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

OA, which is measurable by change in pH, will be strongest in high latitudes (McNeil and Matear, 2008; Orr et al., 2005) due to the temperature dependence of carbonate solubility. Within the polar regions, OA is intensified on the shallow shelves (Hauck et al., 2010; Arrigo et al., 2008b). Antarctic shelves will undergo large changes in pH and calcite and aragonite saturation horizons in the near future. The GLODAP (Key et al., 2004) and CARINA (Key et al., 2010) projects have compiled extensive global biogeochemical data sets which give a broad picture of recent carbon inventories and ongoing acidification.

In contrast, it is not clear how abundant carbonate sediments are on the Antarctic shelves. The Antarctic shelf is unique compared to other continental shelves. It is deeper, has a rugged topography and often a landward-sloping profile, in particular in West Antarctica (Anderson, 1999). The overdeepening of the Antarctic shelf is mainly attributed to long-term glacial erosion, and to a minor degree to the isostatic depression of the bed by the Antarctic ice sheet. The area of the entire Antarctic shelf (depth < 1000 m) is $4.4\ 10^6$ km^2 (based on Timmermann et al. (2010)) and it has a mean water depth of approximately 500 m (Anderson, 1999).

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

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

$$\Omega_C = \frac{[\mathrm{Ca}^{2+}][\mathrm{CO}_3^{2-}]}{K^*_{sp\,C}} \qquad (1)$$

$$\Omega_A = \frac{[Ca^{2+}][CO_3^{2-}]}{K^*_{sp\,A}} \tag{2}$$

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

A variety of planktonic and benthic organisms produce $CaCO_3$ in the Southern Ocean (SO), for example pteropods (aragonite), foraminifera (calcite and high- and low-Mg calcite), bryozoans (calcite in Antarctica), echinoderms (high-Mg calcite), bivalves (calcitic and aragonitic species) and brachiopods (low-Mg calcite) (Milliman, 1994; Blackmon and Todd, 1959; Kuklinski and Taylor, 2009; Weber et al., 1969).

One calcitic foraminifera species, *Neogloboquadrina pachyderma (sin.)*, is omnipresent and the dominant planktonic foraminfera species in the Southern Ocean (e.g. Bergami et al., 2009; Swadling et al., 2010; Donner and Wefer, 1994). Extremely high amounts of *Neogloboquadrina pachyderma* appear in sea ice (Lipps and Krebs, 1974; Spindler and Dieckmann, 1986; Dieckmann et al., 1991). *Neogloboquadrina pachyderma* in sea ice can be 70 times more abundant per volume than in the underlying sea water. The second largest planktonic carbonate producer are pteropods and the dominant species south of the Polar Front is the aragonitic species *Limacina helicina* (Hunt et al., 2008). The distribution of *Limacina helicina* based on meso- and macro-zooplankton analyses is not well understood and appears to be very patchy (Swadling et al., 2010; Hunt et al., 2008; Boysen-Ennen and Piatkowski, 1988). Accornero et al. (2003) and Collier et al. (2000) found *Limacina helicina* to be the main contributor to carbonate fluxes from sediment trap studies in the Ross Sea, with minor contributions of *Neogloboquadrina pachyderma*. Other sediment trap studies on the eastern Weddell Sea shelf (Isla et al., 2009) and in Bransfield Strait (Donner and Wefer, 1994) observed *Neogloboquadrina pachyderma* to be the dominant foraminifera in their sediment traps, but do not report on whether pteropods occurred.

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

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

In this study we investigate the distribution of $CaCO_3$ in surface sediments from Antarctic shelves as well as its mineralogy in order to contribute to the understanding of the fate of biologically produced carbonate. In addition to the analysis of core-top sediments, we estimate the macrozoobenthic $CaCO_3$ standing stocks. The knowledge about $CaCO_3$ distribution and mineralogy leads to a qualitative statement about the buffering capacity of carbonates in surface sediments from Antarctic shelves and forms a basis for future quantification of carbonate dissolution effects.

2. Methods

2.1. Sample material

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

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

Additional $CaCO_3$ *Data.* In addition to the 214 samples that were measured for the first time in this study, we compiled literature data to cover a representative area in terms of geographical coverage and water depth, resulting in a total of 390 data points. Data from the shelves in the Weddell Sea were taken from Melles et al. (1991) and additional published data from the Antarctic Peninsula, the Bellingshausen and Amundsen Seas were included (Hillenbrand et al., 2003, 2010). Data from the George V shelf in East Antarctica were supplied by Post et al. (2011). Furthermore, Antarctic shelf data were extracted and quality controlled from the global data compilation by Seiter et al. (2004). Only data where the water depth is at most 1000 m were used. The location of the samples is depicted in Figure 1.

This study makes use of previously sampled sediment cores and literature data. The regional and bathymetric distribution of our data is therefore not random, but induced by the availability of data and samples. Data from easily accessible areas as the Antarctic Peninsula are frequent, whereas other more remote areas and very shallow depth regions are underrepresented. Data from shallower than 200 m are available from the Bellingshausen Sea (n=1), Ross Sea (n=1), eastern Weddell Sea (n=3), western Antarctic Peninsula (n=9), southwestern Pacific and Indian shelf sectors of the Southern Ocean (n=5), but not from the Amundsen Sea, eastern Antarctic Peninsula and western Weddell Sea. Hence, only 5% of the total 390 data points are from water depths shallower than 200 m. The shallow depth regions contribute only a small percentage to the total area of the Antarctic shelves. Furthermore, these shallows are not easily accessible, because the bathymetry is poorly known and therefore research vessels rarely sample sediments in these areas.

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

2.2. Chemical analyses

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

Large calcareous particles, such as fragments of bryozoans or entire bivalves were excluded, i.e., taken out of the sample before grinding and measurement of TC and TOC. These particles do contribute to the sedimentary $CaCO_3$ inventory, but from a small core-top sample it is difficult to decide, whether these particles are representative for the region and how abundant they are over a larger area. Therefore, our $CaCO_3$ data give a lower boundary of $CaCO_3$ contents. Distribution of carbonate forming macrozoobenthos and their contribution to carbonate budgets is discussed in sections 2.4 and 3.3.

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

$CaCO_3$ quantification. The percentage of calcium carbonate in the bulk sample was determined on the basis of total inorganic carbon (TIC) which is obtained from TC and TOC measurements. TC was measured on subsamples of 10 to 20 mg using a combustion analyzer (Vario EL III, Elementar

Analysensysteme GmbH, Germany) and TOC by a carbon-sulfur determinator (LECO CS-125, LECO Instrumente GmbH, Germany). Samples for TOC measurements (30 to 50 mg) were treated with three drops of ethanol and 0.5 ml HCL (37%) and heated for two hours at 250°C to remove TIC. A salt correction was applied to TC and TOC raw data, hence $CaCO_3$ contents are reported per mass of salt-free dry sediment. Relative analytical precision expressed as the standard deviation obtained under repeatability conditions are 2% for TC and 0.5% for TOC. The $CaCO_3$ percentage was converted to g $CaCO_3$ m^{-2} following the procedure described in detail in Archer (1996). This protocol calculates an average porosity (ϕ) for the top 10 cm of the sediment based on the percentage of $CaCO_3$. Calculated porosities range between 0.751 and 0.863 with a mean of 0.857. We use an average grain density (ρ) of 2.5 g cm^{-3} and consider the top 10 cm (d) of the sediment in which we assume the $CaCO_3$ content to be constant. The top 10 cm of the sediment reflect the bioturbated layer in which dissolution can take place. The $CaCO_3$ content in the 10 cm surface layer is then given as:

$$\mathrm{CaCO_3}\ (\mathrm{g\ m^{-2}}) = \frac{\mathrm{CaCO_3}(\%)}{100} \cdot \rho \cdot (1 - \phi) \cdot \mathrm{d} \cdot \mathrm{f} \tag{3}$$

where f is the conversion factor from g cm^{-2} to g m^{-2}.

2.3. GLODAP and CARINA data

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

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

Potential temperature and salinity were utilized to group the data into different water masses (see Table 2). The following water masses were considered: Circumpolar Deep Water (CDW) which is transported around the continent with the Antarctic Circumpolar Current (ACC). This water mass is mixed with Antarctic Surface Water (AASW) south of the ACC to form modified Circumpolar Deep Water (mCDW). In certain regions (mainly Weddell and Ross Sea), the release of heat and salt during sea-ice formation on the shelf produces High-Salinity Shelf Water (HSSW) and Ice Shelf Water (ISW). These water masses can sink to depth and mix with surrounding mCDW producing Antarctic Bottom Water (AABW).

2.4. Macrozoobenthos data

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

The wet mass was converted to $CaCO_3$ by conversion factors from Brey et al. (2010). For bivalvia and gastropoda, $CaCO_3$ was calculated by converting from wet mass with shell to wet mass without shell. The shell mass was considered equivalent to $CaCO_3$ mass and was taken as $CaCO_3$ standing stock for bivalvia and gastropoda. For all other groups, wet mass was converted to dry mass and ash-free dry mass. We use the ash mass, i.e., the difference between dry mass and ash-free dry mass, as a proxy for $CaCO_3$. This is a valid estimate as only groups with calcareous endo- and exoskeletons were considered. No conversion factor was available for polyplacophora, therefore this group was discarded. The wet mass contribution of polyplacophora to the total wet mass at all stations is 0.2%. The $CaCO_3$ content per dry mass for echinoderms as calculated with conversion factors by Brey et al. (2010) are comparable to the $CaCO_3$ contents of echinoderms as determined by Lebrato et al. (2010) except for holothuroidea. Lebrato et al. (2010) measured only one holothuroidean species with a $CaCO_3$ content of 3.46% per drymass. In contrast, Brey et al. (2010) considered data of 51 species where the ash content ranged from <10 to >80% of the dry weight (mean: 44.5%). In Antarctica, holothuroidea are very diverse and many are heavily calcified (Gutt, 1988). The $CaCO_3$ standing stocks are given in g $CaCO_3$ m^{-2}, where the volume considered depends on the penetration depth of the sampling device into the sediment. The penetration depth varied with the sediment type and was between 10 and 40 cm. These data are available in Pangaea (doi:10.1594/PANGAEA.757933).

3. Results and Discussion

3.1. Geographical and bathymetric $CaCO_3$ distribution

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

The regions show distinct patterns of carbonate preservation in the sediments (Figure 2a and b). In the western and eastern Antarctic Peninsula regions, $CaCO_3$ is hardly preserved in the sediments with mean values of 1.3% $CaCO_3$ (444 g $CaCO_3$ m^{-2}, n=45) and 1.0% (340 g $CaCO_3$ m^{-2}, n=72), respectively, and $CaCO_3$ contents consistently lower than 10%. A similar situation is found in the Ross Sea with a mean $CaCO_3$ content of 2.0% (714 g $CaCO_3$ m^{-2}, n=52) and all $CaCO_3$ contents $< 10\%$. Higher $CaCO_3$ contents were found in the Amundsen Sea (mean: 5.1%, 2053 g $CaCO_3$ m^{-2}, n=44), eastern Weddell Sea (mean: 6.8%, 3138 g $CaCO_3$ m^{-2}, n=24), western Weddell Sea (mean: 4.3%, 2153 g $CaCO_3$ m^{-2}, n=42), and especially in the Bellingshausen Sea (mean 8.0%, 3546 g $CaCO_3$ m^{-2}, n=40). The swP/IO region is not well captured by our data set because of low sample coverage; 58 of the 71 samples are from the George V shelf and 13 from Prydz Bay. The mean $CaCO_3$ content of these samples is 2.0% (719 g $CaCO_3$ m^{-2}).

The $CaCO_3$ content varies with depth (Figure 2b), and shows maxima with $CaCO_3$ contents $> 15\%$ around 150 - 200 m and between 600 and 900 m. However, variances at single depths are quite large. These two depth intervals reflect two different mechanisms of carbonate preservation. On the parts of the shelf shallower than 200 m, carbonates are preserved, where they were produced and possibly concentrated by currents (winnowing). These carbonates include the entire range of carbonates produced by planktonic and benthic organisms. In the depth interval between 600 and 900 m, carbonates are exclusively accumulated at the outer shelf or near the shelf break. These are locations where carbonates are accumulated by currents and also terrigeneous sand contents are high. On the outer shelf in the BS, for example, sand and calcitic foraminifera are enriched by winnowing of silt and clay (Hillenbrand et al., 2003, 2010).

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

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

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

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

Different factors control the deposition and preservation of carbonates in the surface sediments. Important are the flux of organic matter to the ocean floor (related to primary production) and the respiration/remineralization in the sediments, transport of carbonate material by currents and calcium carbonate saturation states of the water mass above the sediment. These factors are discussed below with respect to the distribution of our $CaCO_3$ data.

Primary production. The Ross Sea and the western Antarctic Peninsula are regions known for very high primary production within the Southern Ocean (Arrigo et al., 2008a; Smith and Gordon, 1997). The mean chlorophyll a concentrations from in situ data are four and five times higher in the western Antarctic Peninsula region and Ross Sea, respectively, than in the remaining SO (Arrigo et al., 2008b). The BS, AS, wWS and large parts of the George V shelf are covered by sea ice for most of the year, limiting the phytoplankton growing season and total production, which likely leads to a reduction of the export production. Respiration in the sediments of the RS and wAP with their high primary production rates is expected to be orders of magnitude higher than in the other shelf regions and alters carbonate chemistry. High export production feeds a benthic community which includes carbonate producers (Dayton et al., 1982; Cattaneo-Vietti et al., 1999, 2000; Smith, 2007), but this carbonate is dissolved after the death of the organisms and thus not preserved in the sediments. Accordingly, in regions with low primary productivity and export production, there is a small benthic community with few calcareous organisms. Carbonate contents thus reflect the concentration of planktonic foraminifera. These are especially abundant in sea ice. Spindler and Dieckmann (1986), Dieckmann et al. (1991) and Thomas et al. (1998) report large abundances of *Neogloboquadrina pachyderma* in sea ice of the Weddell and Amundsen Seas. This disparity in primary productivity may be the dominant factor in $CaCO_3$ distribution (Hillenbrand et al., 2003).

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

Calcium carbonate saturation state of water masses. The overlying water mass is another factor controlling carbonate chemistry besides respiration. If the water is undersaturated with respect to one of the carbonate minerals, this mineral will dissolve. The Antarctic shelves with water depths down to 1000 m are today still supersaturated with respect to calcite. This is demonstrated using joint data products from GLODAP and CARINA (see section 2.3). Bottom water calcite and aragonite saturation states for all stations with water depths down to 1500 m adjacent to the Antarctic continent are shown in Figures 4, 5a and b. A regression through the data points provides an estimate of the aragonite saturation horizon of about 1100 m (Figure 5b). However, single data points indicate that the water is undersaturated with respect to aragonite at even shallower depths at particular locations, even though the data do not take into account sedimentary respiration. Thus, dissolution of aragonite by CO_2-rich water masses might play a role on certain locations of the Antarctic shelves already, especially where ACC water masses protrude onto the shelf (see section 3.2). In contrast, dissolution of calcite due to undersaturated water masses can be ruled out for the recent past.

All these factors affect the distribution of $CaCO_3$ in core-top sediments, and they also interact. Primary production appears to be the dominant factor, determining whether significant proportions of $CaCO_3$ ($> 2\%$) can be preserved in the sediments. In addition, carbonate production, width of shelf, sea-ice coverage and calcite saturation state of the overlying seawater impact $CaCO_3$ distribution. The calcite saturation state of the overlying water mass will only play a role when it falls below a threshold. This critical value is dependent on the region and all contributing factors. While a defined calcite saturation state of the bottom water might lead to undersaturation in pore waters in the high-productivity regions, wAP and RS, it might not have any effect in the BS or any other low-productivity region.

Further physical and biological processes play a role in the disintegration of $CaCO_3$ within the sediment (e.g., Smith and Nelson, 2003; Nelson, 1988).

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

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

3.2. Mineralogy

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

Given that aragonitic pteropods and bivalves (see also section 3.3) are common in their respective habitats in the SO, it is astonishing that no aragonite was found.

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

Aragonite undersaturation appears at water depths of 413 and 734 m on the wAP shelf, at 317 m water depth in Prydz Bay and at 398 m water depth at 48°E. The link between these locations is their exposure to Circumpolar Deep Water (CDW, see Figure 5c). The southern boundary of the ACC comes close to the shelf break in these areas (Orsi et al., 1995). CDW can penetrate onto the shelf either directly or further altered as modified Circumpolar Deep Water (mCDW). Salinity and potential temperature reveal that the seawater at locations with $\Omega_A < 1$ belong to CDW (wAP and Prydz Bay locations) or modified Circumpolar Deep Water (at 48°E). The ACC transports these warm and CO_2-rich water masses around the Antarctic continent. In the large cyclonical gyres, i.e. the Weddell, Ross and Kerguelen

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

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

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

100 - 200 μmol kg^{-1} DIC increase is conceivable in high productivity areas based on the oxygen profiles by Sachs et al. (2009).

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

As discussed in section 2, shallow depth intervals are undersampled for several reasons. From the samples available for X-ray diffraction analysis only 10 samples were available from this important depth interval. Nine of those were from the wAP and one from the RS, which all fall into the domain of very high primary productivity and poor $CaCO_3$ preservation. We would expect to find pteropods to be preserved in regions with high pteropod densities, average primary productivity and seasonal sea-ice cover on rather narrow, shallow shelves where the ACC does not penetrate onto the shelf. This reduces possible accumulation sites for pteropods to few locations on the shallow swP/IO shelf, especially the Kerguelen Gyre. More samples along the coast would be needed to prove or disprove this hypothesis.

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

3.3. Macrozoobenthic carbonate abundance

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

In the western Antarctic Peninsula region macrozoobenthic community

$CaCO_3$ contribution (mean: 10.4 g $CaCO_3$ per m^2) is very patchily distributed. The macrozoobenthic $CaCO_3$ contribution in the wAP region is concentrated around the tip of the wAP, especially in the Bransfield Strait. The wAP south of 64°S alone has a mean $CaCO_3$ standing stock of 1.6 g $CaCO_3$ per m^2. At the tip of the Antarctic Peninsula, benthic communities thrive under the high primary productivity and export flux. Most $CaCO_3$ is produced by ophiuroidea (43%), echinoidea (19%), and bivalvia (13%) in the wAP region.

The eastern Antarctic Peninsula region, which is represented in this data set mainly by data from the Larsen shelf and the South Orkney Islands, and the western Weddell Sea show lower $CaCO_3$ contributions (7.4 and 5.4 g $CaCO_3$ m^{-2}, respectively). This is at least partly related to trophic limitations caused by extensive sea-ice cover. $CaCO_3$ is mainly produced by bivalvia (56%) and echinoidea (27%) in the eAP region and by ophiuroidea (35%), holothuroidea (24%) and bivalvia (15%) in the wWS region.

In general, the most important taxonomic groups that contribute to macrozoobenthic $CaCO_3$ standing stocks on the Antarctic shelves are bivalvia (32%), ophiuroidea (20%), asteroidea (12%), echinoidea (11%) and bryozoa (11%). Holothuroidea and gastropoda play a minor role and brachiopoda, scaphopoda, crinoidea and aragonitic hydrozoans contribute less than 2% each. The mean standing stock of $CaCO_3$ by macrozoobenthic organisms (15.6 $\pm$ 45.4 g $CaCO_3$ m^{-2}) and its range (0.001 - 585 g $CaCO_3$ m^{-2}) on the Southern Ocean shelves is comparable to the numbers found by

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

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

Bivalves produce 32% of macrozoobenthic $CaCO_3$ standing stocks, but, although aragonitic species occur, it is unknown to us which percentage of bivalves are aragonitic. However, as macrozoobenthic $CaCO_3$ inventories appear to be two orders of magnitude lower than sedimentary carbonates, aragonite is definitely only an insignificant part of the total $CaCO_3$. Echinoderms are responsible for half of macrozoobenthic $CaCO_3$ standing stocks and produce high-Mg calcite (Weber et al., 1969). Thus their skeletons will probably be the first to dissolve, before calcitic bryozoan and bivalve skeltons as well as calcitic foraminifera will be affected.

4. Conclusions

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

Over the next decades, Antarctic Surface Water might become the most acidic water mass in the Southern Ocean (Hauck et al., 2010) as the surface ocean accumulates most CO_2 from the atmosphere; the CO_2 increase in the deeper layers is much smaller due to mixing with waters poor in anthropogenic CO_2. Once the saturation horizon for calcite will become as shallow to reach the Antarctic shelves, locally present carbonate-rich sediments will dissolve. The capacity to buffer future acidification is small in high-productivity regions as the western Antarctic Peninsula and the Ross Sea and higher in the Bellingshausen, Amundsen and Weddell Seas. The buffering effect cannot be quantified yet, but this will be attempted in a modelling approach.

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

Dissolution of aragonite is not a mechanism which can buffer ocean acidification in the Southern Ocean, as aragonite is not a prominent constituent of surface sediments on the Antarctic shelves.

Comparison of the contributions of sedimentary carbonate and macrozoobenthic carbonate (> 500 μm) in the regions, from which data from both analyses is available (compare Figure 7), emphasized the sedimentary carbonate to be quantitatively more important in the marine carbon cycle. Sedimentary carbonate contents are two orders of magnitude higher than macrozoobenthic carbonate contents. Hence, neglecting large debris in the determination of sedimentary $CaCO_3$ content does not lead to a significant underestimation of the total $CaCO_3$ content. In the eastern Antarctic

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

Although we have no macrozoobenthos data from the Ross Sea, Bellingshausen Sea, Amundsen Sea, southwest Pacific and Indian Ocean, the classification we found in section 3.1 indicates that a situation similar to that in the wWS applies to the Bellingshausen and Amundsen Seas. We expect macrozoobenthic $CaCO_3$ stocks similar to the wAP in the Ross Sea and similar to the eWS in the Kerguelen Gyre. This classification is based on environmental conditions such as sea-ice cover, primary production, width of the shelf and water mass distribution. There was not enough data available to make 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 % $CaCO_3$

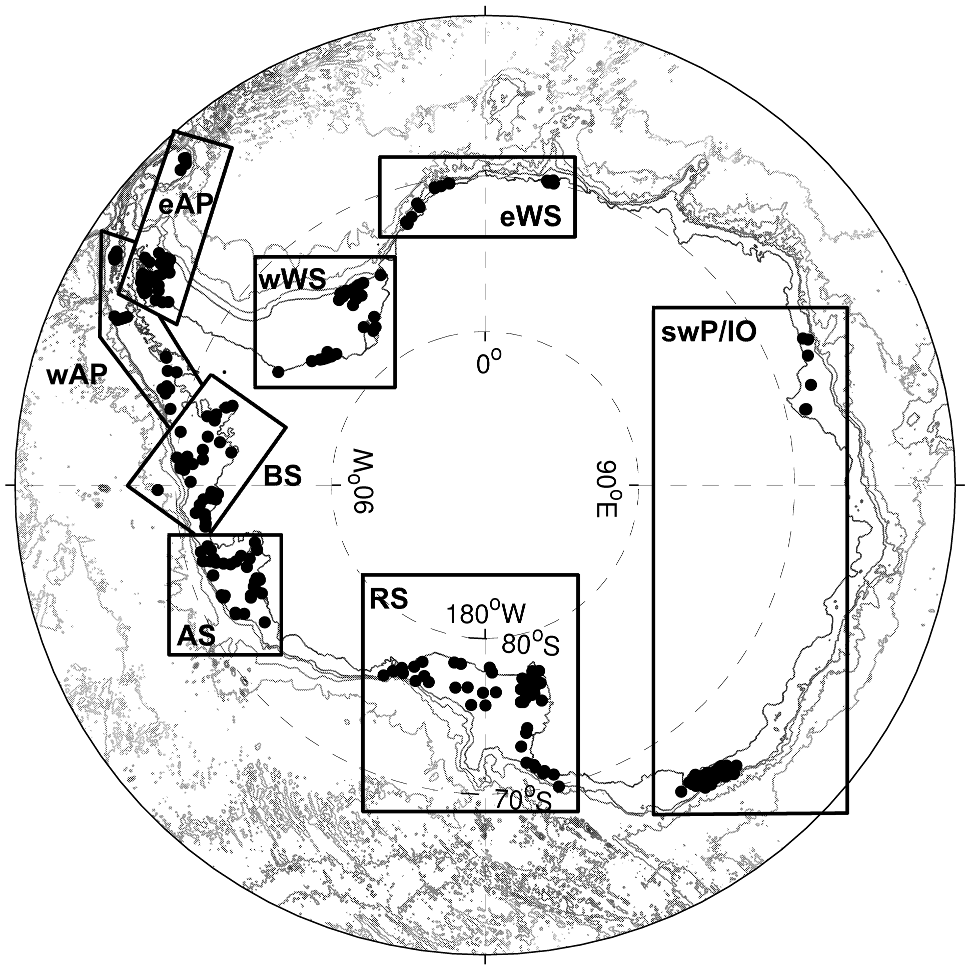
Figure 3: Sedimentary $CaCO_3$ content (%) (a) on the Amundsen Sea shelf and (b) on the Bellingshausen Sea shelf. Isolines are from the topography of Timmermann et al. (2010), lines are drawn every 200 m between 0 and 1000 m and every 500 m at water depths > 1000 m.

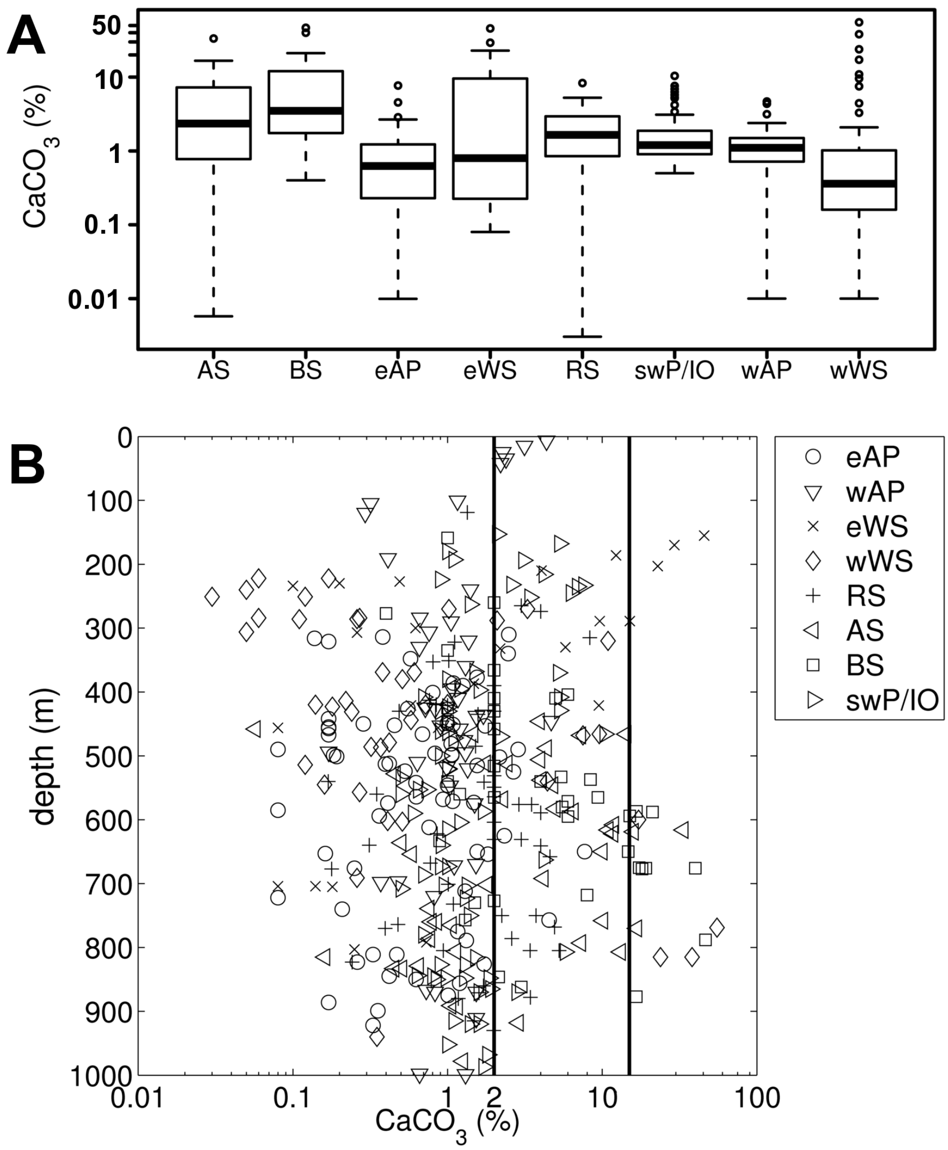
Figure 4: Bottom water Ω_A on the Antarctic shelves from GLODAP and CARINA data. Occurrence of undersaturation at depths shallower than 1100 m is marked with a black cross. Isolines are from the topography of Timmermann et al. (2010) and lines are drawn every 1000 m.

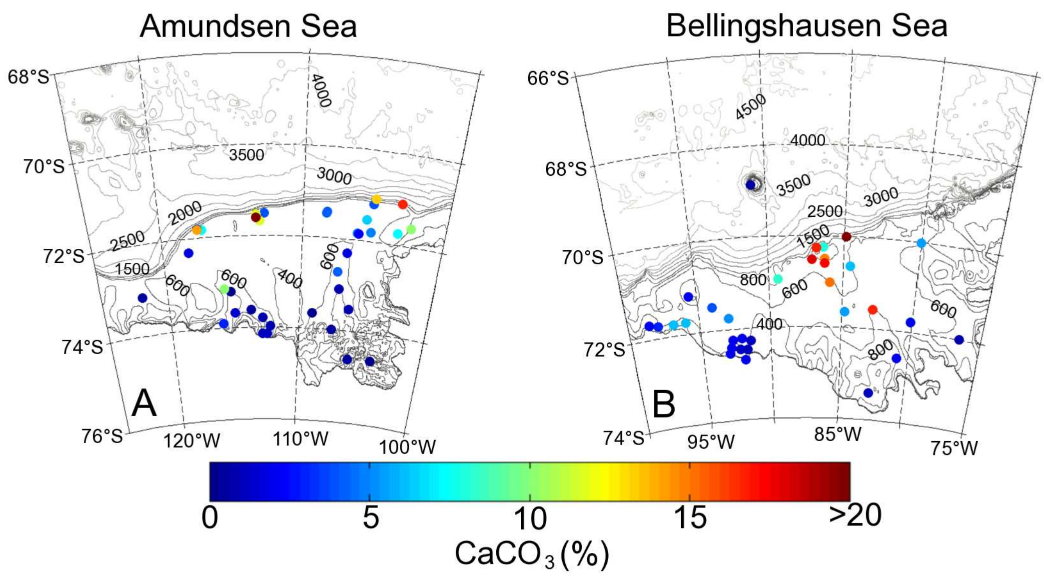
Figure 5: Bottom water saturation states (a) Ω_C and (b) Ω_A on the Antarctic shelves and slope from GLODAP and CARINA data. Calcite is supersaturated at all depths. A linear regression through Ω_A reveals a mean saturation horizon of about 1100 m with certain areas being undersaturated at even shallower depths. The grey diamonds and dotted regression line were calculated assuming a DIC increase of 20 μmol 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).

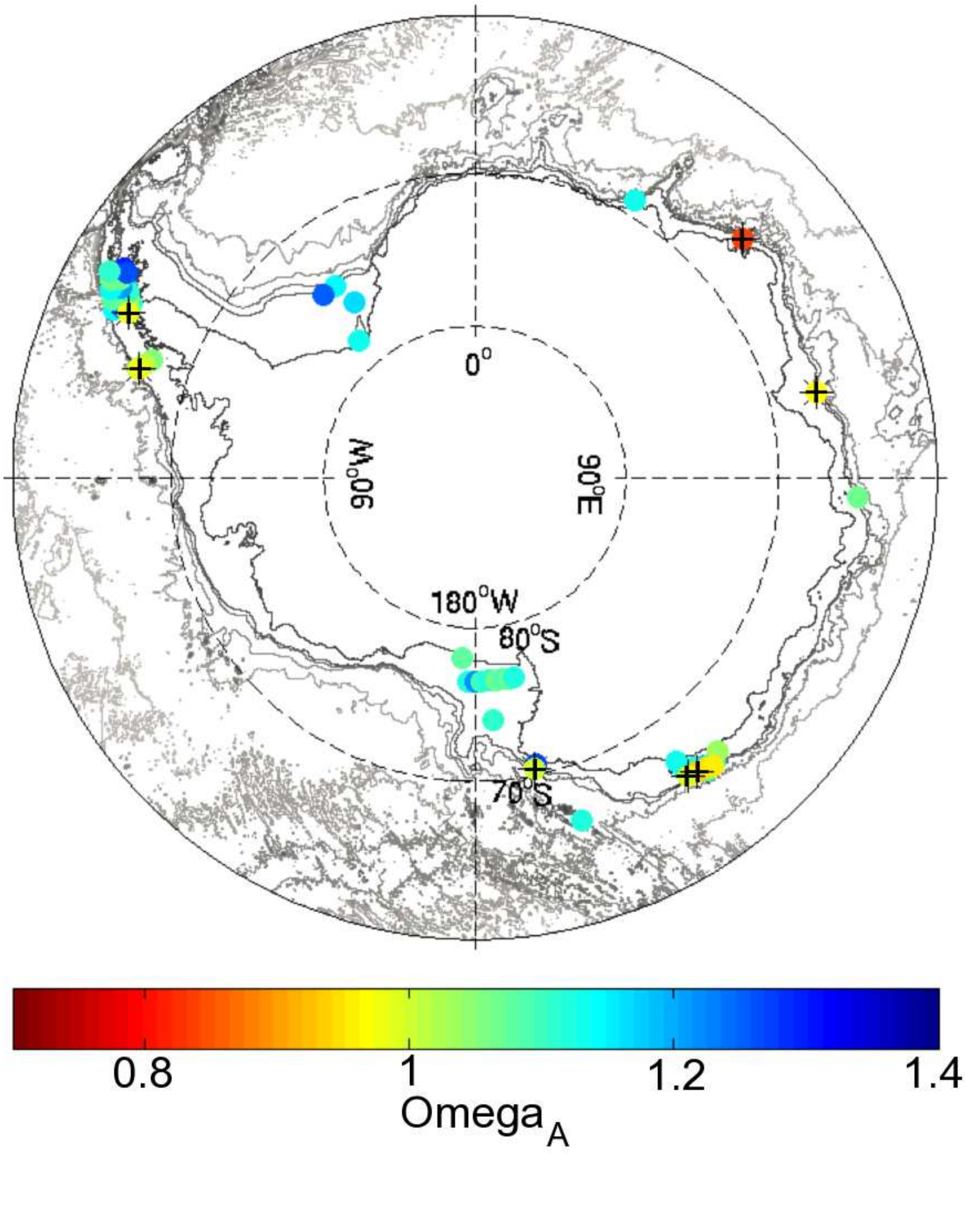
Figure 7: Mean carbonate contribution in g m^{-2} for the west and east Antarctic Peninsula (wAP and eAP) and western and eastern Weddell Sea (wWS and eWS) regions. Bars show the contribution by macrozoobenthos (left scale) and circles depict sedimentary $CaCO_3$ (right scale)

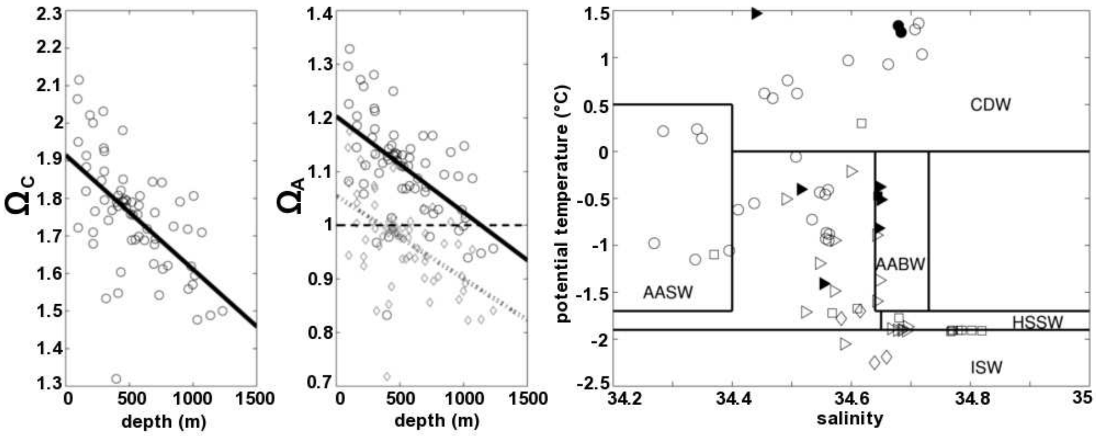

eAP
eWS
wWS
wAP
swP/IO
0°
90°W
90°E
BS
RS
180°W
80°S
AS
70°S


A
50
10
1
0.1
0.01
CaCO3 (%)
AS
BS
eAP
eWS
RS
swP/IO
wAP
wWS
B
0
100
200
300
400
500
600
700
800
900
1000
depth (m)
0.01
0.1
1
2
10
100
CaCO3 (%)
eAP
wAP
eWS
wWS
RS
AS
BS
swP/IO

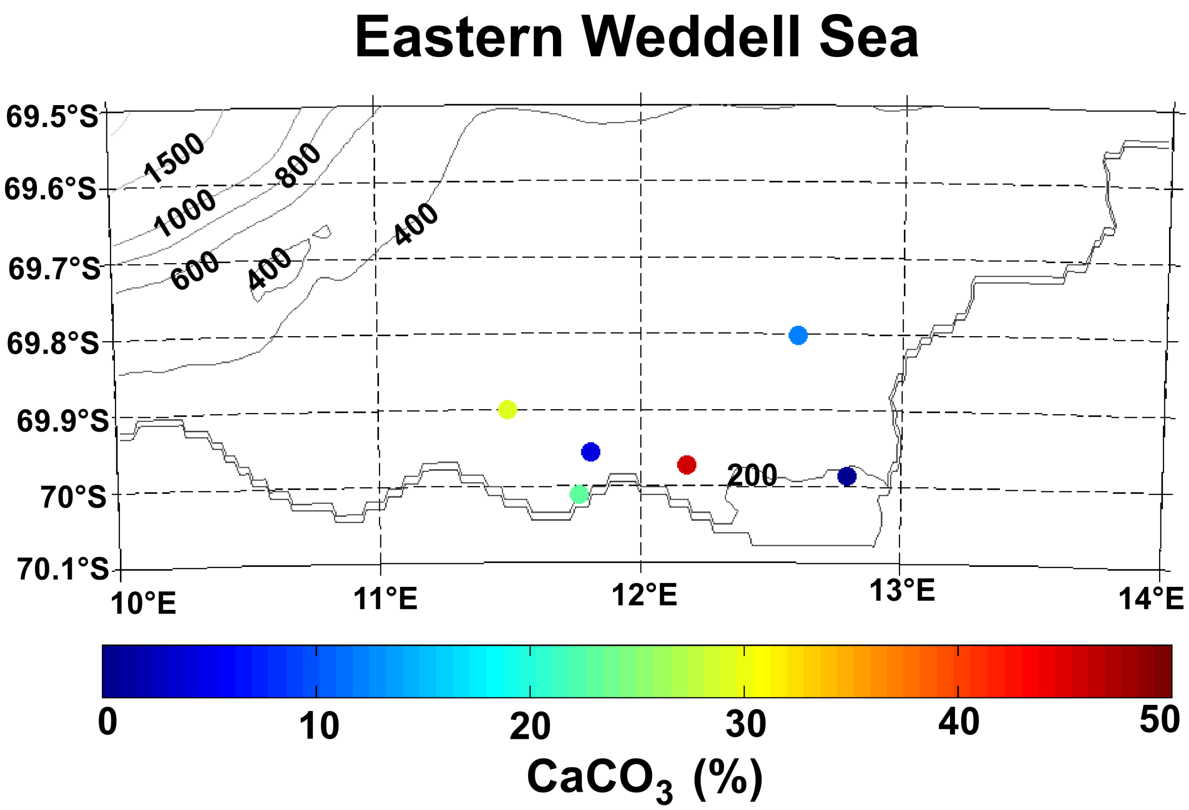


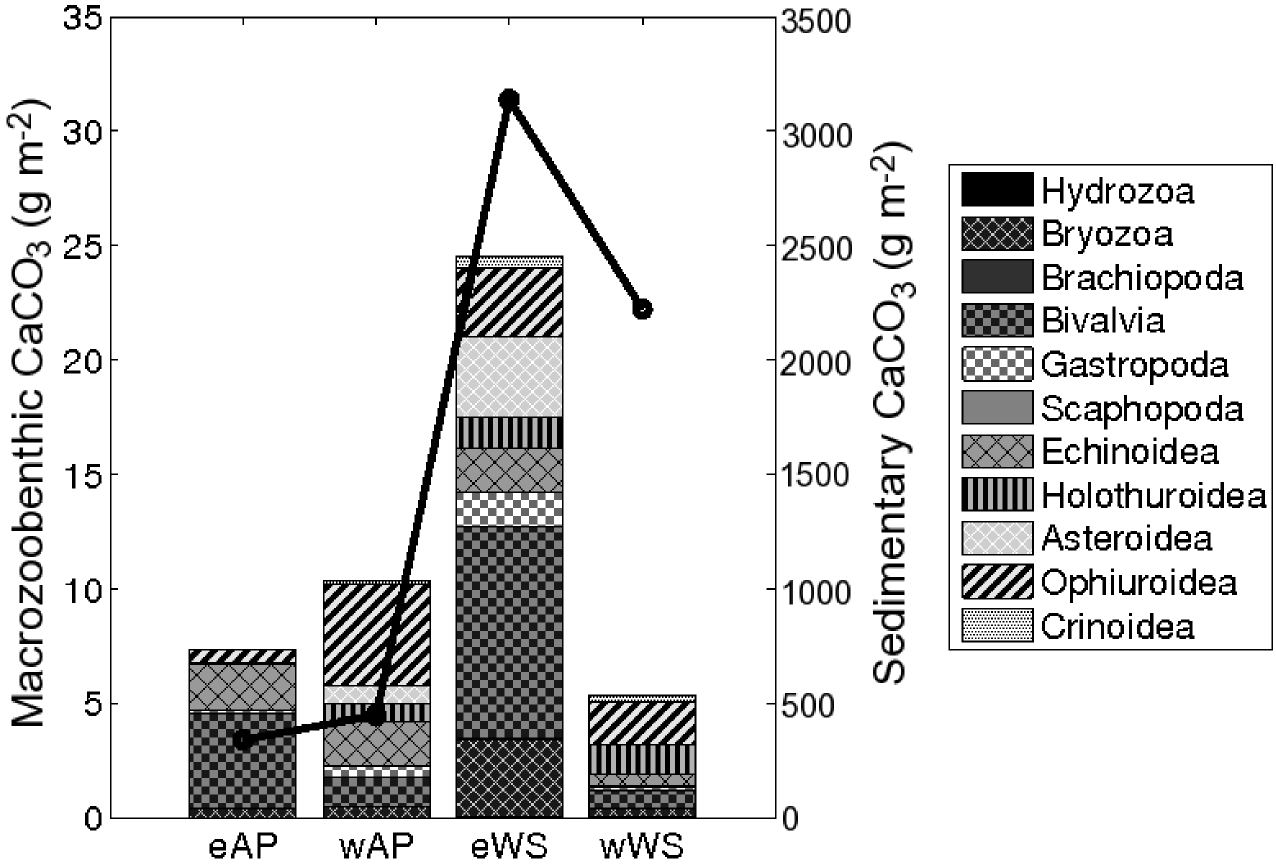
Amundsen Sea
Bellingshausen Sea
68°S
70°S
72°S
74°S
76°S
120°W
110°W
100°W
4000
3500
3000
2000
2500
1500
600
400
A
66°S
68°S
70°S
72°S
74°S
95°W
85°W
75°W
4500
4000
3500
3000
2500
1500
800
600
400
B
0
5
10
15
>20
CaCO3 (%)


0°
90°W
90°E
180°W
80°S
70°S
0.8
1
1.2
1.4
Omega_A



Ω_C
depth (m)
Ω_A
depth (m)
potential temperature (°C)
salinity
CDW
AASW
AABW
HSSW
ISW


Eastern Weddell Sea
69.5°S
69.6°S
69.7°S
69.8°S
69.9°S
70°S
70.1°S
10°E
11°E
12°E
13°E
14°E
1500
1000
800
600
400
400
200
0
10
20
30
40
50
CaCO3 (%)



35
30
25
20
15
10
5
0
Macrozoobenthic CaCO3 (g m-2)
3500
3000
2500
2000
1500
1000
500
0
Sedimentary CaCO3 (g m-2)
eAP
wAP
eWS
wWS
Hydrozoa
Bryozoa
Brachiopoda
Bivalvia
Gastropoda
Scaphopoda
Echinoidea
Holothuroidea
Asteroidea
Ophiuroidea
Crinoidea

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)