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Growth history and inshore migration of the tropical eel, *Anguilla marmorata*, in the Pacific

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**Abstract** A comparative study of the otolith microstructure and microchemistry of *Anguilla marmorata* glass eels in the western North Pacific (Japan, Taiwan, the Philippines, Indonesia) determined the timing of metamorphosis and age at recruitment to freshwater habitats with a view to learning about the early life history and recruitment of this species of tropical anguillid eel, which has a wide range throughout much of the western Pacific and parts of the Indian Ocean. Three new samples (from Japan, Taiwan, Indonesia) were analyzed and statistically compared along with two other previously published samples that were analyzed using the same techniques. Ages at metamorphosis and recruitment, respectively, were $123 \pm 13.4$ days (mean $\pm$ SD) and $154 \pm 17.0$ days in specimens from Japan, $116 \pm 14.6$ days and $145 \pm 15.6$ days in those from Taiwan, $120 \pm 13.0$ days and $154 \pm 13.5$ days in the Philippines stock and $132 \pm 9.7$ days and $159 \pm 11.7$ days, and $120 \pm 15.6$ days and $152 \pm 15.2$ days in the Indonesian stock. The average duration of the period of metamorphosis estimated from otolith microstructure was very similar (15–17 days) in the specimens from all locations. A close linear relationship was found between the ages at metamorphosis and recruitment at all locations, suggesting that individuals that metamorphosed earlier were recruited to freshwater habitats at a younger age. Back-calculated hatching dates ranged over about 6 months of the year, suggesting that this species may spawn throughout much of the year. It is hypothesized that specimens from all four sites are from the same spawning population originating in a spawning area in the North Equatorial Current of the western North Pacific.

**Introduction**

The catadromous tropical eel *Anguilla marmorata* is one of the most common anguillid species in the Indo-Pacific (Ege 1939; Jespersen 1942). The adults of this species reach greater sizes than most temperate species, and range over a much more oceanographically diverse region than any temperate species, since *A. marmorata* is found around the southern half of Japan, throughout the Indo-Pacific, Polynesia, and in several areas in the Indian ocean. Like all anguillid species, *A. marmorata* spawns in the ocean and has a leptocephalus larva that undergoes a remarkable metamorphosis into the glass eel stage before recruitment to fresh water. The lengthy duration of the leptocephalus stage and the timing of metamorphosis is probably an important biological determinant of the geographical distribution of anguillid eels (Tsukamoto and Umezawa 1994). This potential for long-term larval migration in the ocean may have been a key factor in the worldwide distribution and speciation of anguillid eels (Tsukamoto and Aoyama 1998).

Recent progress in otolith analytical techniques has revealed considerable details of the early life history, including the timing and duration of metamorphosis of temperate species of *Anguilla*, such as *A. japonica* (Tsukamoto 1990; Otake et al. 1994; Cheng and Tzeng 1996; Arai et al. 1997), *A. anguilla* (Lecomte-Finiger 1992; Arai et al. 2000a), *A. rostrata* (Wang and Tzeng 1998; Arai et al. 2000a), *A. australis* (Arai et al. 1999a) and *A. dieffenbachii* (Marui et al. 2001). In addition, there have been a few recent studies on the otoliths of the glass eels of several tropical species that were
collected as they recruited to coastal areas (Arai et al. 1999b, c, 2001a), but compared with the information gained from otolith studies in the temperate species of Anguilla, relatively little is known about the early life history of any tropical species.

The wide distribution of A. marmorata throughout the subtropical and tropical western Pacific, the tropical western South Pacific, and Indian Ocean indicates that it differs from temperate species of anguillid eels and has many spawning areas. Recent studies on the genetic species identification, distribution and otolith microstructure of A. marmorata leptocephali in the North and South Pacific indicate that it must have several spawning areas, even within the western Pacific (Aoyama et al. 1999; Arai et al. 2001b). In addition, a genetic study of specimens from a variety of locations throughout the range of this species found genetic differentiation that suggested the presence of several regional populations (Ishikawa 1998).

In the present study, we examined the otolith microstructure and microchemistry of A. marmorata glass eels collected as they recruited to coastal areas in temperate, subtropical and tropical regions of the western North Pacific. We determined the timing and duration of metamorphosis, age at recruitment and hatching date of specimens collected from sites in southern Japan, Taiwan, and Sulawesi Island, Indonesia, ranging over about 30 degrees of latitude. For comparison, we include the data from our previously published analyses of the otolith microstructure and microchemistry of specimens collected at the northern edge of the Philippines and from another nearby river on Sulawesi Island (Arai et al. 1999c). These data form the basis of a discussion of the spawning location and the larval-migration mechanisms of A. marmorata in relation to the major surface currents in the region.

Materials and methods

Fish and otolith preparation

Glass eels of A. marmorata were collected at night during new moon with dip and scoop nets along the beach of Tanegasima Island, Japan, on 16 February 1999, at the mouth of the Tung-Kang River, Taiwan, on 15 February 1999, and near the mouth of the Poigar River, on Sulawesi Island, Indonesia, on 7 July 1997 (Fig. 1). The glass eels sampled were preserved in 99% ethanol immediately after collection. Total lengths were measured to the nearest 0.1 mm and pigmentation stages determined according to Bertin (1956). Sagittal otoliths were extracted from each fish, embedded in epoxy resin (Struers, Epofix) and mounted on glass slides. The otoliths were ground to expose the core in the sagittal plane, using a grinding machine equipped with a diamond cup-wheel (Struers, Dicoplan–TS), and further polished with 6-μm and 1-μm diamond paste on an automated polishing wheel (Struers, Planopol–V). They were then cleaned in an ultrasonic bath and rinsed with deionized water pending subsequent examination.

The previously reported otolith data (Arai et al. 1999c), which are included for comparison, were from specimens collected with scoop nets at the mouth of the Cagayan River, Philippines, on 24 September 1994, and from the mouth of the Dumoga River, on Sulawesi Island, on 5 June 1996. Thus, a total of 88 specimens (19 specimens from Japan, 19 specimens from Taiwan, 10 specimens from Philippines, 20 from the Poigar River and 20 from the Dumoga River, Indonesia) were included in the present study (Table 1).

Otolith X-ray microprobe analysis

For electron microprobe analyses, five glass eel otoliths from each site were carbon coated by a high-vacuum evaporator. Otolith Sr and Ca concentrations were measured along the longest axis using a wavelength dispersive X-ray electron microprobe (JEOL JXA–8900R), with calcite (CaCO₃) and strontianite (SrCO₃) as standards. The procedures for embedding, grinding and polishing, and the conditions for electron-microprobe analyses, followed those described by Arai et al. (1997, 1999a, b, c). Microprobe measurement points, which were seen as burn depressions, were assigned to otolith growth increments that were examined as described below. The averages of successive data of Sr and Ca concentrations pooled for every ten successive growth increments were used for the life history transect analysis. “X-ray intensity maps” of both elements were made for six glass eel samples. The beam current was 0.01 μA, counting time was 0.1 s, and the other analytical conditions followed those for the life-history transect analyses.

Otolith-increment analysis

Following the electron-microprobe analysis, the otoliths were repolished to remove the coating, etched with 0.05-M HCl and vacuum-coated with Pt-Pd in an ion-sputterer for scanning electron