FRDC FINAL REPORT

AGE AND GROWTH OF JACK MACKEREL AND THE AGE STRUCTURE OF THE JACK MACKEREL PURSE SEINE CATCH

J.M. Lyle, K. Krusic-Golub and A.K. Morison

February 2000

FRDC Project No.1995/034

FISHERIES RESEARCH & DEVELOPMENT CORPORATION

MARINE & FRESHWATER RESOURCES INSTITUTE

Tasmanian Aquaculture & Fisheries Institute
University of Tasmania

National Library of Australia Cataloguing-in-Publication Entry

Lyle, J.M.

Age and growth of jack mackarel and the age structure of the jack mackerel purse seine catch.

Bibliography.

ISBN 0-7246-4760-0

1. Trachurus declivis. 2. Trachurus declivis – Age
3 Trachurus declivis – Growth. 4. Purse seining – Tasmania – Data processing. I. Morison, A.K. II. Krusic-Golub, K. III. Tasmanian Aquaculture and Fisheries Institute. IV. Title V. Title: FRDC Project no. 1995/034

597.78209946

Published by the Tasmanian Aquaculture and Fisheries Institute, University of Tasmania 2000

Tasmanian Aquaculture and Fisheries Institute
Marine Research Laboratories
Taroona, Tasmania 7053

Telephone: (03) 6227 7277 Fax: (03) 6227 8035

AGE AND GROWTH OF JACK MACKEREL AND THE AGE STRUCTURE OF THE JACK MACKEREL PURSE SEINE CATCH

J.M. Lyle[1], K. Krusic-Golub[2] and A.K. Morison[2]

February 2000

FRDC Project No. 1995/034

[1] *Tasmanian Aquaculture and Fisheries Institute*
Marine Research Laboratories
Nubeena Crescent Taroona, TAS 7053

[2] *Marine and Freshwater Resources Institute*
P.O. Box 114
Queenscliff, VIC 3225

Table of Contents

1 NON-TECHNICAL SUMMARY

1995/034 Age and growth of jack mackerel and the age structure of the jack mackerel purse seine catch

Principal Investigator: Jeremy Lyle[1]
Co-Investigators: Alexander Morison[2]
Kyne Krusic-Golub[2]

Address: [1] Tasmanian Aquaculture and Fisheries Institute
Marine Research Laboratories
Nubeena Crescent
Taroona, TAS 7053
jeremy.lyle@utas.edu.au

[2] Marine and Freshwater Resources Institute
P.O. Box 114
Queenscliff, VIC 3225

Objectives:

1. Develop and validate an ageing method for jack mackerel.
2. Describe the age and growth of jack mackerel in south east Australian waters.
3. Describe the age structure of the purse seine catch over the history of the fishery.

Non-Technical Summary

Jack mackerel (*Trachurus declivis*) is a pelagic species that is found in waters off southern Australia and New Zealand. It is the subject of a major fishery, predominantly off Tasmania, with annual landings in the range of 9,000 - 42,000 tonnes. The fishery commenced in the mid 1980s and uses purse seines to target dense surface and sub-surface schools that are present over the shelf between September and May. The fishery is managed by a limit on the total tonnage that can be caught. This is currently set at 42,000 tonnes, which represents the largest quantity of fish that has been caught in any one year (in 1986/87). A long-term research and management objective is to develop a more scientific basis for estimating the size of the jack mackerel resource and setting the catch limit.

A 1994 review of jack mackerel research identified the need, in the short term, for a range of methods to indicate the condition the jack mackerel population. These included an understanding of the growth of jack mackerel, the age at which fish enter the fishery, the range of ages of fish caught in the fishery, and how these characteristics may have changed over time.

The age and growth of jack mackerel has been studied previously using growth increments observed in the otoliths. However, there were inconsistencies in this information among researchers within Australia and between Australia and New Zealand workers. There was a clear need to find out whether these were real differences between

jack mackerel populations or were due to errors in the methods used to age the fish.

This study used a new technique to determine the accuracy (validate) methods used to estimate the age of jack mackerel. The technique uses the increase in levels of radioactive carbon in the atmosphere and oceans that occurred after the atmospheric nuclear tests in the 1960s. The year in which a fish is born can be estimated by matching the level of radiocarbon in their otoliths to the levels recorded in the environment.

This method confirmed that jack mackerel could be aged accurately by counting the growth increments present in otoliths. In fact, similar estimates of age were obtained for jack mackerel regardless of whether whole otoliths or thin sections were used. Growth increments were, however, more clearly seen on thin sections and as a result, there was better agreement between repeated age estimates for the same fish when otolith sections were used. A protocol for interpreting jack mackerel otoliths has been developed.

The growth of jack mackerel was described based on samples collected from the Tasmanian fishery between 1985/86 and 1994/95. This suggested that jack mackerel were slower-growing than had previously been reported. On average, jack mackerel are 27 cm long and four years of age when they enter the purse seine fishery, and 33.5 cm long when 10 years of age. Both males and females grow at the same rate. Previous estimates of the age of jack mackerel from purse seine catches were demonstrated to be inaccurate and therefore there is a need to re-age otoliths using techniques developed here.

Based on the age structure of commercial landings for the 1985/86, 1989/90, 1993/94 and 1994/95 fishing years there has been a general decrease in the number of older fish, caught in the Tasmanian purse seine fishery. Whereas over 50% of fish were aged 6 years or older in the samples from 1985/86, in 1994/95 this had fallen to less than 4%. There are several possible reasons for such a change:

- impact of fishing on the age structure of the jack mackerel population,
- changes in the size (and hence age) of fish which are targeted by the fishery (due to changes in the timing and location of fishing operations),
- changes in the population age structure due to recruitment variability, and
- inter- and intra-annual changes in the behaviour of jack mackerel schools, or
- a combination of one or more of these factors.

It is not possible to choose the correct reason from what we know at the moment.

Although the 1995/96 catch was not aged, the length frequency distribution was more typical of landings from the early years of the fishery (i.e. single mode of large fish). It would appear that a complex range of factors influence the size and age structure of the catch.

KEYWORDS: jack mackerel, *Trachurus declivis*, otoliths, age and growth, purse seine fishery

2 BACKGROUND

Jack mackerel (*Trachurus declivis*) is a pelagic species found in the coastal waters of southern Australia and New Zealand. In Australia, the species is distributed from Shark Bay in Western Australia, around to the central New South Wales coast, including the waters around Tasmania.

A major Australian fishery for jack mackerel operates off Tasmania with landings in other states being relatively small. The Tasmanian purse seine fishery began in 1985, and landings rose rapidly to a peak of 42,000 tonnes in 1986/87. Landings have shown a high degree of variability since this peak, ranging from 9,000 - 38,000 tonnes with an average catch of around 16,000 tonnes per annum. Almost all of the catch is processed into fishmeal for use in the aquaculture industry. The remainder is used as rock lobster bait.

The purse seine fishery targets dense surface and sub-surface schools, which form during spring, summer and autumn off eastern Tasmania (Williams and Pullen 1993).

The fishery is managed by Tasmania in State waters while in adjacent waters Commonwealth law applies. These management arrangements are expected to be replaced by a Joint Authority between Tasmania and the Commonwealth, which will see fishing in the region (known as Zone A) under Tasmanian law[1]. While negotiations continue, however, interim management arrangements allow operators under either jurisdiction reciprocal access.

The fishery is managed by output controls in the form of a total allowable catch (TAC) that is currently set at 42,000 tonnes, based on the previous highest purse seine catch. To date no assessment of the size of the resource, or sustainable catch levels on which to base the TAC has been possible. A sound scientific rationale for setting the TAC is a long-term research and management objective.

The Department of Primary Industry and Fisheries (DPIF), now divided into the Department of Primary Industries, Water and Environment (DPIWE) (management) and Tasmanian Aquaculture and Fisheries Institute (TAFI) (research), became actively involved in research into the jack mackerel fishery shortly after it first started in 1985. This research has provided a continuous data set, including catch/effort information (to the present) and biological data (to 1997). Monitoring of the fishery was supplemented by a three year joint DPIF/FRDC program, which investigated fishery independent assessment techniques, the causes and effects of inter-annual variability and the reproductive biology of jack mackerel (Jordan *et al.* 1992).

As part of the jack mackerel research program, fish were routinely aged by counting rings visible in whole jack mackerel otoliths.

[1] In December 1996 the Tasmanian government signed an Offshore Constitutional Settlement (OCS) agreement with the Federal government relating to mackerel and associated species in the area specified as Zone A. Zone A includes all waters within the Australian Fishing Zone east of 146° 30'E and south of 39° 30'S off the north and east coasts of Tasmania and waters south of 42° 12'S off the west coast. Gazettal of an MOU is, however, required to implement these OCS arrangements.

Several authors have previously described the age and growth of jack mackerel in south eastern Australian waters. Webb and Grant (1979) demonstrated regularity in the deposition of rings, but did not validate ages assigned. Stevens and Hausfeld (1982) attempted to validate the annual deposition rings but were unsuccessful and length frequency data was used to support readings as a true indication of age. Early results achieved by the DPIF agreed well with the literature, suggesting that the interpretation of otoliths was consistent between studies.

However, recent literature suggests that the same species grows substantially faster in the early years of life and lives much longer around New Zealand than is reported for Tasmania (Horn 1993). For example, a five year old fish from south eastern Australia would be around 30 cm FL (Stevens and Hausfield 1982), whereas a similar aged fish from New Zealand would be expected to be over 6 cm larger (Horn 1993). As growth slows after 5-7 years of age, the larger size groups from New Zealand would be expected to contain far more age classes than indicated from the Australian studies.

To determine whether the differences in growth rates between Australia and New Zealand are real, or due to different interpretation of otoliths, a subset of Tasmanian otoliths was sent to New Zealand for reading. Ages assigned to those otoliths by the New Zealand readers were significantly different to those assigned by the DPIF reader. While some ages assigned were in reasonable agreement, smaller fish (those aged < 5 by DPIF) were aged 1-3 years younger, and larger fish (> 5 years) were generally aged significantly older. For example, fish aged 5 by DPIF (around the growth plateau) were aged between 2 and 11 years by New Zealand readers. Fish aged 10 years by DPIF were aged between 9 and 18 by the same readers.

Otoliths were also read by the Central Ageing Facility (CAF) and ages assigned tended to agree with the New Zealand results.

These inconsistencies in readings lead to doubts arising over the accuracy of the established ageing techniques.

A detailed review of jack mackerel research was conducted in August 1994 involving DPIF and CSIRO personnel (Pullen and Lyle 1994). As a review of jack mackerel research had been a priority of the now disbanded Jack Mackerel Working Group, the Australian Fisheries Management Authority (AFMA) provided some funding support for the review.

The review identified the complexity of resource assessment for jack mackerel, partly due to the behaviour of jack mackerel and the nature of the fishery, finding no immediate and simple means for determining sustainable catch levels (Pullen and Lyle 1994).

In the short term, a suite of indicators of population stress was considered useful in providing an indication of the status of the resource. Indicators of stock stress identified included changes in growth, age at recruitment and age structure of catches.
In the longer term it may be possible to develop age structured models, particularly if alternate data sources, such as trawl catch information, can account for some of the biases associated with sampling only from the purse seine fishery.

The alternative data sources identified by the research review may also assist validation and/or interpretation of otolith ring formation. At the final Demersal and Pelagic Fisheries Research Group (DPFRG) meeting (August 1994), where a report of the review was tabled, DPFRG endorsed a request for access to available data on jack mackerel held by the member agencies.

An obvious requirement of many of the assessment techniques suggested for investigation by the review is the ability to age fish and the development and validation of a protocol for routine ageing of jack mackerel was identified, therefore, as a high research priority (Pullen and Lyle 1994).

3 NEED

In terms of tonnage, the jack mackerel fishery is one of Australia's most significant fisheries. Management is by output controls and the current TAC of 42,000 tonnes is based on previous catch history. The size of the resource and sustainable yields are unknown. It is essential to the management of this fishery that a meaningful yield estimate is obtained and this project is an important step in attaining that goal.

Accurate ageing of fish is central to much fisheries and assessment research. It forms the basis for a wide range of techniques that may be applicable to assessment of the jack mackerel resource. Uncertainty regarding the interpretation of jack mackerel otoliths must be resolved.

The recent review of jack mackerel research has outlined research priorities and the direction for research over the next few years (Pullen and Lyle 1994). Many of the possible assessment tools identified are invalid without an ability to age fish. The review identified, therefore, that development of a protocol for routine ageing of fish was a high priority.

The age structure of the catch may be informative in providing an indication of the impact that fishing has had on the stock. Such indicators of stock stress might include changes in growth, age at recruitment and the structure of landings.

Tasmania has a continuing and significant commitment to research and management of the jack mackerel fishery. Successful resolution of uncertainty over ageing is integral to continued progress in this research.

It is likely that under the proposed Joint Authority an assessment process involving both jurisdictions will be formalised. Resolution of ageing uncertainty and information on age and growth will be central to the development of such an assessment process.

4 OBJECTIVES

1. Develop and validate an ageing method for jack mackerel.
2. Describe the age and growth of jack mackerel in south east Australian waters.
3. Describe the age structure of the purse seine catch over the history of the fishery.

5 METHODS

5.1 Data collection

Catch data was obtained from the daily fishing logbook used in the fishery since August 1985 (Williams *et al.* 1986). On-board and port based catch sampling provided length-frequency measurements and otolith collections from the commercial purse seine fishery (Williams *et al.* 1986). Supplementary samples, primarily small juveniles, were collected from research fish trawls.

Fish length was measured as fork length to the nearest centimetre.

5.2 Sample selection

Over 2,800 otolith pairs were available from samples collected between 1984 and 1995 (Appendix 3). From these, 2059 otolith pairs were matched with full collection details and individual fish measurements. Samples were grouped by fishing year, which was designated as starting on 1st August based on examination of catch records. Williams and Pullen (1993) used a similar definition of the fishing year for jack mackerel (September to June). A sub-sample for ageing was selected using the following criteria:

- samples for ageing were from the earliest possible fishing year and from selected subsequent years where at least 200 fish that met the other criteria were available,
- fish from commercial samples were preferred over those from research samples, or those for which the source was unknown, so that the resulting age-length keys would be more representative of the commercial catch,
- for the same reason, fish above 20 cm were selected for ageing as the vast majority of fish caught in commercial catch are above this size (Williams *et al.* 1986),
- fish from sexed samples were used where possible to allow for sex differences in growth to be explored, and
- only samples from waters adjacent to the east and south-east coast of Tasmania were used.

Some fish of smaller sizes were also aged to allow for a more representative growth curve to be calculated.

Samples of fish were also made available from CSIRO trawl surveys conducted off eastern Victoria and southern New South Wales. While potentially useful for validation purposes (modal progression and marginal increment analysis) we were concerned that growth rates may vary regionally. Consequently ageing was restricted to fish from eastern and south-eastern Tasmania.

This selection process produced a sub-sample of 2032 otoliths, which were then prepared for ageing. The length-frequency distributions of samples available and those selected for ageing are shown in Figs 1 and 2 respectively.

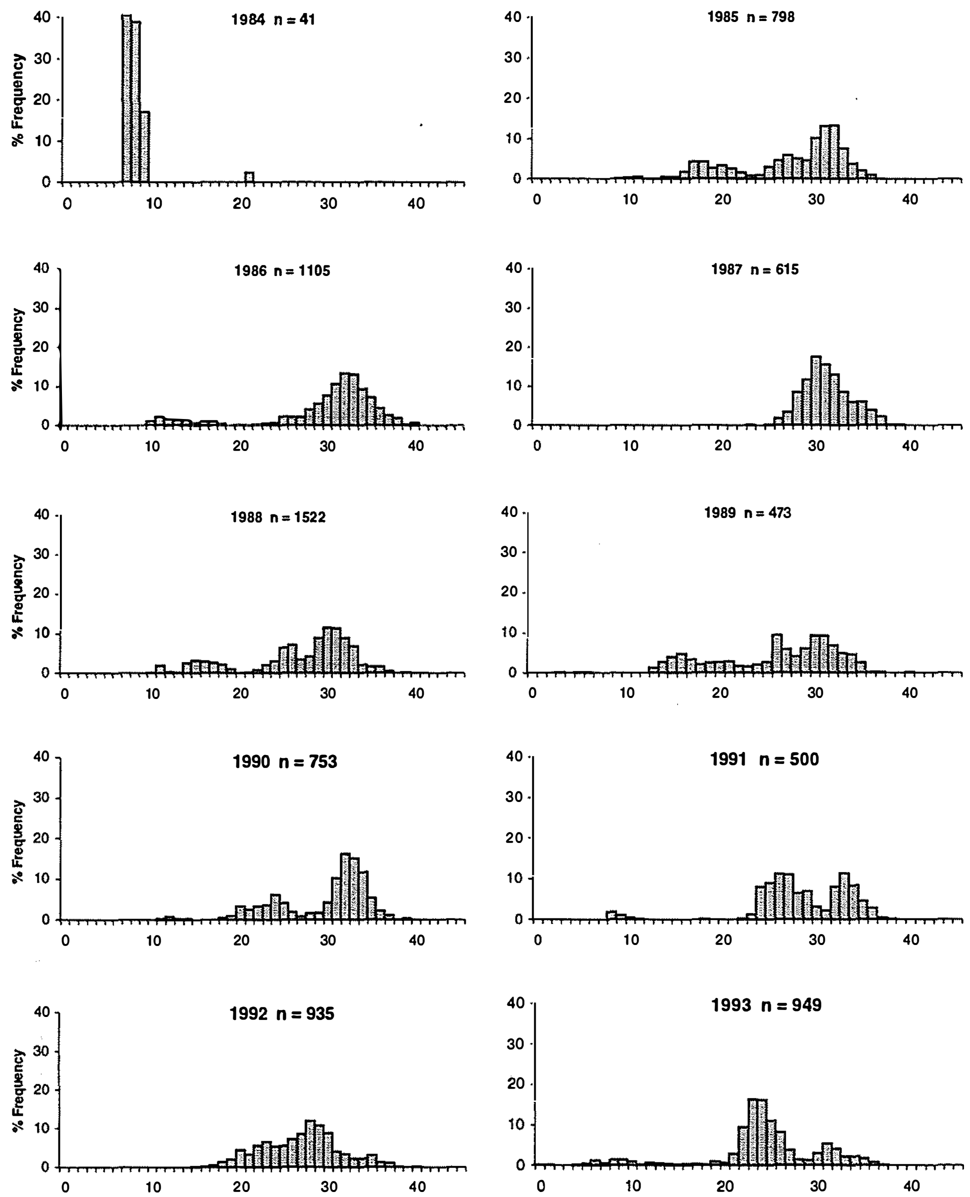

Fig. 1 Length-frequency distributions of jack mackerel otolith samples from which aged samples were selected.

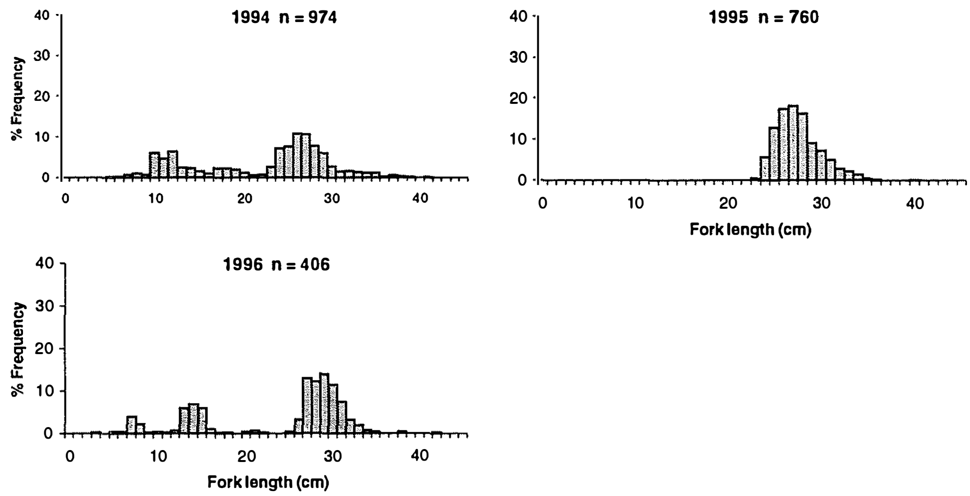

Fig. 1 Continued

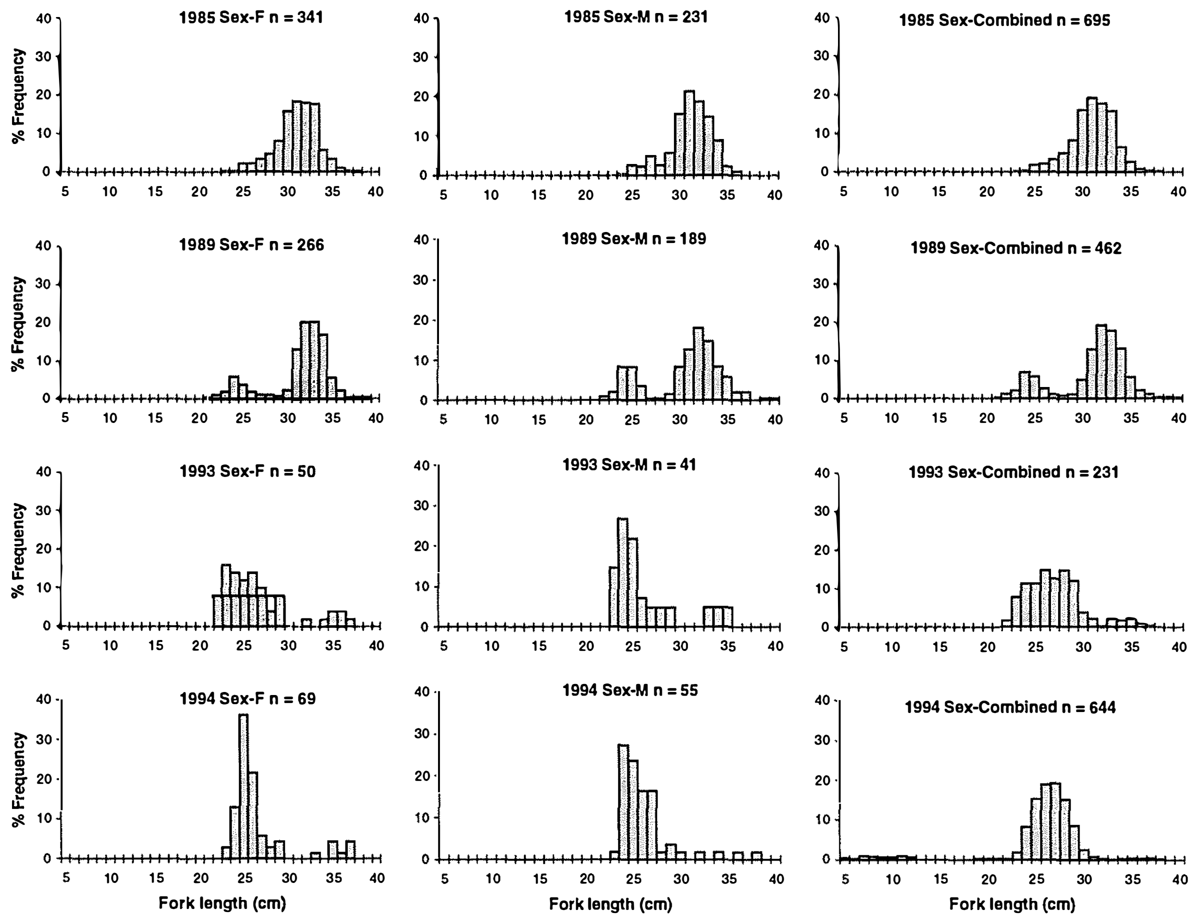

Fig. 2 Length-frequency distributions of aged samples of jack mackerel.

5.3 Otolith preparation and increment counts

Either the left or the right sagittal otolith from each fish was weighed to the nearest 0.001g.

Prior to recording any age estimates, Central Ageing Facility (CAF) staff undertook a period of familiarisation with the material. This involved viewing and making preliminary age estimates on both whole and sectioned otoliths until a consistent interpretation was obtained.

5.3.1 Annual age estimates

Age estimates from whole otoliths were obtained by viewing the otoliths immersed in water under reflected light. To obtain thin sections, otoliths were embedded in polyester resin following the method used by (Anderson *et al.* 1992). Up to four transverse sections (0.3 mm thick) were cut from each row of otoliths to ensure the primordium of each otolith was included in one of the sections. Sections were cleaned and mounted in polyester resin on microscope slides under coverslips.

A sub-sample of over 400 otoliths from a range of years was selected to compare the age estimates obtained by different preparation methods.

Increments on sectioned otoliths comprised alternating, relatively wide translucent zones and narrower opaque zones when viewed under transmitted light. Terminology is based on Kalish *et al.* (1995). Ages were estimated by counting the narrower opaque zones at 10 - 16 × magnification on the section that was closest to the primordium. A customised image analysis system (Morison *et al.* 1998) was used to enable the reader to mark and count zones along a transect between the primordium and the medial edge of the section. To avoid potential bias, all counts were made without knowledge of fish size, sex or date of capture. A full description of the appearance of the sections and the criteria used to identify annual increments is included in the Ageing Protocol section of the report (Appendix 5).

5.3.2 Daily age estimates

Estimates of the age in days of juvenile jack mackerel were attempted to assist in determining the position of the first annual increment. It was hoped that some validation of the method could be demonstrated by comparing the time between sampling dates and increase in age, to confirm the results that have been reported previously for larval jack mackerel (Jordan 1994).

Samples from a sequence of capture dates in 1993 were selected and thin sections were hand-ground after embedding in Crystalbond, a thermoplastic resin. Sagittae were ground down in a two-stage process to obtain transverse sections ≅ 300 µm thick. Sagittae were attached to heated glass slides using a clear thermal glue (Crystal Bond™). Otoliths were arranged with the medial face down, the primordium at the slide edge and the rostrum projecting over the slide edge. The rostrum was ground away to the primordial region using waterproof sandpaper (800 and 1200 grit size). The slide was reheated and the remaining otolith half removed. The ground face of the otolith was attached to a second heated slide with the posterior end facing upward. The otolith was then ground down until the primordium was reached. During this stage, the otolith was continually checked using a dissecting microscope between grindings until the otolith was at a stage where growth increments were visible over the whole section. Sections were covered in immersion oil to conceal scratches and improve resolution. Preparations were viewed using a compound microscope at high magnification.

Birthdates were back-calculated from the date of capture and the estimated age by allowing for an 8 day period between hatching and the formation of the first increment at time of first feeding (Jordan 1994).

5.4 Validation using the bomb radiocarbon chronometer

The bomb radiocarbon chronometer uses the dramatic increase in radiocarbon in the atmosphere and oceans, attributable to the atmospheric testing of thermonuclear bombs during the 1950s and 1960s, as a chemical mark that can validate age estimates (Kalish 1993).

Dr John Kalish of the Australian National University used a sub-sample of 13 otoliths for radio-carbon analysis to validate age estimates from increment counts. These samples were selected to include some of the largest otoliths and fish from a range of presumed birthdates. Jack mackerel are reported to live to 28 years in New Zealand waters (Horn 1993), compared with only 16 years in Australian waters (Webb and Grant 1979). A series of six otoliths from large and presumably old New Zealand jack mackerel were therefore included in this sample. Their inclusion increased the likelihood that the spawning dates for fish sampled would encompass the time period from the late 1950s to 1990 and include the pre 1970 period of most rapid increase in radiocarbon levels in the southern ocean.

5.5 Validation using marginal increment analysis

The original project proposal intended the use of marginal increment analysis to determine the position and time of formation of the first increment from samples of young fish. This work was not undertaken because counts of daily increments were used as an alternative approach. It also became apparent that a consistent interpretation of the inner increments could be obtained without it. Furthermore, the use of the bomb radiocarbon chronometer was adopted as the main source of validation of the age estimates. This method has the benefit of providing a direct estimate of age of individual fish including some of the oldest fish in the population. The marginal increment method is usually only applicable to the younger age classes (where this was proposed to be used), and leaves open the often critical question of whether the pattern of increment deposition identified continues throughout the life of the animal.

5.6 Precision of age estimates

The precision of repeated readings was examined as tables of difference between readings against age, as age bias plots (Campana *et al.* 1995). Precision was quantified using the index of average percent error (IAPE) (Beamish and Fournier 1981). The IAPE is calculated by the following formula:

$$IAPE = \frac{100}{N}\sum_{j=1}^{N}\left[\frac{1}{R}\sum_{i=1}^{R}\frac{|X_{ij}-X_j|}{X_j}\right]$$

where N is the number of fish aged, R is the number of times fish are aged, X_{ij} is the ith age determination for the jth fish, and X_j is the average estimated age of the jth fish.

Three different age estimates were compared using these methods: age estimates from whole otoliths originally made by DPIF staff, age estimates from whole otoliths by the CAF and age estimates from sectioned otoliths by the CAF. Intra-reader comparisons were also made for repeat readings using the same preparation method for the CAF reader.

The probability of obtaining, by chance, the observed differences between IAPE values from repeat readings of whole and sectioned otoliths was estimated using a randomisation test. Pairs of readings from the combined dataset were randomly assigned to either of the two groups, a new IAPE calculated for each group, and the difference in IAPE values between the groups recorded. This was repeated for 1000 randomisations and the number of times that the difference was equal to or greater than the original difference was recorded. This number, expressed as a proportion of the number of randomisations, is an estimate of the probability of obtaining the original difference by chance.

5.7 Growth functions

The von Bertalanffy growth function was fitted to the fish length-at-age data from the samples using the NLIN procedure in SAS®, a non-linear least-squares procedure, and the Secant iterative technique (SAS Institute Inc 1989). An estimated age was assigned to each fish based on the number of annuli counted and a nominal birthday of 1st January. Growth functions were fitted to data for each sex separately and for the sexes combined. Differences between the curves fitted to data for each sex were tested using the likelihood ratio test (Kimura 1980).

5.8 Age composition of the commercial catch

Jack mackerel are caught in schools that may vary greatly in average size, both within and between months (Williams and Pullen 1993). To allow for this variation and provide a representative length-frequency distribution, length distributions for each month were adjusted by the monthly catch before being summed across all months in each fishing year.

The age composition of catches was estimated using the age-length key of a particular fishing year and applying it to the length-frequency data from the same year as follows:

$A_t=\sum_x(L_x p_{tx})$ where

A_t = the estimated number of fish of age t in the length-frequency sample,
L_x = the number of fish of length x in the length-frequency sample, and
P_{tx} = the proportion of aged fish of length x which were age t.

6 DETAILED RESULTS

6.1 Development of an ageing method for jack mackerel

Age estimates were unable to be made for 55 samples as the annual increments could not be resolved for 35 samples (1.7%) and the preparation method failed in a further 20 samples (1.0%).

6.1.1 Validation using the bomb radiocarbon chronometer

The report on the results of the bomb radiocarbon validation work is given in Appendix 4. The results show that, with the exception of two New Zealand fish that were probably incorrectly aged, the estimated ages were consistent with the spawning dates indicated by the radiocarbon levels. These results indicate that jack mackerel may live to over 20 years of age and that ages estimated from increment counts from sections or 'break and burn' methods are a reliable means to estimate age. The authors state that the jack mackerel data describe the bomb radiocarbon curve and are coincident with data from both snapper (*Pagrus auratus*) and redfish (*Centroberyx affinis*) (Appendix Fig. 1A).

The combined data set indicates good agreement between bomb radiocarbon ages and those estimated from otolith increments. However, the data points that cover the period over which radiocarbon levels rise most rapidly (where the resolution of the method is best) are exclusively from New Zealand fish, whose age was estimated using the 'break and burn' method. All the Australian samples, which are of younger fish, have estimated birth dates in the 1970s and 1980s when there is little discriminating ability from radiocarbon levels. However, as none of the Australian samples include fish with $\Delta^{14}C$ levels lower than 87‰, it is unlikely that any had birthdates earlier than 1970. Nevertheless, these results leave unanswered an additional question as to potential differences in the age estimates that may result from the different preparation methods (i.e. break and burn as opposed to sectioning).

This question has been largely addressed previously in a comparison of age estimates made by researchers from New Zealand and the CAF for otoliths from the same fish but prepared by the different methods (CAF, unpublished data). The New Zealand reader used a 'break and burn' method of preparation; the CAF used thin sections. Both preparation methods reveal the internal pattern of increments. This comparison showed that both methods gave similar maximum ages (25 years by the CAF, and 26 years by New Zealand), but there was a suggestion that the CAF's ages were biased upwards for younger fish (Table 1, Fig. 3). There were also a few fish for which the discrepancies were large (8 and 9 years). As a result, for the sample of 95 fish examined, the IAPE was relatively high at 8.31%. This was probably attributable to the CAF reader's inexperience with jack mackerel otoliths. Despite the discrepancies, we believe that the increments that were observed and counted by the New Zealand reader were also visible to, and counted by, the CAF's reader. It follows that the difference in ages of the New Zealand and Australian samples is a real one and not an artefact of different preparation methods. This is supported by the conclusion from the bomb radiocarbon analysis that age estimates based on increment counts in both areas are consistent with the age estimates from the bomb radiocarbon work.

Table 1. Differences in age estimates between the CAF using sectioned otoliths, and New Zealand using the 'break and burn' method.

Difference	Age (CAF sectioned)																				Total	%
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	15	16	17	18	19	25		
-9							1														1	1
-5													1								1	1
-3										1		1				1					3	3
-2										1	1			1	1				1		5	5
-1			1	3	1	1	1	3	1	1	3			1	3		1			1	21	22
0	**2**	**1**	**6**	**2**	**3**	**1**	**3**	**1**	**3**	**2**	**2**	**2**	**2**	**2**			**1**	**1**			**34**	**36**
1			1	2	1	1	3	2	1	1	1	1	1	1		1		1			18	19
2					2	1	2	1				1									7	7
3						1	1			1											3	3
4									1												1	1
8															1						1	1
Total	2	1	8	7	7	5	11	7	6	7	7	5	4	5	5	2	2	2	1	1	95	

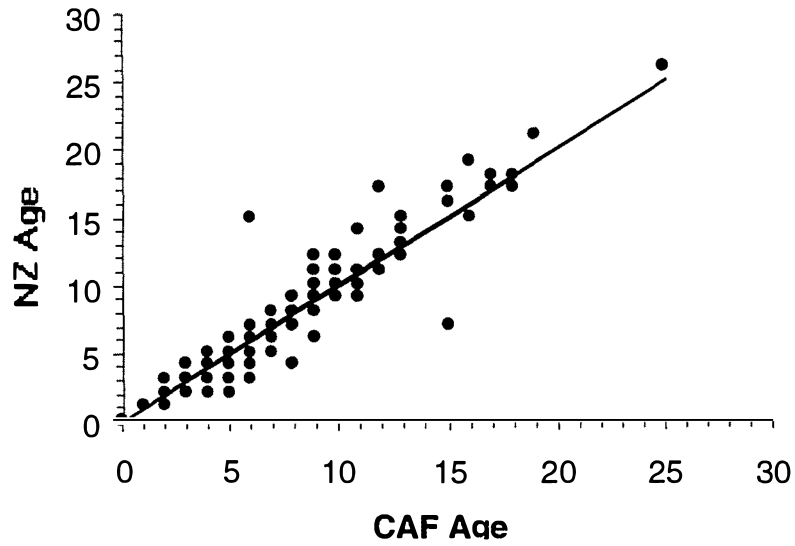

Fig. 3 Comparison of ages estimated by 'break and burn' method (NZ Age) and thin sections (CAF Age). Line indicates equal age estimates.

6.1.2 Comparison of age estimates from whole and sectioned otoliths

Age estimates obtained ranged from 1 to 10 years for whole otoliths and from 1 to 12 years from sectioned otoliths. Fifty four percent of the age estimates agreed exactly and 92% were within one year (Table 2, Fig. 4). The distribution of the differences between the ages estimated by both methods was symmetrical and had a mode and median of zero, indicating no overall bias. Estimates showed closest agreement up to about 7 years of age, after which there was a slight tendency for the estimates from sectioned otoliths to be higher than those for whole otoliths (Fig.5).

Table 2. Differences in age estimates from sectioned and whole otoliths by the CAF.

Difference	Age (CAF Sectioned)												Total	%
	0	1	2	3	4	5	6	7	8	9	10	12		
-2				1	11	9	2						23	6
-1		2	2	20	16	11	12	4	1	1			69	18
0	**1**	**10**	**10**	**22**	**93**	**26**	**24**	**14**	**6**	**1**	**1**		**208**	**54**
1			1	2	28	27	8	7	1	4	1		79	20
2						1		1	1	1		1	5	1
3					1			2		1			4	1
Total	1	12	13	45	149	74	46	28	9	8	2	1	388	100

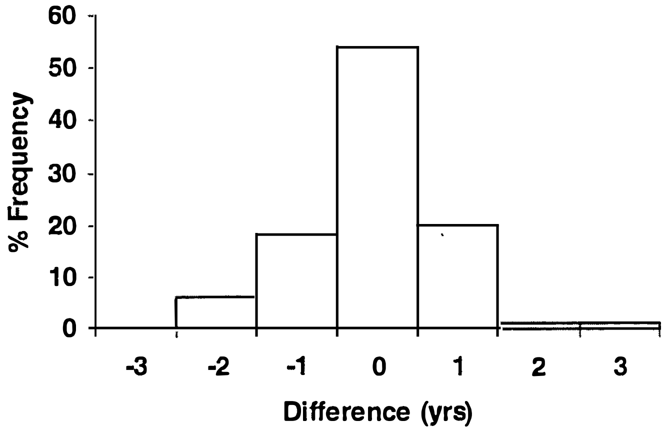

Fig. 4 Percent frequency distribution of the differences in age estimates based on whole and sectioned otoliths (n = 388).

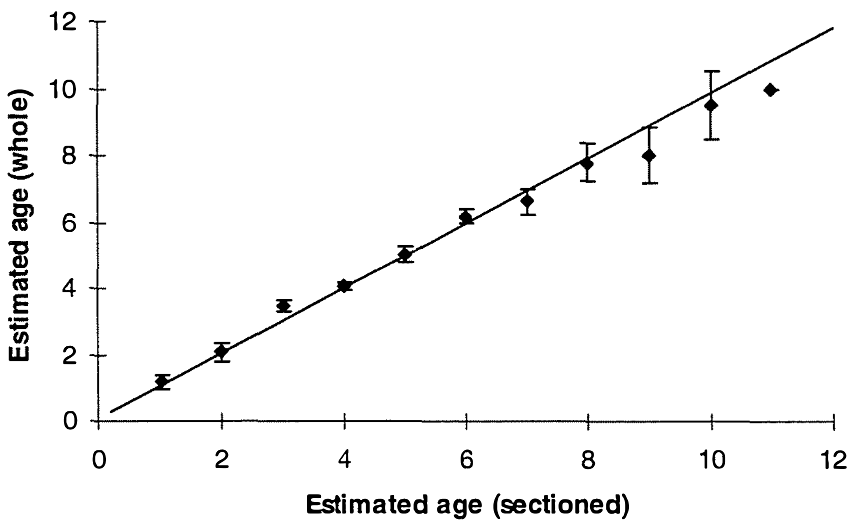

Fig. 5 Age bias plot - mean estimated age (+/- 2 standard errors) from whole otoliths against age from sectioned otoliths. Line indicates equal age estimates.

Estimates of precision from the repeat readings indicated that age estimates from sectioned otoliths were more precise (IAPE 2.9%) than those from whole otoliths (IAPE 5.8%). This difference is significant (P<0.001) since none of the 1000 trials using the randomisation test produced a difference in IAPE values equal to or greater than the observed difference (2.9%).

The precision of age estimates from sectioned otoliths is reported as an age-difference table (Table 3), a plot of the distribution of the differences (Fig. 6) and as an age-bias plot (Fig. 7). These show that 98% of the repeated age estimates are within one year of the first estimate and that there is no indication of a bias in the repeated estimates.

Table 3. Differences in age estimates from repeat readings of sectioned otoliths by the CAF.

Difference	Age 1														Total	%
	2	3	4	5	6	7	8	9	10	11	12	14	15	16		
-2						1		1							2	0.5
-1		10	28	5	12	6	6	4	1	2	1	1	1		77	18.8
0	**2**	**33**	**75**	**78**	**24**	**21**	**16**	**7**	**8**	**5**	**1**				**270**	**66.0**
1			8	17	8	7	6	3	2	3	1	1		1	57	13.9
2						1		1	1						3	0.7
Total	2	43	111	100	44	36	28	16	12	10	3	2	1	1	409	

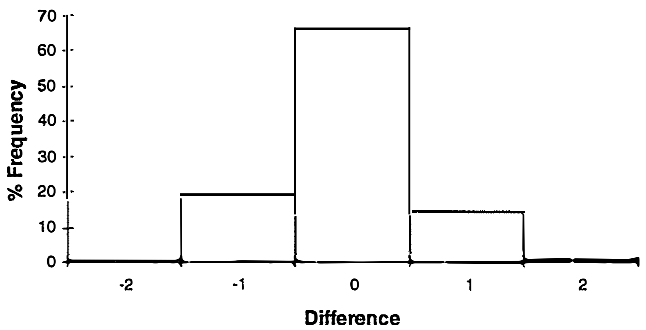

Fig. 6 Percent frequency distribution of the differences in age estimates between first and second readings of sectioned otoliths (n = 409).

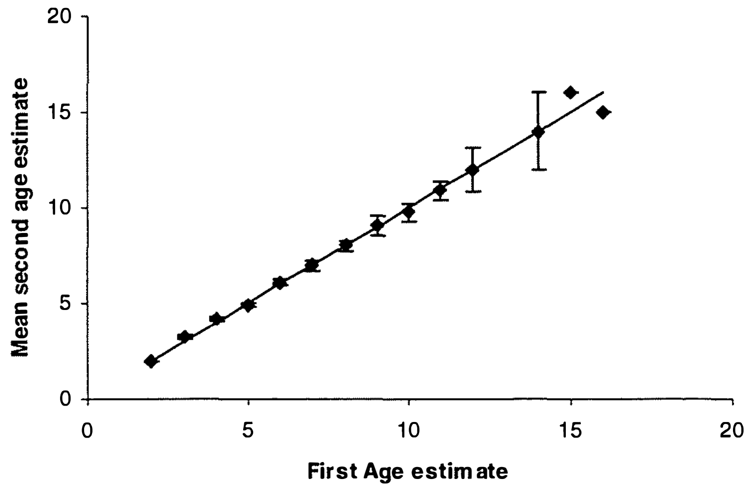

Fig. 7 Age bias plot - mean estimated age (+/- 2 standard errors) from first and second age estimates from sectioned otoliths

6.1.3 Inter-laboratory comparison of age estimates

There was poor agreement between age estimates originally made by DPIF (whole otoliths) and those made by the CAF, whether comparisons were based on CAF age estimates from whole otoliths (Table 4, Fig. 8) or sectioned otoliths (Table 5, Fig. 9). These data indicate that the original age estimates are biased upwards for younger fish and downwards for older fish, relative to the CAF age estimates. Similar differences were observed between DPIF and New Zealand age estimates that were undertaken as background to the present study.

The maximum age assigned by the DPIF reader was 14 years for a fish that was also aged at 14 years from a thin section by the CAF. However, for most fish much younger age estimates were originally assigned from whole otoliths than were estimated by the CAF, regardless of preparation method. The IAPE values for the comparisons were 12.0% (n=130) for whole otoliths and 12.3% (n=962) for sectioned otoliths, reflecting the poor level of agreement between the age estimates.

Table 4. Differences in age estimates from readings of whole otoliths by readers from DPIF and the CAF.

Difference	Age (CAF_whole)								Total	%
	3	4	5	6	7	8	9	10		
-1	2	3							5	3.8
0	**2**	**11**	**12**	**4**					**29**	**22.3**
1		2	14	20	4	1			41	31.5
2			1	12	24	3			40	30.8
3					3	7	1		11	8.5
4							1	1	2	1.5
5							1	1	2	1.5
Total	4	16	27	36	31	11	3	2	130	

Table 5. Differences in age estimates from readings of whole otoliths by DPIF and of sectioned otoliths by the CAF.

Difference	Age (CAF Sectioned)															Total	%
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
-3			1													1	0.1
-2	6	3	2													11	1.0
-1	2	74	36	19	3	1										135	12.3
0		**16**	**74**	**136**	**26**	**4**	**1**						**1**			**258**	**23.5**
1			17	107	120	61	12	1								318	28.9
2				4	16	76	54	10		1						161	14.6
3					2	9	53	36	4	2	1					107	9.7
4							2	27	30	5						64	5.8
5									8	14	3	1				26	2.4
6									1	4	4		1		1	11	1.0
7												1	1			2	0.2
8													1	2		3	0.3
9													1		1	2	0.2
Total	8	93	130	266	167	151	122	74	43	26	8	2	5	2	2	1099	

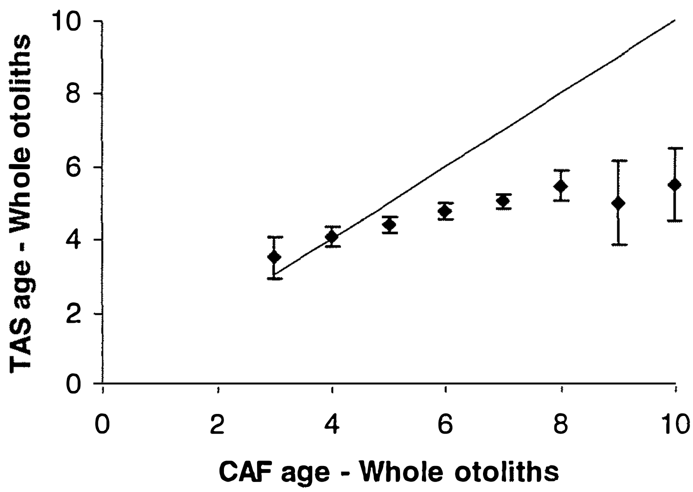

Fig. 8 Age bias plot - mean estimated age (+/- 2 standard errors) by DPIF (TAS) against age by the CAF (both estimates from whole otoliths). Line indicates equal age estimates.

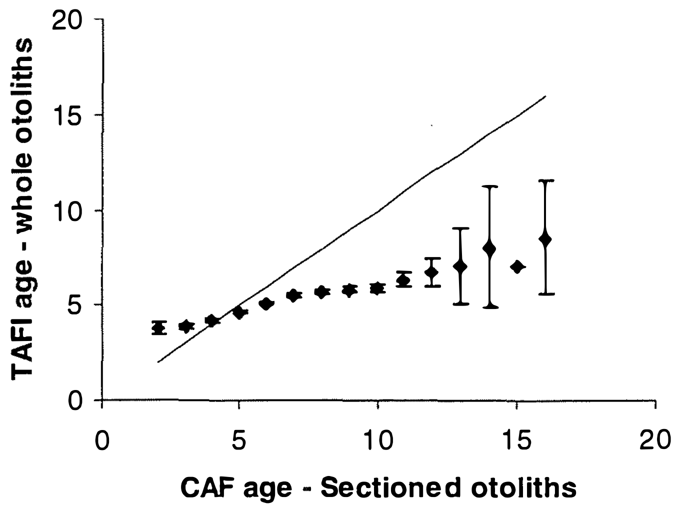

Fig. 9 Age bias plot - mean estimated age (+/- 2 standard errors) by DPIF (whole otoliths) against age by the CAF (sectioned otoliths). Line indicates equal age estimates.

6.1.4 Otolith weight relationships

Otolith weight shows a curvilinear relationship with fork length and a linear relationship with age estimated from sectioned otoliths (Fig. 10). These results are indicative of continued growth of the otolith as growth in fish length slows. Inspection of sectioned otoliths (see Appendix 5) shows that this growth is increasingly confined to the proximal side of the otolith.

6.1.5 Daily age estimates

Daily age estimates were obtained from about half of the 60 samples prepared. These showed that on each sampling occasion, fish of a large range of ages were present, indicating a range of spawning dates (Fig. 11). Back-calculated spawning dates over the whole sample indicated spawning to have occurred over a period of up to 6 months (Fig. 12). Because of the small sample size and the large range of ages present, the relationship between estimated age and capture date was not a good test of the validity of the age estimates. Nevertheless, the results do indicate that the radius of the first annual increment would be expected to be quite variable, depending on the time of spawning. Fish spawned in late November or December would be expected to have a bigger first increment width than those spawned in March or April.

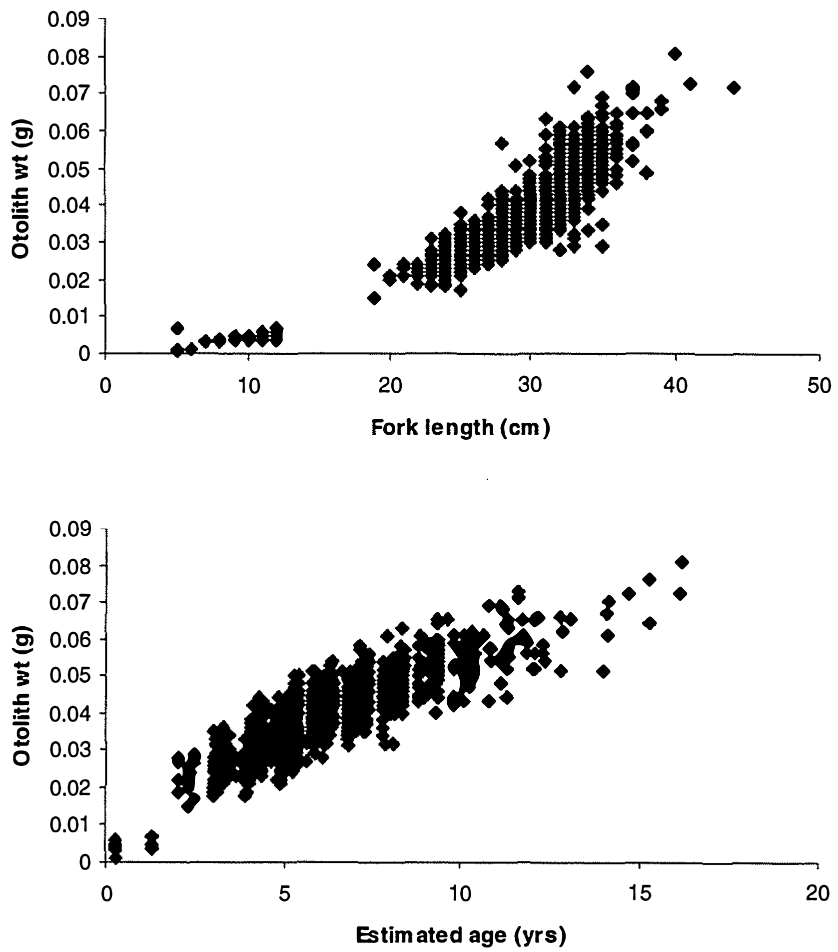

Fig. 10 Otolith weight versus fork length (top) and estimated age (bottom - from sectioned otoliths).

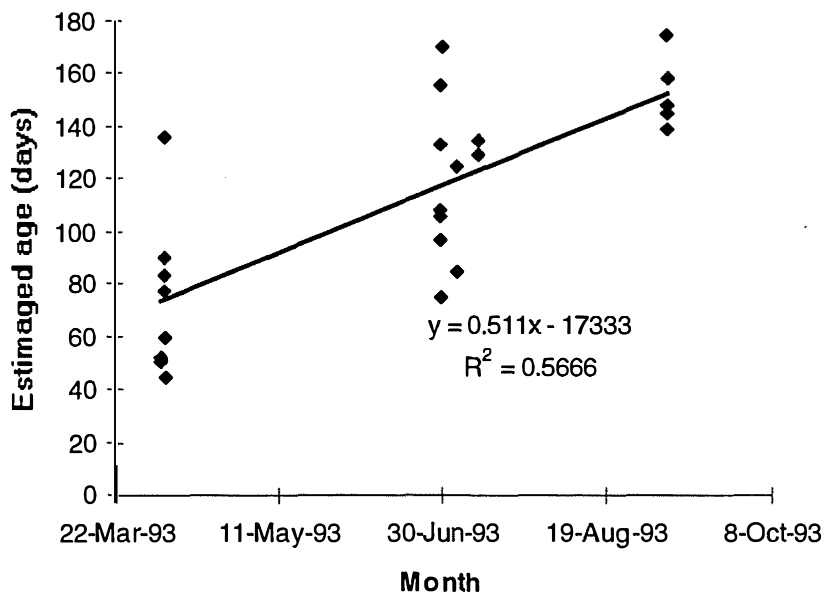

Fig. 11 Estimated age (in days) of juvenile jack mackerel against date of collection.

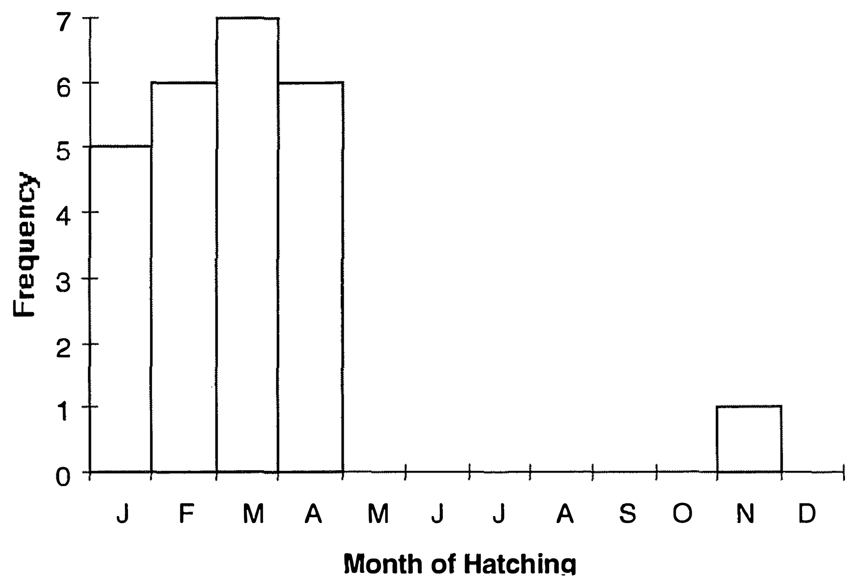

Fig. 12 Back calculated month of hatching of juvenile jack mackerel.

6.1.6 Manual of ageing methods

The differences in age estimates between the original DPIF reader and the CAF, and between DPIF and New Zealand, clearly indicate that there are differences in interpretation of both the inner and outer increments on jack mackerel otoliths. To attempt to resolve these differences, and as a part of the first objective of this project, a description of the method of interpreting the increments visible in jack mackerel otoliths has been compiled as a manual of ageing methods and is included in Appendix 5. This manual concentrates on the interpretation of thin sections as this is the primary preparation method used in this study and is the preferred method of preparation for this species.

6.2 Age and growth of jack mackerel in south east Australian waters

The von Bertalanffy growth functions fitted to data for females and males were not significantly different (χ^2 = 2.38, P=0.498). A single growth function was therefore calculated for all data from females, males and fish of unknown sex (Fig. 13). The parameters (and 95% confidence intervals) were L_∞= 36.2cm (35.6 – 36.8), K = 0.267 yr^{-1} (0.242 – 0.292), and t_0 = -1.21 yrs (-1.529 – -0.892). These estimates of growth of jack mackerel have been compared with previously published estimates for New Zealand (Horn 1993) and south-east Australia (Webb and Grant 1979) and the Great Australian Bight (Stevens *et al.* 1984) (Fig. 13).

A comparison of growth among years was attempted by comparing the von Bertalanffy growth functions fitted to each year of collection. However, major differences in the distribution of fish sizes and ages prevented the calculation of comparable growth functions. Instead, the question was addressed by an examination of changes in the mean length–at-age of particular age classes. There is some evidence of shifts in growth over time in the lower mean lengths-at-age of 4 and 5 year old fish in the 1990s compared to the 1980s (Fig. 14). These two age classes were the only ones that were consistently represented in the samples from all fishing years.

Growth of jack mackerel is also described by the mean lengths-at-age (Table 6). The similarity in size-at-age for females and males is also evident in these data.

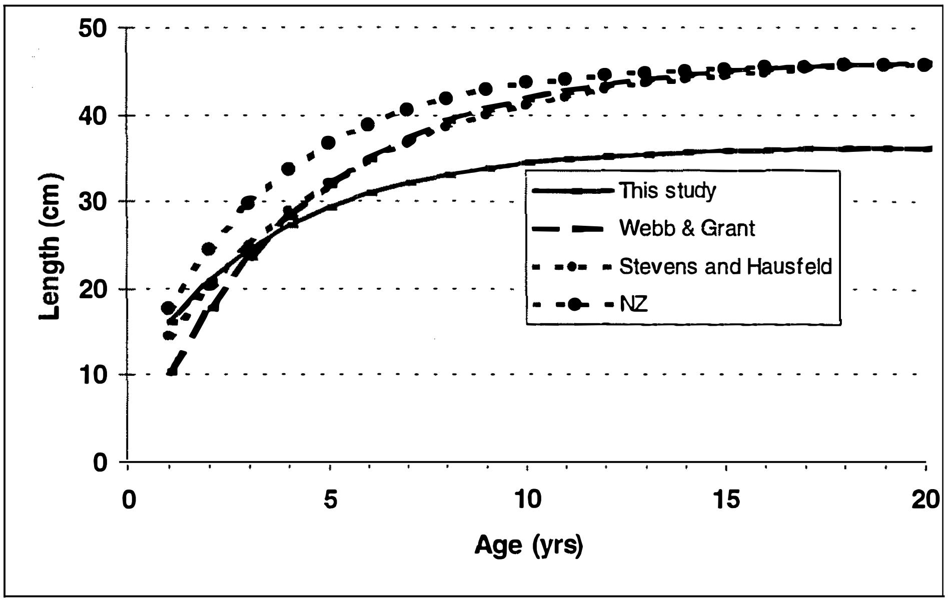

Fig. 13 Top - Length-at-age (from sectioned otoliths) and fitted von Bertalanffy growth function for jack mackerel, sexes and fishing years combined and Bottom - von Bertalanffy growth functions for the present study compared with those of previous workers.

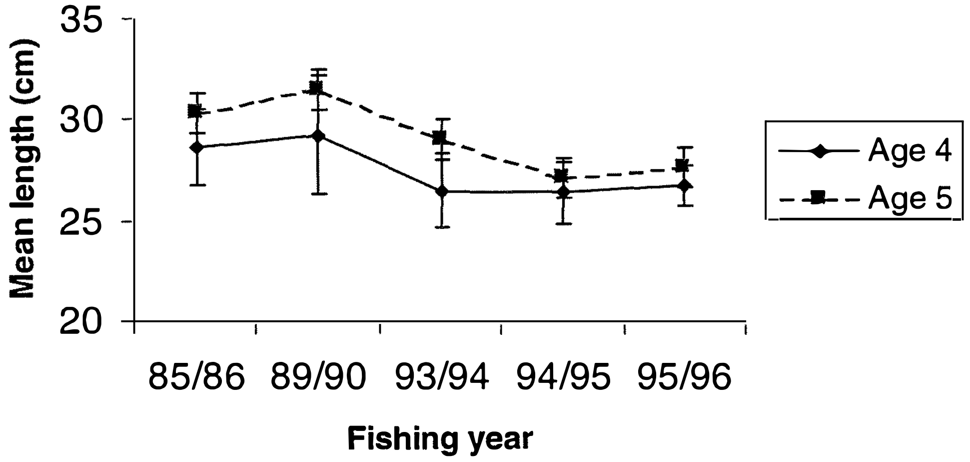

Fig. 14 Mean length (+/- 2 SE) of 4 and 5 year old jack mackerel from each of the fishing years examined.

6.3 Age structure of the purse seine catch over the history of the fishery.

6.3.1 Length-frequency distributions of the purse seine catch

The catch-adjusted length-frequency distributions by fishing year show the variable size of fish caught in the fishery (Fig. 15). The distributions are uni-modal in most years but are strongly bi-modal in others. There are also substantial shifts in the modal sizes (e.g. from 1991/92 to 1992/93) that could not be attributed to strong year-classes moving through the fishery. Despite the year-to-year variation, there is a clear reduction in the average size of fish from the 1980s when the mode and average size exceeds 30 cm to the 1990s when (except for 1995/96) they are less than 30 cm.

6.3.2 Age composition of jack mackerel based on sectioned otoliths

The age composition of the jack mackerel fishery has been estimated for the 4 fishing years for which otolith samples have been re-aged by the CAF: 1985/86, 1989/90, 1993/94 and 1994/95 (Fig. 16). The trend over these years is for a reduction in the proportion of older age classes in the catch.

Five years was the modal age of fish in the catch in 1985/86 and for that year and 1989/90 over 50% of fish were aged 6 years and older. In 1993/94 and 1994/95, the modal age was 4 years, but only 8.7% of the catch was 6 years or older in 1993/94 and this reduced to only 3.4% in 1994/95.

Table 6. Mean length-at-age (based on sectioned otoliths) for jack mackerel by sex, all years combined. N is sample size, SD is standard deviation

Age	Data	Sex			
		Female	Male	Unsexed	All
1	Mean			11.00	11.00
	SD			1.73	1.73
	N			3	3
2	Mean	24.75	24.75	21.69	22.86
	SD	0.96	1.26	1.70	2.10
	N	4	4	13	21
3	Mean	24.33	24.48	25.81	24.78
	SD	1.42	1.08	2.15	1.67
	N	67	64	48	179
4	Mean	26.80	27.25	26.92	26.96
	SD	2.34	2.68	1.68	2.03
	N	119	109	388	616
5	Mean	30.41	30.43	27.97	29.28
	SD	1.88	1.78	1.90	2.23
	N	162	101	228	491
6	Mean	31.78	31.80	31.05	31.63
	SD	1.36	1.12	1.96	1.47
	N	88	61	41	190
7	Mean	32.56	32.54	31.90	32.47
	SD	1.34	1.43	1.41	1.38
	N	94	48	21	163
8	Mean	33.21	33.02	31.60	33.08
	SD	1.35	1.47	2.07	1.45
	N	76	45	5	126
9	Mean	33.60	33.39	34.50	33.57
	SD	1.56	1.23	1.91	1.46
	N	45	28	4	77
10	Mean	33.48	33.61	33.00	33.51
	SD	1.58	1.14	2.83	1.44
	N	25	18	2	45
11	Mean	35.10	34.44	32.00	34.81
	SD	2.23	2.01		2.18
	N	21	9	1	31
12	Mean	34.60	36.00		35.22
	SD	1.14	2.58		1.92
	N	5	4		9
13	Mean	37.00	33.00		35.00
	SD				2.83
	N	1	1		2
14	Mean		38.00	32.00	36.80
	SD		4.08		4.44
	N		4	1	5
15	Mean	34.50			34.50
	SD	0.71			0.71
	N	2			2
16	Mean		38.50		38.50
	SD		2.12		2.12
	N		2		2

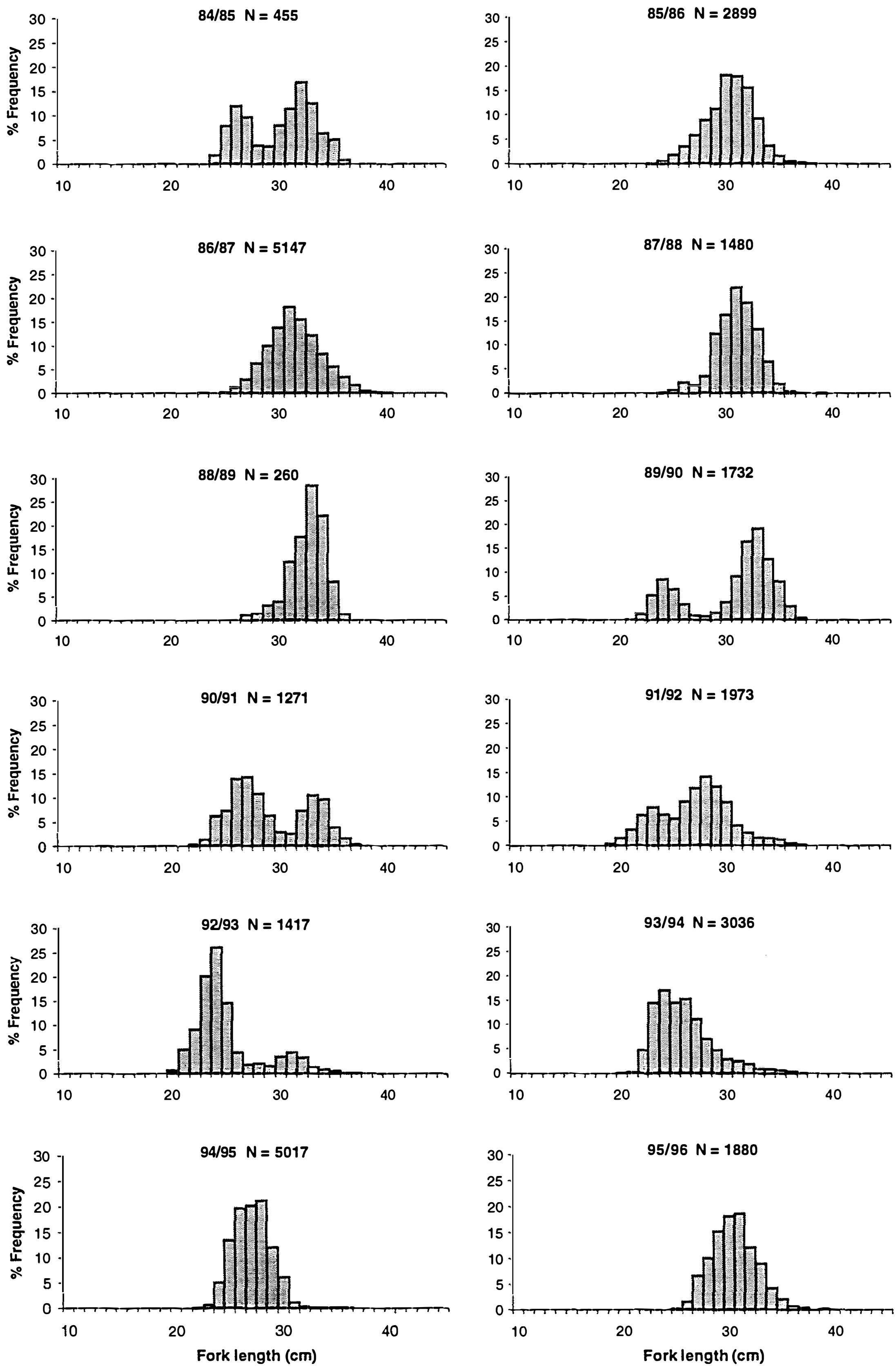

Fig. 15 Length-frequency distributions weighted by the monthly catch and summed by fishing year. N is the unweighted sample size.

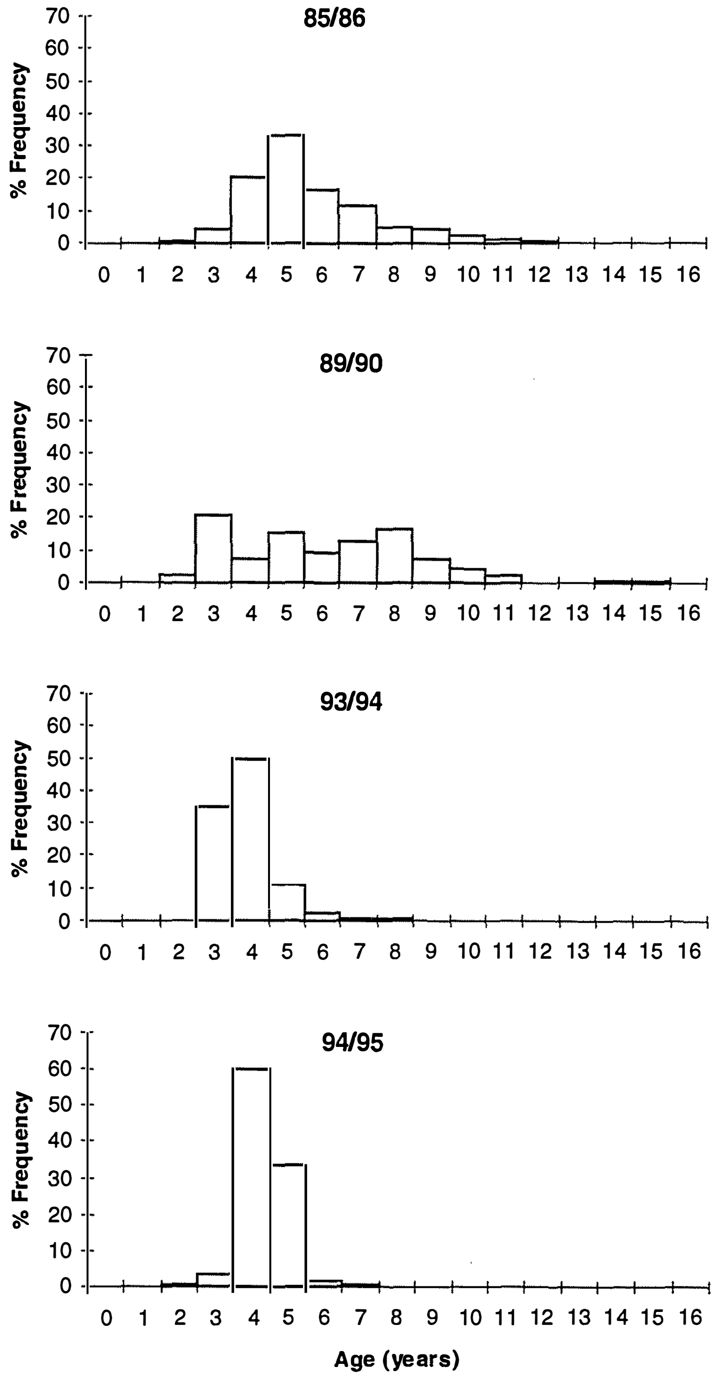

Fig. 16 Estimated age composition for the Tasmanian purse seine fishery catch of jack mackerel (based on sectioned otoliths) for fishing years for which samples have been re-aged.

7 DISCUSSION AND CONCLUSIONS

7.1 Development of an ageing method for jack mackerel

7.1.1 Validation of age estimates

The age estimates provided have been validated up to the maximum reported age of 23 years. Samples from Australian waters used in the radiocarbon analysis were aged to only 12 years, whereas other samples examined in this study were estimated to be 16 years of age. However, since the interpretation used for the validated samples was also applied to the other samples, and the appearance of increments and the pattern of their deposition show no differences between fish of various ages, it can be concluded that our interpretation of age has been adequately validated. Furthermore, the comparison of age estimates obtained by the different preparation methods shows that this is not a significant source of bias.

The maximum ages reported for south-east Australian waters are consistent with those previously reported from both exploited (Webb and Grant 1979) and unexploited (Stevens and Hausfeld 1982) populations. The maximum age obtained from samples from New Zealand (23 years) is similar to the maximum age reported by Horn (1993). However, whereas the age estimates in these previous studies had been only weakly validated, and only to quite young ages, the bomb radiocarbon technique has provided evidence of the longevity in the species.

7.1.2 Comparison of age estimates from whole and sectioned otoliths

It is not unusual to find that age estimates from whole otoliths underestimate those obtained from sectioned otoliths (Beamish 1979). A similar concern was presumably behind the decision of Webb and Grant (1979) to use the 'break and burn' technique for the otoliths of older fish. It has been recommended that age estimates of the closely related horse mackerel (*T. trachurus*) be based on sectioned otoliths for similar reasons (Eltink and Kuiter 1989). However, the present study showed no consistent bias between the two preparation methods for jack mackerel otoliths from Australian waters.

The main difference between the two preparation methods was in the level of precision obtained. The lower precision from whole otoliths is probably partly due to greater ambiguity in the pattern of increments seen in whole otoliths and partly due to a greater familiarity with sectioned otoliths on the part of the reader.

Sectioned otoliths are the preferred method of preparation for jack mackerel otoliths as:

- fish 7 years and older tend to be under-aged using whole otoliths,
- the species potentially lives to over 20 years, and
- higher precision is obtainable with sectioned otoliths.

However, the use of whole otoliths could be supported if:

- the number of older fish in the samples was considered negligible,
- the precision obtained by readers was acceptable, and
- the costs of the extra preparation of sections could not be met or justified.

.
A combination of whole otoliths for younger fish and sectioned otoliths for older fish is another option, and has been previously applied by Webb and Grant (1979). This has the advantages of reduced preparation time (and hence costs) for many samples without introducing biased age estimates for older fish. However, this approach has the disadvantage of the need for identification and separation of samples needing sectioning. Such separation is most simply done based on otolith weight or fish length. It can also be done based on age estimated from whole otoliths, but with a time penalty of double processing of these samples. In addition, the differences in the estimates of precision for the different preparation methods obtained in this study suggest that a single meaningful estimate of precision could not be obtained for a combined sample.

Experience with otoliths from a range of species aged by the CAF suggests that the interpretation of whole otoliths is intrinsically more difficult than for sectioned otoliths. The reasons for such a difference are due in part to the three-dimensional structure being interpreted, and to differences in the nature of the increments themselves. The opaque increments that are observed in whole otoliths are relatively broad sub-surface features that are frequently divided into one or more sub-annual increments whose spacing and definition vary greatly. Interpreting the spacing and grouping of these units adds greatly to the subjectivity of an age estimate based on whole otoliths. When viewed in section, the opaque increments observed are narrower and often more clearly defined in the sulcal side of the otolith. There is less subjectivity and greater consistency in the interpretation and counts from otolith sections. For these reasons, the use of sectioned otoliths frequently produces more precise age estimates.

The greater ambiguity inherent in whole otoliths is evident in the detailed documentation and variety of illustrations provided in the attempt to standardise the interpretation of whole otoliths of Cape horse mackerel (*T. trachurus capensis*) (Anon 1986).

7.1.3 Precision of age estimates

The level of precision reported for age estimates from sectioned otoliths is within the suggested acceptable range for an IAPE (Morison *et al.* 1998), whereas that for whole otoliths should be considered marginal. The age-bias plots show that there is no consistent bias. Additional experience with whole otoliths would be likely to improve the precision from whole otoliths, but it is unlikely to match that obtained from otolith sections.

Previous estimates of precision for repeat readings of jack mackerel otoliths (reported as percent agreement) are slightly higher than those obtained here at 85% (Webb and Grant 1979) and 71% (Stevens and Hausfeld 1982). Similar precision was reported for differences within one year. This method of reporting precision is, however, prone to problems where the age composition of the sample (and hence the likelihood of errors) differs among studies (Campana *et al.* 1995).

The IAPE reported of 2.9% is lower than the 3.5% reported for *T. trachurus capensis* for age estimates from whole otoliths (Kerstan 1995), even though they discarded 10% of the samples as being ambiguous. In this study only 1.7% of jack mackerel otoliths were discarded. A higher discard rate would be expected to produce greater precision by excluding more of the difficult to read samples. The results of Kerstan (1995) also show the benefit of experience, as the precision increased with 2^{nd} and 3^{rd} readings.

7.1.4 Daily age estimates

The back-calculated months of spawning (November to May) is a much wider range than the December to February range previously reported for jack mackerel off eastern Tasmania (Jordan 1994; Jordan *et al.* 1995). The difference may reflect inter-annual variation in the timing of spawning of jack mackerel or result from differences in the samples analysed.

Samples analysed for this study were juvenile fish collected between April and September with ages estimated to be between 40 and over 160 days. Previous work was based on larval jack mackerel from samples collected between December and March and these fish had a maximum estimated age of 25 days (Jordan 1994). Fish spawned well before or after this sampling period may have been missing from the samples. In fact no jack mackerel eggs were recorded from plankton samples collected in February in the period 1988-91 (Jordan *et al.* 1995), although subsequent back-calculation of the time of spawning from larval fish collected at the same time suggested some spawning took place in this month (Jordan 1994).

7.1.5 Inter-laboratory comparison of age estimates

The comparisons of age estimates among laboratories suggest that the previous DPIF reader had applied different criteria than were applied by New Zealand or CAF readers. These latter two laboratories seemed to be estimating age in a consistent manner. The nature of the difference cannot be determined clearly from the data available. However, the tendency to under-age the older fish suggests that the DPIF reader had not adjusted sufficiently for the tendency for the outer increments to be narrower. As such, earlier DPIF age estimates are considered unreliable.

7.2 Age and growth of jack mackerel in south east Australian waters

The von Bertalanffy growth function parameters calculated from the present study show substantial differences from those of previous workers in southeast Australia and New Zealand. These differences may arise from differences in the size distribution of fish in the samples used or from differences in interpretation of the otoliths. They may also reflect real shifts or differences in the growth rates of jack mackerel.

The age composition of the 1977 catch reported by Stevens and Hausfeld (1982) has over 63% of the fish being less than 4 years of age, whereas in the present study very few young fish were present in the samples analysed. This difference would account for the slightly higher value for t_0 in their study but not the much higher value for L_∞. The samples of Webb and Grant (1979) show an age composition more similar to that of the present study, but their growth parameters are very similar to those of Stevens and Hausfeld (1982). None of the samples aged by previous workers were available for examined by the CAF to determine whether there are differences in interpretation.

The comparison of mean-length at age over a decade, from 1985/86 to 1995/96, suggests that changes in growth rates are occurring between years but these seem insufficient to account for the larger differences observed between present and previous studies. It is also unclear whether these differences represent natural variability in growth rates of individual cohorts (possibly linked to availability of food, specifically krill) or a response to fishing, or a combination of factors.

The comparison with the New Zealand reader indicates that differences in the age and growth of jack mackerel between Australia and New Zealand are not due to differences in the interpretation of the otoliths; they represent real differences in the biology of the different jack mackerel stocks.

7.3 Age structure of the purse seine catch over the history of the fishery.

The lack of agreement between age estimates from the CAF and the original DPIF ages indicates that the two sets of age estimates cannot be combined to produce a single data series of the age composition of the catch of jack mackerel. Such a data set could be derived by applying age-length keys from fishing years for which samples have already been aged by the CAF to the length-frequency distributions for other years. However, this method is prone to substantial errors if the size and age composition of the catch differs among years, as appears to be the case with jack mackerel. A more accurate method would be to re-age at least a sub-sample of the otoliths from the years for which there are no age estimates and use these data to estimate the age composition of the catch.

The following comments will be based solely on the age compositions derived from the data from the CAF. In 1985/86 and 1989/90 the catch was dominated by at least four year classes, with over half of the catch over 6 years of age. By contrast, in 1993/94 and 1994/95 only two year classes accounted for over 80% of the catch and less that 10% were older that 6 years. In fact there is evidence of recruitment of 3 and 4 year olds in 1993/94 and which are strongly represented as 4 and 5 year olds in 1994/95. While ages are not available for 1995/96, the general increase in size of fish and a unimodal size distribution is not inconsistent with the further growth of these two cohorts.

There are several possible reasons for the observed changes, including:

- impact of fishing on the age structure of the jack mackerel population,
- changes in the size (and hence age) of fish which are targeted by the fishery (due to changes in the timing and location of fishing operations),
- changes in the population age structure due to recruitment variability, and
- inter- and intra-annual changes in the behaviour of jack mackerel schools (influenced by availability of food and/or oceanographic conditions), or
- a combination of one or more of these factors.

The size and behaviour of jack mackerel schools is known to vary seasonally (Williams and Pullen 1993) as does the size composition of fish within the schools (Williams *et al.* 1987). Variations in the distribution and schooling behaviour of jack mackerel and thus availability and vulnerability of fish to purse seine may be associated with changes in oceanography, productivity and swings in the El Nino/Southern Oscillation Index. Furthermore the catch in the fishery is believed to be influenced by the availability of krill (*Nyctiphanes australis*) their main food species (Young *et al.* 1993; Williams and Pullen 1993). It is likely that the association between krill abundance and schooling of jack mackerel is important on both inter- and intra-annual scales (Young *et al.* 1993; Williams and Pullen, 1993).

Changes in recruitment have been shown to be a major influence on the size and age composition of the catch of *T. trachurus* in South Africa (Geldenhuys 1973). Here, two strong year classes dominated the catch for several years, but were followed by several years of much poorer recruitment. The possible impact of recruitment variability on the size and age composition of the jack mackerel catch is difficult to assess from this study given the lack of a continuous time series of age structure information. Such an analysis would require re-ageing available otoliths across all years.

Given the interplay of factors such as fish behaviour, influence of oceanographic conditions and dynamics of the fishing fleet, resource assessment for jack mackerel will be an extremely complex issue.

8 BENEFITS

The ability to age jack mackerel reliably represents an important step towards the development of a scientifically based assessment for jack mackerel. Errors surrounding ageing will not only substantially affect growth parameter estimation but any subsequent age structured modelling.

With present moves towards formalising the management of the jack mackerel fishery through the establishment of a Joint Authority, a management plan is being developed. The plan will include requirements to set and review the TAC as well as monitoring the fishery against specific performance indicators or trigger points. While the age structure of the catch is, in itself, unlikely to be fully representative of the relative strengths of the major year classes (due to gear selectivity effects, influences of schooling behaviour, the limited spatial scale of the fishery in relation to the distribution of the species), such information may be useful at a qualitative level in identifying changes that could be indicative of stock stress and/or natural variability. In the longer term age and growth information may represent an input into age structured models of resource status.

9 FURTHER DEVELOPMENTS

Although an extremely complex species from the point of view of stock assessment, this study has demonstrated some interesting changes in age structure over the history of the jack mackerel fishery. The significance of these changes remains uncertain since a continuous time series of ageing data has not been established and the interplay between the dynamics of the fishery and the behaviour of the fish have not been fully explored. As otoliths have been collected from each of the fishing years between 1985/96 and 1996/97 and detailed catch and effort data are available from the fishery, there would be considerable value in undertaking a detailed synthesis of fishery and biological data in the light of these new findings. As part of this analysis, otoliths from years other than those aged here would need to be aged. The Tasmanian Scalefish Fishery Research Advisory Group has in fact identified this as a medium research priority in its 1999-2004 research plan. Further impetus for this work will no doubt come with the implementation of a management plan for jack mackerel and the need to formally review the TAC.

Although not unequivocally demonstrated in this study, there does appear to be some evidence for recruitment variability in jack mackerel. Associations between the availability of jack mackerel to the fishery and the oceanographic conditions off Tasmania have been postulated and plankton surveys have demonstrated marked inter-annual variability in the abundance of jack mackerel eggs and larvae (Jordan 1994). If recruitment variability can be demonstrated then there would be considerable value in seeking possible linkages between environmental conditions and subsequent recruitment. Much of the basic environmental and oceanographic data are available for waters adjacent to Tasmania.

10 ACKNOWLEDGEMENTS

We are particularly indebted to Grant Pullen for establishing this project and his input in the early stages of the work. Without the dedication of other research staff who have been responsible for the collection and analysis of biological and fishery data over the years, in particular Howel Williams, Alan Jordan and Carl Waterworth, a comprehensive data set would not have been available.

Kylie Hall was responsible for registering the otoliths with the CAF and Corey Green undertook the preparation and daily ageing of juvenile otoliths. We also wish to acknowledge John Kalish and Justine Johnston of the Australian National University for conducting the radiocarbon analyses.

11 REFERENCES

Anderson, J. R., Morison, A. K., and Ray, D. J. (1992). Validation of the use of thin sectioned otoliths for determining the age and growth of Golden Perch *Macquaria ambigua* (Perciformes : Percichthyidae) in the lower Murray Darling Basin, Australia. *Australian Journal of Marine and Freshwater Research* **43**, 231-256.

Anon (1986). ICSEAF otolith interpretation guide. No. 2 Cape horse mackerel. 24 pp. (International Commission for the Southeast Atlantic Fisheries: Madrid.)

Beamish, R. J. (1979). Differences in the age of Pacific hake (*Merluccius productus*) using whole otoliths and sections of otoliths. *Journal of the Fisheries Research Board of Canada* **36**, 141-152.

Beamish, R. J., and Fournier, D. A. (1981). A method for comparing the precision of a set of age determinations. *Journal of the Fisheries Research Board of Canada* **36**, 1395-1400.

Campana, S. E., Annand, M. C., and McMillan, J. I. (1995). Graphical and statistical methods for determining the consistency of age determinations. *Transactions of the American Fisheries Society* **124**, 131-138.

Eltink, A., and Kuiter, C. J. (1989). Validation of ageing techniques on otoliths of horse mackerel (*Trachurus trachurus* L.). Pelagic Fish Committee, C.M. No. 1989/H:43 15 pp. (International Council for the Exploration of the Sea: .)

Geldenhuys, N. D. (1973). Growth of the South African Maasbanker *Trachurus trachurus* Linnaeus and age composition of the catches, 1950-71. Investigational Report Sea Fisheries Branch South Africa 101, 1-24.

Horn, P. L. (1993). Growth, age structure, and productivity of jack mackerels (Trachurus spp.) in New Zealand waters. *New Zealand Journal of Marine and Freshwater Research* **27**, 145-155.

Jordan, A. R. (1994). Age, growth and back-calculated birthdate distributions of larval Jack mackerel, *Trachurus declivis* (Pisces: Carangidae), from eastern Tasmanian coastal waters. *Australian Journal of Marine and Freshwater Research* **45**, 19-33.

Jordan, A., Pullen, G. and Williams, H. (1992) Jack mackerel resource assessment in south eastern Australian waters. Final report to the Fishing Industry Research and Development Council, Project DFT2Z.

Jordan, A. R., Pullen, G., Marshall, J., and Williams, H. (1995). Temporal and spatial patterns of spawning in Jack mackerel, *Trachurus declivis* (Pisces: Carangidae), during 1988-91 in eastern Tasmanian waters. *Marine and Freshwater Research* **46**, 831-42.

Kalish, J. M. (1993). Pre- and post-bomb radiocarbon in fish otoliths. *Earth and Planetary Science Letters* **114**, 549-554.

Kalish, J. M. et al. (1995). Glossary for otolith studies. In 'Recent Developments in Fish Otolith Research'. (Eds Secor, D. A., Dean, J. M., and Campana, S. E.) Vol. pp 723-729. (University of South Carolina Press: South Carolina.)

Kerstan, M. (1995). Ages and Growth Rates of Agulhas Bank Horse Mackerel *Trachurus trachurus capensis* - Comparison of Otolith Ageing and Length Frequency Analyses. *South African Journal of Marine Science* **15**, 137-156.

Kimura, D. (1980). Likelihood methods for the von Bertalanffy growth curve. *Fishery Bulletin* **77**, 765-766.

Morison, A. K., Robertson, S. G., and Smith, D. C. (1998). An integrated system for production fish aging: image analysis and quality assurance. *North American Journal of Fisheries Management* **18**, 587-98.

Pullen, G. (1994) Fishery status report: Purse seine (The Tasmanian jack mackerel fishery). The Department of Primary Industry and Fisheries, Marine Resources Division Internal Report No. 13.

Pullen, G. and Lyle, J. (1994) Jack mackerel research review. The Department of Primary Industry and Fisheries, Marine Resources Division.

SAS Institute Inc (1989). SAS/STAT User's Guide, Version 6, Fourth Edition, Volume 2. 846 pp. (SAS Institute Inc .: Carey, N. C.)

Stevens, J. D., and Hausfeld, H. F. (1982). Age determination and mortality estimates of an unexploited population of Jack mackerel *Trachurus declivis* (Jenyns, 1841) from south-east Australia. Marine Laboratories Report No. 148 (CSIRO: Hobart.)

Stevens, J. D., Hausfeld, H. F., and Davenport, S. R. (1984). Observations on the biology, distribution and abundance of *Trachurus declivis*, *Sardinops neopilchardus* and *Scomber australasicus* in the Great Australian Bight. Marine Laboratories report No. 164 (CSIRO: Hobart.)

Webb, B. F., and Grant, C. J. (1979). Age and growth of jack mackerel, *Trachurus declivis* (Jenyns), from south-eastern Australian waters. *Australian Journal of Marine and Freshwater Research* **30**, 1-9.

Williams, H., Kirkwood, R., Pullen, G., and Kecerans, G. (1986). The Jack mackerel purse seine fishery in Tasmania, 1985-86. Technical Report No. 13, 43 pp. (Division of Sea Fisheries, Tasmania, Marine Laboratories: Taroona.)

Williams, H., and Pullen, G. (1993). Schooling behaviour of Jack mackerel, *Trachurus declivis* (Jenyns) observed in the Tasmanian purse seine fishery. *Australian Journal of Marine and Freshwater Research* **44**, 577-87.

Williams, H., Pullen, G., Kucerans, G., and Waterworth, C. (1987). The Jack mackerel purse seine fishery in Tasmania, 1986-87. Technical Report No. 19 32 pp. (Department of Sea Fisheries, Tasmania, Marine Laboratories: Taroona.)

Young, J. W., Jordan, A. R., Bobbi, C., Johannes, R., Haskard, K., and Pullen, G. (1993). Seasonal and interannual variability in krill (*Nyctophanes australis*) stocks and their relationship to the jack mackerel (*Trachurus declivis*) fishery off eastern Tasmania, Australia. *Marine Biology* **116**, 9-18.

Appendix 1

Intellectual Property

Attribution of intellectual property derived from this project was 35.95% to the Fisheries Research and Development Corporation and 64.05% to the University of Tasmania and the Marine and Freshwater Resources Institute.

Appendix 2

Staff

Tasmanian Aquaculture and Fisheries Institute

Jeremy Lyle

Grant Pullen[1]

Marine and Freshwater Resources Institute

Alexander Morison

Kyne Krusic-Golub

[1] Feb 1996 - Jan 1997

Appendix 3

Jack mackerel otoliths from TAFI as registered with the Central Ageing Facility.

Batch	*No of otoliths*	*TAFI Otolith_No's*	*Date of Capture*	*Vessel*	*Area*
5	46	JMK00829 to JMK00862	19/05/85	Unknown	
6	35	JMK00794 to JMK00828	16/07/85	Unknown	
7	77	JMK00613 to JMK00686	25/10/85	Unknown	
8	58	JMK00687 to JMK00743	31/10/85	Unknown	
9	50	JMK00747 to JMK00793	31/10/85	Unknown	
10	50	JMK00880 to JMK00929	12/11/85	Unknown	
11	20	JMK00931 to JMK00949	19/11/85	Unknown	
12	22	JMK00950 to JMK00969	27/11/85	Unknown	
13	37		29/11/85	Unknown	
			25/05/85		
14	20	JMK01010 to JMK01029	12/01/86	Unknown	
15	20	JMK01030 to JMK00049	23/01/86	Unknown	
16	20	JMK01050 to JMK01069	24/01/86	Unknown	
17	20	JMK01070 to JMK01089	3/02/86	Unknown	
18	20	JMK01090 to JMK01109	4/02/86	Unknown	
19	20	JMK01010 to JMK01129	11/03/86	Unknown	
20	20	JMK01030 to JMK01149	17/02/86	Unknown	
21	20	JMK01050 to JMK01169	1/02/86	Unknown	
22	20	JMK01070 to JMK01189	3/01/86	Unknown	
23	21		25/05/86		
24	40	JMK01251 to JMK01290	23/04/86	Unknown	
25	40	JMK01291 to JMK01330	28/04/86	Unknown	
			29/04/86		
26	60	JMK01331 to JMK01390	6/05/86	Unknown	
27	20	JMK01391 to JMK01410	14/05/86	Unknown	
28	50	JMK01411 to JMK01440	7/05/86		
		&	15/05/86		
		JMK01491 to JMK01510	28/05/86		
29	40	JMK01531 to	12/05/86	Unknown	
		JMK01570	27/05/86		
30	40	JMK01231 to	9/04/86	Unknown	
		JMK01270	11/04/86		
31	74	JMK01551	9/07/86	Unknown	
		JMK01628	14/07/86		
32	134	JMK03847	12/11/89	Unknown	
			18/11/89		
			19/11/89		
		to	15/08/89		
			16/08/89		
			17/08/89		
		JMK03988	3/10/89		
33	57	JMK03989 to	10/11/89	Unknown	
		JMK04025	21/11/89		
34	58	JMK04046	30/12/89	Unknown	
		to	13/01/90		

Batch	*No*	*TAFI Otolith_No's*	*Date of Capture*	*Vessel*	*Area*
		JMK04103	21/01/90		
35	60	JMK04104 to	13/02/90		
		JMK04163	14/02/90		
36	60	JMK04164	20/02/90	Unknown	
		to	28/02/90		
		JMK04223	1/03/90		
37	46	JMK04284	28/02/90	Unknown	
		to	21/03/90		
		JMK04329	25/04/90		
38	60	JMK04330	19/04/90	Unknown	
		to	10/05/90		
		JMK04389	11/05/90		
39	140	JMK04390	16/05/90	Unknown	
		to	21/05/90		
		JMK04529	29/05/90		
40	38	JMK04531 to	5/06/90	Unknown	
		JMK04569	12/06/90		
41	117	5305	13/08/91	Unknown	
			6/04/93		
			5/04/93		
			1/07/93		
			12/07/93		
			8/07/93		
		to	5/07/93		
			6/04/93		
			6/09/93		
			7/09/93		
			15/09/93		
			14/09/93		
			30/06/93		
		7505	28/01/94		
42	140	7506	29/03/94	SeaTas	
			26/04/94	SeaTas	
			22/03/94	SeaTas	
		to	20/03/94	SeaTas	
			24/03/94	SeaTas	
			25/03/94	SeaTas	
		7645	20/03/94	SeaTas	
43	58	7945 to	31/08/94	Southern Surveyor	
		7992	4/12/94	SEATAS 3	
44	180	8053	10/01/95	SeaTas	
		to	8/01/95	SeaTas	
		8092	1/01/95	SeaTas	
			16/01/95	SeaTas	
		&	1/12/94	SeaTas	
			26/01/95	SeaTas	
		8113	27/04/95	SeaTas	
		to	27/08/95	SeaTas	
		8253	28/03/95	SeaTas	
45	127	150020	19/05/95	SeaTas	
		to	18/05/95	SeaTas	

Batch	*No*	*TAFI Otolith_No's*	*Date of Capture*	*Vessel*	*Area*
		150159	17/05/95	SeaTas	
46	131	150160	19/05/95	SeaTas	
			27/04/95	SeaTas	
			12/04/95	SeaTas	
		to	28/03/95	SeaTas	
			26/04/95	Ocean Lady	
		150299	19/05/95	SeaTas	
47	105	150302	29/03/95	SeaTas	
			6/04/95	SeaTas	
		to	27/01/95	SeaTas	
			30/01/95	Ocean Lady	
			17/05/95	SeaTas	
		150419	19/05/95	SeaTas	
48	61	150420	12/01/94	Challenger	Station 12
			12/01/94	Challenger	Station 16
			24/08/94	Challenger	Station 26
			18/04/94	Challenger	Reidel Bay
		to	30/08/94	Southern Surveyor	Station 94
			30/08/94	Southern Surveyor	Station 92
			28/08/94	Southern Surveyor	Station 72
			28/08/94	Southern Surveyor	Station 36
			2/09/94	Southern Surveyor	Station 125
		150480	7/12/95	Lella	White Rock
49	74	151081	18/04/95	Unknown	
			12/04/94	Unknown	
			11/04/94	Unknown	
		to	14/04/94	Unknown	
			13/04/94	Unknown	
		151154	23/08/94	Unknown	
50	48	150502	10/01/94	Unknown	
			11/01/94	Unknown	
		to	12/01/94	Unknown	
			17/01/95	Unknown	
			11/12/95	Unknown	
		150554	3/01/96	Unknown	
51	194	661	13/11/85	Unknown	
			11/01/94	Unknown	
			12/01/94	Unknown	
			23/01/94	Unknown	
		to	26/01/94	Unknown	
			8/02/94	Unknown	
			20/03/94	Unknown	
			22/03/94	Unknown	
			25/08/94	Unknown	
		857	28/08/94	Unknown	
Total	2848				

Appendix 4

Validation of jack mackerel (*Trachurus declivis*) age based on otolith radiocarbon

John M. Kalish and Justine M. Johnston

Division of Botany and Zoology
The Australian National University
Canberra, ACT 2600
Australia

Telephone: 61-6-249-3119
Fax: 61-6-249-5573
Email: John.Kalish@anu.edu.au

Introduction

This study provides validations for both the thin section and break and burn method of age estimation used for jack mackerel (*Trachurus declivis*).

Materials and methods

Otoliths were obtained from two sources to increase the likelihood that samples would encompass the time period from about 1960 to 1990 and include the period of rapid increase in radiocarbon. Peter Horn (NZ NIWA) provided a series of jack mackerel otoliths from large and presumably old fish. These fish were collected in New Zealand waters. The remaining samples were from jack mackerel collected off the east coast of Tasmania and were supplied by TAFI. Although the fish were derived from different regions, previous research on radiocarbon in otoliths from snapper (*Pagrus auratus*) from New Zealand and redfish (*Centroberyx affinis*) from south east Australia has demonstrated that changes in ^{14}C over time were similar for the two regions.

Two methods were used to estimate age for these samples. Fish age was estimated from otoliths of New Zealand and Australian caught jack mackerel based on the 'break and burn' and 'thin section' methods, respectively.

Otolith cores were removed from individual otoliths and analysed for ^{14}C with accelerator mass spectrometry (Kalish 1993).

Results

Table A1 contains fish, otolith and radiocarbon data for all samples. The birth dates estimated from thin sectioned or broken and burnt otoliths are plotted against $\Delta^{14}C$ measured in the otolith core (Fig. A1). Similar data from previous studies of New Zealand snapper and south east Australian redfish are included with the jack mackerel data.

The jack mackerel data describe the bomb radiocarbon curve and are coincident with data from both snapper and redfish. Two New Zealand jack mackerel (JMKNZ16 and JMKNZ18) are likely to have been assigned incorrect ages based on the break and burn method. JMKNZ16, with an estimated birth date of 1959 (22 years old), was probably spawned after 1960. A $\Delta^{14}C$ of −14.5 per mil indicates levels of bomb radiocarbon that are unlikely to be present prior to 1960. A $\Delta^{14}C$ of −46.2 per mil measured in otolith JMKNZ18 suggests the inclusion of little, if any, bomb radiocarbon. Therefore, JMKNZ18 is likely to have been spawned prior to 1960, not in 1965 as estimated from the broken and burnt otolith. No other errors in age estimation can be identified from these jack mackerel otoliths.

Conclusion

Satisfactory age estimates for jack mackerel can be provided based on both the thin section and break and burn methods. Jack mackerel can live in excess of 20 years, however, the larger and older jack mackerel have only been sampled in the New Zealand fishery.

Table A1. Fish, otolith, and radiocarbon data for Australian and New Zealand Jack Mackerel (*Trachurus declivis*).

Sample No.	Collection date	Fish length (mm)	Otolith weight (g)	Sample weight (mg)	$\Delta^{14}C$ (‰)	Otolith section age (yrs)	Birth date (yearA.D.)
JMKNZ 16	10/02/81	454	0.0663	3.1	-18.5±7.7	22	1959
JMKNZ 4	08/02/81	453	0.0821	5.3	-44.4±6.4	23	1958
JMKNZ 18	10/02/81	447	0.0955	4.3	-46.2±18.7	16	1965
JMKNZ 19	10/02/81	452	0.0985	4.7	-38.5±6.6	18	1963
JMKNZ 2	08/02/81	425	0.0673	3.9	69.9±7.9	10	1971
JMKNZ 5	08/02/81	429	0.0824	5.2	44.2±6.9	14	1967
JMK 30	14/07/86	157	0.0085	8.5	87.4±5.8	1	1985
JMK 861	10/12/95	359	0.0580	4.6	116.3±6.5	10	1985
JMK 558	12/12/95	351	0.0535	4.6	106.9±7.5	12	1983
JMK 517	11/12/95	338	0.0545	5.1	110.1±8.8	8	1987
JMK 594	18/06/85	341	0.0604	3.7	107.1±16.7	11	1974
JMK 531	24/05/85	344	0.0526	6.1	121.8±6.7	7	1978
JMK 525	24/05/85	351	0.0550	7	138.5±6.6	10	1975

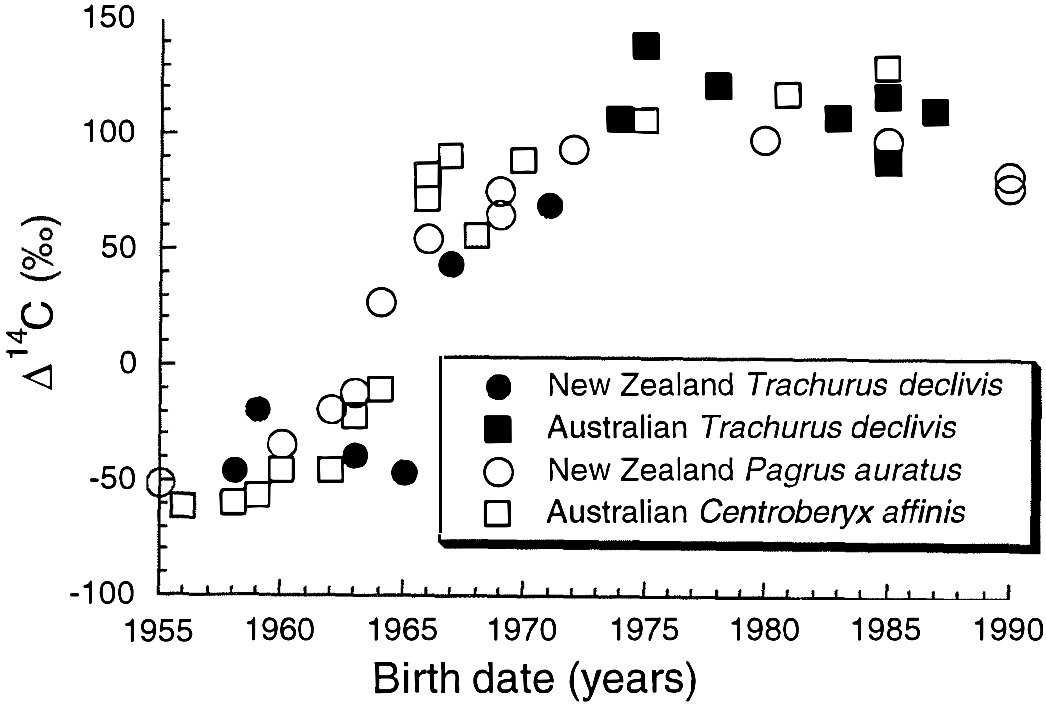

Fig. A1 Relationship between radiocarbon level ($\Delta^{14}C$ (‰)) and estimated birth for jack mackerel and two other temperate fish species.

Appendix 5

Manual for ageing jack mackerel otoliths

The growth of the otolith

Relative rates of growth within the otolith in different dimensions can be inferred from observations of the relative width of increments in each direction. Initial growth of the jack mackerel otolith occurs in length (anterior-posterior), width (dorsal-ventral) and depth (proximal-distal), and in otolith weight. There is very little deposition of material on the distal surface and as a consequence the primordium remains close to the distal surface even in older fish. After approximately 5-6 years of age, growth in otolith length and width slows significantly but growth continues in both depth and weight (Fig. B1). In jack mackerel the reduction in growth in length and width reduces the width of annual increments in these dimensions. In other species the reduction is so marked that the outermost annual increments can not be discerned on older fish and this leads to an underestimation of their age if whole otoliths are used.

Daily age estimates

Daily age estimates for juvenile jack mackerel were performed and the time of first feeding (hatch dates) were back calculated. Otoliths were viewed using a compound microscope under transmitted light to reveal the daily growth zones, which appeared as translucent (light) and opaque (dark) zones. Age was estimated by counting the number of opaque zones from the primordia out to the edge along the area of greatest zone definition.

The time between spawning and hatching varies according to species. Jordan (1994) estimated that the time interval between spawning and first feeding was approximately 8 days. This figure was added to the individual ages and a spawning period back calculated. In this study the spawning period ranged from 21st November to 1st April. An indication of spawning period enables a birthdate to be set for a particular species.

Defining inner structure

In many of the otoliths from juvenile jack mackerel, a larger optically opaque zone was recognisable from the daily growth zones (Fig. B2). Counts were made from the end of the larger dark zone to the outer margin. The number of opaque zones was subtracted from the date of capture to indicate the timing of this first opaque zone formation. In one otolith examined, the counts place the timing of this optically opaque zone formation at approximately 2nd May.

In a majority of other otoliths examined an opaque zone was observed close to the primordia and may easily be confused with the first annual increment. The protracted spawning period suggests that at the timing of this first opaque zone formation the otolith may have only experienced as little as one or two months growth. If this inner opaque zone was observed it was not counted and the deposition of the subsequent opaque zone was counted as the first annual increment (Fig. B3).

In both sectioned and whole otoliths the position of the first annual increment was frequently difficult to determine, its clarity and position varying between individual specimens (Fig. B4). Clarity of this zone was affected by the large opaque centre and its position presumably by when the individual was spawned during the protracted spawning period.

Age estimation from otolith sections

Sectioned otoliths revealed a large opaque inner region followed by alternating translucent and opaque zones, which under transmitted light appear light and dark respectively. The distance between successive opaque zones (annual increments) generally decreased with age (Fig. B5). Age was estimated as the number of completed opaque zones.

Jack mackerel otoliths were aged from the primordia out to the proximal edge on the ventral side. Increments were also visible on the dorsal side and in various individuals the incremental clarity was far superior to that on the ventral side. The clarity of dorsal increments was however inconsistent, particularly within older specimens, and therefore it is suggested that a ventral transect close to the crista inferior be used for age estimation (Fig. B5).

A large majority of sectioned otoliths revealed numerous sub-annual increments between the annual increments. They were recognisable as narrow opaque zones that were not continuous throughout the section and were irregularly spaced. They were more clearly evident under higher magnification (25 to 40x) and a reduction in magnification generally increased the ability to differentiate between annual and sub-annual zones. Age estimates from larger fish were generally easier to obtain than estimates of age from smaller specimens.

Morphology characteristics were used, where appropriate, as an aid to identify the position of the opaque zone and consequently estimation of age. Various otoliths exhibited a series of rounded ridges were observed on the distal face, particularly on the ventral side of the section (Fig. B6). These ridges frequently corresponded with opaque zones visible in the sections. This morphological feature was not evident on every otolith and was only used as an ageing guide when appropriate.

Age estimation from whole otoliths

Whole otoliths were aged immersed in water and illuminated using reflected light. When viewed this way, the otoliths appear as a predominantly opaque (lighter) with relatively narrow translucent (darker) zones. A large opaque centre was observed with the opaque zones becoming narrower with increasing age such that the relative width of the two types of zones becomes more similar in the otoliths of older fish.

The first annual increment was often obscured by the large opaque centre, and could only be distinguished by careful focusing. Some individuals exhibited an incomplete translucent zone close to the primordia. This zone was assumed to be sub-annual and was not counted. The subsequent translucent zone was marked as the first annual increment. Age was estimated as the number of completed translucent annual zones from the primordia to the edge. Translucent zones were counted if they were regularly spaced and interrupted the solid opaque material continuously over the whole distal face (Fig. B7).

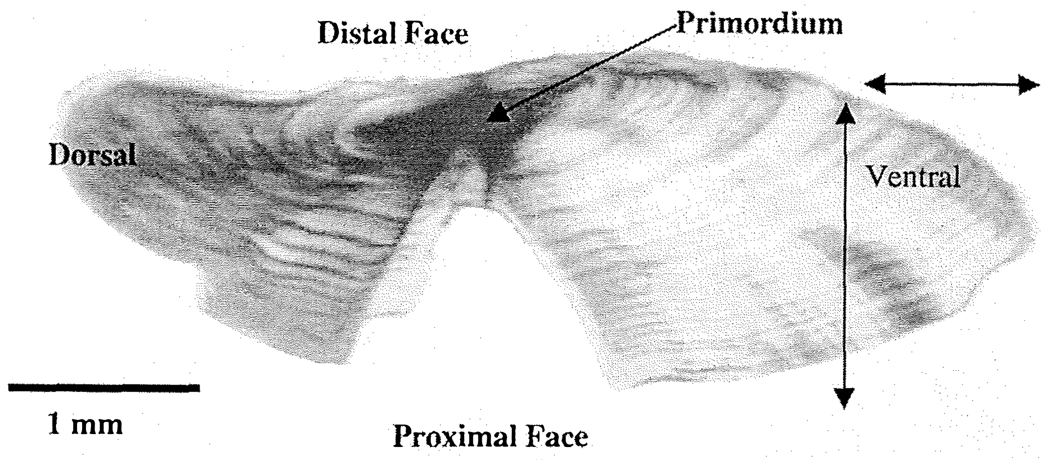

Fig. B1. Sectioned jack mackerel otolith showing the decrease in dorsal ventral deposition (horizontal line) after approximately 4 to 5 years relative to the continuous deposition on the primordial face (vertical line). Estimated age of fish = 15 years.

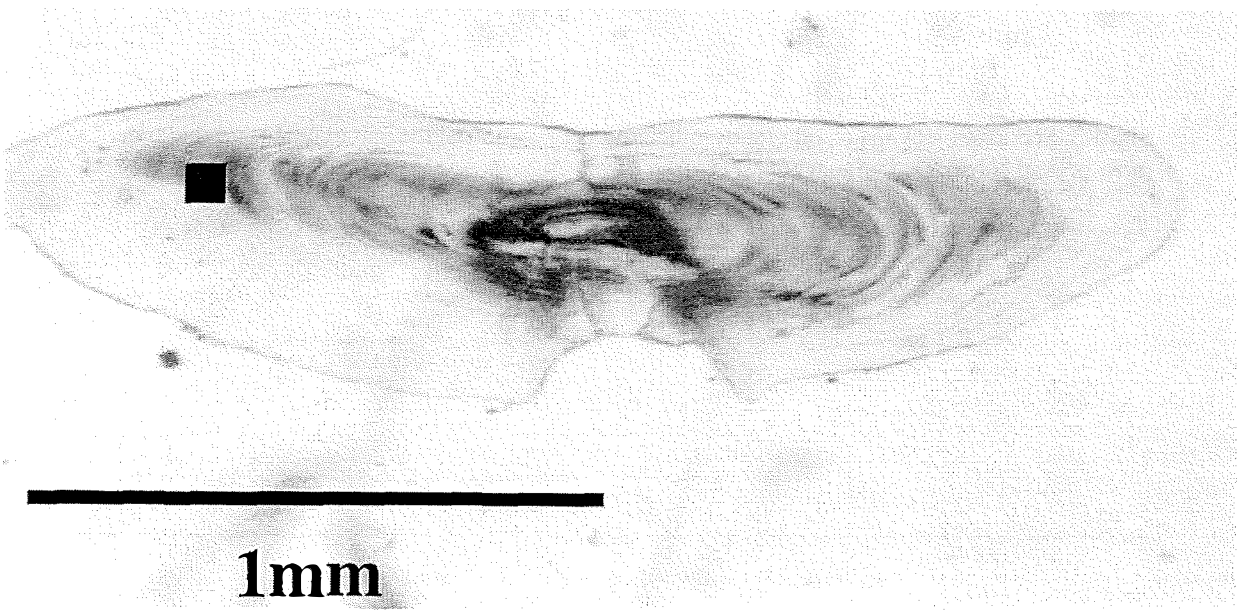

Fig. B2. Ground juvenile jack mackerel otolith section, fork length = 12.4 cm, collected 12/01/93, estimated age 170 days. Opaque zone (Black Square) was estimated to have formed in May.

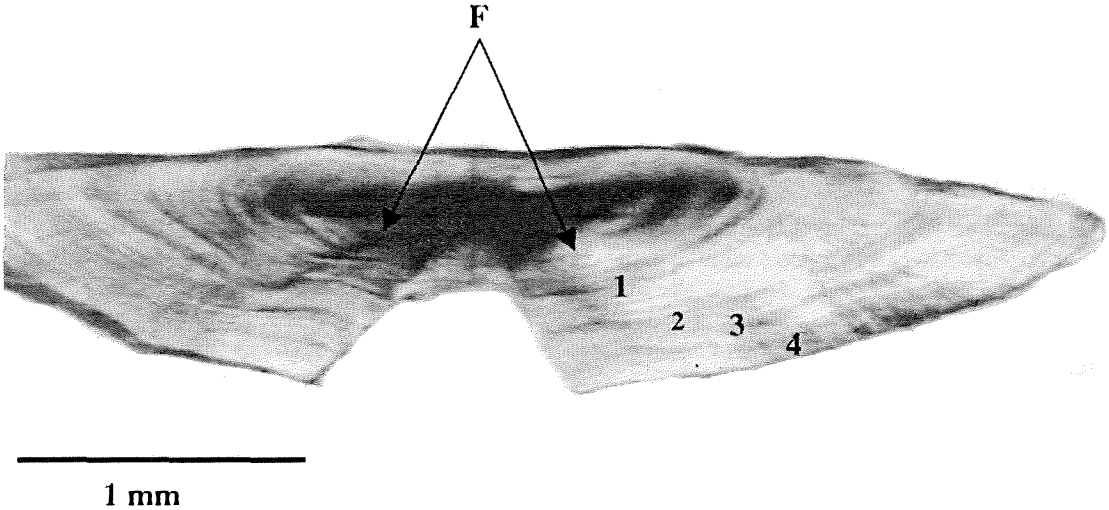

Fig. B3 Sectioned jack mackerel otolith indicating the position of the sub-annual inner increment (arrows) and subsequent annual zones. (1- 4).

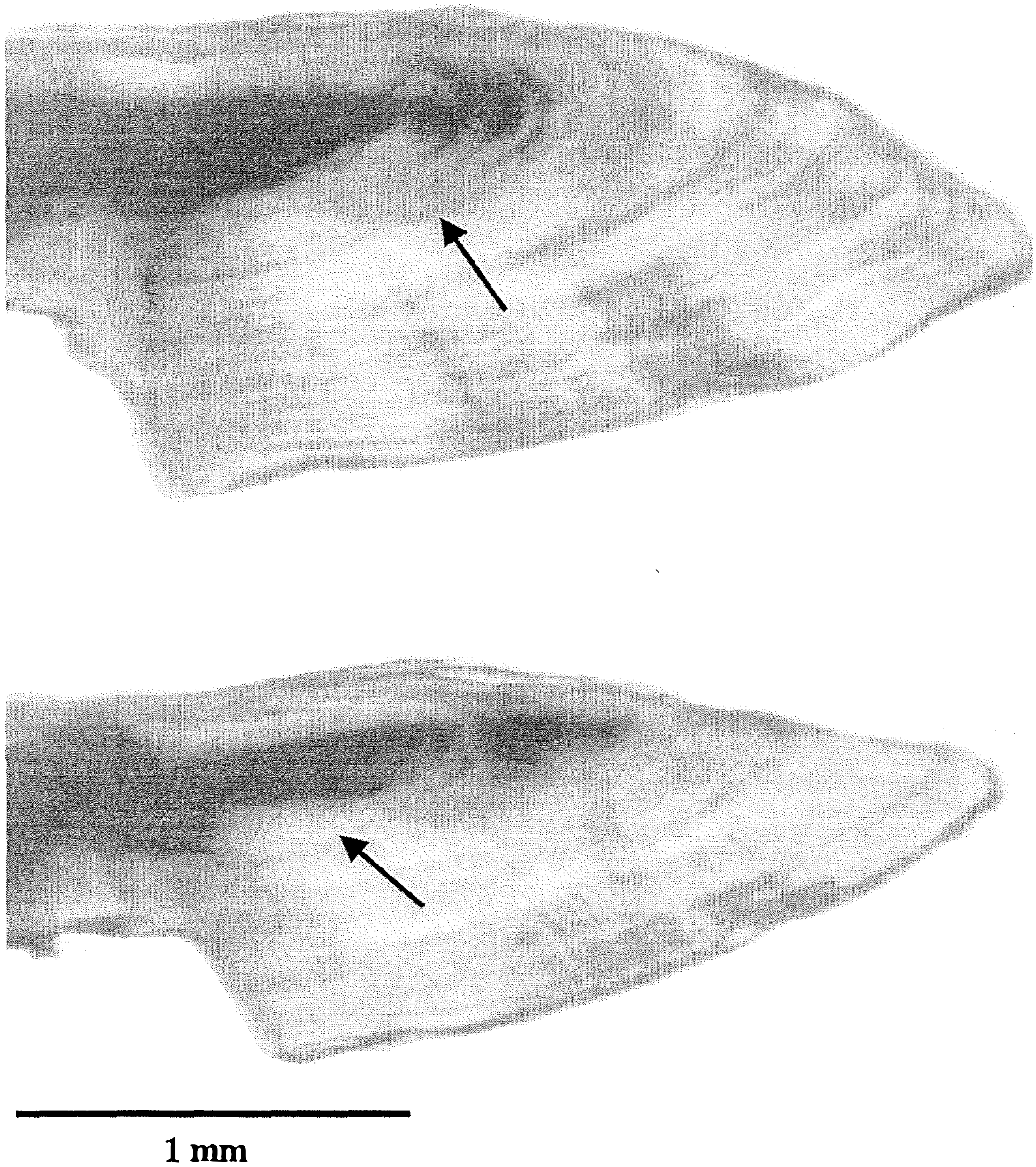

Fig. B4 Sectioned jack mackerel otoliths indicating the difference in positioning of the first annual opaque zone (black arrows).

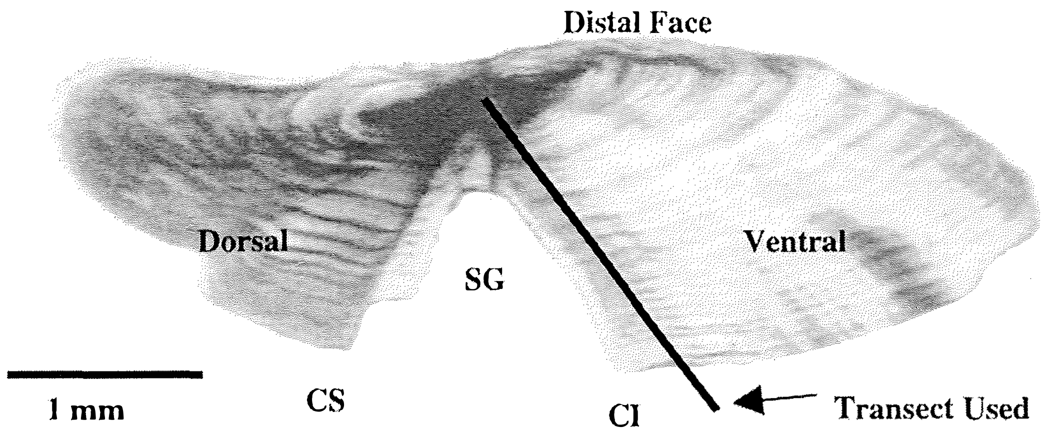

Fig. B5 Sectioned jack mackerel otolith showing particular features: crista inferior (CI), crista superior (CS), sulcal groove (SG), and transect used for marking increments. Estimated age = 15 years (fork length = 35 cm).

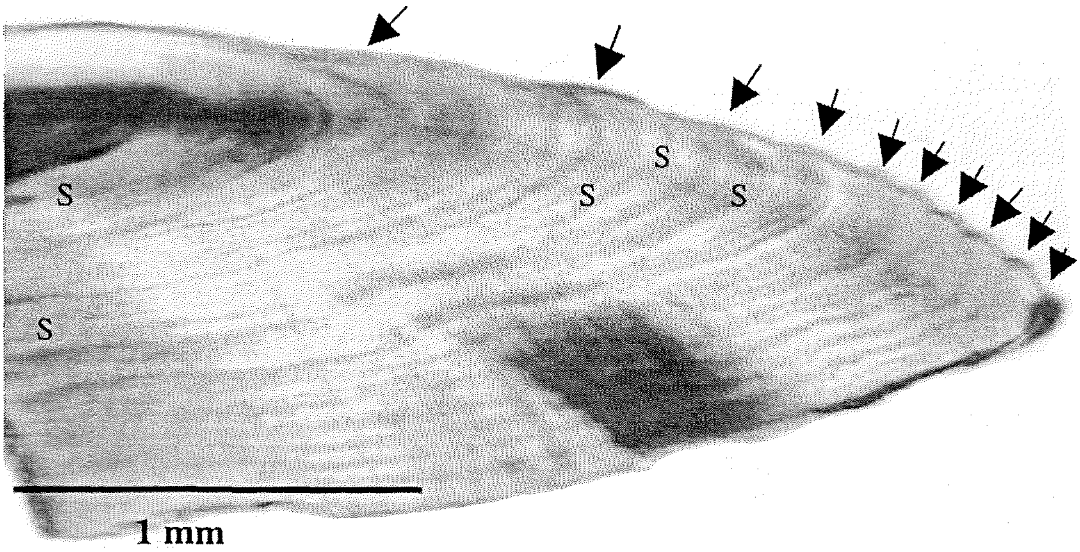

Fig. B6 Sectioned jack mackerel otolith showing the rounded ridges (black arrows) corresponding with the annual opaque increment deposition, and the presence of sub-annual increments (S). Age of fish = 10 years (fork length 33.8 cm).

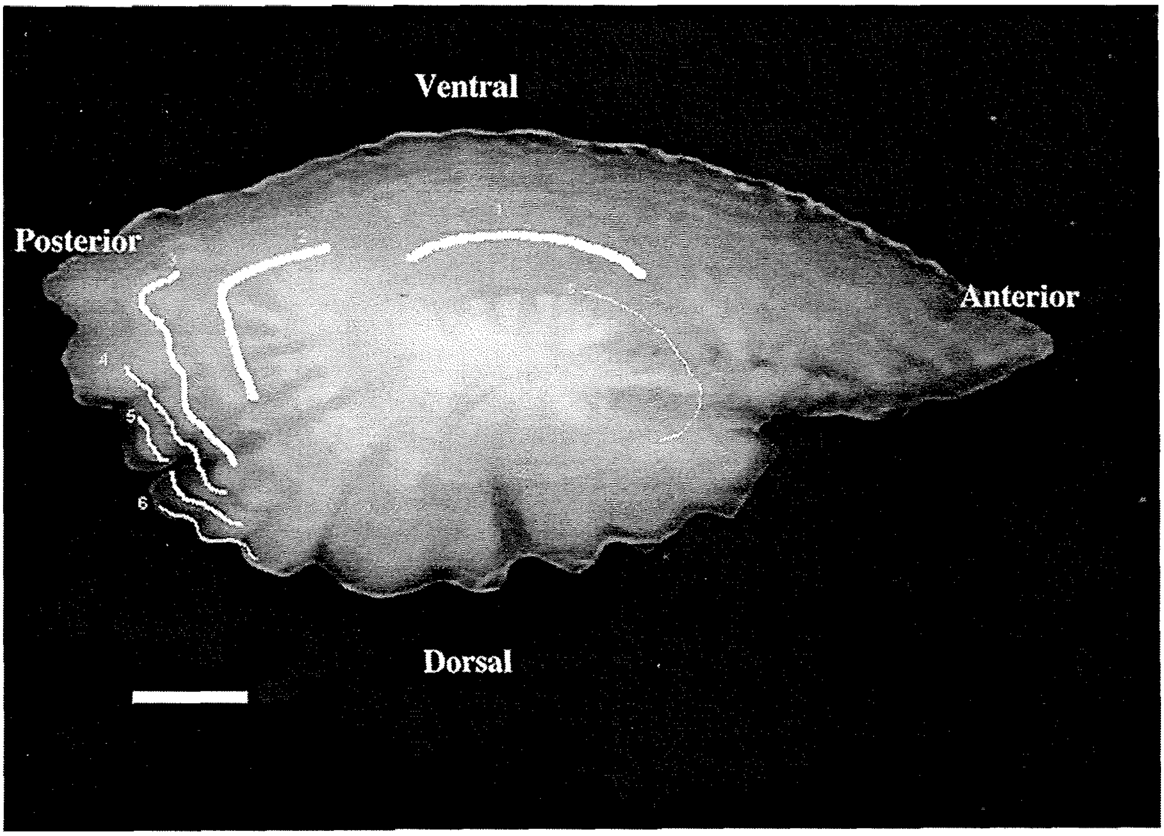

Fig. B7 Whole jack mackerel otolith estimated at 6 yrs old, showing the position of annual zones (1 - 6) and the first sub-annular increment (s) close to the primordia. Scale bar = 1 mm.