 1988). These facts indicate that the Sanriku coast did not have an autochthonous population of *O. sulcata* originally; rather this species must have extended its distribution into this region during the Recent, although its density is still extremely low.

In relation to recruitment, the simultaneous finds in 1994 of larvae and several juveniles of this species at Sakihama

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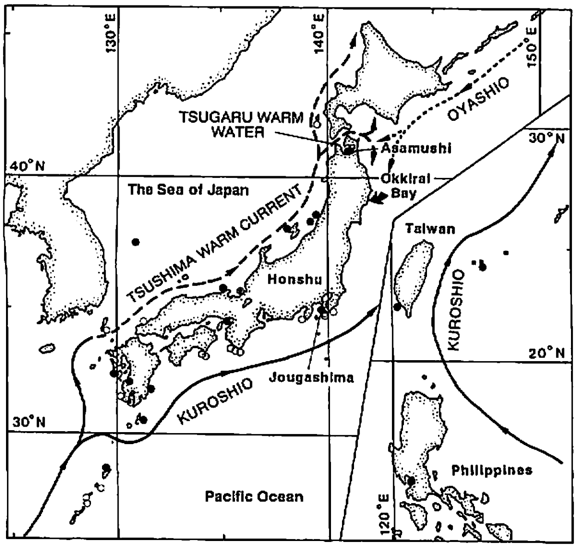

Fig. 1. Distribution of *Octomeris sulcata* and the ocean currents around Japan. Closed circles indicate published data, open and double circles unpublished data (O from Yamaguchi, ◉ from Kado).

harbor in Iwate Prefecture is important. The juveniles were attached to test plates that had been suspended in the lower littoral zone on a pier. The Sanriku coast, where Kirikiri and Sakihama harbor are located, is affected not only by a warm current, but also by a cold current (Hanawa & Mitsudera 1987; Ueno & Yamazaki 1987; Takasugi & Murakami 1994). One might therefore suppose that the specimens collected from the Pacific coast of northern Honshu are waifs transported as larvae by warm currents, either the Tsugaru Warm Current or the Kuroshio, or both.

This paper aims to deduce preliminarily whether the recently observed occurrence of *O. sulcata* along the north-eastern coast of Honshu resulted from larval dispersion alone or from a reproducing population in the region. The results of field experiments on adults, larval density, recruitment, growth, and survival are described. The origin of the population is also considered in light of reported observations on other marine organisms having distributions similar to that of the present species.

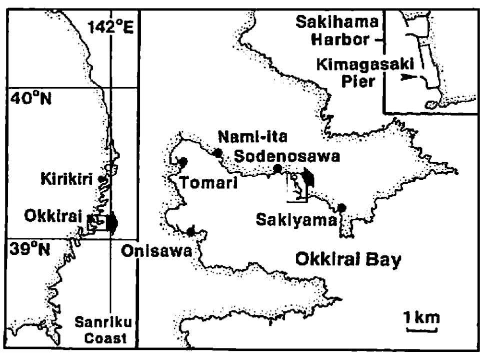

Fig. 2. Study site in Okkirai Bay, Sanriku coast, north-eastern part of Honshu, Japan.

Materials and Methods

This study was conducted at the end of the pier (Kimagasaki Pier) in Sakihama Harbor, Okkirai Bay, Iwate Prefecture, Japan, except for the survey of adult individuals (Fig. 2).

Searches for adults of *Octomeris sulcata* were conducted in 1999 in the littoral zone on five rocky shores (Nami-ita, Tomari, Onisawa, Sakiyama, and Sodenosawa) in Okkirai Bay.

Plankton samples were taken at the study site once during the first 6 d of every month in 1990–1996 with three vertical hauls of a plankton net (mouth area: 0.03 m^2, mesh opening: 0.10 mm) from the bottom. As the tide oscillated, the hauling depth changed from 9.0 to 10.5 m. Sorting and identification of *O. sulcata* larvae were performed based on the larval description by Kado & Kim (1996).

Settlement was determined using test plates (grayish PVC, 25×25 cm) with frosted surfaces in 1995 and 1996. Two plates were fixed vertically with plastic bands and set next to each other (edge-to-edge with a slight separation) inside a rectangular frame of iron rods (35×70 cm). These plate arrays were placed 8 cm away from the wall of the pier at 0.1 m above Extreme Low Water Spring (E.L.W.S.). At each sampling, two plates that had been exposed for one month were removed from the frame and two new plates were set in their place. At the same time, surface water temperature was recorded at the site. Recovered plates were brought into the laboratory and the number of settled juveniles of *O. sulcata* was counted separately on the illuminated (facing the end of the bay) and the shaded side (facing the pier) of the plates under a magnifying glass. Young juveniles of more than 1 mm in rostral-carinal length were identified on the basis of their color (light reddish brown) and relatively low shell height.

For growth and survival determination, a separate plate was placed at 0.1 m above E.L.W.S. from August to December 1994. Fifteen individuals of *O. sulcata* that settled on the shaded side of the plate were used for growth measurement using the rostral-carinal length of the base. Measurements started on 7 December 1994 and continued monthly until 4 November 1996, when the plate was lost in a storm. Survival was determined by counting the number of living individuals through time. When two barnacles developed close contact between their shells as a result of growth, one of the two was artificially removed. When the barnacles were covered with other sessile animals, including other barnacle species, at the time of growth measurement, the fouling organisms were artificially removed with a scraper and tweezers.

Results

Only one adult individual of *Octomeris sulcata* was

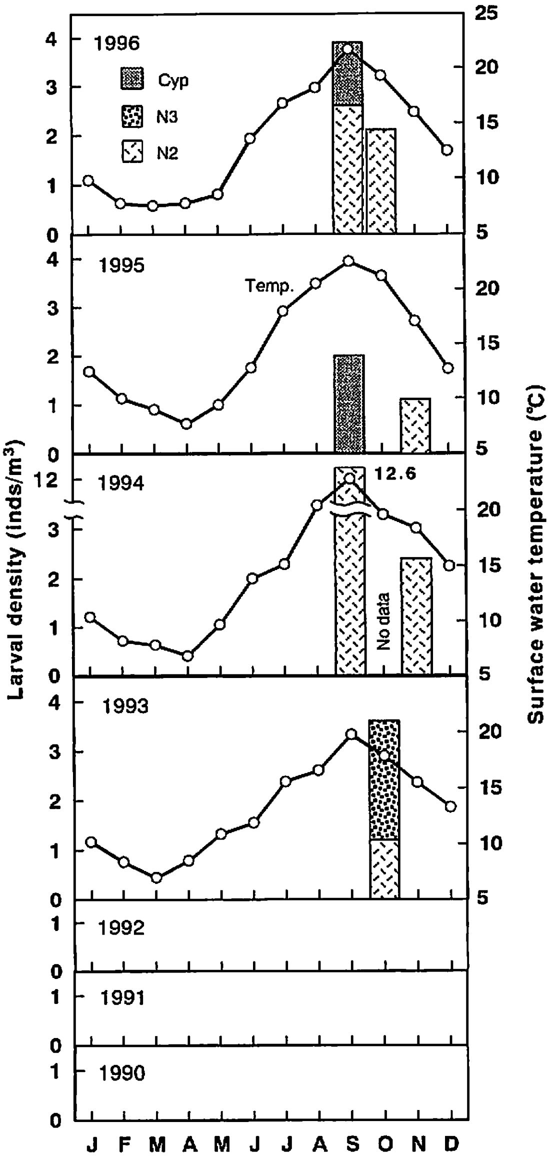

Fig. 3. Monthly changes of larval density of *Octomeris sulcata* and surface water temperature at Kimagasaki pier in Okkirai Bay from1990 to 1996. Temperatures in 1990 to 1992 are not shown.

found in 1999. It was attached to the underside of a rock in the lower littoral zone at Nami-ita. The specimen was 15.7 mm long (rostral-carinal length) and was surrounded by other barnacles, *Semibalanus cariosus* (Pallas). No other adult was found in the other five locations.

O. sulcata larvae were caught at low densities (less than 4 indiv. m^{-3}) in every autumn month beginning in 1993 except in September, 1994, when a high density (12.6 indiv. m^{-3}) of the second-stage nauplii (N2) was recorded. Only N2 and N3 and cyprids were collected at the site. Cypris larvae were found in September in both 1995 and 1996, but none were obtained in 1990, 1991, and 1992 (Fig. 3).

Seasonal recruitment of *O. sulcata* was consistently observed between August and October in the two years examined, 1995 and 1996. Juveniles were attached only to the

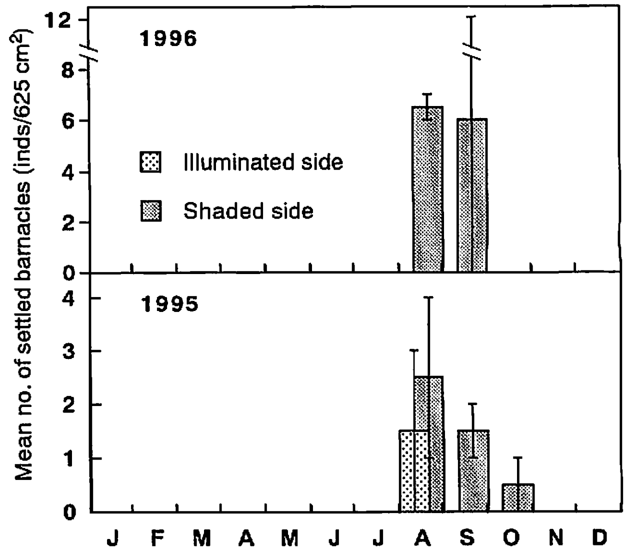

Fig. 4. Monthly changes in the number (mean) of settled young barnacles of *Octomeris sulcata* on test plates immersed at 0.1 m above E.L.W.S. for one month at Kimagasaki Pier in Okkirai Bay in 1995 and 1996. Vertical bars represent ranges.

shaded side of the plates except in August 1995, when three juveniles were found settled on the illuminated side. Settlement peaks occurred in August in both years (Fig. 4).

At the start of the growth study, the minimum, maximum, and mean sizes were 1.8 mm, 5.1 mm, and 3.3 mm, respectively, in rostral-carinal length. The size increased linearly until January at a rate of 1.8 mm $month^{-1}$, followed by slower growth with only two significantly higher growth periods occurring in July 1995 (1.2 mm $month^{-1}$), and in July–August 1996 (1.1 mm $month^{-1}$). These periods coincided with an increase in surface water temperature from 17–18°C to more than 20°C at the study site. Growth continued until the first winter without any deaths. The average size attained was 16 mm after 22 months and the maximum size was approximately 18 mm. Survival through the coldest period (February to April) was commonplace in 1995. The decrease in survival during March and April 1996 was caused by heavy settlement of *Semibalanus cariosus*, rather than by the low temperature. Final survival was 60% at the end of the study in 1996 (Fig. 5).

Discussion

Octomeris sulcata has been reported to be a warm-water species (Utinomi 1955; Yamaguchi 1988), and all specimens ever reported had been distributed along coasts where the Kuroshio or its branches dominate (Fig. 1). In addition, reports that *O. sulcata* broods its embryos in summer (Kado 1982; Kim 1995; Kado & Kim 1996) have supported the idea that this species is a warm-water species. This is the first study reporting *O. sulcata* from the cooler waters of the Sanriku coast on the Pacific side of northern Japan.

The Sanriku coast is seasonally affected by the cold Oya-

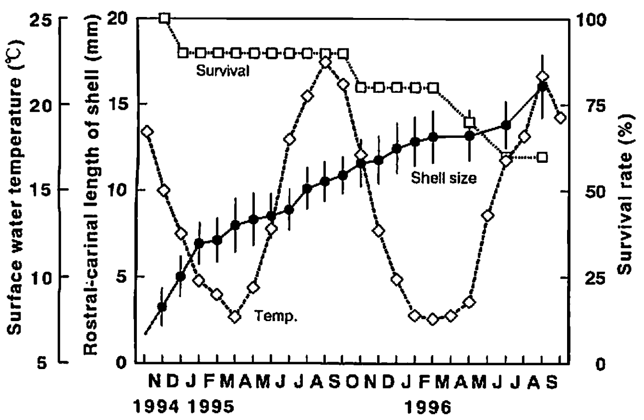

Fig. 5. Monthly changes in rostral-carinal length (mean±SD) as a growth parameter, and survival of *Octomeris sulcata* with surface water temperature at Kimagasaki Pier in Okkirai Bay from December 1994 to September 1996.

shio current and the Tsugaru Warm Water current, which is one of the branches of the warm Kuroshio current. The Oyashio approaches the Sanriku coast in spring (Takasugi & Murakami 1994; Takasugi & Yasuda 1994), and the Tsugaru Warm Water comes alongside this region from summer to autumn from the north via the Tsugaru Strait between Honshu and Hokkaido. The latter current passes by the middle of the Sanriku coast (Ueno & Yamazaki 1987; Yasuda et al. 1988), where Kirikiri and Okkirai Bay are located.

Larval occurrence and settlement of *O. sulcata* was observed in Okkirai Bay from August to November, which coincides with the period of dominance of Tsugaru Warm Water in the region. Assuming that the current's velocity is about 2.2 km h^{-1} (Ueno & Yamazaki 1987; Yasuda et al. 1988), it will take about 8 d for planktonic larvae from Asamushi (Fig. 1), which is located near the north end of Honshu and is the closest known locality of *O. sulcata*, to reach Okkirai Bay. Nauplii of *O. sulcata* need 9 to 17 d to develop to the cypris stage at 22°C in the laboratory (Kado & Kim 1996). The surface water temperature along the Sanriku coast from September to November is 17–20°C (Hanawa 1983; Ueno & Yamazaki 1987), so larval development there may take longer, from 10 to 29 d (assuming Q_{10} nearly equal to 2–3 and food is not limiting). Therefore, larval transport from Asamushi to Okkirai Bay seems to be possible. If this is the only way to maintain the Okkirai population, then firstly, the density of the larval suppliers, or parental population, should be very high, and secondly, very few early-stage nauplii should be collected in the Sanriku region. However, *O. sulcata* is not a common barnacle in northern and northwestern Honshu, including Asamushi, nor were N2 of extremely low density or rare in Okkirai Bay. In fact, N2 have been collected every year since 1993, and with a rather high larval density (12.6 indiv. m^{-3}) in September, 1994. During this month, warm water diverging from the Kuroshio in the Pacific, not the Tsugaru Warm Water coming from the Sea of Japan, dominated along the middle to southern Sanriku coast (Iwate Fisheries Technology Center 1994). Kuroshio warm-core rings are also known to impinge upon the southern part of the Iwate coast in summer and autumn (Takasugi & Murakami 1994; Hanawa & Mitsudera 1987). Therefore, larval transport by such water masses from central Japan (e.g. Jougashima Is. in Kanagawa Prefecture), where reproducing populations of *O. sulcata* exist (Kado & Kim 1996), might also be possible. However, the influence of these warm water masses is not periodic and it exhibits great year-to-year variations, so it can hardly explain the clear seasonal appearance of the larvae and the recruitment of this species.

No report has ever been published on the growth of *O. sulcata* for comparison to the present data. However, the results of our growth experiment indicate that *O. sulcata* on the Sanriku coast can tolerate the winter season by retarding shell growth slightly during this time of the year but growing significantly faster in summer. The low seawater temperatures in early spring seem not to be lethal for this species. Also, the high survival rate (>50 %) of settled individuals after two years is an indication of their adaptation to this region.

Due to the low density of adults in Okkirai Bay mentioned above, it was difficult to survey the extent of egg mass brooding inside the mantle cavity. Even so, from the above considerations it can be concluded that the larvae and juveniles of *O. sulcata* in Okkirai Bay originated from parents inhabiting the bay or adjacent areas.

The extreme low density of this species in the Sanriku region may be due to competition for space with other sessile animals such as barnacles, serpulids, mussels, bryozoans, and ascidians. Among these, the barnacle *Semibalanus cariosus*, which is dominant in the littoral zone and upper fringe of the sublittoral zone on these northern Pacific coasts, appears to be the most influential animal limiting the establishment of *O. sulcata*. The low shell height of *O. sulcata* is also a disadvantage, for it can easily by fouled by these barnacles and other sessile animals.

Several biogeographical observations undertaken by various authors offer circumstantial evidence concerning the origin of the sparse *O. sulcata* in the Sanriku region. Two puffer fishes, *Takifugu pardalis* (Temmnich et Schlegel) and *Takifugu chrysops* (Holgendorf), are systematically closely related. However, in Japan the former is distributed along the Sanriku and Sea of Japan coasts, while the latter is distributed along the Pacific coast with the exception of the Sanriku region (Ida 1994). Another consideration is the distribution of the gobiid fish *Pterogobius elapoides* (Günther), having either 6 or 7 horizontal stripes on the body and occurring around the coasts of Japan and Korea. However, the form with 7 stripes is only found along the Japan side of the Sea of Japan and in the Sanriku area (Ida 1994). These examples suggest a community of species cooccurring along the coasts of the Sanriku area and the Sea of Japan.

The sea-grass *Zostera caespitosa* Miki is distributed along the coast of the Sea of Japan between Oki Island (Shimane Prefecture) and Awashima (Niigata Prefecture), as well as in Mutsu Bay (nothern Honshu) (Miki 1932; Omori 1993). The same species is also found along the east coast of Korea and in the northern part of the East China Sea (Miki 1932), as well as from Motoyoshi (southern Sanriku coast, Miyagi Prefecture), Nemuro (Hokkaido), and recently in Yamada Bay (the middle of Sanriku). However, this species has not been found from the coasts of Kyushu and Shikoku, nor the coasts of the Kii Peninsula and Aichi Prefecture in Honshu (Omori et al. 1996). From the character of the distribution of this species, the authors speculated that the sea-grass originated from the Sea of Japan and expanded to the Sanriku coast by propagules carried by the Tsushima Current and Tsugaru Warm Water.

It is likely that several species of both the flora and fauna found in the Sanriku region originated from the Japan side of the Sea of Japan. This indirectly supports the idea that *O. sulcata* is also a species originating in the Sea of Japan, although more direct data are needed to prove this hypothesis.

Along the Sanriku coast, including Okkirai Bay, the annual mean water temperature has been gradually increasing since the occurrence of the minimum sea water temperature recorded in 1984 (Takasugi & Murakami 1994; Sawada & Hayakawa 1997). This increase in water temperature might have brought about the current occurrence of *O. sulcata* larvae in Okkirai Bay as well as their high survival rate and the consequent expansion of this species' distribution. Inasmuch as no study has yet been conducted on the effect of this gradual increase in temperature on the fauna or flora along the Sanriku coast, due to the shortage of long-term quantitative analyses in this area, further investigation on the subject will be needed in the future.

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