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Age and Growth of Pacific Saury *Cololabis saira* (Brevoort) in the Western North Pacific Ocean Estimated from Daily Otolith Growth Increments

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Growth of Pacific saury *Cololabis saira* (Brevoort) inhabiting the western North Pacific was studied based on counting daily growth increments with a scanning electron microscope (SEM). The small-size group (knob length: 200–240 mm), medium-size group (knob length: 240–280 mm) and large-size group (knob length: >280 mm) showed increments of 256±26.0 (S.D.), 405±76.1 and 566±48.2, respectively. Based on daily growth increment formation, we determined that the ages of the 3 groups were about 8, 13, and 19 months. Small- and large-size fish were considered to have been hatched from autumn to winter, and medium-size fish from spring to summer. The oldest specimen of Pacific saury examined in this study was about 23 months of age; thus, the lifespan of Pacific saury in this area seems to be at least 1.5 years.

Key words: Pacific saury, otolith, age determination, daily growth increment, hyaline zone

The Pacific saury *Cololabis saira* (Brevoort) is widely distributed in the sub-arctic and sub-tropical North Pacific Ocean[1] and is one of the most important commercial fish species in Japan. Landings in Japan have been seen to fluctuate greatly from year to year depending on stock size; however, the causes of these fluctuations are unknown. To identify the possible causes of fluctuations in Pacific saury stocks, we considered it necessary to investigate the life history of the species, particularly regarding aspects of age and growth. Determination of age and growth for Pacific saury have been previously estimated from analysis of annual ring counts in scales[2-4] and otoliths,[4] and from length frequency distributions,[5] rearing experiments,[6,7] and enumeration of daily growth increments in sagittal otoliths.[8] Among these methods, those based on counting daily growth increments in otoliths have been found to give the most accurate age estimates. Estimates of age and growth for Pacific saury using sagittal otoliths were first conducted by Nishimura *et al.*,[9] and Watanabe *et al.*[8] suggested that Pacific saury grow about 300 mm (knob length: KnL) within one year based on observations of daily growth increments in otoliths. By rearing larvae from hatching, Watanabe and Kuji[7] verified that one increment is deposited per day. Fukushima *et al.*[10] suggested that large-, medium-, and small-size Pacific saury caught during the fishing season from mid-August to early December had hatched respectively in autumn (12 months old), winter (8–10 months old), and spring (5–7 months old). On the other hand, in counting daily growth increments in otoliths taken from Pacific saury caught in the central North Pacific, we previously estimated large Pacific saury to be more than 1.5 years old.[11] Hyaline zones were observed in the otoliths of only large-size Pacific sauries, and we additionally estimated from counting daily growth increments that these likely form during winter. Previously, the formation of hyaline zones was reported in only otoliths of large-size Pacific sauries in the western North Pacific.[4,12] If any differences exist regarding the growth of Pacific sauries in both areas, then the hyaline zone patterns in the otoliths would also likely differ. Therefore, it was considered that there are no differences in growth between Pacific sauries of these areas.[11] This paper re-examines the age and growth of Pacific saury in the western North Pacific Ocean based on an examination of daily growth increments in the otoliths.

Materials and Methods

Specimens of Pacific saury were collected in the western North Pacific during three cruises from June to October in 1991. The first cruise was conducted aboard the Hokusei-maru (Training Vessel of Hokkaido University), on which Pacific sauries were collected with drift-gillnets (from 19 to 233 mm with 20 different mesh sizes)[13] at five sampling sites. The second and third cruises were conducted aboard the Hokushin-maru (Research Vessel of the Hokkaido Fisheries Experimental Station, Kushiro) using three-size mesh (29, 37 and 48 mm) drift gill-nets, dip-nets and a stick-held dip net. During these two cruises, Pacific sauries were collected at 5 and 10 sampling sites, respectively (Fig. 1, Table 1). Body length in terms of KnL (knob length) in mm[14] was measured on board and specimens were frozen upon capture for laboratory analysis.

In the laboratory, specimen KnL were re-measured and otoliths (sagittae) were extracted, washed with distilled water and air-dried. Otolith radii were then measured and

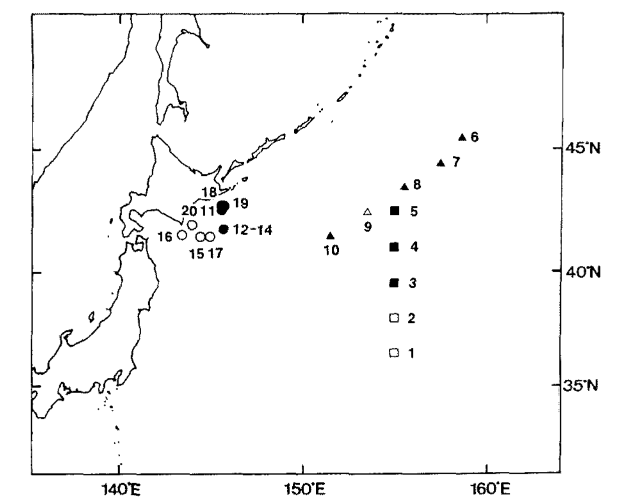


Fig. 1. Study area and sampling locations.
□ ■; the first cruise on the Hokusei-maru from June 4 to June 11 in 1991, △▲; the second cruise on the Hokushin-maru from July 22 to July 26, ○ ●; the third cruise on the Hokushin-maru from September 25 to October 3. Samples for otolith analysis were collected at the 11 stations indicated by a dark symbol. Numbers near symbols indicate station number.

Table 1. Collection records of saury samples in 1991

Station	Date	Location		Gear*1	No. samples*2	
		Lat. (N)	Long. (E)		Length	Otolith
First cruise						
1	Jun. 6–7	36°32'	155°01'	G	13	0
2	Jun. 7–8	38°01'	154°59'	G	155	0
3	Jun. 8–9	39°30'	155°01'	G	440	9
4	Jun. 9–10	41°00'	155°02'	G	122	4
5	Jun. 10–11	42°31'	155°00'	G	2	1
				Subtotal	732	14
Second cruise						
6	Jul. 22–23	45°30'	158°30'	G	300	5
7	Jul. 23–24	44°30'	147°30'	G	300	6
8	Jul. 24	43°30'	155°30'	G	300	2
9	Jul. 25–26	42°31'	153°31'	G	58	0
10	Jul. 26–27	41°30'	151°30'	G	44	1
				Subtotal	1002	14
Third cruise						
11	Sep. 25–26	42°30'	145°00'	G	300	3
12	Sep. 26	41°46'	145°38'	S	31	0
13	Sep. 26	41°47'	145°38'	D,S	101	1
14	Sep. 26–27	41°45'	145°45'	G	300	0
15	Sep. 29–30	41°30'	144°30'	G	300	0
16	Sep. 30-Oct. 1	41°30'	143°30'	G	4	0
17	Oct. 1	41°30'	145°00'	D	50	0
18	Oct. 2	42°55'	145°00'	D	22	1
19	Oct. 2	42°45'	145°30'	D	24	2
20	Oct. 3	42°00'	144°00'	D	9	0
				Subtotal	1141	7
				Total	2875	35

*1 Sampling gear. G; gill nets, D; dip net, S; stick-held dip net.
*2 Number of samples used to measure knob lengths and analyse otoliths.

the hyaline zone was examined with a light microscope. Otolith examination of daily growth increments was done as described in a previous study.[11] Otoliths were mounted with epoxy resin on a glass slide, and left to dry for 2 days. After the epoxy resin hardened, otoliths were ground by lapping film (grind paper for hard tissues, 9 μm and 3 μm) under a light microscope at an angle (about 60°) to the flat plane and parallel to the long axis of the otolith until the focus was at the ground surface of the otolith. The ground otolith sections were etched with 0.1 M EDTA for 50 sec and air-dried. After drying, the sections were detached from the glass slide, stuck onto SEM stubs, coated with palladium platinum, and observed with a scanning electron microscope (SEM) at 15 KV. Increment counts and other measurements were made from the SEM photographs at a final magnification of $\times 1000$.

Prior to counting total increments, increments were classified as clear (clearly readable), unclear (counts could be made but increments were vague) or uncountable (increments formed an indistinguishable zone). The number of increments in the uncountable zones were estimated by the average width of 10 readable increments on either side of the zone. After classification, we summed up the number of increments in each of the three levels in each specimen, calling this the total number of daily growth increments. Specimens containing increments of which more than 50% were uncountable and/or unclear were excluded from any further analysis. We initially examined 208 specimens, but as a consequence of the above, a total of only 35 specimens (200–319 mm KnL) remained for use in analysis.

Results

Size Composition

In the previous study, sizes of Pacific saury were divided into 4 to 5 groups.[4,5] In the present investigation, we divided specimens into small (ranging from 200 mm to less than 240 mm), medium (ranging from 240 mm to less than 280 mm) and large (larger than 280 mm) groups.

The length frequency distribution of Pacific sauries in this study varied among the 3 samples (Fig. 2). In June, bi- or tri-modal compositions were seen, *e.g.*, one large group, one small group and one group less than 200 mm in KnL. In contrast, in July and from September to October, only a single mode (large group) was observed. Few medium-size fish were captured during the 3 cruises.

Relationship between Age in Days and Knob Length

The largest individual (319 mm KnL) examined for daily growth increments had 689 daily increments in its otolith, and the smallest one (200 mm KnL) had 209 increments. Otoliths of the small-size group had 209 to 292 increments ($\bar{x}=256.0$, SD=26.0), those of the medium-size group had 291 to 514 ($\bar{x}=405$, SD=76.1) increments, and those of the large-size group had 507 to 689 ($\bar{x}=566.5$, SD=48.2) increments.

Watanabe and Kuji[7] reported that hatched Pacific saury larvae have 4 or 5 increments in the otoliths and that the age in days for Pacific saury can be estimated by subtracting 5 from the number of increments observed. Judging from this increment-age relationship, the specimens from small-, medium- and large-size groups in this study were es-

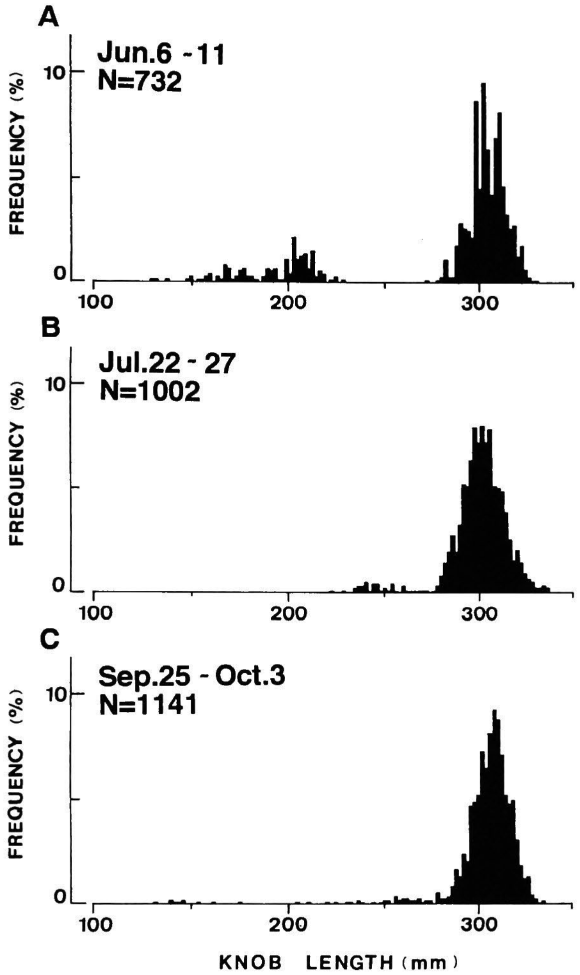


Fig. 2. Size composition of Pacific saury.
A, first cruise. B, second cruise. C, third cruise.

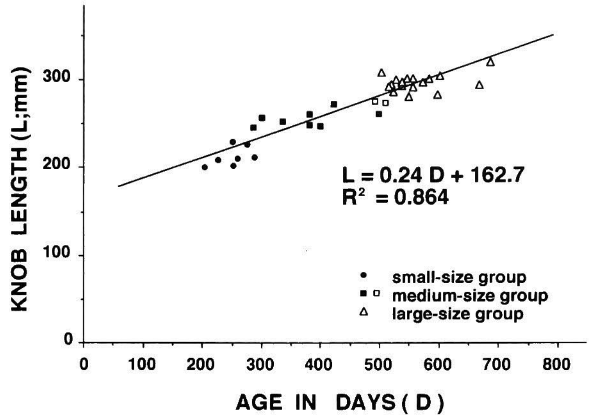
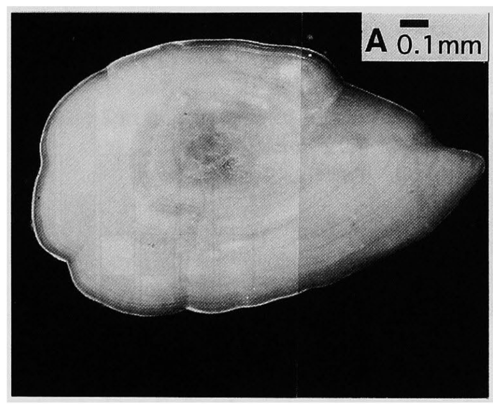


Fig. 3. Relationship between age in days and knob length of the Pacific saury.
●, Small fish (200–240 mm in knob length); ■ □, medium size (240–280 mm) and △, large (more than 280 mm). □ △, individuals who had an observable hyaline zone in the otoliths.



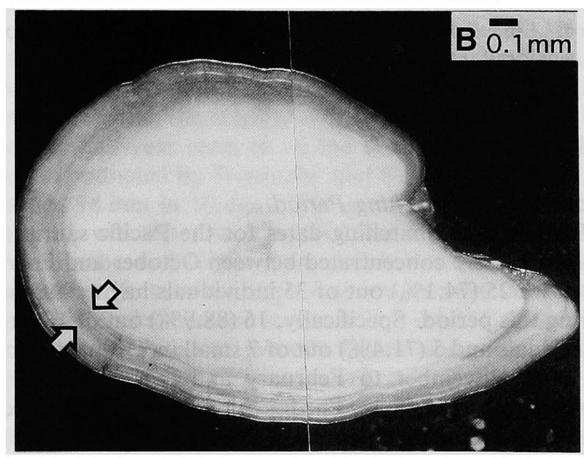


Fig. 4. Light microscope photographs of Pacific saury otoliths.
A, medium-size (246 mm); **B**, large-size fish (281 mm). Areas between arrows corresponded to the hyaline zones.

timated to be about 8, 13, and 19 months old, respectively (Fig. 3).

Hyaline Zones

Hyaline zones were formed only in otoliths of individuals larger than KnL 274 mm (Fig. 3). Thus, otoliths from the large-size group had hyaline zones, while hyaline zones were not observed in the otoliths of medium- and small-sized fish with the exception of two individuals (Figs. 3 and 4).

Daily growth increments in the hyaline zone are often observed as uncountable zones.[11] In this study, hyaline zones also corresponded with uncountable zones, so we regarded uncountable zones as hyaline zones based on observation by SEM. Formation periods of hyaline zones were inferred from estimating the number of increments, and the knob length at the start of hyaline zone formation was estimated by counting the number of increments enclosed by the hyaline zone and extrapolating from the expression in Fig. 3. (Fig. 5)

Hyaline zones were mainly formed from November to March, exhibiting from 31 to 120 ($\bar{x}=74.0$, S.D.$=22.7$) increments. In areas enclosed by the hyaline zones, 298 to 454 increments ($\bar{x}=345.3$, S.D.$=35.8$) were counted. At the start of formation of the hyaline zones, the knob length was estimated to be between 233 to 270 mm.

One specimen (275 mm in KnL) did not have an uncountable zone although hyaline zone was observed in the otolith. The average increment width of this specimen was estimated at 0.93 μm/day in December and 1.67 μm/day

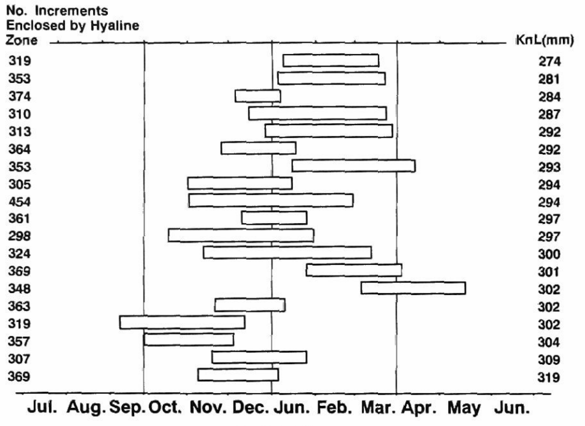


Fig. 5. Estimated formation period of the hyaline zones in otoliths.

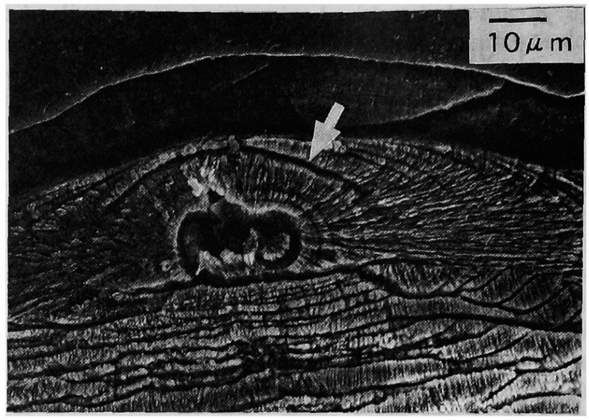


Fig. 7. Scanning electron microscope (SEM) photographs of Pacific saury otoliths.

A, from 292 mm Pacific saury. Arrow shows distinct increment considered to be the hatch ring.

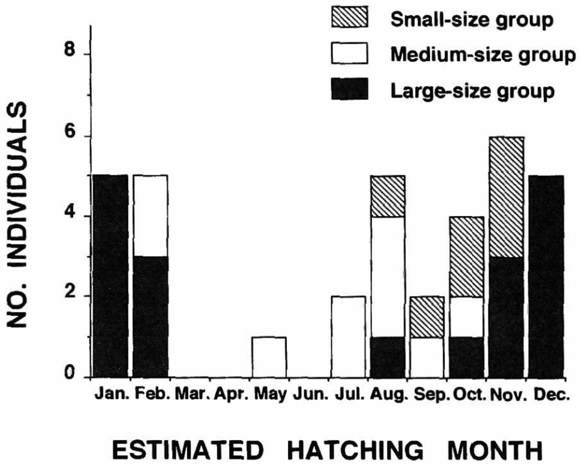


Fig. 6. Estimated month of hatching for each size group based on the number of otolith increments.

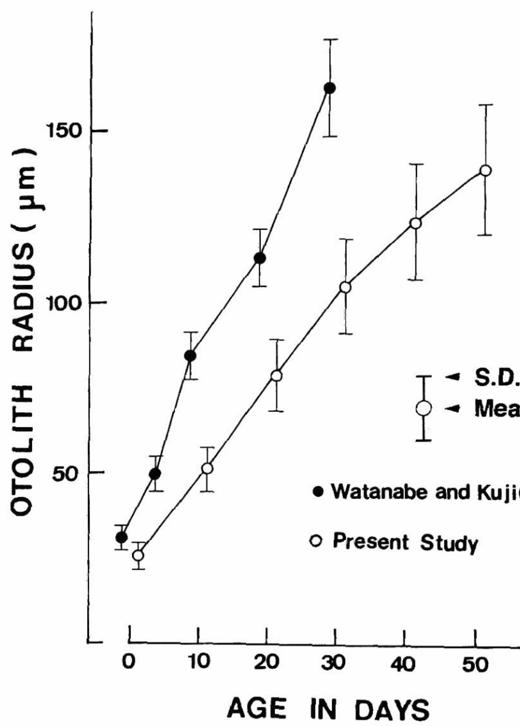


Fig. 8. Relationship between age in days and otolith radius. ○, present study; ●, rearing experiment.[7]

in January.

Estimation of Hatching Period

The estimated hatching dates for the Pacific sauries in this study were concentrated between October and February, with 25 (74.1%) out of 35 individuals having hatched during this period. Specifically, 16 (88.9%) out of 18 large individuals and 5 (71.4%) out of 7 small individuals hatched from November to February and from October to November, respectively. The hatching month of the medium-size group was dispersed, ranging from February to October (Fig. 6). This suggests that the small- and large-size group hatched during the autumn of the previous year (1990), and autumn to winter 2 years before (1989), respectively. Individuals of the large-size group hatched about 1 year earlier than those of the small-size group.

Growth in Larvae Inferred from Daily Growth Increments

Growth rates of the KnL and otolith radius for the first 30 days after hatching were clarified through rearing experiments.[7] Twenty-one (60.0%) out of 35 individuals in the current study showed distinct singular increments which likely represent hatch marks. Four to 10 finer increments ($\bar{x}=5.6$, S.D.$=1.4$) were present inside of this "hatch mark" and the average distance from the center of the focus to the distinct increment was 25.8 (S.D.$=3.9$) μm (Fig. 7).

In spite of rapid otolith growth of 163 μm in the 30-day rearing experiment by Watanabe and Kuji[7] a fairly slow growth of 138 μm in 50 days was estimated from the present study (Fig. 8).

Comparison of Growth Rates between Pacific Sauries in the Central and Western North Pacific Ocean

To compare the growth of Pacific sauries in the western

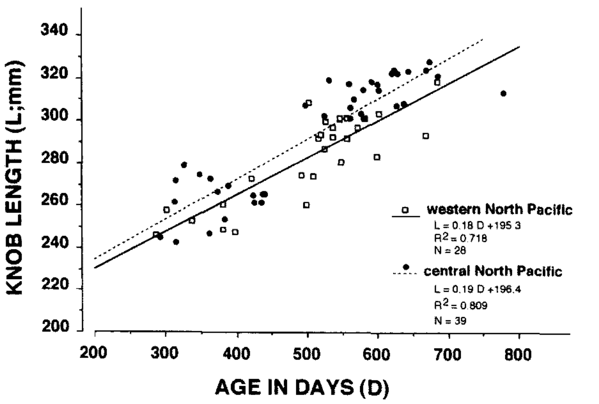


Fig. 9. Comparison of growth of medium- and large-size fish between the western North Pacific and central North Pacific Ocean. ●, central North Pacific[11] and □, western North Pacific.

North Pacific Ocean and central North Pacific Ocean;[11] we examined the relationship between length (KnL) and age in days of medium and large fish (Fig. 9).

Growth rates were estimated to be 0.18 mm and 0.19 mm per day in the western and central North Pacific, respectively. There was no significant difference (t-test $p>0.05$) in growth rates between the two regions.

Discussion

The results of this study differed from a similar aging study based on daily otolith growth increments conducted by Watanabe *et al.*[8] According to their report, Pacific saury reach the large-size group within a year; however, we estimated that it likely takes more than 1.5 years to attain this size. Similarly, they estimated that only a half-year is required to reach the large-size class from the small-size but our estimate is about a year. Concerning the small-size group, in this study, it was estimated to take up to about 8 months to enter this size class, while Watanabe *et al.*[8] reported this time to be about 6 months. Along these lines, there were no great differences between their results and ours in the small-size group; discrepancies may be due mainly to differing estimations of the time required in growth from small- to large-size.

We did not consider that Pacific saury grow as rapidly as Watanabe *et al.*[8] after reaching medium-size. One reason is that the hyaline zones in otoliths were observed mainly in the large-sized group[4,11,12] and it was considered that hyaline zones formed in winter.[4] When the hyaline zones were beginning to be formed, we considered that the Pacific saury was of small- to medium-size from estimating the number of increments in areas enclosed by the hyaline zones. Additionally, in the hyaline zones themselves, daily growth increments were indistinguishable, which reflected a slowing-down in the rate of formation of otoliths.[11] Thus, we considered that the presence of hyaline zones in fish of the large-size group indicated that the fish had lower growth rates after reaching medium-size during winter. We inferred one cause of the discrepancy between the results of Watanabe *et al.*[8] and those of this study to be related to our interpretation of increment counts in the hyaline zones; in Watanabe *et al.*[8] there were no descriptions concerning hyaline zones. However, we can not explain the differences in the two reports as due to only the number of increments in the hyaline zones because in our study, the hyaline zone formation period was estimated at about 74 days (2.5 months), but the estimated age of large-size fish differed by more than 6 months between the two studies. The full reasons for these differences are unclear.

Our results regarding the formation periods of hyaline zones and the relation between size composition and existence of hyaline zones are in agreement with previous studies.[4,11,12] Therefore, we do not consider that the 35 individuals which were counted for daily growth increments in this study grew exceptionally.

Though most of the medium-size fish were more than 1 year old, hyaline zones were not observed in the otoliths except in 2 individuals. We do not know why the medium-size fish did not have hyaline zones in their otoliths even though they were of sufficient age. To better understand the causes for the formation of hyaline zones, we need to conduct more detailed investigation on their migration between sub-tropical and sub-arctic waters and the connection to their maturity.

Another possible reason why the growth rate decreases after fish reach medium-size is that they reach a state of reproductive maturity. It is known that Pacific saury of more than 260 mm caught in late autumn are often in the mature stage.[2,4,15-17] Therefore, it is assumed that the growth rate slows after fish reach medium-size due to maturity.

Many studies on the age and growth of Pacific saury have been conducted (Table 2). Hatanaka[2] estimated the age of large Pacific saury to be 4 years based on the number of scale rings. Hotta[4] examined the annual rings on scales and otoliths, and also estimated the growth rate from rearing experiments using young Pacific sauries for about 80 days.[6] From these two combinative studies, Hotta concluded that Pacific sauries grow to 20–50 mm in 0.5 years, 150–200 mm in a year, 230–250 mm in 1.5 years, 300 mm in 2 years and 315 mm in 2.5 years. In comparison with our results, the original estimates of growth rate[4] for the first half-year seem to be too low. In rearing experiments conducted by Watanabe and Kuji,[7] hatched larvae reached 78 mm in 60 days. The growth rate estimated in our study was about two-thirds of that shown in the results of watanabe and Kuji;[7] such differences were probably due to the effects of rearing water temperature. Watanabe and Kuji[7] reared hatched larvae at 18.5–24.1 °C. However, in the field, larvae and juvenile Pacific saury were caught mainly at 15–21 °C.[16,18,19]

From an analysis of growth based on size composition, Matsumiya and Tanaka[5] also suggested that Hotta's estimates were too slow during the first half-year. They calculated that 0.5, 1.0, 1.5, 2.0, 2.5 year old Pacific sauries reach 182, 223, 266, 312 and 338 mm in KnL, respectively. With regard to growth rates in small fish, Hotta[4] and Matsumiya and Tanaka[5] obtained similar results.

In the present study, no differences in growth rate between fish from the central and western North Pacific were observed. The largest individual (319 mm) in the present study was also the oldest individual with an age of 684 days (about 23 months). In a previous study in the central North Pacific,[11] the largest individual (329 mm) was

Table 2. Comparison of previous studies of growth of *Pacific saura* in the western North Pacific Ocean

Study	Main spawning season	Methods	Size (knob length in mm)				
			0.5 year	1.0 year	1.5 years	2.0 years	2.5 years
Present Study	2 times per year (Autumn to Winter) (Spring to Summer)	Daily growth increments in otoliths	202*	250	295	338*	—
Hotta[4]	2 times per year (March to July) (October to February)	Annual rings in the scale and the otolith	20–50	150–200	230–250	300	315
Matsumiya and Tanaka[5]	2 times per year	Analysis of length composition	182	223	266	312	338
Watanabe *et al.*[8]		Daily growth increments in otoliths	209	294			
Fukushima *et al.*[10]	3 times per year (Spring. Autumn, Winter)		Small size	Large size			

* Estimated by extrapolation.

estimated to be 672 days (about 22 months) old and the oldest fish (314 mm) was 776 days (about 26 months) old. Therefore, the lifespan in these regions was considered to be more than 1.5 years.

We defined medium-size groups from 240 to 280 mm in accordance with previous studies.[4,5] However, it may be necessary to include the 2 individuals that had hyaline zones (274 and 275 mm) in the large-size group. From their size composition (Fig. 2), the range of the large-size group seems to be from about 275 to 330 mm. These 2 individuals were estimated to have hatched in February. If these individuals are removed from the medium-size group and included in the large-size group, the hatching period of the medium-size individuals may be considered to be from May to October.

We considered that fish of the small-size group hatched about a year later than fish of the large-size group, so that both groups hatched in the same spawning seasons (from autumn to winter) but in consecutive years. Between the large-and small-size group, only one other group (medium-size group) has been known. Thus, it appears true that there are two spawning seasons in a year.

Based on the abundance of eggs, larvae and juvenile fish in the Japan Sea, Fukataki[20] reported that Pacific saury spawn in spring and autumn. Hotta[4] considered that the spawning season in the western North Pacific occurs from March to July and from October to February as inferred from seasonal changes of gonad weights and from Fukataki's assumptions. Matsumiya and Tanaka[5] also considered that spawning occurs twice a year. On the other hand, Watanabe and Lo[21] reported that the main spawning season was winter, and autumn and spring were considered to be the early and late segments of the main spawning season.

We also regarded that Pacific saury spawn twice a year as Hotta[4] and Matsumiya and Tanaka[5] described. Therefore, we concluded that small-and large-size fish hatched between autumn and winter, and that medium-size fish possibly hatched from spring to summer. However, in our analysis of daily otolith growth increments, only 3 medium-size fish were determined to have hatched between March to July. In this year (1991) few medium-size fish were caught in our study and in general in the fishing grounds where we operated,*3 which may explain why only a small number of individuals were found to have hatched in this period.

The reasons for the differences in determination of spawning season[4,21] are unclear. It is difficult to determine the exact confines of the spawning season based on only daily growth increments in otoliths because of the frequent presence of uncountable zones in large-size fish. This investigation clarified much concerning age and growth of the Pacific saury, but further investigation is necessary to obtain more knowledge of the spawning season of this species.

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