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Abstract

Deep-sea gorgonian corals secrete a 2-part skeleton of calcite, derived from dissolved inorganic carbon at depth, and gorgonin, derived from recently fixed and exported particulate organic matter. Radiocarbon contents of the calcite and gorgonin provide direct measures of seawater radiocarbon at depth and in the overlying surface waters, respectively. Using specimens collected from Northwest Atlantic slope waters, we generated radiocarbon records for surface and upper intermediate water layers spanning the pre- and post bomb-^{14}C eras. In Labrador Slope Water (LSW), convective mixing homogenizes the pre-bomb Δ^{14}C signature (-67 ± 4 ‰) to at least 1000 m depth. Surface water bomb-^{14}C signals were lagged and damped (peaking at ~ +45 ‰ in the early 1980s) relative to other regions of the northwest Atlantic, and intermediate water signals were damped further. Off southwest Nova Scotia, the vertical gradient in Δ^{14}C is much stronger. In surface water, pre-bomb Δ^{14}C averaged -75 ± 5 ‰. At 250-475 m depth, pre-bomb Δ^{14}C oscillated quasi-decadally between -80 and -100 ‰, likely reflecting interannual variability in the presence of Labrador Slope Water vs. Warm Slope Water (WSW). Finally, subfossil corals reveal no systematic changes in vertical Δ^{14}C gradients over the last 1200 years.

Key words: radiocarbon, bomb-^{14}C, vertical gradient, deep-sea corals, Northwest Atlantic

1. Introduction

The radiocarbon content of dissolved inorganic carbon (DIC) in seawater is an important tracer of oceanic mixing. Radiocarbon produced naturally in the atmosphere is taken up in surface waters and mixed downward into deep waters where it undergoes radioactive decay. Uptake of bomb-^{14}C produced by atmospheric nuclear weapons testing in the late 1950s and early 1960s has amplified the natural ^{14}C gradient between surface and deep waters. While radiocarbon distribution in the world oceans was mapped during the Geochemical Ocean Sections (GEOSECS; Östlund et al., 1987) and subsequent Transient Tracers in the Ocean (TTO) and World Ocean Circulation Experiment (WOCE; Key et al., 2004) expeditions, spatial and temporal variability in seawater ^{14}C is better revealed through study of biogenic archives, such as corals, whose skeletal ^{14}C contents closely reflect that of the seawater in which they grow (Druffel, 1980; Guilderson et al., 1998). Proxy ^{14}C records are useful for constraining marine reservoir ages (Ingram and Southon, 1996; Bondevik et al., 1999; Guilderson et al., 2005), vertical and lateral mixing (Druffel, 1997; Guilderson et al., 2004; Robinson et al., 2005) and air-sea CO_2 exchange (Broecker et al., 1985; Cember, 1989; Fallon et al., 2003). Bomb-^{14}C records are also useful for establishing or validating skeletal chronologies in a variety of organisms (Campana et al., 2002; Kerr et al., 2005; Roark et al., 2006; Kilada et al., 2007).

Deep-sea corals present new archives of seawater ^{14}C, particularly in high-latitude and deep-water environments, where proxy archives generally are scarce (Adkins et al., 1998, 2002; Mangini et al., 1998). Previous work has focused on aragonitic scleractinian species, which are relatively easily dated with U/Th techniques (Cheng et al., 2000;

79 Goldstein et al., 2001; Schröder-Ritzrau et al., 2003; Frank et al., 2004; Robinson et al.,
80 2005; Eltgroth et al., 2006; Cao et al., 2007; Sikes et al., 2008). Deep-sea gorgonian
81 corals secrete a 2-part skeleton of calcite and proteinaceous gorgonin. The calcite is
82 derived from dissolved inorganic carbon at depth, while the gorgonin is tightly coupled to
83 recently fixed and exported particulate organic matter (POC; Griffin and Druffel, 1989;
84 Roark et al., 2005; Sherwood et al., 2005). Radiocarbon content of the calcite and
85 gorgonin fractions therefore provide direct measures of seawater ^{14}C both at depth and in
86 the overlying surface waters, respectively. The difference in ^{14}C age between surface and
87 subsurface waters may then be used to assess the extent of vertical mixing of the water
88 column.
89
90 In this paper, we examine radiocarbon variability in Northwest Atlantic slope waters
91 using deep-sea gorgonians. Records of pre and post bomb-^{14}C are generated for surface
92 and upper intermediate slope water masses along a latitudinal gradient from $42^{0}N$ to
93 $60^{o}N$. Additional measurements from recent and subfossil specimens are used to assess
94 vertical ^{14}C gradients in the upper 2000 m of the water column over the last 1200 years.
95
96 **2. Samples**
97 Specimens were collected with the remotely operated vehicle *ROPOS* and as fisheries
98 bycatch (Fig. 1). A live specimen of *Keratoisis ornata* was collected from the southwest
99 Grand Banks (specimen 1343) at 713 m depth. Subfossil *K. ornata* were collected from
100 Baffin Bay (1298; 1008 m), Davis Strait (715; 923 m), Hudson Strait (1448, 1449; 1193
101 m), southwest Grand Banks (2460; 580 m) and Sable Gully (2431; 1826 m). *Primnoa*

resedaeformis was collected from Hudson Strait (1525-1, 1525-3, 1525-10; 414m) and Northeast Channel, off Southwest Nova Scotia (COHPS2001-1; 250-475 m). An additional 7 samples of *P. resedaeformis* (DFO-2002-con5A1, HUD-2001-055-VG13, HUD-2001-055-VG15, NED-2002-037-1A, NED-2002-037-5-1, ROPOS-639009, ROPOS-6400013; hereafter collectively referred to as S05) were collected from the Northeast Channel, as described earlier (Sherwood et al., 2005). A table of all samples, with dating and radiocarbon results is provided in the supplementary appendix.

3. Analytical Methods

K. ornata secretes a skeleton consisting of gorgonin nodes and calcite internodes (Noé and Dullo, 2006). Skeletons were sectioned longitudinally to facilitate sampling of coeval gorgonin and calcite samples from the same growth layer across the node-internode boundary. To generate timeseries $\Delta^{14}C$ records, samples were milled along transects from the outer margin to the central core, in increments of 0.3 – 0.9 mm, using a micromill fitted with a 0.3 mm diameter bit. *P. resedaeformis* secretes annual rings of calcite and gorgonin towards the inner part of the axial skeleton, enveloped by a crust of massive calcite in older specimens (Fig. 2A). Gorgonin samples were isolated by dissolving skeletal sections in 5% HCl and peeling apart the annual growth rings (Specimens 1525-1, 1525-3, 1525-10). Coeval samples of calcite were isolated from an adjacent section by oxidizing in a 50:50 solution of 30% H_2O_2 and 1N NaOH for 3 weeks (Specimen 1525-3). In a larger specimen of *P. resedaeformis* (COHPS2001-1) calcite samples were milled from a transect of the calcite crust.

125 For ^{14}C analyses, CO_2 aliquots evolved from calcite and decalcified gorgonin samples
126 were reduced to graphite in the presence of iron catalyst. Radiocarbon measurements
127 were performed on graphite targets at the Center for Accelerator Mass Spectrometry,
128 Lawrence Livermore National Laboratory. Results include a background and $\delta^{13}C$
129 correction and are reported as $\Delta^{14}C$ according to Stuiver and Polach (1977). Data for
130 recent, known-age samples are also reported as age-corrected $\Delta^{14}C$ (Stuiver and Polach,
131 1977) for easier comparison to seawater $\Delta^{14}C$ data.
132
133 **4. Dating Methods**
134 Recently living corals were dated by one of 2 means. Young *P. resedaeformis* specimens
135 lacking a calcite crust were dated by counting annual growth rings in transverse section.
136 Ring counts were made by 3 different counters, to determine a mean calendar age (± 1σ)
137 for each sampled growth ring, as described in Sherwood et al. (2005). An older *P.*
138 *resedaeformis* (COHPS2001-1) and a *K. ornata* (1343) were dated with ^{210}Pb. Adjacent
139 sections to those used for ^{14}C analyses were cut into 5-8 sub-samples, each weighing
140 about 1 g. Sub-samples were crushed in an agate mortar, and the powder was oxidized in
141 30% H_2O_2 held at pH 8 by addition of 1N NH_4OH, then washed with de-ionized water
142 and dried at 60°C. Measurement of ^{210}Pb was done by alpha spectrometry of its daughter
143 product, ^{210}Po (Flynn, 1968). The ^{210}Pb-derived growth rate and chronological tie-in
144 points defined skeletal chronology (Fig. 2).
145
146 Subfossil *K. ornata* specimens were dated by conventional ^{14}C dating of the gorgonin
147 fraction. Raw ^{14}C ages were calibrated with the CALIB program (Stuiver and Reimer,

148 1993, version 5) using the Marine04 calibration (Hughen et al., 2004). A correction for
149 local variation in the marine reservoir age (ΔR; Stuiver and Braziunas, 1993) was
150 applied, based on data from recent, known-age specimens presented herein.
151 Marine reservoir ages are expressed either as R(t)' or ΔR (Stuiver et al., 1986). R(t)' is
152 defined as the difference in ^{14}C years between a regional water mass and the 'global'
153 (Northern Hemisphere) atmosphere. ΔR is the difference in ^{14}C years between a regional
154 surface ocean and the modeled 'global' surface ocean (Stuiver et al., 1986). To first
155 approximation, ΔR is time independent and is therefore the preferred method of
156 correcting for the reservoir age of marine samples (Stuiver et al., 1986; Reimer and
157 Reimer, 2001). ΔR is calculated by subtracting from the conventional ^{14}C age of a
158 known-age marine sample the Marine04 model age for that calendar year. The Marine04
159 calibration and ΔR reflect the ^{14}C of surface waters. Because gorgonin reflects surface
160 waters in terms of ^{14}C (Roark et al. 2005; Sherwood et al. 2005), only this fraction was
161 used for ΔR calculations and age calibrations.
162
163 **5. Results**
164 Paired gorgonin and calcite $\Delta^{14}C$ records spanning pre- and post-nuclear bomb eras were
165 generated for Hudson Strait, Grand Banks and Northeast Channel (Fig. 3). The $\Delta^{14}C$
166 content of gorgonin represents that of surface water, as indicated by good agreement with
167 contemporaneous surface water values extracted from nearby TTO and WOCE stations.
168 In all 3 records, bomb-^{14}C began to increase around the year 1958. This validates our
169 dating accuracy as 1958 ± 2 marked the year of initial increase in bomb-^{14}C in the mixed
170 layer of the oceans (Grottoli and Eaken, 2007). The records from Hudson Strait and

171 Grand Banks were similar: pre-bomb, age-corrected $\Delta^{14}C$ averaged -68 ± 3 ‰ (pooled
172 mean, 1σ, n = 10) and bomb-^{14}C peaked at around +45 ‰ in the early 1980s. At
173 Northeast Channel, pre-bomb values averaged slightly lower (-75 ± 5 ‰, 1σ, n = 5) and
174 bomb-^{14}C peaked at +80 ‰ in 1970. No long term trends during the pre-bomb era were
175 evident at any of the sites.
176
177 The $\Delta^{14}C$ content of calcite represents the $\Delta^{14}C$ of upper intermediate water at the depth
178 where the corals were living (414 m, 713 m, and 250-475 m respectively for Hudson
179 Strait, Grand Banks, and Northeast Channel; Fig. 3). At Hudson Strait and Grand Banks,
180 intermediate water pre-bomb, age-corrected $\Delta^{14}C$ values averaged -64 ± 4 ‰ (pooled
181 mean,1σ, n = 6), within error of the corresponding surface water values. No long term
182 trends were apparent during the pre-bomb era. At Northeast Channel, values were much
183 more negative and oscillated quasi-decadally between -80 and -100 ‰. Relative to
184 surface waters, intermediate water bomb-^{14}C signals were damped and lagged by varying
185 amounts. Intermediate water bomb-^{14}C appeared damped by approximately 10 ‰ at
186 Hudson Strait and 80 ‰ at Northeast Channel, but more data are needed to resolve the
187 signals at these sites. At Grand Banks, the intermediate water signal was better resolved
188 by more data points and lagged the surface water signal by at least 20 years as $\Delta^{14}C$ had
189 not peaked as of the year 2001.
190
191 In Fig. 4 we compare our bomb-^{14}C records with two previously published records
192 obtained from otoliths extracted from fish of age 0-3 years (Campana et al., 2008). One
193 of these records was derived from otoliths of Greenland halibut (*Reinhardtius*

194 *hippoglossoides*) collected from the northern and western margins of the Labrador Sea
195 (western Greenland, Davis Strait and Labrador shelf areas) from an average depth of 300
196 m. This record is most similar to our intermediate water data from Hudson Strait, and
197 slightly depleted relative to our combined Hudson Strait and Grand Banks surface water
198 data. The second otolith record was derived from haddock (*Melanogrammus aeglefinus*),
199 redfish (*Sebastes* spp.) and yellowtail flounder (*Limanda ferruginea*) collected from the
200 shelf waters of the southern Grand Banks. This record is more similar to our Northeast
201 Channel surface water record.
202
203 Radiocarbon measurements of known-age samples from before AD 1950 are important
204 for constraining the marine reservoir age. Table 1 shows local reservoir ages, R(t)',
205 calculated from known-age, pre-bomb coral ^{14}C data. Values of R(t)' were statistically
206 equal overall all regions and depths ($T = 6.55 < 11.07 = \chi^2_{2;\,0.05}$; Ward and Wilson,
207 1978) with a weighted mean of 420 ± 20 ^{14}C years (1σ, n = 6). Even though the values
208 were statistically equal, the reservoir age for intermediate waters at the Northeast
209 Channel was notably older at 600 ± 95 (1σ, n = 3). Values of ΔR were calculated
210 separately for the surface waters using gorgonin samples. Again, values were statistically
211 equal ($T = 0.15 < 5.99 = \chi^2_{2;\,0.05}$), so we computed a weighted mean of ΔR = 135 ± 20
212 (1σ, n = 3), representing surface slopewaters of the Northwest Atlantic, from Northeast
213 Channel to offshore Hudson Strait. Similar ΔR values have been reported for the adjacent
214 shelf and coastal waters in the Marine Reservoir Correction Database (Reimer and
215 Reimer, 2001). For example, for coastal Labrador ΔR = 150 ± 67 (weighted mean, 1σ, n

= 26) and for coastal and shelf waters from the Gulf of Maine to the southern Grand Banks $\Delta R = 87 \pm 64$ (n = 33).

Coeval gorgonin and calcite samples from live-collected and subfossil corals were used to assess vertical ^{14}C gradients over a latitudinal range of 42-68^{o}N and over the last 1200 years (Table 2). From one of the subfossil corals, we generated a continuous record of ^{14}C across the calcite internode, indicating a lifespan of 200 years (Fig. 5). We attempted to date the subfossil specimens independently using U/Th dating; however, femtogram concentrations of Th made it difficult to calculate reliable U/Th ages. Instead, we used the ^{14}C age of the gorgonin fraction to calculate calendar age, using the 135 +/- 20 year ΔR correction established above. By differencing the $\Delta^{14}C$ of paired gorgonin and calcite samples, we obtained vertical gradients in ^{14}C age (and corresponding $\Delta^{14}C$, uncorrected for age at formation) of the water column (Fig. 6). Positive values of the difference in ^{14}C age represent a normally stratified water column, with younger waters overlying older waters. The most positive value was found at Northeast Channel, where subsurface waters are older than surface waters by an average of 125 ^{14}C years. A positive value was also found at the next most northerly location, the Sable Gully. Northward of the Scotian Slope, values averaged around zero or were negative. There were no apparent long term trends in vertical $\Delta^{14}C$ gradients over the past 1200 years (Fig. 6). For example, excluding the Northeast Channel (S05/COHPS2001-1) and Sable Gully (2431) samples, all of the remaining samples were within error of each other in terms of the difference between surface and intermediate water ^{14}C ages (Fig. 6).

6. Discussion

Slope waters of the Northwest Atlantic comprise a mixture of different water masses. In the northern Labrador Sea, a 100 m deep surface layer forms during the summer. In winter, convective mixing homogenizes the water column to ~1500 m, forming an upper, recently ventilated layer of Labrador Sea Water (Azetsu-Scott et al., 2005). Because of mixing, the vertical $\Delta^{14}C$ gradient near Hudson Strait is minimal: pre-bomb values are identical between 0 and 400 m, and the bomb-^{14}C signal at 400 m is only slightly depleted relative to the surface signal (Fig. 3A). A previously published bomb-^{14}C record based on Greenland Halibut otoliths collected from the margins of the Labrador Sea (Campana et al., 2008) is most similar to our 400 m deep Hudson Strait data because the fish were collected at an average depth of 300 m (Fig. 4). Overall, vertical mixing dampens and lags bomb-^{14}C records in the Labrador Sea relative to our more southerly record from the Northeast Channel (Fig. 4) and relative to other regions of the North Atlantic, where bomb-^{14}C peaked between +80 and +150 ‰ in the early 1970s (Druffel, 1980; Kalish, 1993; Weidman and Jones, 1993; Campana et al., 2008).

The offshore branch of the Labrador Current transports part of the upper Labrador Sea Water as Labrador Slope Water (LSW) southward from Hudson Strait along the continental slope of Newfoundland and Labrador. At 43^{o}N, it bifurcates and part of it continues westward along the southern flank of the Grand Banks (Drinkwater, 1996). It takes < 1 year for the Labrador Current to transit from Hudson Strait to the Grand Banks (Lazier and Wright, 1993); therefore, surface water $\Delta^{14}C$ records at the 2 areas are nearly identical (Fig. 3A,B). The 700 m deep record at the Grand Banks reflects a deeper layer

262 of LSW in which bomb-^{14}C lags that of surface waters by at least 20 years (Fig. 3B).
263 During the pre-bomb era, however, the vertical Δ^{14}C gradient from 0 – 700 m remained
264 near zero.
265
266 A previously published bomb-^{14}C record from nearby shelf waters of the southwest
267 Grand Banks, based on otoliths of age 1-3 haddock (*Melanogrammus aeglefinus*), redfish
268 (*Sebastes* spp.) and yellowtail flounder (*Limanda ferruginea*) (Campana et al., 2008),
269 showed a more rapid increase in bomb-^{14}C, virtually identical in timing and amplitude to
270 our Northeast Channel surface water record (Fig. 4). This record primarily reflects
271 Labrador Shelf Waters (LShW) of the inshore branch of the Labrador Current (Houghton
272 and Fairbanks, 2001). Compared with the slope region, vertical mixing on the shelf is
273 limited by bathymetry to < 250m, thus leading to more rapid equilibration of LShW with
274 atmospheric bomb-^{14}C. These results highlight important differences in bomb-^{14}C signals
275 from adjacent regions.
276
277 The Labrador Current carries LSW further westward toward the Nova Scotia slope where
278 it forms a front with Warm Slope Water (WSW) originating from the south. WSW
279 occupies the region between the shelf break and the north wall of the Gulf Stream. The
280 frontal boundary between LSW and WSW moves along-slope between approx. 69^{o}W and
281 57^{o}W, in response to basin-scale forcing associated with the modal state North Atlantic
282 Oscillation (NAO; Petrie and Drinkwater, 1993; Greene and Pershing, 2003). Thus,
283 during positive years of the NAO the upper slope region off Nova Scotia is occupied by
284 WSW; during negative states it is occupied by LSW.

285

286 The pre-bomb vertical $\Delta^{14}C$ gradient at Northeast Channel is much higher than anywhere
287 else further north over the last 1200 years (Fig. 6). This is caused by the presence of
288 older, ^{14}C depleted water at 250-475 m at the Northeast Channel. Negative excursions to -
289 100 ‰ during the pre-bomb era cannot be associated with the presence of LSW, based on
290 values of -70 ‰ upstream at Grand Banks and Hudson Strait (Fig. 3). Instead, the
291 negative values must originate from WSW. From nutrient data, WSW is thought to mix
292 with Antarctic Intermediate Water (AAIW), located at ~1000 m below the Gulf Stream,
293 via isopycnal shoaling (Richardson, 1977; Atkinson, 1983; Csanady and Hamilton,
294 1988). AAIW has a $\Delta^{14}C$ signature of -110 ‰ (Broecker et al., 1960). Mixing with
295 AAIW would impart a more negative $\Delta^{14}C$ signature to WSW, as previously suggested
296 for the slope waters south of the Northeast Channel (Tanaka et al., 1990). If WSW is the
297 source of negative $\Delta^{14}C$ excursions, then the $\Delta^{14}C$ record for subsurface Northeast
298 Channel may reflect NAO-driven shifts in the relative dominance of younger LSW vs.
299 older WSW. The resolution of our ^{210}Pb-dated record does not permit a timeseries
300 correlation with the NAO; however, future developments in precise U/Th dating of
301 gorgonian calcites may allow for the development of detailed, long term proxy records of
302 slope water movements here, and in other dynamic regions.

303

304 **7. Conclusions**

305 Deep-sea corals present new archives of seawater ^{14}C, particularly in high latitude and/or
306 deep-water environments where proxy data generally are lacking. One of the benefits of
307 deep-sea gorgonians versus scleractinian corals is the ability to generate both surface and

deep-water ^{14}C chronologies from the same skeleton. From ^{14}C measurements on both fractions, we determined new estimates of radiocarbon reservoir ages of Northwest Atlantic slopewaters, which could be used for more precise ^{14}C dating of cores recovered from this area. From measurements on co-eval gorgonin and calcite fractions we generated new data on seawater vertical ^{14}C gradients over the last 1200 years. While there were no apparent changes in vertical ^{14}C gradients over this time period, the most significant finding was the presence of a ^{14}C -depleted water mass which invades the southern region of the Scotian Slope on decadal timescales. These findings demonstrate the utility of deep-sea gorgonians in tracking water mass movements in oceanographically dynamic regions.

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Table 1: Summary of pre-bomb ^{14}C ages of gorgonin and calcite fractions of recent, known-age corals and corresponding R(t)' and ΔR values. Values in brackets are 1σ errors.

Coral ID	Band or subsample	Year AD	CAMS #	^{14}C Age (years)	IntCal Age [d]	R(t)'	Marine04 Age [e]	ΔR
Hudson Strait, 60.5°N/61.4°W, 275-450 m								
Gorgonin								
1525-3	53	1925 (8) [b]	131411	610 (25)	132 (7)	478 (26)	451 (23)	159 (34)
1525-1	31	1946 (2) [b]	131423	585 (25)	188 (8)	397 (26)	464 (23)	121 (34)
1525-3	32	1949 (7) [b]	131410	585 (30)	197 (9)	388 (31)	468 (24)	117 (38)
				Mean (s.d.)		421 (50)		132 (23)
Calcite								
1525-3	C5	1941(10) [b]	132208	555 (30)	176 (8)	379 (31)		
Grand Banks, 44.13°N/52.93°W, 713 m								
Gorgonin								
1343	G19	1943 (10) [c]	131278	570 (25)	182 (8)	388 (26)	462 (23)	108 (34)
1343	G25	1934 (12) [c]	131279	605 (30)	157 (7)	448 (31)	456 (23)	149 (38)
1343	G32	1925 (13) [c]	131280	585 (25)	132 (7)	453 (26)	451 (23)	134 (34)
1343	G37	1919 (14) [c]	131281	590 (25)	126 (7)	464 (26)	449 (23)	141 (34)
1343	G43	1910 (15) [c]	131282	675 (25)	96 (7)	579 (26)	448 (23)	227 (34)
1343	G52-53	1896 (18) [c]	131382	575 (25)	75 (7)	500 (26)	459 (23)	116 (34)
1343	G58	1884 (20) [c]	131383	625 (30)	103 (7)	522 (31)	470 (23)	155 (38)
				Mean (s.d.)		479 (61)		147 (39)
Calcite								
1343	C9	1949 (10) [c]	132003	560 (25)	197 (9)	363 (27)		
1343	C11	1934 (12) [c]	132004	525 (30)	157 (7)	368 (31)		
1343	C15	1909 (16) [c]	132005	590 (30)	95 (7)	495 (31)		
1343	C17	1894 (18) [c]	132006	525 (25)	81 (7)	444 (26)		
1343	C19	1879 (21) [c]	132007	605 (25)	111 (7)	494 (26)		
				Mean (s.d.)		433 (65)		
NE Channel, 42.0°N/65.5°W								
Gorgonin								
S05:								
NED-2002-037-1A [a]	58	1947 (1) [b]	111330	630 (35)	193 (8)	437 (36)	466 (23)	164 (42)
DFO-2002-con5A1 [a]	37	1948 (4) [b]	97103	620 (30)	195 (9)	425 (31)	467 (23)	153 (38)
DFO-2002-con5A1 [a]	43	1942 (5) [b]	97104	545 (30)	179 (8)	366 (31)	461 (23)	84 (38)
DFO-2002-con5A1 [a]	50	1934 (6) [b]	97105	595 (30)	157 (7)	438 (31)	456 (23)	139 (38)
DFO-2002-con5A1 [a]	58	1924 (6) [b]	97106	550 (30)	131 (7)	419 (31)	451 (23)	99 (38)
				Mean (s.d.)		417 (30)		128 (35)
Calcite								
COHPS-2001-1E	1&2	1890 (22) [c]	97759	640 (40)	98 (7)	542 (41)		
COHPS-2001-1E	3&4	1895 (21) [c]	97760	700 (40)	78 (7)	622 (41)		
COHPS-2001-1E	5&6	1900 (19) [c]	97761	850 (60)	70 (7)	780 (60)		
COHPS-2001-1E	7&8	1905 (17) [c]	97762	680 (35)	83 (7)	597 (36)		
COHPS-2001-1E	9&10	1911 (16) [c]	97763	770 (60)	97 (7)	673 (60)		
COHPS-2001-1E	11&12	1916 (15) [c]	97764	705 (40)	110 (7)	595 (41)		
COHPS-2001-1E	13&14	1921 (13) [c]	97765	625 (40)	130 (7)	495 (41)		
COHPS-2001-1E	15&16	1926 (110 [c]	97766	785 (50)	135 (7)	650 (50)		
COHPS-2001-1E	17&18	1930 (10) [c]	97767	695 (40)	151 (7)	544 (41)		
COHPS-2001-1E	19&20	1936 (8) [c]	97768	835 (40)	159 (8)	676 (41)		
COHPS-2001-1E	21&22	1941 (7) [c]	97769	625 (40)	176 (8)	449 (41)		
				Mean (s.d.)		602 (93)		

[a] Data from Sherwood et al., 2005, 2006
[b] Growth ring counted age
[c] ^{210}Pb-dated age
[d] Intcal04 model age (Reimer et al., 2004)
[e] Marine04 model age (Hughen et al., 2004)

Table 2: Summary of recent (pre-1950) and subfossil samples, with paired radiocarbon data from coeval gorgonin and calcite fractions. All errors (in brackets) are ± 1σ. Where N > 1, the mean ± 1σ of multiple samples are reported.

Coral ID	Band or subsample	Skeletal fraction	N	$\Delta^{14}C$ (‰)	Diff. (‰) [a]	^{14}C age (yrs)	Diff. (yrs) [b]	Cal Age (yrs AD)
Subfossil corals								
Baffin Bay, 67.93°N/59.45°W, 1008 m								
1298	G1	gorgonin	1	-82 (3)	9 (4)	685 (25)	-75 (36)	1750 (50)[c]
	C1	calcite	1	-73 (2)		610 (25)		
Davis Strait, 63.53°N/58.75°W, 923 m								
715	G1	gorgonin	1	-194 (2)	0 (4)	1735 (25)	-5 (39)	780 (50)[c]
	C1	calcite	1	-194 (3)		1730 (30)		
Hudson Strait, 60.6°N/60.38°W, 1193 m								
1448	G1	gorgonin	1	-184 (2)	7 (4)	1640 (25)	-70 (35)	900 (50)[c]
	C1	calcite	1	-177 (3)		1570 (25)		
1449	G1 to G6/7	gorgonin	6	-181 (4)	3 (7)	1601 (39)	-32 (71)	950 (50)[c]
	C1 to C6	calcite	6	-178 (6)		1569 (59)		
Grand Banks, 44.83°N/54.47°W/ 578 m								
2460	G1	gorgonin	1	-92 (3)	0 (4)	775 (30)	0 (39)	1670 (40)[c]
	C1	calcite	1	-92 (3)		775 (25)		
Sable Gully, 43.68°N/58.82°W, 1826 m								
2431	G1	gorgonin	1	-147 (3)	-5 (4)	1280 (25)	45 (35)	1260 (30)[c]
	C1	calcite	1	-152 (3)		1325 (25)		
Recent corals								
Hudson Strait, 60.5°N/61.4°W, 414 m								
1525-1 1525-3	G31 G32, G53	gorgonin	3	-71 (1)	4 (3)	593 (14)	-38 (33)	1940 (13)[d]
1525-3	C5	calcite	1	-67 (3)		555 (30)		1941 (10)[d]
Grand Banks, 44.13°N/52.93°W, 713 m								
1343	G19 to G58	gorgonin	7	-72 (4)	4 (6)	604 (37)	-43 (52)	1916 (21)[e]
1343	1343-C9 to C19	calcite	5	-68 (4)		561 (37)		1913 (29)[e]
NE Channel, 42.0°N/65.5°W, 275-450 m								
S05: NED-2002-037-1A DFO-2002-con5A1	G58 G37 to G58	gorgonin	5	-77 (5)	-14 (12)	588 (39)	125 (103)	1939 (10)[d]
COHPS2001-1E	C13&14 to C21&22	calcite	5	-91 (11)		713 (95)		1931 (8)[e]

[a] Calcite $\Delta^{14}C$ minus gorgonin $\Delta^{14}C$
[b] Calcite ^{14}C age minus gorgonin ^{14}C age
[c] ΔR-corrected Marine04 calibrated age; ΔR = 135 ± 20.
[d] Growth ring counted age
[e] ^{210}Pb-dated age

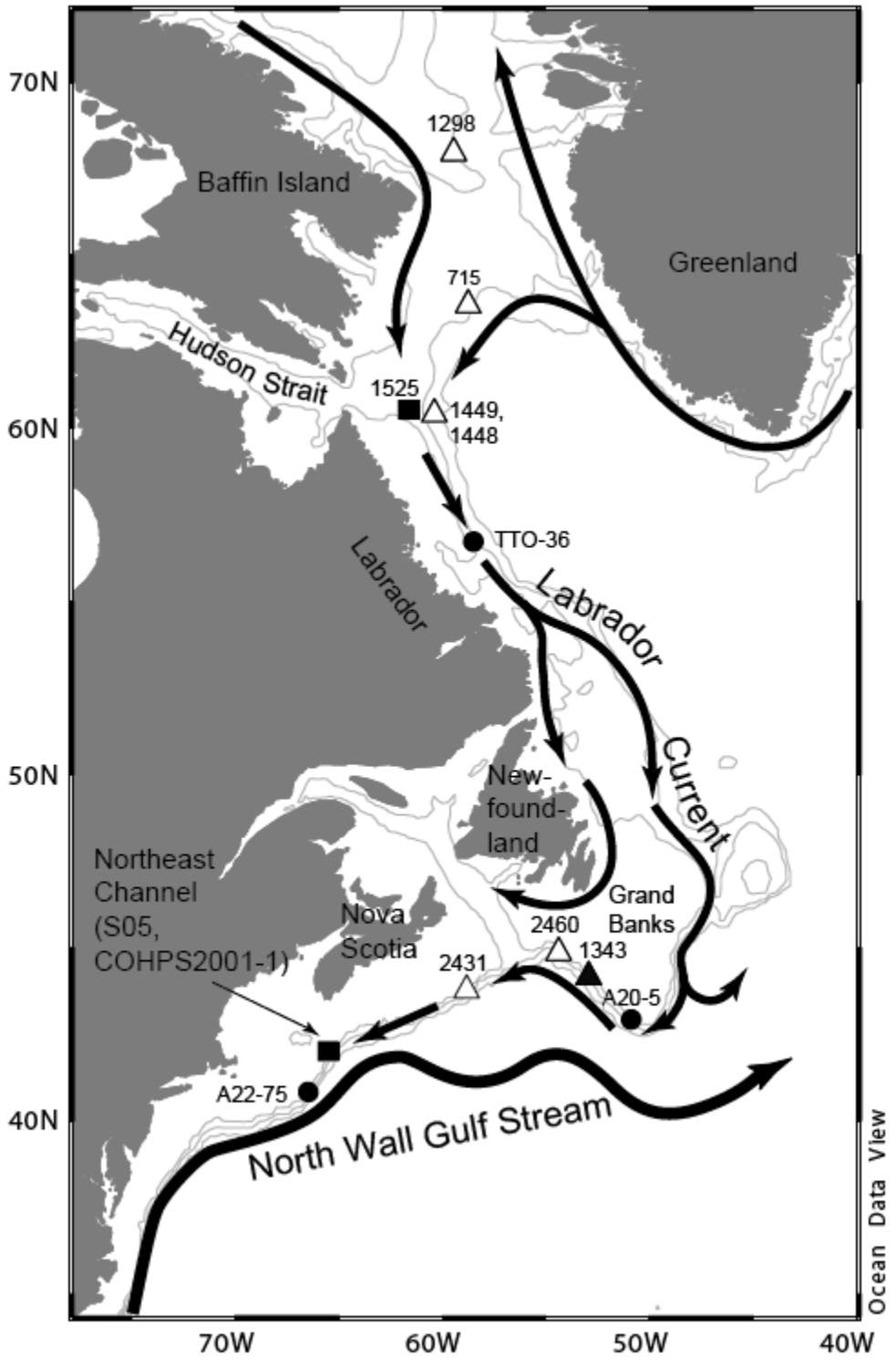


Fig. 1: Map of Northwest Atlantic region showing locations of coral samples. Closed triangle, recent *K. ornata*; open triangle, subfossil *K. ornata*, squares, recent *P. resedaeformis*. Also shown, nearby TTO and WOCE seawater stations extracted from the GLODAP dataset (circles; Key et al. 2004). Major surface currents indicated with arrows. Map drawn with ODV software (Schlitzer, 2006)

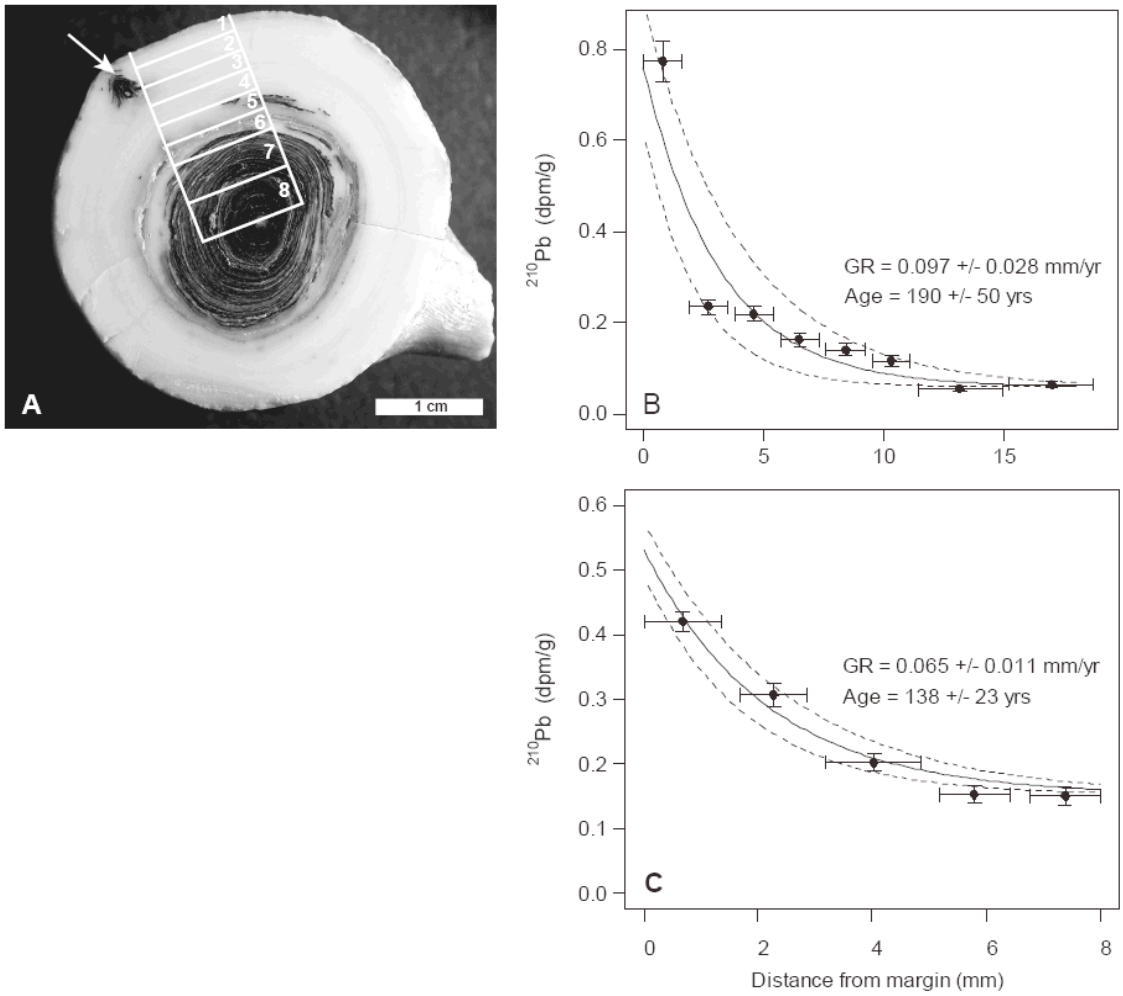
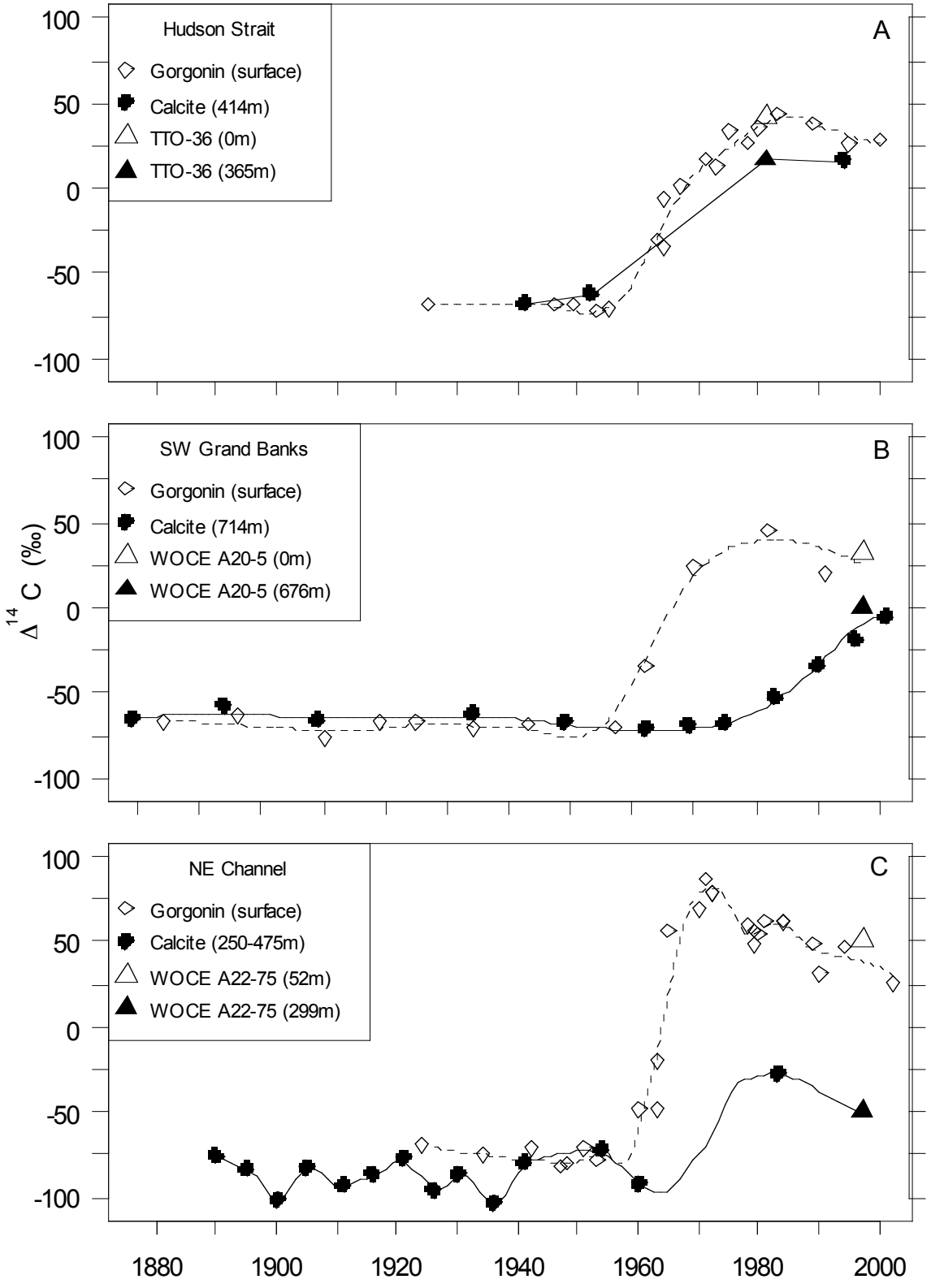
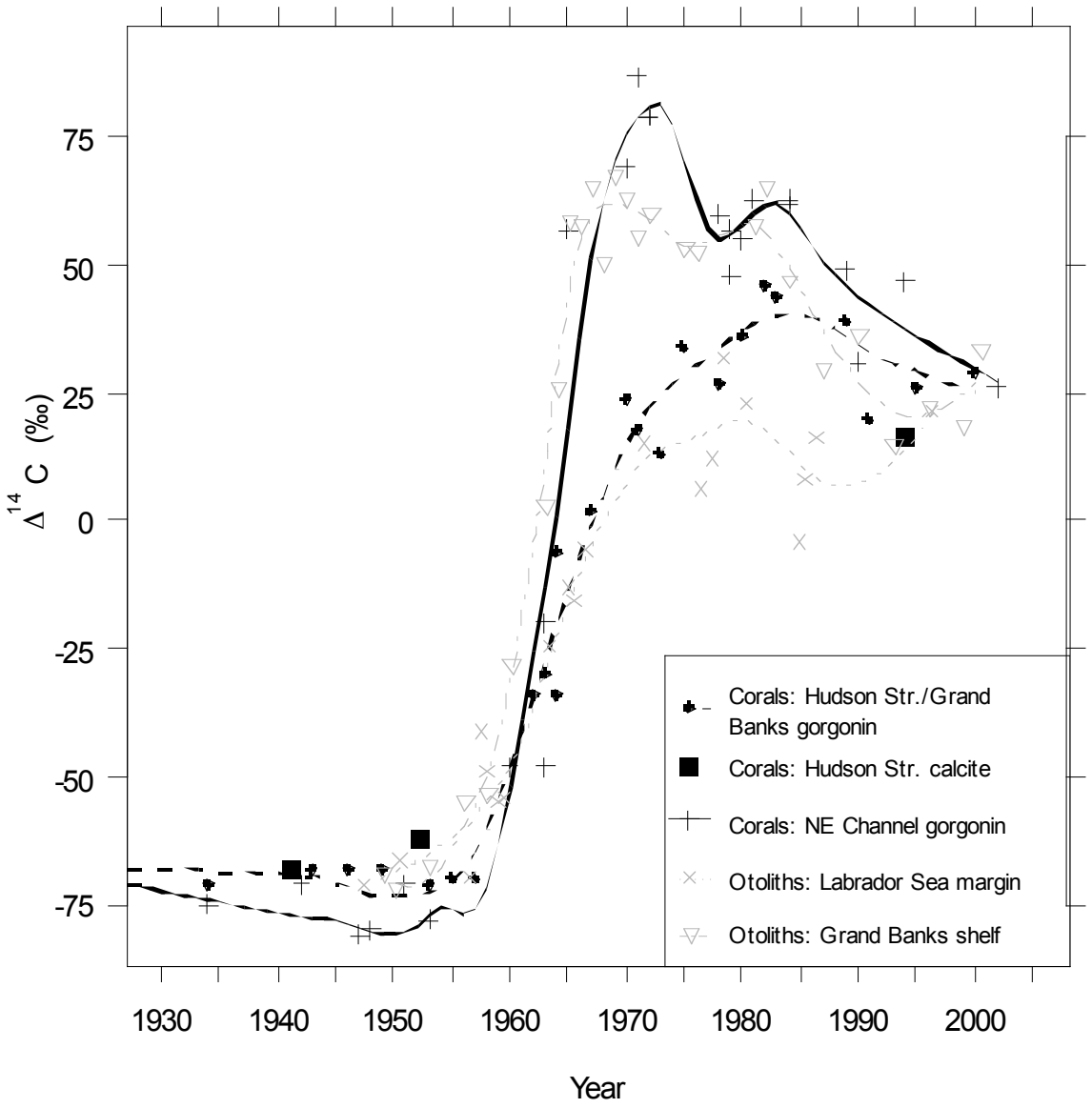


Fig. 2: (A) *P. resedaeformis* specimen COHPS2001-1 in transverse section, showing inner, annually banded gorgonin region overgrown by calcite crust. Arrow points to a gorgonin layer near the outer margin of the skeleton used as a chronological tie-in point. $\Delta^{14}C$ in this sample measured -27 ± 4 ‰; based on calibration to the local bomb-^{14}C curve (Fig. 3C) it was formed in the year 1961 ± 5. White lines indicate sub-samples for ^{210}Pb analysis. (B) ^{210}Pb data for specimen COHPS2001-1. Solid curve is the solution to the ^{210}Pb decay equation at the indicated growth rate (GR). Error bands (dashed curves) and vertical bars are 1σ errors; horizontal bars represent widths of sub-samples. (C) ^{210}Pb data for *K. ornata* specimen 1343. This specimen was collected alive; therefore the date of collection (2006) was used as the tie-in point.


Hudson Strait
Gorgonin (surface)
Calcite (414m)
TTO-36 (0m)
TTO-36 (365m)
A
SW Grand Banks
Gorgonin (surface)
Calcite (714m)
WOCE A20-5 (0m)
WOCE A20-5 (676m)
B
NE Channel
Gorgonin (surface)
Calcite (250-475m)
WOCE A22-75 (52m)
WOCE A22-75 (299m)
C
Δ14C (‰)
100
50
0
-50
-100
1880
1900
1920
1940
1960
1980
2000

575
576

Fig. 3: Paired gorgonin (surface water) and calcite (intermediate water) age-corrected $\Delta^{14}C$ records. (A) Hudson Strait records generated from 3 growth ring-dated colonies of *P. resedaeformis* (1525-1, 1525-3, 1525-10; depth = 414 m). (B) Southwest Grand Banks records generated from a single ^{210}Pb-dated *K. ornata* (1343; depth = 713 m). (C) Northeast Channel records from specimens of *P. resedaeformis* collected between 250-475 m. Gorgonin record from Sherwood et al. (2005); calcite record from the massive calcite zone of an older ^{210}Pb-dated colony (COHPS2001-1). Seawater $\Delta^{14}C$ data are from TTO and WOCE stations indicated in Fig. 1. 1σ errors in $\Delta^{14}C$ are smaller than symbols.



586
587
588 Fig. 4: Comparison of bomb-^{14}C records from this study with those of Campana et al.
589 (2008), derived from otoliths extracted from fish of age 0-3 years collected from the
590 northern and western margins of the Labrador Sea and the Grand Banks shelf.
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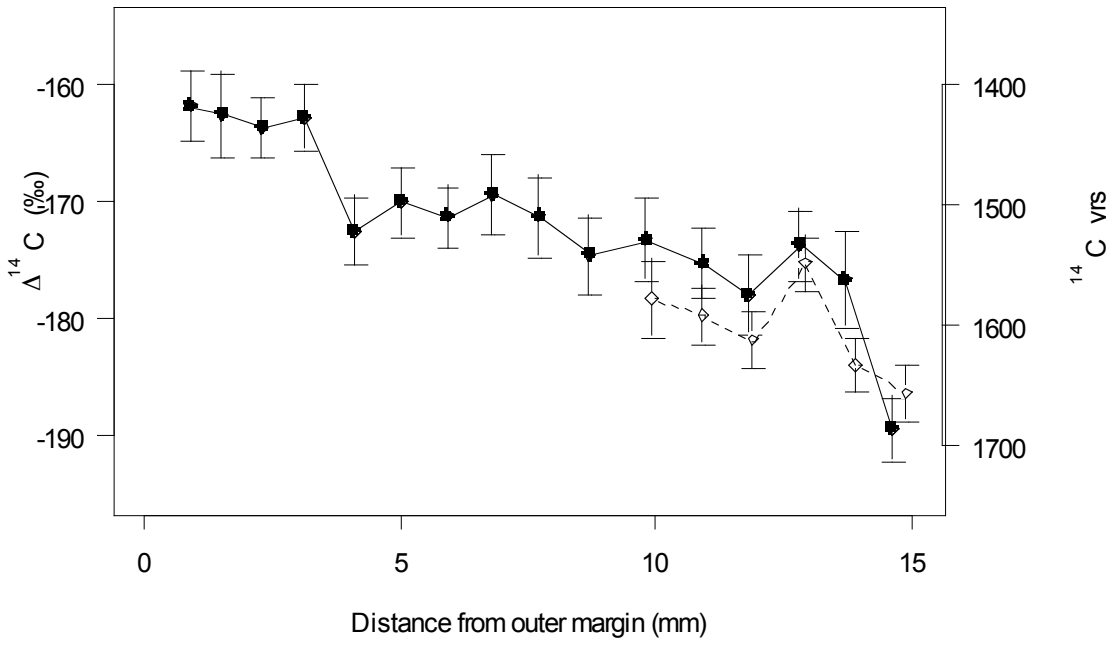

595
596 Fig 5: Radiocarbon data from a subfossil *K. ornata* (specimen 1449). Left-hand y-axis
597 shows $\Delta^{14}C$; right hand y-axis shows corresponding ^{14}C age (uncalibrated). Paired
598 gorgonin and calcite profiles were generated from the inner 5 mm of the sample; outer 10
599 mm was overgrown with calcite and gorgonin could not be sampled. Gorgonin and
600 calcite profiles yield the same growth rate of 0.076 mm/yr, yielding a lifespan of 200 yrs.

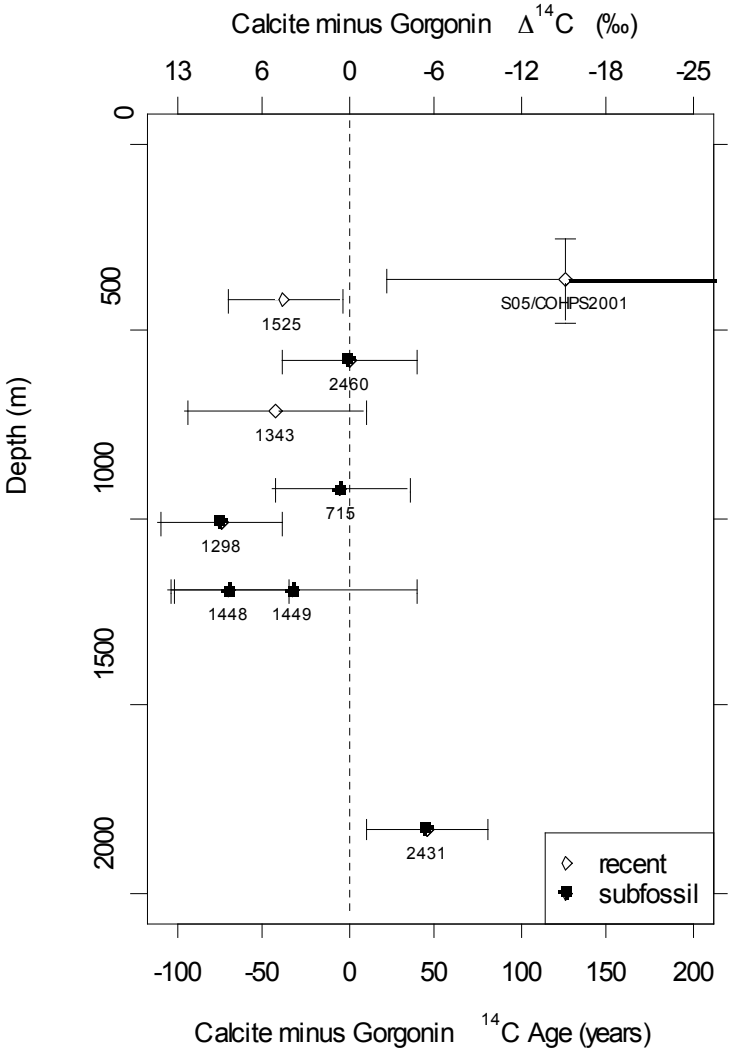

Fig. 6: Seawater vertical ^{14}C gradients derived from coeval samples of calcite and gorgonin from recent and subfossil corals. Sample codes correspond with those in Table 2. The line at zero represents a well mixed column of water. Positive values of the calcite minus gorgonin ^{14}C age represent a normally stratified water column with younger waters overlying older waters (e.g. samples 2431 (Sable Gully) and S05/COHPS2001 (Northeast Channel). Reverse stratification is indicated by the remaining samples, all of which were collected northward of the Scotian Slope. Corresponding calcite minus gorgonin $\Delta^{14}C$ is indicated along the upper x-axis. Errors are 1σ.