

Distribution and mineralogy of carbonate sediments on Antarctic shelves

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Abstract

We analyzed 214 new core-top samples for their CaCO_3 content from shelves all around Antarctica in order to understand their distribution and contribution to the marine carbon cycle. The distribution of sedimentary CaCO_3 on the Antarctic shelves is connected to environmental parameters where we considered water depth, width of the shelf, sea-ice coverage and primary production. While CaCO_3 contents of surface sediments are usually low, high (>15%) CaCO_3 contents occur at shallow water depths (150-200 m) on narrow shelves of the eastern Weddell Sea and at a depth range of 600-900 m on the broader and deeper shelves of the Amundsen, Bellingshausen and western Weddell Seas. Regions with high primary production, such as the Ross Sea and the western Antarctic Peninsula region, have generally low CaCO_3 contents in the surface sediments.

The predominant mineral phase of CaCO_3 on the Antarctic shelves is

low-magnesium calcite. With respect to ocean acidification, our findings suggest that dissolution of carbonates in Antarctic shelf sediments may be an important negative feedback only after the onset of calcite undersaturation on the Antarctic shelves.

Macrozoobenthic CaCO_3 standing stocks do not increase the CaCO_3 budget significantly as they are two orders of magnitude lower than the budget of the sediments.

This first circumpolar compilation of Antarctic shelf carbonate data does not claim to be complete. Future studies are encouraged and needed to fill data gaps especially in the under-sampled southwest Pacific and Indian Ocean sectors of the Southern Ocean.

Key words: Southern Ocean, carbonate sediments, ocean acidification, macrozoobenthos, carbon cycle

1. Introduction

Human emissions of CO_2 lead to ocean acidification (OA): as the oceans take up CO_2 from the atmosphere, carbonate equilibria in the oceans shift towards lower pH and lower carbonate ion concentration. As a result, undersaturation with respect to carbonate minerals can occur, leading to disso-

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6 lution of carbonates in marine sediments. The dissolution reaction releases
7 carbonate ions and subsequently tends to increase pH. This mechanism is
8 known as buffering, and it will occur on centennial time scales on the abyssal
9 sea floor (Archer et al., 1997). Within this century, it will be significant and
10 observable at those places where carbon chemistry will change significantly
11 and seafloor sediments bear sufficient carbonate.

12 OA, which is measurable by change in pH, will be strongest in high lat-
13 itudes (McNeil and Mearns, 2008; Orr et al., 2005) due to the temperature
14 dependence of carbonate solubility. Within the polar regions, OA is in-
15 tensified on the shallow shelves (Hauck et al., 2010; Arrigo et al., 2008b).
16 Antarctic shelves will undergo large changes in pH and calcite and aragonite
17 saturation horizons in the near future. The GLODAP (Key et al., 2004) and
18 CARINA (Key et al., 2010) projects have compiled extensive global biogeo-
19 chemical data sets which give a broad picture of recent carbon inventories
20 and ongoing acidification.

21 In contrast, it is not clear how abundant carbonate sediments are on the
22 Antarctic shelves. The Antarctic shelf is unique compared to other continen-
23 tal shelves. It is deeper, has a rugged topography and often a landward-
24 sloping profile, in particular in West Antarctica (Anderson, 1999). The
25 overdeepening of the Antarctic shelf is mainly attributed to long-term glacial
26 erosion, and to a minor degree to the isostatic depression of the bed by the
27 Antarctic ice sheet. The area of the entire Antarctic shelf (depth < 1000 m)
28 is $4.4 \cdot 10^6 \text{ km}^2$ (based on Timmermann et al. (2010)) and it has a mean water

29 depth of approximately 500 m (Anderson, 1999).

30 It has been common knowledge that extensive carbonate oozes appear
31 only in shallow low-latitude sediments (e.g. Milliman (1994); Archer et al.
32 (1994); Seiter et al. (2004)). However, a first data compilation including
33 the Southern Ocean (Seiter et al., 2004) showed that also sediments from
34 the Southern Ocean may have moderate to high carbonate contents. In the
35 global data set of Seiter et al. (2004), though, samples from polar areas
36 are still underrepresented, and it is unknown, how abundant carbonates re-
37 ally are in Antarctic shelf sediments, and which main factors control their
38 distribution. In the past, circum-Antarctic and regional carbonate distribu-
39 tions were mainly inferred from distributions of calcareous and agglutinated
40 foraminifera in surface sediments (e.g. Anderson, 1975; Kellogg and Kellogg,
41 1987; McCoy, 1991) rather than from bulk CaCO_3 contents.

42 Calcium carbonate is produced by marine organisms in the form of two
43 main polymorphs, calcite and aragonite. Its solubility increases with pressure
44 and with decreasing temperature. The depth levels below which aragonite or
45 calcite are undersaturated are denominated aragonite and calcite saturation
46 horizons. The saturation states for calcite (Ω_C) and aragonite (Ω_A) are
47 defined as

$$\Omega_C = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K_{spC}^*} \quad (1)$$

$$\Omega_A = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K_{spA}^*} \quad (2)$$

48 where K_{sp}^* is the stoichiometric solubility product (Zeebe and Wolf-Gladrow,
 49 2001; Mucci, 1983). By definition, Ω is > 1 above and < 1 below the sat-
 50 uration horizon. Aragonite is the more soluble phase, hence its saturation
 51 horizon is shallower than that of calcite. An additional factor that controls
 52 the solubility of calcite is the amount of magnesium incorporated into calcite,
 53 with high-Mg calcite being more soluble than pure calcite (Mucci and Morse,
 54 1984).

55 A variety of planktonic and benthic organisms produce CaCO_3 in the
 56 Southern Ocean (SO), for example pteropods (aragonite), foraminifera (cal-
 57 cite and high- and low-Mg calcite), bryozoans (calcite in Antarctica), echin-
 58 oderms (high-Mg calcite), bivalves (calcitic and aragonitic species) and bra-
 59 chiopods (low-Mg calcite) (Milliman, 1994; Blackmon and Todd, 1959; Kuk-
 60 linski and Taylor, 2009; Weber et al., 1969).

61 One calcitic foraminifera species, *Neogloboquadrina pachyderma* (*sin.*), is
 62 omnipresent and the dominant planktonic foraminifera species in the South-
 63 ern Ocean (e.g. Bergami et al., 2009; Swadling et al., 2010; Donner and Wefer,
 64 1994). Extremely high amounts of *Neogloboquadrina pachyderma* appear in
 65 sea ice (Lipps and Krebs, 1974; Spindler and Dieckmann, 1986; Dieckmann
 66 et al., 1991). *Neogloboquadrina pachyderma* in sea ice can be 70 times more
 67 abundant per volume than in the underlying sea water. The second largest

68 planktonic carbonate producer are pteropods and the dominant species south
69 of the Polar Front is the aragonitic species *Limacina helicina* (Hunt et al.,
70 2008). The distribution of *Limacina helicina* based on meso- and macro-
71 zooplankton analyses is not well understood and appears to be very patchy
72 (Swadling et al., 2010; Hunt et al., 2008; Boysen-Ennen and Piatkowski,
73 1988). Accornero et al. (2003) and Collier et al. (2000) found *Limacina*
74 *helicina* to be the main contributor to carbonate fluxes from sediment trap
75 studies in the Ross Sea, with minor contributions of *Neogloboquadrina pachy-*
76 *derma*. Other sediment trap studies on the eastern Weddell Sea shelf (Isla
77 et al., 2009) and in Bransfield Strait (Donner and Wefer, 1994) observed
78 *Neogloboquadrina pachyderma* to be the dominant foraminifera in their sed-
79 iment traps, but do not report on whether pteropods occurred.

80 Benthic foraminifera are much more diverse than planktonic foraminifera.
81 Mikhalevich (2004) found Antarctic shelf species to be circum-Antarctic, but
82 highly patchy. Representative species include agglutinated, high-Mg calcitic
83 and low-Mg calcitic species in equal shares (Blackmon and Todd, 1959).
84 Bryozoans and echinoderms are crucial parts of the Antarctic macrobenthos
85 (Brey and Gerdes, 1998; Gutt, 2007; Smith, 2007; Hayward, 1995). Together
86 with sponges, bryozoans are the most significant occupiers of the seafloor
87 and their remains may comprise the majority of the coarse bottom sediment
88 (Bullivant, 1961; Hayward, 1995; Barnes and Clarke, 1998). Echinoderms
89 can dominate the community standing stocks, especially at water depths >
90 500 m (Brey and Gerdes, 1998; Brey et al., 1999). The aragonitic bivalve

91 *Laternula elliptica* is widespread in the Antarctic nearshore waters (Ahn and
92 Shim, 1998) and is generally preserved in the sediments as it is one of the most
93 common macrofossils of Antarctic Quaternary and Tertiary sediments (Tada
94 et al., 2006). Other common calcareous macroorganisms in the Southern
95 Ocean are the aragonitic bivalve *Yoldia eightsi* and calcitic gastropods and
96 brachiopods (McClintock et al., 2009).

97 In this study we investigate the distribution of CaCO_3 in surface sedi-
98 ments from Antarctic shelves as well as its mineralogy in order to contribute
99 to the understanding of the fate of biologically produced carbonate. In ad-
100 dition to the analysis of core-top sediments, we estimate the macrozooben-
101 thic CaCO_3 standing stocks. The knowledge about CaCO_3 distribution and
102 mineralogy leads to a qualitative statement about the buffering capacity of
103 carbonates in surface sediments from Antarctic shelves and forms a basis for
104 future quantification of carbonate dissolution effects.

105 **2. Methods**

106 *2.1. Sample material*

107 214 core-top samples from the core repositories at the British Antarctic
108 Survey (BAS), the British Ocean Sediment Core Research Facility (BOSCORF),
109 the Antarctic Marine Geology Research Facility (AMGRF, Florida State
110 University, USA), from recent Polarstern cruises (ANT-XXVI/3 and ANT-
111 XXIII/9) and from Jubany station (Potter Cove) were analyzed. The samples
112 cover the eastern and western Antarctic Peninsula, the Bellingshausen and

113 Amundsen Seas, the Ross Sea and small parts of the southwest Pacific and
114 Indian shelf sectors of the Southern Ocean. All samples were taken from
115 the surface sediments, mostly from 0-1 cm core depth, but a few samples
116 were taken from 1-2, 2-3 or 3-4 cm depth. Wherever possible, we took the
117 samples from box and multiple cores, because surface sediments in gravity
118 and vibrocores are sometimes disturbed or partially lost.

119 *Additional CaCO₃ Data.* In addition to the 214 samples that were measured
120 for the first time in this study, we compiled literature data to cover a repre-
121 sentative area in terms of geographical coverage and water depth, resulting
122 in a total of 390 data points. Data from the shelves in the Weddell Sea
123 were taken from Melles et al. (1991) and additional published data from the
124 Antarctic Peninsula, the Bellingshausen and Amundsen Seas were included
125 (Hillenbrand et al., 2003, 2010). Data from the George V shelf in East
126 Antarctica were supplied by Post et al. (2011). Furthermore, Antarctic shelf
127 data were extracted and quality controlled from the global data compilation
128 by Seiter et al. (2004). Only data where the water depth is at most 1000 m
129 were used. The location of the samples is depicted in Figure 1.

130 This study makes use of previously sampled sediment cores and literature
131 data. The regional and bathymetric distribution of our data is therefore not
132 random, but induced by the availability of data and samples. Data from
133 easily accessible areas as the Antarctic Peninsula are frequent, whereas other
134 more remote areas and very shallow depth regions are underrepresented.
135 Data from shallower than 200 m are available from the Bellingshausen Sea

136 (n=1), Ross Sea (n=1), eastern Weddell Sea (n=3), western Antarctic Penin-
137 sula (n=9), southwestern Pacific and Indian shelf sectors of the Southern
138 Ocean (n=5), but not from the Amundsen Sea, eastern Antarctic Penin-
139 sula and western Weddell Sea. Hence, only 5% of the total 390 data points
140 are from water depths shallower than 200 m. The shallow depth regions con-
141 tribute only a small percentage to the total area of the Antarctic shelves. Fur-
142 thermore, these shallows are not easily accessible, because the bathymetry is
143 poorly known and therefore research vessels rarely sample sediments in these
144 areas.

145 The CaCO_3 data and all metadata such as position, sample depth, core
146 type and data origin of all individual samples is listed in a data table in
147 Pangaea (doi:10.1594/PANGAEA.757933).

148 *2.2. Chemical analyses*

149 All geochemical analyses were carried out on samples that were freeze-
150 dried and ground to homogeneous powders. The mineralogical phase iden-
151 tification was done by means of X-ray diffraction (XRD) on all samples.
152 In a second step, total carbon (TC) and total organic carbon (TOC) were
153 determined.

154 Large calcareous particles, such as fragments of bryozoans or entire bi-
155 valves were excluded, i.e., taken out of the sample before grinding and mea-
156 surement of TC and TOC. These particles do contribute to the sedimentary
157 CaCO_3 inventory, but from a small core-top sample it is difficult to decide,

158 whether these particles are representative for the region and how abundant
159 they are over a larger area. Therefore, our CaCO_3 data give a lower bound-
160 ary of CaCO_3 contents. Distribution of carbonate forming macrozoobenthos
161 and their contribution to carbonate budgets is discussed in sections 2.4 and
162 3.3.

163 *Phase identification.* The bulk sediment was analyzed using a Philips PW
164 diffraction analyzer with a cobalt anode ($\text{CoK}\alpha$ radiation, 40 kV, 40 mA). A
165 range of $3\text{-}100^\circ 2\theta$ was scanned with a step scan speed of $0.02^\circ 2\theta$ per sec-
166 ond. The diffractograms were evaluated with the program "X'Pert HighScore
167 Plus" (Version 2.2c, PANalytical B.V., Almelo, The Netherlands) without in-
168 ternal standard. The position of the calcite peak was corrected for the offset
169 of the quartz peak position from its theoretical value (Tucker, 1996). The
170 Bragg equation was used to convert the 2θ angle into lattice spacing (d). The
171 relationship of Goldsmith et al. (1961) was employed to relate the peak shift
172 of the d_{104} peak with the Mg content in the calcite of the specific sample
173 as recommended by Milliman (1994) and Tucker (1996). Samples with more
174 than 2% CaCO_3 (see Table in Pangaea) were used for the analysis of the
175 carbonate mineralogy.

176 *CaCO_3 quantification.* The percentage of calcium carbonate in the bulk sam-
177 ple was determined on the basis of total inorganic carbon (TIC) which is
178 obtained from TC and TOC measurements. TC was measured on subsam-
179 ples of 10 to 20 mg using a combustion analyzer (Vario EL III, Elementar

180 Analysensysteme GmbH, Germany) and TOC by a carbon-sulfur determi-
 181 nator (LECO CS-125, LECO Instrumente GmbH, Germany). Samples for
 182 TOC measurements (30 to 50 mg) were treated with three drops of ethanol
 183 and 0.5 ml HCL (37%) and heated for two hours at 250°C to remove TIC. A
 184 salt correction was applied to TC and TOC raw data, hence CaCO₃ contents
 185 are reported per mass of salt-free dry sediment. Relative analytical precision
 186 expressed as the standard deviation obtained under repeatability conditions
 187 are 2% for TC and 0.5% for TOC. The CaCO₃ percentage was converted to
 188 g CaCO₃ m⁻² following the procedure described in detail in Archer (1996).
 189 This protocol calculates an average porosity (ϕ) for the top 10 cm of the
 190 sediment based on the percentage of CaCO₃. Calculated porosities range
 191 between 0.751 and 0.863 with a mean of 0.857. We use an average grain
 192 density (ρ) of 2.5 g cm⁻³ and consider the top 10 cm (d) of the sediment in
 193 which we assume the CaCO₃ content to be constant. The top 10 cm of the
 194 sediment reflect the bioturbated layer in which dissolution can take place.
 195 The CaCO₃ content in the 10 cm surface layer is then given as:

$$\text{CaCO}_3 \text{ (g m}^{-2}\text{)} = \frac{\text{CaCO}_3(\%)}{100} \cdot \rho \cdot (1 - \phi) \cdot d \cdot f \quad (3)$$

196 where f is the conversion factor from g cm⁻² to g m⁻².

197 *2.3. GLODAP and CARINA data*

198 The GLODAP and CARINA data bases were used to estimate bottom
 199 water saturation states of calcite and aragonite on the Antarctic shelves.

200 These data bases provide global, extensive quality controlled and internally
201 consistent full water column data of carbon and carbon-relevant variables
202 (Key et al., 2004, 2010). The data were filtered to find stations adjacent
203 to the Antarctic continent with water depths shallower than 1500 m. An
204 offset in water depth of 300 m compared to the bathymetry by Timmermann
205 et al. (2010) was accepted. This procedure assured that only bottom data
206 were considered, but also that data were not discarded due to uncertainties
207 in water depth. As discussed for the sediment samples (section 2.1), also the
208 GLODAP and CARINA data sets consist mainly of non-shelf data. After the
209 filtering procedure, 67 data points remained. These data cover the western
210 Antarctic Peninsula, Ross Sea, western Weddell Sea and southwest Pacific
211 and Indian shelf sectors of the Southern Ocean, include data from 1989 to
212 2003 and allow a valid estimate for Ω_C and Ω_A during the period when most
213 of the sediment cores were taken. Dissolved inorganic carbon (DIC) and total
214 alkalinity (A_T) as well as potential temperature, salinity, pressure, phosphate
215 and silicate data were used from GLODAP/CARINA to calculate Ω_C and
216 Ω_A with the program CO2SYS (Lewis and Wallace, 1998). The carbonic
217 acid dissociation constants from Mehrbach et al. (1973) refit by Dickson and
218 Millero (1987) and the KSO_4 dissociation constant by Dickson (1990) were
219 used.

220 Potential temperature and salinity were utilized to group the data into
221 different water masses (see Table 2). The following water masses were con-
222 sidered: Circumpolar Deep Water (CDW) which is transported around the

223 continent with the Antarctic Circumpolar Current (ACC). This water mass
224 is mixed with Antarctic Surface Water (AASW) south of the ACC to form
225 modified Circumpolar Deep Water (mCDW). In certain regions (mainly Wed-
226 dell and Ross Sea), the release of heat and salt during sea-ice formation on
227 the shelf produces High-Salinity Shelf Water (HSSW) and Ice Shelf Water
228 (ISW). These water masses can sink to depth and mix with surrounding
229 mCDW producing Antarctic Bottom Water (AABW).

230 *2.4. Macrozoobenthos data*

231 Macrozoobenthic wet mass data were analyzed to estimate the contri-
232 bution of macrozoobenthic carbonate producers to the carbonate budget in
233 surface sediments from the Antarctic shelves. The dataset consists of 243 sta-
234 tions on the western Antarctic Peninsula and the southeastern Weddell Sea
235 shelf and slope. Only data where the water depth is <1000 m were used (218
236 stations). Samples were collected with giant box corers, multiple box corers
237 and Van Veen grabs between 1985 and 2007. These samples were sieved over
238 500 μm meshsize screens and abundance and wet mass were determined for
239 35 major taxonomic groups. For the present study, only taxonomic groups
240 which are known to produce CaCO_3 were considered: hydrozoa, bryozoa,
241 brachiopoda, polyplacophora, bivalvia, gastropoda, scaphopoda, echinoidea,
242 holothuroidea, asteroidea, ophiuroidea and crinoidea.

243 The wet mass was converted to CaCO_3 by conversion factors from Brey
244 et al. (2010). For bivalvia and gastropoda, CaCO_3 was calculated by con-

245 verting from wet mass with shell to wet mass without shell. The shell mass
246 was considered equivalent to CaCO_3 mass and was taken as CaCO_3 stand-
247 ing stock for bivalvia and gastropoda. For all other groups, wet mass was
248 converted to dry mass and ash-free dry mass. We use the ash mass, i.e., the
249 difference between dry mass and ash-free dry mass, as a proxy for CaCO_3 .
250 This is a valid estimate as only groups with calcareous endo- and exoskele-
251 tons were considered. No conversion factor was available for polyplacophora,
252 therefore this group was discarded. The wet mass contribution of polypla-
253 cophora to the total wet mass at all stations is 0.2%. The CaCO_3 content per
254 dry mass for echinoderms as calculated with conversion factors by Brey et al.
255 (2010) are comparable to the CaCO_3 contents of echinoderms as determined
256 by Lebrato et al. (2010) except for holothuroidea. Lebrato et al. (2010) mea-
257 sured only one holothuroidean species with a CaCO_3 content of 3.46% per
258 drymass. In contrast, Brey et al. (2010) considered data of 51 species where
259 the ash content ranged from <10 to >80% of the dry weight (mean: 44.5%).
260 In Antarctica, holothuroidea are very diverse and many are heavily calcified
261 (Gutt, 1988). The CaCO_3 standing stocks are given in $\text{g CaCO}_3 \text{ m}^{-2}$, where
262 the volume considered depends on the penetration depth of the sampling
263 device into the sediment. The penetration depth varied with the sediment
264 type and was between 10 and 40 cm. These data are available in Pangaea
265 (doi:10.1594/PANGAEA.757933).

266 **3. Results and Discussion**

267 *3.1. Geographical and bathymetric CaCO₃ distribution*

268 The sediment samples can be grouped into different regions: the western
269 Antarctic Peninsula (wAP) including Marguerite Bay; the eastern Antarctic
270 Peninsula (eAP) including the South Orkney Islands; the Bellingshausen Sea
271 (BS); the Amundsen Sea (AS); the eastern Weddell Sea (eWS), the western
272 Weddell Sea (wWS) and the Ross Sea (RS). Samples from the southwestern
273 Pacific and Indian shelf sectors of the Southern Ocean (swP/IO) are rare and
274 thus were not further split into different regions.

275 The regions show distinct patterns of carbonate preservation in the sedi-
276 ments (Figure 2a and b). In the western and eastern Antarctic Peninsula re-
277 gions, CaCO₃ is hardly preserved in the sediments with mean values of 1.3%
278 CaCO₃ (444 g CaCO₃ m⁻², n=45) and 1.0% (340 g CaCO₃ m⁻², n=72),
279 respectively, and CaCO₃ contents consistently lower than 10%. A similar
280 situation is found in the Ross Sea with a mean CaCO₃ content of 2.0%
281 (714 g CaCO₃ m⁻², n=52) and all CaCO₃ contents < 10%. Higher CaCO₃
282 contents were found in the Amundsen Sea (mean: 5.1%, 2053 g CaCO₃ m⁻²,
283 n=44), eastern Weddell Sea (mean: 6.8%, 3138 g CaCO₃ m⁻², n=24), west-
284 ern Weddell Sea (mean: 4.3%, 2153 g CaCO₃ m⁻², n=42), and especially in
285 the Bellingshausen Sea (mean 8.0%, 3546 g CaCO₃ m⁻², n=40). The swP/IO
286 region is not well captured by our data set because of low sample coverage;
287 58 of the 71 samples are from the George V shelf and 13 from Prydz Bay.
288 The mean CaCO₃ content of these samples is 2.0% (719 g CaCO₃ m⁻²).

289 The CaCO_3 content varies with depth (Figure 2b), and shows maxima
290 with CaCO_3 contents $> 15\%$ around 150 - 200 m and between 600 and 900 m.
291 However, variances at single depths are quite large. These two depth inter-
292 vals reflect two different mechanisms of carbonate preservation. On the parts
293 of the shelf shallower than 200 m, carbonates are preserved, where they were
294 produced and possibly concentrated by currents (winnowing). These car-
295 bonates include the entire range of carbonates produced by planktonic and
296 benthic organisms. In the depth interval between 600 and 900 m, carbon-
297 ates are exclusively accumulated at the outer shelf or near the shelf break.
298 These are locations where carbonates are accumulated by currents and also
299 terrigenous sand contents are high. On the outer shelf in the BS, for exam-
300 ple, sand and calcitic foraminifera are enriched by winnowing of silt and clay
301 (Hillenbrand et al., 2003, 2010).

302 The different shelf regions can be grouped according to which CaCO_3
303 preservation mechanism applies to them. In the regions with broad and
304 deep shelves, i.e, in the Bellingshausen and Amundsen Seas and in the wWS
305 (Figures 2b and 3), carbonates are found to be deposited on the outer shelf
306 (note that no data are available from depths shallower than 200 m in the
307 wWS and in the AS and only one data point in the BS). This corresponds to
308 calcareous foraminifera distributions which were found in high concentrations
309 only on the outer shelf of the Amundsen and western Weddell Seas (Kellogg
310 and Kellogg, 1987; Anderson, 1975; Hillenbrand et al., 2003, 2010).

311 In the eWS, which is characterized by narrow, shallower shelves, CaCO_3

312 accumulates only at the shallow depth interval. High carbonate concen-
313 trations in the eWS are mainly produced by benthic communities, such as
314 bryozoan colonies and molluscs (Gingele et al., 1997). While in our dataset
315 hardly any sample from the George V shelf contains $> 10\%$ CaCO_3 , Domack
316 (1988) reported carbonate contents of 10 - 30% with barnacles, bryozoans,
317 and ostracods dominating the sand and gravel fractions of surface sediments.
318 Post et al. (2010) observed bryozoans and foraminifera, with rare abundances
319 of bivalves, gastropods, ostracods, as well as aragonitic hydrocorals on the
320 continental slope. The 13 samples from Prydz Bay are consistently below
321 2% CaCO_3 .

322 In the Ross Sea, carbonate concentrations are generally low, independent
323 of water depth (Figure 2a and b). This is surprising in the light of reports of
324 high densities of aragonitic pteropods in the water column (Hunt et al., 2008)
325 and sediment traps (Accornero et al., 2003). A total number of 52 sediment
326 samples from the Ross Sea were analysed, however, the shallow banks in
327 the western Ross Sea are represented by only two samples. Domack et al.
328 (1999) reported CaCO_3 contents of $>10\%$ for two cores from one of these
329 shallow banks. Despite the high number of data points in the RS, the mean
330 carbonate deposition might be underestimated due to the fact that these
331 banks are undersampled and often contain winnowed bioclastic carbonates
332 (Anderson, 1999). Likewise, the eastern and western Antarctic Peninsula are
333 very poor in CaCO_3 independent of water depth.

334 Different factors control the deposition and preservation of carbonates in

335 the surface sediments. Important are the flux of organic matter to the ocean
336 floor (related to primary production) and the respiration/remineralization
337 in the sediments, transport of carbonate material by currents and calcium
338 carbonate saturation states of the water mass above the sediment. These
339 factors are discussed below with respect to the distribution of our CaCO_3
340 data.

341 *Primary production.* The Ross Sea and the western Antarctic Peninsula are
342 regions known for very high primary production within the Southern Ocean
343 (Arrigo et al., 2008a; Smith and Gordon, 1997). The mean chlorophyll a
344 concentrations from in situ data are four and five times higher in the western
345 Antarctic Peninsula region and Ross Sea, respectively, than in the remaining
346 SO (Arrigo et al., 2008b). The BS, AS, wWS and large parts of the George V
347 shelf are covered by sea ice for most of the year, limiting the phytoplankton
348 growing season and total production, which likely leads to a reduction of the
349 export production. Respiration in the sediments of the RS and wAP with
350 their high primary production rates is expected to be orders of magnitude
351 higher than in the other shelf regions and alters carbonate chemistry. High
352 export production feeds a benthic community which includes carbonate pro-
353 ducers (Dayton et al., 1982; Cattaneo-Vietti et al., 1999, 2000; Smith, 2007),
354 but this carbonate is dissolved after the death of the organisms and thus not
355 preserved in the sediments. Accordingly, in regions with low primary produc-
356 tivity and export production, there is a small benthic community with few
357 calcareous organisms. Carbonate contents thus reflect the concentration of

358 planktonic foraminifera. These are especially abundant in sea ice. Spindler
359 and Dieckmann (1986), Dieckmann et al. (1991) and Thomas et al. (1998)
360 report large abundances of *Neogloboquadrina pachyderma* in sea ice of the
361 Weddell and Amundsen Seas. This disparity in primary productivity may
362 be the dominant factor in CaCO_3 distribution (Hillenbrand et al., 2003).

363 *Currents.* Current velocities are not available for the entire study region.
364 There are indications for a strong current in the BS close to the shelf edge,
365 associated with the southern boundary of the ACC with velocities of up to
366 28 cm s^{-1} (Read et al., 1995). This current probably winnows silt and clay
367 and favours an enrichment of calcitic particles in the sand fraction. Carbon-
368 ates are mainly represented by *Neogloboquadrina pachyderma* (Hillenbrand
369 et al., 2003). Winnowing by strong currents on the outer shelf and continen-
370 tal slope was suggested to facilitate carbon accumulation by other studies
371 (Gingele et al., 1997; Melles and Kuhn, 1993).

372 *Calcium carbonate saturation state of water masses.* The overlying water
373 mass is another factor controlling carbonate chemistry besides respiration. If
374 the water is undersaturated with respect to one of the carbonate minerals,
375 this mineral will dissolve. The Antarctic shelves with water depths down to
376 1000 m are today still supersaturated with respect to calcite. This is demon-
377 strated using joint data products from GLODAP and CARINA (see section
378 2.3). Bottom water calcite and aragonite saturation states for all stations
379 with water depths down to 1500 m adjacent to the Antarctic continent are

380 shown in Figures 4, 5a and b. A regression through the data points provides
381 an estimate of the aragonite saturation horizon of about 1100 m (Figure 5b).
382 However, single data points indicate that the water is undersaturated with
383 respect to aragonite at even shallower depths at particular locations, even
384 though the data do not take into account sedimentary respiration. Thus,
385 dissolution of aragonite by CO₂-rich water masses might play a role on cer-
386 tain locations of the Antarctic shelves already, especially where ACC water
387 masses protrude onto the shelf (see section 3.2). In contrast, dissolution of
388 calcite due to undersaturated water masses can be ruled out for the recent
389 past.

390 All these factors affect the distribution of CaCO₃ in core-top sediments,
391 and they also interact. Primary production appears to be the dominant
392 factor, determining whether significant proportions of CaCO₃ (> 2%) can
393 be preserved in the sediments. In addition, carbonate production, width of
394 shelf, sea-ice coverage and calcite saturation state of the overlying seawater
395 impact CaCO₃ distribution. The calcite saturation state of the overlying
396 water mass will only play a role when it falls below a threshold. This critical
397 value is dependent on the region and all contributing factors. While a defined
398 calcite saturation state of the bottom water might lead to undersaturation
399 in pore waters in the high-productivity regions, wAP and RS, it might not
400 have any effect in the BS or any other low-productivity region.

401 Further physical and biological processes play a role in the disintegration
402 of CaCO₃ within the sediment (e.g., Smith and Nelson, 2003; Nelson, 1988).

403 Early sea-floor processes include abrasion, bioturbation and bioerosion. The
404 latter involves microbial organisms, that burrow, bore and excavate the car-
405 bonate substrate (Smith and Nelson, 2003). Further petrographic work could
406 shed light on the impact of microbially mediated dissolution. This is beyond
407 the scope of our study, which is trying to disentangle environmental impacts
408 on CaCO_3 distribution and mineralogy.

409 Although we observe general patterns of carbonate distribution, these
410 patterns do not imply that the entire shallow shelf of the eastern Weddell
411 Sea, for example, is covered by biogenic carbonates. The distribution of
412 CaCO_3 is highly patchy, as subsets of samples taken very close to each other
413 in the Lazarev Sea (eWS) demonstrate (Figure 6, data from Gingele et al.
414 (1997)). The patchiness is not well understood, but we assume it is triggered
415 by small-scale topographic features, e.g., differences in substratum for benthic
416 communities or variations of currents.

417 *3.2. Mineralogy*

418 The X-ray diffractograms of the samples with more than 2% CaCO_3 (52
419 out of 189 samples available for X-ray diffraction) showed only one carbonate
420 component to be present and this was calcite throughout all samples. Only
421 in one sample, a calcite and a weak aragonite peak were detected. Low-Mg
422 calcite is dominating throughout the samples, whereas high-Mg calcite was
423 detected in 8% of the samples with a range of 9.9 to 13.9 mol % MgCO_3 .

424 Given that aragonitic pteropods and bivalves (see also section 3.3) are

425 common in their respective habitats in the SO, it is astonishing that no
426 aragonite was found.

427 As discussed above, aragonite undersaturation in the overlying water may
428 be a reason at certain locations, but cannot explain the general absence of
429 aragonite. In Figure 4, locations with $\Omega_A < 1$ are highlighted. These occur
430 on the wAP shelf and in the swP/IO region. The occurrences of aragonite
431 undersaturation on the George V shelf and close to the Ross Sea can be
432 explained by the relation between Ω_A and depth (Figure 5b). Here, aragonite
433 undersaturation is found at water depths between 963 and 1233 m which fall
434 in the range of the saturation horizon. The data points below 1000 m water
435 depth show the characteristics of Antarctic Bottom Water (Figure 5c). Solely
436 the one point at 963 m water depth is less saline.

437 Aragonite undersaturation appears at water depths of 413 and 734 m on
438 the wAP shelf, at 317 m water depth in Prydz Bay and at 398 m water depth
439 at 48°E. The link between these locations is their exposure to Circumpolar
440 Deep Water (CDW, see Figure 5c). The southern boundary of the ACC
441 comes close to the shelf break in these areas (Orsi et al., 1995). CDW can
442 penetrate onto the shelf either directly or further altered as modified Cir-
443 cumpolar Deep Water (mCDW). Salinity and potential temperature reveal
444 that the seawater at locations with $\Omega_A < 1$ belong to CDW (wAP and Prydz
445 Bay locations) or modified Circumpolar Deep Water (at 48°E). The ACC
446 transports these warm and CO₂-rich water masses around the Antarctic con-
447 tinent. In the large cyclonical gyres, i.e. the Weddell, Ross and Kerguelen

448 Gyres, the ACC cannot penetrate near to the shelf. This is consistent with
449 the finding of $\Omega_A > 1$ in the Ross and Weddell Seas and the Kerguelen Gyre
450 (Figure 4). The large gyres impede the exposure of the shelf to naturally
451 more acidic water masses (CDW). There is also a cyclonic gyre in the Prydz
452 Bay region. Although there is only one data point available in Prydz Bay,
453 which indicates aragonite undersaturation, we hypothesize that in the small
454 gyre CDW is less modified and therefore more acidic than in the large gyres.

455 Ice Shelf Water, High-Salinity Shelf Water and Antarctic Surface Water
456 are not undersaturated with respect to aragonite (Figure 5c). This is in
457 contrast to the conclusion of Anderson (1975) that relates the absence of
458 calcareous foraminifera in the southwestern Weddell Sea to the predominance
459 of Ice Shelf Water. We hypothesize that the low numbers of calcareous, but
460 also arenaceous foraminifera are caused by the low primary productivity in
461 this area which cannot feed a benthic community.

462 High respiration rates in the sediment-water interface can further reduce
463 Ω_A . CO_2 is produced in Southern Ocean shelf sediments due to respiration
464 and can be assessed assuming that 1 mol CO_2 is produced for 1 mol O_2
465 respired at constant alkalinity as a first approximation. Oxygen consumption
466 is highly variable in the Antarctic shelf and slope sediments with oxygen
467 penetration depths reaching from 1.2 cm up to several meters (Sachs et al.,
468 2009). If we assume an increase in DIC in the sediment by $20 \mu\text{mol kg}^{-1}$, this
469 would bring the actual aragonite saturation horizon to about 400 m depth
470 (Figure 5b). An increase of $20 \mu\text{mol kg}^{-1}$ DIC is a conservative estimate, a

471 100 - 200 $\mu\text{mol kg}^{-1}$ DIC increase is conceivable in high productivity areas
472 based on the oxygen profiles by Sachs et al. (2009).

473 Given the observation that carbonate accumulations occur either shall-
474 lower than 200 m or deeper than 600 m, aragonite could only be preserved
475 at very shallow depths, i.e., at narrow shelves with limited sea-ice cover and
476 limited primary productivity where CO_2 -rich water masses do not impinge
477 onto the shelf. The review of Hunt et al. (2008) identified the Antarctic
478 Peninsula, Weddell Sea, Lazarev Sea and a coastal region between 30 and
479 90°E as regions with low *Limacina helicina* densities. South Georgia and
480 the Ross Sea are regions of high *Limacina helicina* densities. Additionally
481 a continuous plankton recorder transect between 60 and 160°E longitude
482 and between 50°S and the Antarctic continent exhibited high abundances of
483 *Limacina spp.*. This is in accordance with the finding of large numbers of
484 pteropods by E. Domack (pers. communication) at very shallow depths on
485 the George V shelf. A. Post (pers. communication) found traces of pteropods
486 at two stations at water depths of 233 and 520 m on the George V shelf.

487 As discussed in section 2, shallow depth intervals are undersampled for
488 several reasons. From the samples available for X-ray diffraction analysis
489 only 10 samples were available from this important depth interval. Nine
490 of those were from the wAP and one from the RS, which all fall into the
491 domain of very high primary productivity and poor CaCO_3 preservation.
492 We would expect to find pteropods to be preserved in regions with high
493 pteropod densities, average primary productivity and seasonal sea-ice cover

494 on rather narrow, shallow shelves where the ACC does not penetrate onto the
495 shelf. This reduces possible accumulation sites for pteropods to few locations
496 on the shallow swP/IO shelf, especially the Kerguelen Gyre. More samples
497 along the coast would be needed to prove or disprove this hypothesis.

498 The aragonitic bivalve *Laternula elliptica* is reported to be preserved in
499 sediments as a macrofossil (Tada et al., 2006). As stated in section 2, large
500 calcareous particles were disregarded for the bulk sediment analysis. If this
501 bivalve is preserved as a whole and not ground into a smaller size fraction
502 by natural processes, it will be completely missed by the bulk CaCO_3 and
503 XRD analysis. Therefore, the contribution of macrozoobenthos to carbonate
504 distribution is assessed in the following section.

505 3.3. Macrozoobenthic carbonate abundance

506 Since the contribution of the macrozoobenthic community is not included
507 in the core-top analyses, we present an estimate of the carbonate abundance
508 due to this group of organisms from our analysis of box corers and grab
509 samples. Mean macrozoobenthic carbonate standing stocks are presented in
510 Figure 7. The largest CaCO_3 standing stock from macrozoobenthic commu-
511 nities is found in the eastern Weddell Sea with 24.5 g CaCO_3 per m^2 . This is
512 in line with the report of coarse calcareous debris in the Lazarev Sea (eWS)
513 by, e.g., Gingele et al. (1997). The main contributors are: bivalvia (38%),
514 asteroidea (15%), bryozoa (14%), and ophiuroidea (12%).

515 In the western Antarctic Peninsula region macrozoobenthic community

516 CaCO₃ contribution (mean: 10.4 g CaCO₃ per m²) is very patchily dis-
517 tributed. The macrozoobenthic CaCO₃ contribution in the wAP region is
518 concentrated around the tip of the wAP, especially in the Bransfield Strait.
519 The wAP south of 64°S alone has a mean CaCO₃ standing stock of 1.6 g
520 CaCO₃ per m². At the tip of the Antarctic Peninsula, benthic communities
521 thrive under the high primary productivity and export flux. Most CaCO₃
522 is produced by ophiuroidea (43%), echinoidea (19%), and bivalvia (13%) in
523 the wAP region.

524 The eastern Antarctic Peninsula region, which is represented in this data
525 set mainly by data from the Larsen shelf and the South Orkney Islands,
526 and the western Weddell Sea show lower CaCO₃ contributions (7.4 and 5.4 g
527 CaCO₃ m⁻², respectively). This is at least partly related to trophic lim-
528 itations caused by extensive sea-ice cover. CaCO₃ is mainly produced by
529 bivalvia (56%) and echinoidea (27%) in the eAP region and by ophiuroidea
530 (35%), holothuroidea (24%) and bivalvia (15%) in the wWS region.

531 In general, the most important taxonomic groups that contribute to
532 macrozoobenthic CaCO₃ standing stocks on the Antarctic shelves are bi-
533 valvia (32%), ophiuroidea (20%), asteroidea (12%), echinoidea (11%) and
534 bryozoa (11%). Holothuroidea and gastropoda play a minor role and bra-
535 chiopoda, scaphopoda, crinoidea and aragonitic hydrozoans contribute less
536 than 2% each. The mean standing stock of CaCO₃ by macrozoobenthic or-
537 ganisms (15.6 ± 45.4 g CaCO₃ m⁻²) and its range (0.001 - 585 g CaCO₃
538 m⁻²) on the Southern Ocean shelves is comparable to the numbers found by

539 Lebrato et al. (2010), who only considered echinodermata. The high degree
540 of variability that was found for the carbonate contents of the sediments (sec-
541 tion 3.1) characterizes also the distribution of calcareous macrozoobenthos on
542 the Antarctic shelves, although numbers are generally two orders of magni-
543 tude lower for macrozoobenthos. This high degree of variability is caused by
544 several factors. Mühlenhardt-Siegel (1989) named sediment structure as the
545 most important parameter determining Antarctic zoobenthos assemblages.
546 Gerdes et al. (1992) reported that a high portion of soft-bottom sediment
547 and strong water currents caused the absence of bryozoans in the Filchner
548 Depression area. Additional factors are productivity of the water column
549 and disturbance by ice action (Mühlenhardt-Siegel, 1988). The influence of
550 iceberg scouring was investigated in Gerdes et al. (2003, 2008). Iceberg scour-
551 ing wipes out benthic communities, thereby reducing the total abundance of
552 macrozoobenthos and CaCO_3 standing stocks. During recolonization, motile
553 fauna such as echinoderms dominate the earliest succession stage, followed
554 by sessile pioneers such as bryozoans. The disturbance by icebergs may also
555 partly explain the low CaCO_3 standing stocks in the eAP and wWS region.

556 Within the phylum of echinodermata, ophiuroidea (39%) provide most
557 CaCO_3 , followed by asteroidea (22%). We observe that echinoidea make
558 up 22% which is significantly more than the 9% found by Lebrato et al.
559 (2010) and more than holothuroidea (13%). Crinoidea account for 4% of the
560 echinodermata CaCO_3 standing stock.

561 Bivalves produce 32% of macrozoobenthic CaCO_3 standing stocks, but,

562 although aragonitic species occur, it is unknown to us which percentage of
563 bivalves are aragonitic. However, as macrozoobenthic CaCO_3 inventories
564 appear to be two orders of magnitude lower than sedimentary carbonates,
565 aragonite is definitely only an insignificant part of the total CaCO_3 . Echin-
566 oderns are responsible for half of macrozoobenthic CaCO_3 standing stocks
567 and produce high-Mg calcite (Weber et al., 1969). Thus their skeletons will
568 probably be the first to dissolve, before calcitic bryozoan and bivalve skeltons
569 as well as calcitic foraminifera will be affected.

570 **4. Conclusions**

571 We presented the first circum-Antarctic data set of carbonate content
572 and mineralogy. Up to today, there was no systematic sampling effort to
573 study CaCO_3 production and preservation on Antarctic shelves. Large areas,
574 especially in the southwest Pacific and Indian Ocean sectors of the Antarctic
575 shelves are still largely under-sampled. Future research in these regions is
576 essential to achieve a process-based understanding of the fate of CaCO_3 in
577 the sediments and the Southern Ocean CaCO_3 cycle in general.

578 Over the next decades, Antarctic Surface Water might become the most
579 acidic water mass in the Southern Ocean (Hauck et al., 2010) as the sur-
580 face ocean accumulates most CO_2 from the atmosphere; the CO_2 increase
581 in the deeper layers is much smaller due to mixing with waters poor in an-
582 thropogenic CO_2 . Once the saturation horizon for calcite will become as
583 shallow to reach the Antarctic shelves, locally present carbonate-rich sedi-

584 ments will dissolve. The capacity to buffer future acidification is small in
585 high-productivity regions as the western Antarctic Peninsula and the Ross
586 Sea and higher in the Bellingshausen, Amundsen and Weddell Seas. The
587 buffering effect cannot be quantified yet, but this will be attempted in a
588 modelling approach.

589 The water masses most corrosive to CaCO_3 are Antarctic Bottom Water
590 and Circumpolar Deep Water. Today, the cyclonic gyres, the Weddell, Ross
591 and Kerguelen Gyres, keep the corrosive Circumpolar Deep Water away from
592 the shelf in the respective regions. Undersaturation with respect to aragonite
593 at depths shallower than 1100 m is found only outside these gyres. The cor-
594 rosiveness of pore water depends on the combination of carbonate saturation
595 state of the bottom water and the amount of CO_2 released by respiration.

596 Dissolution of aragonite is not a mechanism which can buffer ocean acid-
597 ification in the Southern Ocean, as aragonite is not a prominent constituent
598 of surface sediments on the Antarctic shelves.

599 Comparison of the contributions of sedimentary carbonate and macro-
600 zoobenthic carbonate ($> 500 \mu\text{m}$) in the regions, from which data from
601 both analyses is available (compare Figure 7), emphasized the sedimentary
602 carbonate to be quantitatively more important in the marine carbon cy-
603 cle. Sedimentary carbonate contents are two orders of magnitude higher
604 than macrozoobenthic carbonate contents. Hence, neglecting large debris in
605 the determination of sedimentary CaCO_3 content does not lead to a signifi-
606 cant underestimation of the total CaCO_3 content. In the eastern Antarctic

607 Peninsula (eAP) region, macrozoobenthic contribution and sedimentary car-
608 bonate contents are low. In the western Antarctic Peninsula (wAP) region
609 the macrozoobenthic carbonate standing stock is very patchy, whereas the
610 sedimentary CaCO_3 is uniformly distributed, but low compared to the other
611 regions. In the eastern Weddell Sea (eWS), both the CaCO_3 percentages
612 in sediments and calcareous macrozoobenthos abundance are very high on
613 their respective scales. Here, strong production and preservation favour high
614 CaCO_3 contents. Considering only the eAP, wAP and eWS regions, there
615 appears to be a relation between macrozoobenthic stocks and sedimentary
616 carbonate contents. The western Weddell Sea is different. The macrozooben-
617 thic carbonate abundance is the smallest within the study area, but the
618 sedimentary part is comparable to the one in the eastern Weddell Sea. This
619 underlines that in the regions with broad shelves, major sea-ice cover and lim-
620 ited primary production, benthic CaCO_3 production has a minor influence
621 on sedimentary CaCO_3 contents (compare section 3.1). Calcium carbonate
622 is mainly produced by planktonic organisms, presumably to a large extent
623 by *Neogloboquadrina pachyderma* living in the water column and in the sea
624 ice.

625 Although we have no macrozoobenthos data from the Ross Sea, Belling-
626 shausen Sea, Amundsen Sea, southwest Pacific and Indian Ocean, the classifi-
627 cation we found in section 3.1 indicates that a situation similar to that in the
628 wWS applies to the Bellingshausen and Amundsen Seas. We expect macro-
629 zoobenthic CaCO_3 stocks similar to the wAP in the Ross Sea and similar to

630 the eWS in the Kerguelen Gyre. This classification is based on environmen-
631 tal conditions such as sea-ice cover, primary production, width of the shelf
632 and water mass distribution. There was not enough data available to make
633 statements about the entire southwest Pacific and Indian Ocean region.

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Figure 1: Position of all core-top data (new and literature data). Isolines are from the topography of Timmermann et al. (2010) and lines are drawn every 1000 m. Different shelf regions are indicated by boxes. AS: Amundsen Sea; BS: Bellingshausen Sea; eAP: eastern Antarctic Peninsula; eWS: eastern Weddell Sea; RS: Ross Sea; swP/IO: southwest Pacific/Indian Ocean; wAP: western Antarctic Peninsula; wWS: western Weddell Sea

Figure 2: (a) Boxplots of sedimentary CaCO_3 content (%) in the different Antarctic shelf regions. AS: Amundsen Sea ($n = 44$); BS: Bellingshausen Sea ($n = 40$); eAP: eastern Antarctic Peninsula ($n = 72$); eWS: eastern Weddell Sea ($n = 24$); RS: Ross Sea ($n = 52$); swP/IO: southwest Pacific/Indian Ocean ($n = 71$); wAP: western Antarctic Peninsula ($n = 45$); wWS: western Weddell Sea ($n = 42$), (b) Sedimentary CaCO_3 content (%) versus water depth on the Antarctic shelves. Different shelf regions are indicated by symbols. Bold lines indicate 2 and 15 % CaCO_3

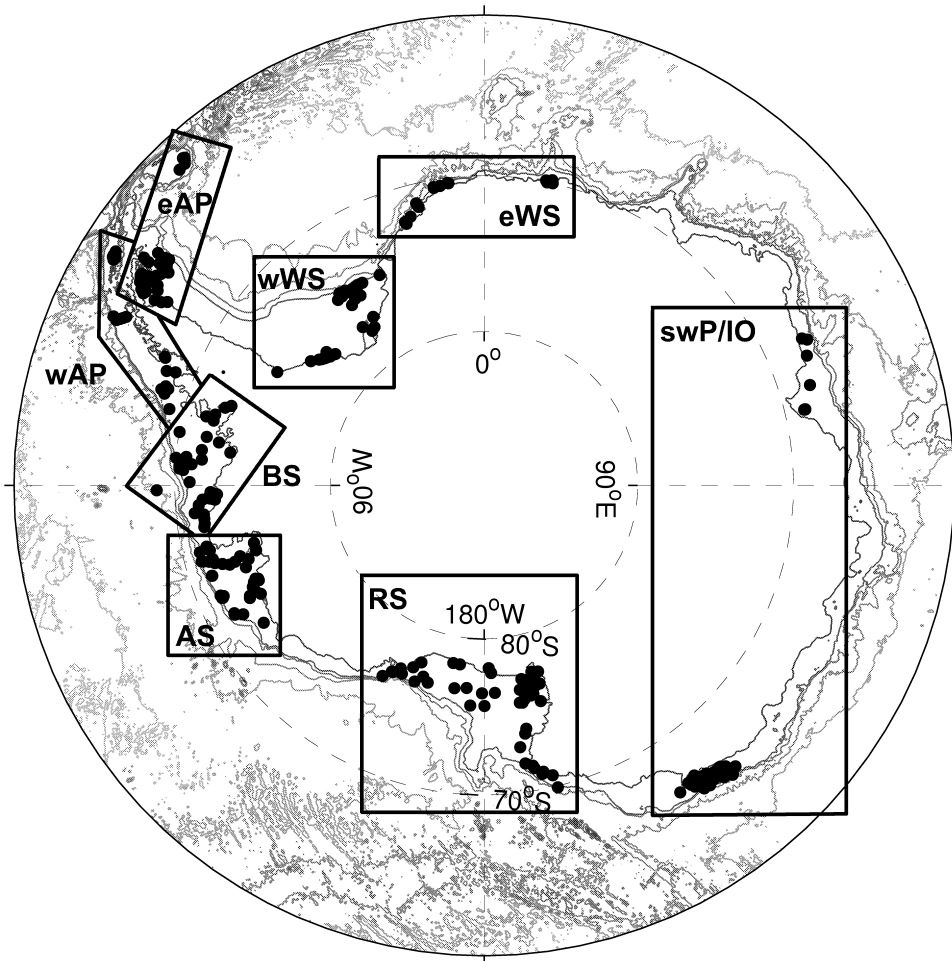
Figure 3: Sedimentary CaCO_3 content (%) (a) on the Amundsen Sea shelf and (b) on the Bellingshausen Sea shelf. Isolines are from the topography of Timmermann et al. (2010), lines are drawn every 200 m between 0 and 1000 m and every 500 m at water depths > 1000 m.

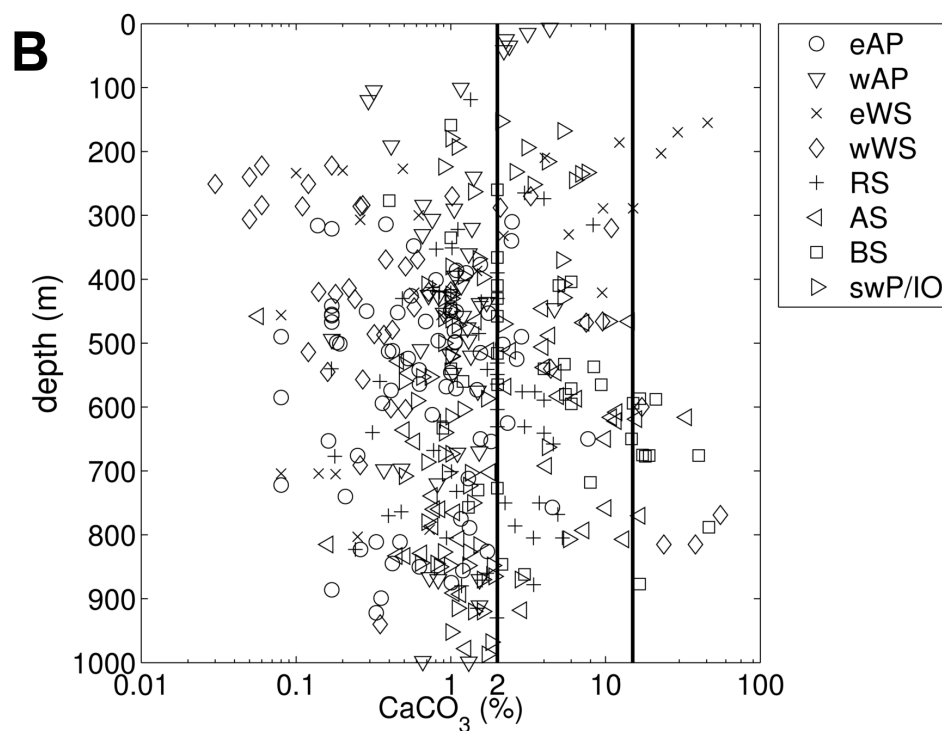
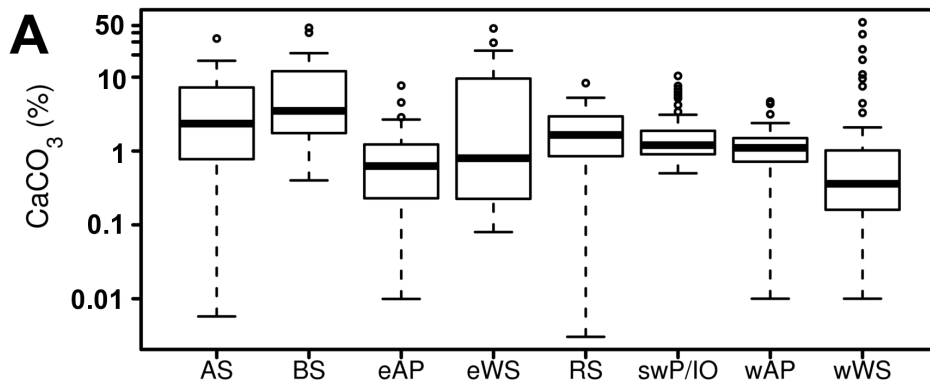
Figure 4: Bottom water Ω_A on the Antarctic shelves from GLODAP and CARINA data. Occurrence of undersaturation at depths shallower than 1100 m is marked with a black cross. Isolines are from the topography of Timmermann et al. (2010) and lines are drawn every 1000 m.

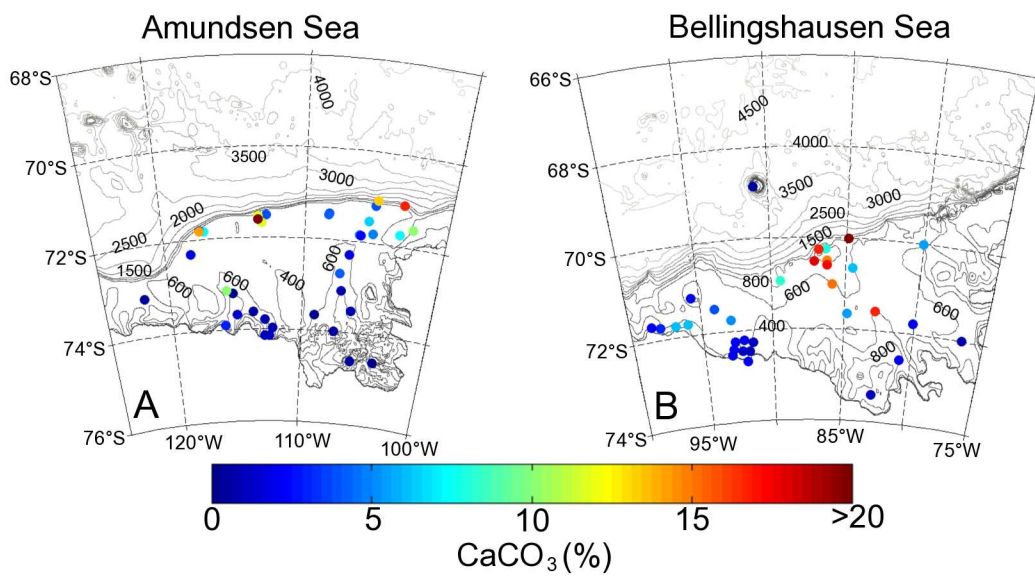
Figure 5: Bottom water saturation states (a) Ω_C and (b) Ω_A on the Antarctic shelves and slope from GLODAP and CARINA data. Calcite is supersaturated at all depths. A linear regression through Ω_A reveals a mean saturation horizon of about 1100 m with certain areas being undersaturated at even shallower depths. The grey diamonds and dotted regression line were calculated assuming a DIC increase of $20 \mu\text{mol kg}^{-1}$ within the first cm of the sediment related to oxic remineralization of organic matter. (c) T/S-diagram of Antarctic shelf data from the GLODAP and CARINA data sets. Filled markers indicate $\Omega_A < 1$. Different markers indicate different regions: Ross Sea (squares), western Antarctic Peninsula (circles), western Weddell Sea (diamonds), southwest Pacific and Indian shelf sectors of the Southern Ocean (triangles). The properties of the main watermasses are indicated by boxes. Modified Circumpolar Deep Water is not indicated, but is defined as being colder and less saline than Circumpolar Deep Water. See text, Table 1 and Table 2 for further explanation and abbreviations.

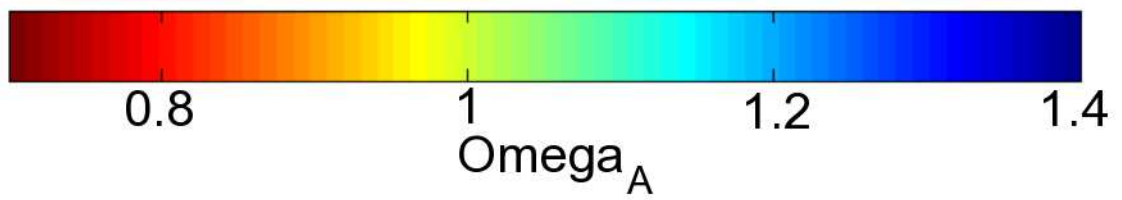
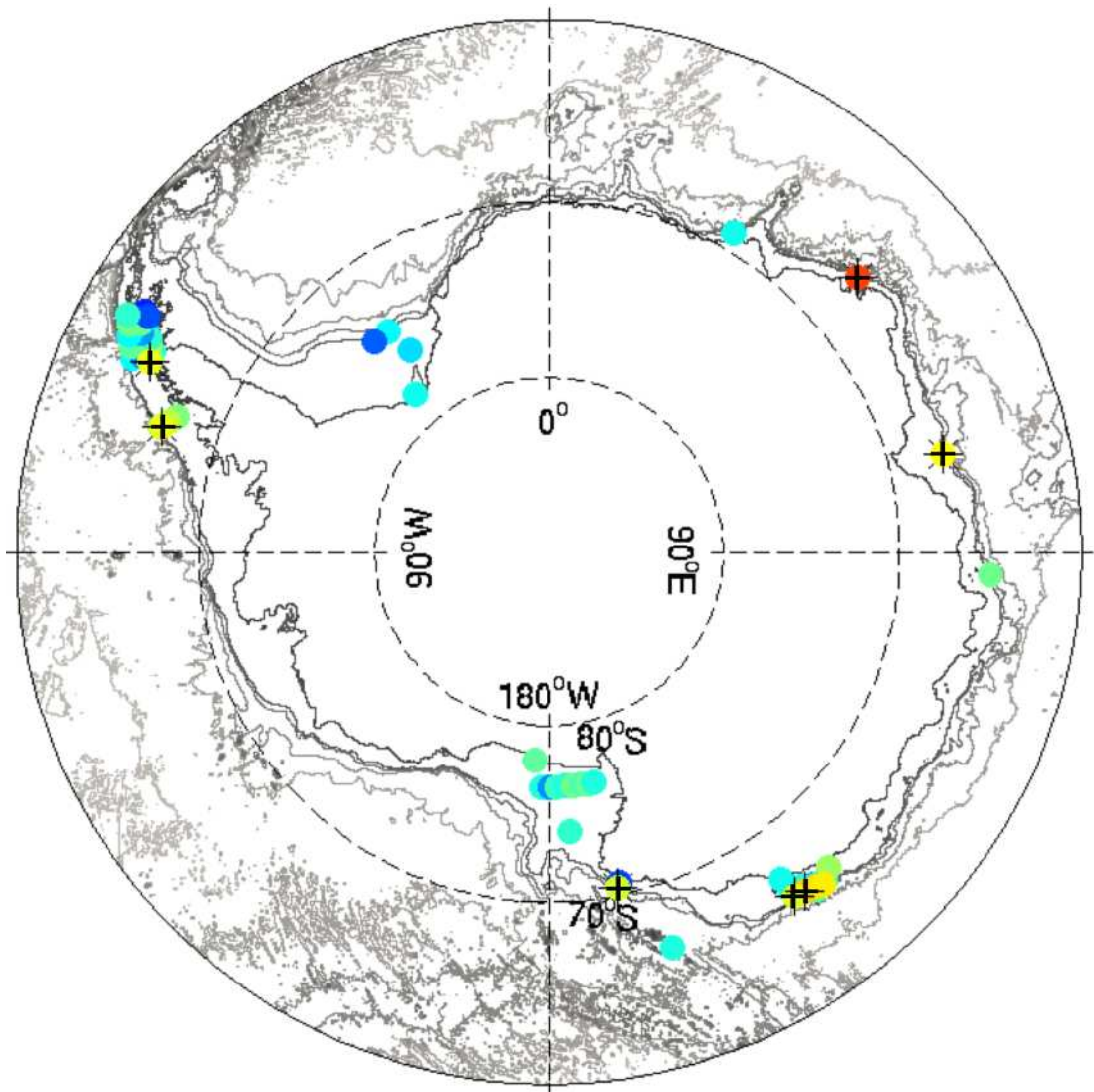
Figure 6: Sedimentary CaCO_3 content (%) on the eastern Weddell Sea shelf with data from Gingele et al. (1997).

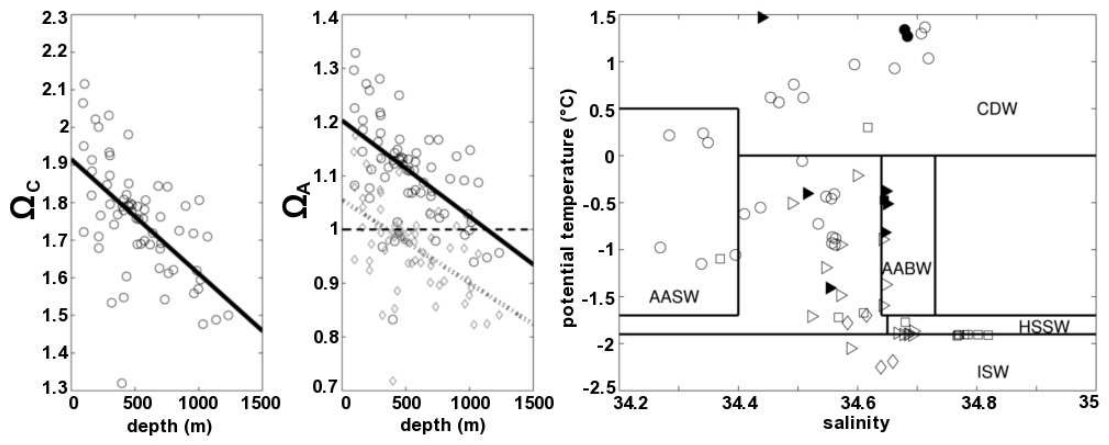
Figure 7: Mean carbonate contribution in g m^{-2} for the west and east Antarctic Peninsula (wAP and eAP) and western and eastern Weddell Sea (wWS and eWS) regions. Bars show the contribution by macrozoobenthos (left scale) and circles depict sedimentary CaCO_3 (right scale)



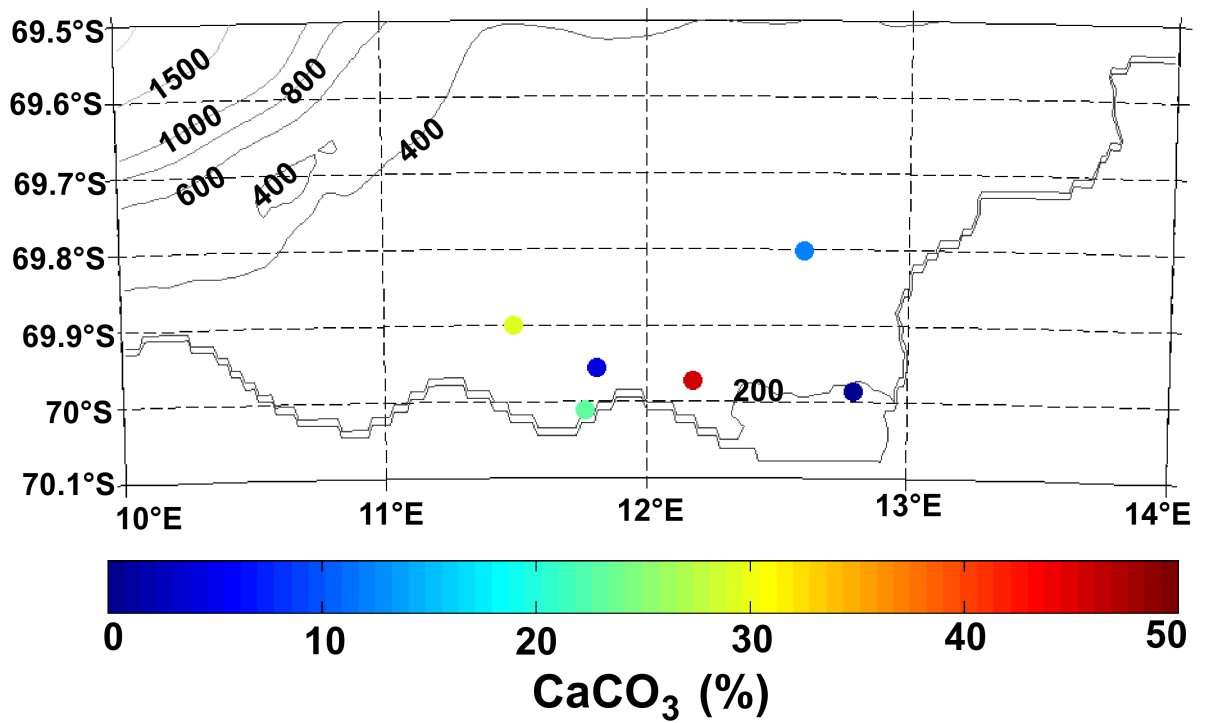








Eastern Weddell Sea



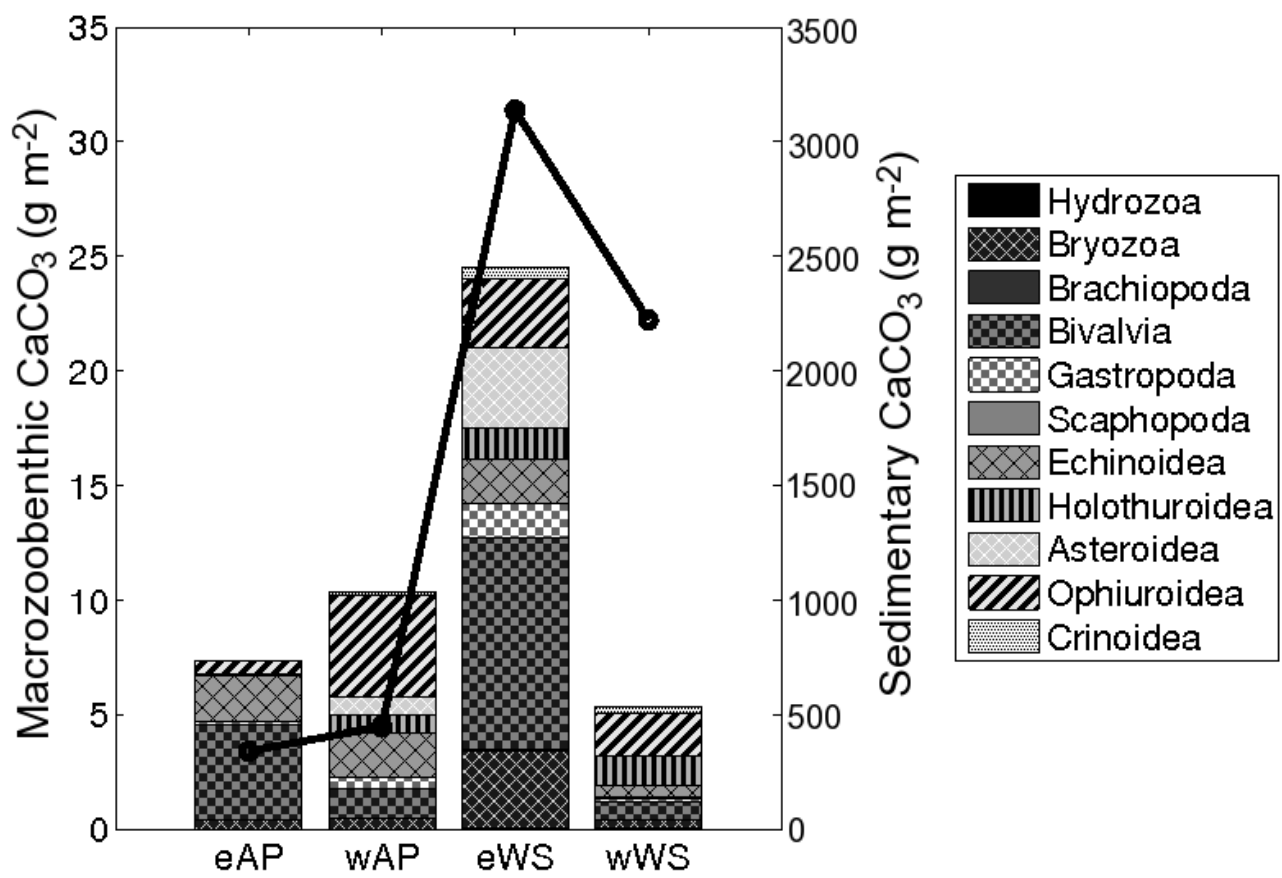


Table 1: List of acronyms

Acronym	Full Name
AABW	Antarctic Bottom Water
AASW	Antarctic Surface Water
ACC	Antarctic Circumpolar Current
AS	Amundsen Sea
A_T	Total alkalinity
BS	Bellingshausen Sea
CDW	Circumpolar Deep Water
DIC	Dissolved inorganic carbon
eAP	Eastern Antarctic Peninsula
eWS	Eastern Weddell Sea
HSSW	High-Salinity Shelf Water
ISW	Ice-Shelf Water
mCDW	Modified Circumpolar Deep Water
RS	Ross Sea
SO	Southern Ocean
swP/IO	Southwestern Pacific and Indian Ocean
TC	Total carbon
TIC	Total inorganic carbon
TOC	Total organic carbon
XRD	X-ray diffraction
wAP	Western Antarctic Peninsula
wWS	Western Weddell Sea

Table 2: Main water masses occurring in the Antarctic shelf and slope region.

Water Mass ^a	θ ^b (°C)	Salinity	Reference
AABW	-1.7 to 0	34.64 to 34.73	Gordon (1974); Carmack (1977)
AASW	-1.7 to 0.5	< 34.4	Orsi et al. (1995); Grosfeld et al. (2001)
CDW ^c	> 0		Orsi et al. (1995, 1993)
HSSW	-1.9 to -1.7	> 34.65	Grosfeld et al. (2001)
ISW	< -1.9		Grosfeld et al. (2001)

^a AABW: Antarctic Bottom Water, AASW: Antarctic Surface Water, HSSW: High-Salinity Shelf Water, ISW: Ice-Shelf Water, CDW: Circumpolar Deep Water

^b potential temperature

^c modified Circumpolar Deep Water (mCDW) is defined as being colder and less saline than CDW (Whitworth III et al., 1998)