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Age and growth of Greenland Halibut in the Northwest Atlantic

by

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Introduction

Despite a considerable amount of scientific research on Greenland halibut, a deepwater fish in the Northwest Atlantic, many questions regarding age and growth remain unresolved. Since 1996, the Arctic Fisheries Working Group at ICES and in NAFO Scientific Council have expressed concern over the lack of precision and potential underageing of the oldest fish in the population in. In 1997, the first of three workshops was carried out, with the most recent having taken place in 2011 (ICES 1997; NAFO 2006 and ICES 2011). The report from the 2011 Working Group on the Age Reading of Greenland Halibut concluded that: "… there may be differences in population growth between areas that would warrant use of different interpretation methods… Validation of total age by bomb radiocarbon analyses is therefore warranted for all stock units for which required archived samples are available" (ICES 2011).

Several studies have been carried out on the age and growth of Greenland Halibut in other regions. Differences in stock dynamics exist between populations of Greenland Halibut, but few studies exist for the SA 2 + 3KLMNO stock. Using surface read whole otoliths (the traditional method of ageing Greenland Halibut) there is a suggestion of fast, linear growth, with a maximum age of about 20 years old. Except for the validation of the first few years of growth using length frequency modes (Lear and Pitt 1975; Bowering and Nedreaas 2001), there has been no age validation across the entire age range of the species. Studies carried out by Treble *et al.* (2008), using thin sections, indicated that the Arctic stock (including some samples from SA 2) is slow growing, reaching an age of 27 years. The authors used bomb radiocarbon to validate the oldest fish in the population, and concluded that thin sections provided an accurate age (on average), but still underestimated the ages of the oldest fish in the population.

Bomb radiocarbon assays are one of the best techniques currently available to determine the accuracy of an ageing method (Kalish, 1993, 1995; Campana 2001). The amount of $\Delta^{14}C$ in otolith cores of older fish can be compared to a reference chronology of known age fish to determine whether an assigned age based on annulus counts is accurate (thus validating an age). If the difference between the true age and the assigned age is significant and cannot be resolved, this suggests the ageing method has failed and should be re-evaluated.

It is possible that the age-based assessment of Greenland Halibut that is currently used to evaluate this stock may underestimate age, and age-based analyses may not be the optimal method to assess this resource unless a more robust age determination method can be developed for this species.

This paper compares the traditional method of surface ageing of whole otoliths to the method of using thin sections. We then employ the bomb radiocarbon method to determine whether whole or sectioned otoliths provide accurate ages for Greenland Halibut in the Northwest Atlantic.

Materials and Methods

Part 1: Comparison of ageing methods

The traditional method of determining age in Greenland halibut at the Northwest Atlantic Fisheries Centre (NAFC) is based on surface reading of whole otoliths. When necessary, the surface of the otolith was ground using a rotary grinding wheel, usually for older fish, in order to make the annuli more visible. A comparison of this method with the broadly accepted thin-sectioning method (Chilton and Beamish 1982) was investigated by comparing ages estimated from whole and thin sectioned otoliths from the same fish. Both sagittal otoliths were removed from 266 otoliths, mainly from 1976 and 1977 annual autumn surveys in NAFO SA 2 + 3K, as well as some smaller fish collected in 2007. Whole otoliths were aged by experienced readers at the time of capture, and a portion of these re-read by current age readers to ensure there was no drift. The left otolith is preferred over the right for age determination because it is more symmetrical, with a centric nucleus, resulting in clearer, more evenly spaced annuli.

The left otoliths were thin sectioned by embedding them in blocks of clear polyester casting resin in a custom-made silicon mould and left to partially cure. Otoliths were arranged in five rows on the resin. The blocks were labelled and coated with another layer of resin and then oven cured for 24 hours at 55°C. Otoliths were sectioned using a Gemmasta lapidary saw fitted with diamond blades. From each row, five sections were taken (~350 mm in thickness), to ensure the nucleus of each otolith was captured. Sections were then cleaned in alcohol and stored in vials. A small amount of resin was poured on each slide and the sections laid on the resin, with the identification label placed at the top of the slide. Once the resin had semi-cured, further resin was added to the section preparations and coverslips applied. The slides were oven-cured again at 30°C for 3 hours.

Whole otoliths were immersed in 95% alcohol in a black watchglass and examined using a stereomicroscope at 10X magnification with reflected light. Higher magnification was used when examining annuli close to the edge for larger fish. The preferred age reading zone is within the widest half of the longitudinal axis (although this does vary) on the distal or convex side. Translucent bands (dark under reflected light) were counted as annuli (Figure 1).

Thin sectioned otoliths were examined on slides using magnification of 16-40 X with reflected light. Ages were determined by reading along an axis from the core (nucleus) to the proximal edge (thickened "dome") or toward either the dorsal or ventral edge (Figure 1).

Bias of annulus counts between the ageing methods was evaluated using age bias plots (Campana 1995a).

<u>Part 2. Bomb radiocarbon age validation</u>

Twenty four pairs of otoliths, from 22 females and 2 males (Div 2H *n* = 4; Div. 2J *n* = 11; Div 3K *n* = 7 and Div. 3L *n* = 2), were selected from the archived materials collected by the research surveys carried out in NAFO SA 2 + 3K between 1971 and 1990. These ranged in length from 57-108 cm. The largest and seemingly oldest fish, which may have hatched in the 1950s and 1960s, were selected as these are the year classes most suited to bomb radiocarbon dating. The left otoliths, where possible, were embedded in epoxy resin and sectioned (1.0-1.5 mm thick) transversely through the core using a low-speed, diamond-bladed saw. After polishing lightly to improve clarity, digital images of each section were taken and enhanced using Adobe Photoshop CS2 (Adobe Systems Incorporated, San Jose, California). No other treatments were applied to the sections.

<u>Reference chronology</u>

Treble *et al.* (2008) developed a chronology for Greenland Halibut from an area within Davis Strait to the north of the NAFO Subarea 2+3 stock area (but included some fish from SA 2). They found that the Greenland Halibut chronology was delayed and peak levels depleted compared to the Northwest Atlantic otolith chronology (Campana *et al*. 2008). The $\Delta^{14}C$ in otolith cores of 6 young Greenland halibut from the 1960s, 1970s and 1980s collected from NAFO Subarea 2 and 3K were compared to the two reference chronologies in order to determine which would best fit the pattern of increase of ^{14}C. Samples of the young fish were less than 21 cm, and effectively of known age (±1 year) based on the Petersen method of age validation (Bowering and Nedreaas 2001).

The cores corresponding to the first 3 years of growth of the left and right otoliths were extracted and combined to form a single sample to bring total sample mass used for ^{14}C analyses to at least 3 mg, as individual core masses were insufficient for assays. The radii for the first three presumed annuli were confirmed through measurements of the dimensions of the sagittae collected from ages 0-3 individuals. Cores were isolated with a Merchantek computer-controlled micromilling machine using 300 µm diameter steel cutting bits and burrs. All otolith material was then decontaminated, stored in acid-washed glass vials and assayed for ^{14}C using accelerator mass spectrometry (AMS) (Campana 2001). AMS assays also provided $\delta^{13}C$ (‰) values, which were used to correct for isotopic fractionation effects. Radiocarbon values were subsequently reported as $\Delta^{14}C$, which is the per mil (‰) deviation of the sample from the radiocarbon concentration of 19th-century wood, corrected for sample decay prior to 1950 according to methods outlined by Stuiver and Polach (1977).

The reference chronology provides a known and dated $\Delta^{14}C$ series against which the Greenland Halibut core assays can be compared. Uncertainty around the reference line is no more than 2 years between 1958 and 1972. Otolith cores from samples with prebomb levels of radiocarbon (as indicated by the reference chronology) must have been born before 1958, because postbomb radiocarbon levels are always much higher. Therefore, comparison of the radiocarbon levels of the validation otolith cores with the reference chronology allowed a ^{14}C -based age for the fish to be determined.

The $\Delta^{14}C$ value for a sample analyzed from Div. 2J, collected in 1990, fell well below the other values (-107.7) and was outside the area where it would be possible to predict the year of birth based on ^{14}C assay (aged as 22). Therefore it was removed from the analysis.

Growth curves

A von Bertalanffy growth curve was fit to the length and age data from the method comparison and bomb radiocarbon studies above. The equation for von Bertalanffy is:

$$L_t = L_\infty(1-e^{-K(t-t_0)})$$

where L_t is the expected length at age t; L_∞ is the asymptotic average length; K is the growth rate coefficient (units are year^{-1}) and t_0 is meant to represent the time or age when the average length was zero. Curves were fitted to the data for each sex using R script (Ogle, 2013).

Results

Age structure comparison

The comparison of whole and thin sectioned otoliths indicated that whole otoliths underestimated section ages by more than 50% in some older fish. An age bias plot indicated that young fish were aged similarly using both methods (±1 year) but the whole otolith method increasingly underestimated ages compared to the thin sections after about age 10 (approximately 60 cm) by up to 18 years (Figure 2).

The maximum age determined for whole otoliths was 18, and for thin sections was 33 years. In this study the maximum size was 70 cm total length (TL) for males, and 110 cm TL for females. Since these samples are amongst the largest sizes for Greenland halibut, they may represent something close to the longevity of the species in this region.

Means and 95% confidence intervals of fish length at age using thin sections to derive age are shown in Table 1. The oldest specimen in the sample was a 17 year old male, measuring 70 cm TL, and a 33 year old female, measuring 109 cm TL.

^{14}C Validation

The six young fish (<21 cm) A comparison of the ^{14}C reference chronology of young Greenland Halibut from NAFO Div. 2 + 3K in the 1960s, 1970s and 1980s with the commonly used Northwest Atlantic reference chronology (Campana *et al.* 2008) and with the Greenland Halibut reference chronology determined by Treble *et al*. (2008) indicates that the reference chronology for Greenland Halibut would be best used to validate the ages of Div. 2J3K fish, despite the fact that mostly otoliths from the Arctic stock were used to compose the curve (Figure 3). Therefore, the reference chronology developed by Treble *et al*. (2008) for Greenland Halibut, as supplemented by the 6 new young fish cores, was utilized in this study (Figure 3; Table 2) in order to validate the older fish from Div. 2J3K.

The period of increasing radiocarbon values (1958-1970) in the Greenland Halibut curve results in a relatively narrow range of $\Delta^{14}C$ values (-10 to -80) that can be used for precise core validation. When the curve has flattened out (both pre- and post-bomb areas) then it is harder to get accurate ages during those periods.

The ages from sectioned otoliths indicated that the birthdates for these fish were close to those indicated by the reference chronology (Table 3; Figure 4), indicating that ages were therefore accurate. Some of the fish of lengths 57-69 cm TL were slightly over aged using thin sections. Furthermore the assigned age of three fish (aged 18-27 years) exceeded the ^{14}C age by > 5 years. Because ^{14}C ages represent the minimum possible ages consistent with the radiocarbon data, these results indicate that the age readings from the otolith sections are on average, close to the actual age of these fish. The maximum observed age from whole and section ages from this subset of otoliths was 16 and 27 years respectively (Table 3; Figure 4).

Growth curve estimates

The observed length at age was similar up to age 8 (53-54 cm TL) for both males and females, after which growth slowed disproportionately for females (Table 4). The predicted growth from the von Bertalanffy model supports this observation, with similar growth rates until about age 8-9 for both sexes. Females, however, reached a larger asymptotic length (106 cm) than males (90 cm) (Figure 5).

The von Bertalanffy growth curves fit both male and female thin-sectioned age and length data reasonably well, but underestimated observed lengths of mature females and overestimated mature males slightly. There are small numbers of these fish at the largest length classes so this may improve with the addition of data points (Figure 5).

A comparison of growth rates from this study with those of previous studies indicates a major difference in growth rates estimated from whole otoliths and those estimated from thin sections, as expected (Figure 6). The growth estimates from Bowering and Nedreaas (2001) showed little if any slowing of growth as the fish aged, reaching a L_∞ of 260 cm (male) and 269 cm (female); this pattern of age truncation may also be indicative of the larger, old fish being underaged while the younger fish are not. All of the studies that used thin sections for age determination showed fast growth for ages up to age 9, with slowing thereafter.

Discussion

This is the first true age validation study that has been carried out for Greenland Halibut off Newfoundland and Labrador across all ages. Other ageing studies for Greenland Halibut in this region have corroborated age for the earliest ages; Lear and Pitt (1975) used length frequency patterns (Petersen method) to conclude that there was an annual formation of opaque and translucent zones on the whole otoliths of Greenland Halibut up to the age of 3 years. Bowering and Nedreaas (2001) used the same method to provide length at age estimates up to the age of 4 years with an average growth of 6-8 cm per year. There were some differences in length at age even between these two studies. For example, Lear and Pitt (1975) determined that an average three year old was 16 cm in length, while Bowering and Nedreaas (2001) concluded that three year old fish averaged 21 cm. This is likely due to the presumed occurrence of a protracted spawning season, and therefore large variation in size for the youngest year classes (Bowering and Nedreaas 2001). It also may be due to confusion on selection of the first annulus as the settling mark (mark on the otolith that forms during metamorphosis) appears strongly in this species.

Bomb radiocarbon analyses presented here were successful in validating the thin section method for ageing Greenland Halibut otoliths in NAFO Div. 2+3K. Greenland Halibut can be aged accurately, on average, up to 27 years using thin sectioned otoliths. A comparison of the ^{14}C in the otolith cores of adults compared to the reference collection indicates that ages are the true ages because biased ages would be phase-shifted in relation to the reference chronology. As reported throughout the literature, bomb radiocarbon assays derived from nuclear testing in the 1950s and 1960s provide one of the best validation techniques for old fish (Kalish 1993; Campana 1999; Campana *et al.* 2008). This method has been used to validate age in other flatfish species such as Atlantic Halibut (Armsworthy and Campana 2010), Petrale Sole (Haltuch *et al.* 2013), Pacific Halibut (Piner and Wischniowski, 2004) and Yellowtail Flounder (Dwyer *et al*. 2003).

Whole otoliths have provided underestimates of age in many studies and are not accurate for most fish at the oldest ages (Campana 2001), with few exceptions (American Plaice, *Hippoglossoides platessoides*; Morin *et al.* 2013). In this study, whole otoliths gave the same age as thin sections up to 9 years of age (60 cm) after which estimates from whole otoliths underestimated the true age of Greenland Halibut for the oldest fish, up to 60% in some cases (up to 18 years). This bias increases with fish size. Information from prior workshops and exchanges for age interpretation of Greenland Halibut indicated that the divergence in age between whole and sectioned otoliths begins around age 5 (ICES 2011). This difference in results may be due to the fact a very slightly different method was used to section the whole otoliths in prior workshops and in this study. There may also be an improved ability to age using thin sections over time.

As with other species, the new otolith material in whole otoliths is laid down over the old growth (Chilton and Beamish 1982); this lack of relationship between fish length and age has been called uncoupling (Wright *et al*. 1990). The Greenland Halibut otolith, which is quite thin compared to other flatfish species, with its unusual finger-like protrusions and thickened "dome" region on the left otolith, is especially difficult to age (for both whole and thin sectioned otoliths). This "peri-sulcular" thickening of the left otolith is unique to Greenland halibut (J. Casselman, Pers. Comm.) and may be the best area along which to count annuli in cross-section.

Generally there was a good fit of the amount of ^{14}C in the cores of the Greenland Halibut otoliths to the reference chronology. However, there were three thin-sectioned otoliths that did not fit well and resulted in underageing. Kalish *et al.* (1997) indicated that differences seen in the timing and magnitude of peak values might be due to the penetration and dilution of radiocarbon in deeper water, as well as various water mixing characteristics. The habitat of Greenland Halibut is on the Continental shelf and deep slopes > 1500 m (although generally found between 300-500 m) off the Grand Bank and into the Flemish Pass. As such the habitat is affected by major water currents, such as the Labrador Current and Gulf streams. It is thought that large mature females prefer deeper waters (Morgan and Bowering 1997) and these three otoliths might have been from correctly aged, but for environmental reasons did not fit the chronology. However, there was no correlation with depth and the amount of ^{14}C in the three otolith cores that did not fit the reference curve, indicating these fish had to be even older than the age estimated from the thin section. Thin-sections can sometimes fail to provide an accurate age for other species, such as sablefish (*Anaoploma fimbria*) (Beamish and McFarlane 2000), and Yellowtail Flounder (*Limanda ferruginea*) (Dwyer *et al.* 2003) but in most cases this has just been by a few years at most. Treble *et al*. (2008) reported this for Arctic Greenland halibut on a larger scale. It seems that annuli are much clearer and easier to interpret from otoliths in populations further south, although growth rates appear to be similar. This may indicate that thin sections are appropriate for ageing Arctic Greenland halibut as well, but may need enhancement of the annuli. Indeed, even whole otoliths from northern stocks are more difficult to age than whole otoliths from more southern stocks (M. Treble, Pers. Comm.).

Maximum age from ^{14}C indicates that both the Arctic and Northwest Atlantic stocks have longevity of at least 30 years and since the bomb radiocarbon sample here included fish lengths close to the known maximum fish size, it seems likely that this approximates the actual longevity of the species. Greenland Halibut is considered a moderately lived flatfish; other flatfish are considered long lived, such as Atlantic Halibut (40-50 years; Armsworthy and Campana 2010), Pacific Halibut (55 years; Piner and Wischniowski 2004), Dover Sole (60 years; Munk 2001) and some less long lived, but with longevities greater than age estimates from traditional whole otoliths would have indicated (Yellowtail Flounder 25 years; Dwyer *et al.* 2003) and Starry Flounder (*Platichthys stellatus*, 24 years; Campana 1984).

Growth rates estimated from thin sections are slower than those estimated from whole otoliths, which indicate linear growth (Bowering 1978). Despite difficulties associated with ageing the Arctic stock using thin sections, it would seem that both the Arctic and more southern stocks of Greenland Halibut have similar growth rates. Treble *et al.* (2008) concluded that growth estimated from bomb radiocarbon ages and oxytetracycline (OTC)-marked tagging returns was about 3.5 cm/year for 50 cm adult Greenland Halibut and 1.8 cm/year for 70 cm fish. From our study, the growth rate for 50-70 cm fish was about 2.4 cm/year, and for >70 cm fish was 1.4 cm/year. Recent tagging results indicate that some degree of mixing between stocks occurs; at least 10 fish (out of 240 returns; approximately 4.2%) tagged in either the Arctic or off Greenland and Norway have been recaptured off Labrador and Newfoundland (M. Treble, Pers. Comm.). Prior tagging from this experiment indicated slow growth for these fish, demonstrated (from OTC/SrCl marking) that new growth on the whole otolith masks old growth, and revealed that the expected number of annuli based on time at liberty were not visible in this structure. Even OTC marking examined from the thin section indicated that otolith growth was uneven and that annuli could not always be seen (Treble *et al.* 2008).

As with other marine flatfish (Beverton 1964; Pitt 1974; Dwyer *et al*. 2002), Greenland Halibut exhibit pronounced sexual dimorphism with respect to size, with males reaching a lower maximum length (L_∞) than females. The difference between sexes is thought to be due to the manner in which males and females channel surplus energy into growth and reproduction. Growth rate is similar between males and females up to about age 10 years but females live much longer than males. Greenland Halibut appear to mature considerably later, and at larger sizes, in the northern area of this region (Div. 2+3K) than in other stocks (Bowering and Nedreaas 2001). This study would indicate that this late maturation would occur even later, based on ages estimated from thin sectioned otoliths. Males have an L_{50} of 60 cm, corresponding to an A_{50} of 10 years, which is not affected by new ageing from thin sections. Females have an L_{50} of 70-75 cm, which corresponds to an A_{50} of 14-15 years, thus requiring further exploration.

In the current stock assessment, the proportion of old fish in the population is very small; in the RV survey this number is less than 2% and for the commercial catch this value depends on gear and fleet but ranges from 1-11% (Healey 2011). Thus it does not appear that the ageing problem that occurs with older fish is critical to the assessment model, but will have to be examined more closely. It cannot be assumed that incorrect ageing of the oldest fish using whole otoliths would not have any impact, as maximum age affects M and this study would suggest that the value for M used in the assessment (0.2) may need to be re-evaluated. Gregg *et al*. (2006) estimated an M of 0.15 for Greenland halibut using thin sections stained with aniline blue. Cooper *et al*. (2007) independently concluded that M was about 0.12 for the same stock of Greenland halibut using the relationship with gonadosomatic index (GSI). Using $M \approx t_{max}/4.22$ (maximum age in years) as a rule of thumb (Hewitt and Hoenig 2005), and assuming a maximum age of 33 years, natural mortality is 0.13, which is comparable to 0.15 from Gregg *et al.* (2006) and 0.12 from Treble *et al.* (2008).

This study concluded that Greenland halibut in SA 2+3KLMNO are slower growing and longer lived than was previously believed based on ages from whole otoliths. They reach a maximum age of approximately 35 years, and growth slows after age 9 (based on newly validated ages) in both males and females, with females reaching a larger maximum size than males. This paper focuses on improved age estimation for Greenland halibut, a commercially and ecologically important fish species in the Northwest Atlantic. Hence, knowledge of age and growth is vital in assessing this resource and determining biological parameters for the region. Thin sectioning of otoliths is recommended for ageing all or a subsample of fish older than 9 years. Therefore the age-disaggregated results for fish older than 9 years old are likely to be biased, and multiple cohorts may be within the assigned ages. Examination of the age distribution from the last assessment of this stock (Healey 2011), however, indicated that the overall effect of revising these ages on the assessment may be limited. In order to examine how to treat the fish aged 10+ that have already been aged using whole otoliths, this will have to be studied further, but could involve such things as: subsampling the females (as most males are unaffected) > 60 cm and re-ageing or determining whether a plus group of 10+ would be suitable in the assessment. Conversion factors have not been the answer to most ageing problems (herring (*Clupea harengus*, Melvin and Campana 2010), Haddock (Campana 1995b), Yellowtail Flounder (Koen-Alonso *et al*. 2006) because of somatic and otolith growth uncoupling. During the 2006 Greenland Halibut assessment (Healey and Mahé 2006)), sensitivity analyses indicated that model results were robust for differing choices of the plus-group age (down to as low as ages 11+), but future work should focus on how to incorporate this new knowledge into the assessment and/or any review of the management strategy that currently exists for this stock. Results will be used to make recommendations to the Greenland halibut NAFO SA 2+ 3KLMNO assessment, and possibly other stocks of Greenland halibut assessed at NAFO.

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Table 1. Means and confidence intervals of length at age for male and female Greenland Halibut (*Reinhardtius hippoglossoides*) from thin sectioned otoliths.

Age	Male			Female		
	Mean Length (cm)	CI	*n*	Mean Length (cm)	CI	*n*
0	9	-	1	9.2	0.7	5
1		-	0	13.5	0.6	4
2	16.4	1.9	10	17.1	1.7	10
3	22.9	2.5	14	22.5	2.7	11
4	28.6	2.5	9	27.4	1.6	18
5	35.4	2.3	17	34.7	4	11
6	40	3.3	13	42.2	3.4	14
7	45.2	4.3	10	48.4	1.7	8
8	52.6	5.7	8	54	6.1	6
9	58.1	4.5	8	64.5	4.1	6
10	59.3	6.5	4	60.8	5.4	5
11	60		1	62	-	1
12				71	8.5	6
13	50		1	74.2	10.4	6
14	55		1	86.2	6.7	6
15				86.4	10.4	7
16				81.6	6.8	7
17	68	3.9	2	77	5.5	6
18				78	6.9	6
19				78	10.8	3
20				-	-	-
21				92	10.1	5
22				89	10.3	7
23				85	-	2
24				85	-	1
25				-	-	-
26				104	2	2
27				84.5	32.3	2
28				-	-	-
29				-	-	-
30				88	-	1
31				-	-	-
32				-	-	-
33				109	-	1

Table 2. Results of ^{14}C assays for young (<21 cm) Greenland Halibut (*Reinhardtius hippoglossoides*) to determine fit into Greenland Halibut reference chronology.

NAFO	Year Sampled	Length (cm)	Sex	Whole Age	Section Age	$\Delta^{14}C$
Div. 2G	1966	14	F	1	2	-32.15
Div. 2G	1966	17	M	2	3	-20.15
Div. 3K	1970	21	F	3	3	-10.1
Div. 3K	1970	16	F	2	3	-23.56
Div. 2J	1980	16	F	2	2	7.06
Div. 2J	1980	21	F	3	3	30.01

Table 3. Results of ^{14}C assays for larger Greenland halibut (*Reinhardtius hippoglossoides*) otoliths selected for validation from fish between 57-108 cm. Shaded not used in analysis.

NAFO	Year sampled	Length (cm)	Sex	Whole Age	Section Age	Year of Formation	$\Delta^{14}C$
Div. 2J	1976	84	F	12	12	1965.5	-66.8
Div. 3K	1980	72	F	8	9	1973.5	-9.4
Div. 3K	1990	70	F	11	20	1980.5	5.55
Div. 2J	1990	70	F	11	18	1980.5	-5.65
Div. 2J	1976	71	F	11	18	1966.5	-38.5
Div. 2J	1983	108	F	16	15	1968.5	-49.2
Div. 3K	1990	70	F	10	18	1981.5	-48.52
Div. 2J	1990	79	F	13	21	1978.5	-4.53
Div. 2J	1990	69	F	11	19	1980.5	1.56
Div. 3K	1990	70	F	11	16	1980.5	4.18
Div. 2H	1984	82	F	13	16	1972.5	-22.1
Div. 2J	1990	68	F	11	27	1980.5	-14.77
Div. 2H	1984	75	F	12	22	1973.5	-6.89
Div. 2J	1990	79	F	13	22	1978.5	-107.7
Div. 3L	1971	57	F	9	12	1960.5	-60.0
Div. 3L	1971	62	F	9	13	1959.5	-52.9
Div 2J	1976	59	F	8	13	1964.5	16.8
Div 2J	1976	57	M	8	9	1968.5	11.8
Div 2H	1979	64	F	10	11	1969.5	-5.8
Div 2H	1979	64	F	9	11	1969.5	14.2
Div. 3K	1977	61	F	10	10	1968.5	18.0
Div. 3K	1979	69	F	9	12	1968.5	5.4
Div. 3K	1977	62	F	10	12	1967.0	6.7
Div. 2J	1976	57	M	9	12	1965.5	10.5

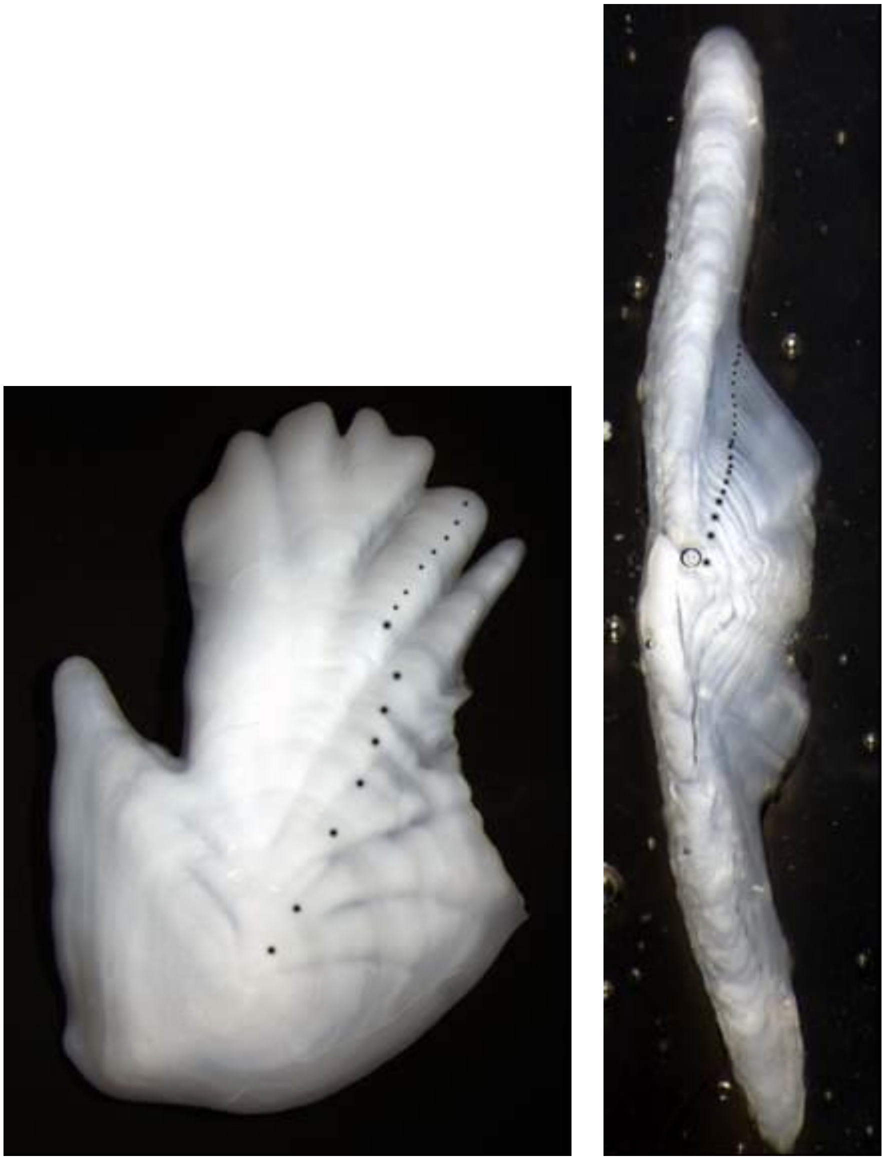

Figure 1. Comparison of whole otolith (8X) from an 83 cm female Greenland Halibut and the resulting thin section (16 X). Whole otolith aged as 15 years old; section estimated age at 22 years.

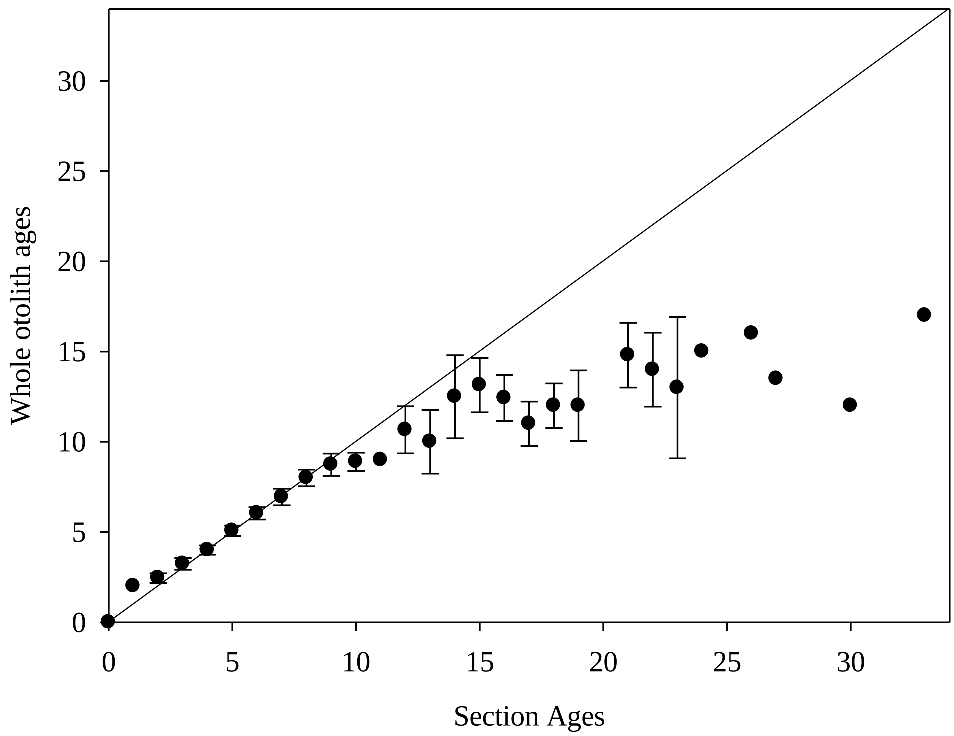

Figure 2. Age bias plot comparing ages from whole otoliths and thin sections from Greenland Halibut collected from NAFO SA 2+3K. Each error bar represents the 95% confidence interval about the mean age assigned for one otolith for all fish assigned a given age for the second otolith. The 1:1 equivalence (solid line) is also indicated.

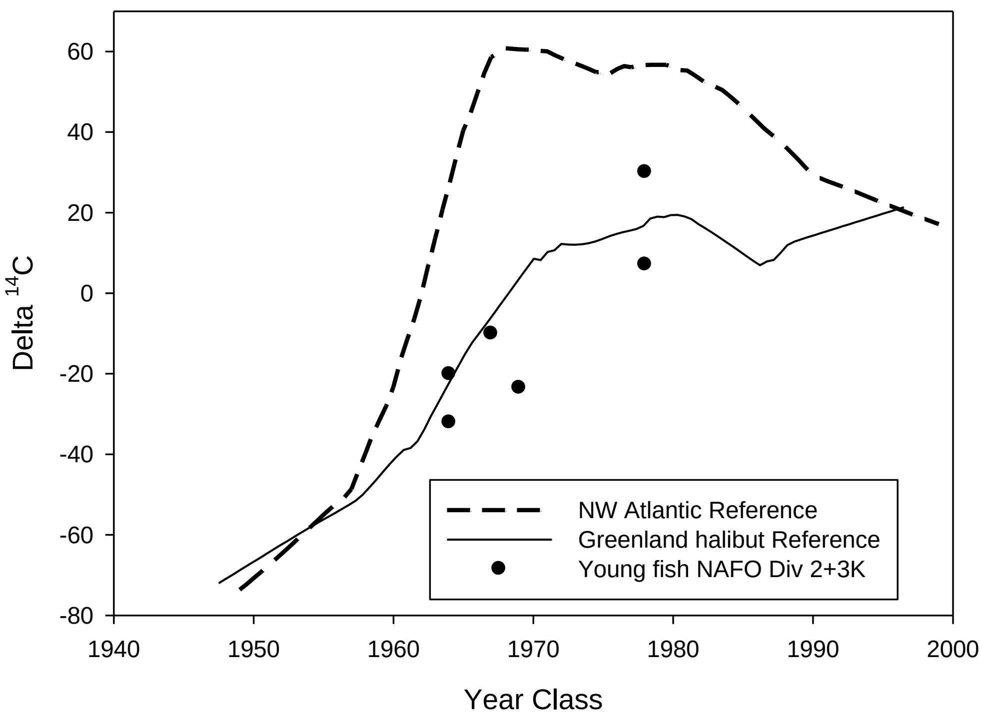

Figure 3. ^{14}C reference chronology characteristic for the Northwest Atlantic haddock-redfish (Campana *et al.* 1997) and Greenland Halibut (Treble *et al.*, 2008) along with the 6 young fish assayed to determine the reference chronology which best fit the pattern of increase of Δ^{14}C in the deep water for NAFO Div. 2+3K.

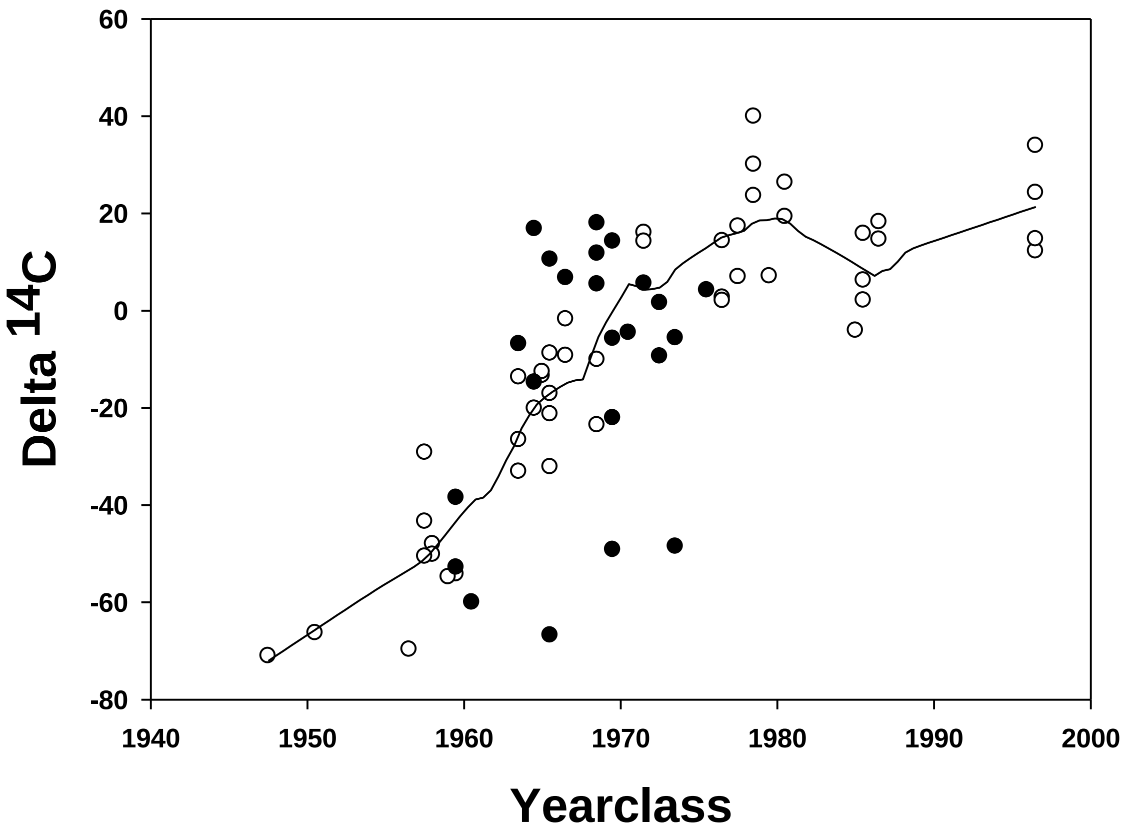

Figure 4. Greenland Halibut age estimates from thin-sectioned otoliths (solid circles) estimated from 23 otolith cores from older Greenland halibut (57-108 cm) and $\Delta\ ^{14}C$ reference chronology for Greenland Halibut (open circles, including young fish added in this study) fitted with a Lowess smoother (solid line;from Treble *et al.* (2008)).

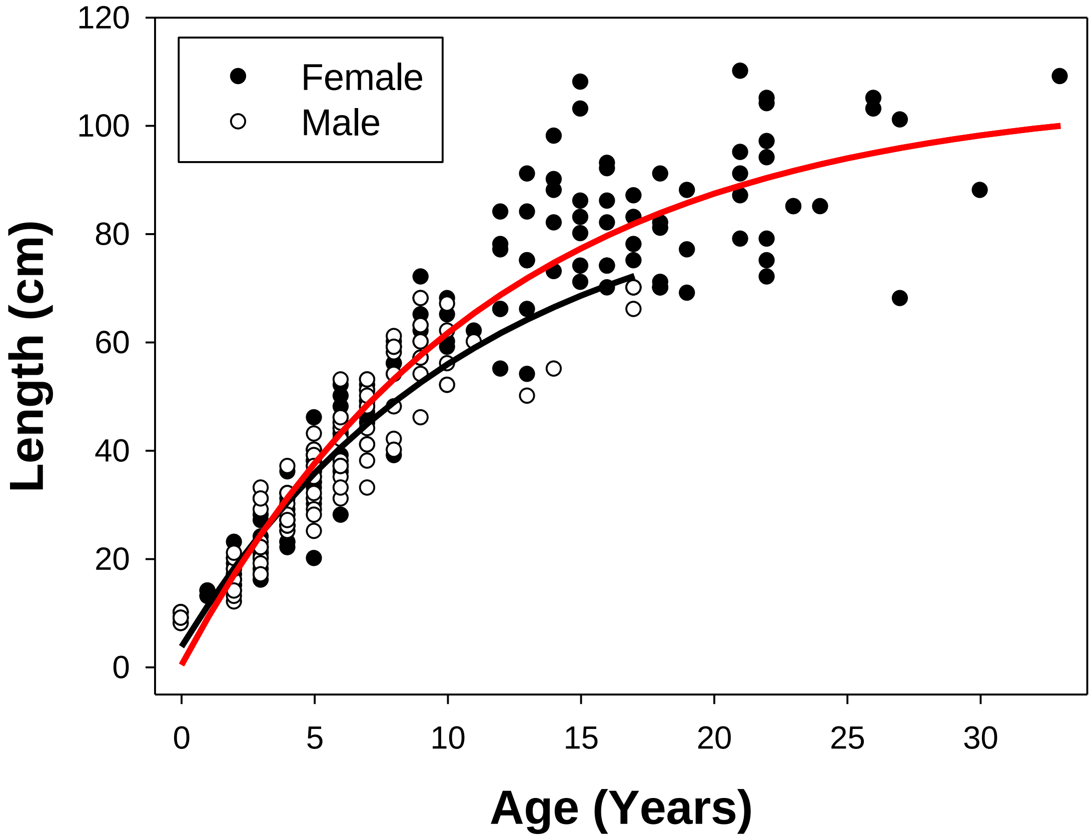

Figure 5. Length at age for male (open circles; L_{∞} = 90; K = 0.09; t_0=-0.05) and female (solid circles; L_{∞} = 109; K = 0.09; t_0=-0.05) Greenland Halibut. The black line is the fitted von Bertalanffy growth curves for the data.

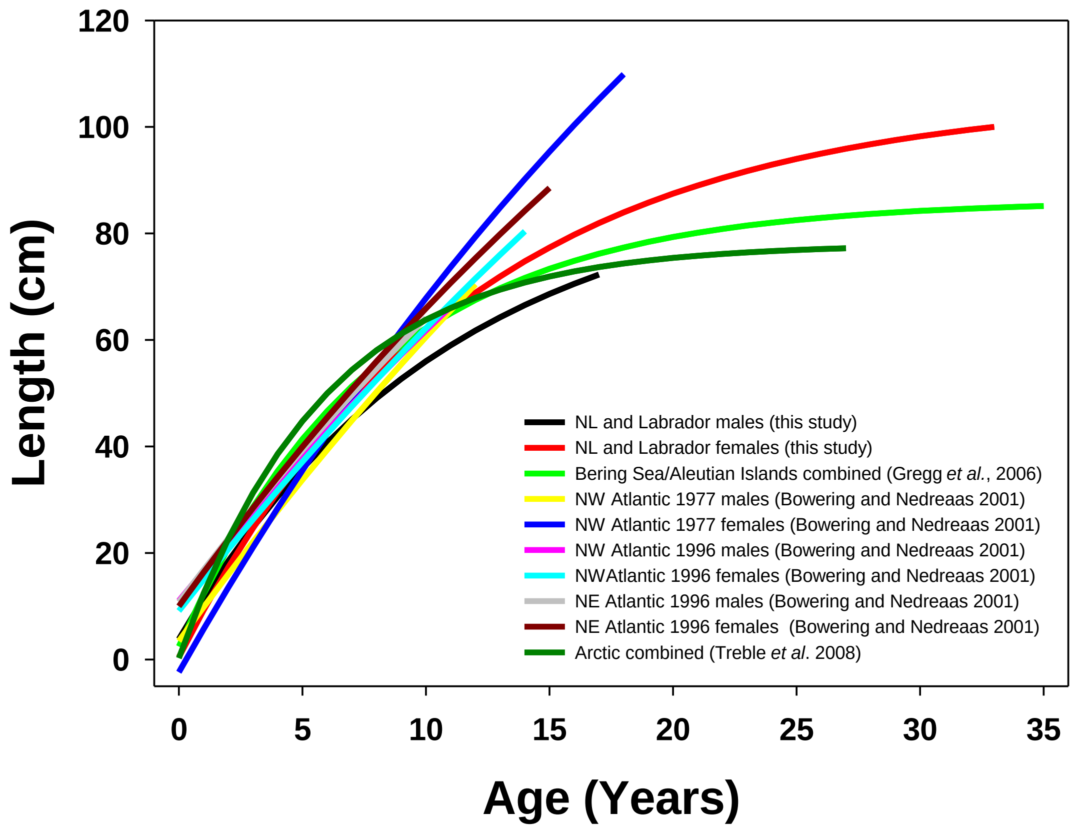

Figure 6. Comparison of von Bertalanffy growth curves for Greenland Halibut from this study (red line: females, black line: males) and published growth information.