The age and growth of New Zealand protected corals at high risk:
Bathypathes patula

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Prepared by:

Peter Marriott, Di Tracey, Helen Bostock (NIWA), Nicholas Hitt (NIWA/Victoria University of Wellington (VUW), Stewart Fallon (Australian National University, (ANU), Canberra, Australia)

For any information regarding this report please contact:

Di Tracey
Scientist
Deepwater
+64-4-386 866
di.tracey@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Private Bag 14901
Kilbirnie
Wellington 6241

Phone +64 4 386 0300

Quality Assurance Statement		
Peter Horn	Reviewed by:	
P Allen	Formatting checked by:	
Dr Rosemary Hurst	Approved for release by:	

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Contents

Tables

Figures

Executive summary

Ten individual colonies of the Antipatharian black coral species *Bathypathes patula* were selected from the NIWA Invertebrate Collection (NIC) for the purposes of this ageing study. Corals were selected based on their size, completeness of the colony (whole colony from base to tip), and the regional water mass within which they grew. Corals from the Chatham Rise and the Bay of Plenty were selected as the water masses for these two regions are reasonably well understood, and this work will support other comparable ageing work on deep-sea corals in these regions.

Thin section preparations of the main-stem of the ten specimens were observed with compound microscopes. Two interpretation protocols were defined to describe the zone structure observed, both coarse and fine zones, and counts were made of these structures. Four of the specimens were also sampled for radiocarbon assay. The radiocarbon isotope (^{14}C) age data results were used to independently verify if either of the developed zone counting protocols reflected annual periodicity. Neither method was verified, indicating the developed zone counting protocols could not be used to generate reliable age estimates for *B. patula*. The identification of one of the selected coral colonies was revised during the study to *Bathypathes cf. conferta.* This specimen was aged using zone counts but ^{14}C dates were lost during processing.

Twenty radiocarbon results were used to derive the age and growth rates estimates presented here. The radiocarbon results from this work show *B. patula* to be a long-lived species, attaining ages in excess of 385 years, with linear growth rates of 5.2–9.6 mm yr^{-1}, and radial growth rates ranging from 11.1–35.7 μm yr^{-1}. The delicate nature of these organisms along with their longevity and slow growth rates means a low resilience and low recoverability from anthropogenic activities such as fishing and mining.

1   Background

Deep-sea corals are a highly diverse group of marine organisms, several of which are characterised by slow growth and extreme longevity. Due to their fragile forms, skeletal composition, and location, they are vulnerable to various anthropogenic threats with some groups expected to have little to no ability to recover. Impacts include fishing such as bottom trawling and bottom long-lining, mineral exploration and deep-sea mining (Clark *et al.* 2015). Environmental impacts predicted from climate change, such as ocean warming, is also expected to threaten the health of deep-sea corals (e.g., see Anthony & Marshall, 2009). To better inform future risk assessments and marine resource management, an understanding of deep-sea coral age and growth is key to determining coral regeneration times and recoverability following anthropogenic disturbances or other natural damage.

In year one of this project, Tracey *et al.* (2018) included a literature review describing the methods to age protected coral species. The advantages and disadvantages of each method were discussed. The main methods that have been successfully applied to measure age and growth of deep-sea corals are (1) direct observation, such as in situ measurements or in-aquaria experiments of linear growth or surface extensions; polyp addition rate; estimation of calcification rates (e.g., using the buoyant weight technique), (2) enumeration of skeletal growth bands (sclerochronology), and (3) radiometric analyses.

Recommended next steps for coral ageing research in the New Zealand region and details of an appropriate method to apply to obtain accurate age and growth data for the Antipatharian black coral were also made in Year 1. Tracey *et al.* (2018) proposed that two ageing methods be applied to this group; counts of skeletal growth bands and the radiometric method of radiocarbon dating (^{14}C). The application of these methods would enable comparisons with other ongoing New Zealand coral ageing studies and with previous work that has been undertaken both in New Zealand and globally. Sclerochronology can provide estimates of age from visible growth rings in the skeletal structure but this approach requires validation of the ring formation periodicity (Andrews *et al.* 2002). For example, the micro-milling of skeletal material and preparation of basal and tip thin sections to obtain count zones was carried out at NIWA using bamboo octocoral species (*Keratoisis* sp. and *Lepidisis* sp.) and the lead 210 (^{210}Pb) radiometric method was applied to these bamboo coral samples to validate the assumed annual zone counts (Tracey *et al.* 2007). In this instance the zone counts were higher than ages estimated from the radiometric method and it was hypothesised that zones observed by light microscope have a bi-annual periodicity and that SEM-observed zones at the nodal juncture may represent an environmental event, such as lunar periodicity.

A previously determined 'High Risk' protected coral species (Clark *et al*. 2014), the black coral genus *Bathypathes* (Family Schizopathidae), was recommended for study (Tracey *et al.* 2018). The analytical methodology proposed included radiocarbon (^{14}C) dating of base and tip regions of colonies compared with growth ring counts from about 10 basal sections for selected specimens of *Bathypathes.* The micro-milling of material, and the interpretation of results was also to be carried out in Year 2 of the project.

In late November 2018, visiting PhD student and specialist in black coral taxonomy (Jeremy Horowitz James Cook University (JCU)) reviewed the identifications of several samples in the NIC. During this process one of the black coral colonies selected for this ageing research and assumed to be *Bathypathes patula*, was given a revised identification. Black coral NIWA24190 has now been identified as being *Bathypathes cf. conferta*. The sample has been referred to as *Bathypathes cf. conferta*

throughout the report, the most likely correct identification. Further taxonomic review of this specimen is ongoing.

1.1 Zone counts on skeletal sections

Enumeration of growth bands is ideal for deep-sea corals that have a high contrast between growth bands while noting that a validation method be used to help interpret the zone counts (Andrews *et al.* 2002). The method to obtain visible growth rings counts in the skeletal structure has proved successful for both bamboo corals and black corals (Roark *et al.* 2005, Love *et al.* 2007, Rogers *et al.* 2007, Tracey *et al.* 2007, Noe *et al.* 2008). Most studies that have successfully applied counting of growth bands to determine age and growth rate data are for gorgonian octocorals including 400 year old bamboo corals *Keratoisis*, 100 year old seafan *Primnoa* spp., and 60 year old bamboo coral *Lepidisis* sp. (Mortensen & Buhl-Mortensen 2005, Sherwood *et al.* 2005, Thresher *et al.* 2004, 2007, Tracey *et al.* 2007, Sherwood & Edinger 2009). Black corals have also been successfully aged using growth zone or counts, with ages of 150 years old to 480 years for *Antipathes dendrochristos* and *Leiopathes glaberrima*, respectively (Love *et al.* 2007, Williams *et al.* 2007). In a study of the black coral *Stauropathes arctica*, zone counts of 55–58 were obtained (Sherwood & Edinger 2009), with the authors noting that radiocarbon dating constrained these ages to 55 and 82 years. Growth rates of black corals via growth band enumeration reveal low radial growth from 0.008–0.140 µm y^{-1} (Love *et al.* 2007, Prouty *et al.* 2011).

There are potential limitations to the enumeration of growth bands method (see summary in Tracey *et al.* 2018). The gorgonian bubblegum corals (e.g., *Paragorgia* sp.) and red precious corals (e.g., *Corallium* sp.) have not been aged successfully using growth band counts due to inherently complex or poorly defined banding patterns (Griffin & Druffel 1989, Andrews *et al.* 2005).

1.2 Radiocarbon dating to validate zone counts

The most common radiometric method used in deep-sea corals is dating with the radiocarbon (^{14}C) isotope (Tracey *et al.* 2018). This method relies on the fact that a very small amount of natural carbon in the atmosphere is radioactive in the form of ^{14}C and is incorporated into the coral skeleton when it forms its calcium carbonate or protein and chitin (Adkins *et al.* 2002, Tracey *et al.* 2003, Consalvey *et al.* 2006). Because the half-life of radiocarbon is known to be 5,730 years, this method, albeit expensive, can be used to reliably age specimens to 50,000 years ago; beyond that, the activity of ^{14}C becomes too low to detect (Coleman 1991). During the 1950s–60s, there was rapid increase of atmospheric ^{14}C resulting from the testing of nuclear devices; this "bomb carbon" can also be used as a tool to calibrate ages, providing a reference point for more recent samples (Coleman 1991, Tracey *et al.* 2003, Roark *et al.* 2009, Sherwood & Edinger, 2009). Radiocarbon dating has been successfully used on a number of coral species, including stony corals, black corals and gorgonian octocorals (Druffel *et al.* 1990, Roark *et al.* 2006, Carriero-Silva *et al.* 2013, Prouty *et al.* 2016, Neil *et al.* in review). However, there are also limitations with this method and these were outlined in Tracey *et al.* (2018).

This report describes the methodology to determine the age and growth characteristics of a key high-risk New Zealand deep-sea coral species, the black coral *B. patula.* Zone count data are also provided for *a B. cf. conferta* colony initially assumed to be *B. patula.* Sample selection, micro-milling of material and sectioning methods, and the interpretation of age result data are presented. Age and growth characteristics of the black coral *B. patula* are provided.

This document meets the reporting requirements for Year Two of the Conservation Services Programme (CSP), Department of Conservation (DOC) Project POP2017-07 Objective to "Develop a

methodology to determine the age and growth characteristics of key high-risk New Zealand deep-sea (cold-water) coral species".

2   Methods

The selection of a priority species to age was based on the risk assessment priority list (Clark *et al.* 2014) and the literature review (Tracey *et al.* 2018), coupled with availability of samples (location and total numbers), and complementary black coral research under the paleoclimate Marsden project, *Corals, currents, and phytoplankton: Reconstructing 3000 years of circulation and marine productivity in the world's largest ocean gyre,* NIW1602 (Hitt *et al.* 2018, in prep.).

Two methods to age the coral colonies were applied:

1.   preparation of 10 thin basal sections to obtain assumed annual zone counts and

2.   radiocarbon (^{14}C) dating.

The aim was to age two colonies and obtain three ^{14}C dates per colony from the base and growing tip region to obtain radial and linear growth estimates. Analytical methods followed that of Tracey *et al.* (2007) and Sherwood & Edinger (2009).

2.1   Sample selection

Coral sample selection focused on corals collected from the Chatham Rise and Bay of Plenty regions. Corals from the Chatham Rise were chosen as there are modern ^{14}C reservoir age data from this area. Knowing the local ^{14}C reservoir age enables a more precise radiocarbon age estimate from corals. High surface productivity also occurs in this region providing a significant food source and hence carbon supply for these corals. Samples selected from the Bay of Plenty region were chosen to compare data from a different region to assess the variability in the growth rates between areas with different oceanography and food availability. Both regions were also included in the Marsden Project (Hitt *et al.* 2018, in prep.), and so there was value in comparing age data between species as well as by region. Also, bottom trawling occurs in both areas and impacts from fishing is also a key consideration for risk assessments and estimating recoverability (Clark *et al.* 2014).

The samples were selected from existing specimens collected by Fisheries New Zealand (FNZ), Ministry for Primary Industries (MPI) Observers and NIWA researchers and are held in the NIWA Invertebrate Collection (NIC). A plot of the distribution data for *B. patula* helped the decision on colony site selection and sample numbers (Figure 2-1). Two specimens from the Bay of Plenty (NIWA24190 and NIWA85940) were selected for radiocarbon dating and thin sections for zone counts. The balance of the specimens was from the Chatham Rise. A taxonomic review of *B. cf. conferta* is ongoing, and one of the selected samples was subsequently identified as this species (Figure 2-2). The distribution map (Figure 2-1) may include additional examples of *B. cf. conferta*.

2.2   Preparation of material

Once suitable samples had been identified, small (less than 10mm sections) were excised from the growing tips and basal portion of the corals' main stem. As many of the samples had been broken during the collection process, additional sections were taken along the main stem so that reliable estimates of linear growth rate could be generated (see Figure 2-3). The samples from the growing tips were then split into two fragments, one for radiocarbon dating the other for thin section preparation.

The main stem sections were first micro-milled for radiocarbon analysis and then the remainder of the section was used for thin section preparation to obtain zone counts.
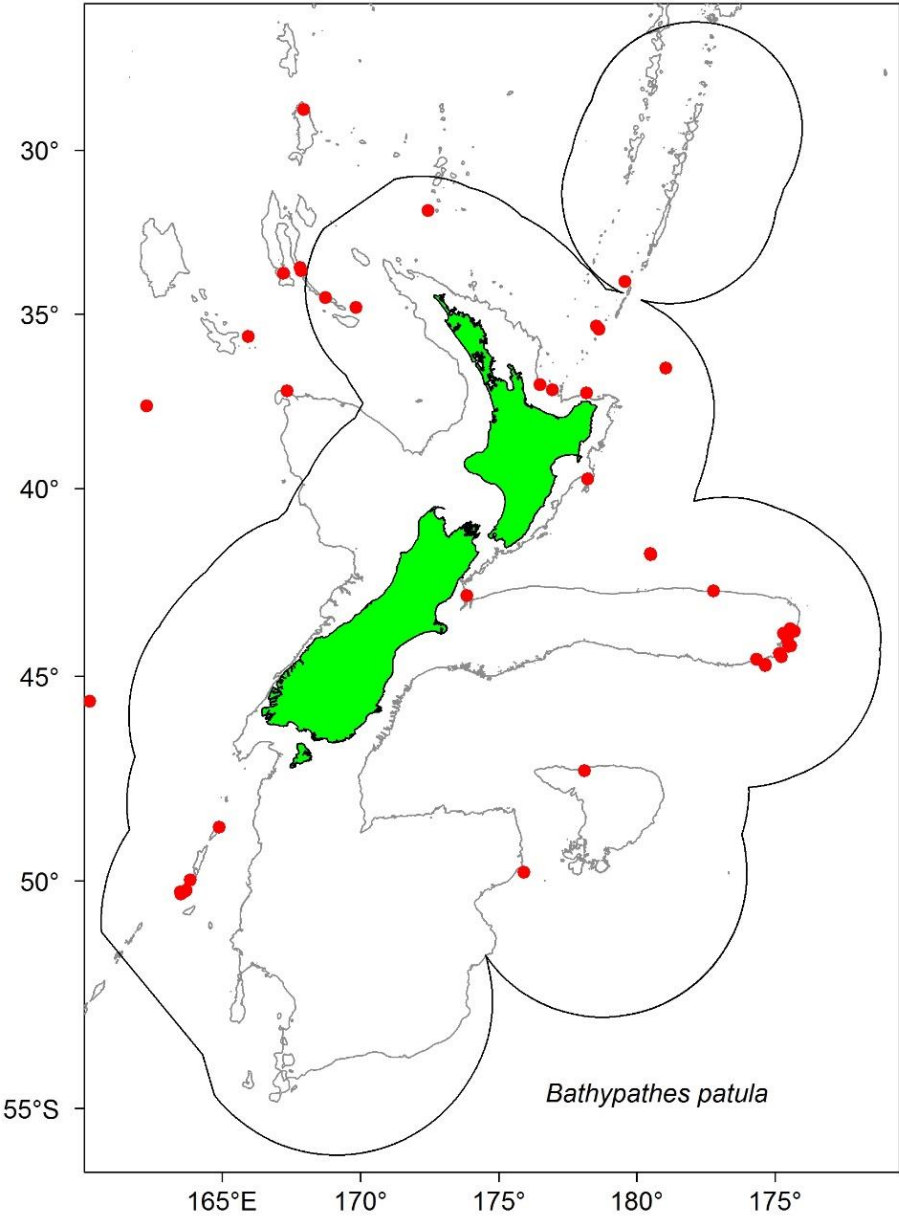
Figure 2-1:   Locations where *Bathypathes patula* has been sampled in the New Zealand region.

Figure 2-2: *Bathypathes cf. conferta.* **NIWA24190.** Specimen showing where samples were extracted for analysis. A is the growing tip, B the basal section. Specimen from Bay of Plenty, New Zealand. Scale bar is a 35cm ruler.

Figure 2-3: *Bathypathes patula* **NIWA85940.** Specimen showing where samples were extracted for analysis. A is the growing tip, C the basal section and B is an intermediate sample sites as the specimen was broken on collection and unknown lengths of the main branch stem may be missing above this site. Specimen from Bay of Plenty, New Zealand. Scale bar is a 35cm ruler.

Ageing deep-sea corals black coral *Bathypathes patula*

Figure 2-4: *Bathypathes patula* **NIWA49468.** Specimen showing where samples were extracted for analysis. A is the growing tip, D the basal section and B and C are intermediate sample sites as the specimen was broken on collection and an unknown length of the main branch stem may be missing from between these two sites. Specimen from Chatham Rise, New Zealand. Scale bar is a 35cm ruler.

Figure 2-5: *Bathypathes patula* **NIWA47911.** Specimen showing where samples were extracted for analysis. A is the growing tip, F the basal section and B to E are intermediate sample sites taken to look for the radiocarbon bomb signal. Specimen from Chatham Rise, New Zealand. Scale bar is a 35cm ruler.

2.3   Micro-milling of material

From previous work it had been noted that black coral sections are prone to drawing resin up through their porous matrix via capillary action and so the sections in this study could not be bonded with resin to a baseplate for milling, as is our usual practice. Instead a chuck was manufactured to hold the section during the milling process, thus eliminating the risk of resin contaminating the radiocarbon samples.

Powdered radiocarbon samples were extracted from the edge and core of sections using a New Wave^{TM} micromill with a 0.5 mm Brassler H2.11.006 milling burr. The edge samples comprised material from the outer 250 microns of the section, the core samples were obtained from material within a 750 micron radius of the primordium. We attempted to extract at least 1.5 mg of material per sample. The samples were then weighed and sent to Stewart Fallon at the Australian National University (ANU) Radiocarbon Laboratory for radiocarbon analysis.

2.4   Thin sectioning method

As stated in the literature review by Tracey *et al*. (2018), growth bands in some deep-sea coral skeletons are formed repeatedly over discrete time periods and can be used to determine colony age and growth rates. This method involves counting bands or zones formed over a given distance of skeleton and is comparable to counting fish otolith zones or the rings of trees, the latter referred to as dendrochronology.

Coral stem sections were embedded in clear two-part epoxy resin and sectioned with a diamond-wafering saw. The sections were polished on one side and mounted polished side down on a glass microscopy slide, then ground and polished until they were an optimum thickness for viewing the growth zone structure using transmitted light. The optimum thickness for sections of this species was about 250–300 microns and follows standard procedure for thin section preparation see (Andrews *et al.* 2002, Mortensen & Buhl-Mortensen 2005, Tracey *et al.* 2007). Counting the periodic growth bands or increments, assumed to be formed annually, took place after thin section preparation.

2.5   Radiocarbon dating method

Analyses were carried out at the Radiocarbon Laboratory, Australian National University (ANU), Canberra. This facility was selected to date the samples as we were able to link in with the analyses being carried out at the same time by NIWA/VUW Marsden study on *Leiopathes* black coral age estimates (Hitt *et al.* 2018, in prep.).

Prior to analyses, the samples were cleaned (e.g., acid leached) of black crusts and endolithic activity to remove any younger contaminant ^{14}C which may alter results (Adkins *et al.* 2002, Neil *et al.* in review). Powdered coral samples were treated with <1ml of 0.1M HCL. The acid was then pipetted off and samples were then washed 3 times with milliQ water. The sample was then frozen with dry ice and lyophilized. Approximately 1mg of cleaned coral sample was weighed into a 6mm OD quartz tube, ~60mg CuO and a silver cup was added. The tubes were evacuated to <3e-3 torr and sealed with a torch. Tubes were then baked at 900°C for 6 hours to generate CO_2. The resulting CO_2 was purified and converted to graphite in the presence of hydrogen with powered Fe as a catalyst. The graphite was then measured on the ANU single stage accelerator mass spectrometer (Fallon *et al*. 2010). All data were corrected using on-line AMS δ^{13}C, normalised to Oxalic Acid I and background subtracted using ^{14}C free coal treated in the same manner as the coral samples. Data are presented according to the recommendations of Stuiver & Polach (1977).

3   Results

3.1   Radiocarbon analysis

The milled samples listed in Table 3-1 were sent to ANU for radiocarbon dating. The radiocarbon results from 17 coral samples is shown in the radiocarbon results (Table 3-2). Three samples (Samples 47911-F2; 24190-B1; 85940-B1) failed in the laboratory and there was insufficient material to attempt a duplicate. The radiocarbon results from the remaining corals were calibrated to a calendar age using OxCal4.3 (Bronk Ramsey 2001), the Marine13 curve and a New Zealand local deltaR (radiocarbon reservoir offset) of -18 ± 36 (Reimer & Reimer 2001). The age range distributions for pre-bomb coral samples are shown in Figure 3-1. Coral 85940 is approximately 380±50 years old, coral 49468 is approximately 310 ±70 years old and coral 47911 is approximately 120 ±50 years old (Table 3-2). All of the coral outer edge and tip samples contained radiocarbon values $F^{14}C>1$ (Table 3-2), except for 85940-B2 and 85940-C2, which indicates these corals were alive and incorporating surface water carbon at the time of collection. Corals 85940-B2 and 85940-C2 had outer edge radiocarbon values F14C<1 (Table 3-2) indicating that part of the skeleton was not actively adding material. This has been observed previously where the basal part of the coral colony stops growing however the upper section continues to grow (Komugabe-Dixon *et al.* 2016).

Table 3-1:   **Samples extracted for radiocarbon dating.**   NIWA_ID is the unique collection number from the National Invertebrate Collection (NIC), Date of collection is when the specimen was sampled from the environment, Sample site is the region of the branch stem that was sampled, Sub-site designates where larger diameter sections had radiocarbon samples extracted from the core as well as the marginal edge, Sample Name is a unique identifier for that sample, Net WT (mg) is the sample mass extracted for subsequent radiocarbon analysis. Indicative age is a 'ball park' expected age classification based on the physical presence of the sampled segment; where growing tips were classed present, narrow stem diameters classed young, moderate stem diameters classed mid and wide stem diameters classed old.

Species	NIWA_ID	Date of collection	Sample site	Sub-site	Sample Name	Net WT (mg)	Indicative age
Bathypathes cf. conferta	NIWA24190	10/09/1998	A		24190-A	2.28	present
B. cf. conferta	NIWA24190	10/09/1998	B	core	24190-B1	1.21	young
B. cf. conferta	NIWA24190	10/09/1998	B	edge	24190-B2	1.83	present
B. patula	NIWA85940	27/03/2000	A		85940-A	1.79	present
B. patula	NIWA85940	27/03/2000	B	core	85940-B1	1.98	young
B. patula	NIWA85940	27/03/2000	B	edge	85940-B2	1.41	present
B. patula	NIWA85940	27/03/2000	C	core	85940-C1	1.20	mid
B. patula	NIWA85940	27/03/2000	C	edge	85940-C2	3.11	present
B. patula	NIWA49468	26/02/2009	A		49468-A	1.52	present
B. patula	NIWA49468	26/02/2009	B	core	49468-B1	1.87	mid
B. patula	NIWA49468	26/02/2009	B	edge	49468-B2	4.22	present
B. patula	NIWA49468	26/02/2009	D	core	49468-D1	3.09	old
B. patula	NIWA49468	26/02/2009	D	edge	49468-D2	3.59	present
B. patula	NIWA47911	08/03/2008	A		47911-A	2.35	present
B. patula	NIWA47911	08/03/2008	B		47911-B	3.30	young
B. patula	NIWA47911	08/03/2008	C		47911-C	5.74	young
B. patula	NIWA47911	08/03/2008	D		47911-D	9.21	young
B. patula	NIWA47911	08/03/2008	E		47911-E	10.00	young
B. patula	NIWA47911	08/03/2008	F	core	47911-F1	2.50	old
B. patula	NIWA47911	08/03/2008	F	edge	47911-F2	1.48	present

Table 3-2:   Radiocarbon results.   S-ANU# is the external unique sample number for ANU radiocarbon results, Sample ID is the NIWA unique sample number, Sub-site designates where larger diameter sections had radiocarbon samples extracted from the core as well as the marginal edge, internal ID is an internal ANU sample working ID number, F14C is the samples fraction of modern 14C allowing for ⊠13C fractionation and background corrections, ± is the error estimate for F14C, 14C age is the uncorrected radiocarbon age of the sample, Oxcal calibrated calendar ages and median age are the corrected radiocarbon ages using "Marine 13" (Reimer et al. 2013).

| S-ANU#	Sample ID	Sub-site	internal ID	F^{14}C	± (1 sigma)	^{14}C age	OxCal calibrated calendar age from (calendar years AD)	OxCal calibrated calendar age to (calendar years AD)	median age (calendar years AD)	Error (years 1 sigma)
60016	24190-A		19942	1.0774	0.0030	>MODERN				
lost sample	24190-B1	core	19943							
60017	24190-B2	edge	19944	1.0739	0.0036	>MODERN				
60018	85940-A		19945	1.0726	0.0042	>MODERN				
lost sample	85940-B1	core	19946							
60019	85940-B2	edge	19947	0.9634	0.0036	300	1894	1942	1912	29
60020	85940-C1	core	19948	0.9206	0.0025	664	1567	1671	1615	52
60021	85940-C2	edge	19949	0.9297	0.0039	586	1653	1804	1707	66
60023	49468-A		19950	1.0455	0.0026	>MODERN				
60024	49468-B1	core	19951	0.9486	0.0047	424	1852	1950	1883	58
60025	49468-B2	edge	19952	1.0293	0.0030	>MODERN				
60026	49468-D1	core	19953	0.9281	0.0023	599	1638	1802	1690	67
60027	49468-D2	edge	19954	1.0439	0.0051	>MODERN				
60029	47911-A		19955	1.0431	0.0025	>MODERN				
60030	47911-B		19956	1.0425	0.0025	>MODERN				
60031	47911-C		19957	1.0447	0.0025	>MODERN				
60032	47911-D		19958	1.0416	0.0031	>MODERN				
60033	47911-E		19959	1.0470	0.0025	>MODERN				
60035	47911-F1	core	19960	0.9515	0.0026	400	1868	1950	1896	51
lost sample	47911-F2	edge	19961							

3.2   Thin sections for zone counts

The zone structure for these species is very complex and can be interpreted in many ways. Here we applied two methods – counting both coarse and fine zones.

To generate zone counts, thin section preparations of the main branch sections were viewed under a compound microscope with transmitted light. As an aid to zone interpretation the sections were also viewed using ultra-violet light following the methodology of Sherwood & Edinger (2009). For this work zone counts were made using transmitted bright field lighting. Ultraviolet illumination was a useful aid for defining the observed zone structure.

On the coral skeleton there is an initial coarse coloured banding pattern largely defined by alternating darker and lighter zones (Figure 3-2) when observed under lower power (10 – 20x). On closer examination under higher power (100 – 200x), there is a reasonably regular fine scale banding pattern (Figure 3-3). Zone counts were made using both interpretation protocols (Table 3-3).

For the youngest part of the colony, the tip, or near tip region, counts ranged from 4 to 7 (coarse zone counts) and 10 to 19 (fine zone counts). In the mid region of the main branch counts ranged from 55 to 60 (coarse zone counts) and 370 to 374 (fine zone counts). For the colony base region counts ranged from 37 to 193 (coarse zone counts) and from 78 to 481 (fine zone counts). The complexity of the zonation patterns highlighted the need for validation.
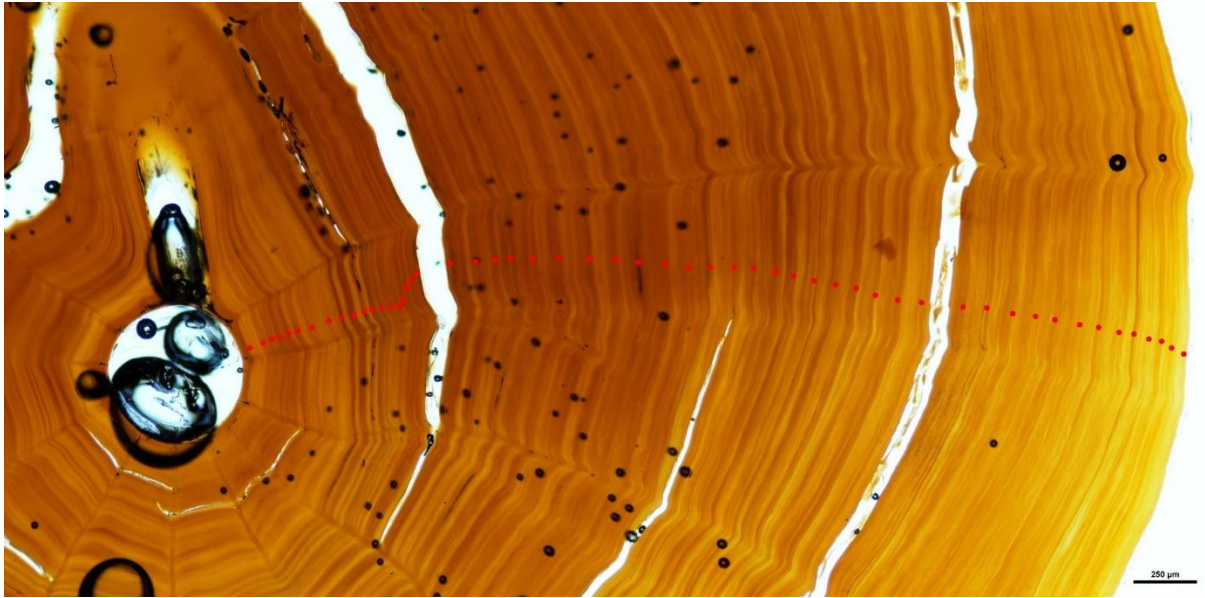
Figure 3-1:   Basal section of coral NIWA47911 showing the coarse coloured banding interpretation of the observed zone structure. The specimen shows 54 zones marked with red dots.
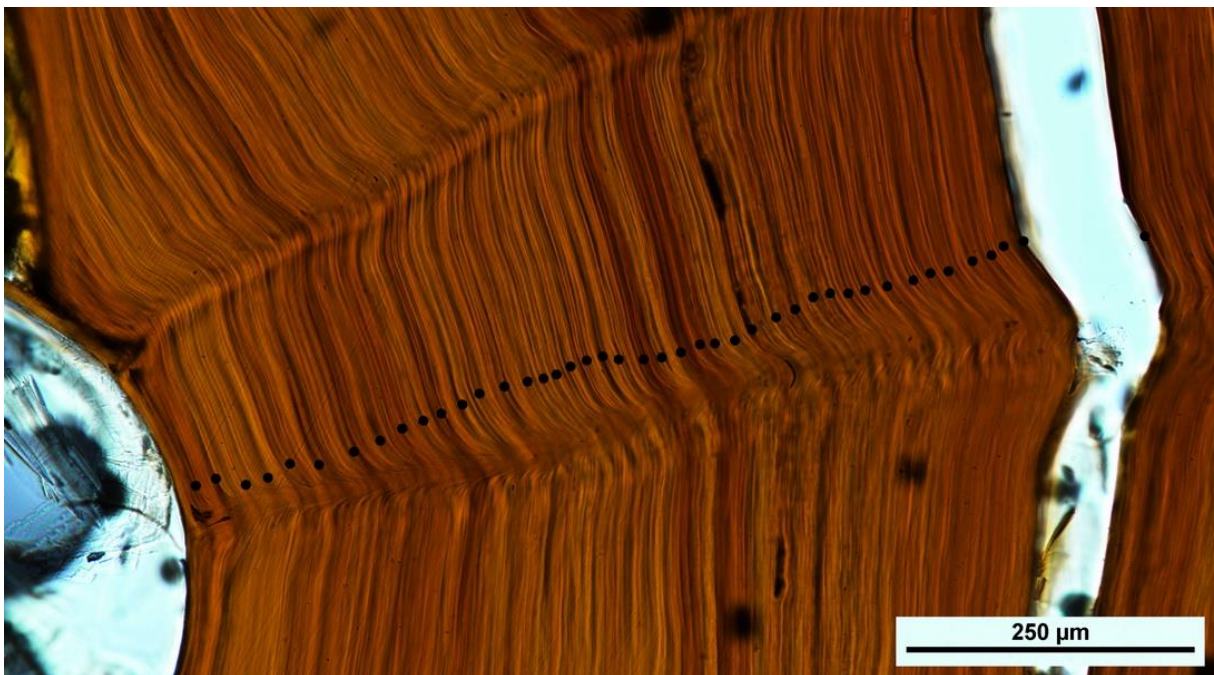
Figure 3-2:   Central portion of the basal section of coral NIWA47911 showing the fine scale interpretation protocol of the observed zone structure. The specimen shows 42 zones marked with black dots across this inner region of the section; the whole section showed 211 zones.

Table 3-3: **Zone counts from thin sections.** Zone counts were derived using the coarse coloured banding interpretation of the observed zone structure protocol, fine scale zone counts were derived using the fine scale interpretation protocol. For comparison the calibrated radiocarbon age (yr BP) are included, these are derived from the median age (calendar years AD) (see Table 3-2).

Sample Name	Geographic region	Sample region	Coarse zone counts	Fine scale zone counts	Calibrated radiocarbon age (yr BP)
NIWA 24190-B	Bay of Plenty	Base	37	78	
NIWA 85940-C	Bay of Plenty	Base	54	176	385
NIWA 49468-A	Chatham Rise	Tip	4	11	
NIWA 49468-B	Chatham Rise	Mid stem	55	370	126
NIWA 49468-C	Chatham Rise	Mid stem	60	374	
NIWA 49468-D	Chatham Rise	Base	72	481	319
NIWA 47911-A	Chatham Rise	Tip	4	10	
NIWA 47911-B	Chatham Rise	Near tip	4	12	
NIWA 47911-C	Chatham Rise	Near tip	5	16	
NIWA 47911-D	Chatham Rise	Near tip	7	19	
NIWA 47911-F	Chatham Rise	Base	54	211	112
NIWA 66335-A	Chatham Rise	Base	94	301	
NIWA 42807-A	Chatham Rise	Base	66	221	
NIWA 66354-A	Chatham Rise	Base	66	221	
NIWA 42812-A	Chatham Rise	Base	74	359	
NIWA 66337-A	Chatham Rise	Base	104	285	
NIWA 47879-A	Chatham Rise	Base	193	406	

3.3   Growth rate estimates

Growth rate estimates were based on the radiocarbon results as zone counts could not reliably generate growth rate estimates (see section 4.1 for a further discussion on zone counting). Growth rates were derived from the physical distances between sampling points and the calibrated radiocarbon ages at the relevant sample site. Due to some samples failing during the radiocarbon analysis only a limited set of growth rate estimates could be generated. Radial growth rates, the rate at which the colony branch thickens radially over time, were estimated by dividing the mean radius of the branch segment by the calibrated calendar years of growth between the core and the edge of the sample site. Radial growth ranged from 11.1 to 35.7 μm yr^{-1}. Linear growth rates, the rate at which the colony branch lengthens longitudinally over time, were estimated by dividing the distance between two sample sites by the difference between the calibrated calendar ages of the core samples at those sample sites. Two linear growth rates were obtained, 5.2 and 9.6 mm yr^{-1}.

Table 3-4: *Bathypathes patula* growth rate estimates.

Specimen	Section	Segment	Calibrated radiocarbon age (yr BP)	Segment length (mm)	Linear growth rate (mm/yr)	Section radius (µm)	Radial growth rate (µm/yr)
NIWA-85940	C		385			4280	11.1
NIWA-49468	B		126			4280	34.0
		NIWA-49468 A-B		650	5.2		
NIWA-49468	D		319			6300	19.7
NIWA-47911	F		112			4000	35.7
		NIWA-47911 A-F		1070	9.6		

4 Discussion

4.1 *Bathypathes patula* age and growth estimates

B. patula is a long-lived species, attaining ages in excess of 385 years. Slow linear (5.2–9.6 mm yr^{-1}) and radial (11.1–35.7 µm yr^{-1}) growth rates were obtained d from the radiocarbon age data.

Neither of the two zone count protocols reliably correlated with the independent radiocarbon age estimates. The fine scale zone counting protocol showed the closest correlation with the ^{14}C age data providing some overall support for longevity when comparing the zone counts with ^{14}C dates. Age estimates between the radiocarbon age data and the fine scale zone count data routinely showed a disparity of more than one hundred years in branch sections with calibrated radiocarbon ages of 112–385 years (Tables 3-3 and 3-4). Differences in estimated ages from comparable samples using the two methods were negative and positive; there was no under- or over-ageing using zone counts by a proportional amount (Table 3-3). This means the observed zone structure may not display annual periodicity and our zone counting protocols cannot be used to reliably generate age estimates for *B. patula*.

The edge radiocarbon results from specimen NIWA-85940 suggest that the basal section (C2) of the main stem stopped depositing skeletal material on its outer surface 293 years pre-harvest, and the mid-section (B2) stopped depositing skeletal material 88 years preharvest. This is despite the observation that these sections of branch stem were immediately adjacent to lateral pinnules with living polyps. The optical appearance of these sections gave no indication that zone deposition had ceased on their outer margin. This suggests if branch stems can stop accreting skeletal layers, while the branch ends continue to grow, then zone counting method protocols can't be utilised to generate age estimates for this species of coral.

Research by Love *et al*. (2007) on the black coral species *Antipathes dendrochristos* also reported two interpretations of the zone structure similar to our coarse and fine protocols. However, they found that the coarser coloured banding structure correlated with their radiocarbon and ^{210}Pb results (Love *et al.* 2007).

The skeleton of black corals is proteinaceous and derives its ^{14}C from the Particulate Organic Matter (POM) it feeds on. This particulate organic matter falls as planktonic detrital rain from the surface waters (Prouty *et al*. 2011). The radiocarbon measurements from the current work exhibited F^{14}C>1 in samples from the growing branch tips and main-branch surface, indicating these samples showed modern post-bomb levels of radiocarbon. This result supports previous work that the ^{14}C in the

proteinaceous skeletal matrix of these corals is sourced from surface derived particulate organic carbon (POC) (Williams & Grottoli 2010, Prouty *et al*. 2011). The deep ambient water that these corals are living in has much lower ^{14}C values, as the post-bomb testing elevated ^{14}C values found in the New Zealand surface waters are yet to filter down.

The radiocarbon results from this work show *B. patula* to be a long-lived species, with ages in excess of 385 years. The delicate nature of these organisms means they are vulnerable to anthropogenic activities which affect the seabed, such as fishing and mining, and will have slow recovery from these impacts.

4.2   Comparisons with recent New Zealand coral age data

The radiocarbon derived age estimates and growth rates from this project compared favourably with the results of a number of other age and growth studies on New Zealand black corals (Antipatharia) that have recently been or are currently being undertaken for key deep-sea corals in the New Zealand region (Table 4-1). The research also supports overseas studies that have shown black corals in general, to be some of the slowest-growing deep-sea corals (Sherwood & Edinger, 2009). All of this age and growth research provides a significantly improved dataset of age data for key high-risk New Zealand deep-sea coral species.

Table 4-1: Radiocarbon ageing studies on New Zealand black corals (Antipatharia).

Coral species	Location of collection	Depth (m)	Age (years old)	Growth (mm/ yr)	Growth parameter measured	Method	Reference
Black coral (no species name)	Norfolk Ridge, Tasman Sea	560	300–330	0.002–0.1	Radial growth	^{14}C dating; U/Th dating	Komugabee *et al.* 2014
Antipatharia	Chatham Rise	870	909-2672			^{14}C dating	Hitt *et al.* in prep.
Antipatharia	Fiordland	35	263-present			^{14}C dating	Hitt *et al.* in prep.
Antipathella fiordensis	Fiordland	34	129-present			^{14}C dating	Hitt *et al.* in prep.
Antipathes sp.	Chatham Rise	?	380-present			^{14}C dating	Hitt *et al.* in prep.
Leiopathes secunda	Chatham Rise	758	35–1269			^{14}C dating	Hitt *et al.* in prep.
Leiopathes secunda	Bay of Plenty	750	506–1960			^{14}C dating	Hitt *et al.* in prep.
Leiopathes sp.	Bay of Plenty	758	289–2901			^{14}C dating	Hitt *et al.* in prep.
*Bathypathes patula	Chatham Rise	758-1269	112-319	0.0197-0.0357 5.2-9.9	Radial growth Linear growth	^{14}C dating	Marriott *et al.* 2019
*Bathypathes patula	Bay of Plenty	800-949	385	0.011	Radial growth	^{14}C dating	Marriott *et al.* 2019

*Current study

5   Acknowledgements

6   References

Adkins JF, Griffin S, Kashgarian M, Cheng H, Druffel ERM, Boyle EA, Lawrence Edwards R and Shen CC (2002). Radiocarbon dating of deep-sea corals. *Radiocarbon* 44(2):567-580.

Andrews AH, Cordes EE, Mahoney MM, Munk K, Coale KH, Cailliet GM and Heifetz J (2002). Age, growth and radiometric age validation of a deep-sea, habitat-forming gorgonian (*Primnoa resedaeformis*) from the Gulf of Alaska. *Hydrobiologia* 471:101-110.

Andrews AH, Cailliet GM, Kerr LA, Coale KH, Lundstrom C and DeVogelaere AP (2005). Investigations of age and growth for three deep-sea corals from the Davidson Seamount off central California. In: Freiwald A and Roberts JM (eds) (2005). *Cold-water Corals and Ecosystems*. Springer-Verlag Berlin Heidelberg: 1021-1038.

Anthony, K.R.N., Marshall, P.A. (2009). Coral reefs and climate change. Marine Climate Change Impacts and Adaptation Report Card for Australia 2009. [www.oceanclimatechange.org.au/content/images/uploads/Coral_Reefs_Final.pdf.]

Bronk Ramsey, C. (2001). Development of the radiocarbon calibration program OxCal. *Radiocarbon*, 43(2A), 355-363.

Carreiro-Silva M, Andrews AH, Braga-Henriques A, de Matos V, Porteiro FM and Santos RS (2013). Variability in growth rates of long-loved black coral *Leiopathes* sp. from the Azores. *Marine Ecology Progress Series* 473:189-199.

Clark, M., Tracey, D., Anderson, O., and Parker, S. (2014). Pilot ecological risk assessment for protected corals. *NIWA Client Report*. WLG2014-70 , Wellington. 32p.

Clark, M.; Althaus, F.; Schlacher, T.; Williams, A.; Bowden, D.; Rowden, A. (2015). The impacts of deep-sea fisheries on benthic communities: a review. *ICES Journal of Marine Science*, 73: 51–69.

Coleman DC (1991). *Carbon isotope* techniques. University of California: Academic Press.

Consalvey M, MacKay K and Tracey D (2006). Information review for protected deep-sea coral species in the New Zealand region. *NIWA Client Report*. WLG2006-85. 60p.

Druffel ERM, King LL, Belastock RA and Buesseller KO (1990). Growth rate of a deep-sea coral using 210Pb and other isotopes. *Geochimica et Cosmochimica Acta* 54:1493-1500.

Fallon, S.J., Fifield, L.K., Chappell, J.M., (2010). The next chapter in radiocarbon dating at the Australian National University: Status report on the single stage AMS. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms., *Proceedings of the Eleventh International Conference on Accelerator Mass Spectrometry* 268, 898–901. doi:10.1016/j.nimb.2009.10.059

Griffin S, Druffel EM (1989). Sources of carbon to deep-sea corals. *Radiocarbon* 31(3):533-543.

Hitt, N.T., Neil, H. L., Sinclair, D. J., Fallon, S. J., Tracey, D. M., Komugabe-Dixson, A., (2018). Southwest Pacific Gyre Dynamics During the Common Era: A New Perspective from Deep-Sea Antipatharians   AGU Fall Meeting 2018. (Poster presentation *PP43C-1948*)

Hitt, N.T., Neil, H. L., Sinclair, D.J., Fallon, S.J., Tracey, D.M., Komugabe-Dixson, A. (in prep). An Age and Growth Rate Distribution of New Zealand's Deep-Sea Antipatharian Colonies. *Deep-Sea Research II xx.*

Komugabe-Dixson, A.F., Fallon, S.J., Eggins, S.M., Thresher, R.E. (2016). Radiocarbon evidence for mid-late Holocene changes in southwest Pacific Ocean circulation, *Paleoceanography* 10.1002/2016PA002929

Love MS, Yoklavich MM, Black BA and Andrews AH (2007). Age of black coral (*Antipathes dendrochristos*) colonies, with notes on associated invertebrate species. *Bulletin of Marine Science* 80(2):391-400.

Mortensen PB and Mortensen LB (2005). Morphology and growth of the deep-water gorgonians *Primnoa resedaeformis* and *Paragorgia arborea. Marine Biology* 147:775-788.

Neil H, Tracey DM, Marriott P and Clark MC (in review). Age and growth of a reef-forming deep-sea coral *Solenosmilia variabilis* in the New Zealand region: information to assess recovery potential from human impacts. *New Zealand Journal of Marine and Freshwater Research*.

Noé SU, Lembke-Jene L and Chr Dullo W (2008). Varying growth rates in bamboo corals: sclerochronology and radiocarbon dating of a mid-Holocene deep-water gorgonian skeleton (*Keratosis* sp.: Octocorallia) from Chatham Rise (New Zealand). *Facies* 54:151-166.

Prouty NG, Fisher CR, Demopoulous AWJ and Druffel ERM (2016). Growth rates and ages of dee-sea corals impacted by the Deepwater Horizon oil spill. *Deep-Sea Research II* 129:196-212.

Prouty NG, Roark EB, Buster NA and Ross SW (2011). Growth rate and age distribution of deep-sea black corals in the Gulf of Mexico. *Marine Ecology Progress Series* 423:101-115.

Reimer, P J and Reimer, R W, (2001). A marine reservoir correction database and on-line interface. *Radiocarbon* 43:461-463. (supplemental material URL:http://www.calib.org).

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J. (2013). IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55(4):1869–1887.

Roark EB, Guilderson TP, Dunbar RB and Ingram BL (2006). Radiocarbon based ages and growth rates: Hawaiian deepsea corals. *Marine Ecology Progress Series* 1-37.

Roark EB, Guilderson TP, Dunbar RB, Fallon SJ and Mucclarone DA (2009). Extreme longevity in proteinaceous deep-sea corals. *Proceedings of the National Academy of Sciences* 106(13):5204-5208.

Roark EB, Guilderson TP, Flood-Page S, Dunbar RB, Lynn Ingram B, Fallon SJ and McCulloch M (2005). Radiocarbon-cased ages and growth rates of bamboo corals from the Gulf of Alaska. *Geophysical Research Letters* 32:1-5. Doi: 10.1029/2004GL021919.

Rogers AD, Baco A, Griffiths H, Hart T and Hall-Spencer JM (2007). Corals on seamounts. Chapter 8. Pp141-169. In Pitcher TJ, Morato T, Hart PJB, Clark MR, Haggan N and Santos RS (eds.) Seamounts: Ecology, Conservation and Management. *Fish and Aquatic Resources Series*, Blackwell, Oxford, UK.

Sherwood OA and Edinger EN (2009). Ages and growth rates of some deep-sea gorgonian and antipatharian corals of Newfoundland and Labrador. *Canadian Journal of Fisheries and Aquatic Science* 66:142-152.

Sherwood OA, Scott DB, Risk MJ and Guilderson TP (2005). Radiocarbon evidence for annual growth rings in the deep-sea octocoral *Primnoa resedaeformis*. *Marine Ecology Progress Series* 301:129-134.

Thresher R, Rintoul SR, Koslow JA, Weidman C, Adkins J and Proctor C (2004) Oceanic evidence of climate change in southern Australia over the last three centuries. *Geophysical Research Letters* 31: l07212.

Thresher RE, MacRae CM, Wilson NC and Gurney R (2007) Environmental effects on the skeletal composition of deep-water gorgonians (*Keratoisis* spp.; Isididae). *Bulletin of Marine Science* 8(3):409-422.

Tracey D, Neil H, Gordon D and O'Shea S (2003). Chronicles of the deep: ageing deep-sea corals in New Zealand waters. *NIWA Water and Atmosphere* 11(2):22-24.

Tracey DM, Neil H, Marriott P, Andrews AH, Cailliet GM and Sanchez JA (2007). Age and growth of two genera of deep-sea bamboo corals (family Isididae) in New Zealand waters. *Bulletin of Marine Science* 81(3):393-408.

Tracey, D., Bostock, H., Shaffer, M. (2018). Ageing methods for protected deep-sea corals: A review and recommendation for an ageing study. DOC Contract 4527 GMC - Age & Growth of coral (POP2017-07). *NIWA Client Report* WN2018035 40 p.

Williams, B.; Risk, M. J.; Ross, S. W.; Sulak, K. J. (2007). Stable isotope data from deep-water antipatharians: 400-year records from the southeastern coast of the United States of America. *Bulletin of Marine Science*, Volume 81, Number 3, November 2007, pp. 437-447(11).

Williams, B., & Grottoli, A. G. (2010). Stable nitrogen and carbon isotope (δ15N and δ13C) variability in shallow tropical Pacific soft coral and black coral taxa and implications for paleoceanographic reconstructions. *Geochimica et Cosmochimica Acta, 74*(18), 5280-5288